AFRL-SN-RS-TR-1998-221
Final Technical Report
January 1999

EHF SATCOM ARRAY DESIGN (ESAD)

TRW Space and Electronics Group

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AFRL-SN-RS-TR-1998-221 has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1999	Final Sep 96 - May 98

4. TITLE AND SUBTITLE

EHF SATCOM ARRAY DESIGN (ESAD)

5. FUNDING NUMBERS

C - F30602-96-C-0026
PE - 63726F
PR - 2863
TA - 92
WU - 78

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory/SNDR
25 Electronic Parkway
Rome NY 13441-4515

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFRL-SN-RS-TR-1998-221

11. SUPPLEMENTARY NOTES

Air Force Research Laboratory Project Engineer: James Nichter/SNDR/(315) 330-7423

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this effort was to develop five EHF SATCOM antenna designs that implement photonics: space and airborne, transmit and receive with nulling. The goal was to identify and develop designs that are performance and cost competitive with RF implementations.

The scope of this effort included investigation of photonically implemented antenna design concepts, an analysis trade of these concepts and detailed development of selected design concepts. Verification experiments were to be conducted as necessary to verify novel/unique photonic concepts.

EHF SATCOM used a 43.5 to 45.5 GHz uplink and a 20.2 to 21.2 GHz downlink. Airborne SATCOM antennas generally must provide wide angle scanning for a single beam, while the spaceborne antennas are multi-beam and include nulling capability.

14. SUBJECT TERMS

EHF, Photonics, Phased Array Antenna

15. NUMBER OF PAGES

262

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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1. Executive Summary

1.1. Program Objectives & Scope

The objective of this effort was to develop five EHF SATCOM antenna designs that implement photonics: spaceborne and airborne, transmit and receive with nulling. The goal was to identify and develop designs that are performance and cost competitive with RF implementations.

The scope of this effort included investigation of photonically implemented antenna design concepts, an analysis trade of these concepts, and detailed development of selected design concepts. Verification experiments were to be conducted as necessary to verify novel/unique photonic concepts. Key deliverables included a final briefing. a final report, and a design plan.

EHF SATCOM uses a 43.5 to 45.5 GHz uplink and a 20.2 to 21.2 GHz downlink. Airborne SATCOM antennas generally must provide wide angle scanning for a single beam, while the spaceborne antennas are multi-beam and include nulling capability.

"Develop **photonically** implemented EHF SATCOM **antenna** design plans"
- Investigate beamforming, beam steering, nulling, signal distribution and control
- Analyze, Trade and Select
- Develop detailed Design Plans for selected implementations

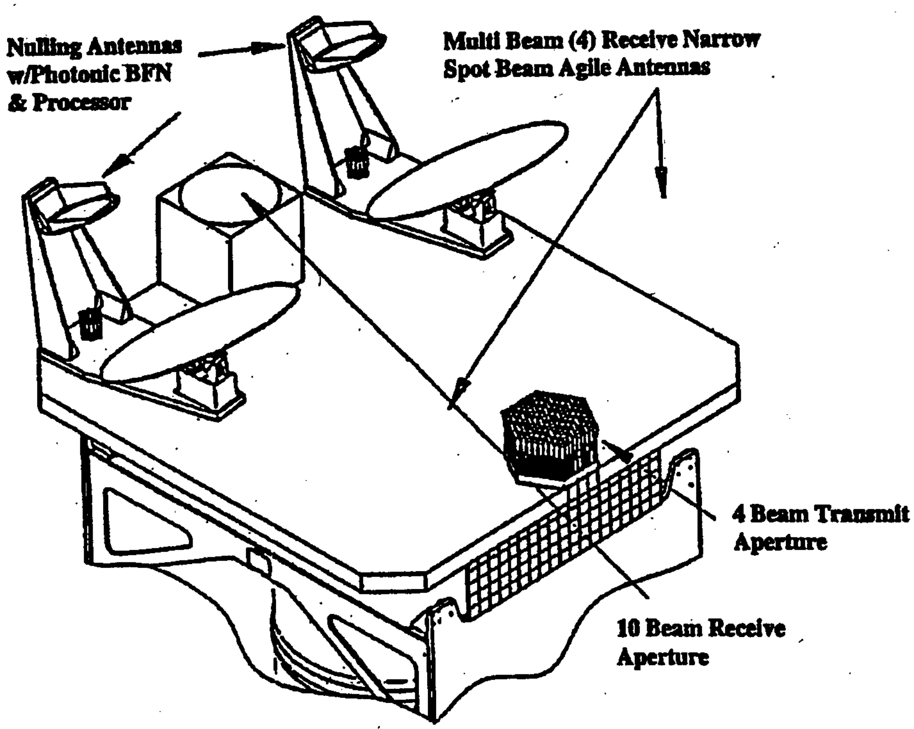


Figure 1. SATCOM Layout Plan.

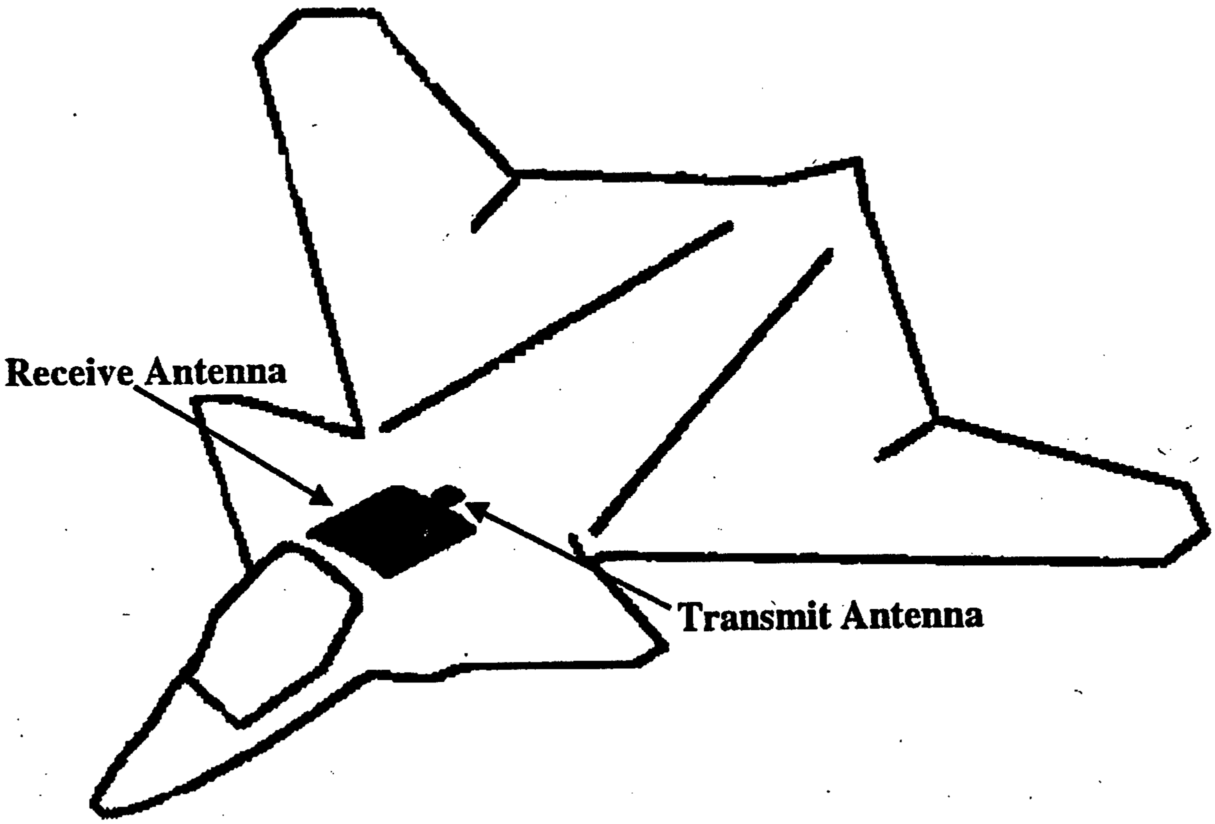


Figure 2. Airbourne layout Plan.

1.2. Accomplishments

In summarizing the key accomplishments of the ESAD program, we identify the successful completion of the several tasks and areas of study identified at the commencement of the contract. The first key accomplishment is the completion of our comprehensive trade study of photonic component technologies and system structures that are relevant to the implementation of phased array and multiple beam antenna beamforming architectures. Our investigation was derived from information obtained through technical research and development literature including technical journal letters and papers, conference reports, government contract reports, and TRW IR&D reports. We examined a wide variety of technologies and provided a thorough evaluation and supporting analysis for the selection of technologies feasible for insertion in SATCOM antenna systems.

Our architecture trade study examined a wide variety of architecture concepts that showed promise for the implementation in photonics for application to SATCOM antenna systems. We provided a sufficient analysis to identify the strengths and drawbacks of each technology and antenna structures that could most benefit from incorporation. We also provide backup analysis, when necessary to clearly recognize the appropriateness of incorporating the several architectures in to the airborne and spaceborne antenna systems. Some supporting analysis was completed to determine component performance goals necessary for adequate system performance, and a size, weight, and power tabulation useful in comparing competing photonic architectures and baseline RF implemented antenna systems.

Antenna architectures were downselected for five SATCOM antennas (including the space based receive nulling antenna) and a design plan was composed to more clearly quantify the structure of the conceptual architecture.

Most importantly, through the performance of these principal tasks, we have identified the key performance and implementation challenges for SATCOM antennas and the key features of photonic technologies and architectures that can enable desired performance and functionality for next generation EHF SATCOM antenna systems.

1.2.1. Comprehensive investigation/trade of relevant photonic components & technologies
Optical sources, modulators, amplified distribution, true time delay, variable phase/RF downconversion, signal combining, WDM multiplexing, switching, photodetectors, optical beamformers (RF Mixing Feed, Rotman, Butler) and optically controlled media

1.2.2. Assessed/traded photonically implemented scanning arrays and several types of MBA
Quasi-optical/circuit MBA's, hybrid beamformers
Performance goals advanced from current Milstar to reflect future aggressive SATCOM applications

1.2.3. Selected 5 candidates, and developed detailed design plan for each
SB RCV: Array Fed Reflector
SB Nuller: Array Fed Reflector with Photonic BFN & Processor
SB TX: Multi-Beam Scanning Array
AB TX: Aperiodic Scanning Array
AB RCV: Single Beam Scanning Array

Identified key performance and implementation challenges for each SATCOM antenna and the principal photonic technology leverage that enables advanced MilSatCom capability

1.3. Three High Leverage Insertions for Photonics

1.3.1. Space Based Receive Antenna

Challenge is packaging for multiple beams _ Precludes scanning array, favors MBA· RF scanning array cannot package ten beams

- · Photonic scanning array consumes prohibitive amount of power

Key challenge with MBA is switching complexity

- · Photonics mitigates swit*ching complexity*

1.3.2. Nulling Antenna

Complexity, cost, performance favors large reflector and more feed elements

- · *Photonics provides low power parallel processing capability*

Nulls move with frequency resulting in decreased wide band jammer suppression

- · *Photonic tapped delay line BFN provides frequency dependent phase weighting*

1.3.3. Airborne Transmit

Key challenge is thermal density

- · Trade density (few elements, high power) and cost (more elements, low power)
- · *Photonics enables reduced element density to mitigate thermal limitations*
- · Reduces thermal density to enable more power per element
- · Reduced scan loss (more isotropic element is possible)
- · Result is fewer elements and lower cost

Aperiodic spacing and TTD required to suppress grating lobes and beam squint

- · *Photonic BFN for packaging and TTD*

1.4. Photonics Provides Less Leverage Against Key SB TX, AB RCV Challenges

1.4.1. Space Based Transmit Antenna

- · Key benefit is reducing weight
- · Trade of beamformer losses vs. weight
- · *Photonic BFN provides reduced weight*
- · Interference/Suppression limitations (multiple carriers in SSPA)
- · Additional challenge is providing multiple beams
- · Limited by <u>packaging</u> and <u>SSPA non-linearities</u> (suppression and interference)
- · *Photonic BFN eliminates packaging constraint, focus on SSPA development*

1.4.2. Airborne Receive Requirements preclude use of quasi-optical MBA

- · Single beam mitigates utility of MBA, favors scanning array
- · *Photonic BFN for multi-beam enables aperture consolidation*
- · Photonic receive array consumes large amounts of power (2x RF BFN)
- · For single beam, RF BFN with no TTD (i.e. band hopping) is favored

1.5. Spaceborne Performance Goals Consistent with MilSatCom

The spaceborne receive antenna performance goals presented in the table below are derived from the ESAD contract SOW, Milstar, and Advanced EHF IR&D programs. The 10 beam coverage is an aggressive performance goal relative to Advanced EHF and current Milstar development. Although a performance goal for receive noise figure was given in the ESAD SOW, the performance metric more common to characterizing the performance of receive antenna systems is the G/T metric. We have chosen the G/T design goal of 10 dB consistent with Advanced EHF.

The table below also presents the channel allocation in the uplink band. The antenna should be designed to allow the uplink of several simultaneous MDR COMM channels from the airborne platform. This is an aggressive requirement relative to Milstar and for the scanning arrays will necessitate the subdivision of the antenna array for true time delay control. The multi-beam requirement also calls for the formation of spot beams or full earth coverage beams through use of the subarray or through beam spoiling. The overall utility of the spaceborne receive antenna is in providing high capacity availability in a consolidated aperture.

Performance goals for the spaceborne transmit antenna are also derived from the ESAD contract SOW, Milstar and Advanced EHF. The most aggressive requirement is capability for 4 simultaneous beams. For the current RF scanning array implementations, the number of beams is limited primarily by the carrier to interference and suppression performance of the output power amplifiers. For this reason the Advanced EHF baseline is likely to be revised from four beams in one aperture to four single beam apertures. We have assumed as a performance goal four beams in one consolidated aperture as this is consistent with the ESAD contract SOW. We have not selected a performance goal more aggressive than 4 beams per aperture because photonics cannot mitigate limitations imposed by the power amplifiers. Incorporation of more than 4 beams is an attractive goal, and could be achievable if relaxation of packaging limitations enable the formation of > 4 beams in a photonically implemented scanning array. Nevertheless, preliminary considerations indicate that significant leverage is obtained from the use of photonics to reduce the overall weight of the multiple beam architecture.

Multi-channel capability provides limited utility to the function of this terminal and as such, phase only beamsteering is adequate and true time-delay is not required. Given this set of performance requirements, the principal challenges associated with implementing this beamformer are to enable aperture consolidation and reduced payload weight. Beamformer remoting may assist in producing a design that meets the harsh environmental constraints consistent with space deployment.

Table 1. Spaceborne Receive Spectrum Allocation

Item	*Requirement*	*Source*
Number of Beams	10	SOW
Beam Shape	Spot and full Earth cov.	SOW
Frequency	43.5 – 45.5 GHz	SOW
Polarization	Single, circular	SOW
Coverage	+ or - 9.3 degrees	SOW , Milstar
Noise Figure	<3.2 dB	SOW
Beam Update Rate	20 kHz	Milstar, Adv. EHF
Beam Settling Time	< 0.9 microseconds	Milstar, Adv. EHF
G/T (spot beam)	10 dB*	Advanced EHF
Sidelobe level (first)	25 dB below peak	Advanced EHF
Spot beamwidth	1.0 degree	Advanced EHF
Jammer Cancellation	40 dB	Advanced EHF
Additional Requirements	Design compatible with space environment	SOW

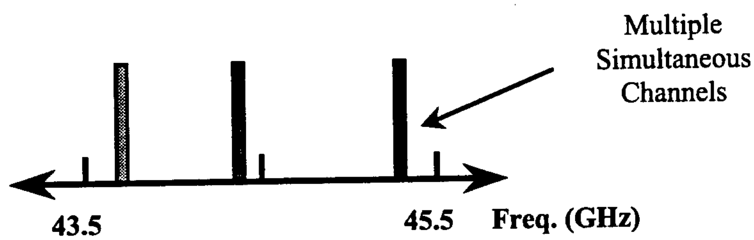


Figure 3. Spaceborne Receive Spectrum Allocation.

Table 2. Spaceborne Transmit Spectrum Allocation.

Item	*Requirement*	*Source*
Number of Beams	4	SOW
Beam Shape	Spot and full Earth cov.	SOW
Frequency	20.2 to 21.2 19.7 to 20.2 for GBS	SOW
Polarization	Single, circular	SOW
Coverage	+ or - 9.3 degrees	SOW , Milstar
EIRP (spot beam at EOC)	<3.2 dB	SOW
Beam Update Rate	20 kHz	Milstar, Adv. EHF
Beam Settling Time	< 0.9 microseconds	Milstar, Adv. EHF
Sidelobe level (first)	Not specified	
Spot beamwidth	1.0 degree	Advanced EHF
Carrier to Noise	15 dBC	Tx MBPA
Additional Requirements	Design compatible with space environment	SOW

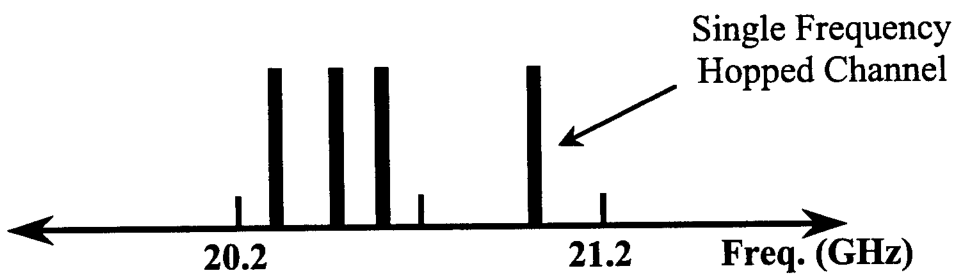


Figure 4. Spaceborne Transmit Spectrum Allocation.

1.6. Airborne Performance Goals Extended Beyond MilSatCom Requirements.

The performance goals for the EHF airborne receive antenna are based on those goals presented in the ESAD contract SOW with additional derivation from sources such as the current Milstar system and Advanced EHF IR&D activity. Photonically implemented scanning arrays provide little leverage over those antennas implemented in RF when compared on the basis of current Milstar requirements. Single channel (50 MHz) capacity in a single beam eliminates the requirement of true time-delay steering and places no strict requirement on the packaging of the array. These performance goals tend to favor RF implementations because Milstar requirements were developed consistent with RF component capability.

Given these conclusions from our initial architecture study, we were compelled to develop a more challenging set of performance goals leading us to consider the consolidation of apertures utilized to establish links with multiple space based COMM assets. By extending the overall bandwidth requirement to cover 7.25 to 21.2 GHz we enable a single aperture to assess multiple assets with multiple beams each requiring relatively narrow spectral coverage. Presently these channels are assessed through at least 4 separate apertures. Consolidation of these apertures would result in slightly increased weight, but would lead to maximal conformity to the aircraft surface. A rather large fraction of the beamforming hardware would be remoted from the surface of the craft which would provide maximal structural integrity by both limiting the number of arrays and the hardware located at the array. These types of multibeam performance goals are consistent with recent USAF and USN efforts (e.g. MERS).

Similarly, although the total transmit bandwidth is 2 GHz (44.5 ± 1 GHz), an RF scanning array can transmit a single 50 MHz data channel without beam squint (< .002 dB penalty) by adjusting the phase weights at each frequency hop. We therefore extended our baseline performance goals by requiring transmission of multiple 50 MHz channels to the Milstar satellite, which provides increased data capacity and functionality. The antenna beamforming then requires some level of true time delay, although because we have retained the 2 GHz bandwidth allocation, we enable only slight leverage from the incorporation of photonically implemented TTD. If this allocation were further increased to enable uplinking of wide-band imaging data the impact of incorporating photonics would be more substantial. However, increasing the 50 MHz channel bandwidth and the 2 GHz spread spectrum bandwidth was rejected because of incompatibility with the existing Milstar communication architecture.

Table 3. Airborne Receive Spectrum Allocation.

Item	*Requirement*	*Source*
Number of Beams	> or = 4	Aggressive SOW
Beam Shape	spot.	SOW
Frequency	see spectrum figure below	Aggressive SOW
Polarization	adaptable ⇒ dual cp	SOW
Coverage	70 degrees cone	SOW , Milstar
G/T (@ max scan)	5 dB*	Advanced EHF
Beam Update Rate	20 kHz	Milstar, Adv. EHF
Beam Settling Time	< 0.9 microseconds	Milstar, Adv. EHF
Sidelobe level (first)	25 dB below peak	Advanced EHF
Spot beamwidth	not specified	
Jammer Cancellation	not specified	
Additional Requirements	Target Search Capability. Flat, thin, compatible with C-17, E-3A, UVA, Fighter	SOW

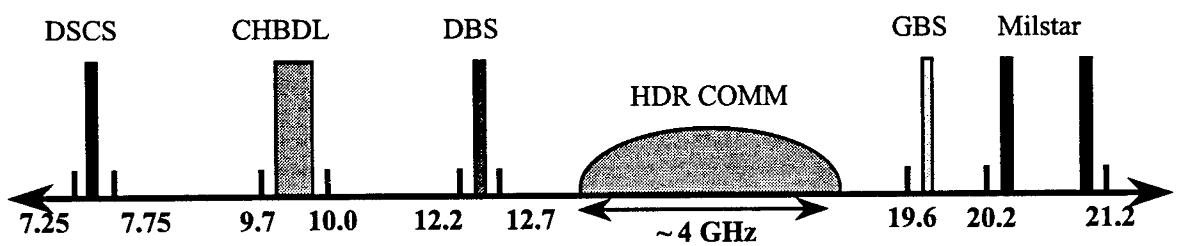


Figure 5. Airborne Receive Frequency Allocation of COMM Assets.

Table 4. Airborne Transmit Spectrum Allocation.

Item	*Requirement*	*Source*
Number of Beams	1	SOW
Beam Shape	spot	SOW
Frequency	43.5 – 45.5 GHz	SOW
Polarization	Single, circular	SOW
Coverage	70 degrees cone	SOW , Milstar
EIRP (@ EOS)	45 dBW	SOW
Beam Update Rate	20 kHz	Milstar, Adv. EHF
Beam Settling Time	< 0.9 microseconds	Milstar, Adv. EHF
Sidelobe level (first)	not specified	
Spot beamwidth	not specified	
Carrier to Noise	15 dBC	Assumed (SB Tx)
Additional Requirements	Flat, thin, compatible with C-17, E-3A, UVA, Fighter	SOW

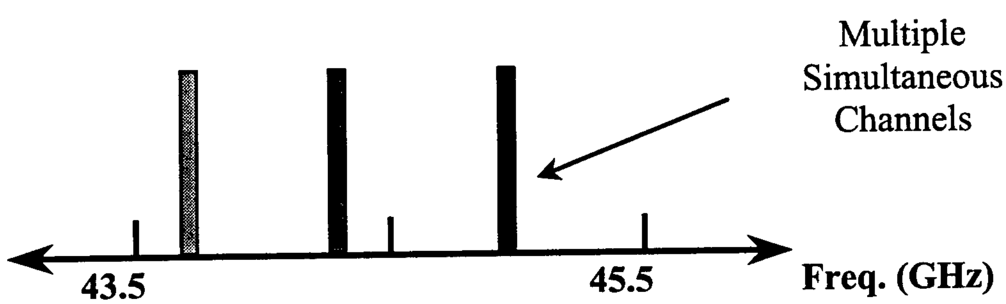


Figure 6. Airborne Transmit Frequency Allocation of COMM Assets.6

1.7. Photonic System Trade Space

The general characteristics of EHF Airborne and Spaceborne antenna systems place certain requirements on the performance and applicability of photonic components considered for insertion. The following paragraphs present the results of our component technology and beamforming concept tradeoff study for optically controlled EHF SATCOM antennas. The conclusions presented here are based on our knowledge of the general performance and reliability requirements of these antennas as well as those lessons learned from the considerable architecture development performed during the course of the ESAD program. The following outlines some of those general characteristics and the principal issues affecting the selection of technologies for insertion.

1.7.1. Large Number of Antenna Elements

The cost of these antennas are primarily driven by the number of elements required to achieve a certain level of performance. Minimizing this number requires that significant levels of optical power be delivered to each element modulator or photodetector. Optical amplification is then required to accomplish the necessary signal distribution, or alternatively, efficient power routing architectures are required to send power to active antenna elements. For receive antennas, large numbers of signals must be coherently combined in order to achieve adequate SNR and performance.

1.7.2. Multiple Beam Requirements

Multiple beams imply highly parallel signal paths and the possible requirement of multiple wavelengths to facilitate beamforming.

1.7.3. RF Downconversion / Variable Phase Control

Adequate phase noise performance, resolution and stability, over adequate bandwidths are important in accomplishing this function. Downconversion from EHF frequencies (up to 46 GHz) is important in enabling high performance beamforming architectures.

1.7.4. Reliability

Minimal complexity and maximal reliability in potentially harsh environments demonstrating radiation, mechanical shock, and temperature extremes is crucial as well in establishing useful antenna architectures.

1.7.5. Integrability

Finally, consideration must be made as to the compatibility of device technologies and beamforming structures with other system structures. For example, if quadrature bias on the modulator is necessary to accomplish a beamforming function, but is incompatible with downconversion, then some adjustments must be made in the architecture to enable the simultaneous execution of these functions.

Several antenna system requirements influence appropriate technology choices for EHF beamformer design.

1.7.5.1. Large number of elements

- High optical power to each element
- Optical amplification/Signal Distribution
- Large order element combining

1.7.5.2. Multiple beams (space based antennas)

- Increased number of parallel channels
- Multiple wavelength operation

1.7.5.3. Microwave downcoversion

- Polarization independence
- Adequate phase noise performance
- Low complexity

1.7.5.4. Variable amplitude-phase-time control

- Resolution-stability
- Reconfiguration Speed
- Bandwidth

1.7.5.5. Reliability

- Temperature-radiation insensitivity
- Minimal size-weight-power
- Mechanical robustness
- Minimal Complexity

1.7.5.6. Integrability
Consistency between component and system requirements

1.8. Photonic Technology Trades

The selection of an optical source impacts the implementation of the entire beamforming architecture through determination of the operation wavelength for all constituent architecture components, optical power available for the photonic distribution or processing, and phase, frequency and amplitude noise performance at the output of the photonic link. DFB or DBR semiconductor lasers seem to offer the most attractive combination of reliability (for space application), compactness, and performance to meet the requirements imposed on the several antenna systems. Although Nd:YAG sources offer high power, this power is not enough to circumvent optical amplification for the distribution and fails to represent an attractive technology for insertion into SATCOM antenna systems.

Optical modulators represent a second critical component for adequate system performance. Modulator V_{Π}, insertion loss, and optical power handling capability impact system gain, noise figure, and linearity of the beamforming architecture. For receive antennas, large numbers of modulators may be necessary and as such should be made compact and biased to require low amounts of DC power. Modulator frequency performance is also critical for adequate operation and tends the overall trade towards EAMs, semiconductor MZ modulators, or polymer devices.

True time delay can be implemented at the subarray level with element level phase control, or entirely at the element level. One result from the SHF program is that there is little difference in the performance of these two systems. For large arrays, subarray level control is adequate. Insertion loss, and environmental stability are the most significant figures of merit.

Optical switching is crucial in the establishment of several multiple beam antenna architectures. A compact, low loss, high isolation, and fast switch is necessary for the successful establishment of these proposed architectures. Candidate technologies are limited, but some are promising for meeting the switching goals established for these systems.

For large arrays, splitting losses are substantial and must be compensated with optical amplification. The main considerations are noise figure, optical power saturation, dynamic range and the possibility of integrated amplitude control.

Photodetectors are critical components for both transmit and receive antennas. High power handling detectors in transmit antennas enable strong RF signal generation which reduces requirements for the driver and power amplifiers. For receive antennas, high power handling with high responsivity enables large scale signal combining without substantial RF gain penalties.

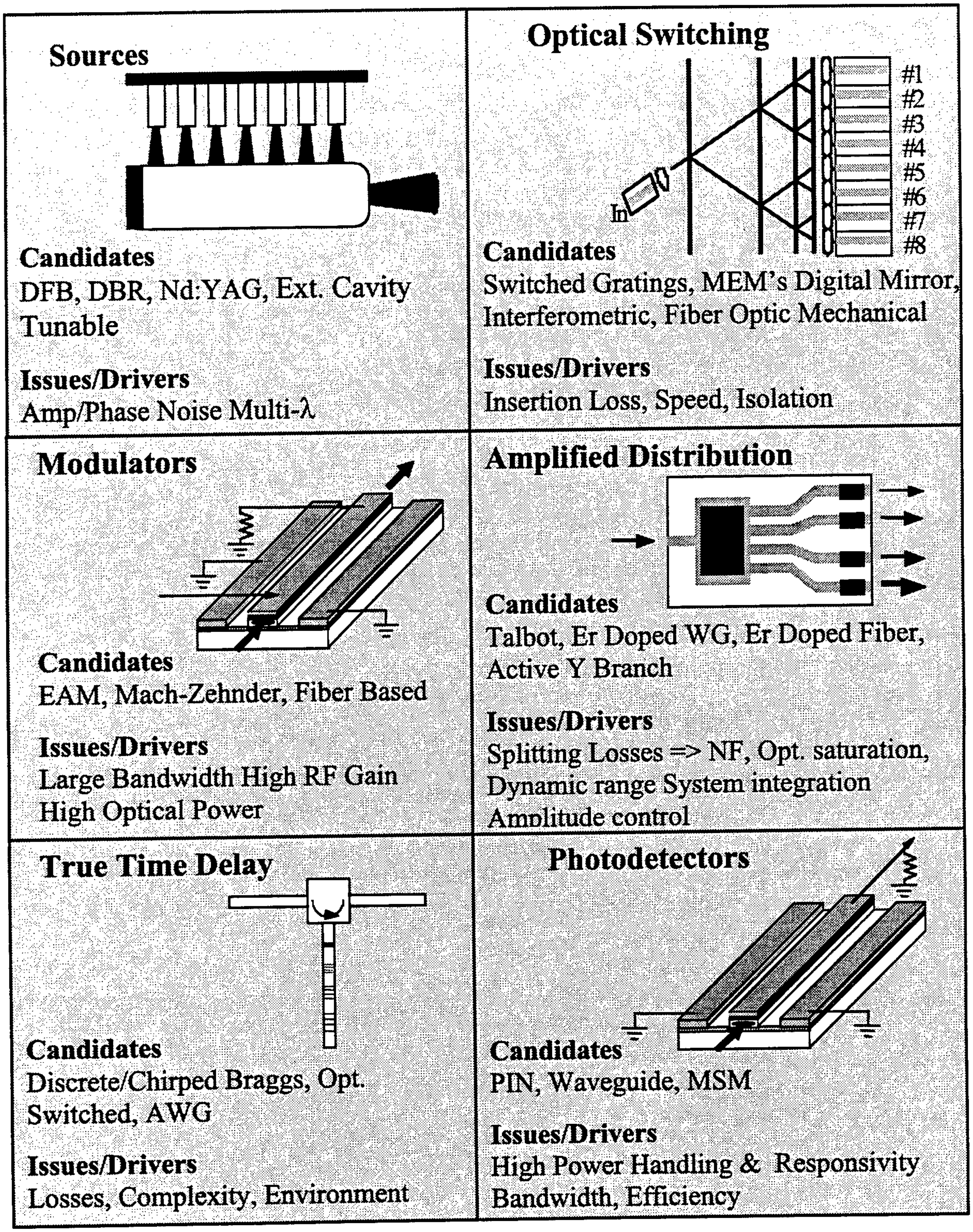


Figure 7a. Photonic Technology Trades One.

Optical variable phase control and RF down (up) conversion are usually implemented together. The challenge is in determining a method for efficiently mapping the variable phase of the RF local oscillator to the RF signal. Some antenna architectures require only frequency conversion and offer the possibility of implementing different techniques and technologies.

Signal combining is required for receive antenna beam forming. Signals can be combined optically or in RF after photodetection. Insertion loss, bandwidth, and scalability are the primary concerns, except in nulling applications where maintenance of amplitude stability is critical to acceptable performance.

WDM multiplexers find use in facilitating multiple beam forming, true-time-delay implementation, and optical signal combining. Until the advent of reliable high power tunable laser sources, Bragg grating true-time-delays will be implemented with multiple DFB lasers at different fixed wavelengths. WDM multiplexers will be required for combining these signals with low insertion loss.

Several types of "optical beamformer" were traded. These included optical implementations of the Rotman Lens, the Butler Matrix, and the "RF mixing feed" approach developed at Hughes. Optically controlled media was also investigated.

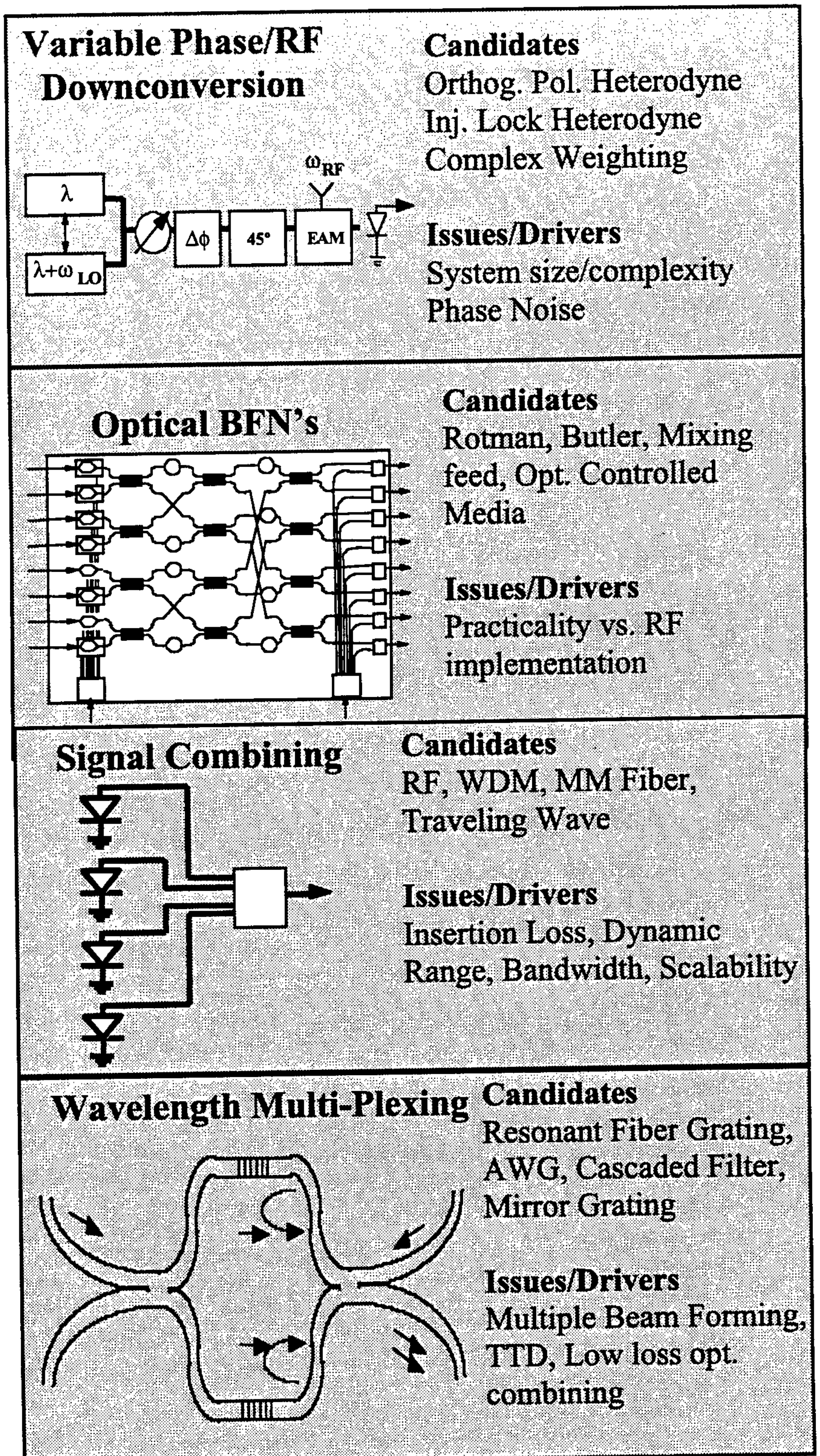


Figure 7b. Photonic Technology Trades Two.

1.9. Photonic Technology Tradeoff Conclusions

1.9.1. Optical Sources

Until DBR lasers are commercially available, there is no reliable tunable source available for implementing WDM architectures. Grating stabilized DFB lasers arrays are the most attractive in meeting the high power, low noise requirements of WDM beamformers.

1.9.2. Modulators (RF to Optical)

High frequency, high dynamic range requirements for receive antennas lead to selecting EAMs or linearized semiconductor MZMs for these systems. High power systems could benefit from a highly efficient polymer modulator as well.

1.9.3. Amplified Distribution

With improved noise figure, semiconductor amplifiers seem the best choice for radiation hardness and the integration of variable amplitude control. The use of Er doped waveguides is also attractive, and for certain applications may provide acceptable performance.

1.9.4. True-Time-Delay

Bragg grating techniques are prolific in architectures being developed by the RF photonics community. They clearly demonstrate the preferred method for most applications.

1.9.5. Variable Phase/RF Downconversion

For phased arrays with many elements, orthogonal-polarization heterodyne techniques will provide the lowest size/weight/power system. For antenna architectures that require no element phase control, injection locked heterodyne techniques are very attractive.

1.9.6. Signal Combining

For phased arrays, the use of RF combiners or WDM to facilitate signal combining is attractive except for very high numbers of elements, where the large number of required wavelengths may make WDM impractical.

1.9.7. WDM Multiplexing

With adequate temperature stabilization, Bragg-grating multiplexers will provide very low-loss multiplexing for WDM systems.

1.9.8. Optical Switching

Switchable gratings and MEMs based switches are most attractive for accomplishing the functionality required in several architectures.

1.9.9. Photodetectors (Optical to RF)

Waveguide photodetectors are useful except for receive antennas utilizing optical combining. The required multi-mode waveguides forces the use of large area photodetectors to maintain a high detecting efficiency.

1.9.9.1. Semiconductor based lasers are most attractive for ESAD architectures
Grating stabilized DFB for single wavelength, DBR or DFB arrays for multiple wavelength

1.9.9.2. EAMs required for high frequency, high dynamic range
Linearized semiconductor and polymer MZM modulators are also very attractive

1.9.9.3. Talbot amplified splitter to provide amplitude control and reliability
Airborne applications require further NF reduction (Er:doped waveguides are also attractive)

1.9.9.4. Bragg grating TTD for low loss and reliability
With multiple DFB WDM discrete gratings most useful

1.9.9.5. Variable phase/RF downconversion selection depends on architecture
Orthogonal polarization heterodyne for many elements and variable phase.
Injection locking if no phase control required and complex weighting for few elements

1.9.9.6. WDM combining impractical for many elements, but attractive for routing architectures
RF combining is our baseline for large scale signal combining

1.9.9.7. Bragg grating multiplexers are best choice for low loss and fiber compatibility

1.9.9.8. Switchable grating or MEMs based switches are attractive for some architectures

1.9.9.9. Waveguide photodetectors provide best trade between bandwidth, power, and responsivity
Improved quantum efficiency could make MSM more attractive

1.10. Photonic Beamforming Structure Tradeoff Conclusions

1.10.1. RF Mixing Feed:
This is an innovative technique that is made much more feasible with fiber optics. The multi-beam capability at first seems to be attractive for a spaceborne antenna implementation. However, multi-beam capability beyond two or three beams leads to significantly increased complexity. More serious is the substantial beam squint that is inherent to this approach. As such, it a relatively unattractive approach for EHF SATCOM antenna applications.

1.10.2. Butler Matrix:
Of all the beamforming architecture concepts we have examined, this approach could eventually lead to the most compact structure possible. The costs of this approach are associated with the requirement of environmental stability (so as to maintain optical coherence), and the necessity of optical LO distribution to all output ports so as to enable optical homodyne detection and achieve adequate link gain (a strong LO is injected so that the detected power is at an acceptable level). Such complexity issues make this architecture concept a challenging one to implement at this time. Finally, a sophisticated switch structure is required for beam selection at the output of the beamformer.

1.10.3. Optically Implemented Rotman Lens:
The Rotman lens is a useful architecture concept that has demonstrated limited success when implemented in optics. The geometry scales with RF signal wavelength making the size of these structures much more compact and attractive for airborne transmit and spaceborne receive antennas. The significant challenge is associated with the optical combining required for both multi-beam transmit and receive applications which leads to the realizable structures incorporating wavelength division multiplexing. Implementation of two dimensional beamforming is challenging as well with this structure. Some attractive insertions might incorporate optical and RF Rotman lens structures. Constrained feed Rotman beamformers implemented in Silica waveguide is also an attractive structure and is considered for several architecture implementations.

1.10.4. Optically Controlled RF Media:
Plasma grating based antennas may be useful for narrowband applications, but will find more limited application in EHF SATCOM systems. Optically induced wavefront steering is attractive because it allows use of a high power source (e.g a TWTA) and eliminates power generation and phase control at the element level (i.e. reduced module cost and thermal design complexity). However, the slow reconfigurability of these structures (due to the high RF loss during plasma stabilization) is unattractive for SATCOM applications and makes this a approach that provides limited utility at this time.

1.10.4.1. RF Mixing Feed

Multi-beamforming capability and single point beam control are good features for SB Tx

Beam squint is severe, precludes EHF applications

1.10.4.2. Butler Matrix

Optical Coherence may preclude use in space environment

1.10.4.3. Optical Rotman Lens

Size impractical for SB Tx

True-time-delay beamforming desirable for airborne transmit

Necessity of optical combining (coupling for single beam) lends to use of multiple _

Alignment tolerances critical (integrated-optic constrained feed structure)

1.10.4.4. Optically Controlled RF Waveguide

Large phase shift is required for adequate RF phase-front tilt

RF insertion loss is large per unit delay, precludes EHF applications

1.11. Architecture Trades Include MBA's and Hybrids

MBA's generally require significantly fewer elements than a direct radiating array, and form beams with passive circuitry as opposed to active weighting at each element as required for a scanning array. The MBA beamformer is designed to form all beams necessary to fill the desired coverage region, and a switch is needed to select a subset of these available beams for simultaneous transmit or reception. On the other hand, a scanning array forms only the simultaneous beams (the subset) that are needed and scans these beams over the coverage region via active element control. Because the MBA forms a fixed set of beams, there is a gain reduction at the beam to beam crossovers and sufficient margin must be included in the link budget design to compensate for these variations. With a scanning array, phase and/or time quantization result in similar effects that must be taken into consideration. However, with narrowband operation and phase only steering sufficient bits can be selected to minimize pointing loss and reduce the gain penalty to acceptable levels.

The ESAD SOW emphasized the design of scanning arrays. However, both the original ESAD performance goals and the aggressive goals developed later in the program include multiple simultaneous beam capability. MBA's have been included in the trade because they are strong candidates for multiple beam systems and are under consideration for current and future Milstar systems. We have considered MBA's in the architecture trades for this reason and for the reason that as the majority of photonics implementations reported in the literature have been with regard to scanning arrays as opposed to MBA's. The value of MBA's for accomplishing the performance goals states for next generation COMM systems demand our examination of these architectures and the determination of the substantive ways photonics can be leveraged to most effectively implement these types of beamformers.

The key drawbacks of an MBA are usually the switching and routing complexity. Packaging is difficult at millimeter wave frequencies because stripline/microstrip BFNs are too lossy and waveguide must be used. Optical switching and routing is one area where photonics may provide an attractive alternative to RF and is preliminarily considered a baseline enabling technology. More sophisticated photonic BFN implementations such as wavelength routing architectures, optical Rotman lens, and Butler Matrix have also been examined for potential application to the antenna structures.

The table below summarizes the several alternate MBA antenna architectures, compares them to scanning arrays, highlights the implementation issues where photonics is expected to provide leverage, and identifies the specific antennas that hold promising potential for useful insertion.

- Photonics Literature tends to emphasize Scanning Array architectures
- Benefits of photonics may also have significant leverage for some MBA/Hybrid implementations
- Cost & performance comparisons with RF scanning arrays need to be done on case by case basis
- Photonic implementations adds new dimension to these trades

Table 5. Architecture Trades Include MBA's and Hybrids.

Alternate MBA's	Advantages vs. Scanning Array	Disadvantages	Photonics "Leverage"	Applications/ Comments
Array Fed Reflector/Lens	50% element reduction Supports more beams	-Trade of BFN loss vs. Packaging complexity (stripline vs. waveguide) -Requires switch matrix -Redundancy issues	-Photonic BFN will Reduce interconnect density & weighgt, ease packaging problems -Optical router and switch may be competitive with RF at EHF	-Promising approach for SB Rcv -SB Tx implementated with TWTA's inconsistent with SSPA's -AB scan range & conformal requirements. preclude this approach
Butler Matrix	Eliminates active phase control and supports more beams	-Trade of BFN loss vs. packaging complexity (stripline vs. waveguide) -Requires switch matrix -Beam squint inherent -Fixed beam crossovers	-Photonic Butler will reduce interconnect density, size and weight, ease packaging problems, may enable use of Butler with larger arrays	-Larger number of AB Rcv elements may render impractical -Requires optically coherent combining *high risk for space -Squint not acceptable for AB -Possibly attractive for SB Tx
Rotman Lens	-Eliminates active phase control -Supports more beams -True Time Delay	-Weight -Requires switch matrix -Crossover loss	-Potentially lower loss at 44 GHz -Weight not clear (optical and RF Rotman size commensurate)	-Good approach for SB Rcv -No Advantage vs. RF for SB Tx -AB Rcv too large, heavy -AB TX is single beam, switch complexity may outweigh benefits
Array of Constant K Lens modules (Hybrid)	MBA provides subarray pattern control, minimizes scan loss, active control	Requires switching at subarray level	-Photonic BFN reduces interconnect density and weight, ease packaging -Optical router and switch may be competitive with RF at EHF	-Promising approach for AB Rcv -Scan losses for SB insignificant -AB Tx is too small to benefit

1.12. Space Based Receive Trades

Three candidate architectures were traded for the spaceborne receive antenna: RF and photonic scanning arrays, and one quasi optical MBA (the array fed reflector). The spaceborne receive antenna must provide at least ten (future systems may require even more) simultaneous beams, which is not practical for a scanning array due to packaging complexity and divider loss (-10 dB after the LNA). An MBA is the more attractive candidate for this application. The main drawback of an MBA is the signal routing and switching required to select the desired subset of beams. A photonic beamformer provides direct leverage against these drawbacks. A photonic BFN allows the BFN to be remoted, occupies much less volume and is more flexible than an RF BFN (e.g. waveguide at 44 GHz!). A switched grating optical switch mitigates the complexity associated with the switch and is readily extendible to more than 10 beams.

Our proposed photonic signal and switch is consistent with any MBA (array fed reflector or lens, a DRA with an RF Butler or Rotman beamformer). The advanced EHF receive antennas will almost certainly be an MBA, as are almost all commercial spaceborne receive antennas, the photonic router and switch has a high potential value for SATCOM.

The three candidate architectures have not been designed to provide nulling capability. The baseline configuration for Advanced EHF is to combine all non-nulling receive beams into one aperture and use the existing Milstar nulling two-antenna design (with some modifications) to provide the required agile beam and jammer suppression capability. Hence we have focused our development for the receive antenna on architectures that do not incorporate nulling. There are other practical reasons for this logic which is discussed in the section on nulling approaches.

1.12.1. Key Challenge is packaging for multiple beams
- Precludes scanning array, favors MBA
- RF scanning array cannot package ten beams
- Photonic scanning array consumes prohibitive amount of power

1.12.2. Key challenge with MBA (e.g. array fed reflector) is **switching complexity**

1.12.3. Photonics used to mitigate switching complexity

Table 6. Space Based Receive Trades.

	Scanning Array (RF)	Scanning Array (Photonic)	Array Fed Reflector (Photonic BFN)
Elements Number	Conical Horn 547	Conical Horn 547	Conical Horn 331
G/T @ EOS Ant. Gain System NF System Gain System IP3 G/t @ BS	10.35 dB 15.03 dB 3.98 dB 66.0 dB 24.5 dBm 11.45 dB	10.35 dB 15.03 dB 3.98 dB 69.42 dB 4.015 dBm 11.45 dB	10.18 dB 18.10 dB 3.98 dB 4.015 dBm 13.8 dB
Size	72,831 cm^3	20,194 cm^3	35,250 cm^3
Weight	45.43 kg	66.59 kg	59.541 kg
Power	325 W	2,245 W	145 W
Complexity	More beams difficult	More beams possible	Optical Switching
Comments	Advanced EHF IR&D	Optical amplification dominates DC Power	Maximum Hardware is Remoted

Notes:
Array Fed Reflector & Photonic BFN Selected for Spaceborne Receive
- Mitigates Packaging Limitations by BFN Remoting
- Provides Expanded Multi-Beam Capability via optical switch
- Driving Photonics Technology: Compact, low power 1xN switch and low V_π modulator

1.13. Array Fed Reflector

Shown on the opposite page is a quasi-optical MBA design for the spaceborne receive. The MBA consists of a dual reflector and array feed of 331 conical horn elements. The beams are formed by combining the elements in clusters of 7 elements. Hence each element will participate in forming 7 beams which could require a 1:7 split at each element. After the split the signals must be weighted in amplitude and phase and recombined in the appropriate groups of 7. This scheme relies on the either optically implemented RF combining or conversion back to RF before combining. Because the same weight values are used for all beams, a minimal approach requires only ten 7:1 combiners. The reflector has been designed to minimize scan aberrations and possibly allow a single set of weights to be used for all the beams, which further simplifies beamforming. The MBA beamformer is relatively narrowband, but represents in some part the conventional wisdom in deploying space based receive communication antennas. The dual reflector design alleviates the element spacing requirement and utilization of the reflector gain allows for a reduced number of elements which can positively impact cost. Additionally only those elements required for forming the desired set of beams are activated at any given time. This feature can lead to significantly reduced DC power relative to active scanning array approaches.

1.13.1. Array Fed Reflector

- 331 elements at 3__spacing in focal plane
  (547 elements at 2.4 __spacing for DRA)

- Clusters of 7 elements form beams
  via phase and amplitude weights

- Weighting is the same for all beams
  (because of small scan range)

Significant advantage for combining, switching, redundancy

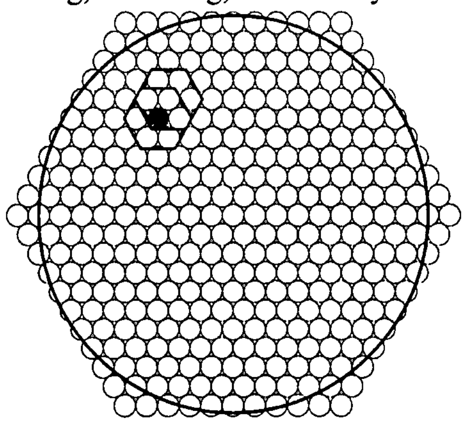


Figure 8. Circles in Hex (Beams).

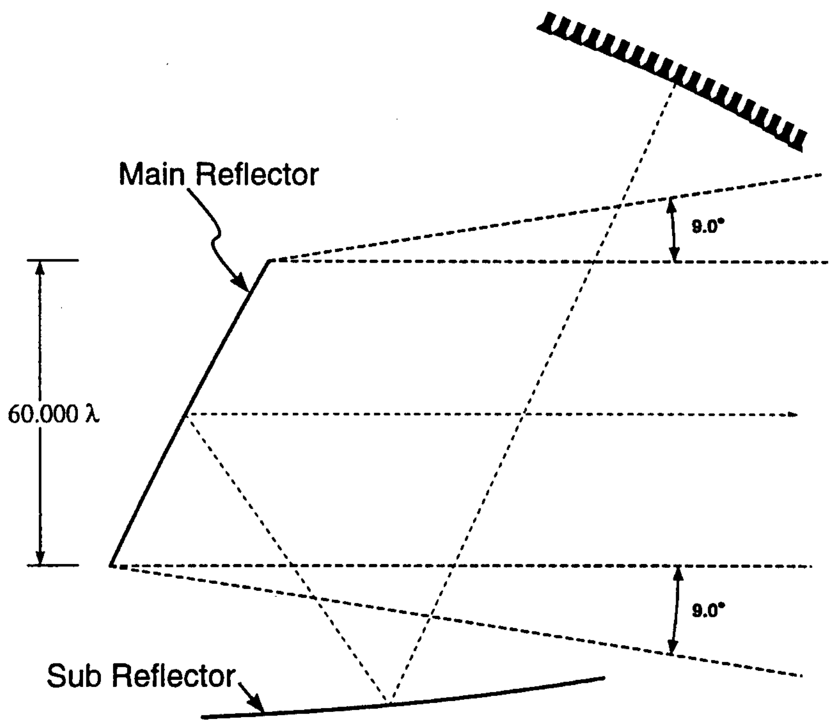


Figure 9. Array Fed Reflector.

1.14. Array Fed Reflector Beamformer with WDM Routing

The figure below illustrates a photonic beamforming architecture for the array fed reflector spaceborne antenna. Unlike the WDM combining architecture, this architecture enables the routing of optical power **only** to those feed elements that are required to form a desired beam. The beamforming architecture incorporates a TRW proprietary routing structure, optical downconversion utilizing complex weighting, and optical switching with the switched grating devices, and wavelength multiplexing. Seven element cluster combining of the RF signals is accomplished with both multi-wavelength optical techniques and conventional RF techniques.

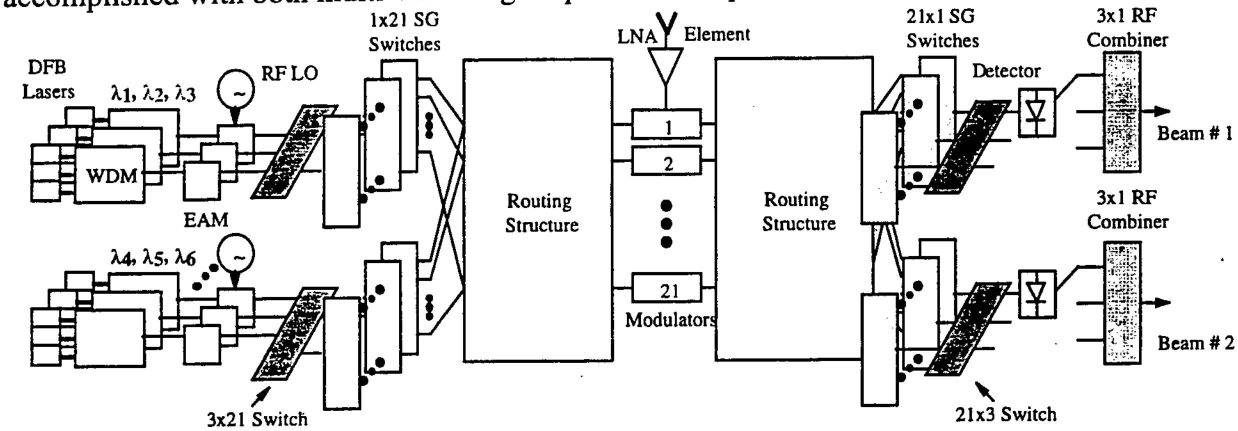


Figure 10. Array Fed Reflector Beamformer with WDM Routing.

Note: Key challenge is enabling expanded multi-beam and reducing size/weight/cost

1.14.1. Trade Considerations

- (+) Downconversion incorporated
- (+) Multiple beam operation
- (+) Low Weight
- (+) Low Power Alternative to DRA
- (+) Passive Beamforming
- (-) Reliability must be maintained

1.14.2. Critical Technologies

Multi-Wavelength EAM or III-V MZM
Switched Grating Switches
MOSAIC (if optical amplification is required)
WDM Multiplexer (cost)

1.15. Detailed Sapeborne Receive Photonic BFN Design & Features

The figure below illustrates an EDM brassboard of the optical source, heterodyne, switching, and combining module. Most of the components could be fiber pigtailed for convenience of assembly and packaging. Not shown in the figure are the heat sinking hardware that would be on the backend of the lasers and local oscillator source unit. Shown in the figure is the majority of the control, bias and DC power electronics that would be required for operation of the module.

The feed horns and receive module structure are also illustrated below. A semiconductor Mach-Zehnder, or an Electroabsorption Modulator is packaged with the LNA and DC power circuit in a multi-chip fashion. Aside from the input and output fiber cables, the only other required connection is the DC power source. No beam control lines are required as the beam steering and control is accomplished remotely from the antenna. Some packaging techniques on the modulator are required to enable easy access to the fiber inputs. TRW is currently developing packaging concepts for establishing LNA modulator assemblies that could be directly applicable to building this antenna hardware.

The full antenna system from a top-down view is illustrated below. The main and sub reflectors are suspended over the array feed in such a way as to allow the ±9° scanning field of view. The antenna would be oriented on the spacecraft so to point towards the earth at the correct angle and the aperture would possibly be covered by a radome not shown in the figure.

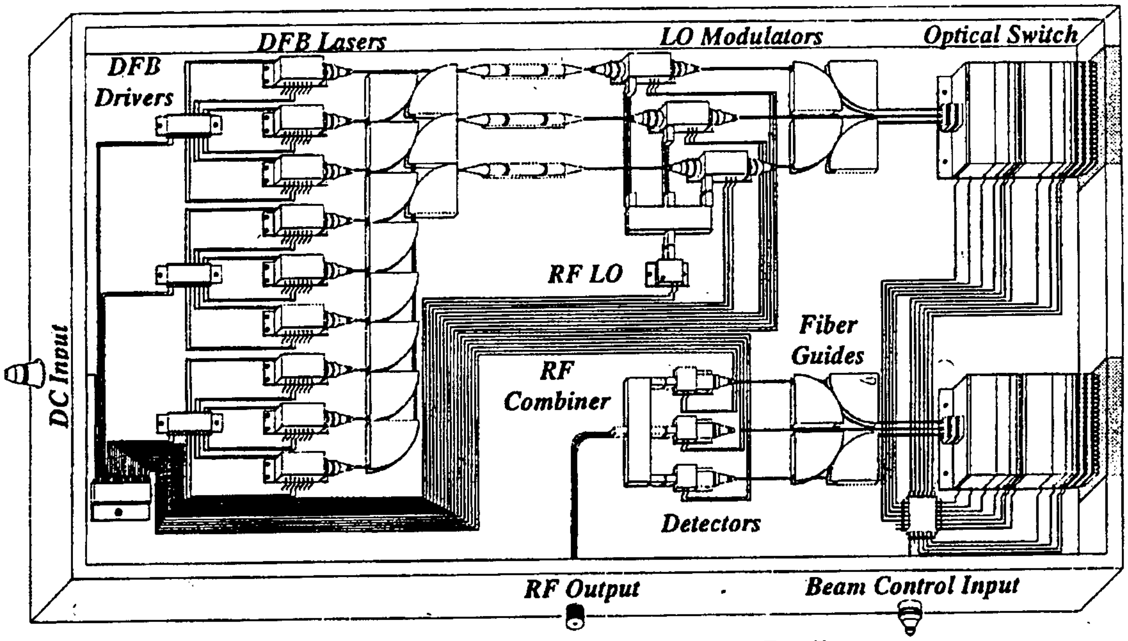


Figure 11. Optical Source Module.

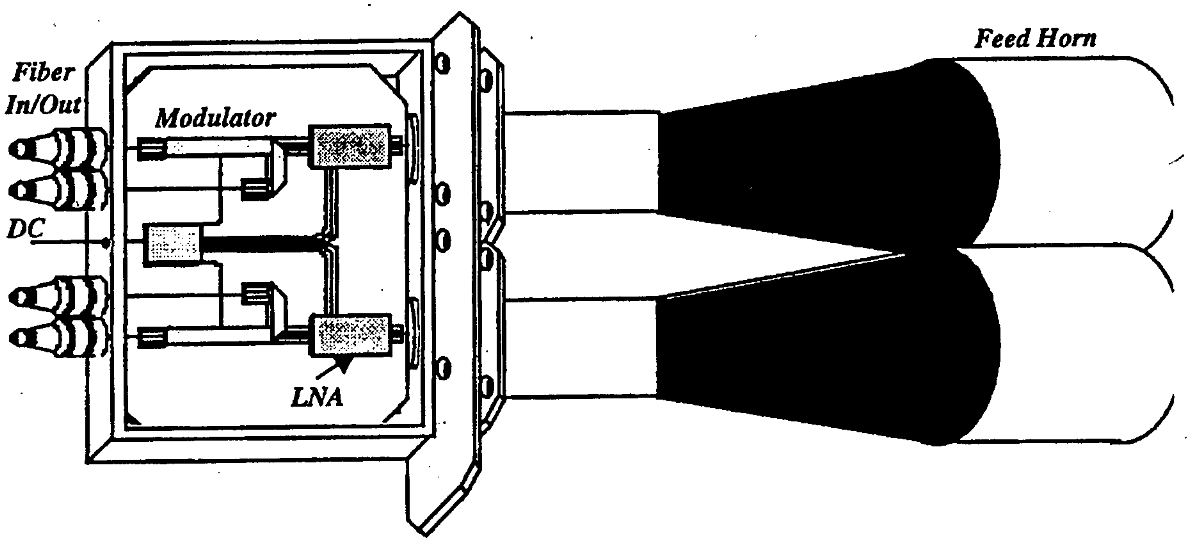


Figure 12. Receive Module.

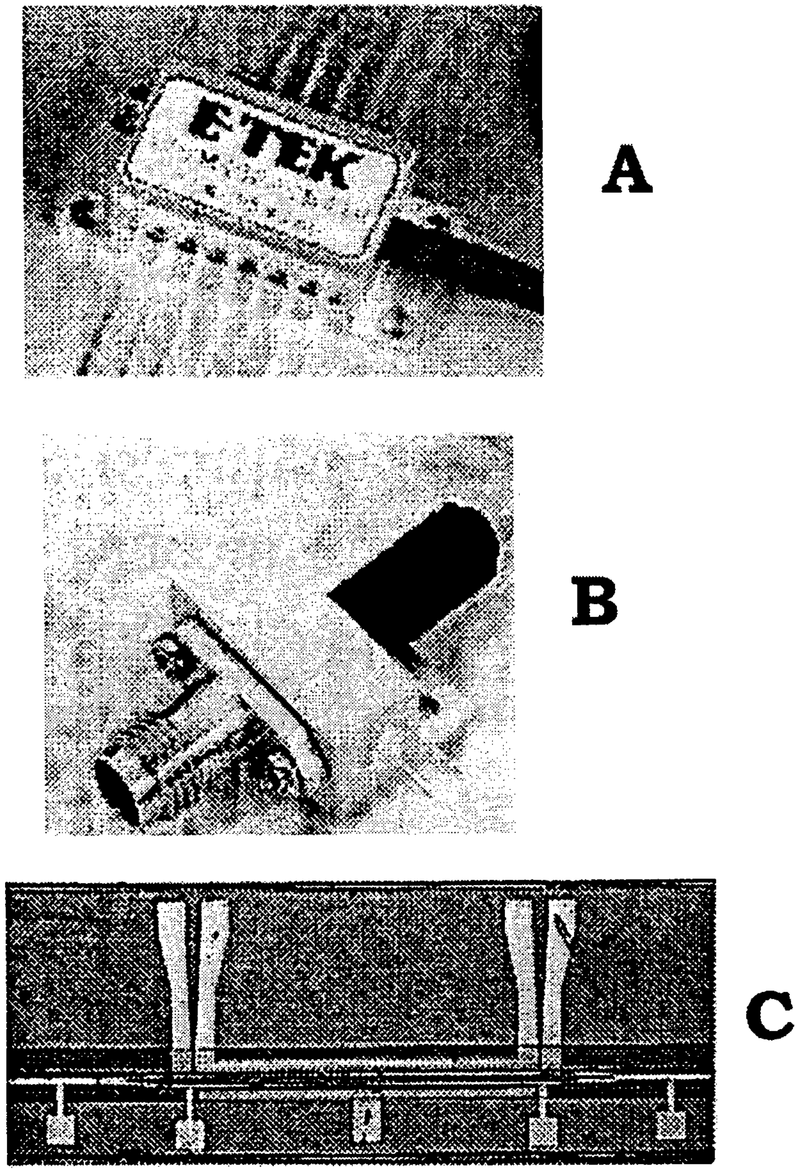


Figure 13. Three Components A- DFB Laser, B- Photodetector, C- Modulator.

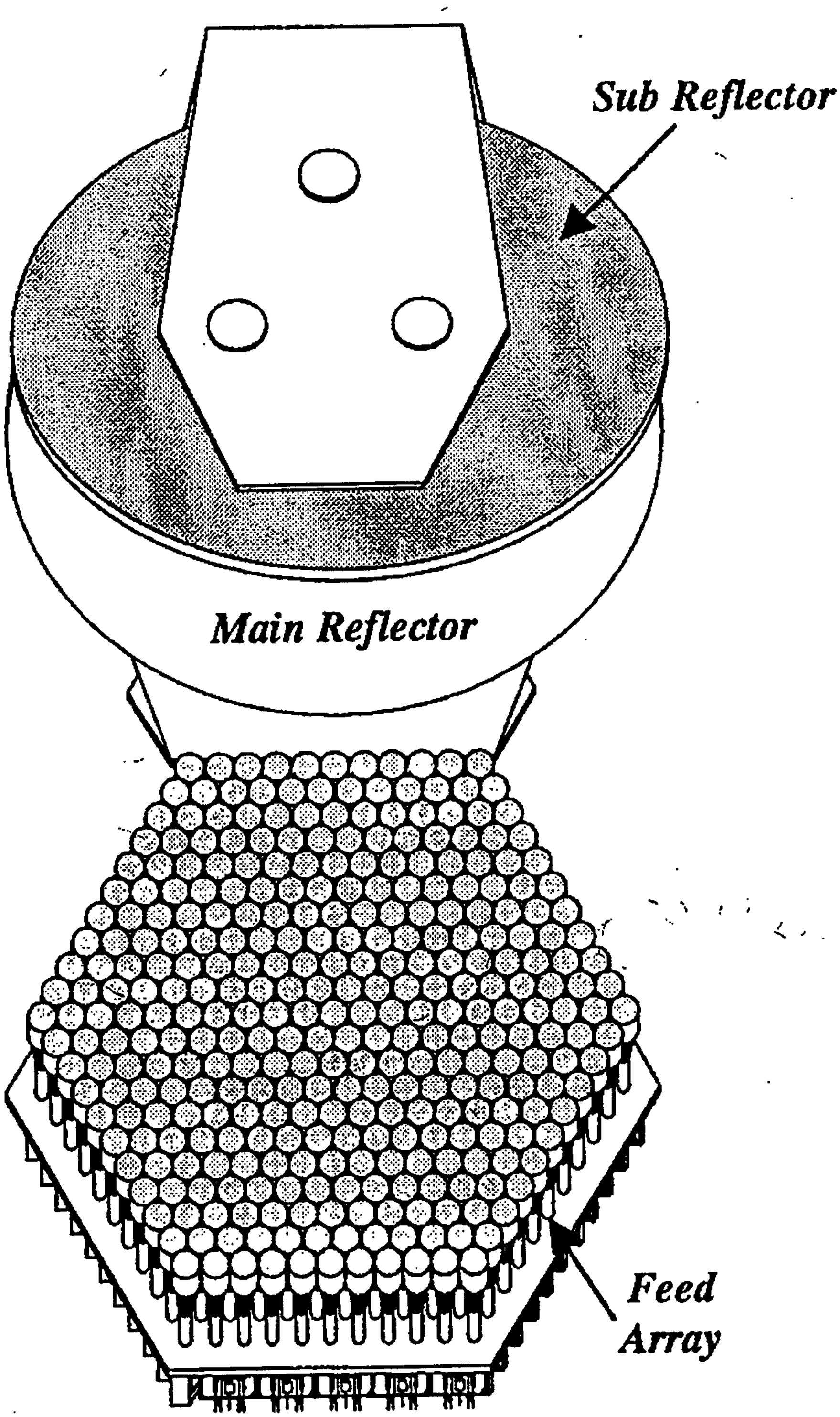


Figure 14. Spacebourne Receive Antenna (Top View).

1.16. Nulling Antenna Trade Conclusions

The architecture trades we have performed have focused on the two primary functions of the antenna system, beamforming and processing. We have considered photonic technologies that could be incorporated in the structures utilized to accomplish both functions. Upon examination of several technologies and techniques that have been presented to the technical community and our own ideas, we have made some general conclusions as to the applicability of photonics to address the challenges associated with the design of next generation nulling antennas and when applicable, which photonic insertions provide the greatest leverage for most effectively achieving current or future nulling antenna performance goals.

We have considered both phased array and MBA nulling antenna architectures to implement a nulling antenna. The current Milstar nulling antenna is an MBA with approximately 13 feeds and a 40 inch main reflector. Phase and amplitude weighting is employed to form the nulls in the antenna coverage area. Some work has been done at MIT Lincoln Labs to utilize photonics for more stable phase and amplitude weighting and has yielded promising results. Additionally, there is current TRW IR&D effort to design the next generation nulling antenna There has also been study work done on phased array nulling antennas by Syracuse Research Corporation and several research groups have looked at utilizing photonic beamforming to enable wideband nulling antennas (UC Boulder, U Florida, Rome Labs).

Based on the key performance goal of reduced standoff distance, we find that the MBA approach seems most attractive. Reduced standoff requires large apertures which is much easier to accomplish with the MBA. Large aperture phased arrays will lead to high complexity both in the array and in the beamforming. Reduced standoff can be accomplished in the MBA by increasing the reflector diameter and incorporating on the order of tens of feeds. Given the differing performance and coverage requirements of the nulling antenna and the agile spot beam antenna, we believe that these antennas should be designed and optimized in separate apertures. There remains some question as to if the null will move with frequency given a set of phase and amplitude weights. If this is the case, a tapped delay line beamformer may be required to fix the position of the null with frequency. Photonics would provide an attractive alternative to this beamforming requirement.

Fast null convergence requires parallel determination of the adaptive weights and consequently a parallel processing correlator. Based on our analysis of a photonically implemented correlator and TRW IR&D examining RF analog and digital correlators, we have determined that the photonic correlator requires half the power of the RF analog and one sixth the power of the digital correlator. This result is despite the Milstar configuration that does the correlation over a relatively narrow bandwidth and doesn't leverage off of the wide band capability of photonics.

1.16.1. Large aperture required to enable reduced standoff and increased percentage coverage area

- Large phased arrays required to achieve performance goals (high level of complexity)
- Increased MBA capability can achieve these aggressive goals (increased reflector size, more feed elements)
- Nulling antenna should be designed and optimized separate from consolidated agile spot beam receive antenna

1.16.2. Fast null convergence required to operate against sophisticated jammers

- Parallel determination of adaptive weights is necessary (fast response)
- Leverage of photonic processors is limited by current system configuration
- In current system 19 element photonic correlator architecture leads to reduced power
  - » One sixth power of digital processor
  - » One half power of RF analog processor
- Photonics processor could enable more correlations (for 37 element feed antenna) and the trade would be more favorable (from the standpoint of total power)

1.17. Selected Nulling Architecture Enhances Milstar Nuller

We have chosen to focus our design effort on determining how photonics can be used to enable or improve performance for the MBA nulling antenna. We summarize here the basis and justification of our design selection for this antenna structure. The first attractive feature of the MBA nuller is that it is consistent with the design plan being developed for advanced EHF. Most development being done for the advanced EHF nulling antenna is extending the design and performance of the current Milstar nulling antenna and our efforts have been consistent with this approach. Another consideration that is common with the reflector fed spot beam antennas is that MBA's require far fewer elements than direct scanning arrays with comparable beam characteristics. The current nuller consists of a 40" dish and 13 feed elements, 7 of which are used for quiescent coverage. To achieve the same aperture size in a phased array arranged on a hexagonal lattice, 2791 elements would be required (2.4_ element spacing is assumed). To establish the gain and resolution equivalent to a 60" dish would require approximately 6,487 elements, a significant number. Based on this consideration, the reflector fed MBA is much more attractive. Our push is to increase the aperture area and number of feed elements to increase the percentage coverage area (PCA) for the desired service area. We have arbitrarily defined the PCA to be the area within 10 dB of the quiescent gain after null formation. This provides us a baseline for which to compare technologies. Increasing the aperture size and number of feed elements will impact the implementation in two ways. The first is that there will be more feeds to correlate simultaneously, a task that is expected to gain great leverage from optical processing techniques. The second is the formation of sharper nulls and consequently more sensitivity to frequency. With but a few elements, the coverage area is angularly wide (or large on the ground). The formed null moves on the ground with frequency, but is wide enough that the movement is undetectable. With a sharper formed null, the same amount of movement will result in decreased jammer suppression over some frequencies. The complex weight, must be tailored over frequency to enable wideband null formation. Tapped delay line beamforming elements are required to accomplish this type of null control and optical techniques can be employed to accomplish this.

- Consistent with Advanced EHF Design Plan
- Current Nuller: 40" dish, 13 feeds (7 for Quiescent)
  - MBA provides higher performance than DRA
    (Larger aperture, less feeds)
- Increase Aperture Size to Increase % Coverage Area
  - Defined as % of Coverage Area within 10 dB of quiescent gain after null formation
- Increase Aperture Size _ More Feeds to form quiescent pattern
  - More feeds to correlate » Optical Processing
  - Sharper Nulls » Optical Tapped Delay Lines

MILSTAR NULLER

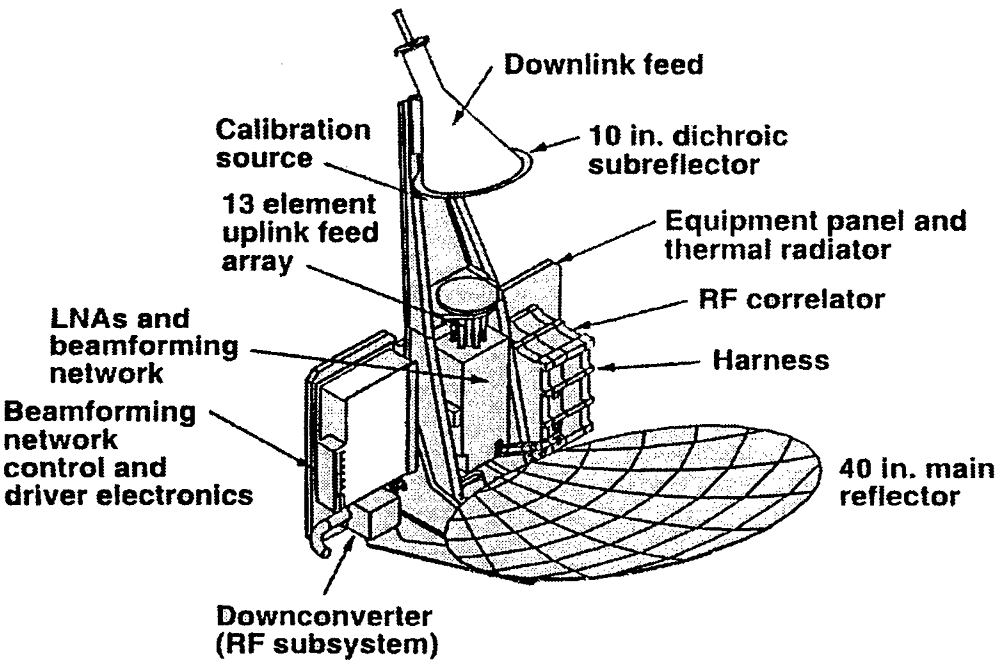


Figure 15. -MILSTAR Nuller.

Key issues are standoff distance, time for null convergence, and nulling bandwidth

- Phased array high complexity favors MBA architecture
- Next generation performance requires large reflector and many feed elements
- **Photonics provides low power parallel processing capability**
- Nulls move with frequency resulting in decreased wide band jammer suppression
- **Photonic tapped delay line BFN provides frequency dependent phase weighting**

1.18. Photonic Nulling Technologies

There are several photonic technologies that uniquely enable nulling antenna beamforming and signal processing. The direct application of the technology depends on the antenna design approach employed.

1.18.1. Single Sideband Suppressed Carrier Modulator

SSB-SC modulation can be accomplished with one of two methods. One method is to minimum bias a Mach-Zehnder modulator and filter the unwanted sideband. The rejected sideband can be filtered of with a mach-zehnder type spectral filter and used for individual signal power estimates if this is required. This technique is simple, but if the rejected sideband cannot be used, this rejected power is lost and there is a 3 dB loss in the conversion. Another method is to use a quadrature modulator comprising a RF hybrid, and two appropriately configured mach-zehnder modulators to enable efficient single sideband modulation while suppressing the optical carrier. This technique is more complex, but does not have the 3 dB penalty associated with the unwanted sideband rejection. Single sideband modulation is critical in the efficient implementation of a photonic correlation processor as the I and Q components of the correlation can be calculated simultaneously.

1.18.2. Photonically Implemented Tapped Delay Line

Tapped delay line processing is necessary if wideband null steering is required. For phased arrays with a significant aperture size and wide instantaneous bandwidth the tapped delay line compensates for the delay of the signal as it propagates across the aperture. Tapped delay lines can also be used to establish fast tunable bandpass or notch filters which may enable removal of signals from the spectrum being used for jammer estimation. The utility of tapped delay line beamforming for the MBA is less clear. There is some squint in the beam pattern with frequency, but it is negligible in the current nulling antenna configuration. As more elements are incorporated and the formed nulls become sharper, beam squint will have more of an impact on the nuller operation and wideband beamforming will be necessary to implement. Current implementations of the tapped delay line beamformer require the use of a low coherence optical source and demonstrate high insertion loss. Some techniques using multiple wavelengths have are being developed and might make this type of photonic beamforming more compatible with other photonic insertions to the architecture.

1.18.3. 4x4 Talbot Correlator

Two signals that are appropriately input to a 4x4 Talbot device can result in the efficient generation of I and Q channel correlation signals. Pairs of the 4 outputs are differentially detected and integrated to provide an estimate of the complex correlation of the two signals. A processor incorporating this technology is ideally fabricated as an integrated device so as to provide the stability needed to accomplish the coherent optical processing of the signals. This technology was developed under the MOSAIC program.

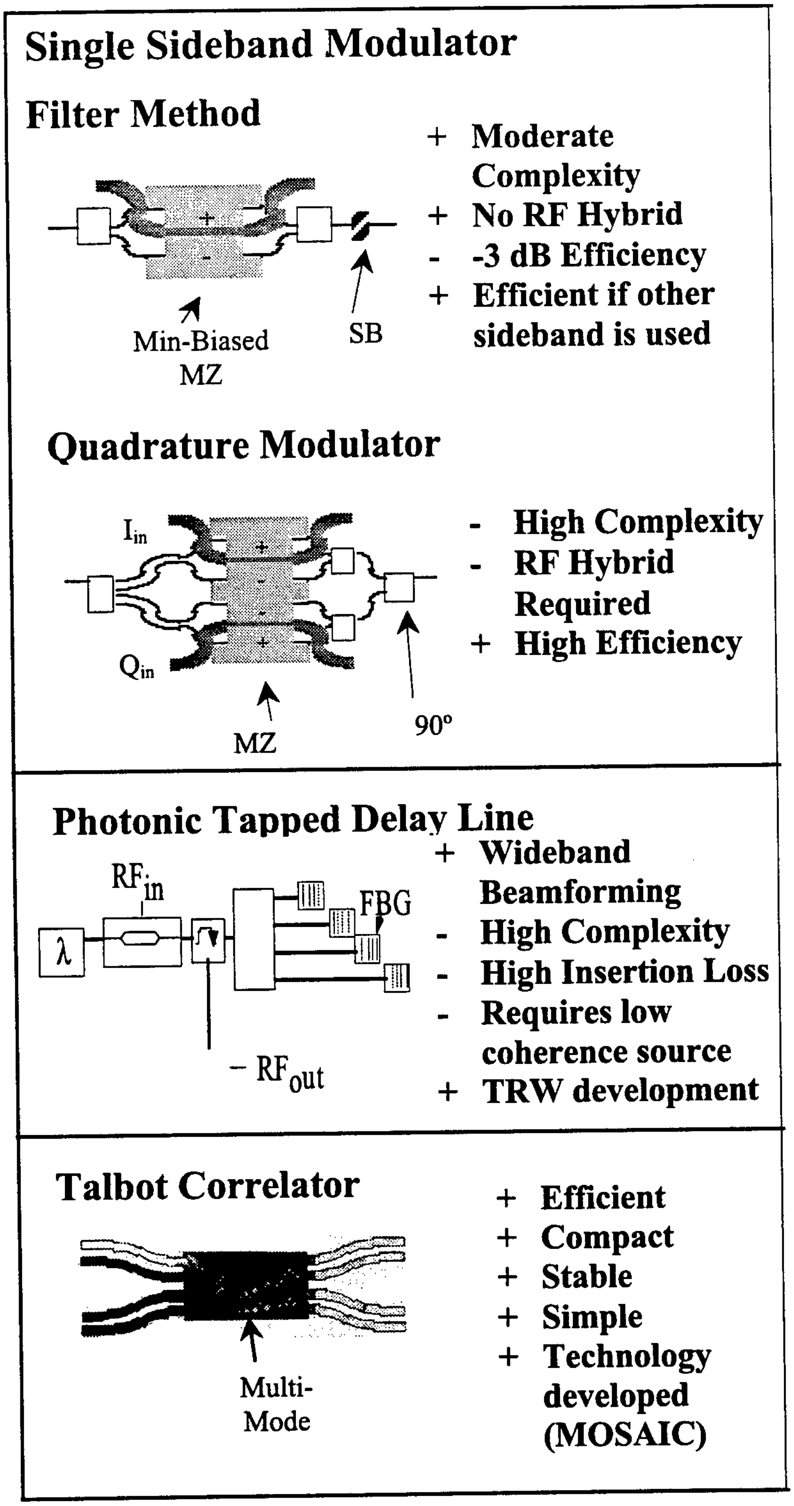


Figure 16. Several component technologies enable nulling antenna beamforming and signal processing.

1.19. Photonic Correlator Multi-Chip Module

The photonic correlation unit that is constructed as a multi-chip module unit is illustrated in the figure below. The DFB laser, MOSAIC type optical amplifier/splitters, modulators, phase compensation sections, and detector array could all be fabricated as individual devices, placed and aligned in the multi-chip module package using active or passive alignment techniques. The routing waveguides could be fabricated using passive silica waveguide, or polymer technology resulting in relatively compact, stable, and low loss signal routing on the chip. The optical phase compensation sections are required to equalize the optical path lengths between the numerous channels, a necessary requirement for optical correlation. The 4x4 Talbot optical correlators could be fabricated with the waveguides in an entirely passive structure. For a processor compatible with the current MILSTAR configuration, the IF inputs would require an approximate bandwidth of 150 MHz, which could be achieved in this type of package. The bending radius of the passive waveguides would have to be large enough to minimize optical bending losses and is the determining factor on the module size. For 1 mm bending radius, the entire package would be about 2 inches square. Waveguide bending radii or 1 mm is not reasonable with most manifestations of planar lightwave circuit technology, but recent developments in high-Δ silica waveguides can provide 1 - 1.5 mm bending radii with only 0.1 dB/cm propagation loss. Such a "correlator on a chip" could provide adequate performance in an extremely small package, which is desirable for next generation nulling antenna systems.

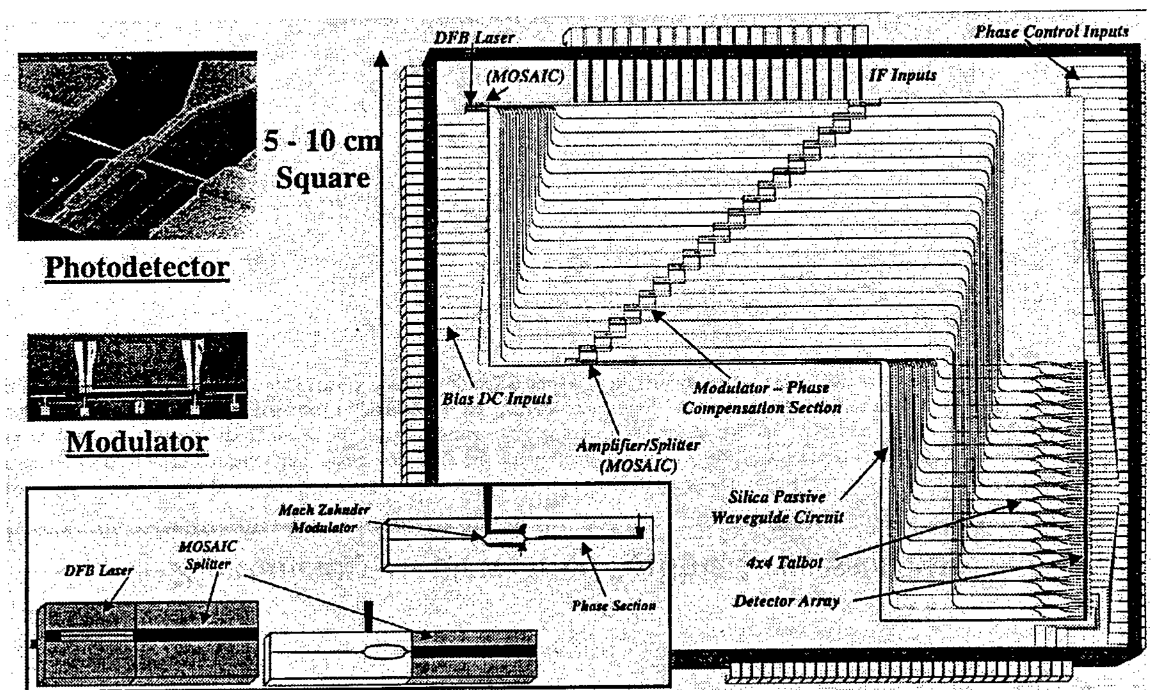


Figure 17. Photonic Correlator Multi-Chip Module.

1.20. Photonically Implemented Nulling Processor Slice

The photonic correlation processor and associated support electronics is illustrated below in the accompanying figure. The RF inputs are routed to the photonic correlation unit that is configured as a multi-chip module. A DC bias ASIC provides the necessary modulator, laser, and amplifier bias for proper operation. The differentially detected output currents are integrated on a charging capacitor that is sampled/quantized and then discharged in preparation for the next integration time. The adaptive weights are updated and the necessary commands sent to the beamforming network thereby forming a null on those jammers in the service area.

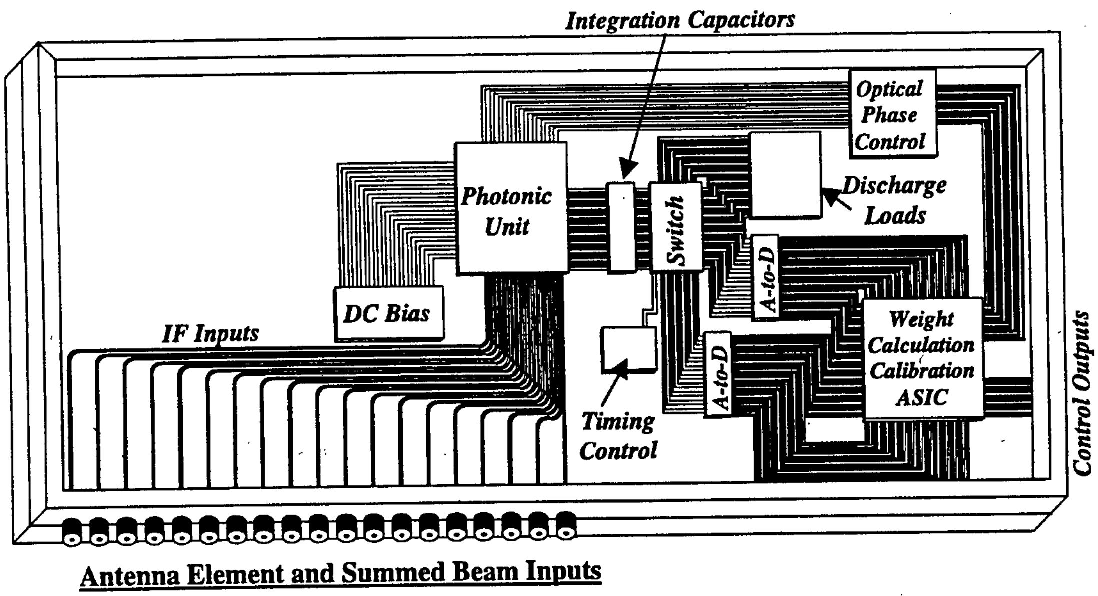


Figure 18. Photonically Implemented Nulling Processor Slice.

1.21. Airborne Transmit Trades

Four candidate architectures were traded for the airborne transmit antenna: RF scanning array, photonic scanning array, hybrid RF/photonic Rotman lens, and Aperiodic photonic scanning array. Since the aperture size is extremely small, a dome lens can be incorporated with the scanning arrays to allow scanning to 70° and beyond with no scan loss. This would allow a 50% reduction in the number of required elements and a reduction in module output power to 0.38 W. The lens would work similarly for both the RF and photonic arrays, and as such was omitted from the trade space.

Although the single beam requirement favors a scanning array approach (an MBA is usually not the best way to produce one beam), a direct radiating hybrid photonic/RF MBA candidate was also analyzed. The direct radiating array allows for solid state power combining in the formed beam, and consists of the same dielectric loaded elements as the scanning arrays. The beamformer consists of a photonically implemented Rotman lens in one plane, followed by an RF Rotman in the other plane which attaches to the lens. The photonic Rotman combines switching, wavelength routing and true time delay functions. A 2D photonic Rotman by itself is complicated to implement in a way that enables independent horizontal and vertical scanning. A 2D RF Rotman requires additional switching and is not consistent with beamformer remoting. The photonic Rotman lens could be incorporated in integrated optics and utilize wavelength division multiplexing to enable the necessary beam combining in a compact structure. The RF Rotman lens would be implemented with parallel plates and loaded with dielectric (e.g. the same dielectric used in the radiating elements). Although a 44 GHz Rotman design is challenging, TRW has developed 60 GHz pillbox antenna designs that are similar in complexity and we are confident that a design could be successfully realized if necessary.

Such beamforming concepts however do not attack the key challenge of mitigating the thermal issues associated with the close spacing and high output power of the elements. A promising approach is to thin the array with fewer elements and higher power per element to reduce the thermal density. TTD is required to maintain acceptable levels of beam squint over the larger aperture and placing the elements in an Aperiodic fashion would suppress grating lobes and maintain acceptable performance over the field of view. Finally, increasing element spacing allows use of a dielectric loaded element that reduces scan loss by several dB at 70 degrees, allowing a further reduction in the number of elements.

1.21.1. Key challenge is thermal density

Trade between density (few elements, high power) and cost (more elements, low power)

Wide scan, conformality, single beam, power combining favors scanning arrays

Table 7. Airborne Transmit Trades.

	Scanning Array (RF)	**Scanning Array (Photonic)**	**1D Ph Rotman 1D RF Rotman**	**Aperiodic Array (Photonic)**
Elements	400	400	400	200
EIRP @ EOS	45.0 dBW	45.0 dBW	45.0 dBW	45.0 dBW
Ant. Gain	-2.86 dB	-2.86 dB	-2.86 dB	0.0 dB
Module Power	0.48 W	0.48 W	0.48 W	0.96 W
EIRP @ BS	52.0 dBW	52.0 dBW	52.0 dBW	46.5 dBW
Size	1,023 cm^3	1,504 cm^3	2,317 cm^3	1,448 cm^3
Weight	0.659 kg	3.310 kg	3.749 kg	2.577 kg
Power	642 W	769 W	699 W	709 W
Complexity	Associated with packing density	Optical heterodyne and TTD	Photonic and RF Rotman	Same as other scanning arrays
Comments	TRW IR&D	TTD at subarray	TTD at element	TTD at subarray

1.21.2. Aperiodic Scanning Array and TTD Photonic BFN Selected for Airborne Transmit

- Enables increased element spacing ⇒ Reduced Thermal Density ⇒ Increased Module Power ⇒ Fewer Modules ⇒ **Lower Cost**
- TTD supports Aperiodic lattice essential for grating lobe suppression
- Driving Technology: IL Source, SG-TTD Devices, MOSAIC, High Freq/High Power Detectors

1.22. Scanning Aperiodic Array (Photonic)

Photonics can also be used to reduce thermal density by increasing element spacing. The Tx power per element can be increased, element patterns can be tailored to reduce scan loss at 70° (a design driver) and the number of elements decreased and placed over a larger area. Aperiodic spacing is used to suppress grating lobes in the antenna pattern. Aperiodic spacing results in the same power dissipation per unit area with fewer elements and lower cost. Photonics enables the Aperiodic spacing as RF microstrip lines are eliminated from the power distribution network. The larger aperture does necessitate the use of true time-delay at the subarray level to reduce the impact of beam squint during multichannel operation. The reduction in the number of elements has a significant impact on the size and power requirements of the antenna as nearly 50 W less power is required of the Aperiodic array even though the power per element is increased. Such a technique is uniquely enabled by photonics and works to solve the most critical challenge of implementing the airborne transmit array.

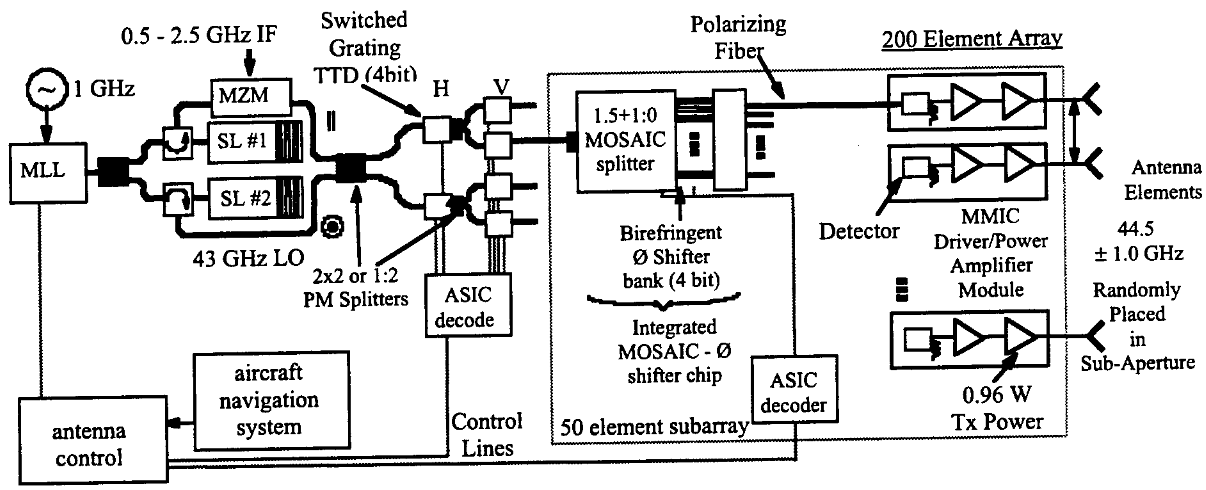


Figure 19. Scanning Aperiodic Array (Photonic).

Note: Photonics enables aperiodic array spacing and true time-delay

Trade Considerations
(+) Upconversion incorporated
(+) Multiple channel operation
(+) Mitigation of thermal density issues
(-) Slightly higher DC power

Critical Technologies
Injection locked laser source (CORE)
SG-TTD device
MOSAIC
High frequency/high power detector

1.23. Aperiodic Array Design & Features

The aperiodic element spacing requires a novel concept for packaging the array. A thermal structure is fabricated with rectangular sections removed in the aperiodic pattern. The transmit modules fit into the slots and the antenna element attaches to the front end of the module. The transmit module, an enlarged version of which is illustrated in the figure below consists of a fiber input, a photodetector, the driver and power amplifier. Although not indicated in the figure, DC power is fed to each module for biasing the photodetector and amplifiers. Also not shown in the illustration below is the vein polarizer and radome. The vein polarizer converts the linear polarization of the 44.5 GHz horn radiation mode into a single sense circular polarization for the uplink channel. This polarization technique is consistent with that previously proposed for EHF airborne transmit phased arrays and finds equivalent use for this design recommendation.

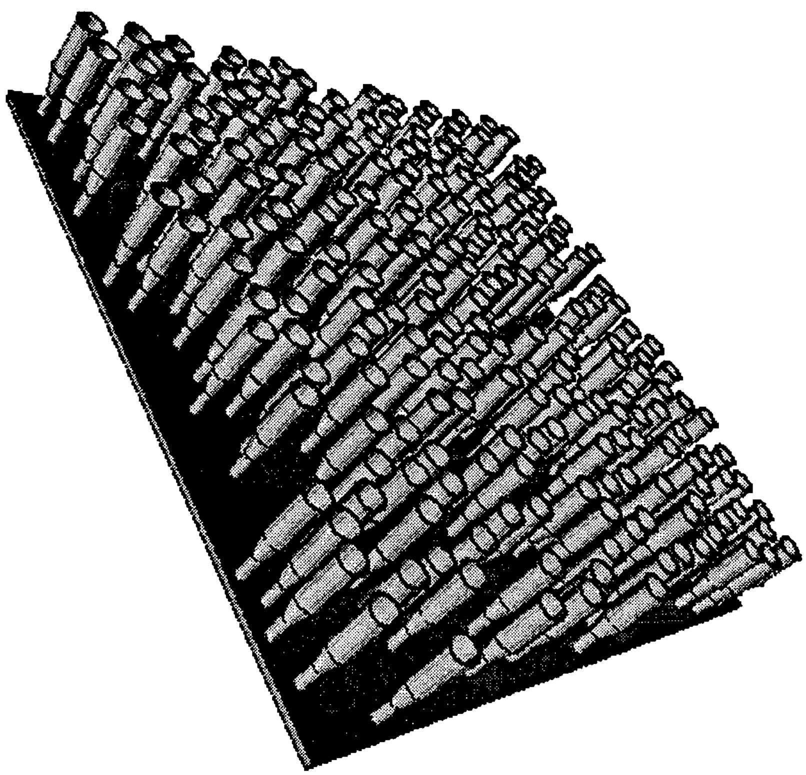


Figure 20. Aperiodic Array Facing View.

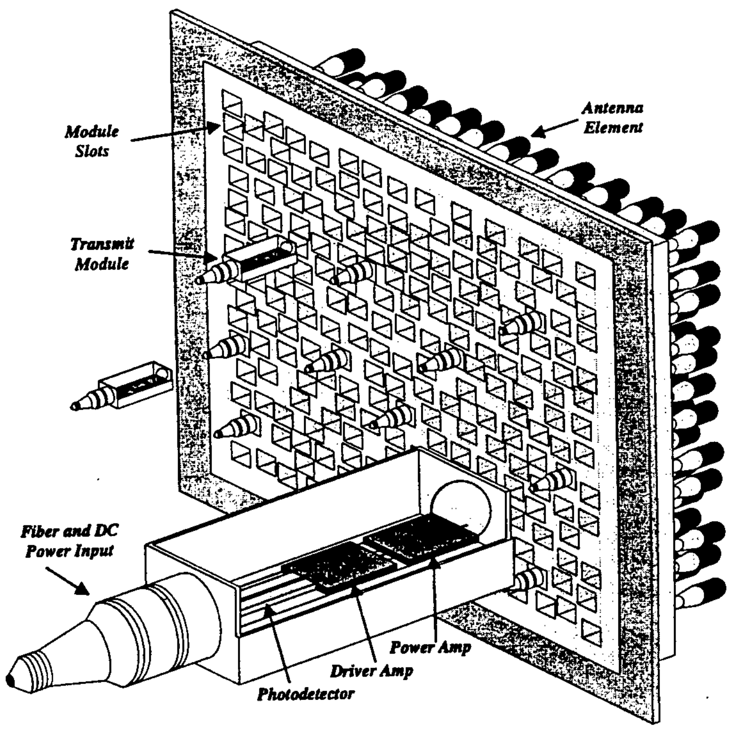


Figure 21. Aperiodic Array Front View.

1.24. Airborne Transmit Array Optical Source Module

The brassboard EDM for the optical source module primarily consists of commercial off the shelf (COTS) devices with the exception of the mode locked laser, the modulator package, the switched grating time delay units, the ASIC decoder circuit, and the DC power distribution circuit. The modulator package consists of two sections. One section contains the IF band modulator and the second is a through path (possibly with a phase calibration capability) section that enables the two optical signals to propagate over an equivalent path length so as to maintain phase coherence up to the 2x2 optical coupler. The assembly would comprise one slice of the photonic beamformer structure. As many of the devices are fiber pigtailed, some structure is required to guide the fibers throughout the assembly as indicated in the figure.

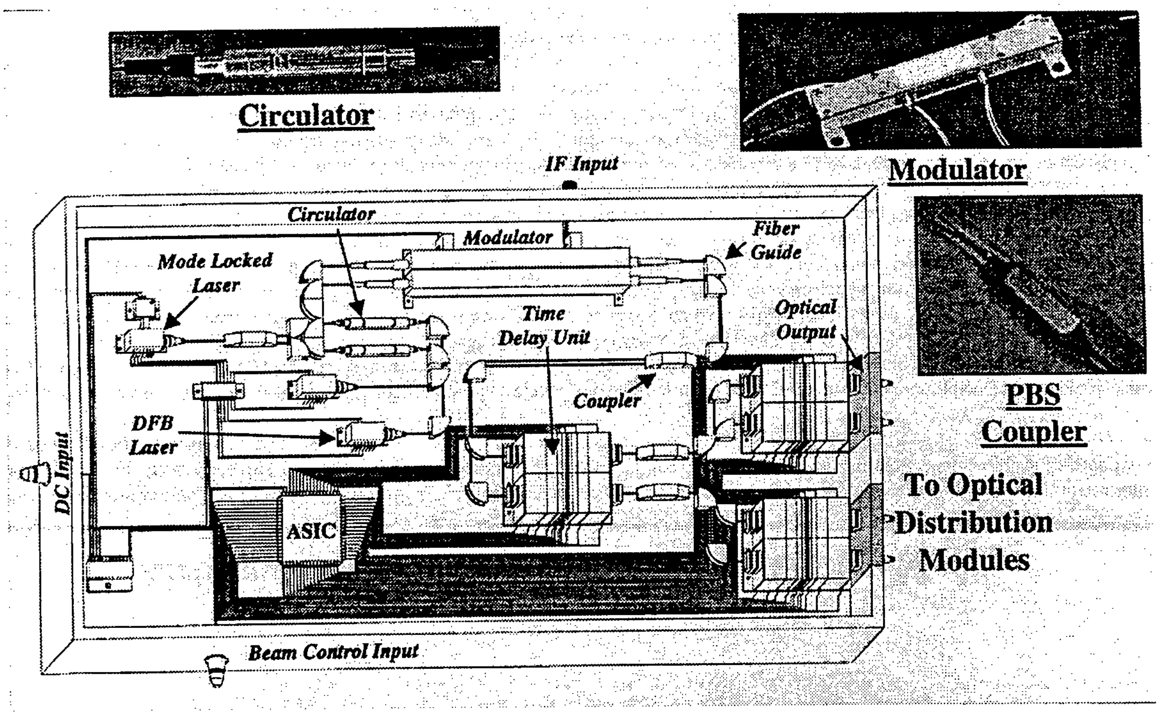


Figure 22. Airborne Transmit Array Optical Source Module.

1.25. Airborne Transmit Array Optical Distribution Module

This optical distribution unit consists of MOSAIC type optical amplifier splitters, silica waveguide routing circuits, birefringent phase shifting arrays, electronic control circuits, and 10-fiber bundle output cables. Two of these units would be required to enable optical distribution and phase weighting for the four subarrays.

Our recommendation is to fabricate the assembly and other optical distribution units as a multi-chip module rather than an optoelectronic integrated circuit. Given that typical yields for the fabrication of active optoelectronic devices (i.e. lasers and amplifiers) can be rather low, it is more likely to be cost effective in the near term to select individual MOSAIC devices rather than attempting to fabricate arrays of optical amplifier devices. A second consideration is optical losses in the fanout waveguides. The use of silica based waveguides can result in significantly lower propagation losses when compared to III-V materials such as Gallium Arsenide or Indium Phosphate. This becomes most important in the fanout to the optical fiber array where the pitch is expanded from 6 μm at the Talbot output waveguides to 250 μm at the fiber output array, which can require long waveguides. The phase modulator chips could most likely be fabricated in large arrays, as the yield for these devices can be much better. We have placed a silica waveguide distribution circuit between the amplifier outputs and the phase control sections, this could possibly be a single integrated unit, depending on the loss and yield of these amplifier/phase shifter units. For optical coupling from III-V based devices to silica waveguides, the use of expanded mode waveguides may be necessary. Expanded mode techniques enable mode matching between optical devices characterized by significantly different mode field profiles. By matching the optical mode from the semiconductor waveguide to the silica waveguide, it is possible to significantly reduce the optical coupling losses. Flip chip bonding and other passive alignment techniques could also be used to more effectively couple light from the amplifier chips to the silica waveguides. Silicon V-groove bench techniques could be utilized to enable the fiber pigtail coupling, although active alignment and laser hammering techniques may be required for the pig-tailing most critically impacting system performance (e.g. at the amplifier inputs).

The use of photonics for RF signal distribution in a phased array provides several ancillary, but substantial reductions in beamformer complexity. RF implemented phased arrays require a control line and sub-decoder ASIC at each transmit or receive module. The implementation of photonic distribution and phase-time control allow a single or very few control signals to be transmitted to a single or few ASIC decoder circuits. The control lines that would normally be distributed to each element module and the decoder circuitry at each element are eliminated which results in additional hardware savings and reduction of antenna complexity. Single point beam control can also possibly lead to faster beam steering and the adaptation that will be necessary for the airborne transmit antenna in order to maintain link operation during airborne combat platform maneuvers.

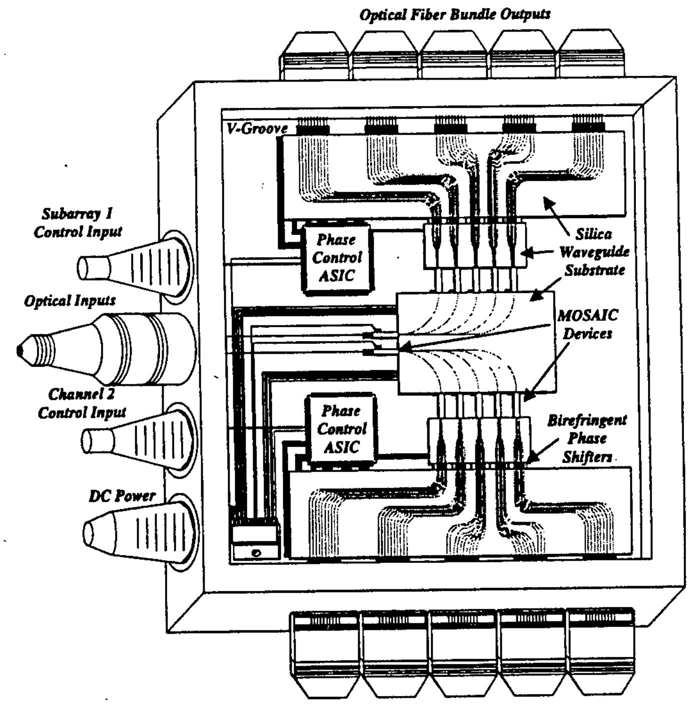


Figure 23. Airborne Transmit Array Optical Distribution Module.

1.26. Space Based Transmit Trades

Three candidate architectures were traded for the spaceborne transmit antenna: RF and photonic scanning arrays, and one direct radiating MBA with an optical Butler Matrix beamformer. The Butler Matrix MBA consists of 256 elements and a slightly higher module RF output power of 0.27 W is needed to achieve the same EIRP as the scanning arrays (module drive power is still 1 μW).

The table below provides the results of the size, weight, and power tabulation. When compared on a per element basis, the size of the three antennas are nearly equal and are primarily determined by the size of the antenna array. However, the size of the photonically implemented scanning array and MBA are significantly less than the RF scanning array. This significant differential is attributed to the weight associated with the 20.7 GHz power distribution network (PDN) required for the RF scanning array. On a DC power basis the photonic scanning array compares unfavorably to the RF scanning array or Butler Matrix MBA, but this is to be expected for photonic scanning arrays. DC power for the optical amplification and signal distribution is required in addition to the DC power required for the RF front end (common to all antenna architectures). The number of photonic beamformers required is equal to number of formed beams, so the total DC power requirement is effectively the sum of the RF power and four times the single beamformer DC power (~ 100 W/beamformer). This results in a substantially increased DC power level. The optical butler matrix utilizes optical power more effectively than the scanning array as only one beamformer is required to form any number of beams.

The significant disadvantage of the optical Butler Matrix beamformer is the complexity of the architecture. Optical coherence must be maintained in the beamformer, which is difficult to accomplish over the volume of the array. As such we did not downselect this beamformer for detailed design. However, development of techniques to maintain the necessary level of optical coherence, would make the optical Butler Matrix an extremely attractive approach for enabling large scale multiple beam capability.

In comparing the multiple beam RF and photonic scanning arrays, it should be noted that for the RF array, the maximum number of beams is limited by both the output power amplifier and packaging of the array components. With the phase shifters located on the same substrate as the SSPA, there is simply no room for additional phase shifting elements. For the photonic scanning array, the maximum number of beams is limited only by the SSPA performance as all of the beamforming is remoted from the antenna array. This makes the photonic scanning array an structure enabling future SSPA development to achieve further multiple beam capability.

Quasi-optical MBA's were not considered as they require traveling wave tube power sources and the trend for MilSatcom is towards power combining arrays (scanning or direct radiating). The 20 GHz transmit array is large and Rotman lenses are too heavy to be competitive with the scanning array (a photonic and RF Rotman lens' are the same size as they are both true time delay beamformers).

1.26.1. Key challenge is providing multiple beams
Limited by packaging and SSPA non-linearities (suppression and interference)

1.26.2. Photonics provides less leverage to MBA's than scanning arrays
Optical Rotman, Butler not competitive with RF Rotman or RF Butler at 20 GHz
Inconsistent with quasi-optical MBA (high RF power routing)

Table 8. Space Based Transmit Trades.

	Scanning Array (RF)	**Scanning Array (WDM MultiBeam)**	**Optical Butler**
Elements	271	271	256
EIRP @ EOS	50.00	50.00	50.00
Ant. Gain	14.64 dB	14.64 dB	14.64 dB
Module Power	0.24 W	0.24 W	0.27 W
Size	66,712 cm^3	61,562 cm^3	57,535 cm^3
Weight	95.494 kg	16.19 kg	16.83 kg
Power	477 W	813 W	523 W
Complexity	PDN/phase shifters dominate weight	Same complexity for any number of beams	High Complexity High Risk for Space
Comments	Beams limited by packaging & SSPA	Beams limited only by SSPA	Optical coherence difficult to achieve

1.26.3. WDM Multi-Beam Scanning Array Selected for Spaceborne Transmit
Photonic BFN yields significant reduction in overall weight (Low loss RF BFN's are heavy)
Eliminates Packaging Constraint, allows focus on SSPA Development
Driving Technology: SSPA, Heterodyne Source, WDM, MOSAIC, High Power Detectors

1.27. Scanning Array (Photonic)

Our proposed architecture for a photonic 4 beam scanning array is presented in the figure below. An optical heterodyne source is required to upconvert the input IF signal and to enable phase weighting beam control. The modulated optical signal is distributed to the 271 elements using the MOSAIC amplified splitting device. Each individual beam is formed in a separate beamformer and the multiple beams are optically combined prior to photodetection. As each beam is formed utilizing a distinct optical wavelength, WDM multiplexing techniques can be used to facilitate the beam combining. Since the EIRP goal must be met by each beam, adequate signal power must be generated at the output for each distinct beam. Therefore, strenuous requirements are placed on the optical power handling of the photodetector and this optical power handling capability increases with increasing number of beams. The transmit module front end is the same set of devices as used for the RF scanning array.

Some trade considerations for the photonic scanning are that it incorporates RF upconversion, multiple beam operation with significantly lower weight than the RF implementation. Critical technologies are the optical heterodyne source (there are several techniques that could be applied to this architecture), the MOSAIC optical splitting device, the WDM multiplexers (in terms of cost and efficiency), and high power photodetection.

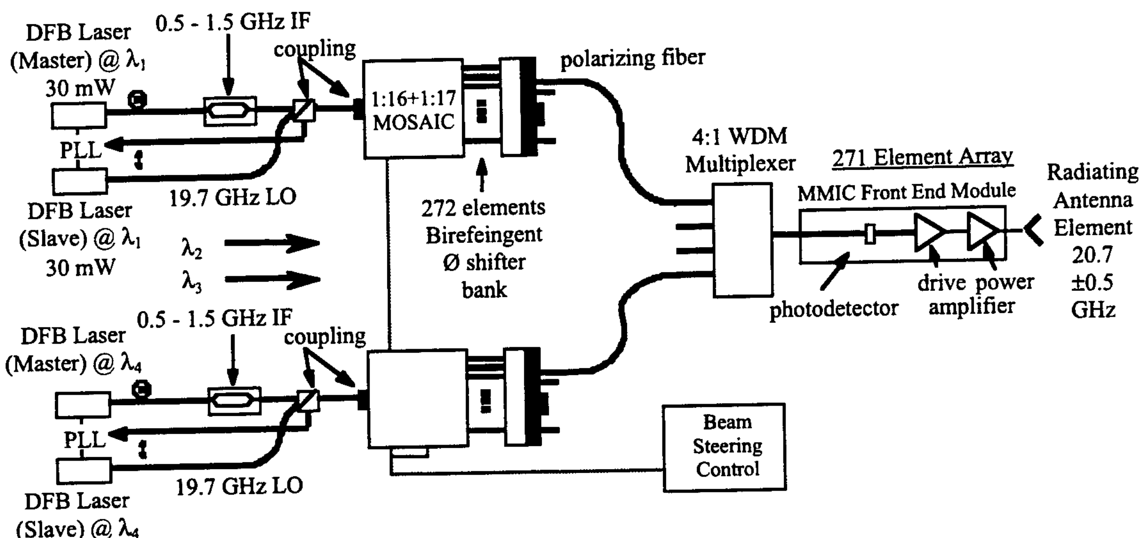


Figure 24. Scanning Array (Photonic).

Note: Photonics enables much less size, weight, power and increased multi-beam

Trade Considerations
(+) Upconversion incorporated
(+) Multiple beam operation
(+) Low Weight
(-) Higher DC power required

MOSAIC
WDM Multiplexer (cost)
High Power Detector and MMIC SSPA

Critical Technologies
Heterodyne laser source

1.28. Spaceborne Transmit Scanning Array Design & Features

The optical heterodyne source module EDM or brassboard assembly could be constructed with primarily off the shelf components. Fiber spools and guides allow packaging of fiber pigtailed components. Although not shown in the figure, heat sinking hardware would protrude from the back end and facilitate thermal stability of the assembly. A single optical source module would be required for each transmit beam.

The spaceborne transmit module and horn element is also illustrated in the chart below. A DC bias ASIC is required at each unit to provide DC power to bias and operate the photodetector and amplifiers.

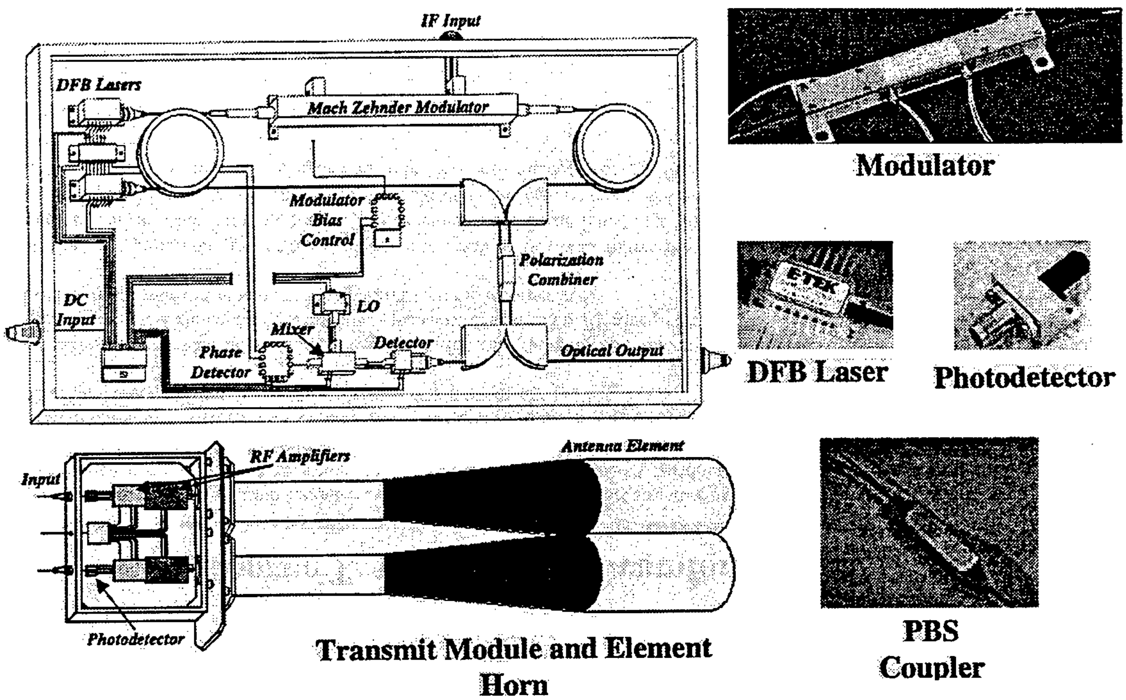


Figure 25. Spaceborne Transmit Scanning Array Design & Features.

1.29. Spaceborne Transmit Array Beamformer and Antenna

The optical source and distribution modules can be assembled on a compact structure as illustrated in the figure below. One source module slice and optical distribution – phase weighting slice is required for each beam. Additional structure is required for optical fiber routing and the WDM multiplexers. The beamforming structure is rather modular to support additional beams by adding more optical source and distribution cards and modification of the WDM multiplexer devices. The beamforming structure can be conveniently located on the spacecraft and remoted from the antenna element array if necessary.

The two element modules can be arranged together to form the radiating structure as illustrated in the figure below without the polarizer and radome. The antenna element array structure is the same design as the RF phased array with the exception that the phase shifter hardware is removed from the transmit module and the photodetector is incorporated.

Fabrication, integration and test of the spaceborne transmit array would follow the well establish design processes representative of other spaceborne EHF antenna array programs. The antenna would be designed and fabricated for the typical mean mission lifetime of seven years. The phased array architecture would enable graceful degradation at the array level. Some redundancy may be required in the beamforming system so to enable adequate reliability and performance over the lifetime of the system.

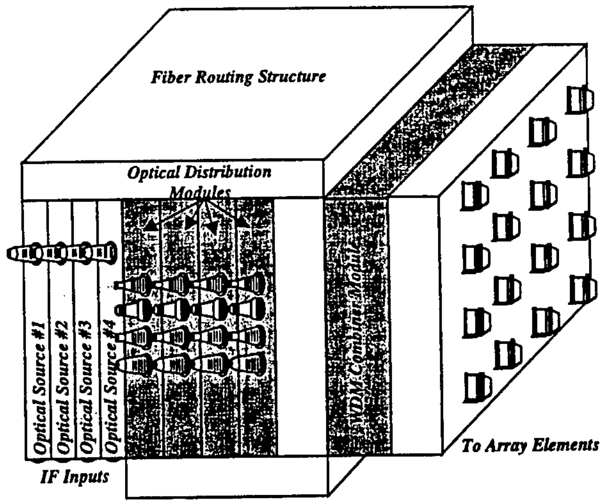


Figure 26. Photonically Implemented Beamformer.

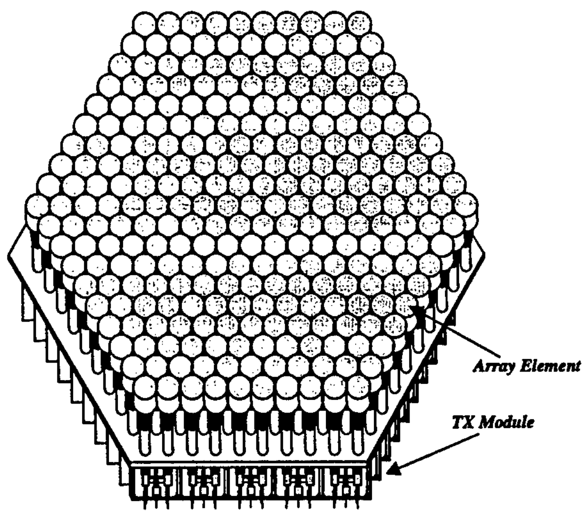


Figure 27. Spaceborne Transmit antenna Array.

1.30. Airborne Receive Trades

Three candidate architectures were traded for the airborne receive antenna: RF and photonic scanning arrays, and a hybrid scanning array of MBA elements. The lens MBA provides a controllable element pattern which can be selected to maximize element gain in the scan direction. This approach mitigates scan loss at the edge of scan (because the element pattern can be pointed to that location) and as such represents an approach worthy of consideration. As the number of required elements for adequate G/T performance is large, the required aperture size of the antenna is relatively large. In addition, the antenna must have a depth consistent with airborne platforms, and the cover a wide scanning field or regard. These factors preclude quasi-optical MBA systems and confine our baseline architecture trades to direct radiating arrays. Since a relatively large number of direct radiating elements are required, circuit MBA's are not feasible as well and are excluded from the trade analysis. Since the receive frequency is near 20 GHz, RF and photonic Rotman lenses will be too large and are impractical for this application as well. As demonstrated elsewhere, Butler matrices exhibit high complexity, and will not meet even moderately wide bandwidth requirements.

The RF scanning array was used as a baseline of comparison. To access the several desired SATCOM assets, several individual antennas are required. The S/W/P estimates are given for 4 antennas while the S/W/P estimates for the photonic scanning array is for a single 4-beam antenna. As the hardware and power associated with TTD is only a small fraction of the total structure, there is little difference in the S/W/P of time delay based and all-phase steering based photonic architectures. The data presented for the candidate hybrid scanning antenna consisting of lens MBA "elements" is for an antenna that forms a single beam. A relatively small amount of hardware could be added to enable multiple beam operation, but with significantly increased complexity.

As seen from the data presented for our S/W/P estimates, the multi-beam photonic scanning array provides for aperture consolidation that results in significantly less size than for the 4 RF receive antennas. This size reduction is provided with moderately less power than the multiple RF antennas, but at a cost of increased beamformer weight. It should be noted however, that photonics enables remoting of a majority of the beamforming hardware and for the photonic scanning array, only 30 kg of weight is located at the front end. The expectation is that by consolidating the apertures and utilizing a single wideband aperture, it is possible to significantly reduce the cost of the resources required to fully utilize multiple military COMM systems.

1.30.1. Key challenge is consolidating all airborne receive functions into single aperture
SOW requirements extended to allow more leverage for photonics

1.30.2. Requirements tend to preclude use of MBA's
Quasi-optical (e.g. Luneberg lenses) too big, not conformal
RF or Optical Rotman/Butler impractical (too many elements, aperture too large)

Table 9. Airborne Receive Trades.

	Scanning Array (RF)	Scanning Array (Photonic)	MBA Array Hybrid
Elements	(4-aperture)	4 beam single aperture	1 beam single aperture
Number	3240	3240	1024 (4x4 module)
G/T @ EOS	5.35	5.35	5.00
Ant. Gain	-1.94 dB	-1.94 dB	1.04 dB
System NF	2.01 dB	2.7 dB	2.71 dB
G/T @ BS	12.34	12.34	11.99 dB
Size	91,604 cm^3	16,456 cm^3	29,353 cm^3
Weight	139 kg	259 kg (30 kg at front end)	66 kg
Power	6496 W	5906 W	655 W
Complexity	MMIC Stripline	Optical Splitting	Large number of wavelengths
Comments	Multi-aperture required	Subarray TTD	TTD control for multi-beam

1.30.3. Scanning Array with Photonic BFN Selected for Airborne Receive

- Remoted electronics, broadband multi-band aperture, reduced component
- count ⇒ **Reduced Cost**
- **Driving Technology:** Heterodyne Source, MOSAIC, DBR Tunable Laser

1.31. Scanning Array (Photonic)

The architecture for the photonically implemented scanning array is presented in the figure below. The front end element, LNA, and 1:4 RF Mux is the same circuit as that used with the RF scanning array design. As the signals are phase weighted and transported to the subarray combining structure with fiber optics, the only other component required to be located at the antenna array is the optical modulator. Electroabsorption modulators are a useful device for this purpose as they are very small and could be incorporated into a MMIC front end with the LNA and splitter. Semiconductor MZ modulators could also be used if the linearity performance goal was difficult to achieve. The optical signals are distributed in a heterodyne configuration using some passive, but mainly active splitting. The phase weights are also established on the optical heterodyne signals to facilitate beamforming at the subarray level. We employ IF power combining and true time-delay steering of the subarrays as illustrated in the block diagram. As the true time delay beamforming is done at the IF frequency, some consideration must be made to implement the correct delays so as to minimize the impact of squint that can result from IF beamforming. Given the aperture consolidation that results from the multi-beam capability, we find the weight and power estimates to be competitive with the RF implementation. The use of optical fiber for hardware remoting and the incorporation of signal downconversion are also attractive features. The critical technologies identified for the successful implementation of this architecture include the optical heterodyne source, the MOSAIC optical splitting device and the DBR based tunable semiconductor laser employed in the true time-delay implementation.

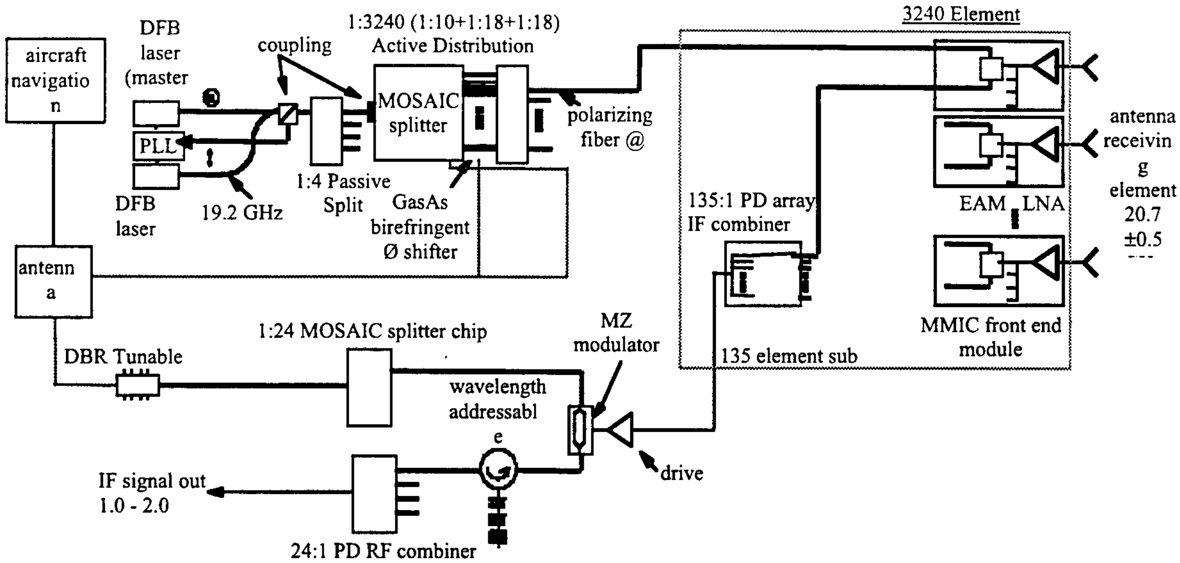


Figure 28. Scanning Array (Photonic).

Note: Multibeam capability leads to aperture consolidation

1.31.1. Trade Considerations
(+) Downcovnersion incorporated
(+) Multiple beam operation
(+) Moderate Weight (≈ 2x RF)
(+) Lower DC power required

1.31.2. Critical Technologies
Heterodyne laser source
MOSAIC
DBR Tunable Laser

1.32. Airborne Receive Wideband Crossed Notched Elements

The wideband cross-notch element array is illustrated below. These elements support dual polarization operation and typically are individually machined and assembled. As there are two feed points for each element (one for each orthogonal polarization), some additional electronics at the front end are required to support arbitrary circular sense polarization. The two feed outputs from the element, are input to a printed circuit 90° hybrid and an RF switch between the two outputs enables the collection of LH or RH sense circularly polarized signals. The additional electronics would add complexity to the receive module, but the cost penalty is expected to be less than implementing multiple beamformers for each frequency band. TRW has demonstrated satisfactory operation over approximately a 20 GHz bandwidth with these devices, which will support the airborne multi-frequency antenna array application.

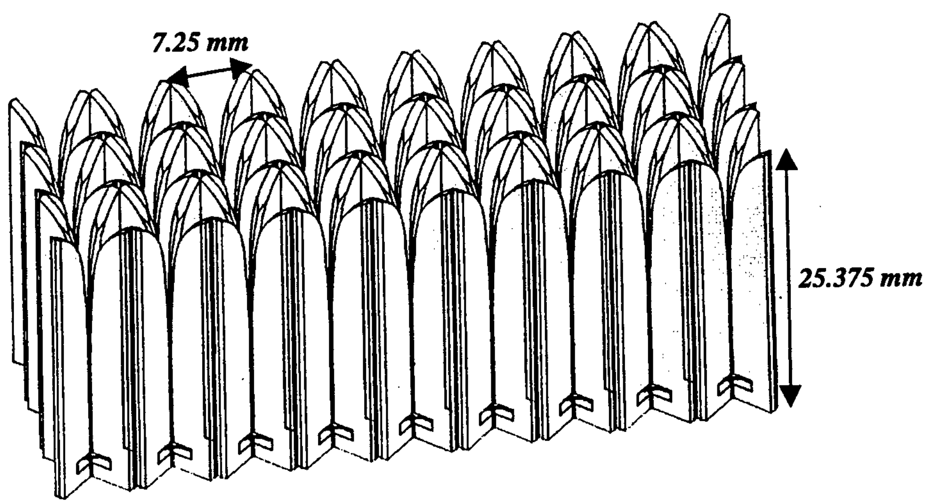


Figure 29. Airborne Receive Wideband Crossed Notched Elements.

2. Verification Experiments

2.1. Verification Experiment Conclusions

Level of effort to acquire data on most recent fabricated MOSAIC devices

Figure 30. Experimental Diagram.

$F_{opt} = SNR_{in}/SNR_{out}$

SNR_{in} = 37.4 dB (accounting for 6.25 dB insertion loss, 10 dB split loss gives 21.15 dB SNR presented to amplifier)

SNR_{out} = 15.15 dB

Estimate for NF = 6 dB

2.1.1. Several antenna architectures selected for design plan require use of MOSAIC devices
Spaceborne Transmit, Airborne Transmit, Airborne Receive

2.1.2. Performance analysis relies on accurate/current MOSAIC component performance data
Photonic performance to meet system performance goals
Impact on beamformer complexity, size, weight, power

2.1.3. We propose to collect measured component data on "Low Noise MOSAIC" device
1:8 device was fabricated on "Low Noise MOSAIC" program
Data for previously fabricated 1:10 device is available (measurements are straightforward)

2.1.4. Performance parameters of interest
Optical noise figure
Optical saturation power/gain
Optical gain uniformity
Response over optical wavelength

2.1.5. Data will enable quantification of improved performance available from latest generation of development and verify viability of technology for insertion into phased array antenna architectures

3. Lessons Learned

3.1. Photonics is an enabler for Advanced EHF Satellite

3.1.1. Spaceborne Receive will almost certainly be an MBA implementation.
Photonic Switching, Remoting significantly reduces packaging complexity.

3.1.2. Nulling antenna will almost certainly be an MBA (the array-fed reflector)
Photonic processor provides high PCA, fast convergence nulling at low power

3.1.2.1. Spaceborne Transmit will almost certainly be a Direct Radiating Array (MBA or Scanning)
Photonic BFN significantly reduces weight of array
Photonics provides no direct leverage against key DRA issue: SSPA linearity

3.1.3. True time delay is not needed (10% bandwidth, GEO orbit)

3.2. Photonics can provide significant benefits to Airborne Transmit Antenna

3.2.1. Mitigates thermal density - Reduced No. of Elements - Reduced Cost
True Time Delay essential for aperiodic spacing for multi-channel aperture (extended requirements)

3.3. Photonics advantages for Consolidated Airborne Receive are less certain

3.3.1. True time delay not essential (can always MUX & frequency hop in separate bands)

3.4. Photonic scanning arrays must enable significant reduction in weight or number of elements to be competitive with RF scanning arrays

3.4.1. High optical power per element needed for low noise figure or high C/I

3.4.2. Requires large amounts of DC power over and above that necessary for comparable RF BFN's
Modulator V_p must be reduced to make photonic scanning arrays more competitive
High power photodetectors are needed to provide sufficient SSPA drive power(for Tx.)

3.4.3. Large number of TTD states may be necessary for wide scan applications
Switched Grating Delays need further development

3.5. Photonics can significantly enhance MBA performance

3.5.1. Direct leverage against key MBA disadvantages of signal routing, switching complexity
- Photonics provides most leverage when used to implement signal routing architectures
  (Much less leverage is provided in implementing signal distribution architectures)

3.6. Advantages of photonically implemented "circuit MBA" beamformers not clear

3.6.1. Opt. Rotman generally not competitive with RF Rotman (same size, more losses, more complex)

3.6.2. Potential advantage of Optical Butler is reduced packaging complexity, enabling Butler implementations where RF Butler is impractical (higher frequencies. larger arrays)
Requirement for optical coherence is a significant drawback (precludes use in space)

3.7. Most photonic beamforming techniques provide maximum leverage for linear arrays

3.7.1. Implementation of two dimensional beamformers results in exceedingly high complexity

3.8. Phase noise performance of heterodyne optical source must be adequate to meet system goals

3.8.1. For injection locked lasers, complexity of mode locked laser source is significant and requires design effort. For phase locked lasers, a reference oscillator is required as well as a PLL with significant locking bandwidth

3.9. Size and cost of WDM multiplexers used to form multibeam can be a system cost driver for some antennas

3.9.1. For multibeam antennas, hundreds of multiplexers may be required.
Packaging of WDM's needs to be further developed

3.10. Tunable optical sources must provide wide tuning range and high power in a robust package

3.10.1. DBR technology is promising, but limited COTS availability

4. Recommendations for Future Work

Our recommendations for future work are based on the results of our extensive trade analysis (component and architecture) and our composition of a design plan for each SATCOM antenna architecture.

One area of future work relates to the photonic component development necessary to meet the required SATCOM performance goals. Although most of the technologies examined and highlighted in this report are within reach of realizing the necessary performance for required system performance, most devices still fall short in one or two ways. The paragraphs below identifies several technology developments that are required to enable meeting the system performance goals required for MilSatCom applications.

A second area of future work is in the integration of component technologies together to enable further reductions in the size and weight associated with packaging and the integration of photonic components into existing RF transmit or receive amplifier modules. This is a key integration step that would enable acceptable levels of system performance and result in optimal system architecture configuration. Integration of optoelectronic circuits must take into consideration material system compatibility, processing yield and reliability. This is an area of future work that will do much to enable the eventual incorporation of photonics into these antenna systems.

Packaging is an ever important consideration for photonic and optoelectronic components. While most commercial-off-the-shelf, and TRW internal packaging efforts have focused on individual device packaging, most antenna architectures will require the packaging of arrays of devices, be they modulators, photodetectors, or optical amplifiers. Such packaging efforts will also be critically important to demonstrating the feasibility of photonic technologies for insertion in SATCOM antenna systems.

Finally, we recommend brass-board level demonstration of some of the highest leverage photonically implemented structures. Three primary candidates are the space borne receive MBA, the Nuller processor or beamformer, or the Airborne transmit aperiodic array. The downselected architectures and design plans provide sufficient development to spring into a developmental demonstration program of these high leverage photonic technologies. Such demonstrations could leverage off of existing engineering models or breadboards and would go far to validate the concepts developed for this program and establish credibility and visibility for this research and development effort.

4.1. Moderate level of photonic device development to meet beamforming performance goals

4.1.1. Most device technologies are near but still fall short of required performance

Modulator BW and V_π,
Optical amplifier NF and P_{sat},
DFB laser output power and RIN noise performance
DBR laser output power wavelength tunability
Optical switch packaging and insertion loss
WDM Packaging

4.2. Opto-electronic device integration

4.2.1. Modulators (EAM) incorporated into LNA front end receive module

4.2.2. Photodetectors incorporated into SSPA front end Tx modules

4.3. Packaging development for some components and device arrays

4.3.1. WDM's and arrays of modulators, photodetectors, and MOSAIC amplifiers

4.4. System (unit) POC/Brassboard Demonstration

4.4.1. SB RCV MBA, Nuller or AB Tx demo

4.4.2. Leverage off of existing RF brassboards (e.g. "attach" photonic BFN/processor)

4.4.3. Validate System level performance, establish credibility

5. Photonic Component Trades

5.1. Photonic System Trade Space

The general characteristics of EHF Airborne and Spaceborne antenna systems place certain requirements on the performance and applicability of photonic components considered for insertion. The following paragraphs present the results of our component technology and beamforming concept tradeoff study for optically controlled EHF SATCOM antennas. The conclusions presented here are based on our knowledge of the general performance and reliability requirements of these antennas as well as those lessons learned from the considerable architecture development performed during the course of the ESAD program. This paragraph outlines some of those general characteristics and the principal issues affecting the selection of technologies for insertion.

5.1.1. Large Number of Antenna Elements

The cost of these antennas are primarily driven by the number of elements required to achieve a certain level of performance. Minimizing this number requires that significant levels of optical power be delivered to each element modulator or photodetector. Optical amplification is then required to accomplish the necessary signal distribution, or alternatively, efficient power routing architectures are required to send power to active antenna elements. For receive antennas, large numbers of signals must be coherently combined in order to achieve adequate SNR and performance.

5.1.2. Multiple Beam Requirements

Multiple beams imply highly parallel signal paths and the possible requirement of multiple wavelengths to facilitate beamforming.

5.1.3. RF Downconversion / Variable Phase Control

Adequate phase noise performance, resolution and stability, over adequate bandwidths are important in accomplishing this function. Downconversion from EHF frequencies (up to 46 GHz) is important in enabling high performance beamforming architectures.

5.1.4. Reliability

Minimal complexity and maximal reliability in potentially harsh environments demonstrating radiation, mechanical shock, and temperature extremes is crucial as well in establishing useful antenna architectures.

5.1.5. Integrability

Finally, consideration must be made as to the compatibility of device technologies and beamforming structures with other system structures. For example, if quadrature bias on the modulator is necessary to accomplish a beamforming function, but is incompatible with downconversion, then some adjustments must be made in the architecture to enable the simultaneous execution of these functions.

Note: Several antenna system requirements influence appropriate technology choices for EHF beamformer design.

5.1.5.1. Large number of elements
- High optical power to each element
- Optical amplification/Signal Distribution
- Large order element combining

5.1.5.2. Multiple beams (space based antennas)
- Increased number of parallel channels
- Multiple wavelength operation

5.1.5.3. Microwave downcoversion
- Polarization independence
- Adequate phase noise performance
- Low complexity

5.1.5.4. Variable amplitude-phase-time control
- Resolution-stability
- Reconfiguration Speed
- Bandwidth

5.1.5.5. Reliability
- Temperature-radiation insensitivity
- Minimal size-weight-power
- Mechanical robustness
- Minimal Complexity

5.1.5.6. Integrability
- Consistency between component and system requirements

5.2. Optical Sources

5.2.1. DFB Lasers

DFB lasers are characterized by low RIN (-165 dB/Hz), moderate phase noise (< 5 MHz linewidth), up to 50 mW optical power with ~1% wall-plug efficiency, and commercial availability. The increased phase noise places great demands on PLL performance if required for optical heterodyning applications. Grating stabilized DFBs are useful for fixed wavelength WDM systems with no thermal control. DFBs require less packaging and power consumption than Nd:YAG lasers resulting in less size, weight, and power.

5.2.2. Nd:YAG Lasers

Nd:YAG lasers are characterized by low RIN (-165 dB/Hz), low phase noise (< 5 kHz linewidth), high output powers (200 mW @ 1310 nm) with ~2% wall plug efficiency, up to 60 GHz heterodyne generation, and commercial availability. Thermal tuning necessitates temperature control which adds weight and power consumption to the system. The crystal may also be more susceptible to radiation than semiconductor materials making these lasers potentially less desirable for space applications. The high power and performance comes with the cost of increased size, weight, and DC power relative to other laser technologies.

5.2.3. DBR Lasers

DBR lasers are characterized by electronic tunability over 50 to 100 nm, moderate power (25 mW, not fiber coupled), but little commercial availability (there seems to be little demand for them in telecom systems). Electronic tuning eliminates the need for mechanical assemblies which provides increased reliability. Despite the limited availability of these devices, they are attractive for wavelength agile systems.

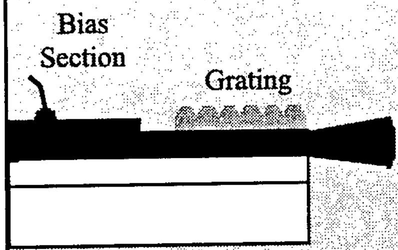
5.2.4. External Cavity Tunable Lasers

External cavity lasers are characterized by 60 nm tuning, moderate RIN (-145 dB/Hz), < 5 MHz linewidth, 4 mW output power, and commercial availability. Some work is proceeding on high power gain elements to increase output power. Reliability is low with these lasers as mechanical vibration and shock can impact the alignment of the laser and impair performance. With the exception of a micro-cavity tunable laser available from Santec Corporation, these devices are bulky and unreliable making them less attractive for spaceborne and airborne platforms.

5.2.5. Erbium Fiber Ring Lasers

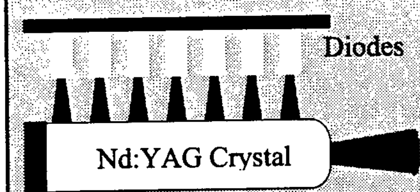
Commercially available can demonstrate very high powers with up to 4% wall-plug efficiency, but with significantly degraded RIN and phase noise performance relative to other optical sources. Electronic tunability has been demonstrated in some research devices, but has not yet reached a state of development that would justify insertion into next generation phased array antenna systems.

DFB



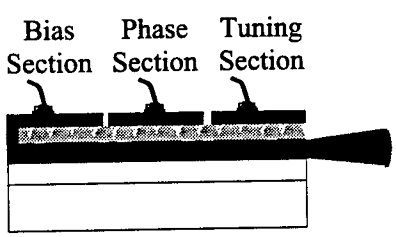
+ Moderate power
  - • 20-50 mW
- Moderate noise
  - + -165 dB/Hz RIN
  - - 1-5 MHz linewidth
+ Multiple wavelengths
  - - thermal tuning
+ Commercial device
+ ~1% Wall-Plug Eff.
+ Reliable/rugged

Diode Pumped Nd:YAG



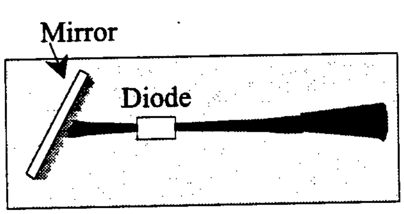
+ High power
  - • 200 mW
+ Low noise
  - + -165 dB/Hz RIN
  - + 5-50 kHz linewidth
- Narrow tuning range
  - • 60 GHz
+ Commercial device
+ 1-2% Wall-Plug Eff.
- Limited reliability

DBR



+ Moderate power
  - • 20 mW MAX
- Moderate noise
  - • Similar to DFB
+ Electronic tuning
  - • up to 100 nm
- Research device
+ Reliable/rugged

External Cavity Tunable Laser



- Low power
  - • 2-4 mW
- Moderate noise
  - - -145 dB/Hz RIN
  - + 300 kHz linewidth
- Mechanical tuning
  - • up to 60 nm
+ Commercial device
- Bulky and Fragile

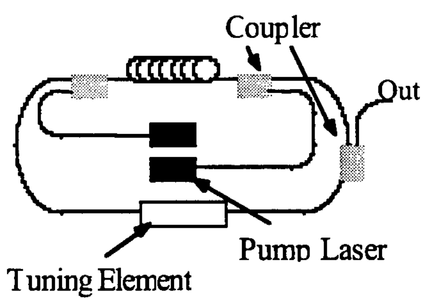
Figure 31. Optical Sources.

Note: Low amplitude and phase noise requirements as well as multi-wavelength operation lead to the choice of DFB or Nd:YAG lasers for optical sources.

5.2.6. General Conclusions

For high optical power, low amplitude and phase noise requirements, Nd:YAG lasers are the optical source to be chosen. Most EHF antenna systems however, require optical amplification even with high power sources. The flexibility of integration, the reduced size and weight requirements, and the potential reliability on space platforms move towards the selection of DFB lasers for most antenna architectures. In heterodyne systems, the low noise performance of Nd:YAG lasers demonstrate distinct advantages over DFB and other types of lasers. These advantages are somewhat diminished if injection locking techniques can be incorporated. For WDM systems, DFB lasers can demonstrate lower RIN noise and much higher optical power performance than most commercially available tunable diode laser sources. With the absence of any commercially available DBR tunable laser source and significant wavelength agility requirements, the use of multiple rugged, high-power, grating stabilized, fixed wavelength DFB lasers is an attractive alternative to mechanically fragile external cavity laser sources. Further development of DBR lasers in the future may change their usefulness for WDM beam forming systems.

Erbium Fiber



+ **Moderate power**
  - **1-40 mW**
- **High noise**
  - **-80 dB/Hz RIN**
  - **1 GHz linewidth**
+ **Multiple wavelengths**
+ **Electronic Tunability**
+ **Commercial device**
+ **Wall-Plug Eff. 3-4%**

Figure 32. Optical Sources (2).

5.3. Modulators (RF to Optical)

5.3.1. Electro-absorption Modulators

EAMs are characterized by low V_π (< 5 V), high RF bandwidth (< 40 GHz), narrow optical bandwidth (20 nm), high insertion loss (lower with mode matching), polarization independence (with strained structures), low input power (30-40 mW), and near term commercial availability (integrated DFB laser/EAM in GaAs). Higher powers and bandwidth, with lower V_π may be accomplished with traveling wave electrode devices.

5.3.2. Mach-Zehnder Modulators

Semiconductor modulators are characterized by moderate V_π (10 V @ 50 GHz, 5 V @ 20 GHz), high insertion loss (~10 dB), and lower power handling (30-40 mW). The incorporation of quantum well structures can lead to improved linearity over standard MZM devices. Standard MZM devices are available from GEC Marconi and linearized devices are being developed at TRW. Velocity matched electrodes are most likely required to achieve lower V_π. Narrowband operation can facilitate optimum electrode designs resulting in substantially improved performance at 44 GHz.

Polymer modulators are characterized by high V_π (> 20 V), very high RF bandwidth (up to 110 GHz), moderate insertion loss, easy integration with III-V devices, temperature stability, and the potential for high power handling and radiation hardness. The low dispersion in polymers makes for easy velocity matching with little effort. Continued progress in modulator development may reduce V_π and make these devices the optimum choice for EHF beamforming networks.

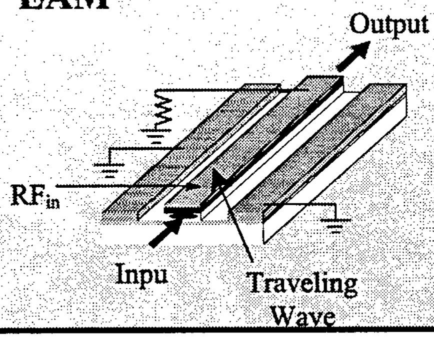
$LiNbO_3$ modulators are characterized by high V_π (> 10 V), moderate RF bandwidth (< 20 GHz), broad wavelength operation, moderate insertion loss (< 4 dB), and high input power (200 mW). For high frequency operation, velocity matching is important to reduce V_π, but the electrode structures are complicated and require substantial design effort. Most commercial products are grown in $LiNbO_3$, but recent products have been grown in GaAs for integration with DFB lasers with the reliability of semiconductors materials.

5.3.3. Fiber Modulators

Fiber modulators are characterized by very low insertion loss (0 dB), but with high V_π and low bandwidth operation. Further development may make these modulators useful at EHF frequencies, but so far improvements have progressed slowly.

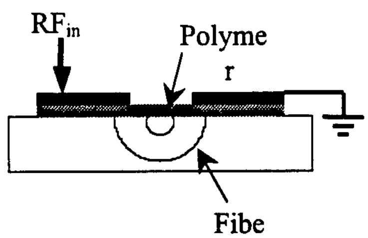
For high frequency applications (20-40 GHz), EAMs are the best readily available choice for modulators. High power, low frequency applications (or with WDM) lead to choosing MZ modulators unless power handling capability of EAM can be increased. Further development in polymer based modulators may make them the most useful all around modulator for EHF applications. Reduced insertion loss for all modulator structures will help in improving the RF performance of photonic beamforming systems.

EAM



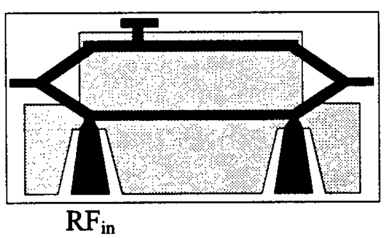
+ Large bandwidth
  • 40 GHz
+ Large DR
+ Low V_{π}
- High coupling loss
  • expanded mode
- Low input power
- Wavelength/Pol.
- Research device

Fiber Based



- Low bandwidth
+ Large DR
- Large V_{π}
+ Low coupling loss
+ High input power
+ Wavelength/Pol.
- Research device

Mach-Zehnder



(Polymer)

+ Large bandwidth
  • 110 GHz
- Limited DR
- Large V_{π}
- High coupling loss
+ High input power
+ Wavelength/Pol.
+ High reliability
- Research device

(Semiconductor)

+ Large bandwidth
  • 50 GHz
+ Large DR
- Moderate V_{π}
- High coupling loss
- Low input power
+ Wavelength/Pol.
+ High reliability
- Research device

($LiNbO_3$)

-Limited bandwidth
- Limited DR
- Large V_{π}
  • if large bandwidth
- High coupling loss
+ High input power
+ Wavelength/Pol.
+ Commercial device

Figure 33. Modulators (RF to Optical).

Note: Large bandwidth and high RF gain lead to the use of EAMs or III-V MZMs for receive antennas except when high optical power handling is required.

5.4. Amplified Distribution

For large arrays, splitting losses are substantial and must be compensated with optical amplification. The main considerations are noise figure, optical power saturation, dynamic range and the possibility of integrated amplitude control.

5.4.1. Semiconductor Based Talbot Amplifiers

MMI splitters fabricated in semiconductors are characterized by high saturation power, high noise figure (8 dB), and limited dynamic range (due to small carrier lifetime). The high noise figure is a consequence of substantial coupling loss which may be reduced with improved mode matching. Electronic pumping of the gain material allows integrated amplitude control of the individual outputs. Strained structures can accomplish polarization independence that would be useful for some optical heterodyne systems.

5.4.2. Erbium Doped Glass Based Talbot Amplifiers

Er doped waveguide MMI splitters are characterized by high saturation power, low noise figure (< 4 dB), high dynamic range (large carrier lifetime), low coupling loss, polarization independence, and the possibility of large fanout. Optical pumping precludes the use of integrated amplitude control while the wavelength dependent imaging of the pump and signal may limit the gain and noise figure. Er doped glass has also demonstrated reduced performance in radiation environments that may limit its use in space applications.

5.4.3. Erbium Doped Fiber Amplifiers

EDFAs are characterized by high saturation power, low insertion loss, low noise figure, and commercial availability. They face the same disadvantages as Erbium doped waveguides without the reduced size from an integrated structure. An EDFA is functionally a y-branch splitter and demonstrates the increased noise figure characteristic of this method of amplified distribution.

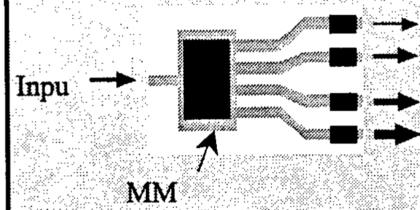
5.4.4. Semiconductor Y-Branch Splitter

Semiconductor y-branch splitters are characterized by low saturation power, high noise figure (11 dB), and limited dynamic range. Increased fanout is possible as is the possibility of integrated amplitude control. Y-branch splitters generally deliver reduced performance compared to MMI splitters as they require very high saturation powers to deliver comparable performance.

5.4.5. General Conclusions

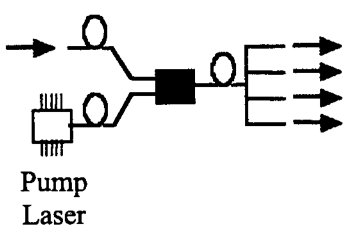
MMI splitters (semiconductor or glass) seem preferable for highly integrated amplified distribution. The possibility of variable amplitude control and radiation hardness must be traded with low noise figure and large fanout (in a single structure). Given that reduced coupling losses (with expanded mode waveguides) and the use of strained structures can lead to low noise figures and polarization independence in semiconductor based splitters, the possibility of output waveguide amplitude control and the environmental robustness makes the use of semiconductor based splitters more appealing at this time over doped waveguide structures.

Talbot Amplifier



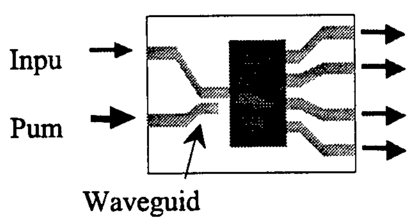
- \+ Reliable/rugged
- \+ Device compatibility laser/mod./detector
- \+ Amplitude control
- \- Limited DR
- \- Moderate NF coupling limited
- \- Wavelength/Pol. strain/structure

Er Doped Fiber Amplifier



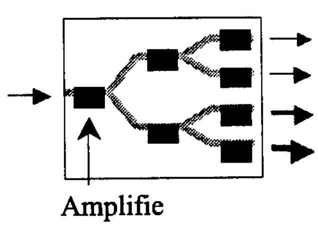
- \+ Moderate reliability commercial device
- \- Ltd. compatibility
- \- No amplitude control
- \+ High DR
- \+ Low NF
- \+ Wavelength/Pol.
- \+ Low coupling loss < 1dB

Er Doped



- \- Limited reliability Pump absorption
- \- Ltd. compatibility
- \- No amplitude control
- \+ High DR
- \+ Low NF ? near 3 dB
- \+ Wavelength/Pol.
- \+ Low coupling loss

Active Y-branch



- \+ Reliable/rugged
- \+ Device compatibility laser/mod./detector
- \+ Amplitude control
- \- Limited DR
- \- High NF
  - • structure limited
- \- Wavelength/Pol. strain/structure

Figure 34. Amplified Distribution.

Note: Noise figure, system integration and the incorporation of variable amplitude control impact the choice of optical amplification for EHF beamformers.

5.5. True-Time-Delay

True time delay can be implemented at the subarray level with element level phase control, or entirely at the element level. One result from the SHF program is that there is little difference in the performance of these two systems. For large arrays, subarray level control is adequate. Insertion loss, and environmental stability are the most significant figures of merit.

5.5.1. Bragg Grating Techniques

Bragg grating based true-time-delays are characterized by low loss (3 dB), low complexity, wavelength addressability, and commercial availability. The use of discrete gratings allow for truly programmable delays independent of the wavelength separation of the WDM sources, while chirped gratings allow for time resolution limited only by the wavelength resolution of a tunable source. There is some concern with signal dispersion from chirped gratings for applications with very large bandwidths (~ 5 GHz). For EHF applications, bandwidths of less than 1 GHz would not prohibit the use of chirped grating implementations.

5.5.2. Optically Switched Delays

Optically switched delays are characterized by faster switching speeds than fiber based delays, but demonstrate significant insertion loss from the optical switches. Current electro-optic switches are bulky and rely on materials that might not withstand harsh environments.

5.5.3. Arrayed Waveguide Grating

AWG based true time delays are characterized by higher complexity and insertion loss (7 dB for 16 delays) relative to Bragg-grating techniques. They also require thermal control and may be more difficult to use in harsh environments. Current AWGs have been fabricated with up to 32 channels but with increased insertion losses.

5.5.4. General Conclusions

Bragg grating based devices are most preferable for implementing true-time-delay at the subarray level. Delay resolution and range requirements will determine whether discrete gratings or chirped gratings are more useful. The incorporation of temperature compensation into Bragg grating implementations will increase their reliability in space qualified environments. As the insertion loss of these devices originates in the use of an optical circulator, improvements in this technology will greatly improve the performance of these devices. The high loss associated with optically switched delays would prohibit their use unless rapid beam steering was required.

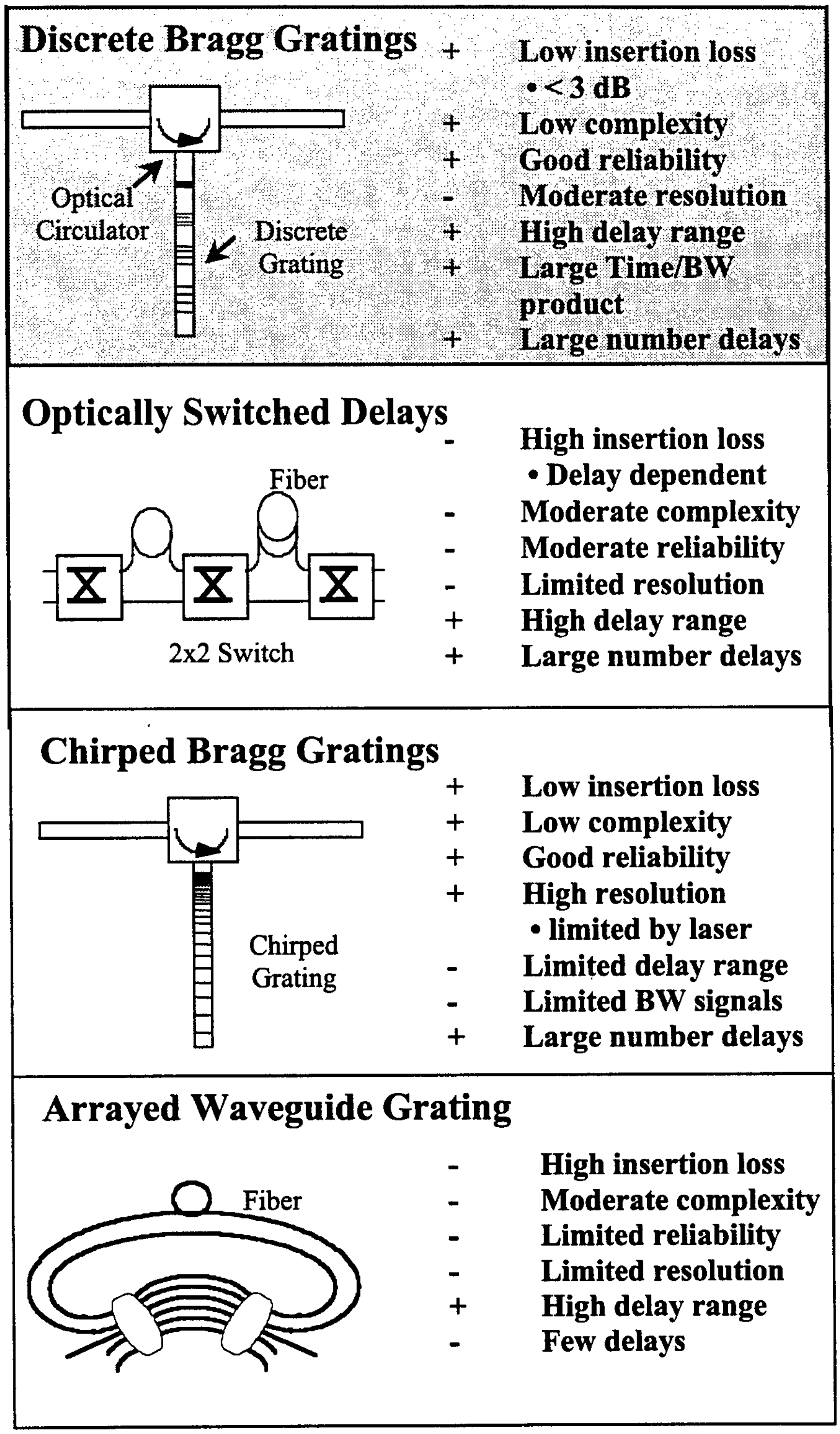


Figure 35. True-Time-Delay.

Note: Low loss and low complexity in harsh environments lead to using Bragg grating techniques for true-time-delay control.

5.6. Variable Phase Control RF up/down-conversion

Optical variable phase control and RF down (up) conversion are usually implemented together. The challenge is in determining a method for efficiently mapping the variable phase of the RF local oscillator to the RF signal. Some antenna architectures require only frequency conversion and offer the possibility of implementing different techniques and technologies.

5.6.1. Orthogonal-Polarization Heterodyne

Two lasers are phase locked at an offset frequency and set to orthogonal polarizations before being coupled together. This signal is input to a birefringent electro-optic phase shifter where the two polarized signals realize equal and opposite phase shifts. A 45° polarizer results in amplitude modulation of the optical signal at the established RF frequency and phase. Upon modulation by the input signal and photodetection, the RF signal is down-converted to the IF frequency with the variable phase from the local oscillator. This technique requires two low phase noise lasers, a single local oscillator, and provides LO generation up to 60 GHz. Temperature stability is accomplished since the orthogonally polarized signals travel together to the 45° polarizer. Any offset bias phase results from unequal path length from the laser outputs to the coupling fiber inputs. It is expected that any drift can be minimized in this short path. Integrated implementations in GaAs should be environmentally robust.

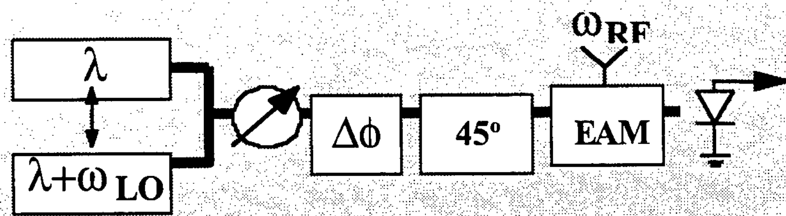
5.6.2. Injection Locked Optical Heterodyne

A mode locked laser, driven by a 1 GHz tone acts as an optical comb frequency generator. The slave lasers are temperature tuned to line up with different tines of the frequency comb and become injection phase locked to the MLL. The outputs are combined and become the optical heterodyne source. The phase noise performance of the photodetected output is dominated by the performance of the 1 GHz oscillator. The frequency span can range as high as 100 GHz depending on the output of the MLL. Unequal path lengths between the lasers and the 50/50 output coupler will lead to a phase bias, so careful control of this part of the device is required.

5.6.3. Complex Weighting

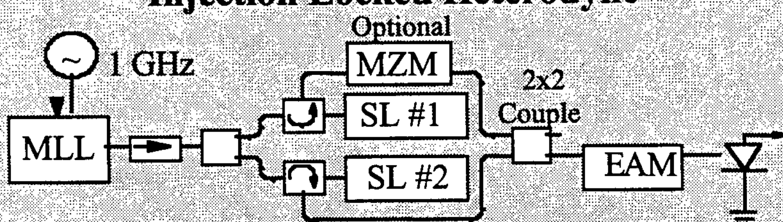
An optical signal is first modulated by a RF local oscillator with varied RF phase. Amplitude control is either provided in RF or by adjusting the bias of the modulator. This modulated optical signal passes through another modulator which is input the RF signal. The two sidebands mix at the photodetector to down convert the RF signal to an IF frequency with applied phase. A single laser is required with relaxed phase noise requirements, but a local oscillator is required for every antenna element which can result in increased hardware and complexity. This technique also provides environmental stability as the local oscillator and the RF signals are on sidebands of the optical carrier.

Orthogonal Polarization Heterodyne



- \+ Single local oscillator generation
- \+ Good temperature stability
- \+ Low size, weight power
  - For large number of elements
- \- Phase noise limited by lasers
- \- Two lasers required
- \- PLL required between lasers
- \+ High frequency LO generation
  - Limited by lasers to 60 GHz
- \+ Phase Control Possible

Injection Locked Heterodyne



- \+ Single local oscillator generation
- \+ Good temperature stability
- \+ Low size, weight power
  - For large number of elements
- \- Phase noise limited by 1 GHz reference
- \- MLL required (complexity)
- \- PLL not required
- \+ Extremely High frequency LO generation
  - Up to 100 GHz (limited by MLL)
- \- No Phase Control

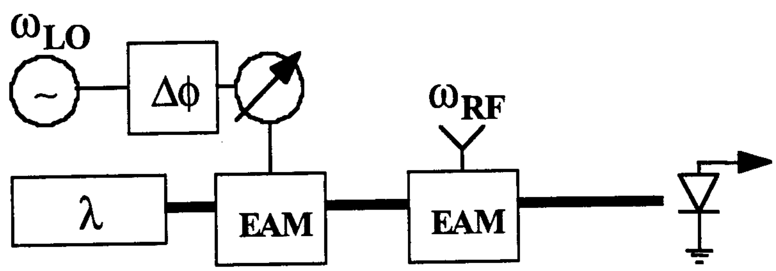
Figure 36a. Variable Phase Control RF up/down-conversion.

Note: System complexity trades will lead to the use of orthogonal polarization techniques for many elements and complex weighting for few elements.

5.6.4. General Conclusions

The type of downconversion scheme that is appropriate depends on the antenna system architecture and the desired functionality. For antenna systems with many elements and where phase control is required, orthogonal-polarization heterodyne techniques appear to be more useful as the cost of the additional electronics is probably much greater than the cost and complexity of an additional laser. For antenna systems with few elements where phase control is required, the relaxed laser requirements and elimination of a phase locked loop will lead to a preference for complex weighting. For antenna system architectures which do not incorporate phase control, the injection locked technique is attractive as it offers potentially superior phase noise performance as it is limited primarily by the performance of a low frequency RF source.

Complex Weighting



- Multiple local oscillators required
+ Good temperature stability
- Low size, weight power
  - For small number of elements
+ Phase noise limited by RF LO
+ Single laser required
+ PLL not required
+ Very high frequency LO generation
  - Limited by RF local oscillator
+ Phase Control Possible

Figure 36b. Variable Phase Control RF up/down-conversion.

5.7. Signal Combining

Signal combining is required for receive antenna beam forming. Signals can be combined optically or in RF after photodetection. Insertion loss, bandwidth, and scalability are the primary concerns, except in nulling applications where maintenance of amplitude stability is critical to acceptable performance.

5.7.1. Photodetector Array with Matched RF Combiner

With detection of individual signals and combining in RF, high bandwidth and amplitude stability can be maintained. A Wilkinson or other type of impedance matched RF combiner provides the necessary isolation to maintain acceptable RF bandwidth. Amplitude and phase matching is crucial to establishing high combining efficiency. This technique significantly reduces the required power on the photodetectors and mitigates the need for the complexity associated with WDM or Multi-mode fiber combiners.

5.7.2. WDM Multiplexing

Signal combining can be accomplished by implementing WDM and using WDM multiplexers. The total photodetected power can be quite high and the need for multiple lasers at different wavelengths would normally preclude the use of this technique for antenna systems with a large numbers of elements. However, some signal power routing architectures are clearly enabled by this technique and can benefit from its incorporation.

5.7.3. Multi-mode Fiber Optic Combiners

Multi-mode fiber optic combiners are characterized by low insertion loss (< 1 dB), high dynamic range, moderate size (> 20:1), limited bandwidth, and limited amplitude stability. The most reasonable implementation is etching the cladding from input single-mode fibers and then fusing to a multi-mode fiber. A preliminary statistical analysis indicates that multi-mode combining should lead to an output with high variance which is undesirable. Additionally, these combiners are impractical for nulling applications as more modes are required for amplitude stability than can be excited in a reasonably sized multi-mode fiber.

5.7.4. Traveling Wave Lumped Photodetectors

Traveling wave photodetectors have been demonstrated with moderate success. A high level of impedance matching is required for high frequency operation. The frequency response of most demonstrated devices fall rapidly when incorporating increasing numbers of photodetectors.

The more attractive approaches are RF or WDM combining. With the incorporation of RF downconversion, it should be easy to maintain acceptable bandwidth. High power handling photodetectors are required when WDM combining is established.

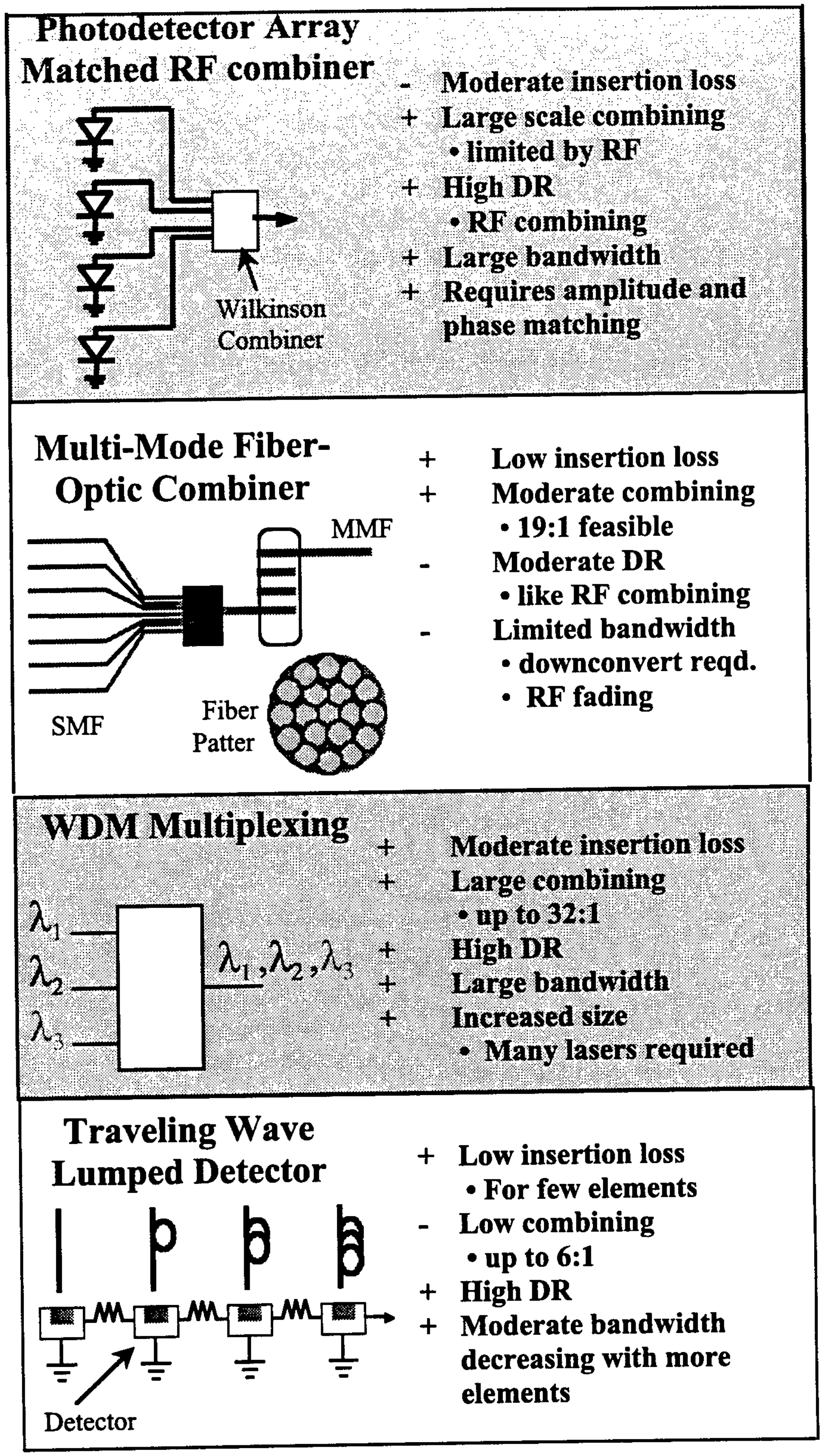


Figure 37. Signal Combining.

Note: The need for low loss combination of many elements while maintaining adequate amplitude control poses serious challenges to all-optical techniques.

5.8. WDM Multiplexing

WDM multiplexers find use in facilitating multiple beam forming, true-time-delay implementation, and optical signal combining. Until the advent of reliable high power tunable laser sources, Bragg grating true-time-delays will be implemented with multiple DFB lasers at different fixed wavelengths. WDM multiplexers will be required for combining these signals with low insertion loss.

5.8.1. Resonant Fiber Gratings

Resonant fiber grating multiplexers are characterized by very low insertion loss (0.5 dB), cascadability to multiplex large numbers of WDM signals, temperature stability (with compensation), and commercial availability. Such multiplexers are very compatible with fiber-pigtailed DFB lasers.

5.8.2. Cascaded Bandpass Filters

Cascaded bandpass filters are useful for multiplexing small numbers of channels. There is increased insertion loss (7 dB for 16 channels), but increased temperature stability due to the commercial availability of highly robust thin film coatings. If required, temperature control is difficult as the entire device cavity temperature must me maintained.

5.8.3. Arrayed Waveguide Grating

AWGs are characterized by high insertion loss (7 dB for 16 channels), required temperature control, and a planar structure is compatible with integrated systems. As they are fabricated in silica glass, radiation harness is expected. Some recent development has been done with polymer based AWGs that would provide high temperature stability and reduced cost.

5.8.4. Concave Mirror and Grating

Concave mirror/grating devices are characterized by moderate insertion loss, reduced temperature stability, and commercial availability. Large devices can be constructed to multiplex very large numbers of channels. Quartz crystal is used in the device, increasing susceptibility in radiation environments.

When required, resonant fiber gratings offer an attractive method of WDM multiplexing. The fiber based design provides compatibility with DFB laser devices while maintaining low loss and environmental stability. The technology is compatible with Bragg grating based true-time-delay which makes the development of adequate temperature compensation common to both devices. Elimination of the need for temperature control of these devices results in a very lightweight and small size device that is easily integrated into beamforming structures.

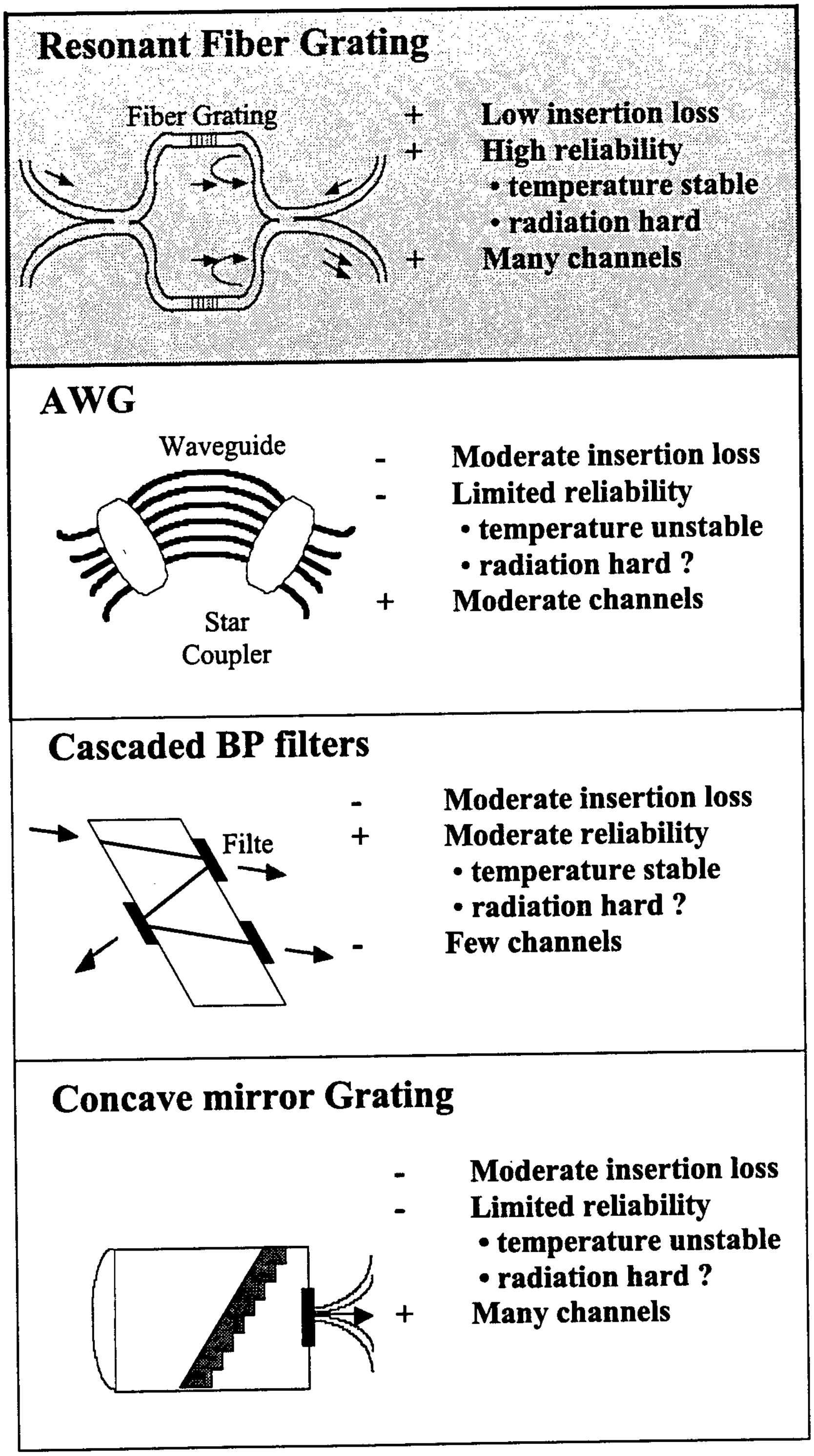


Figure 38. WDM Multiplexing.

Note: Multiple-beam forming, true-time-delay, and low-loss signal combining may necessitate the use of WDM multiplexers for EHF antenna systems.

5.9. Optical Switching

Optical switching is crucial in the establishment of several multiple beam antenna architectures. A compact, low loss, high isolation, and fast switch is necessary for the successful establishment of these proposed architectures. Candidate technologies are limited, but some are promising for meeting the switching goals established for these systems.

5.9.1. Switchable Diffraction Gratings

Resonant fiber grating multiplexers are characterized by very low insertion loss (0.5 dB), cascadability to multiplex large numbers of WDM signals, temperature stability (with compensation), and commercial availability. Such multiplexers are very compatible with fiber-pigtailed DFB lasers.

5.9.2. Interferometric Switch

Cascaded bandpass filters are useful for multiplexing small numbers of channels. There is increased insertion loss (7 dB for 16 channels), but increased temperature stability due to the commercial availability of highly robust thin film coatings. If required, temperature control is difficult as the entire device cavity temperature must me maintained.

5.9.3. MEMs based Optical Switch

AWGs are characterized by high insertion loss (7 dB for 16 channels), required temperature control, and a planar structure is compatible with integrated systems. As they are fabricated in silica glass, radiation harness is expected. Some recent development has been done with polymer based AWGs that would provide high temperature stability and reduced cost.

5.9.4. Fiber Optic Mechanical Switch

Concave mirror/grating devices are characterized by moderate insertion loss, reduced temperature stability, and commercial availability. Large devices can be constructed to multiplex very large numbers of channels. Quartz crystal is used in the device, increasing susceptibility in radiation environments.

When required, resonant fiber gratings offer an attractive method of WDM multiplexing. The fiber based design provides compatibility with DFB laser devices while maintaining low loss and environmental stability. The technology is compatible with Bragg grating based true-time-delay which makes the development of adequate temperature compensation common to both devices. Elimination of the need for temperature control of these devices results in a very lightweight and small size device that is easily integrated into beamforming structures.

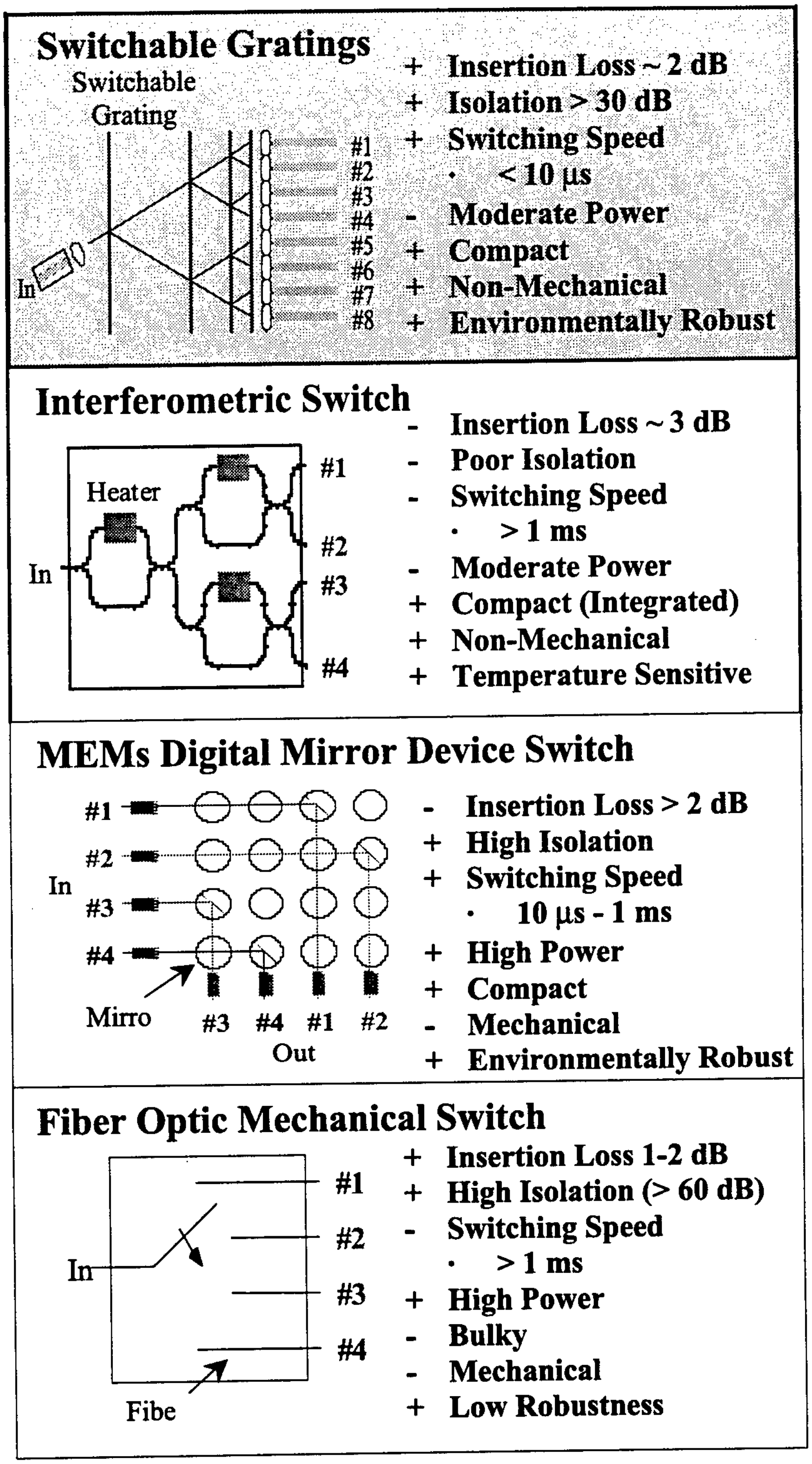


Figure 39. Optical Switching.

Note: Optical switching technologies can enable multiple-beam antenna architectures. Low insertion loss and robust structures are most desirable.

5.10. Photodetectors (Optical to RF)

Photodetectors are critical components for both transmit and receive antennas. High power handling detectors in transmit antennas enable strong RF signal generation which reduces requirements for the driver and power amplifiers. For receive antennas, high power handling with high responsivity enables large scale signal combining without substantial RF gain penalties.

5.10.1. Waveguide Photodetectors

Waveguide photodetectors are characterized by high bandwidth (< 45 GHz), high power handling (10 mW), high insertion loss, high quantum efficiency (near 100 %), and limited commercial availability. The high insertion loss results in low responsivity (< 0.5 A/W) that may be improved with better fiber to waveguide coupling. High power handling capability is established by decreasing the material absorption, increasing the device length, and utilizing traveling wave electrodes. Such material control may be difficult to achieve, but could lead to high responsivity, high power devices.

5.10.2. MSM Photodetectors

Metal-semiconductor-metal photodetectors are characterized by very high bandwidth (> 45 GHz), very high power handling (> 10 mW), high insertion loss, low quantum efficiency (40 %), and limited commercial availability. As these detectors work by coupling evanescent fields from the optical waveguide, many devices must be used in traveling wave structures to achieve the quantum efficiencies of 40 %. Insertion loss again originates in fiber-to-waveguide coupling. High power handling is achieved by adjusting the coupling to the individual detectors which is easily accomplished by adjusting the placement of the detector on the waveguide.

5.10.3. p-i-n Photodetectors

p-i-n detectors are characterized by high responsivity (> 0.8 A/W), low insertion loss, and commercial availability, but demonstrate limited bandwidth (< 18 GHz), and limited power handling capability. High bandwidth requires small devices which results in the reduced power handling capability.

For low frequency, low power applications, p-i-n detectors are an acceptable choice due to their wide commercial availability. However for most EHF antenna applications, higher bandwidth, and definitely higher power detectors are required. Waveguide photodetectors are attractive because of their potential for high power handling without sacrificed quantum efficiency. The ability of a detector to handle more power provides little benefit when accompanied by reduced RF gain. Development of detectors that provide the right balance between bandwidth and power handling capability (i.e. RF gain) will be crucial to establishing the feasibility of photonic beamforming networks for EHF phased array antennas.

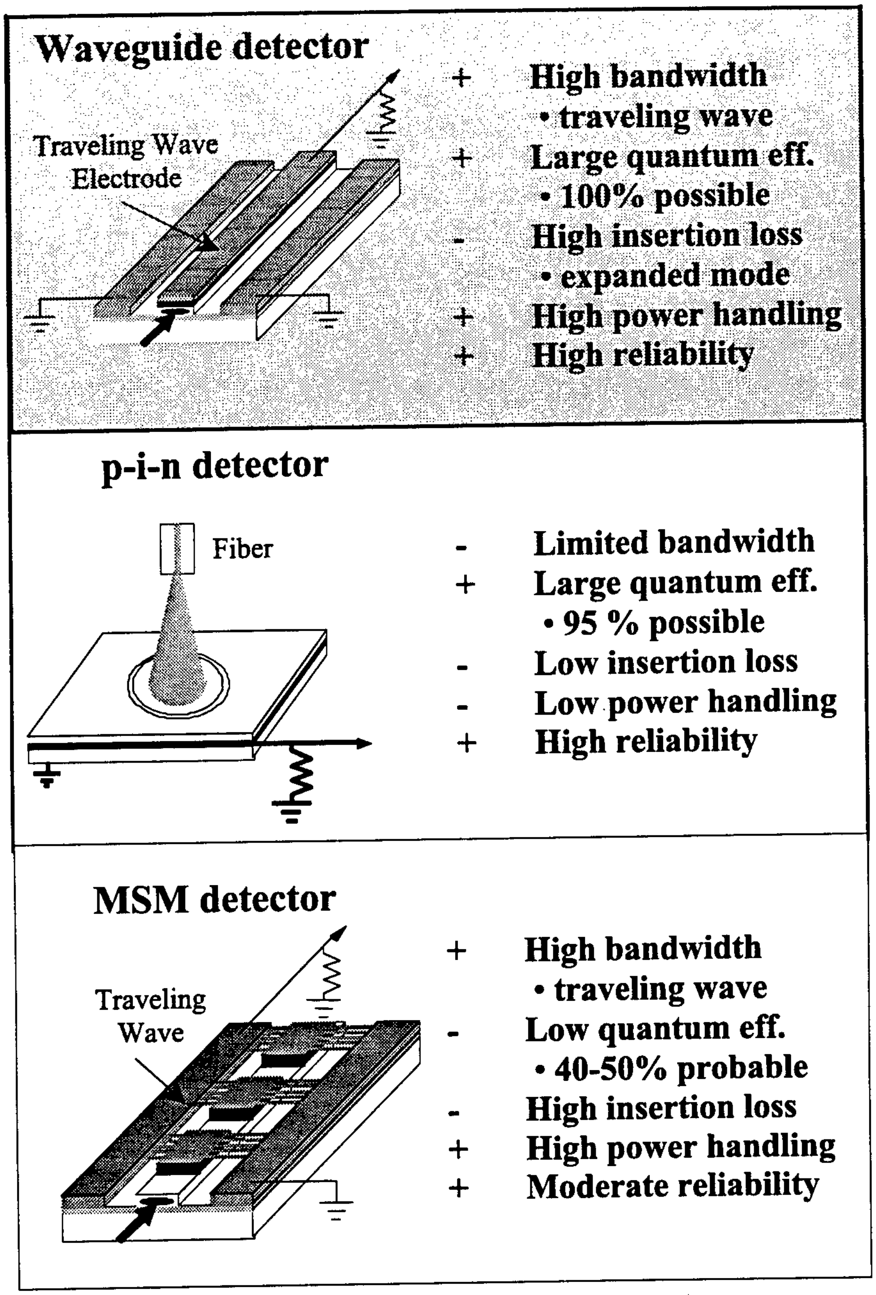


Figure 40. Photodetectors (Optical to RF)

Note: High gain on receive and high power and bandwidth on transmit prohibit the use of p-i-n detectors for EHF beamforming networks.

5.11. Photonic Technology Tradeoff Conclusions

5.11.1. Optical Sources
Until DBR lasers are commercially available, there is no reliable tunable source available for implementing WDM architectures. Grating stabilized DFB lasers arrays are the most attractive in meeting the high power, low noise requirements of WDM beamformers.

5.11.2. Modulators (RF to Optical)
High frequency, high dynamic range requirements for receive antennas lead to selecting EAMs or linearized semiconductor MZMs for these systems. High power systems could benefit from a highly efficient polymer modulator as well.

5.11.3. Amplified Distribution
With improved noise figure, semiconductor amplifiers seem the best choice for radiation hardness and the integration of variable amplitude control. The use of Er doped waveguides is also attractive, and for certain applications may provide acceptable performance.

5.11.4. True-Time-Delay
Bragg grating techniques are prolific in architectures being developed by the RF photonics community. They clearly demonstrate the preferred method for most applications.

5.11.5. Variable Phase/RF Downconversion
For phased arrays with many elements, orthogonal-polarization heterodyne techniques will provide the lowest size/weight/power system. For antenna architectures that require no element phase control, injection locked heterodyne techniques are very attractive.

5.11.6. Signal Combining
For phased arrays, the use of RF combiners or WDM to facilitate signal combining is attractive except for very high numbers of elements, where the large number of required wavelengths may make WDM impractical.

5.11.7. WDM Multiplexing
With adequate temperature stabilization, Bragg-grating multiplexers will provide very low-loss multiplexing for WDM systems.

5.11.8. Optical Switching
Switchable gratings and MEMs based switches are most attractive for accomplishing the functionality required in several architectures.

5.11.9. Photodetectors (Optical to RF)
Waveguide photodetectors are useful except for receive antennas utilizing optical combining. The required multi-mode waveguides forces the use of large area photodetectors to maintain a high detecting efficiency.

5.11.9.1. Semiconductor based lasers are most attractive for ESAD architectures
Grating stabilized DFB for single wavelength, DBR or DFB arrays for multiple wavelength

5.11.9.2. EAMs required for high frequency, high dynamic range
Linearized semiconductor and polymer MZM modulators are also very attractive

5.11.9.3. Talbot amplified splitter to provide amplitude control and reliability
Airborne applications require further NF reduction (Er:doped waveguides are also attractive)
5.11.9.4. Bragg grating TTD for low loss and reliability
With multiple DFB WDM discrete gratings most useful

5.11.9.5. Variable phase/RF downconversion selection depends on architecture
Orthogonal polarization heterodyne for many elements and variable phase
Injection locking if no phase control required and complex weighting for few elements

5.11.9.6. WDM combining impractical for many elements, but attractive for routing architectures
RF combining is our baseline for large scale signal combining

5.11.9.7. Bragg grating multiplexers are best choice for low loss and fiber compatibility

5.11.9.8. Switchable grating or MEMs based switches are attractive for some architectures

5.11.9.9. Waveguide photodetectors provide best trade between bandwidth, power, and responsivity
Improved quantum efficiency could make MSM more attractive

6. Nulling Antenna Design Trades

6.1. Photonically Implemented Nulling

The design of a nulling antenna system must take into consideration several overall design approaches and several possible locations for insertion.

6.1.1. Design Approach

The first consideration concerns the overall design approach taken in establishing a nulling antenna. There are two primary types of nulling antennas. The first is a reflector based multiple beam antenna with feed elements. Each beam forms a pattern on the Earth's surface that comprises a main lobe and diminishing side lobes. Increasing the number of feed elements reduces the spot size of the individual beams. Nulls are formed in the main beam of the reflector pattern by adding the phase and amplitude signal outputs. The current Milstar nulling antenna is an MBA and Lincoln Lab has done work in improving the phase and amplitude resolution of this architecture so to establish deep nulling depths. The main advantage of this architecture is the high gain and potentially short jammer standoff. The main disadvantage is the mechanical awkwardness associated with the reflector assembly.

A second design option is a direct phased array or phased array feed. The nulling antenna research done at UC Boulder and by the Air Force with University of Florida has been towards phased array based architectures. The nulls in the array pattern are steered and maintained over wide bandwidths with a tapped delay line beamformer. The advantage of this architecture is the mechanical compactness of the antenna while the primary disadvantage is the complexity associated with achieving adequate performance.

6.1.2. Photonics Insertions

Photonically implemented beamforming is necessary for wideband phased array nulling antennas to enable the tapped delay line structures. This is also true for large aperture MBA antennas where phase only weighting is normally incorporated. As the reflector aperture is increased and nulls are made more narrow (i.e. the standoff distance is decreased) the nulls will move with frequency unless the complex weight is tailored with frequency to maintain a stable null position. Photonics can be used to accomplish this function.

6.1.3. General Insertion Strategy

Our strategy for insertion of photonics into nulling antenna architectures is to focus on development of processing structures that can enable the establishment of the current Milstar nuller with more elements and improved performance. An integrated optic photonic correlation processor can easily support the increase of the number of multiple beam elements from 13 currently to greater than 37 elements. Phased array architectures do not seem as attractive at this time as the current MBA system. There are several constraints imposed by the current nuller that limit the leverage photonic can bear on the problem. Nevertheless, photonics seems to be an attractive alternative to tackling some of the processing hurdles faced by nuller development over the next 5 - 10 years.

6.1.4. Preliminary Considerations

6.1.4.1. Two fundamental approaches to nulling antenna design

- Multiple Beam Reflector Antenna (Milstar, Lincoln Lab)
- Direct Radiating Phased Array or Phased Array Feed (UC Boulder, AFRL - UF)

6.1.4.2. Photonics can enable two key nulling antenna functions

- Wideband Beamforming (becomes more critical as stand-off distance is reduced)
- Signal Processing (closed loop calculation of correlations necessary for setting adaptive weights)

6.1.4.3. Strategy for insertion depends on design approach

- MBA: Significant payoff of photonics insertion is in enabling low power signal processing
- MBA: Tapped delay line beamforming is required for large aperture nullers
- Phased Array: Direct payoff in wideband beamforming as well as signal processing

6.1.4.4. Currently, most attractive path is to enable processing for Milstar insertion

- Even within constraints of current system, an integrated photonic correlator may be attractive

6.1.4.5. Correlation calculation is the same problem addressed in aperture synthesis imaging

- 19 or 37 element array is compatible with integrated photonic correlator approaches

6.2. Phased Array Nuller Architectures

There are currently two techniques for phased array nuller beamforming under development by members of the RF photonics community. The following paragraphs describes those techniques and the advantages and disadvantages of the approach.

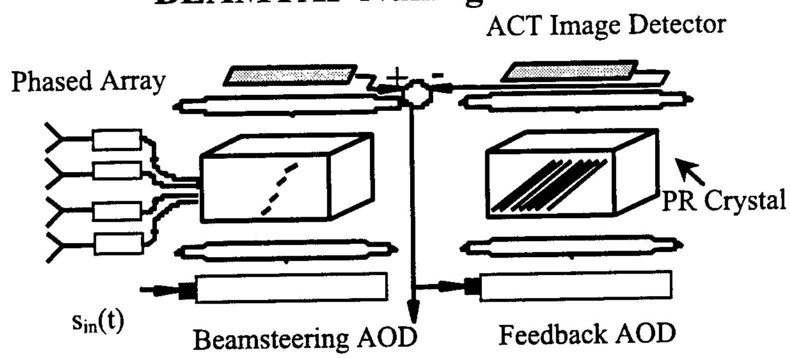
6.2.1. BEAMTAP Nulling Beamformer (Kelvin Wagner @ UC Boulder)

This technique is the implementation of a Widrow type algorithm that utilizes acousto-optic Bragg cells, photorefractive crystals, and charge transport sliding window photodetection to establish a jammer nulling phased array tapped delay line beamformer. A reference signal drives the beamforming Bragg cell to provide and optical reference wave that propagates through the photorefractive crystal. One polarization of a set of fiber inputs to the photorefractive cell provides the optical signal that propagates through the crystal perpendicular to the reference signal. These two optical signals form interference fringes that write a grating in the crystal such that the other polarization of the signal is reflected towards the charge transport detector. The delay imposed on each individual signal is such that the power is coherently combined as the window of the detector moves across the output aperture. The detector sweeps up the signal power in phase to result in a formed beam at the output. The same thing happens in a second crystal where now the output is fed back to form the reference signal. The end result is that the jammer signal is subtracted out of the formed beam and a null is formed. For antennas with many phased array elements and for RADAR type signals, this approach is very attractive. However, for communication signals, generating a useful reference signal is problematic and represents a significant disadvantage. Also, the time constant of the photorefractive crystal is slow enough that large feedback gain is required for the nuller to converge quickly which can be a severe disadvantage in blinking jammer environments.

6.2.2. Broadband Null Shifting Phased Array (Air Force Research Lab and University of Florida)

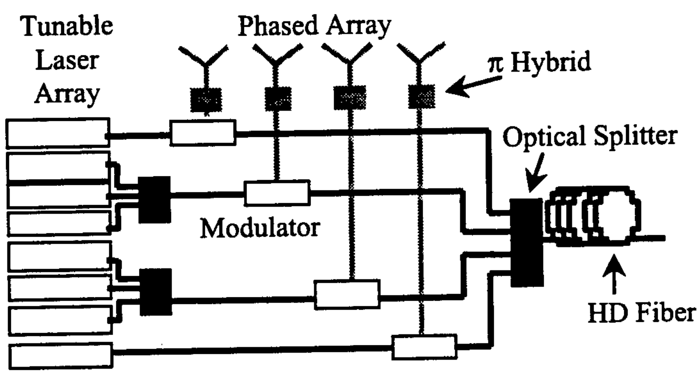
Another clever technique has been proposed by Henry Zmuda at UF and collaborators at AFRL. The tapped delay line beamforming is accomplished with an array of tunable lasers and high dispersion fiber. Multiple copies of the modulated signals are placed on several wavelengths to accomplish different delays. Fundamentally this technique enables very wideband beamforming. The significant limit to the bandwidth results from use of the high dispersion fiber, which will result in a frequency dependent delay that is undesirable. This technique is unattractive for many elements forming multiple nulls since for N+1 antenna elements, 2^N tunable lasers are required. There is also substantial insertion loss in accomplishing the beamforming. It is possible that this technique could be useful for MBA nuller beamforming. However, for phased arrays, the complexity of this beamforming architecture quickly becomes prohibitive.

BEAMTAP Nulling Antenna



- \+ **Supports Large Arrays**
- \- **Requires Reference Signal (OK for RADAR application)**
- \- **ACT detector requires technology development**
- \- **Slow response of PR requires high feedback gain**

Wideband Null Shifting Antenna



- \+ **Tapped delay line provides wideband null shifting**
- \- **Bandwidth limited by HDF**
- \- **N nulls requires 2^N tunable lasers (high complexity for useful beamformers)**
- \- **High DC power consumption (inefficient use of laser power)**

Figure 41. Phased Array Nuller Architectures.

Note: Phased array wideband nulling antennas incorporating tapped delay line beamforming are currently under development by several research groups.

6.3. Selected Nulling Antenna Extends Milstar Capability

Based on the technical considerations made above to the phased array nulling antenna concepts, we have chosen to focus our design effort on determining how photonics can be used to enable or improve performance for the MBA nulling antenna. We summarize here the basis and justification of our design selection for this antenna structure. The first attractive feature of the MBA nuller is that it is consistent with the design plan being developed for advanced EHF. Most development being done for the advanced EHF nulling antenna is extending the design and performance of the current Milstar nulling antenna and our efforts have been consistent with this approach. Another consideration that is common with the reflector fed spot beam antennas is that MBA's require far fewer elements than direct scanning arrays with comparable beam characteristics. The current nuller consists of a 40" dish and 13 feed elements, 7 of which are used for quiescent coverage. To achieve the same aperture size in a phased array arranged on a hexagonal lattice, 2791 elements would be required (2.4λ element spacing is assumed). To establish the gain and resolution equivalent to a 60" dish would require approximately 6,487 elements, a significant number. Based on this consideration, the reflector fed MBA is much more attractive. Our push is to increase the aperture area and number of feed elements to increase the percentage coverage area (PCA) for the desired service area. We have arbitrarily defined the PCA to be the area within 10 dB of the quiescent gain after null formation. This provides us a baseline for which to compare technologies. Increasing the aperture size and number of feed elements will impact the implementation in two ways. The first is that there will be more feeds to correlate simultaneously, a task that is expected to gain great leverage from optical processing techniques. The second is the formation of sharper nulls and consequently more sensitivity to frequency. With but a few elements, the coverage area is angularly wide (or large on the ground). The formed null moves on the ground with frequency, but is wide enough that the movement is undetectable. With a sharper formed null, the same amount of movement will result in decreased jammer suppression over some frequencies. The complex weight, must be tailored over frequency to enable wideband null formation. Tapped delay line beamforming elements are required to accomplish this type of null control and optical techniques can be employed to accomplish this.

6.3.1. Consistent with Advanced EHF Design Plan

6.3.2. Current Nuller: 40" dish, 13 feeds (7 for Quiescent)
MBA provides higher performance than DRA (Larger aperture, less feeds)

6.3.3. Increase Aperture Size to Increase % Coverage Area
Defined as % of Coverage Area within 10 dB of quiescent gain after null formation

6.3.4. Increase Aperture Size ⇒ More Feeds to form quiescent pattern
More feeds to correlate ⇒ Optical Processing Sharper Nulls ⇒ Optical Tapped Delay Lines

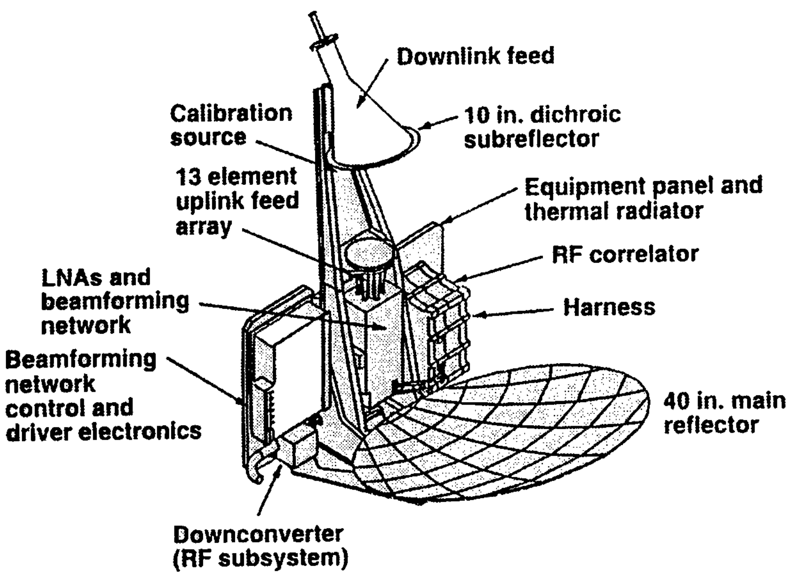


Figure 42. Milstar Nuller.

Notes: Key issues are standoff distance, time for null convergence, and nulling bandwidth
- Phased array high complexity favors MBA architecture
- Next generation performance requires large reflector and many feed elements
⇒ Photonics provides low power parallel processing capability
- Nulls move with frequency resulting in decreased wide band jammer suppression
⇒ Photonic tapped delay line BFN provides frequency dependent phase weighting

6.4. MBA Nuller Processing

The figure below describes the pertinent functional configuration of the MilStar Nulling antenna. There are two nulling antennas on the MilStar satellite and each is designed to cover a 1° coverage service area corresponding to the distributed user coverage antenna (DUCA). The coverage area can be steered to a desired area and then nulls formed in what is called the medium service area (MSA). The two nulling antennas can be steered to adjacent MSA to provide what is described as the wide service area (WSA). The figure in the figure below illustrates the WSA coverage and the distribution of the individual beam spots for a 7 element feed antenna.

6.4.1. MBA Nuller Architecture

The MBA Nuller consists of N elements (current goal is 19) that are fed from a dual reflector antenna so that each feed covers an individual spot in the coverage area. The signals are complex weighted and summed to form an output beam and a portion of this signal is tapped and input to the adaptive processor. Each input signal is also tapped and input into the adaptive processor, but only after being downconverted to a convenient IF by a tunable local oscillator. The IF filter is a bandpass filter that covers a 100 - 200 MHz band and is used to filter out all signals in the 2 GHz EHF bandwidth except the wideband jammer signal. The LO must be tunable as the jammer only portion of the spectrum changes as the multiple user frequency bands hop at the spread spectrum chip rate.

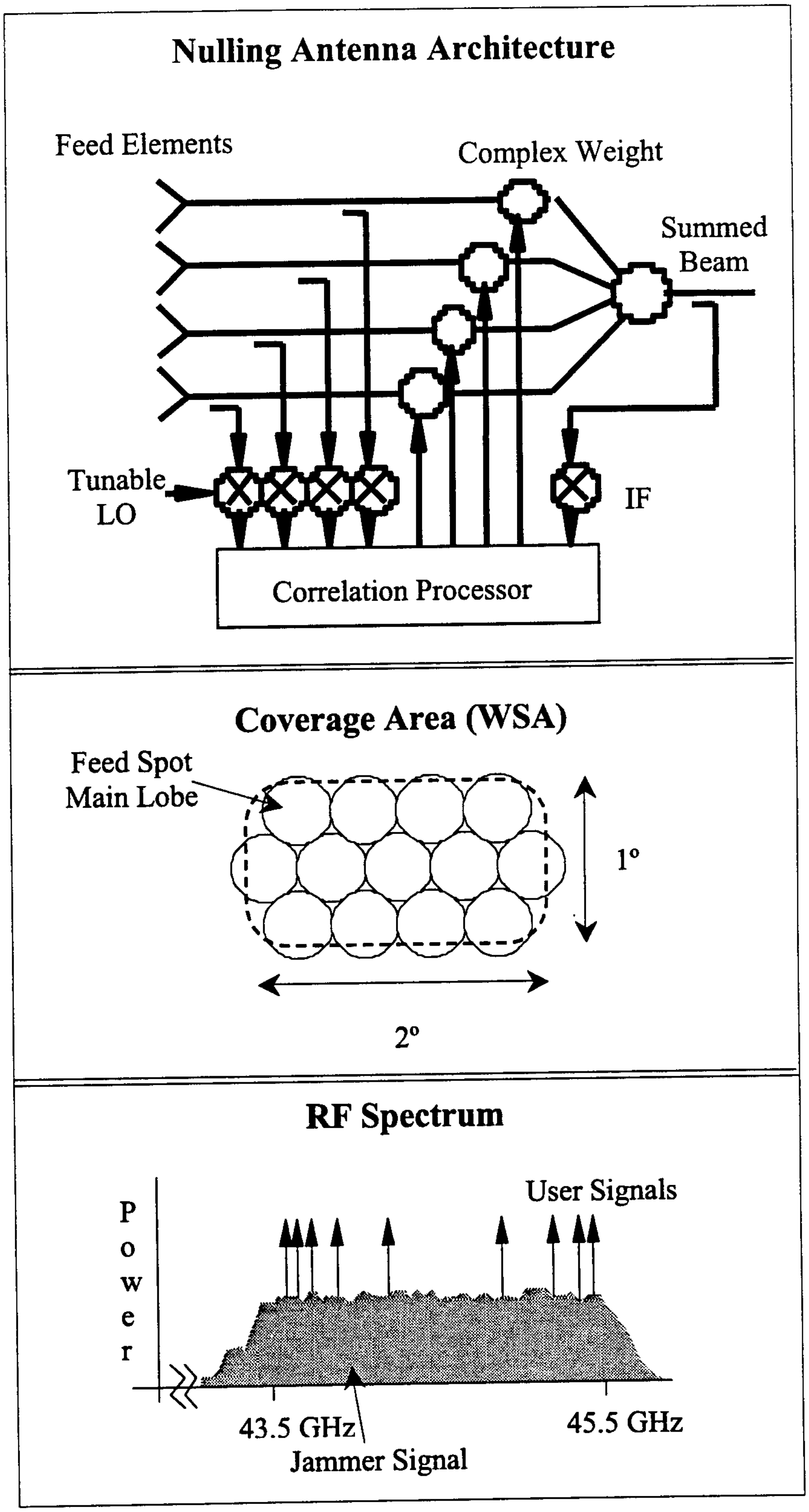


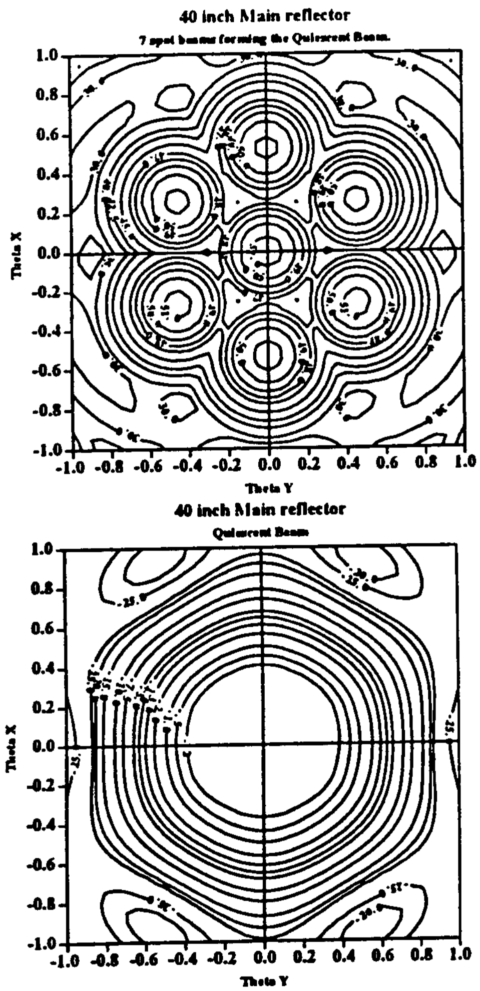
Figure 43. MBA Nuller Processing.

6.5. Larger Aperture Requires More Feeds

The following figures illustrate the effect of increasing the reflector size and increasing the number of feed elements. The cases we have examined are for a 40" main reflector, a 67" main reflector, and a 90" reflector utilizing 7, 19, and 37 feed elements respectively. The figure below illustrates the individual spot beams formed by the distinct feed elements and the quiescent pattern formed by the 0° phase summation of the feed signals. The individual spot beams are representative of the coverage area established by each individual feed element. Nulls are formed by summing nearest neighbor feed elements with the appropriate phase and amplitude to cancel the incident RF signal. Increasing the reflector size and number of feed elements results in increasing the number of spots covering the same field of view, thereby increasing the resolution of the nulling antenna. As illustrated in the figures, the impact on the array pattern is increasing undesirable modulation of the pattern amplitude across the field of regard and sharper rolloff of the pattern outside the coverage area.

6.5.1. Improves PCA

The most significant impact of increasing the reflector size and number of feed elements is seen in the formation of a null. The figures below provide the results of calculation of the PCA for different locations over the 1° field of regard. To determine the max, mean, 90% and min PCA, the ±0.5° field of regard in the θ_x and θ_y dimensions are divided into 21x21 locations. If the null steering location falls within the ± 0.5° conical field of regard, the PCA is determined for the formed antenna pattern. The statistics of the distribution of the PCA are then tabulated and also presented. The 90% PCA is the PCA that at least 90% of the null locations meet and provides some indication of the distribution of the overall coverage of the nulling antenna. The standoff distance is related to the minimum PCA value presented. We see from the results presented that significant reduction in standoff distance can be achieved by increasing the number of feeds from 7 to 19. However, it is not clear that this allows for adequately reduced standoff distance. For example, assuming a 200 mile diameter MSA, 95% PCA results in a standoff distance of approximately $200/2\sqrt{(1-.95)} = 22.4$ miles. Standoff distances lower than this can only be achieved with increased reflector size and more feed elements. A secondary consideration should also be made to the impact of the null on the antenna pattern. Near the edge of the scan region, a wide null significantly degrades the quiescent pattern. However, a sharper null will allow users at the edge of the service region to maintain communications over a wider variety of tactical scenarios. A final consideration is made to the possibility of forming multiple nulls in the service area. Nulling multiple jammers will require extremely high PCA performance. For example 95% PCA performance could easily allow for 3 or 4 jammers to simultaneously be nulled while a 77% PCA will result in nearly zero coverage in the presence of more than 4 jammers. These considerations will lead to ever increasing requirements for PCA performance.



40" Reflector

Max PCA	= 95.96 %
Mean PCA	= 86.39%
90% PCA	= 80.15%
Min PCA	**= 77.71%**

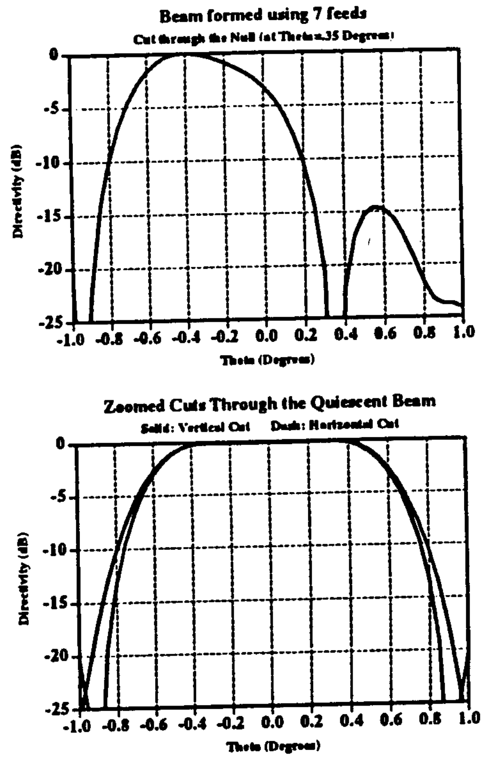
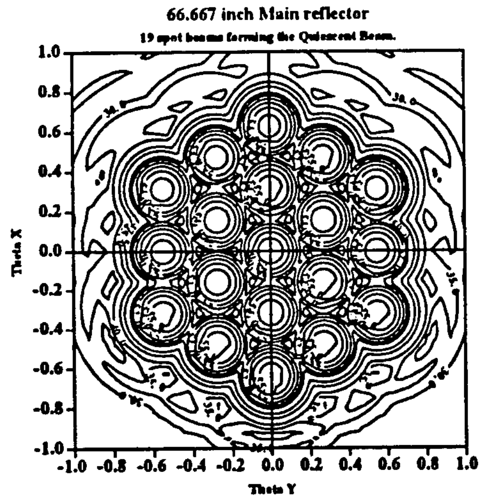
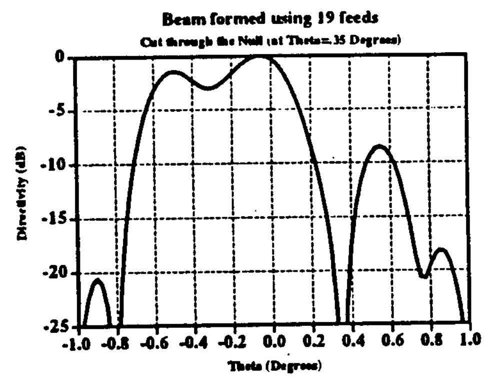


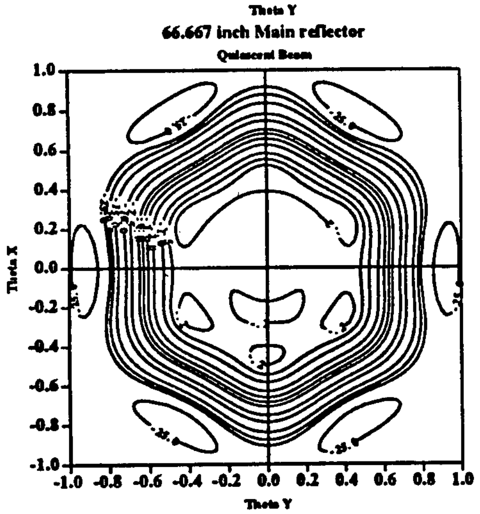
Figure 44. 40" Main Reflector Data.

67" Reflector

Max PCA	= 98.77 %
Mean PCA	= 94.80%
90% PCA	= 92.35%
Min PCA	**= 91.17%**







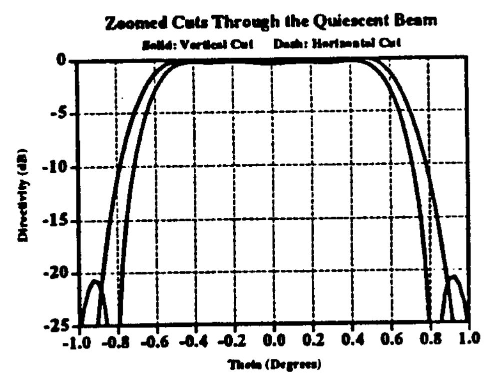
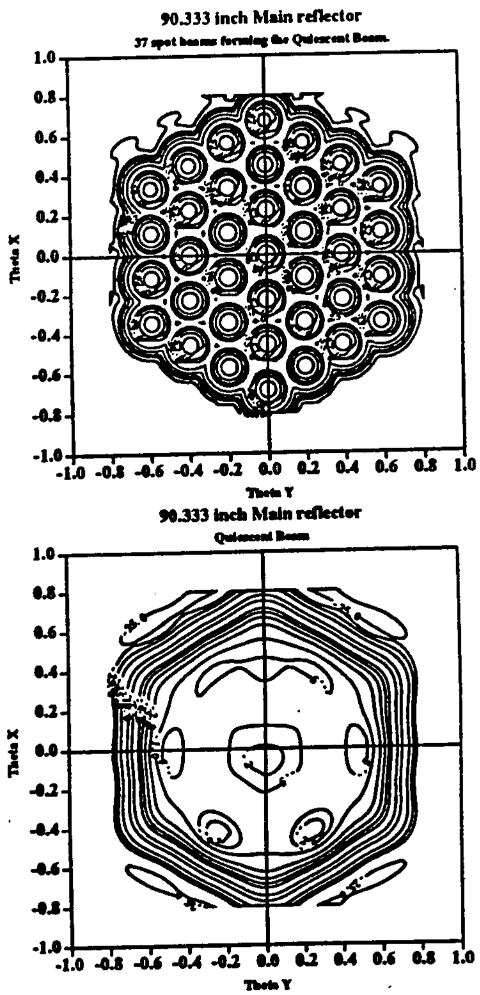


Figure 45. 67" Main Reflector Data.



93" Reflector

Max PCA	= 98.63 %
Mean PCA	= 96.74%
90% PCA	= 95.34%
Min PCA	**= 95.20%**

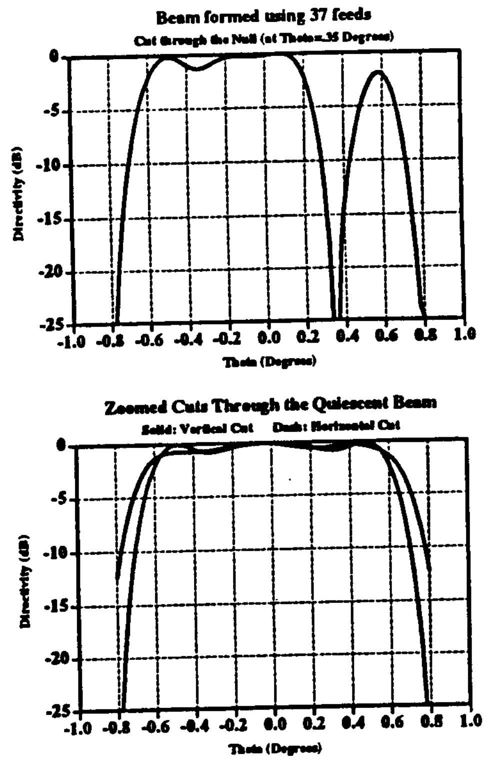


Figure 46. 93" Main Reflector Data.

6.6. Higher Resolution Requires Photonic Tapped Delay Line BFN

The figure below describes the impact of frequency on jammer suppression. As the MBA beamformer is phase only steered, a small amount of null squint is experienced by each antenna regardless of reflector size. The effects of null squint can be described in another way by noting that in order to place a null in a fixed position over frequency, the phase weighting provided for each frequency must be correct to form the null in the correct position. The correct phase profile varies slightly over frequency and for constant phase vs. frequency weighting, the null position varies slightly with frequency. This effect will be more pronounced as the size of the reflector and the number of feed elements is increased and as the null is steered to positions further off axis. Other minor factors will determine the placement of the feed elements relative to the main reflector and subreflector and the steered location of the service area. The figure below illustrates the variation in jammer suppression that can result from increasing the reflector size. For 7 and 19 elements the jammer suppression is relatively flat. However, for the 37 element antenna the jammer suppression varies by about 8 dB over the EHF uplink band. This is the price that is paid for the increased resolution and reduced standoff distance and indicates that something more than phase only steering is required for adequate jammer suppression over the entire uplink band. These types of results motivate our investigation of tapped delay line beamforming structures to accomplish wideband jammer suppression and improved performance.

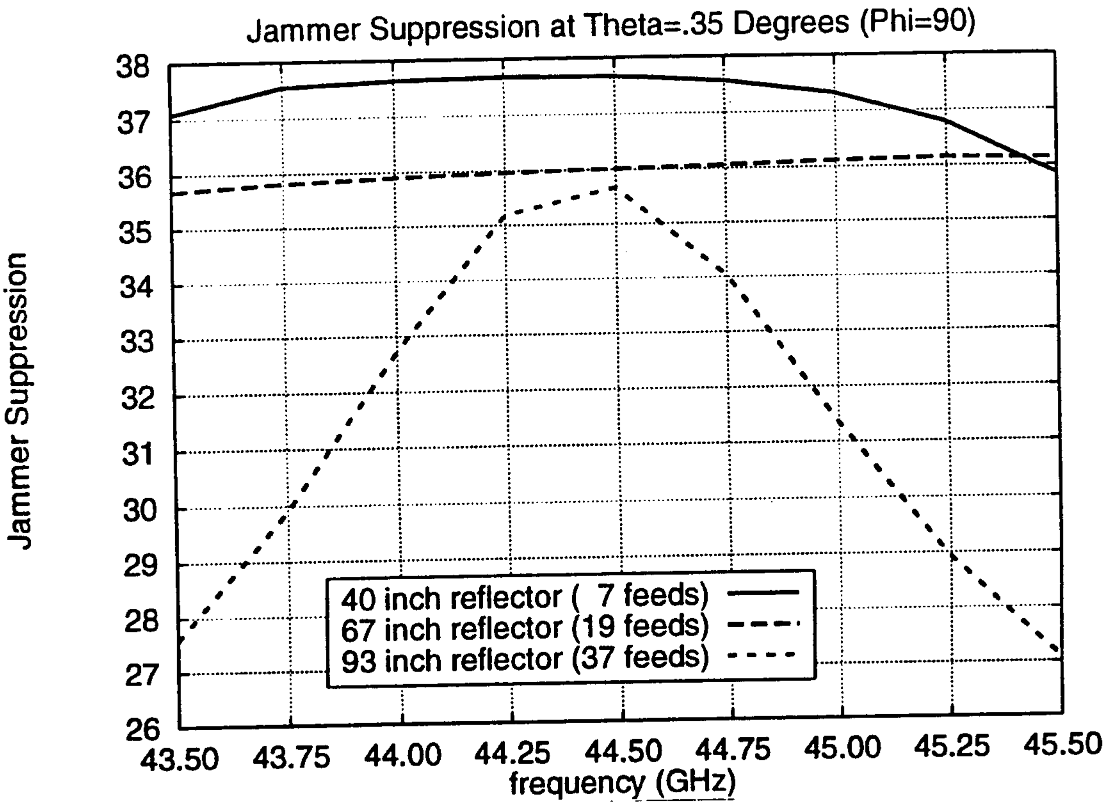


Figure 47. Higher Resolution Requires Photonic Tapped Delay Line BFN.

Note: Larger Aperture ⇒ Sharper Nulls ⇒ Increased Frequency Dependence
(Tapped delay line transversal filter enables frequency dependent phase weighting)

6.7. Photonic Nulling Technologies

There are several photonic technologies that uniquely enable nulling antenna beamforming and signal processing. The direct application of the technology depends on the antenna design approach employed.

6.7.1. Single Sideband Suppressed Carrier Modulator

SSB-SC modulation can be accomplished with one of two methods. One method is to minimum bias a Mach-Zehnder modulator and filter the unwanted sideband. The rejected sideband can be filtered of with a mach-zehnder type spectral filter and used for individual signal power estimates if this is required. This technique is simple, but if the rejected sideband cannot be used, this rejected power is lost and there is a 3 dB loss in the conversion. Another method is to use a quadrature modulator comprising a RF hybrid, and two appropriately configured mach-zehnder modulators to enable efficient single sideband modulation while suppressing the optical carrier. This technique is more complex, but does not have the 3 dB penalty associated with the unwanted sideband rejection. Single sideband modulation is critical in the efficient implementation of a photonic correlation processor as the I and Q components of the correlation can be calculated simultaneously.

6.7.2. Photonically Implemented Tapped Delay Line

Tapped delay line processing is necessary if wideband null steering is required. For phased arrays with a significant aperture size and wide instantaneous bandwidth the tapped delay line compensates for the delay of the signal as it propagates across the aperture. Tapped delay lines can also be used to establish fast tunable bandpass or notch filters which may enable removal of signals from the spectrum being used for jammer estimation. The utility of tapped delay line beamforming for the MBA is less clear. There is some squint in the beam pattern with frequency, but it is negligible in the current nulling antenna configuration. As more elements are incorporated and the formed nulls become sharper, beam squint will have more of an impact on the nuller operation and wideband beamforming will be necessary to implement. Current implementations of the tapped delay line beamformer require the use of a low coherence optical source and demonstrate high insertion loss. Some techniques using multiple wavelengths have are being developed and might make this type of photonic beamforming more compatible with other photonic insertions to the architecture.

6.7.3. 4x4 Talbot Correlator

Two signals that are appropriately input to a 4x4 Talbot device can result in the efficient generation of I and Q channel correlation signals. Pairs of the 4 outputs are differentially detected and integrated to provide an estimate of the complex correlation of the two signals. A processor incorporating this technology is ideally fabricated as an integrated device so as to provide the stability needed to accomplish the coherent optical processing of the signals. This technology was developed under the MOSAIC program.

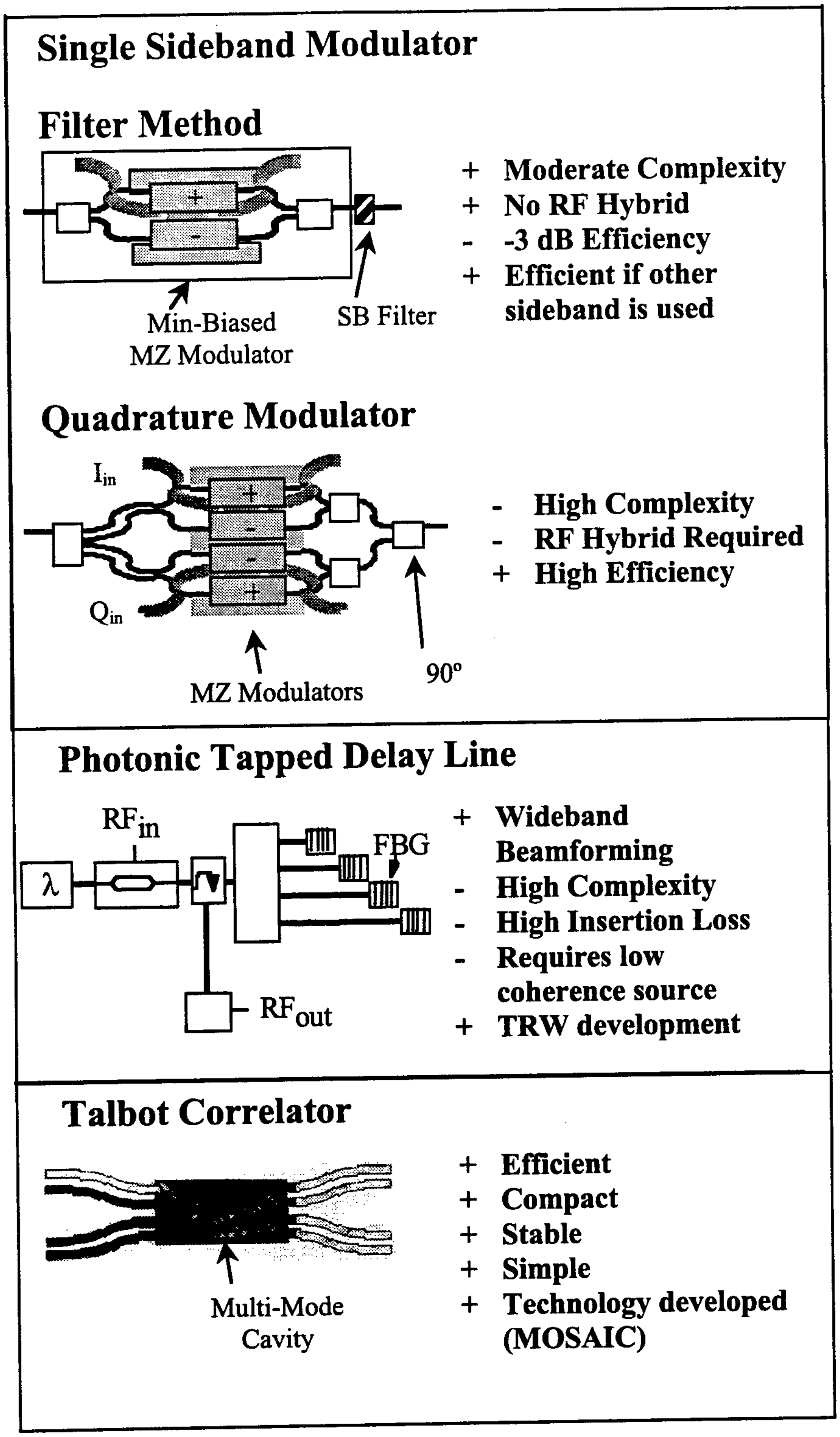


Figure 48. Photonic Nulling Technologies.

Note: Several component technologies have been developed at TRW that enable nulling antenna beamforming and signal processing.

6.8. MBA Nuller Processing Architectures

6.8.1. Processing Candidate Structures

A digital processing structure is established by analog-to-digital conversion of the processor input signals (200 - 400 Mb/s) and digitally correlation and accumulation (integration) of the input signals and the summed output signal to determine the values of the updated weights. The advantage of this technique is its simplicity, while accomplishing the wide bandwidth A/D conversion and CMOS processing leads to significant DC power requirements that can be disadvantageous.

RF analog correlation is accomplished by inputting the individual signals to 90° hybrids and then mixing these outputs with a portion of the summed signal. The mixed signals are input to a Miller integrating circuit and the I and Q components of the correlation are determined. These outputs are sampled (at a low rate) and provide the values used to update the complex beamforming weights.

The photonic analog correlator is established in a manner similar to the analog RF correlator. A laser is split among several modulators, one for each correlation signal. The modulators are minimum biased so as to accomplish DSB-SC modulation. A sideband filter taps off one sideband that is used for an average power measurement. The modulated sum signal is split multiple ways and a copy of it is input with one of the individual signals into a 4x4 Talbot device. The two signals optically interfere and the appropriate pairs of outputs are differentially detected. This output is integrated and sampled in the same way the analog RF correlator outputs are integrated and sampled. Preliminary estimates indicate that the photonic processor requires 1/2 the power of the RF analog and 1/12 of the power of the digital processor which is encouraging for insertion of this technology.

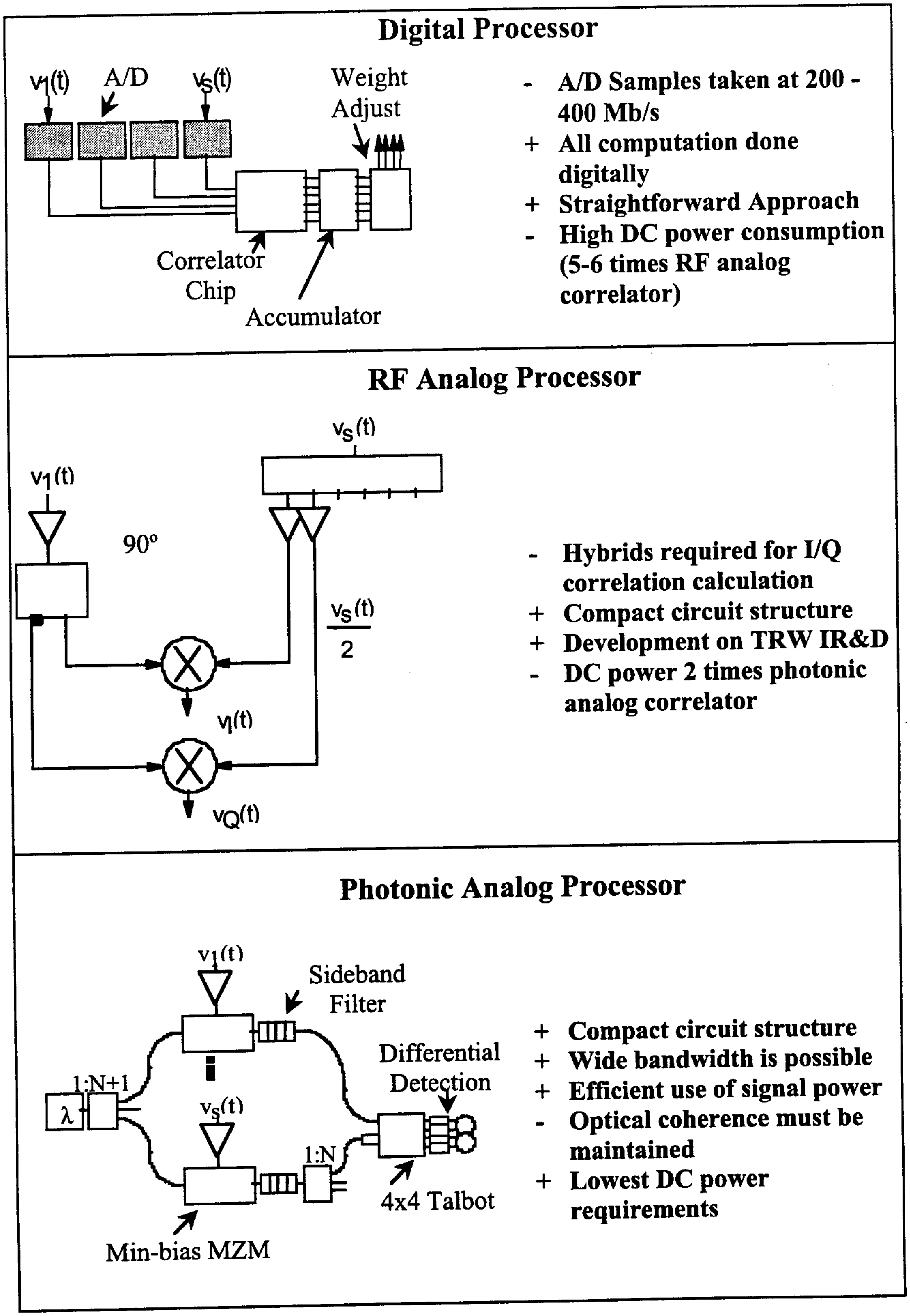


Figure 49. MBA Nuller Processing Architectures.

6.9. Nulling Antenna Conclusions

The architecture trades we have performed have focused on the two primary functions of the antenna system, beamforming and processing. We have considered photonic technologies that could be incorporated in the structures utilized to accomplish both functions. Upon examination of several technologies and techniques that have been presented to the technical community and our own ideas, we have made some general conclusions as to the applicability of photonics to address the challenges associated with the design of next generation pulling antennas and when applicable, which photonic insertions provide the greatest leverage for most effectively achieving current or future pulling antenna performance goals.

We have considered both phased array and MBA pulling antenna architectures to implement a pulling antenna. The current Milstar pulling antenna is an MBA with approximately 13 feeds and a 40 inch main reflector. Phase and amplitude weighting is employed to form the nulls in the antenna coverage area. Some work has been done al MIT Lincoln Labs to utilize photonics for more stable phase and amplitude weighting and has yielded promising results. Additionally, there is current TRW JR&D effort to design the next generation pulling antenna There has also been study work done on phased array pulling antennas by Syracuse Research Corporation and several research groups have looked at utilizing photonic beamforming to enable wideband pulling antennas (UC Boulder, U Florida, Rome Labs).

Based on the key performance goal of reduced standoff distance, we find that the MBA approach seems most attractive. Reduced standoff requires large apertures which is much easier to accomplish with the MBA. Large aperture phased arrays will lead to high complexity both in the array and in the beamforming. Reduced standoff can be accomplished in the MBA by increasing the reflector diameter and incorporating on the order of tens of feeds. Given the differing performance and coverage requirements of the pulling antenna and the agile spot beam antenna, we believe that these antennas should be designed and optimized in separate apertures. There remains some question as to if the null will move with frequency given a set of phase and amplitude weights. If this is the case, a tapped delay line beamformer may be required to fix the position of the null with frequency. Photonics would provide an attractive alternative to this beamforming requirement.

Fast null convergence requires parallel determination of the adaptive weights and consequently a parallel processing correlator. Based on our analysis of a photonically implemented correlator and TRW JR&D examining RF analog and digital correlators, we have determined that the photonic correlator requires half the power of the RF analog and one sixth the power of the digital correlator. This result is despite the Milstar configuration that does the correlation over a relatively narrow bandwidth and doesn't leverage off of the wide band capability of photonics.

6.9.1. Large aperture required to enable reduced standoff and increased percentage coverage area

- Large phased arrays required to achieve performance goals (high level of complexity)

- Increased MBA capability can achieve these aggressive goals (increased reflector size, more feed elements)
Nulling antenna should be designed and optimized separate from consolidated agile spot beam receive antenna

6.9.2. Fast null convergence required to operate against sophisticated jammers

- Parallel determination of adaptive weights is necessary (fast response)
- In next generation pulling antenna system 19 element photonic correlator architecture leads to greatly reduced power
• ⇒ Photonic analog correlator one-twelfth DC power of digital processor
• ⇒ Photonic analog correlator one-half DC power of RF analog processor

- Photonics processor could enable even more correlations (for 37 element feed antenna) and the trade would be even more favorable (from the standpoint of total DC power)

- Leverage of photonic processors is only slightly limited by the necessity of RF downconversion and jammer signal spectral isolation (only a small portion of uplink band is "jammer only")

7. Photonically Implemented Beamforming Structures.

7.1. RF Mixing Feed.

7.1.1. Introduction to Photonic Beamforming Structures:
The following several figures detail our investigation of several general beamforming techniques that looked promising for EHF antenna applications. Many of these techniques were developed up to 3() years ago. Advancements in the last 10 years have provided cause for reinvestigation of these structures implemented with pl1otonic techniques. In examining these techniques, we studied the underlying principles of' operation as well as what distinct advantages the incorporation of photonics provided and if, given incorporation of photonics if these techniques were attractive for implementing the required EHF antenna functionality.

7.1.2. RF Mixing Feed:
The RF mixing feed is a beamforming technique invented by Welty at Hughes in 1963. This technique is currently under development at Hughes for shipboard multi-beam antennas at SHF frequencies. As illustrated in the first figure, two counter-propagating signals at different frequencies mix at the antenna elements to establish a phase profile across the antenna aperture to scan a transmitted beam at the RF carrier frequency. The sum of the frequencies determines the RF phase profile and the difference frequency determines the RF carrier.

With multiple counter-propagating frequencies, it is possible to form multiple-beams with a single beamformer which motivates our interest in this beamformer for use with spaceborne transmit antennas. The active phase shifter at each element is replaced with an RF mixer to facilitate single point beam control. 2M frequencies are required for independent control of M beams from a linear array. A two-dimensional NxN array would most likely require 2 mixers at each element and 3 frequencies for each independently scanned beam.

A fiber-optic feed is probably more useful which would enable a lighter weight beamformer but with increased precision required on the fixed fiber lengths but with the reduced crosstalk and excess loss associated with an RF feed. Both of these configurations neglect the significant issue of splitting loss to the many elements. This consideration is relevant to any direct radiating array.

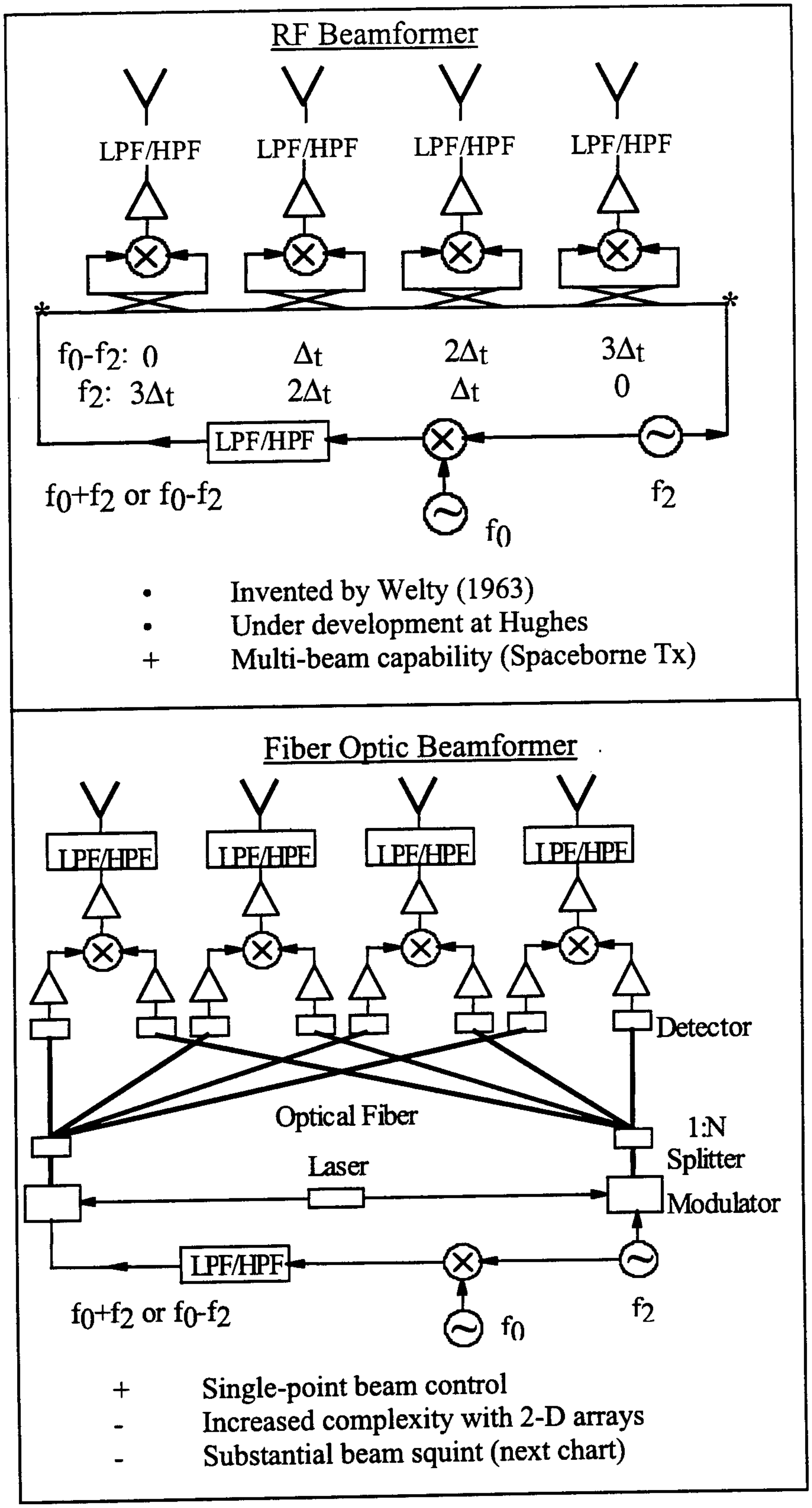


Figure 50. RF Mixing Feed.

7.2. RF Mixing Feed Performance

Shown in the figure below is the antenna array pattern at boresight and 9° for a 17 element linear array at 20.2, 20.7 and 21.2 GHz with a Hamming weighted feed. The f_2 that provides a boresight steered beam is 0.9986 GHz. This is adequate to support the 1 GHz band, but as illustrated in the figure, the scan loss at the band edges is significant at > 10 dB. This 1 GHz band equates to a 5% fractional bandwidth and illustrates the significant challenge in beamsteering with this RF mixing technique. Similar performance is demonstrated at ± 9° steering angle.

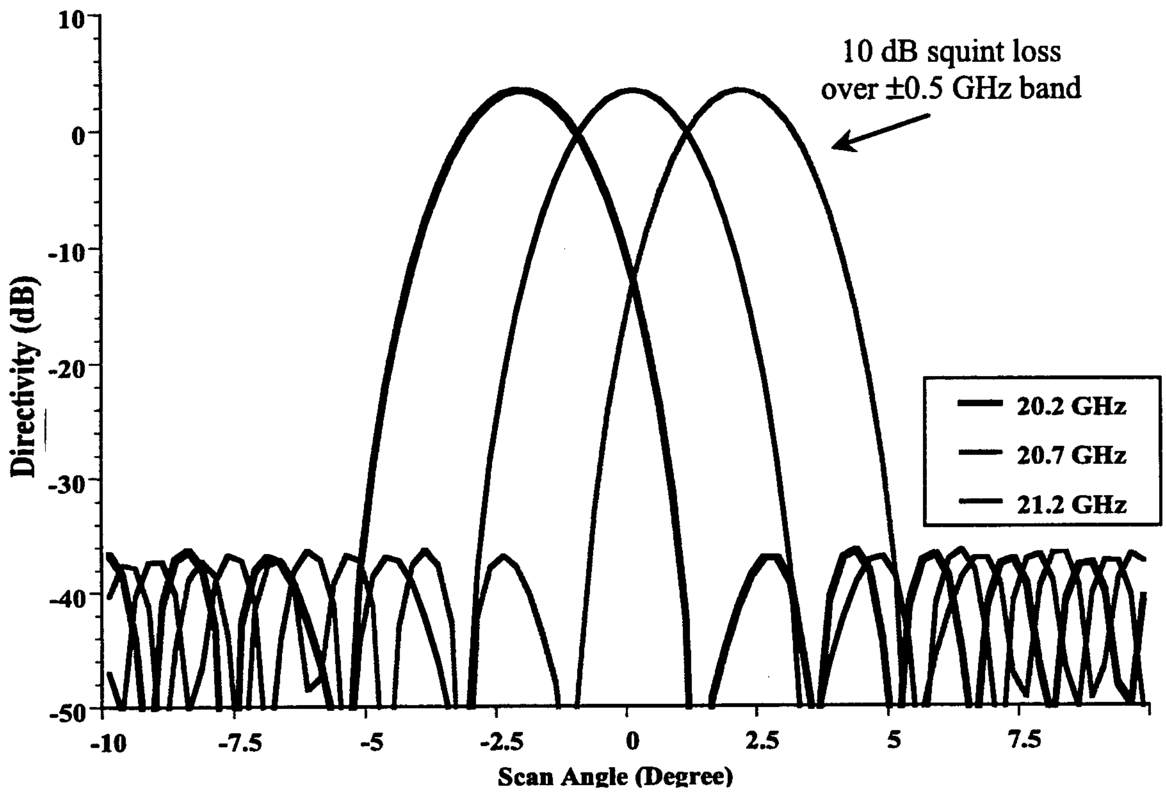


Figure 51. RF Mixing Feed Performance.

7.3. Butler Matrix Beamformer

The Butler Matrix is a fixed-phase-shift multiple beamformer that effectively computes a spatial Discrete Fourier Transform of the antenna field of view. RF butler matrices are difficult to implement in RF due to the substantial crosstalk that is generated in the phase-shift-network. Optical versions of the butler matrix have been developed by W. Charczenko at the University of Colorado and by J.T. Gallo at Harris corporation that have done much in the way of understanding this beamformer, but have met with limited success from a performance standpoint.

Proper operation of the butler matrix relies on single-sideband modulation and a very compact and stable phase shift network. High precision is required because the necessary phase shifts are generated by path length delays on the order of the optical wavelength. The phase shift is very broadband since the RF bandwidth at the optical carrier frequency results in an extremely small fractional bandwidth. The directional couplers studied by Charczenko are a less than desirable component to use for the 90° hybrids. These devices are relatively large and rely on precision manufacturing for acceptable performance. The use of a 2x2 Talbot imager would provide a more fabrication tolerant device and result in significantly reduced size of the beamformer. This substitution could enable semiconductor or Silica based butler matrices to be fabricated and would result in a very compact beamformer.

Because these beamformers work by coherent combination of optical signals in each of the Talbot devices, it is possible to efficiently utilize the input optical power. For a single beam formed in a given direction, all of the optical power couples to a single output. Proper operation does rely on injection of a strong local oscillator at each of the multiple outputs that results in homodyne detection of the baseband signal.

Several characteristics of butler matrix beamformers distinguish them from other beamformers. The number of elements must be a power of 2. The number of formed beams equals the number of elements, and the beams are spread over the intended field of view with -3 dB crossovers. A 2-D NxN beamformer requires 2N butler matrices, one set for the rows and another set for the columns. A single LO can be injected at the N^2 outputs, but optical coherence must be maintained through the entire beamformer.

The principal disadvantage of the butler matrix beamformer is the complexity associated with maintaining an optically coherent system. Extreme temperature and mechanical stability must be maintained. The size of the beamformer is much smaller than the size of the array which makes the transition from antenna array to beamformer difficult to construct. Such disadvantages make current implementations of this beamformer difficult at this time.

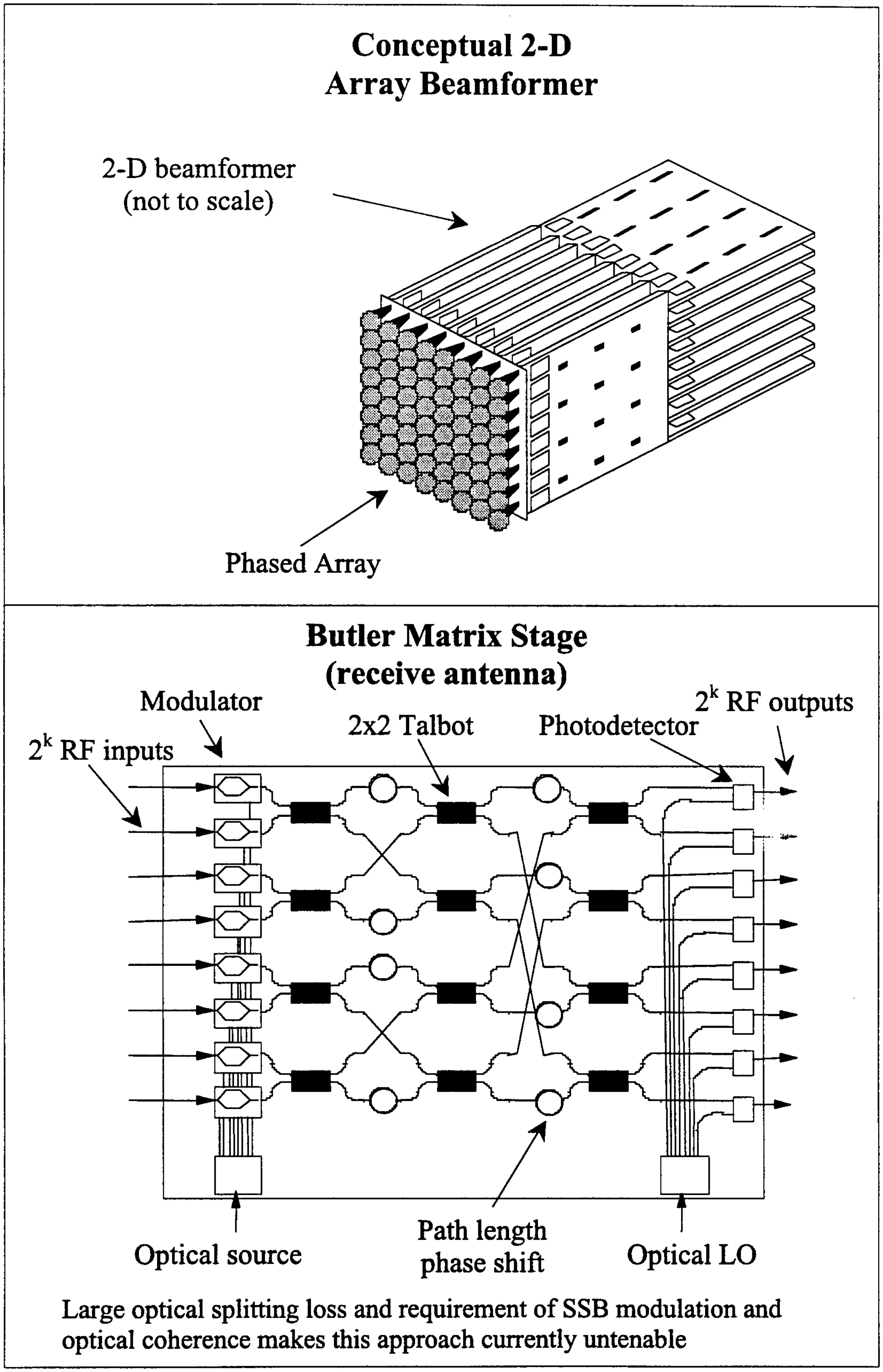


Figure 52. Butler Matrix Beamformer.

7.4. Butler Matrix Beamformer Performance

As the butler matrix is a phase shift beamformer, beam squint can be a significant problem for large fractional bandwidths. To illustrate the severity of this effect for spaceborne receive antenna, the figure below shows the boresight beam and the +9° beam for the center frequency of 44.5 GHz and upper and lower limits of the signal band (±1 GHz). The 16 antenna elements for this beamformer are separated by 3.0λ so as to form the 16 beams in the ±9° field of view for the spaceborne receive antenna. The elements are weighted with a uniform windowing function. The boresight beam demonstrates very little beam squint and the +9° beam demonstrates a squint penalty of 0.25 dB. Over this field of view and bandwidth, this level of squint is acceptable. This performance is for the formed beams, not for the nulls which would demonstrate worse performance. This beamformer would meet the performance requirements of an agile beam antenna, but would fail to meet the requirements of the nulling antenna.

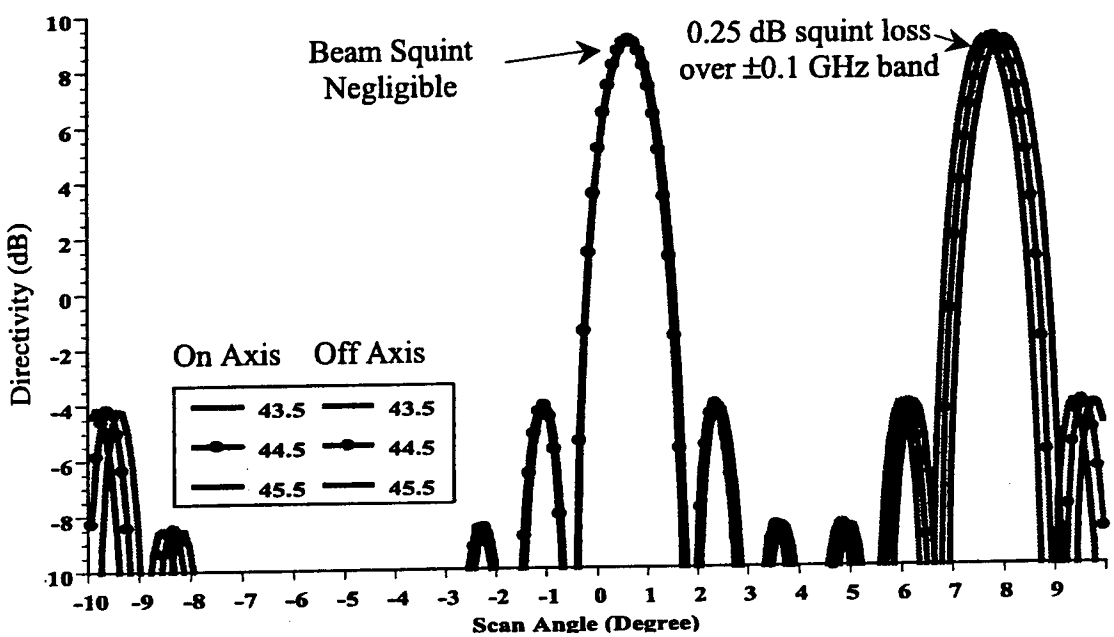


Figure 53. Butler Matrix Beamformer Performane.

7.5. Optical Rotman Lens

The Rotman lens is a true-time-delay beamformer in which the relative signal delay to the various elements result from the geometry of the beamformer lens. The Rotman lens was first developed in the early sixties but has found little application to RF phased arrays due to issues of insertion loss and manufacturability. There are two approaches to Rotman lens design that are illustrated in the figure below. The first is the lens beamformer in which the geometry of the lens structure results in the signal delays necessary for beamforming. Not all of the path lengths provide exactly the correct delays to form a beam which leads to some slight aberration in the lens. A second approach is to design a constrained feed beamformer in which the delays are correct to accurately form the desired beam. Some work has been done to develop both types of beamformers. Whether a lens or constrained feed, the Rotman Lens is a beamformer that works on a linear array. For beamforming with two dimensional arrays, cascaded horizontal and vertical beamformers are required which can significantly increase the complexity of the beamformer.

An optical Rotman lens for a linear antenna array was developed by David Curtis at Rome Laboratory in 1995 in which a free space beamformer was constructed and tested for SHF applications. Curtis used diffractive optical elements to form single beams in a transmit antenna but did not address the application of simultaneous beamforming for transmit or even single beamforming for receive (both significantly more challenging problems). Richard Sparks presented work at PSAA-8 he completed on a constrained feed Rotman lens single beam antenna for RADAR applications.

For these beamformers, the significant challenge is in the optical combining for both multi-beam transmit as well as receive operation. Single wavelength optical combining is difficult because alignment tolerances must be on the order of optical wavelengths. We have developed some ideas to address this challenge by using multiple wavelength optical combining, but for two-dimensional beamformers, the complexity is high.

Simultaneous beamforming would be useful for spaceborne transmit applications and true-time-delay beamforming would be useful for airborne transmit applications. Some practical considerations must be taken into consideration for beamforming applications. Since the Rotman lens performs a true-time-delay operation, an optical Rotman lens must have the same geometry (i.e. size) as the RF beamformer. For 20.7 GHz operation at 2.4λ spacing, the lens will be quite large, but for 0.5λ spacing or 44.5 GHz operation, the lens is a manageable size. A second issue is in the alignment tolerance of the path lengths. Although high frequency operation enables a small lens, it reduces the tolerance available for path length errors. These considerations are accounted for in the following figures.

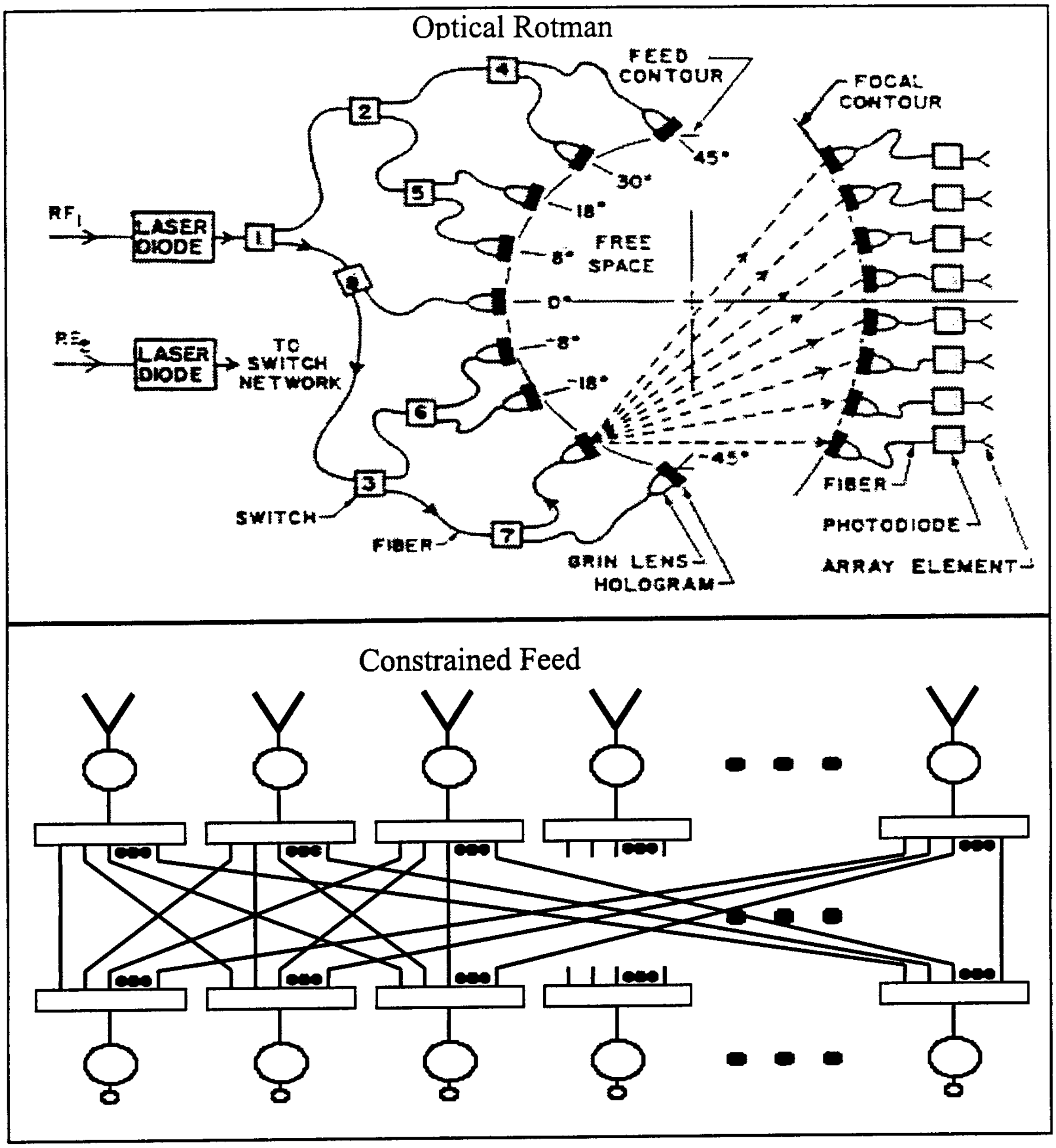


Figure 54. Optical Rotman Lens.

Notes: Motivated by multiple beamforming (Spaceborne Transmit), True-Time-Delay (Airborne Transmit)
- Optical Rotman lens is same geometry as RF lens (size, input/output spacing, etc.)
- Spot size limitation requires optical fanout (splitting of focused beams) to multiple elements
- Multiple beamforming on transmit and receive beamforming is difficult as it requires optical combining (added complexity in hardware)
- Constrained feed results in exact delays (some aberration for lens beamformer due to the geometry)
- Constrained feed beamformer can be made very compact

7.6. Optical Rotman Lens Geometry @ EHF

The figures below show the geometry of the Rotman lens for an airborne transmit (44.5 ± 1.0 GHz) with 0.5λ spacing and a spaceborne transmit (20.7 ± 0.5 GHz) antenna with 2.4λ element spacing. These beamformers are for a linear arrays that are designed to cover a ± 70° field of view for the airborne transmit antenna and a ± 9° field of view for the spaceborne antenna. Since a 2.4λ spacing array at 20.7 GHz would result in a very large lens, the spacing is scaled down to 0.5λ at the input to the lens. To form the proper beams, the output ports must be spread apart by a factor of 2.4/.5 = 4.8 to cover the ± 9° field of view. The lens is designed as if it were a 0.5λ spaced array covering beams spanning ± 43.2°. The axes indicate the dimension in mm. For the 44.5 GHz lens, the scale is 1:1 and the lens is approximately 10 cm square. It is clear that the output spacing precludes the use of an integrated optical approach for this application.

The Rotman lens is equivalent to an optical star coupler. However, if a star coupler were fabricated of this size, the light would be nearly uniformly spread over the output surface contour. As the area of the output waveguides cover only a small fraction of the total area, the insertion loss would be very large. This insertion loss would be even greater for the spaceborne transmit beamformer. Consequently, we have concluded that a constrained feed approach is most attractive for a photonically implemented beamformer. The constrained feed Rotman could be constructed to be very small and demonstrate low loss. The input signals would each be split and delayed the proper amount then combined through some efficient technique such as wavelength division multiplexing. Such a beamformer would be extremely attractive for a 1-D beamformer. One of the very real challenges in phased array beamforming is the implementation of a 2-D beamformer. We have developed one possible architecture as presented in the next figure.

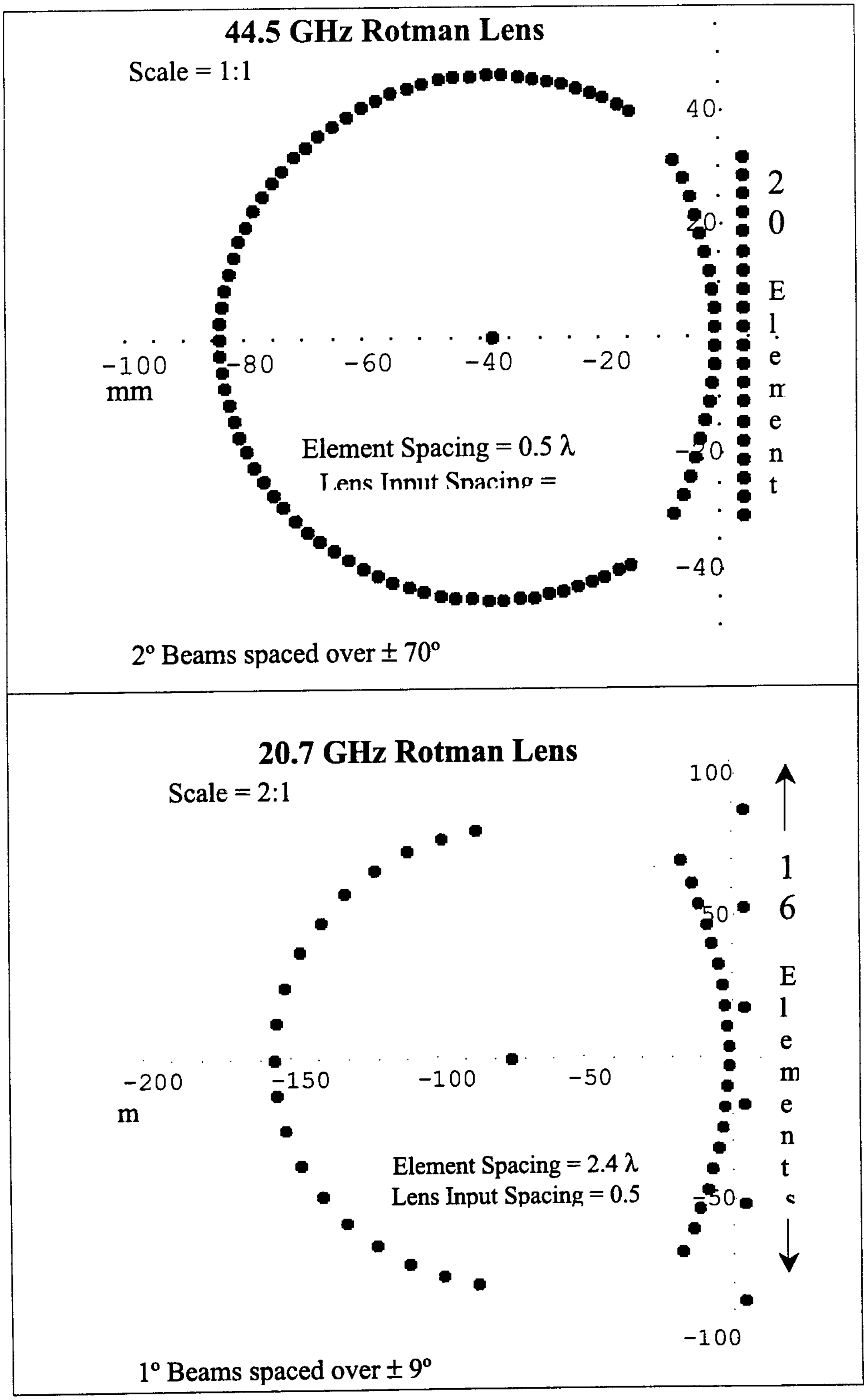


Figure 55. Optical Rotman Lens Geometry @ EHF.

7.7. 2-D Beamformer Structure

Shown below is a TRW concept for the optical Rotman lens for a 2-D phased array. This structure incorporates wavelength division multiplexing in either a free-propagation optical slab Rotman, or in an integrated optic constrained feed Rotman. The integrated optic Rotman would probably be most preferable due to the stringent alignment tolerances required (shown in the next figure). Also a three-dimensional free space optical Rotman lens beamformer is envisioned that could provide some hardware compression but would require the tight alignment tolerances. For the beamformer presented below, at most 2M optical wavelengths can provide for M^2 beams. The three-dimensional beamformer would require M^2 wavelengths to form M^2 beams. Although the beamformer is schematically represented as a lens, a constrained feed approach is preferable as the alignment is expected to be more feasible. The high complexity associated with this beamformer, leads to our limited implementation of it in our selected architectures.

Given recent advances in the design of RF Rotman lens devices, we are more apt to baseline them into our selected architectures. Incorporating two-dimensional beamforming and RF downconversion is challenging with the photonic concepts that have been presented in the literature and by our own development. Further advances in the technology may make photonic implementation of these beamformers more practical in the near future.

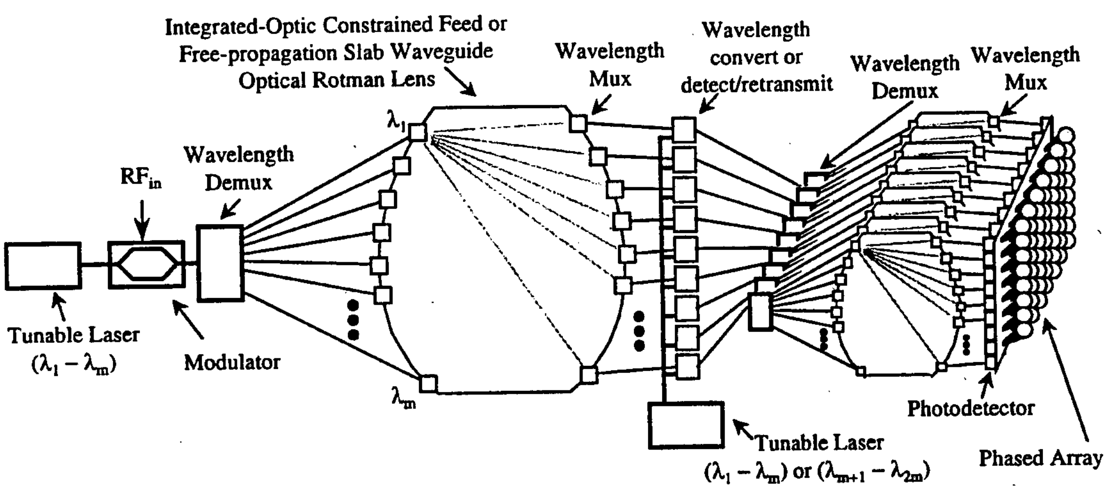


Figure 56. 2-D Transmit Multi-Beamformer Structure.

7.8. Alignment Tolerance

As described previously, the alternative to the lens beamformer is to construct a constrained feed structure with fixed path lengths between the numerous inputs and outputs. This was originally proposed by Leo Cardone of ITT in 1985 but was dismissed by David Curtis of Rome Laboratory in 1995 as being to difficult due to the necessity of precision fiber line lengths. If the constrained feed were constructed as an integrated optic structure, this may enable the small tolerance in the path lengths that is necessary for adequate performance. To understand what precision is required, the figure below shows the degradation of the boresight beam quality for various tolerances. Random path lengths were added to the path lengths derived from the Rotman design equations and the array pattern was computed. The maximum variations are given in fractions of the RF wavelength (6.7 mm for 44.5 GHz). The 0 tolerance is given for comparison. Notice that for >λ/128 tolerance, the sidelobes begin to rise although the main beam maintains the proper pointing angle. The sidelobes continue to rise as the tolerance is relaxed further. For tolerances >λ/4, the main beam is significantly degraded. This indicates that better than 50 μm tolerances are required at 44.5 GHz to maintain acceptable performance. This will most likely only be achieved with a constrained feed, integrated optic structure.

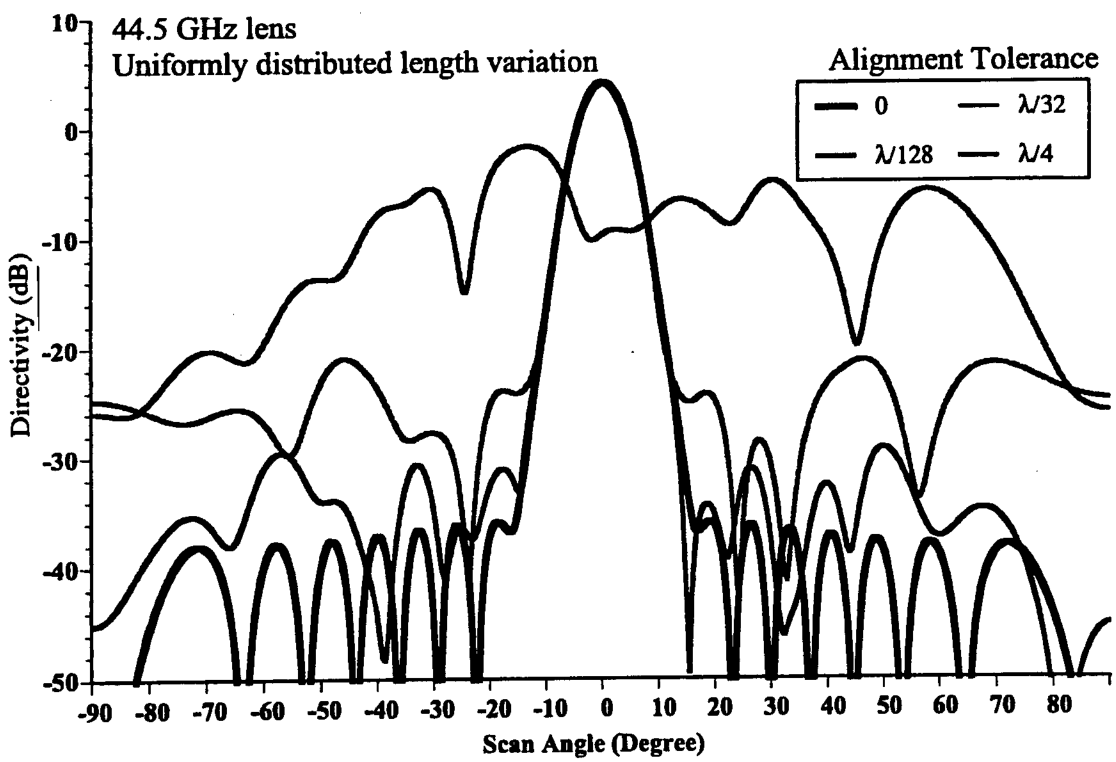


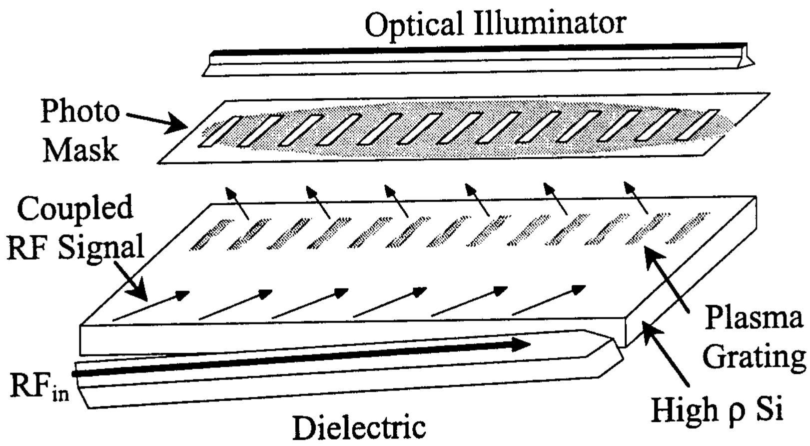
Figure 57. Alignment Tolerance.

7.9. Optically Controlled RF Waveguide

7.9.1. Diffraction Grating Steerable Antennas:
Some work has been performed on steerable antennas using photo-induced plasma gratings in high resistivity Silicon. A slab of high resistivity Silicon is illuminated by an masked high intensity optical beam. The mask results in strips of illumination on the slab that generate strips of electron plasma in the material. The strips of plasma form a diffraction grating for an incident MMW signal that reflects off the grating to be radiated in a direction that is dependent on the period of the induced grating. Experimental work on linear antennas constructed with this technique has been performed and has demonstrated that it is possible to achieve adequate gain (i.e. the antenna is long enough). One disadvantage is that it seems difficult to implement this structure for two-dimensional beam steering. Another more significant disadvantage is that the formed grating is dispersive, resulting in approximately 0.6°/GHz of squint which is unacceptable for EHF applications (1.2° over the ± 1 GHz bandwidth).

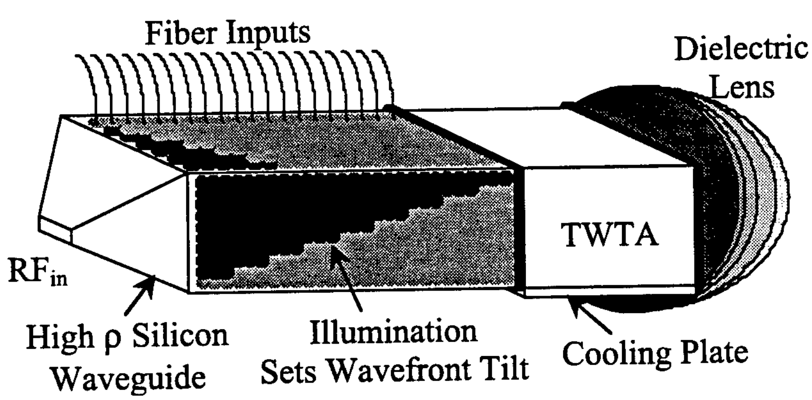
7.9.2. Optically Controlled RF phase shifting:
As the plasma grating generates a refractive index change in the RF waveguide, we have investigated the possibility of using this technique to tilt the wavefront of a guided RF signal and enable beam steering. Our concept of a two-dimensional antenna structure is show in the figure below for illustration purposes. A two dimensional array of light sources are mounted along two sides of a dielectrically loaded RF waveguide (high resistivity Silicon is the dielectric). Each optical source acts to illuminate an incremental section of the waveguide and generate an induced plasma. If the plasma density is high enough and covers a sufficiently thin region, the plasma acts as a metallic surface and the waveguide becomes an image guide resulting in a relative phase delay. Along the dimension of the waveguide, the length of illuminated section is varied so as to tilt the wavefront of the RF signal. When done on two sides of the waveguide, it is possible to tilt the wavefront in both dimensions. The phased signal is input to a power amplifier TWTA that enables the potentially high EIRP. An output dielectric lens enables the wide field of view scanning with the minimum possible waveguide dimensions. The beam is scanned by adjusting the illumination of the walls of the waveguide. Multiple fiber arrays can be used to deliver the optical power most efficiently. Since the TWTA is remote from the aperture surface, it is possible to efficiently cool the device and deliver maximum power which is the primary advantage of this approach. There are several disadvantages in the structure as currently envisioned. High optical power is required to generate a sufficient plasma density for low loss operation. As the antenna is reconfigured and plasma recombines (with time constant on the order of ms), the loss to the RF signal is substantially increased. There is no multi-beam capability possible with this structure, so its applicability is limited to airborne transmit antennas.

Optically Induced RF Grating



- \+ **Compact Structure**
- \+ **Adequate gain with sufficiently long device**
- \+ **EIRP not limited by MMIC SSPA module**
- \- **Two-dimensional antenna difficult to implement**
- \- **Dispersion of grating leads to beam squint (1.2° over 43.5 - 45.5 GHz bandwidth)**

Optically Controlled RF Waveguide



- \+ **TWTA used to increase EIRP (no limitation from MMIC SSPA)**
- \- **High optical power density required for low RF loss**
- \- **Long waveguide required for adequate delay**
- \- **Large loss associated with plasma recombination during antenna reconfiguration (ms lifetime)**
- \- **No multi-beam capability**

Figure 58. Optically Controlled RF Waveguide.

Note: Optically induced grating and RF wavefront tilting techniques are primarily characterized by beam squint and limited reconfiguration capability.

7.10. Photonic Beamforming Structure Tradeoff Conclusions

7.10.1. RF Mixing Feed:
This is an innovative technique that is made much more feasible with fiber optics. The multi-beam capability at first seems to be attractive for a spaceborne antenna implementation. However, multi-beam capability beyond two or three beams leads to significantly increased complexity. More serious is the substantial beam squint that is inherent to this approach. As such, it a relatively unattractive approach for EHF SATCOM antenna applications.

7.10.2. Butler Matrix:
Of all the beamforming architecture concepts we have examined, this approach could eventually lead to the most compact structure possible. The costs of this approach are associated with the requirement of environmental stability (so as to maintain optical coherence), and the necessity of optical LO distribution to all output ports so as to enable optical homodyne detection and achieve adequate link gain (a strong LO is injected so that the detected power is at an acceptable level). Such complexity issues make this architecture concept a challenging one to implement at this time. Finally, a sophisticated switch structure is required for beam selection at the output of the beamformer.

7.10.3. Optically Implemented Rotman Lens:
The Rotman lens is a useful architecture concept that has demonstrated limited success when implemented in optics. The geometry scales with RF signal wavelength making the size of these structures much more compact and attractive for airborne transmit and spaceborne receive antennas. The significant challenge is associated with the optical combining required for both multi-beam transmit and receive applications which leads to the realizable structures incorporating wavelength division multiplexing. Implementation of two dimensional beamforming is challenging as well with this structure. Some attractive insertions might incorporate optical and RF Rotman lens structures. Constrained feed Rotman beamformers implemented in Silica waveguide is also an attractive structure and is considered for several architecture implementations.

7.10.4. Optically Controlled RF Media:
Plasma grating based antennas may be useful for narrowband applications, but will find more limited application if EHF SATCOM systems. Optically induced wavefront steering is attractive in that it addresses some significant issues associated with the limited capability of MMIC based single-stage power amplifier (SSPA) modules. However, the slow reconfigurability of these structures (due to the high RF loss during plasma stabilization) is unattractive for SATCOM applications and makes this a approach that provides limited utility at this time.

7.10.4.1. RF Mixing Feed

- Multi-beamforming capability and single point beam control are good features for spaceborne transmit
- Beam squint appears to be a substantial problem

7.10.4.2. Butler Matrix

- Potential for environmentally robust spaceborne receive beamformer (multi-receive beams)
- Moderate beam-squint off-axis could make nulling difficult

7.10.4.3. Optical Rotman Lens

- Size impractical for spaceborne transmit
- True-time-delay beamforming desirable for airborne transmit
- Necessity of optical combining (coupling for single beam) lends to use of multiple wavelengths
- Alignment tolerances critical to proper performance (lend to integrated-optic constrained feed structure)

7.10.4.4. Optically Controlled RF Waveguide

- Large phase shift (delay) is required for adequate RF phase-front tilt
- RF insertion loss is extremely large during reconfiguration

8. Antenna Architecture Trades.

8.1. Antenna Architecture Trades Overview

8.1.1. Overview

The following paragraphs will cover the selection of photonically implemented architectures for the design plan phase of the ESAD program. Architectures will be downselected for Airborne and Spaceborne - Transmit and Receive antennas. The documents will first describe the relative merits and trades of scanning phased arrays versus multiple beam antennas. Following will be sections relevant to each of the four antennas following the general format described below.

8.1.2. Format of Trade Presentation

When discussing each of the four SATCOM antennas, the first item presented will be the key performance goals. The goals for each antenna are derived from either the ESAD contract SOW, Milstar, or Advanced EHF contract and IR&D work. As these performance goals do not always require the enabling features of photonics (i.e. wideband or multibeam operation), we will indicate where some have been made more aggressive so to leverage off of the attractive features of photonically implemented beamforming architectures. The SATCOM functionality enabled by these aggressive performance goals will also be described to motivate our strategy.

Following will be pages that summarize an EIRP or G/T analysis based on current RF transmit or receive module technology and the associated antenna link budgets that lead to selection of such items such as module power (transmit) noise figure (receive) and number of elements.

A page or two will be presented to describe the considerations made to configuration of the array. Such items that are relevant include, the element lattice structure, the level of true time-delay (division of array into subarrays) required to achieve adequate squint performance, estimated beamwidths and crossover points, and the effect of time and phase quantization. An understanding of these considerations will impact the required number of time/phase delay states, time/phase resolution, appropriate choice of beamforming component technologies, and the amount of required hardware.

The candidate architectures (block diagram) will then be presented and a comparison made in relation to meeting the EIRP or G/T goal, size - weight - power requirements, and architecture complexity. An RF phased array beamforming architecture representing the current state-of-art will also be presented as a baseline for comparison.

The downselected photonic architecture will be presented and justification of the choice provided.

8.1.2.1. Scanning Arrays vs. Multiple Beam Antennas

8.1.2.2. Full Duplex? (consolidated aperture trades)

8.1.2.3. Antenna Trades (Format): Airborne - Spaceborne, Transmit - Receive, Nuller

- Performance goals
  - Source (SOW, Milstar, Advanced EHF, Aggressive)
  - Applications (Spectrum Allocation, SATCOM functions)
- Antenna Link Budget Analysis (EIRP, G/T)
- Antenna Array Configuration
- Candidate Architectures
  - RF beamforming architecture provided as baseline
- Downselection for Design Plan
  - Justification
- Conclusions

8.2. Architecture Trades Include MBA's and Hybrids

MBA's generally require significantly fewer elements than a direct radiating array, and form beams with passive circuitry as opposed to active weighting at each element as required for a scanning array. The MBA beamformer is designed to form all beams necessary to fill the desired coverage region, and a switch is needed to select a subset of these available beams for simultaneous transmit or reception. On the other hand, a scanning array forms only the simultaneous beams (the subset) that are needed and scans these beams over the coverage region via active element control. Because the MBA forms a fixed set of beams, there is a gain reduction at the beam to beam crossovers and sufficient margin must be included in the link budget design to compensate for these variations. With a scanning array, phase and/or time quantization result in similar effects that must be taken into consideration. However, with narrowband operation and phase only steering sufficient bits can be selected to minimize pointing loss and reduce the gain penalty to acceptable levels.

The ESAD SOW emphasized the design of scanning arrays. However, both the original ESAD performance goals and the aggressive goals developed later in the program include multiple simultaneous beam capability. MBA's have been included in the trade because they are strong candidates for multiple beam systems and are under consideration for current and future Milstar systems. We have considered MBA's in the architecture trades for this reason and for the reason that as the majority of photonics implementations reported in the literature have been with regard to scanning arrays as opposed to MBA's. The value of MBA's for accomplishing the performance goals states for next generation COMM systems demand our examination of these architectures and the determination of the substantive ways photonics can be leveraged to most effectively implement these types of beamformers.

The key drawbacks of an MBA are usually the switching and routing complexity. Packaging is difficult at millimeter wave frequencies because stripline/microstrip BFNs are too lossy and waveguide must be used. Optical switching and routing is one area where photonics may provide an attractive alternative to RF and is preliminarily considered a baseline enabling technology. More sophisticated photonic BFN implementations such as wavelength routing architectures, optical Rotman lens, and Butler Matrix have also been examined for potential application to the antenna structures.

The table below summarizes the several alternate MBA antenna architectures, compares them to scanning arrays, highlights the implementation issues where photonics is expected to provide leverage, and identifies the specific antennas that hold promising potential for useful insertion.

Table 10. Architecture Trades Include MBA's and Hybrids.

Alternate MBA's	Advantages vs. Scanning array	Disadvantages	Photonics "Leverage"	Applications/ Comments
Array Fed Reflector/Lens	- 50% element reduction - Supports more Beams	-Trade of BFN loss vs. packaging complexity (stripline vs. waveguide) - Requires switch matrix - Redundancy issues	- Photonic BFN will reduce interconnect density and weight, ease packaging problems - Optical router and switch may be competitive with RF at EHF	-Promising approach for SB Rcv - SB Tx implemented with TWTA's, inconsistent with SSPA's - AB scan range & conformal reqts. Preclude this approach
Butler Matrix	- Eliminates active phase control - Supports more beams	-Trade of BFN loss vs. packaging complexity (stripline vs. waveguide) - Requires switch matrix - Beam squint inherent - Fixed beam crossover	- Photonic Butler will reduce interconnect density, size and weight, ease packaging problems, may enable use of Butler with larger arrays	- Large number of AB Rcv elements may render impractical - Requires optically coherent combining ⇒ high risk for space - Squint not acceptable for AB - Possibly attractive for AB Tx
Rotman Lens	- Eliminates active phase control - Supports more beams - True Time Delay	- Weight - Requires switch matrix - Crossover loss	- Potentially lower loss at 44GHz - Weight not clear (optical and RF Rotman size commensurate)	- Good approach for SB Rcv & Tx - AB Rcv too large, Heavy - AB Tx is single beam, switch complexity may outweigh benefits
Array of Constant K lens modules (Hybrid)	- MBA provides subarray pattern control, minimizes scan loss, active controls	- Requires switching at subarray level	- Photonic BFN reduces interconnect density and weight, ease packaging - Optical router and switch may be competitive with RF at EHF	- Promising approach for AB Rcv - Scan losses for SB insignificant - AB Tx is too small to benefit

Notes: Photonics Literature tends to emphasize Scanning Array architectures

Benefits of photonics may also have significant leverage for some MBA/Hybrid implementations

Cost & performance comparisons with RF scanning arrays need to be done on case by case basis

- Photonic implementations adds new dimension to these trades

8.3. MBA Types Quasi-Optical and Circuit

MBA antennas can be represented by two general categories: quasi-optical and direct radiating arrays fed by a circuit beamformer. Quasi-optical MBA's include reflectors, lenses (dielectric and constrained) and require fewer elements than direct radiating arrays (active scanning or MBA), form beams by weighting and combining small numbers of elements (e.g. 7 or 19), and require only a few active elements per beam (i.e. the rest can be off); all of these can be enabled by photonics implementations (i.e. routing power to the small subset of active elements required to form a beam). DRA's on the other hand must combine large numbers of elements in order to work properly (i.e. for receive antennas). Optical combining of RF signals appears impractical with current implementations; a realistic photonic receive array will most likely be forced to convert back to RF prior to combining.

The key drawbacks of quasi-optical MBA's are the need for redundancy and the complexity and size of low loss RF beamformers. Because the quasi-optical MBA typically requires many fewer elements than a DRA, (nearly by a factor of two), redundancy of parts is less an issue than the additional complexity and size of the beamformer when implemented in RF. Typically, practical RF beamformer designs limit MBA's to a few simultaneous beams. However, the much smaller volume required for photonic beamformers may mitigate this drawback and enable an MBA with more simultaneous beams (up to ten or more). Critical developments for a photonic MBA will be an integrated coherent optical combiner for weighting and combining a few elements, and a reliable beamforming implementation.

Direct radiating array MBA's rely on circuit beamformers such as Butler matrices and Rotman lenses. The advantage of this type of array over a scanning array is that the RF beamformer is passive; this advantage does not exist for photonic "circuit" implementations as optical power must be routed to each of the feed elements. The DRA's form beams with all array elements, therefore enabling graceful degradation which is an attractive feature. In addition, for transmit applications, the DRA has the advantage of power combining the radiation from each element. RF circuit beamformers are practical for at most 32 by 32 elements; limitations for the photonic implementations remain to be fully assessed, but should be expected to enable up to 64 by 64 elements.

8.3.1. Quasi-Optical (e.g. Lenses & reflectors)

- Beam location determined by feed displacement from the focal point
- Each beam formed by **small cluster** of feeds (single feed is inefficient)
- Few total and few active elements but **reliability an issue** (lose a feed, lose a beam)
- Beamformer complicated by switching, redundancy

⇒ Photonics mitigates BFN packaging, complexity and is compatible with combining small clusters

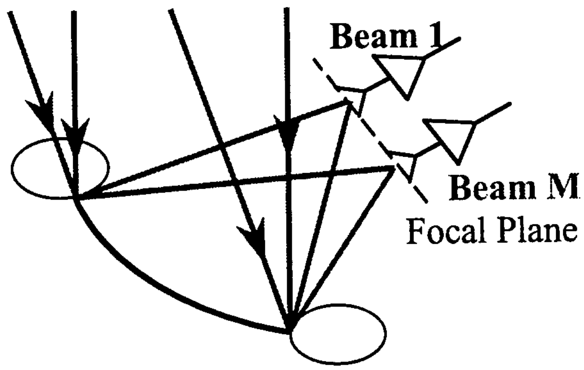


Figure 59a. Quasi-Optical (e.g. Lenses & reflectors)

8.3.2. Circuit (e.g. Rotman, Butler)

- Beam location determined by fixed progressive phase between elements
- Each beam formed with **all feeds** (as in scanning array)
- Many active elements, but **graceful degradation**
- RF Power combining also necessary for transmit
- RF BFN is passive; photonic BFN's are active
- Beamformer complicated by switching

⇒ Photonics mitigates BFN packaging, complexity and may have less loss at EHF frequencies

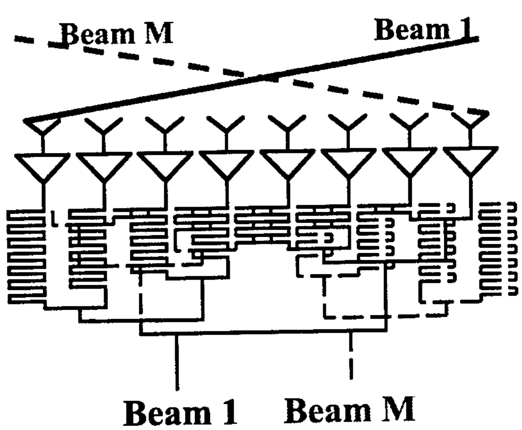


Figure 59b. Circuit (e.g. Rotman, Butler)

8.4. Why Not Full Duplex?

For the most part, our architecture trades have excluded full duplex designs (the Milstar nulling antenna is the one exception). There are several reasons for this determination some related to the practical issues of implementation of the antennas on the spaceborne and airborne platforms, while some are related to an assessment of the leverage that photonics can bring to solve the critical problems associated with implementing full duplex antenna systems. The relevant issues presented in the following discussion are primarily related to the implementation of antennas for COMM systems. Some of the issues described here as relevant would not be so if we were considering the establishment of a RADAR antenna as the argument for a full duplex system is more convincing.

For the airborne antennas, we first recognize that the area required for the transmit antenna is very small and as such there is little to be saved in terms of real estate if we implement a full duplex system. A second important consideration is the large disparity in the array size and element spacing for the transmit and receive antennas. These physical considerations make it difficult at best to implement a full duplex architecture for the airborne antennas.

For the spaceborne antennas, we recognize that full duplex is rare in most implementations, aside from the Milstar nulling antenna where a frequency selective subreflector (FSS) is used to enable duplex capability. Other considerations are made to the problems of intermod interference between the transmit and receive portions of the modules and beamforming networks. These considerations make it difficult to justify the implementation of full duplex capability for most of the spaceborne antennas, definitely the phased arrays.

Further complications are associated with the difficulty of performing the analysis adequate to produce successful designs that incorporate the effects of aperture fields, mutual coupling and both active and passive intermodulation sources and signal levels.

Aside from these significant challenges, photonics does not provide substantial leverage in addressing these design challenges. Photonics also provides little leverage in addressing the difficult issues associated with thermal management of the transmit and receive modules (the transmit modules can generate significant heat which can impact the phase uniformity of the receive front end elements.

All of these considerations substantially increase the risk of design efforts that produce development modules that can fail at the brassboard test phase of a development effort. As this study has been focused to presenting a robust design plan for developmental phases, we have excluded the full duplex configurations from consideration.

8.4.1. Architecture trades did not include full-duplex candidates

8.4.1.1. No identifiable advantage for airborne
- Tx array is very small ⇒ negligible reduction in "real estate"
- Large disparity in Tx/Rcv array sizes, spacing and number of elements obviate

8.4.1.2. Full duplex for spaceborne is rare
- Historically plagued with intermod problems (FLTSATCOM, MARISAT, ...)
- Successful designs are MBAs with Tx/Rcv feeds isolated by FSS (Milstar Nuller)

8.4.1.3. Reliable analyses are either not available or not practical
- Detailed intermod analysis
- Sophisticated, computation intensive model of aperture fields & mutual coupling
- Modeling of passive intermod sources and signal levels (?)

8.4.1.4. Photonics provides limited leverage against critical Full-Duplex design challenges:
- Tx/Rcv Isolation
- Active and passive generation of intermodulation interference
- Thermal management

8.4.1.5. High risk of developing designs that ultimately fail at brassboard test

8.5. Spaceborne Receive Performance Goals

The spaceborne receive antenna performance goals presented in the table below are derived from the ESAD contract SOW, Milstar, and Advanced EHF IR&D programs. The 10 beam coverage is an aggressive performance goal relative to Advanced EHF and current Milstar development. Although a performance goal for receive noise figure was given in the ESAD SOW, the performance metric more common to characterizing the performance of receive antenna systems is the G/T metric. Whereas the noise figure metric places the focus on the front end LNA and electronics, the G/T metric incorporates the gain of the antenna and background noise sources and as such more accurately reflects the SNR improvement that can results form coherent combination of the signals detected at the many individual antenna elements. We have chosen the G/T design goal of 10 dB to match the performance goals derived Advanced EHF development. The other performance goals are common to characterizing spaceborne receive antennas and are all consistent with other receive antenna development activities.

The table below also presents the channel allocation in the uplink band. The antenna should be designed to allow the uplink of several simultaneous MDR COMM channels from the airborne platform. This is an aggressive requirement relative to Milstar and for the scanning arrays will necessitate the subdivision of the antenna array for true time delay control. The multi-beam requirement also calls for the formation of spot beams or full earth coverage beams through use of the subarray or through beam spoiling. The overall utility of the spaceborne receive antenna is in providing high capacity availability in a consolidated aperture.

Table 11. Spaceborne Receive Performance Goals.

Item	*Requirement*	*Source*
Number of Beams	10	SOW
Beam Shape	Spot and Full Earth Coverage	SOW
Frequency	43.5 – 45.5 GHz	SOW
Polarization	Single, circular	SOW
Coverage	+ or – 9.3 degrees	SOW, Milstar
Noise Figure	<3.2 dB	SOW
Beam Update Rate	20 kHz	Milstar, Advanced EHF
Beam Settling Time	<0.9 microseconds	Milstar, Advanced EHF
G/T (spot beam)	10 dB*	Advanced EHF
Sidelobe level (first)	25 dB below peak	Advanced EHF
Spot beamwidth	1.0 degree	Advanced EHF
Jammer Cancellation	40 dB	Advanced EHF
Additional requirements	Design compatible with space environment	SOW

Performance Notes:
SOW goals consistent with Milstar and Advanced EHF

Multiple Beam Uplink - Reconfigurable for spot or FEC

Multi-channel Operation - Aggressive performance goal relative to current Milstar
- May necessitate subarray TTD

Applications - Simultaneous COMM channels - High capacity reconfigurable COMM

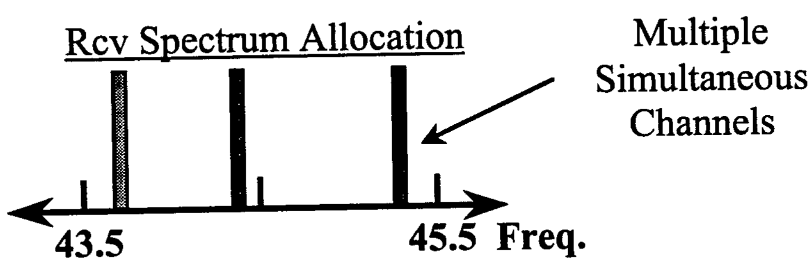


Figure 60. Spaceborne Receive Performance Goals.

8.6. Receive Antenna G/T and LNA Front End Design

The driving design requirement for the spaceborne receive antennas is G/T= 10 dB/K and one degree spot beamwidth. Each antenna architecture candidate is designed to meet the requirement and the antenna system size, weight and power of the several candidates is compared. A common antenna element and RF pre-amplifier are used for both the RF and photonic scanning arrays, which enables a fair comparison of RF and photonics (i.e. we don't assume different pre-amp gain or noise figure which would skew the comparison). Antenna gain values were determined with analysis software and loss estimates based on existing hardware (e.g. polarizer and radome loss). The pre-amplifier performance is based on projected performance of wideband GaAs pre-amplifiers currently in development at TRW. A link budget analysis has been performed on the RF beamforming architecture and we have determined that the RF components result in a system temperature of 450.9 K° which equates to a system noise figure for the beamformer of 3.98 dB. Calculation of the G/T for the antenna array results in the determination that at least 512 elements are required to meet the stated performance goals. The 512 elements can be arranged in a rectangular array (hexagonal lattice) resulting in a G/T of 10.03 dB or 547 elements can be arranged in a hexagonal array resulting in a 10.35 dB G/T. Given that the pre-amplifier transmission line loss is approximately 0.5 dB and the LNA is characterized by a 3.0 dB noise figure, approximately 0.48 dB of noise figure margin is provided to the beamforming network of any scanning or direct radiating array candidates. However, if the 547 element array is utilized, some additional margin may be possible.

One candidate is a quasi-optical MBA. The feed elements for this MBA are small horns, and the antenna gain was determined with reflector analysis software. The LNA gain and noise figure is assumed to be the same as for the scanning and direct radiating arrays.

8.6.1. Scanning antennas designed for 10 dB G/T at 9.3°scan _ Requires >512 RF modules/elements
- Link budgets for traded designs will be provided in Supporting Analysis Package

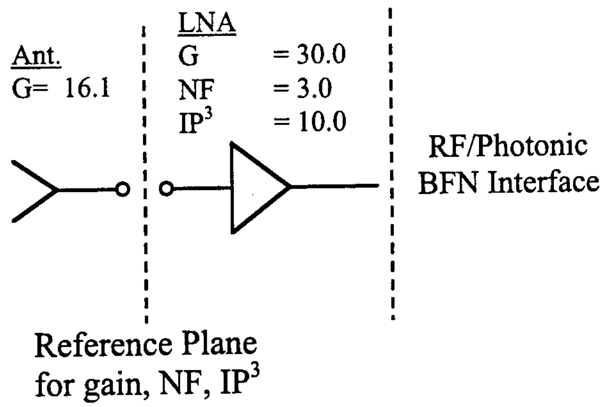


Figure 61. Conical horn elements.

Notes: **14 ring hexagonal array (hex lattice)**
547 elements @ 2.4λ spacing
GaAs 44 GHz LNA
Consistent with TRW IR&D devices

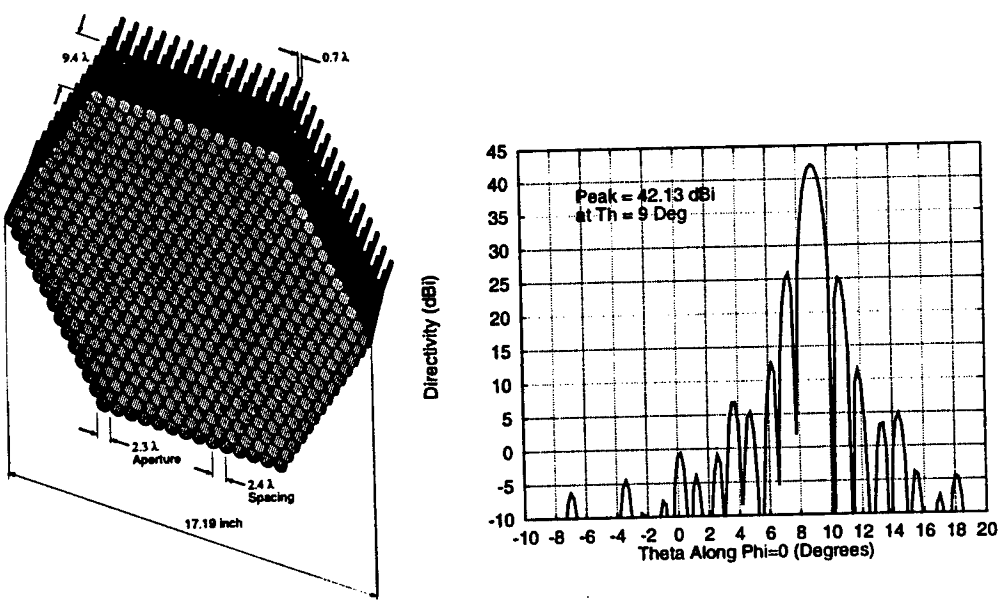


Figure 62. Antenna Array and Gain Calculation.

Note: Antenna Array gain calculated with software and loss estimates

8.7. Spaceborne Receive Antenna Array Configuration

The paragraphs below describes the considerations made to the design and configuration of the antenna array. Due to the narrow scan range, the 6 bits of phase quantization result in only a 0.0054 dB penalty from the zero phase error baseline. The scan loss of the array at the edge of scan is 1.11 dB for the 547 element hexagonal array. This value is derived from measured element performance. The field of view is allocated so that adjacent beams crossover at the -3 dB points allowing multiple channel transmission from multiple airborne platforms or from multiple terminals located on the ground. Setting this level of adjacent beam crossover results in a -3 dB beamwidth of 0.782° and requires approximately 654 beams to fully cover the field of regard. We have provided comparable numbers for 1 dB crossovers which results in 0.463° beamwidth and 2058 beams required for full coverage.

We have calculated the loss due to beam squint for 9.3° beam steering (the worst case position) and found that with no true time delay, there is a 0.8051 dB penalty to those signals at the edge of the uplink band (43.5 GHz or 45.5 GHz). Division of the array into for subarrays can result in a reduced squint loss of 0.2127 dB considered acceptable for the allocated receiver link budget and G/T margin. An interesting consequence of the narrow scan range, level of subdivision, and array element spacing is that little time delay quantization is required for acceptable performance. The maximum delay required between subarrays when scanning to 9.3° is 122.02 ps. If we use zero time delay for scanning to ± 4.7° and 122.02 ps time delay for larger scan angles, we find that the quantization penalty is nearly 0 dB. This would require at most only 9 true time delay states using the FBG true time delay. Of course the time delay is done at the IF frequencies, so there will be some slight additional penalty from the IF beamforming, but this penalty will be minor compared to the squint reduction that results from subdividing the array.

8.7.1. Phase steered at elements
6 bit quantization (see figure below)

@ 9.3° scan pattern

Quantized closely matches ideal pattern (0.0054 dB penalty)

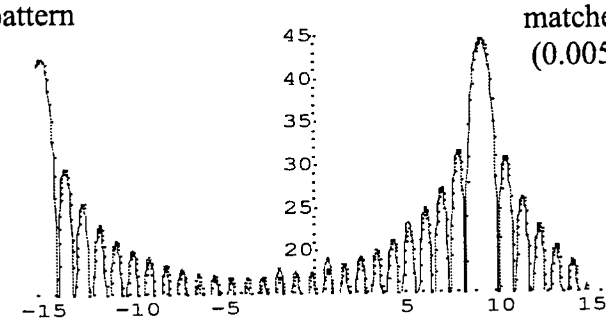


Figure 63. Phase steered at elements.

Scan loss at 9.3° = 1.11 dB (547 elements) based on measured element pattern

Edge of coverage loss = -3 dB

Beamwidth (for 547 elements)
0.463° for 1.0 dB crossover
0.782° for 3.0 dB crossover

Beams for full coverage (approximate)
2,058 for 1.0 dB crossover
654 for 3.0 dB crossover

Time delay steered at subarray
Squint loss at 9.3°
0.8051 dB (no TTD)
® 0.2127 dB (4 subarrays)
0.0870 dB (9 subarrays)

Time delay quantization (using FBG TTD)
t_{max} = 122.02 ps
0 bits (0°-EOS) _9 states
(0 dB penalty)

Time delay "ON" or "OFF" is satisfactory for squint reduction

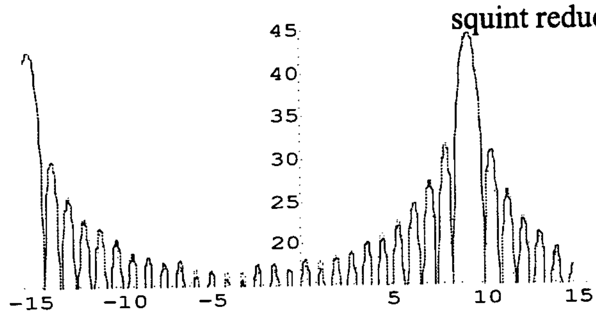


Figure 64. Time delay quantization.

8.8. Spaceborne Receive Candidates

Three candidate architectures were traded for the spaceborne receive antenna: RF and photonic scanning arrays, and one quasi optical MBA (the array fed reflector). As the spaceborne receive antenna must provide at least ten (future systems may require even more) simultaneous beams the MBA is an attractive candidate for this application.

The three candidate architectures have not been designed to provide nulling capability. The baseline configuration for Advanced EHF is to combine all non-nulling receive beams into one aperture and use the existing Milstar nulling two-antenna design (with some modifications) to provide the required agile beam and jammer suppression capability. Hence we have focused our development for the receive antenna on architectures that do not incorporate nulling. There are other practical reasons for this logic which is discussed in the section on nulling approaches.

A comparison of the three candidate architectures in terms of size weight and power provides some interesting but not unexpected conclusions. The baseline RF scanning array is an architecture developed on Advanced EHF work and provides moderate size, weight, and power. The photonically implemented scanning array demonstrates significantly less size, comparable weight, but considerably more DC power. This is reasonable when one considers that the photonic active scanning array requires the power for the LNAs (i.e. the DC power requirement of the RF scanning array) and power for the optical signal generation and distribution. For the large number of elements and beams, this DC power is significant and makes the photonic scanning array a weak competitor based on this figure of merit. The array fed reflector MBA with a photonic beamformer results in less size, slightly more weight, but nearly half the DC power of the RF scanning array. The tabulation has not included the required redundancy for the MBA, but it will still be considerably less in terms of DC power than the RF scanning array. The size will at most be doubled, and the weight can be somewhat more than the RF beamformer, but the payoff is in greater numbers of beams as compared to the scanning array.

The array fed reflector enables a potentially large number of beams and remoting of the BFN from the feed electronics for comparable size, weight, and power. As such, the array fed reflector MBA is a favored candidate for further development effort and promises an attractive way to leverage the payoff of the incorporation of photonics.

Table 12. Spaceborne Receive Candidates.

	Scanning Array (RF)	Scanning Array (Photonic)	Array Fed Reflector (Photonic BFN)
Elements	Conical Horn	Conical Horn	Conical Horn
Number	547	547	331
G/T @ EOS	10.35 dB	10.35 dB	10.18 dB
Ant. Gain	15.03 dB	15.03 dB	18.10 dB
System NF	3.98 dB	3.98 dB	3.98 dB
System Gain	66.0 dB	69.42 dB	
System IP3	24.5 dBm	4.015 dBm	4.015 dBm
G/T @ BS	11.45 dB	11.45 dB	13.8 dB
Size	72,831 cm^3	20,194 cm^3	35,250 cm^3
Weight	45.43 kg	66.59 kg	59.541 kg
Power	325 W	2,245 W	145 W
Complexity	More beams difficult	More beams possible	Optical Switching
Comments	Advanced EHF IR&D	Optical amplification dominates DC Power	Maximum Hardware is Remoted

Notes: Key challenge is packaging multi-beams in limited volume at antenna array
Array Fed Reflector Photonic BFN Enables
- Mitigation of packaging limitations
  - Remoting of BFN from feed elements
- Expanded multi-beam capability
  - Switching is feasible with photonics

8.9. Scanning Array (RF)

The figure below illustrates the architecture of the baseline RF scanning array. The design for 512 elements is based off of standard MMIC components and RF combiner devices. The architecture front end consists of the antenna element and LNA followed by a 10 beam RF splitter/phase shifter/ amplifier circuit. The back end of the beamformer consists of the RF power combining units that may consist of either stripline or waveguide. The circuit block diagram for calculation of the receiver link budget is illustrated in the figure below. From analysis of the link budget we determine the system noise figure to be 3.98 dB and the output IP^3 to be 24.5 dBm. The 66.1 dB of system gain includes 27.1 dB of combining gain for 512 elements.

The detailed architecture has been developed under TRW advanced EHF IR&D efforts and demonstrates optimized levels for size, weight, and power, but can only effectively operate for narrowband COMM links. The advanced EHF design incorporates a maximum of 8 simultaneous beams due to packaging limitations at the array front end. This demonstrates the critical technology issue associated with this RF baseline design.

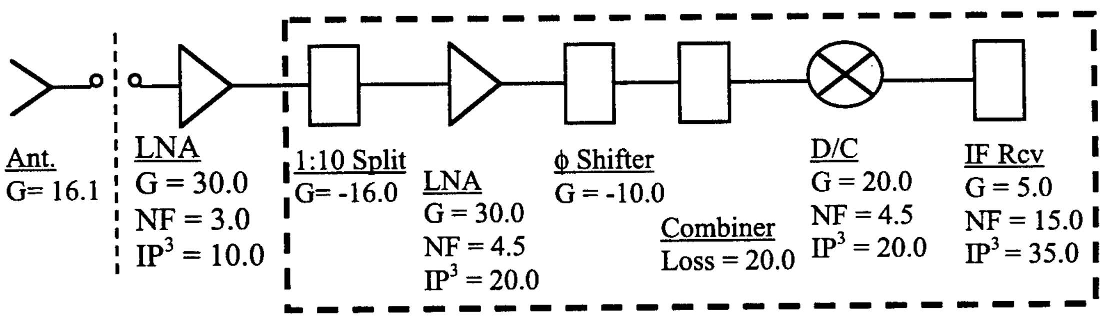


Figure 65. Scanning Array (RF).

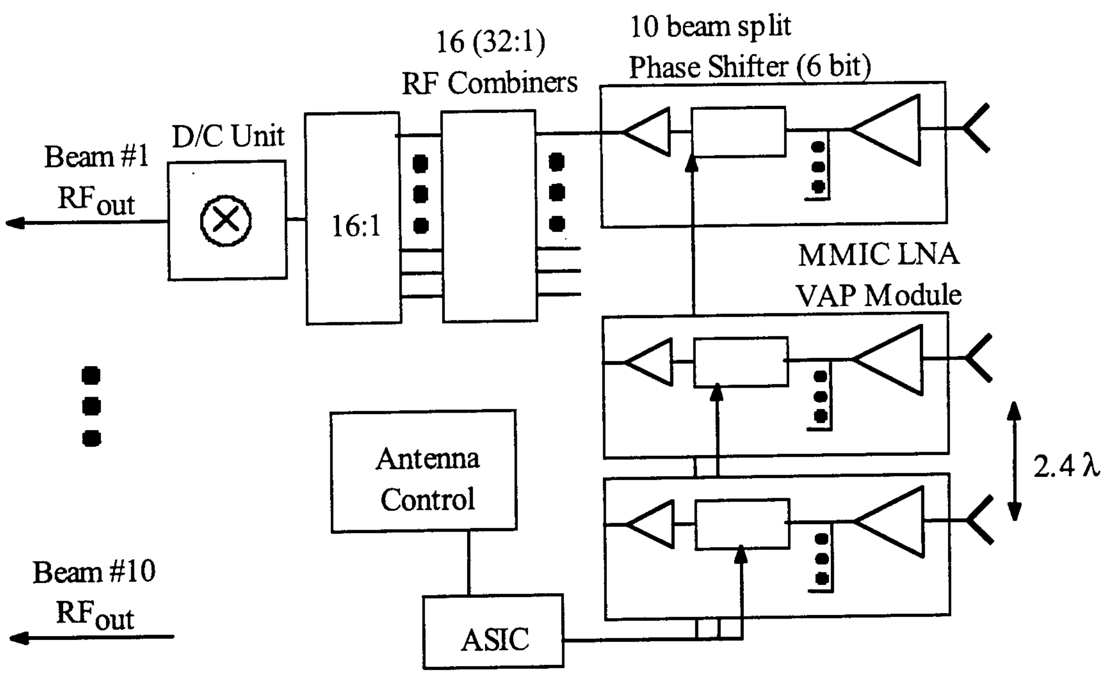


Figure 66. RF scanning array based on Advanced EHF IR&D incorporating standard MMICs.

Notes: Gain = 66.1 dB
Includes 27.1 dB combiner gain

Noise Figure = 3.98 dB
Reference at element "terminal"

Output IP^3 = 24.5 dBm

SFDR = 64 dB $Hz^{2/3}$

8.9.2. Trade Considerations

(+) Small size, weight, power
(-) Narrowband operation
(-) Challenge in implementing multibeam

8.9.3. Critical Technologies

Packaging multiple beams

8.10. Scanning Array (Photonic)

The figure below illustrates the traded photonically implemented scanning array. An optical heterodyne source generates the optical two tone signal that is amplified and split 550 ways then transported to the array via polarization maintaining fiber. The MMIC front end module consists of the input LNA and EAM integrated together in GaAs or InP. The modulated optical signals are then amplified and split further for multiple beam formation. Upon photodetection and power combination, the subarrayed signals can be time delayed, or the TTD subsystem can be excluded to implement phase only beam control. The one challenge with subarray TTD is that the RF signals are effectively downconverted upon photodetection and the time delay beamforming is accomplished at the IF frequency. This leads to some levels of squint, but it is expected that the subarray beamforming would still result in some improvement. It is clear from the figure that the large DC power is a consequence of the substantial amount of optical amplification and splitting that is required for the multiple beamforming. However, there is no packaging limit to the number of beams since all hardware except the LNA and modulator are remoted from the array. The technologies critical to the successful implementation of this beamforming architecture are the optical heterodyne source, the MOSAIC optical splitters, and the high frequency (45 GHz) EAM devices.

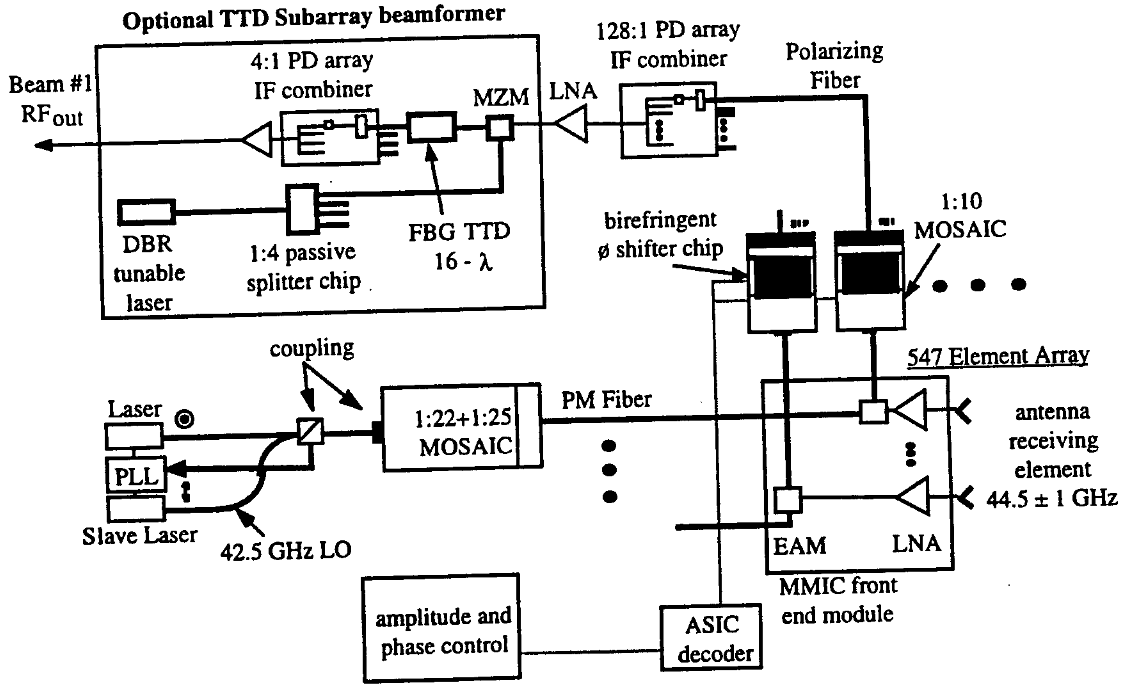


Figure 67. Scanning Array (Photonic)

Notes: Photonic scanning array enables multibeam, but with high DC power requirements

8.10.1. TTD optional
can compensate for slight squint penalty

8.10.2. Subarray leads to IF beamforming
TTD is on downconverted signals

8.10.3. IF power combiners
requires larger size/weight than RF combiner

8.10.4. Trade Considerations
- (+) Multichannel operation
- (+) No packaging limitations
- (-) Large DC power

8.10.5. Critical Technologies
Optical heterodyne source
MOSAIC
High Frequency EAM

8.11. Array Fed Reflector

Shown on the opposite page is a quasi-optical MBA design for the spaceborne receive. The MBA consists of a dual reflector and array feed of 331 conical horn elements. The beams are formed by combining the elements in clusters of 7 elements. Hence each element will participate in forming 7 beams which could require a 1:7 split at each element. After the split the signals must be weighted in amplitude and phase and recombined in the appropriate groups of 7. This scheme relies on the either optically implemented RF combining or conversion back to RF before combining. Because the same weight values are used for all beams, a minimal approach requires only ten 7:1 combiners. The reflector has been designed to minimize scan aberrations and possibly allow a single set of weights to be used for all the beams, which further simplifies beamforming. The MBA beamformer is relatively narrowband, but represents in some part the conventional wisdom in deploying space based receive communication antennas. The dual reflector design alleviates the element spacing requirement and utilization of the reflector gain allows for a reduced number of elements which can positively impact cost. Additionally only those elements required for forming the desired set of beams are activated at any given time. This feature can lead to significantly reduced DC power relative to active scanning array approaches.

8.11.1. 331 elements at 3λ spacing in focal plane
(547 elements at 2.4 λ spacing for DRA)

8.11.2. Clusters of 7 elements form beams
via phase and amplitude weights

8.11.3. Weighting is the same for all beams
(because of small scan range)

– Significant advantage for combining, switching, redundancy

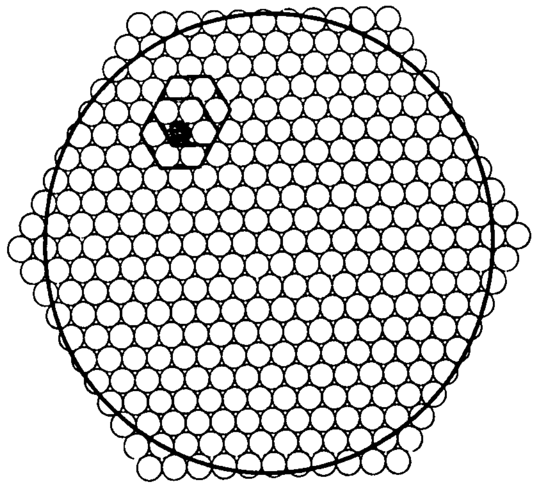


Figure 68. Hex element Grouping.

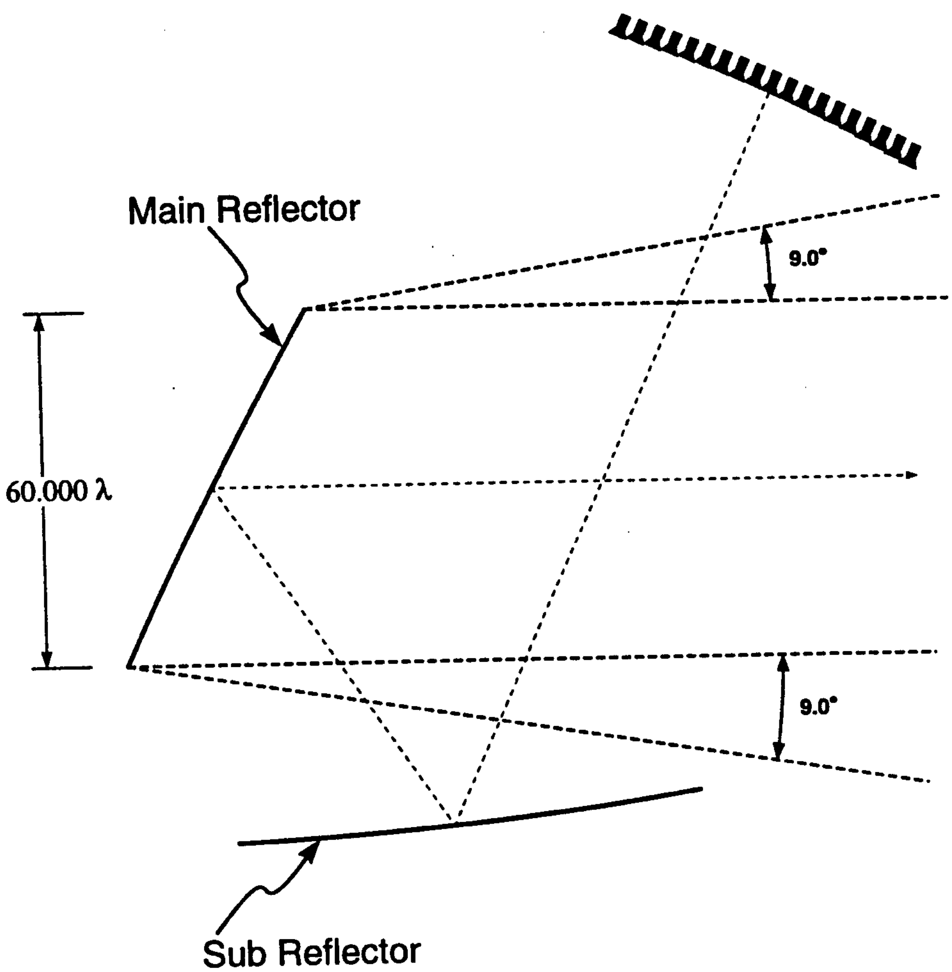


Figure 69. Array Fed Reflector.

8.12. Array Fed Reflector Beamformer with WDM Combining

Shown in the figure below is a schematic for one possible photonic beamformer for the spaceborne MBA. A ferrite switch is placed on each element to provide a redundant path through the photonic BFN. After the switch, the RF signal is amplified, modulated onto an optical carrier at one of seven wavelengths and then split into 7 channels. Each channel is appropriately weighted and combined with a channel from each of six adjacent elements to form a beam (i.e. each beam is formed from a cluster of 7 elements). Note that channels from adjacent elements are modulated onto different optical wavelengths allowing a multiplexer approach for optically combining the RF signals that form the clusters. The output of the combiner consists of N_B available beams, where $N_B \leq N_E$. An optical switch matrix is then used to select the $N_S = 10$ signals to form the simultaneous beams. These signals are photodetected and input to the ten receivers allocated for the available N_B beams.

The wavelength assignment for the feed elements is also illustrated in the figure below. Wavelengths are assigned to feed elements so that for any cluster of seven elements that is selected, each feed is modulated onto a unique optical wavelength. The wavelength assignment is similar to the assignment of frequencies in a cellular communication network and can be expanded to accommodate 19 element or 37 element clusters as well. We have indicated the use of a redundant photonic beamformer, but an entire secondary beamformer is most likely not necessary. As a reliability study has not been performed on the lasers, modulators, and LNAs it is not clear at this time what the redundant path should include. Most likely, the LNA, EAM can be made redundant very cheaply and other redundancy in the beamformer can be made remote from the feed elements. The selection switch could be constructed from the switched grating devices and provide a compact and efficient method of incorporating the beam selection. However, depending on the requirements for beam selection, the complexity of this switching structure could be significant.

One significant disadvantage of this beamforming structure is that optical power is not optimally utilized. The signals from the feed elements are split regardless of which desired beam is formed. In other words, all of the possible beams are formed independent of which beams will be selected. As the multiple beam requirement is increased, this structure will be more attractive.

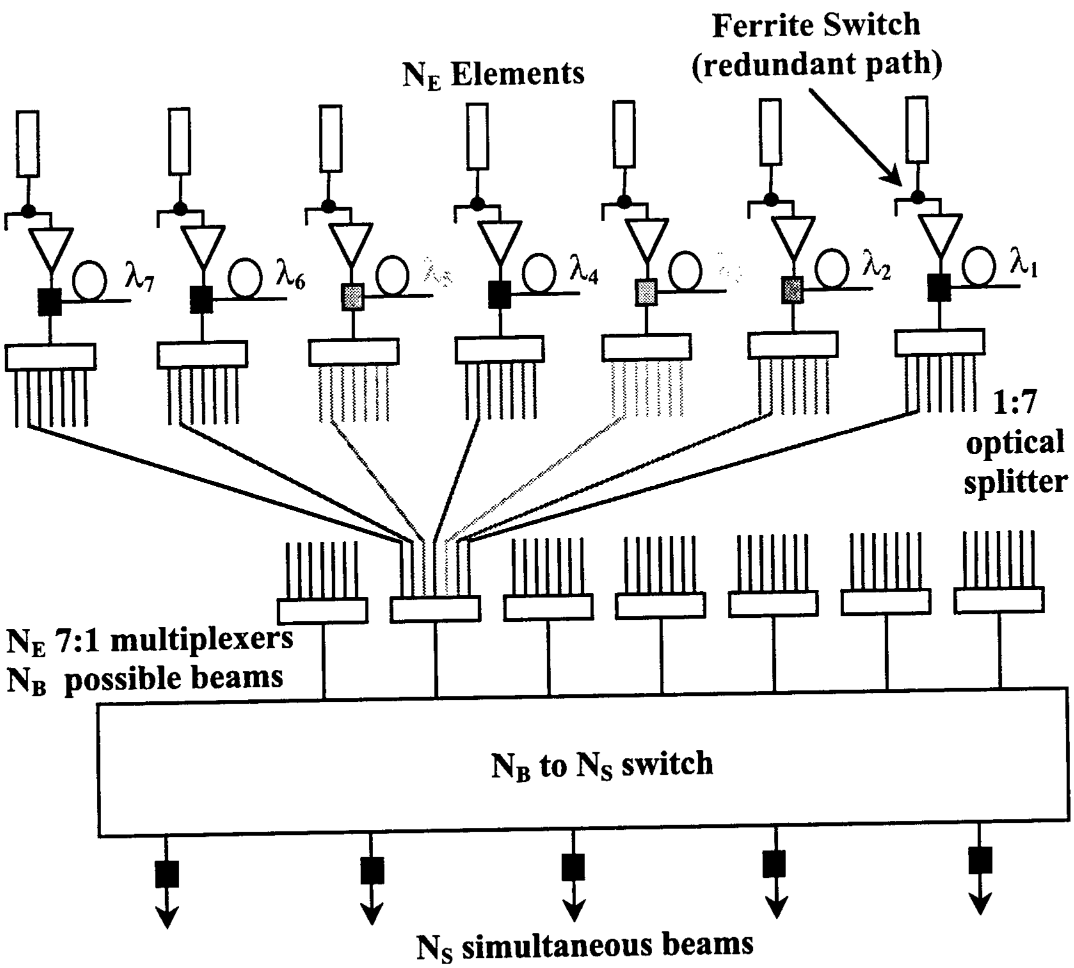
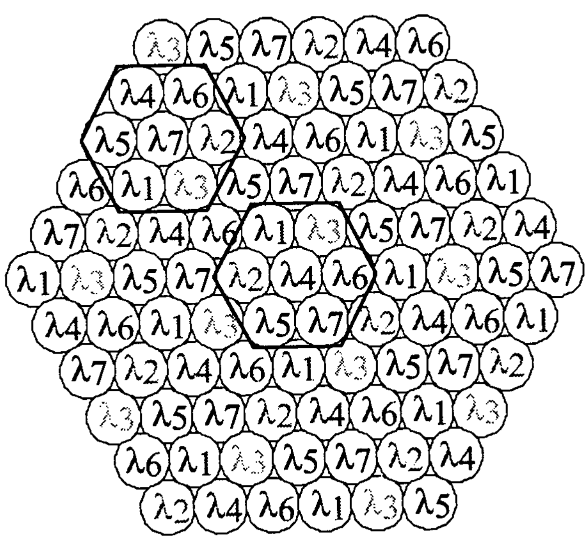


Figure 70. Array Fed Reflector Beamformer with WDM Combining.



Non Optimal Power Usage
- **Laser with each element**

N_B x N_S Switch
- **Significant complexity**

Figure 71. Feed Element Optical Wavelength Assignment.

8.13. Array Fed Reflector Beamformer with WDM Routing

The figure below illustrates a photonic beamforming architecture for the array fed reflector spaceborne antenna. Unlike the WDM combining architecture, this architecture enables the routing of optical power **only** to those feed elements that are required to form a desired beam. The beamforming architecture incorporates a TRW proprietary routing structure, optical downconversion utilizing complex weighting, and optical switching with the switched grating devices, and wavelength multiplexing. Seven element cluster combining of the RF signals is accomplished with both multi-wavelength optical techniques and conventional RF techniques.

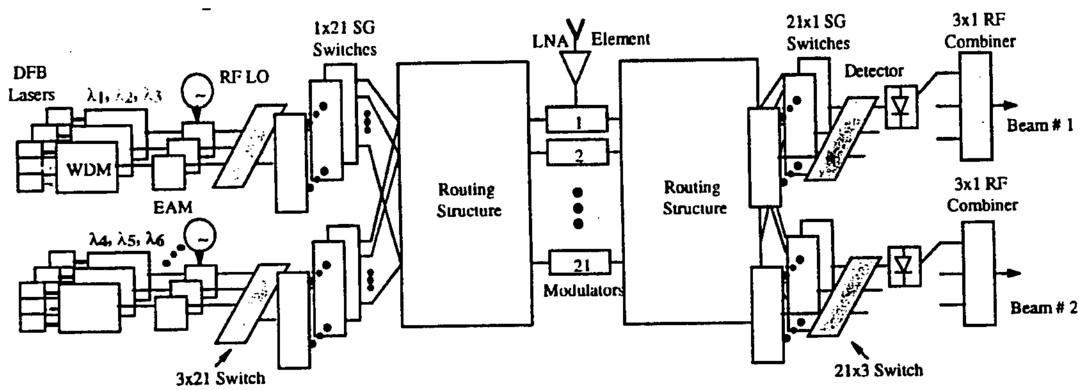


Figure 72. Array Fed Reflector Beamformer with WDM Routing.

Key challenge is enabling expanded multi-beam and reducing size/weight/cost

Trade Considerations

(+) Downconversion incorporated
(+) Multiple beam operation
(+) Low Weight
(+) Low Power Alternative to DRA
(+) Passive Beamforming
(-) Reliability must be maintained

Critical Technologies

- Multi-Wavelength EAM or III-V MZM
- Switched Grating Switches
- MOSAIC (if optical amplification is required)
- WDM Multiplexer (cost)

8.14. Array Fed Reflector Selected for Spaceborne Receive

The figure below illustrates an EDM brassboard of the optical source, heterodyne, switching, and combining module. Most of the components could be fiber pigtailed for convenience of assembly and packaging. Not shown in the figure are the heat sinking hardware that would be on the backend of the lasers and local oscillator source unit. Shown in the figure is the majority of the control, bias and DC power electronics that would be required for operation of the module.

The feed horns and receive module structure are also illustrated below. A semiconductor Mach-Zehnder, or an Electroabsorption Modulator is packaged with the LNA and DC power circuit in a multi-chip fashion. Aside from the input and output fiber cables, the only other required connection is the DC power source. No beam control lines are required as the beam steering and control is accomplished remotely from the antenna. Some packaging techniques on the modulator are required to enable easy access to the fiber inputs. TRW is currently developing packaging concepts for establishing LNA modulator assemblies that could be directly applicable to building this antenna hardware.

The full antenna system from a top-down view is illustrated below. The main and sub reflectors are suspended over the array feed in such a way as to allow the ±9° scanning field of view. The antenna would be oriented on the spacecraft so to point towards the earth at the correct angle and the aperture would possibly be covered by a radome not shown in the figure.

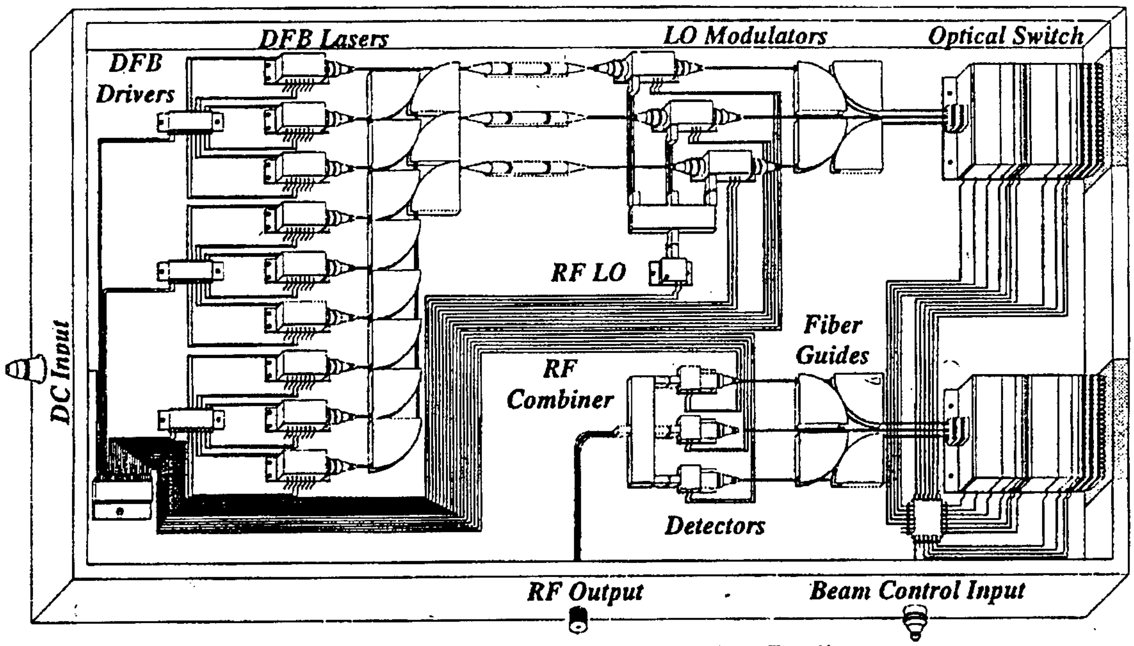


Figure 73. Optical Source Module.

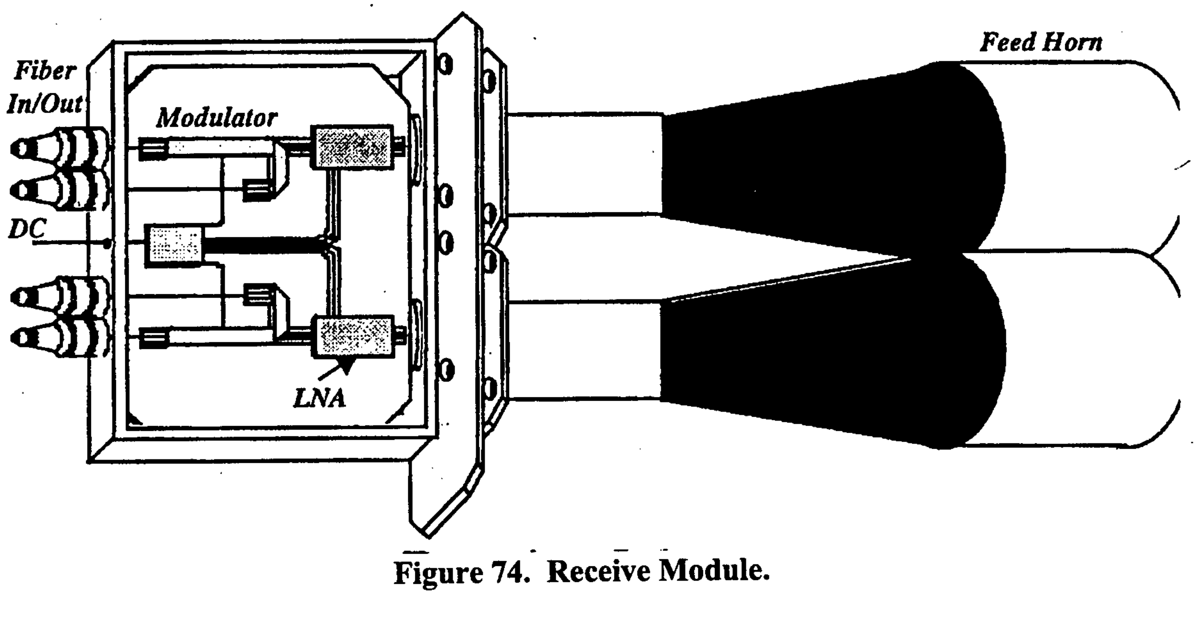
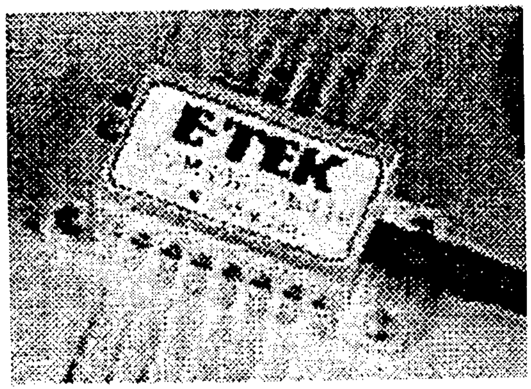
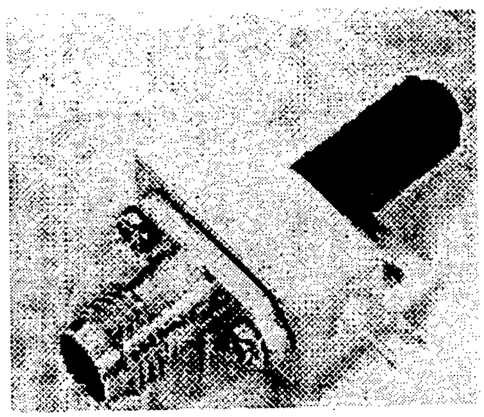


Figure 74. Receive Module.



A



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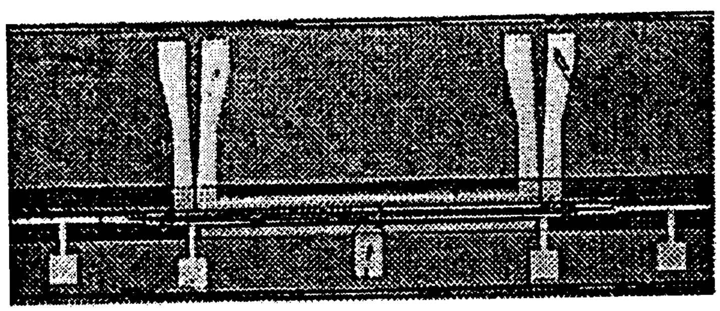


C

Figure 75. Three Components A- DFB Laser, B- Photodetector, C- Modulator.

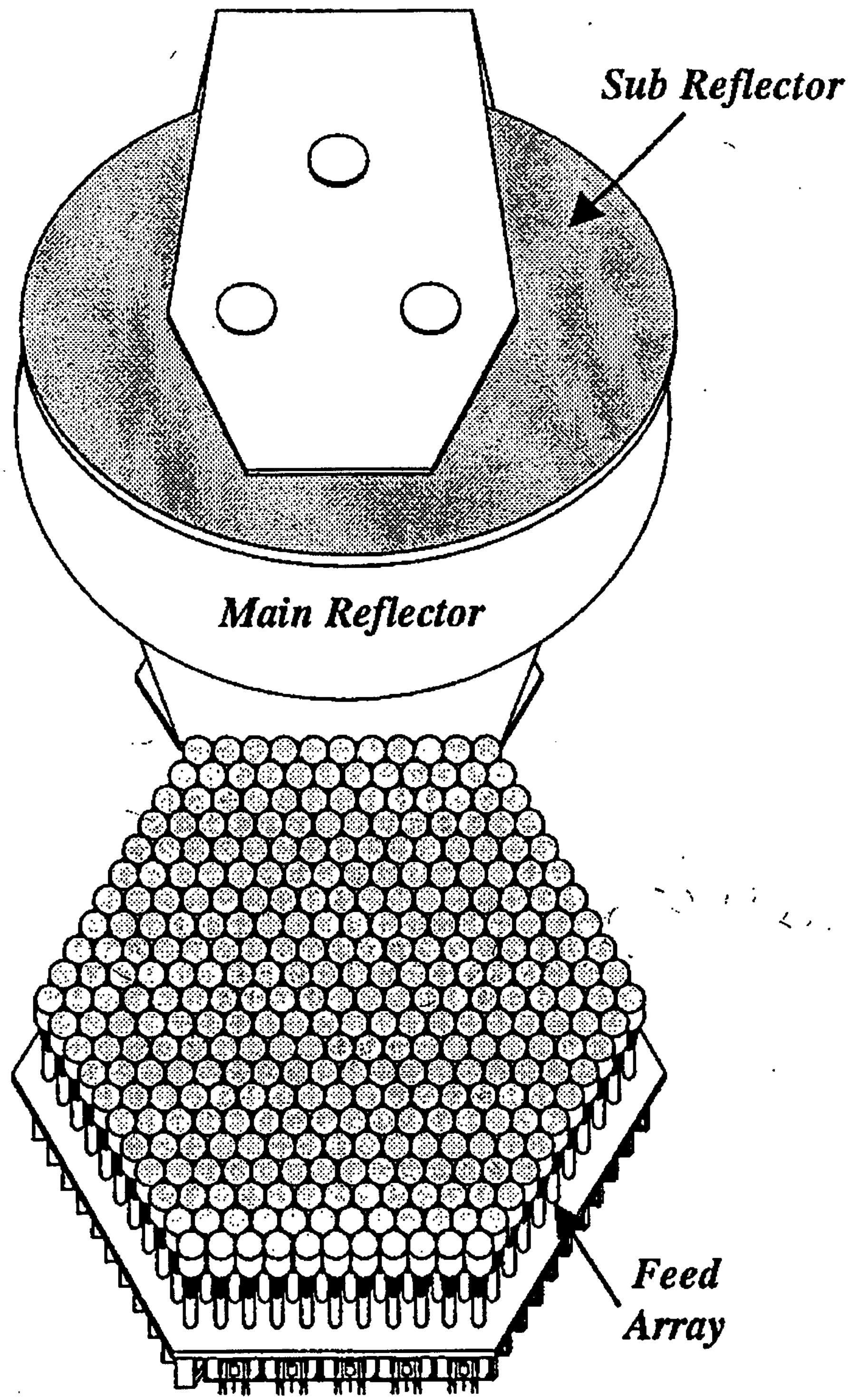


Figure 76. Spaceborne Receive Antenna (Top View).

8.15. Spaceborne Receive Conclusions

As demonstrated in the figures above, the key challenge in implementing the spaceborne receive antenna is the packaging limitations imposed by implementing a large number of beams. The high element density for the array at 44.5 GHz and the high losses from remoting the beamforming network prohibit the implementation of multi-beam phased arrays with RF beamformers. Photonics can be used to mitigate these packaging limitations for scanning arrays, but with the cost of exceedingly high DC power requirements.

These implementation challenges lead to the consideration of MBA's for servicing the COMM uplink. MBA's offer many attractive features, but must provide adequate reliability (through beamformer redundancy) and mitigate the significant switching requirements that arise in selecting the set of desired beams from the sum total of the formed beams available. Photonics can clearly enable the necessary redundancy through beamformer remoting and can alleviate the challenging switching requirements through the use of highly compact optical switching structures. The photonic wavelength routed beamforming network for the array fed reflector primarily requires the use of 1xN or Nx1 switches many of which are set to the same switching state. Highly compact parallel structures can be implemented that leverage off of the high interconnect density that is possible with optical structures. We have identified the switched grating optical switching technology as a compact, low loss approach for meeting the beamforming switching requirements.

8.15.1. Key challenge is packaging for multiple beams (limited volume at array elements)

8.15.1.1. Photonic mitigates packaging challenge of multiple beams through beamformer remoting

Architecture trades preclude the implementation of scanning arrays, favors MBA

- RF scanning array cannot be configured to implement 10 simultaneous beams
- Photonic scanning array consumes a prohibitive amount of DC power

Key challenge with MBA is switching complexity

8.15.1.2. Photonics used to mitigate switching complexity

- Array fed reflector primarily requires 1xN or Nx1 switch
- Switched grating optical switch is attractive technology to implement beam selection

8.16. Airborne Transmit Performance Goals

The current RF implemented airborne phased array antenna, based on the proposed "Low Cost EHF Phased Array" (LEAP) architecture, radiates in a single beam transmitting a single 50 MHz channel to the Milstar satellite. Although the total coverage bandwidth is 2 GHz (44.5 ± 1 GHz), an RF scanning array can transmit a single 50 MHz data channel without beam squint (< .002 dB penalty) by adjusting the phase weights at each frequency hop. Based on the requirements of such a communication system configuration, photonic techniques provide little advantage over currently conceived RF implementations. As the front end TX module is identical regardless of an RF or Photonic implementation, incorporating photonics results in comparable size, but significantly increased weight and power. Our baseline photonically implemented transmit antenna provides increased data capacity and functionality by simultaneously transmitting multiple 50 MHz channels to the Milstar satellite. When incorporating this flexibility, the antenna beamforming requires some level of true time delay. In retaining the 2 GHz bandwidth allocation, we enable only slight leverage from the incorporation of photonically implemented TTD. If this allocation were further increased to enable uplinking of wide-band imaging data the impact of incorporating photonics would be more substantial. However, increasing the 50 MHz channel bandwidth and the 2 GHz spread spectrum bandwidth was rejected because of incompatibility with the existing Milstar communication architecture.

Functions that are enabled by multi-channel operation include simultaneous communications from multiple airborne crew members or platform terminals, uplinking of platform telemetry gathered from GPS or other location sources, and uplinking of MDR digital imaging data gathered from reconnaissance platforms such as the E-3A or unmanned air vehicles (UAV).

Table 13. Airborne Transmit Performance Goals.

Item	Requirement	Source
Number of Beams	1	SOW
Beam Shape	spot	SOW
Frequency	43.5 to 45.5 GHz	SOW
Polarization	single, circular	SOW
Coverage	70 degree cone	SOW, Milstar
EIRP (@EOS)	45 dBW	SOW
Beam Update	20 kHz	Milstar, Advanced EHF
Beam Settling Time	<0.9 microseconds	Milstar, Advanced EHF
Sidelobe level (first)	not specified	
Spot Beamwidth	not specified	
Carrier to Noise	15 dBC	Assumed (SB Tx)
Additional Requirements	Flat, thin, compatible with C-17, E-3A, UVA, Fighter	SOW

Notes:
Performance
SOW goals consistent with Milstar

Single Beam Uplink
Limited utility of multibeam

Multi-channel Operation
Aggressive performance goal relative to current Milstar
Necessitates Subarray TTD

Applications
Simultaneous COMM channels
Telemetry uplink (GPS)
MDR Imaging uplink (UAV)

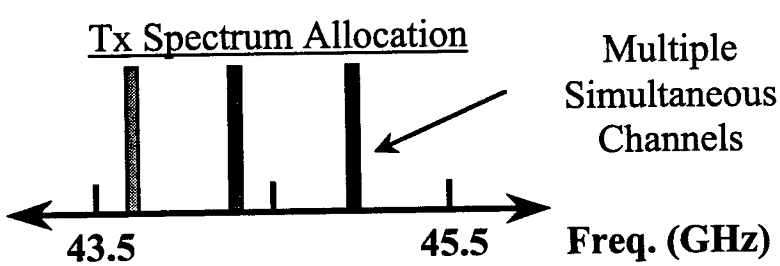


Figure 77. Airborne Transmit Performance Goals.

8.17. Transmit Antenna EIRP Analysis and RF Module Design

The driving design requirement for the airborne transmit antennas is 45 dBW EIRP at a 70° scan angle. A common cylindrical waveguide antenna element and RF module are used for all architecture candidates incorporating RF or photonically implemented beamforming. Each architecture is required to provide the module driver amplifier the specified power level of 0.48 mW - 0.96 mW.

For the photonically implemented architectures, this implies a certain DC optical power level is required to be incident onto the photodetector. Although the driver amplifier provides some VSWR isolation to the power amplifier, we have assumed that the output impedance of the photodetector should be matched to 50Ω, requiring a passive matching circuit at the output of the photodetector. A 50Ω resistor is placed in shunt with the detector so to match the output impedance of the device to the input of the driver amplifier. This results in dividing the photo current at the detector output and further increases the incident optical power requirement.

An EIRP link budget analysis with 0.48 W module output power (consistent with TRW IR&D) results in the requirement of 400 elements. Increasing the number of elements and decreasing the Tx power per element is typically done for consideration of thermal issues. We expect the TX modules on which this analysis is based can operate up to 0.96 W output power which would only require 200 elements (≈ 14x15 aperture) and operating at 25% efficiency would dissipate 576 W of power. The resulting power/area density for a periodic array of this size is approximately 0.21 W/mm^2. This power density is expected to necessitate forced cooling of the array leading to increased weight. Choosing 0.48 W per element results in the dissipation of the same 576 W of power, but with a power density of 0.13 W/mm^2, or nearly half that of the smaller array. We expect that this will enable the use of passive array cooling and substantially reduced size and weight. However, the number of required elements is significant and will substantially impact the cost of the antenna. We note that if we can spread out the 200 elements operating at 0.96 W output it would be possible to simultaneously achieve the EIRP goal, enable passive cooling of the array, and lower the component count and cost of the antenna.

Antenna gain values and scanned array patterns were determined with a combination of antenna feed analysis software and loss estimates based on existing hardware (e.g. polarizer and radome loss). Other considerations such as end of life degradation (assumed to be 95%) and pointing loss were also factored into the EIRP budget calculation.

The figures provided illustrate the array layout and the resulting antenna pattern.

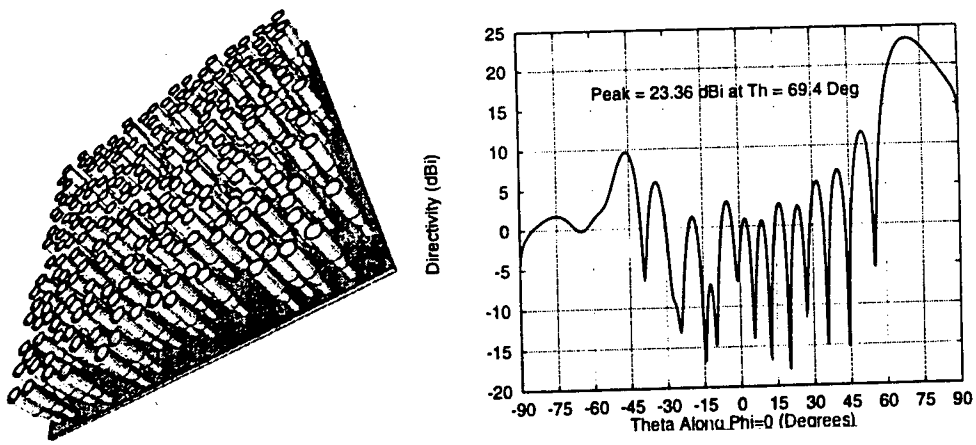


Figure 78. Transmit Antenna EIRP Analysis.

Note: Antenna Array gain calculated with software and loss estimates

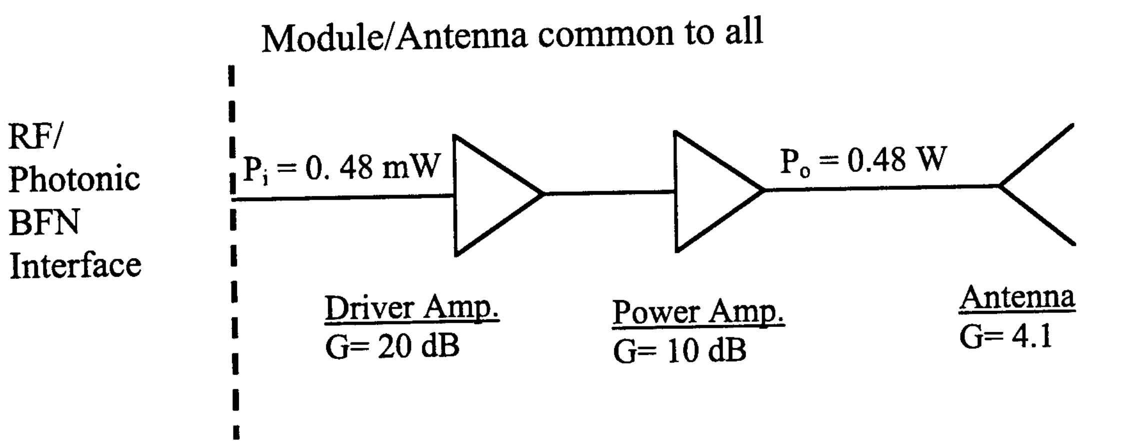


Figure 79. RF Module Design.

Note: Scanning Antenna designed for 45 dBW EIRP @70°scan ⇒ 200 - 400 TX modules - elements
- Link budgets for traded designs will be provided in Supporting Analysis Package

8.17.1. Cylindrical waveguide elements - Dielectric loaded

8.17.2. Rectangular lattice - 0.5 λ spacing

8.17.3. Output RF power = 0.48 - 0.96 W - Consistent with TRW devices

8.17.4. RF drive power = 0.48 - 0.96 mW - Consistent with TRW devices

8.18. Airborne Transmit Antenna Array Configuration

For the Airborne receive antenna array configuration, 4 bits of phase quantization at the element is adequate to suppress grating lobes in the array pattern. As indicated by the figure in the paragraphs below, the sidelobes are increased relative to infinite phase quantization, but are below the maximum sidelobes found in the unquantized pattern. The element scan loss is assumed to be -7 dB at the edge of scan; consistent with data measured from typical elements. As the dimension of the array is slightly skewed, the formed beam shape is slightly skewed as well.

8.18.1. Phase steered at elements
4 bit quantization (see figure below)

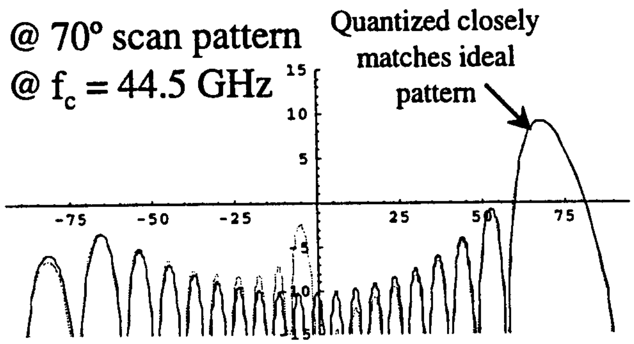


Figure 80. Phase steered at elements.

8.18.2. Scan loss at 70° = 7 dB (400 elements)
based on measured element pattern

8.18.3. Beamwidth (for 400 elements)
2.132° for 0.5 dB crossover
2.997° for 1.0 dB crossover

8.18.4. Beams for full coverage (approximate)
26,398 for 0.5 dB crossover
13,523 for 1.0 dB crossover

8.18.5. Time delay steered at subarray
Squint loss at 70°

0.6451 dB	(no TTD)
0.1583 dB	(4 subarrays)
0.0382 dB	(16 subarrays)

Unseparable configuration
(using FBG TTD)
$\tau_{max} = 224.0$ ps
2 bits (0°-EOS) ⇒81 states
(22.7 dB penalty)

Separable configuration
(using SG TTD)
$\tau_{max} = 158.4$ ps
5 bits (0°-EOS) ⇒ 4096 states
(0.507 dB penalty)

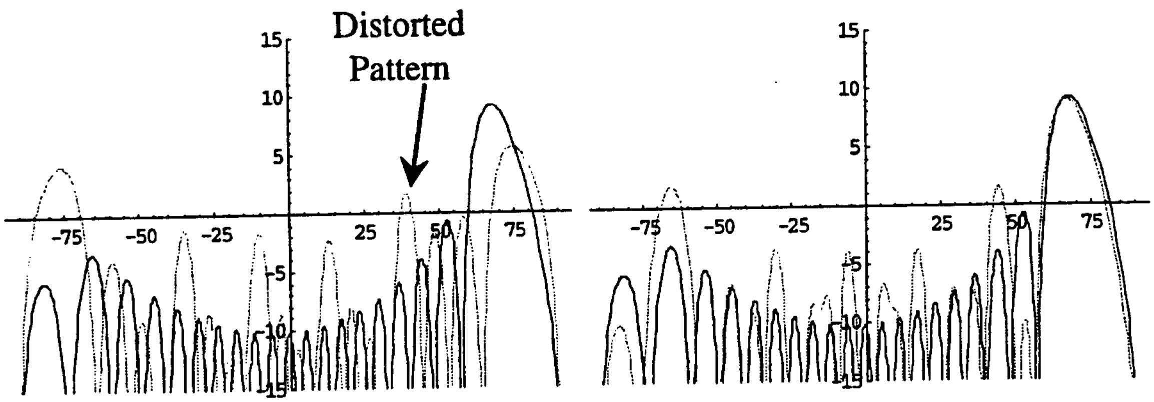


Figure 81. Time delay quantization.

8.19. Airborne Transmit Candidates

Four candidate architectures were traded for the airborne transmit antenna: RF scanning array, photonic scanning array, hybrid RF/photonic Rotman lens, and Aperiodic photonic scanning array. Since the aperture size is extremely small, a dome lens can be incorporated with the scanning arrays to allow scanning to 70° and beyond with no scan loss. This would allow a 50% reduction in the number of required elements and a reduction in module output power to 0.38 W. The lens would work similarly for both the RF and photonic arrays, and as such was omitted from the trade space.

True time delay weighting is required for multiple channel operation and is implemented with a photonic switched grating. This time delay structure enables 5 bits of time resolution in both the vertical and horizontal dimension of the field of view. The resulting 1024 time steered positions are satisfactory to reduce the beam squint penalty to acceptable levels at the edge of scan.

A direct radiating hybrid photonic/RF MBA candidate was also analyzed. The direct radiating array allows for solid state power combining in the formed beam, and consists of the same dielectric loaded elements as the scanning arrays. The beamformer consists of a photonically implemented Rotman lens in one plane, followed by an RF Rotman in the other plane which attaches to the lens. The photonic Rotman combines switching, wavelength routing and true time delay functions. A 2D photonic Rotman by itself is complicated to implement in a way that enables independent horizontal and vertical scanning. A 2D RF Rotman requires additional switching and is not consistent with beamformer remoting.

The photonic Rotman lens could be incorporated in integrated optics and utilize wavelength division multiplexing to enable the necessary beam combining in a compact structure. The RF Rotman lens would be implemented with parallel plates and loaded with dielectric (e.g. the same dielectric used in the radiating elements). Although a 44 GHz Rotman design is challenging, TRW has developed 60 GHz pillbox antenna designs that are similar in complexity and we are confident that a design could be successfully realized if necessary.

Such beamforming concepts however do not attack the key challenge of mitigating the thermal issues associated with the close spacing and high output power of the elements. A promising approach is to thin the array with fewer elements and higher power per element to reduce the thermal density. TTD is required to maintain acceptable levels of beam squint over the larger aperture and placing the elements in an Aperiodic fashion would suppress grating lobes and maintain acceptable performance over the field of view.

Table 14. Airborne Transmit Candidates.

	Scanning Array (RF)	Scanning Array (Photonic)	1D PH Rotman 1D RF Rotman	Aperiodic Array (Photonic)
Element Number	400	400	400	200
EIRP @ EOS Ant. Gain Module Power EIRP @ BS	45.0 dBW -2.86 dB 0,48 W 52.0 dBW	45.0 dBW -2.86 dB 0,48 W 52.0 dBW	45.0 dBW -2.86 dB 0,48 W 52.0 dBW	45.0 dBW 0.0 dB 0,96 W 46.5 dBW
Size	1,023 cm^3	1,504 cm^3	2,317 cm^3	1,448 cm^3
Weight	0.659 kg	3.310 kg	3.749 kg	2.577 kg
Power	642 W	769 W	699 W	709 W
Complexity	Associated with packing density	Optical heterodyne and TTD	Photonic and RF Rotman	Same as other scanning arrays
Comments	TRW IR&D	TTD at subarray	TTD at element	TTD at subarray

Note: Key challenge is thermal management and increasing COMM channel capacity
Photonic Beamformer with Aperiodic Array Enables
⇒ Reduced thermal density ⇒ Increased module power
⇒ Reduced component count ⇒ REDUCED COST

8.20. Scanning Array (RF)

The RF scanning array design is based on components developed on TRW IR&D as part of the LEAP program. The LEAP design consisted of 256 elements with λ/2 element spacing. The Tx modules for this design were driven to their maximum output power of 0.8 W. The resulting heat dissipation required the use of forced liquid cooling on the array. Our design has backed off the module power to 0.48 W and incorporated 400 total elements. The resulting design should be amenable to passive cooling techniques. This results in a significant reduction in hardware associated with cooling the array. The resulting RF baseline array is characterized by moderate size, weight, and power but works only in a narrowband mode due to the utilization of phase only steering. As the 44 GHz Tx modules benefit from several years of TRW development, there are no identifiable critical technology risks or developmental requirements associated with this design.

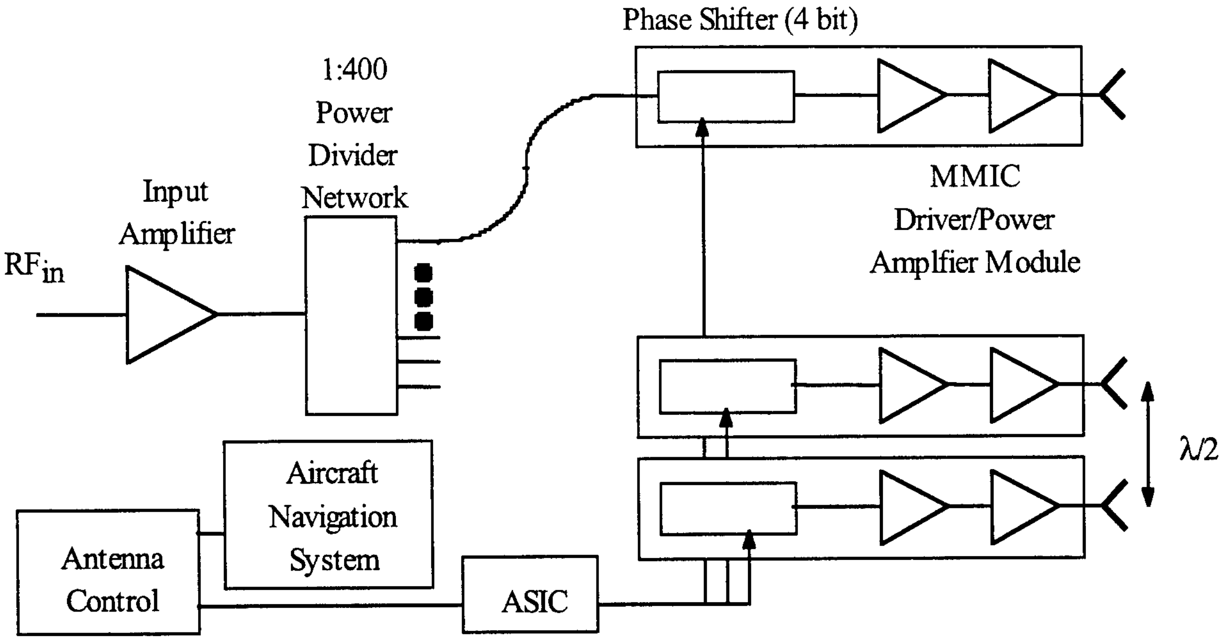


Figure 82. Scanning Array (RF).

Note: RF scanning array design is based on LEAP design incorporating standard MMIC components

Trade Considerations

(+) Small size, weight, power
(-) Narrowband operation

Critical Technologies

Packaging
Thermal management

8.21. Scanning Array (Photonic)

Our photonically implemented scanning array design utilizes photonic upconversion and true time delay at the subarray level. Adequate time resolution requirements result in the use of separated time delays (horizontal and vertical) using the switched grating time delay technology. This time delay implementation allows the use of single wavelength, injection locked DFB lasers at the input to provide high power and high performance upconversion of the input IF signal. The six true time-delay units enable ± scanning over the entire field of view with 4 to 5 bits of time resolution for the four subarrays. After time delay steering, the optical signals are split 1:100 by the MOSAIC devices and then photodetected at each antenna element. The 44 GHz Tx module provides t he specified output power for the signals radiated at the antenna elements. The advantages of this design are the incorporated upconversion and the true time delay which enables multi-channel operation. The disadvantage is the high DC power requirements associated with the optical splitting. The critical component technologies are the injection locked laser source, the switched grating true time delay device, the MOSAIC splitter devices, and high frequency - high power photodetectors.

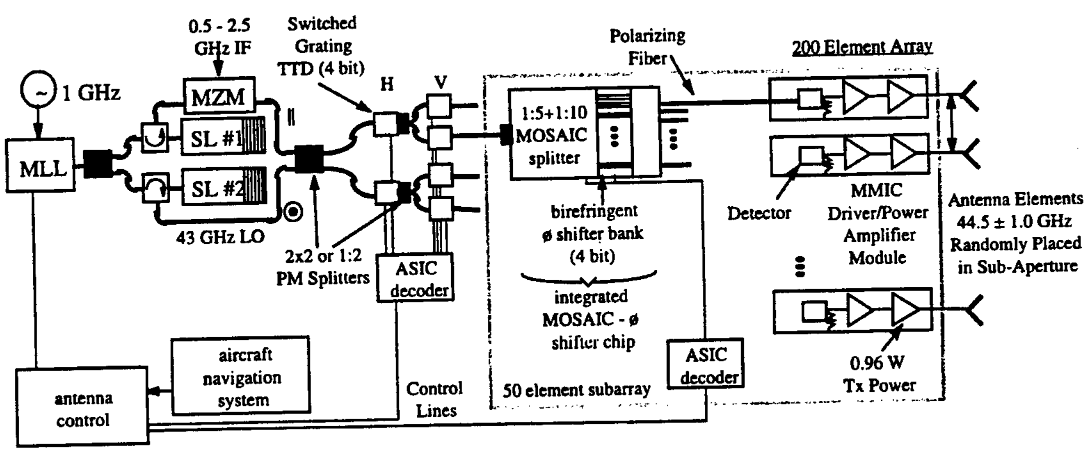


Figure 83. Scanning Array (Photonic).

8.21.1. Trade Considerations

(+) Upconversion incorporated
(+) Multiple channel operation
(-) High DC power required

8.21.2. Critical Technologies

Injection locked laser source (CORE)
SG-TTD device
MOSAIC
High Frequency/Power Detector

8.22. Scanning Aperiodic Array (Photonic)

Photonics can also be used to enable thinning of the scanning array. The Tx power per element is increased and the number of elements decreased and placed over a larger area. Aperiodic spacing is used to suppress grating lobes in the antenna pattern. Thinning the array results in the same power dissipation per unit area with fewer elements and lower cost. Photonics enables the thinning of the array as RF microstrip lines are eliminated from the power distribution network. The larger aperture does necessitate the use of true time-delay at the subarray level to reduce the impact of beam squint during multichannel operation. The reduction in the number of elements has a significant impact on the size and power requirements of the antenna as nearly 50 W less power is required of the Aperiodic array even though the power per element is increased. Such a technique is uniquely enabled by photonics and works to solve the most critical challenge of implementing the airborne transmit array.

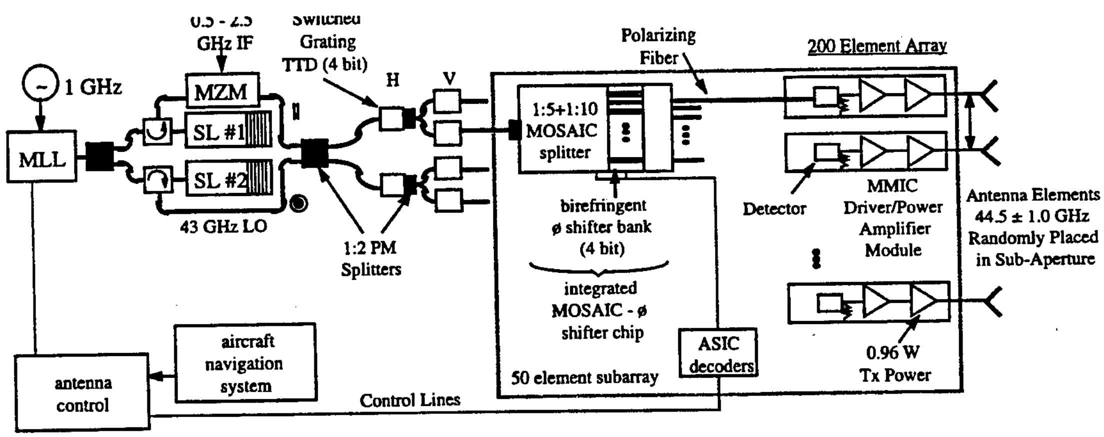


Figure 84. Scanning Aperiodic Array (Photonic)

Note: Photonics enables low loss thinning of the array and true time-delay

8.22.1. Trade Considerations

- (+) Upconversion incorporated
- (+) Multiple channel operation
- (+) Mitigation of Thermal
- (-) Slightly higher DC power

8.22.2. Critical Technologies

Injection locked laser source (CORE)
SG-TTD device
MOSAIC
High Frequency/High Power Detector

8.23. Hybrid Photonic/RF 40x10 Rotman MBA

The figure below illustrates an architecture for a hybrid photonic/RF Rotman lens beamformer for 400 elements. Photonics are used to accomplish the signal upconversion and beamforming in one dimension while electronics and parallel plate waveguides are utilized to accomplish the beamforming in the orthogonal dimension. We have examined this hybrid architecture so to combine the attractive features of photonics and RF technology to accomplish the beamforming. The input IF signal band is modulated onto one of two optical carriers established in a heterodyne configuration for optically implemented upconversion. The first Rotman is implemented in photonics using wavelength tuning to accomplish the beam steering. As the wavelength of the optical signal is tuned to a different wavelength, the distributed signals experience a different set of relative time delays to form a steered beam in a different direction. The photonic Rotman can be considered a constrained feed type where the path lengths are exactly set in individual integrated optic waveguides rather than in a lens structure. The most attractive structure to realize these path length delays are arrayed waveguide grating delay lines (as described by B. Jalali at UCLA). The MOSAIC optical splitter devices would be used for the optical signal distribution and switched grating optical switches would be used to accomplish the beam selection for the RF Rotman lens inputs. This optical switching structure would be easily incorporated since all of the switches are set to the same state. This leads to a highly compact switching device to be used with the large number (40) or RF Rotman lens. High frequency (44.5 GHz)/high power photodetectors would be required to accomplish the optical to RF conversion at the multiple inputs to the RF Rotman lens' associated with the multiple vertical beam positions.

Although this beamformer architecture is attractive from a size, weight, and power as well as performance standpoint, it does represent some overkill for the intended application. Being an entirely true time-delay beamformer, it would be most useful for extremely wide band applications. The true time-delay features provide only limited utility for the moderate bandwidths of 2-4 GHz that would be conceivable for this application. This beamformer also does not solve the critical problem of thermal dissipation in the array that is common to most beamforming approaches photonic or electronic. As such, although an attractive alternative beamforming approach, the hybrid photonic/RF Rotman lens approach still fails to provide the best solution for the airborne transmit array antenna.

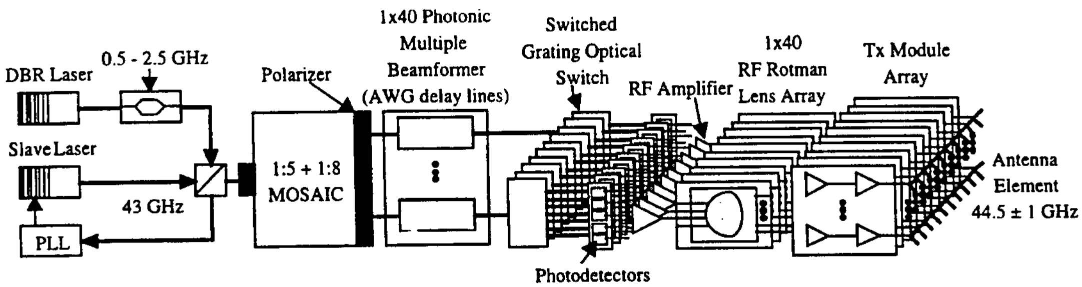


Figure 85. Hybrid Photonic/RF 40x10 Rotman MBA.

8.23.1. Trade Considerations

- (+) Upconversion incorporated
- (+) Multiple channel operation
- (-) High DC power required
- (+) Wide band multi-beam possible
- (-) High complexity

8.23.2. Critical Technologies

DBR Tunable Laser
MOSAIC
Low-loss Arrayed Waveguide Grating
SG Optical Switching Device
High Frequency/Power Detector
44.5 GHz RF Rotman Lens

8.24. Aperiodic Scanning Array Selected For Airborne Transmit

The aperiodic element spacing requires a novel concept for packaging the array. A thermal structure is fabricated with rectangular sections removed in the aperiodic pattern. The transmit modules fit into the slots and the antenna element attaches to the front end of the module. The transmit module, an enlarged version of which is illustrated in the figures below consists of a fiber input, a photodetector, the driver and power amplifier. Although not indicated in the figure, DC power is fed to each module for biasing the photodetector and amplifiers. Also not shown in the illustration below is the vein polarizer and radome. The vein polarizer converts the linear polarization of the 44.5 GHz horn radiation mode into a single sense circular polarization for the uplink channel. This polarization technique is consistent with that previously proposed for EHF airborne transmit phased arrays and finds equivalent use for this design recommendation.

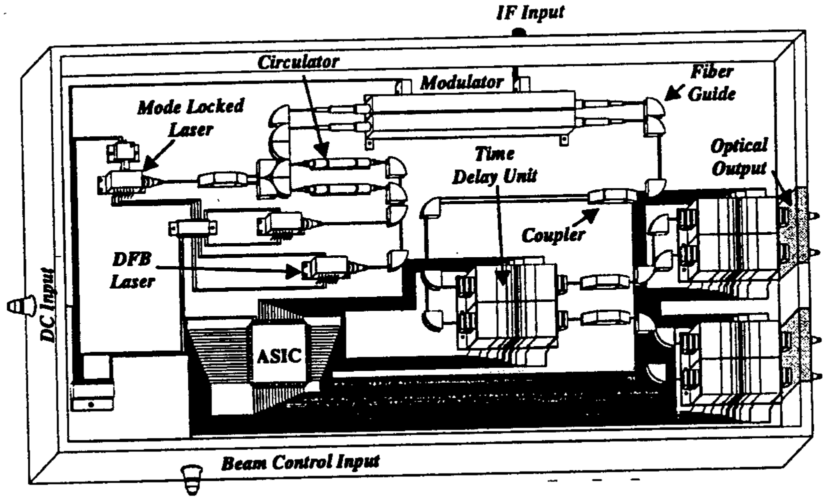


Figure 86. Optical Source Module.

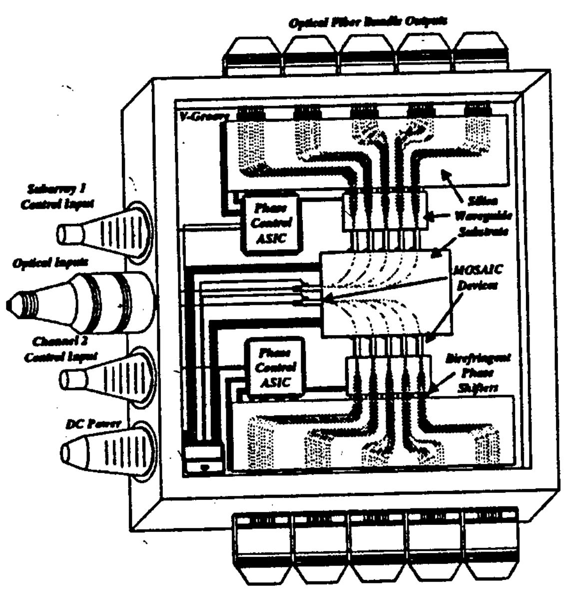


Figure 87. Optical Distribution Module.

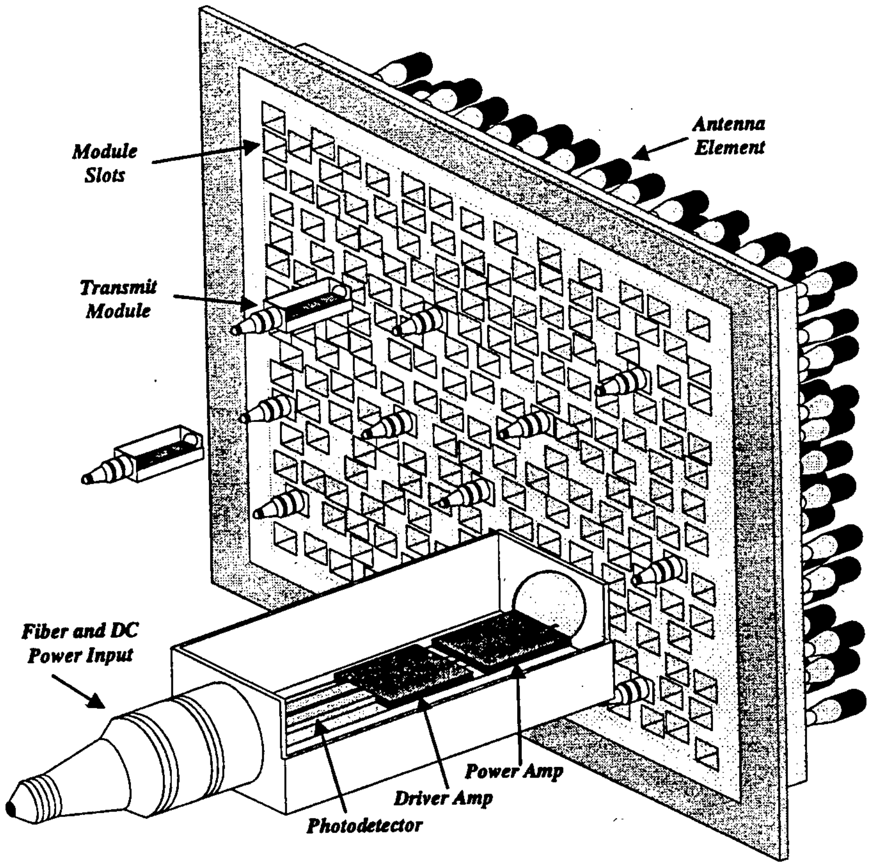


Figure 88. Aperiodic Array Front View.

8.25. Airborne Transmit Conclusions

Upon examination of the primary requirements and design issues for the airborne transmit antenna, we have found that the key challenge is associated with mitigating the impact of the thermal power density and power dissipation at the array. Given the moderate bandwidth requirements and size of the antenna array (even with multi-channel operation), photonics provides only limited leverage in enabling true time delay steering at the subarray level. The significant leverage of photonically implemented beamforming results in enabling the thinning of the array so that fewer elements can be incorporated and the full power capability of the transmit modules can be utilized. Using fewer elements spread over a larger aperture area results in lower cost to achieve the same level of performance. Aperiodic placement of the elements can work to reduce the level of grating lobes and is easy to accommodate with the incorporation of photonics. Increasing the power per element also enables modification of the element antenna pattern to one more isotropic which results in reduced scan loss at the edge of scan.

Some additional considerations must be made to the implementation of the antenna architecture. Optical heterodyne techniques can be incorporated to accomplish the signal upconversion. In doing this, the IF signal is modulated onto the optical carrier with a low biased MZ modulator. As such, techniques developed for the DARPA sponsored OERFM program can be utilized to improve the modulation efficiency and substantially improve the RF performance of the array for the given DC power requirements.

8.25.1. Key challenge is thermal density and power dissipation

- Trade density (few elements, high power) and cost (more elements, low power)

8.25.2. Photonics enables reduced element density to mitigate thermal limitations

- Reduces thermal density to enable more power per element
- Reduced scan loss (more isotropic element is possible)
- Result is fewer elements and lower cost

- Aperiodic spacing and TTD required to suppress grating lobes and beam squint

8.25.3. Photonic BFN for packaging and TTD

- Large optical power levels must be delivered to elements to achieve module power — required for EIRP goal
- OERFM could be used to improve modulation efficiency (for low-biased MZM)

8.26. Spaceborne Transmit Performance Goals

Performance goals for the spaceborne transmit antenna are derived from the ESAD contract SOW, Milstar and Advanced EHF. The most aggressive requirement is capability for 4 simultaneous beams. For the current RF scanning array implementations, the number of beams is limited by the packaging density of the phase shifters behind each element, the carrier to interference and suppression performance of the output power amplifiers, and heat generated by the output amplifiers. For this reason the Advanced EHF baseline is likely to be revised from four beams in one aperture to four single beam apertures. We have assumed as a performance goal, four beams in one consolidated aperture as this is consistent with the ESAD contract SOW. We have not selected a performance goal more aggressive than 4 beams per aperture because photonics cannot mitigate limitations imposed by the power amplifiers. Incorporation of more than 4 beams is an attractive goal, and could be achievable if relaxation of packaging limitations enable the formation of > 4 beams in a photonically implemented scanning array. Nevertheless, preliminary considerations indicate that significant leverage is obtained from the use of photonics to reduce the overall weight of the multiple beam architecture.

Multi-channel capability provides limited utility to the function of this terminal and as such, phase only beamsteering is adequate and true time-delay is not required. Given this set of performance requirements, the principal challenges associated with implementing this beamformer are to enable aperture consolidation and reduced payload weight. Beamformer remoting may assist in producing a design that meets the harsh environmental constraints consistent with space deployment.

Table 15. Spaceborne Transmit Performance Goals.

Item	Requirement	Source
Number of Beams	4	SOW
Beam Shape	Spot and full Earth coverage	SOW
Frequency	20.2 to 21.2 GHz 19.7 to 20.2 GHz for GBS	SOW
Polarization	Single, circular	SOW
Coverage	9.3 degree cone (Visible Earth)	SOW, Milstar
EIRP (spot beam at EOC)	50 dBW	SOW
Beam Update Rate	20 kHz	Milstar, Advanced EHF
Beam Settling Time	<0.9 microseconds	Milstar, Advanced EHF
Sidelobe level (first)	Not specified	
Spot beamwidth	1.0 degree	Advanced EHF
Carrier to Noise	15 dBC	TX MBPA
Additional Requirements	Design compatible with space environment	SOW

8.26.1. Performance
SOW goals consistent with Milstar

8.26.1.1. Multiple Beam Downlink
capability for > 4 beams is attractive

8.26.1.2. Single Channel Operation
Limited utility for multi-channel
Phase only beamsteering is adequate

8.26.1.3. Capability Limitations
Packaging for multiple beams
Linearity of SSPA

8.26.1.4. Applications
Standard Milstar COMM

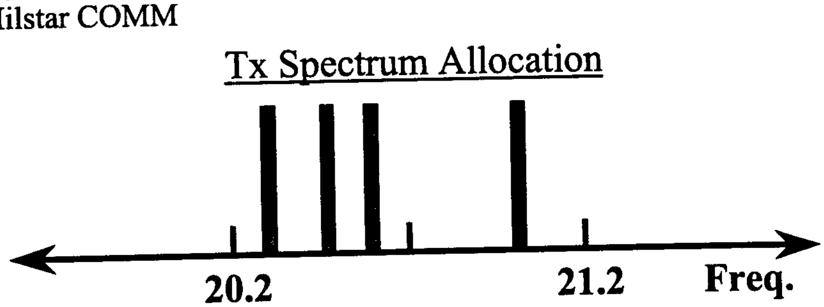


Figure 89. Spaceborne Transmit Performance Goals.

8.27. Transmit Antenna EIRP Analysis and RF Module Design

The driving design requirement for the spaceborne transmit antennas is 50 dBW EIRP at the edge of scan for each of four beams. A common antenna element and RF module were used for all candidates. Each beamforming architecture is required to provide 0.001 mW to the driver amplifier in order to meet the required EIRP goal and the size, weight, and DC power is compared between all architectures.

For the photonically implemented architectures, the required driver input power impacts the optical power and photodetector current requirements. Passive impedance matching of the photodetector output to 50Ω is baselined into the photonic architectures. Given the output amplifier performance (based on devices developed under on the MBAPA program supported by Rome Labs), 271 elements are required to meet the stated EIRP performance goal. With no requirements for subdividing the antenna into subarrays, the elements can easily be arranged in an arbitrary fashion and we have selected a 10 ring hexagonal lattice configuration. Separation of the antenna elements by 2.4 λ at 20.7 GHz assures that grating lobes will be well outside the 9.3° conical scanning field of regard.

Antenna element and array gain values were determined with a combination of antenna feed analysis software and loss estimates based on existing hardware (e.g. polarizer and radome loss). Other considerations such as end of life degradation (assumed to be 95%) and pointing loss were also incorporated into the EIRP calculation.

The antenna array and module circuit configuration are illustrated in the figure provided below.

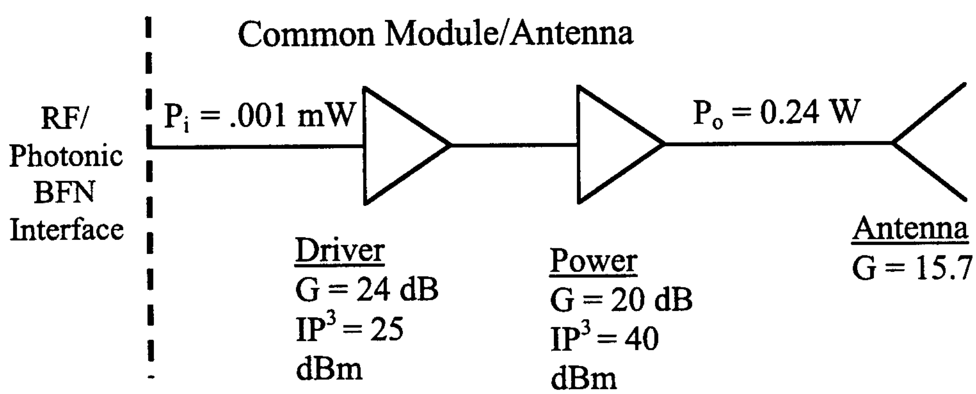


Figure 90. Transmit Antenna Common Module.

Note: Scanning Antennas designed for 50 dBW EIRP at 9.3°scan ⇒ 271 RF elements required
- Link budgets for traded designs will be provided in Supporting Analysis Package

8.27.1. 271 conical horn elements

8.27.2. 10 ring hex lattice   2.4 λ spacing

8.27.3. Module Output RF power = 0.24 W
Consistent with MBAPA Program

8.27.4. Module drive power = 0.001 mW
Consistent with MBAPA Program

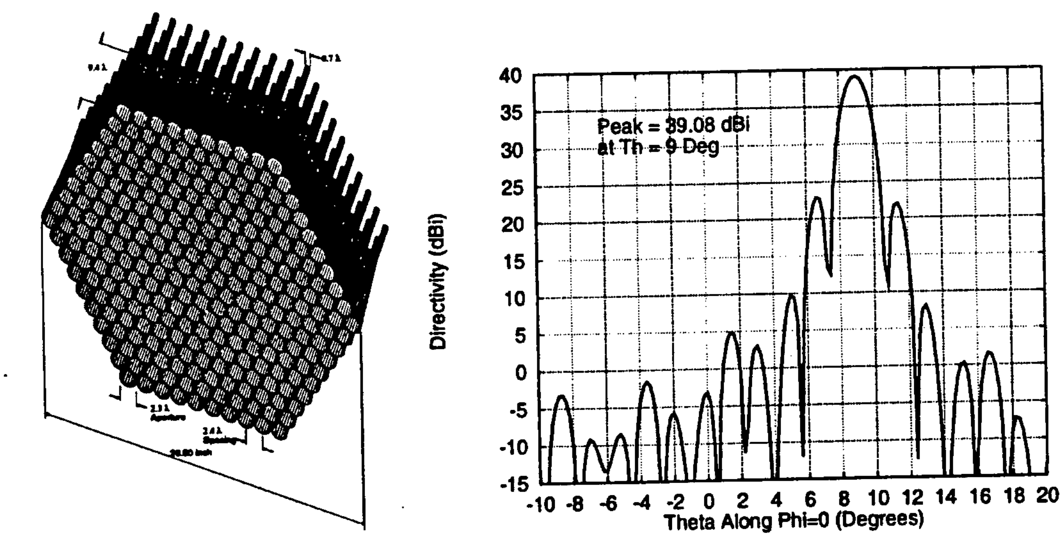


Figure 91. Transmit Antenna EIRP Analysis.

Note: Antenna array gain calculated with software and loss estimates.

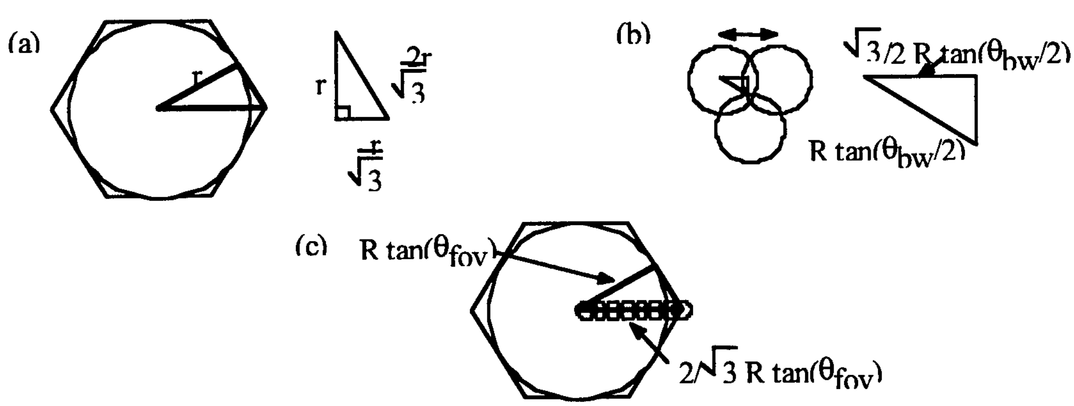
8.28. Spaceborne Tx Antenna Array Configuration

The spaceborne transmit antenna is required to access a 9.3° conical scan field of view to support full earth coverage. With knowledge of the scanning field of view and definition of a grating lobe free field of view, one can determine the allowable element separation as a fraction of RF wavelength by the simple expression:

$$\frac{d}{\lambda} = \frac{1}{\sin(\theta_{gf}) + \sin(\theta_{fov})}$$

If we desire a 14.3° grating free field of view, we find the element separation can be 2.4λ. The element diameter will be slightly smaller than this value and will determine the antenna element pattern characteristic. Based on measured data of EHF downlink elements, we estimate the scan loss at 9.3° due to the element to be 0.05 dB. Antenna array pattern analysis can be performed to determine that the full width, -x dB maximum beamwidth is 0.468° for x = 0.5 and 0.658° for x = 1.

The number of beams required for full coverage of the desired field of view can be estimated through allocation of beams onto a hexagonal lattice that covers the conical volume of the field of view. This calculation is accomplished by examination of the beam patterns on a reference plane orthogonal to the antenna boresight at a distance R from the array. The conical field of view traces a circle on the reference plane and we begin by defining a hexagon that circumscribes the circle as illustrated in Figure A below. Note that the ratio of circle area to hexagon area is given by $(\pi r^2)/(6 r^2/\sqrt{3}) = \pi\sqrt{3}/6$. As shown in Figure B if we place the beam positions so the array gain never drops below the designed level, the separation between adjacent spots is given by $\sqrt{3}$ R $\tan(\theta_{bw}/2)$. As shown in Figure C, the diameter of hexagonal coverage area is given by $2/\sqrt{3}$ R $\tan(\theta_{fov})$. From these derivations we find that the hexagonal lattice must consist of at least $2/3 \tan(\theta_{fov})/ \tan(\theta_{bw}/2)$ rings in the structure. The number of elements in an M ring hexagonal lattice is M (M-1) 3 +1. Scaling by the ratio of circular to hexagonal area gives a good approximation for the number of beams required to fully cover the antenna field of view. Doing this calculation for the spaceborne transmit antenna results in 1911 beams for x = 0.5 and 1035 beams for x = 1. Also illustrated in the paragraphs below is the impact of phase quantization. As indicated in the figures, 6 bit quantization results is extremely small penalty in the beam steered to the edge of scan.



8.28.1. Scan loss at 9.3° = .05 dB based on measured element pattern

8.28.2. Beamwidth(10 ring hex lattice) 0.468° for 0.5 dB crossover
0.658° for 1.0 dB crossover

8.28.3. Beams for full coverage (approximate) 1,911 for 0.5 dB crossover
1035 for 1.0 dB crossover

8.28.4. Phase steered at elements 6 bit quantization (from MBPA)

@ 9.3° scan pattern @ f_c = 20.7 GHz

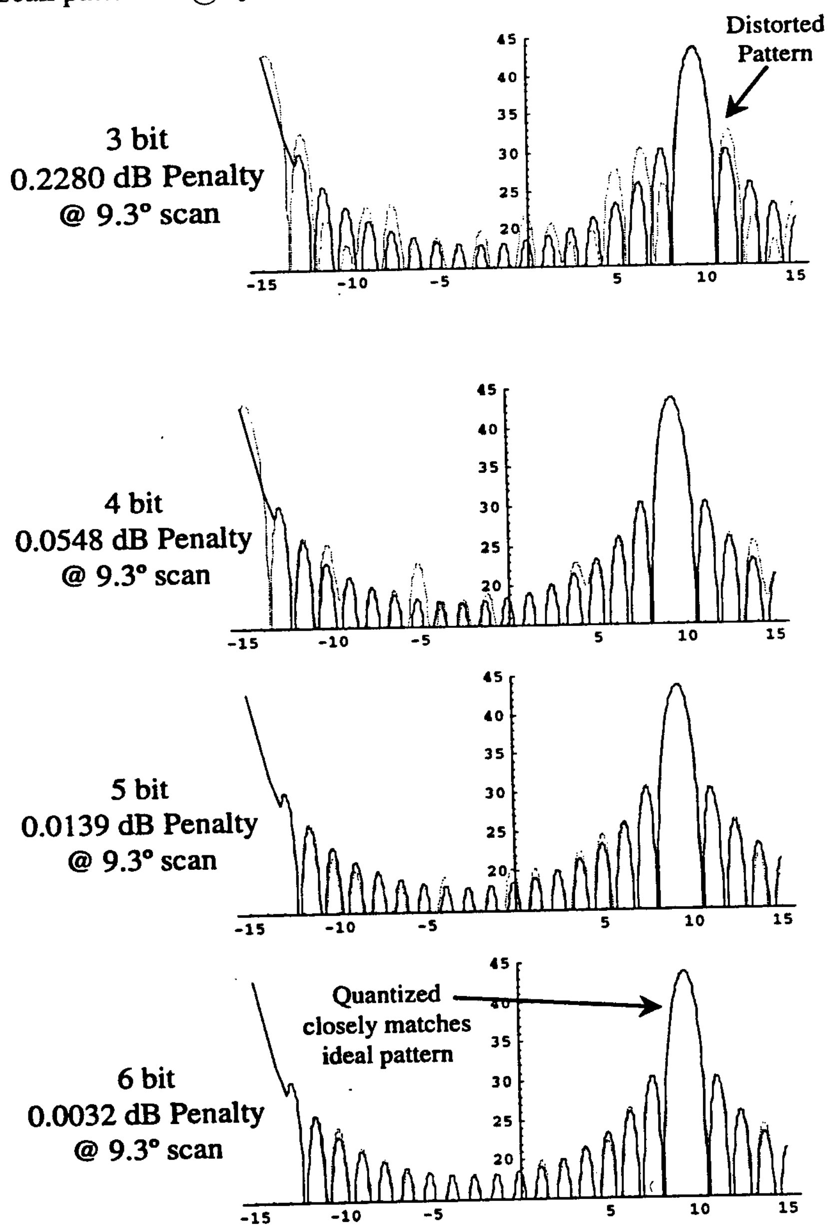


Figure 92. Spaceborne Transmit Antenna Array Configuration.

8.29. Spaceborne Transmit Candidates

Three candidate architectures were traded for the spaceborne transmit antenna: RF and photonic scanning arrays, and one direct radiating MBA with an optical Butler Matrix beamformer. The Butler Matrix MBA consists of 256 elements and a slightly higher module RF output power of 0.27 W is needed to achieve the same EIRP as the scanning arrays (module drive power is still 1 μW).

The table below provides the results of the size, weight, and power tabulation. When compared on a per element basis, the size of the three antennas are nearly equal and are primarily determined by the size of the antenna array. However, the size of the photonically implemented scanning array and MBA are significantly less than the RF scanning array. This significant differential is attributed to the weight associated with the 20.7 GHz power distribution network (PDN) required for the RF scanning array. On a DC power basis the photonic scanning array compares unfavorably to the RF scanning array or Butler Matrix MBA, but this is to be expected for photonic scanning arrays. DC power for the optical amplification and signal distribution is required in addition to the DC power required for the RF front end (common to all antenna architectures). The number of photonic beamformers required is equal to number of formed beams, so the total DC power requirement is effectively the sum of the RF power and four times the single beamformer DC power (~ 100 W/beamformer). This results in a substantially increased DC power level. The optical butler matrix utilizes optical power more effectively than the scanning array as only one beamformer is required to form any number of beams.

The significant disadvantage of the optical Butler Matrix beamformer is the complexity of the architecture. Optical coherence must be maintained in the beamformer, which is difficult to accomplish over the volume of the array. As such we did not downselect this beamformer for detailed design. However, development of techniques to maintain the necessary level of optical coherence, would make the optical Butler Matrix an extremely attractive approach for enabling large scale multiple beam capability.

In comparing the multiple beam RF and photonic scanning arrays, it should be noted that for the RF array, the maximum number of beams is limited by both the output power amplifier and packaging of the array components. With the phase shifters located on the same substrate as the SSPA, there is simply no room for additional phase shifting elements. For the photonic scanning array, the maximum number of beams is limited only by the SSPA performance as all of the beamforming is remoted from the antenna array. This makes the photonic scanning array an structure enabling future SSPA development to achieve further multiple beam capability.

Quasi-optical MBA's were not considered as they require traveling wave tube power sources and the trend for SatCom is towards power combining arrays (scanning or direct radiating). The 20 GHz transmit array is large and Rotman lenses are too heavy to be competitive with the scanning array (a photonic Rotman lens is the same size as an RF Rotman since they are both true time delay lenses).

Table 16. Spaceborne Transmit Candidates.

	Scanning Array (RF)	Scanning Array (WDM MultiBeam)	Optical Butler
Element Number	Conical Horn 271	Conical Horn 271	Conical Horn 256
EIRP @ EOS Antenna Gain Module Power EIRP @ BS	50.00 14.64 dB 0.24 W 51.27	50.00 14.64 dB 0.24 W 51.27	50.00 14.64 dB 0.24 W 51.27
Size	66,712 cm^3	61,562 cm^3	57,535 cm^3
Weight	95.494 kg	16.19 kg	16.83 kg
Power	477 W	813 W	523 W
Complexity	PDN/phase shifters dominate weight	Same complexity for any number of beams	High Complexity High Risk for Space
Comments	Beams limited by packaging & SSPA	Beams limited **only** by SSPA	Optical coherence difficult to achieve

Key challenge is providing multiple beams with reduced payload weight

Photonic Scanning Array Enables

⇒ Reduced weight (17% of RF) ⇒ Acceptable technology risk

⇒ Moderate DC power (1.7x RF) ⇒ Expanded Capability

8.30. Scanning Array (RF)

The architecture illustrated in the figure below represents a straightforward configuration for a 4 beam RF scanning transmit array. The power distribution network (PDN) represents the significant portion of the beamformer size and weight. At the transmit module, a 6 bit phase shifting element is incorporated for each of the 4 beams. The signals are combined and amplified with units developed by TRW for the MBPA program. These InP HBT based devices are considered to be attractive as their IP^3 performance allow running multiple beams through the amplifier without backing off from a saturated output power and still achieve acceptable performance. The major trade considerations concern the size, weight, and power, as well as the packaging limitations on the number of beams. As the required devices are currently under TRW development, we believe there are no additional critical technologies for development.

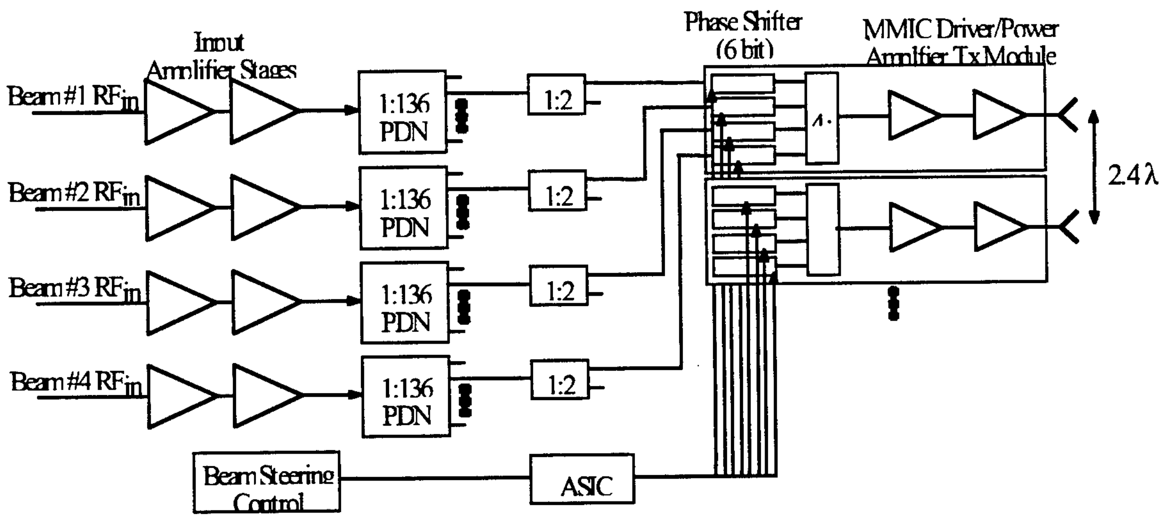


Figure 93. Scanning Array (RF).

Note: RF scanning array design is based on MBPA design incorporating standard MMIC components

8.30.1. Trade Considerations

- (-) Moderate size, weight, power
- (-) Limited Number of beams

8.30.2. Critical Technologies

Packaging

SSPA Module

8.31. Scanning Array (Photonic)

Our proposed architecture for a photonic 4 beam scanning array is presented in the figure below. An optical heterodyne source is required to upconvert the input IF signal and to enable phase weighting beam control. The modulated optical signal is distributed to the 271 elements using the MOSAIC amplified splitting device. Each individual beam is formed in a separate beamformer and the multiple beams are optically combined prior to photodetection. As each beam is formed utilizing a distinct optical wavelength, WDM multiplexing techniques can be used to facilitate the beam combining. Since the EIRP goal must be met by each beam, adequate signal power must be generated at the output for each distinct beam. Therefore, strenuous requirements are placed on the optical power handling of the photodetector and this optical power handling capability increases with increasing number of beams. The transmit module front end is the same set of devices as used for the RF scanning array.

Some trade considerations for the photonic scanning are that it incorporates RF upconversion, multiple beam operation with significantly lower weight than the RF implementation. Critical technologies are the optical heterodyne source (there are several techniques that could be applied to this architecture), the MOSAIC optical splitting device, the WDM multiplexers (in terms of cost and efficiency), and high power photodetection.

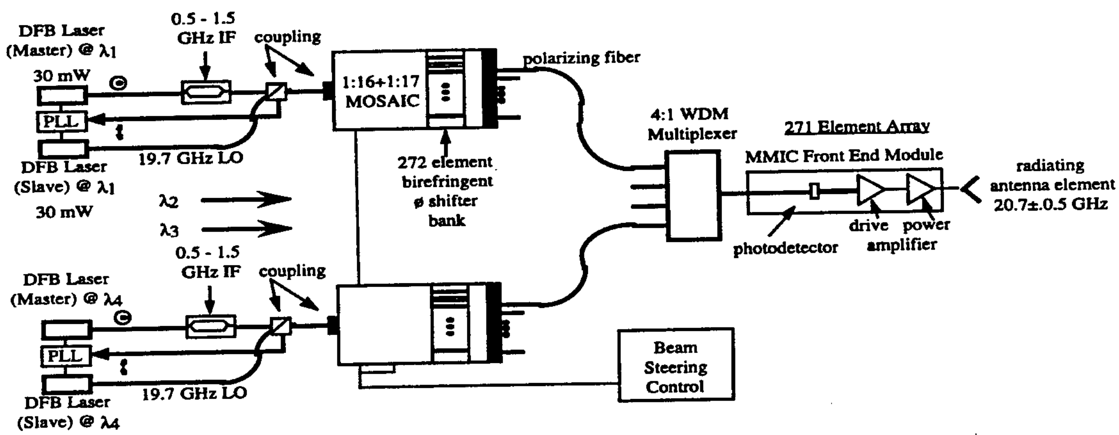


Figure 94. Canning Array (Photonic).

Note: Photonics enables substantially lower cost and potential of increased multi-beam

8.31.1. Trade Considerations

- (+) Upconversion incorporated
- (+) Multiple beam operation
- (+) Low Weight
- (-) Higher DC power required

8.31.2. Critical Technologies

Heterodyne laser source
MOSAIC
WDM Multiplexer (cost)
High Power Detector and MMIC SSPA

8.32. Optical Butler

The third candidate that was examined during the architecture trades was the optical butler matrix beamformer. This beamforming technique requires the use of coherent optical processing techniques to produce the necessary phase profile across the array necessary to form a selected beam. The input IF signal is single sideband suppressed carrier modulated onto the optical input signal. A network of optical 90° hybrid devices and path length difference phase shifts are used to generate the desired phase profile among the output signals. An optical switching structure is used to route the input modulated optical signal to the beamformer input corresponding to the desired beam direction. For a 256 element antenna array, 16 horizontal beamformer slices are cascaded with 16 vertical beamformer slices to enable θ_x and θ_y scanning of the output beam. At the outputs of the horizontal beamformer slices, an optical local oscillator offset by the RF carrier frequency is injected and the combined signals photodetected, then passed to the transmit module. The relative optical phases generated in the beamformer become relative RF phases and the formed beam steers in the desired direction.

The desirable features of this beamforming technique include the incorporation of upconversion, the potential for multiple beam operation (up to the limit of the Tx module) and low weight and DC power. If the optical hybrids must be amplified, the required DC power could be substantially higher. Although not indicated in the figure below, the beamforming can also be remoted from the array if necessary which is also a desirable feature.

One disadvantage is the inherently narrowband performance of the beamforming structure. Unlike the scanning array where the phase weights can be updated on a per hop basis, the Butler matrix beamformer provides fixed phase weights that are inherent to the beamforming structure. As such, this beamformer is rather incompatible with any type of wideband transmission configuration.

A second more significant disadvantage of this beamforming technique concerns the necessity of optical coherence throughout the beamforming structure. The output phased optical signals and the injected optical local oscillator must be frequency and phase locked for acceptable performance. This may be easier to accomplish in a remoted compartment of the spacecraft, but should still be considered an extremely high risk venture for space deployment. Critical technologies for this beamforming structure include the development of these coherent optical detection techniques, the MOSAIC device (definitely if the hybrids are required to be active), SSSC optical modulation, and the optical switching technology (such as the switched grating optical switch).

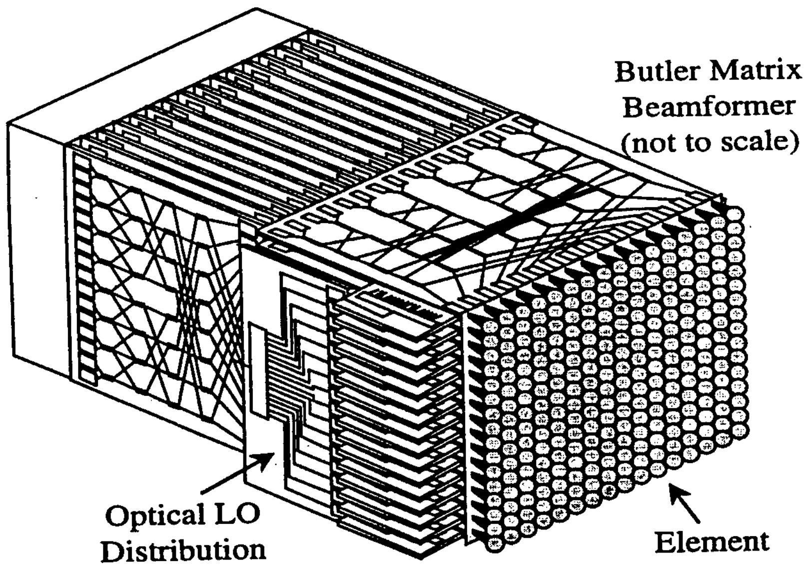


Figure 95. Optical Butler Matrix Beamformer.

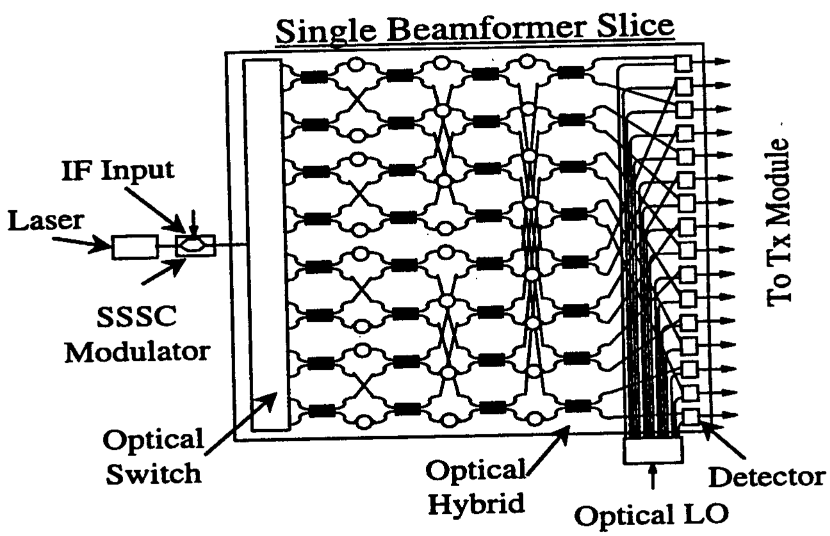


Figure 96. Optical Butler Single Beamformer Slice.

Note: Optical Butler is a powerful beamformer technique, limited by high complexity

8.32.1. Trade Considerations

- (+) Upconversion incorporated
- (+) Multiple beam operation
- (+) Low Weight/Power
- (-) Extremely High Complexity

8.32.2. Critical Technologies

- Optical Coherent Detection Techniques
- MOSAIC (Integration)
- SSSC Optical Modulation
- SG Optical Switch

8.33. Photonic Scanning Array Selected for Spaceborne Transmit

The optical source and distribution modules can be assembled on a compact structure as illustrated in the figure below. One source module slice and optical distribution – phase weighting slice is required for each beam. Additional structure is required for optical fiber routing and the WDM multiplexers. The beamforming structure is rather modular to support additional beams by adding more optical source and distribution cards and modification of the WDM multiplexer devices. The beamforming structure can be conveniently located on the spacecraft and remoted from the antenna element array if necessary.

The two element modules can be arranged together to form the radiating structure as illustrated in the figure below without the polarizer and radome. The antenna element array structure is the same design as the RF phased array with the exception that the phase shifter hardware is removed from the transmit module and the photodetector is incorporated.

Fabrication, integration and test of the spaceborne transmit array would follow the well establish design processes representative of other spaceborne EHF antenna array programs. The antenna would be designed and fabricated for the typical mean mission lifetime of seven years. The phased array architecture would enable graceful degradation at the array level. Some redundancy may be required in the beamforming system so to enable adequate reliability and performance over the lifetime of the system.

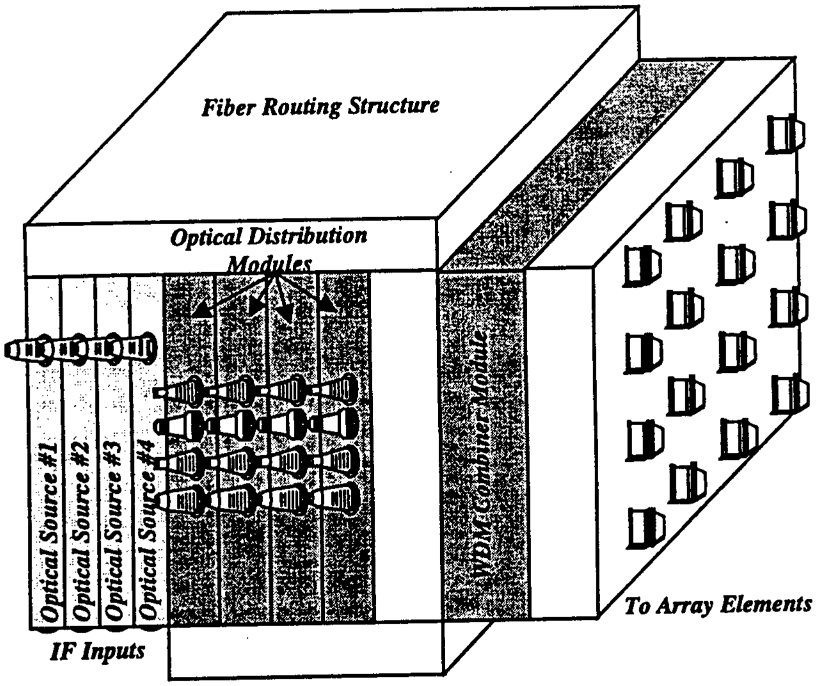


Figure 97. Selected Photonically Implemented Beamformer for Spaceborne Transmit.

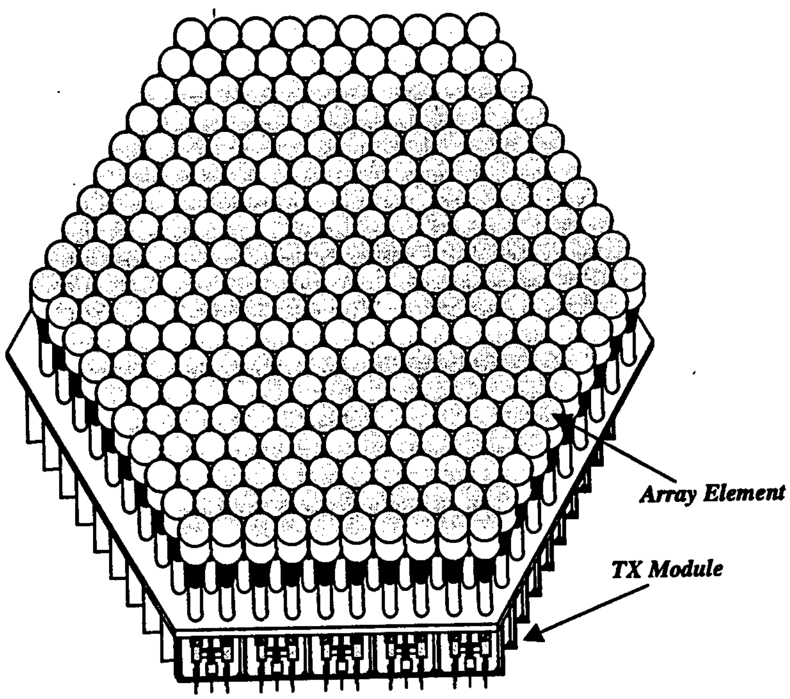


Figure 98. Selected Spaceborne Transmit Antenna Array.

8.34. Spaceborne Transmit Conclusions

For the spaceborne transmit antenna, the key challenge is in supporting multiple beams over the coverage region. These desirable features ideally should be incorporated with minimal size, weight, and power. For RF beamforming techniques, these goals impact the performance of the beamformer structure as lower losses can only be accomplished with distribution structures that demonstrate increased weight. For the RF implemented scanning array, a consequence of this is that the power distribution network comprises much of the overall weight of the architecture and reduction of this portion of the payload can lead to significant weight savings. Implementing the beamformer with photonics can result in significantly reduced weight and enable remoting of a substantial portion of the antenna architecture. Such remoting could be useful to provide higher robustness of the antenna COMM system to natural and hostile environmental effects. The power distribution network implemented in photonics results in substantial weight savings at the expense of moderately increased DC power requirements, providing an attractive alternative to RF implemented antenna structures.

A second, although significant limitation to providing multiple beam capability is the packaging limitations imposed by the tight element spacing. RF scanning arrays are limited in the number of simultaneous beams that can be implemented by the packaging of the RF phase shifting elements. We estimate that 4 beams is near the limit afforded by the RF scanning array based on these considerations alone. For the photonic scanning array and also for the optical Butler Matrix beamformer, there is the potential for many more beams essentially unlimited by packaging considerations.

This leaves final consideration to the limitations imposed by the suppression and interference non-linear effects of the output power amplifier unit. Photonics cannot mitigate the limitations associated with the amplifiers, but the implementation of a photonic beamformer greatly increased the utility of SSPA development for this application. Elimination of the packaging limitation opens the potential of further multi-beam capability from improved SSPA performance.

As described in the previous material, the optical Butler matrix maximizes the leverage available from the incorporation of photonics, but the high level of complexity and risk associated with implementing this beamformer in space has influenced us to select the photonically implemented scanning array and leverage off of the significant desirable features of this beamformer.

As a final item, the point should be made that as the photonic scanning array beamformer relies on use of a low biased modulator, the techniques developed in the DARPA sponsored program OERFM could be used to improve the modulation efficiency and assure acceptable performance of the beamforming architecture.

8.34.1. Key challenge is providing multiple beams with reduced size and weight

- For RF structure trade is between beamformer losses and architecture weight

8.34.2. Photonics BFN provides reduced weight

- Beamforming can also be remoted to provide additional environmental reliability

8.34.3. Additional challenge in providing multiple beams is Tx module non-linearities

- RF beamforming limited by both packaging and SSPA non-linearities (suppression and interference)
- Photonics cannot mitigate Tx module limitations for multiple beams, but!!

8.34.4. Photonic BFN eliminates packaging constraint for focus on SSPA development

8.34.5. As with airborne Tx antenna, large optical power levels must be delivered to elements to achieve module power required for EIRP goal

- OERFM could be used to improve modulation efficiency (for SSSC MZM)

8.35. Airborne Receive Performance Goals

The performance goals for the EHF airborne receive antenna are based on those goals presented in the ESAD contract SOW with additional derivation from sources such as the current Milstar system and Advanced EHF IR&D activity. Photonically implemented scanning arrays provide little leverage over those antennas implemented in RF when compared on the basis of current Milstar requirements. Single channel (50 MHz) capacity in a single beam eliminates the requirement of true time-delay steering and places no strict requirement on the packaging of the array. These performance goals tend to favor RF implementations because Milstar requirements were developed consistent with RF component capability.

Given these conclusions from our initial architecture study, we were compelled to develop a more challenging set of performance goals leading us to consider the consolidation of apertures utilized to establish links with multiple space based COMM assets. By extending the overall bandwidth requirement to cover 7.25 to 21.2 GHz we enable a single aperture to assess multiple assets with multiple beams each requiring relatively narrow spectral coverage. Presently these channels are assessed through at least 4 separate apertures. Consolidation of these apertures would result in slightly increased weight, but would lead to maximal conformity to the aircraft surface. A rather large fraction of the beamforming hardware would be remoted from the surface of the craft which would provide maximal structural integrity by both limiting the number of arrays and the hardware located at the array. These types of multibeam performance goals are consistent with recent USAF and USN efforts (e.g. MERS).

It is conceivable that either multi-channel Milstar COMM or other high data rate information could be downlinked to the airborne platform with the requirement and expense of higher levels of true time-delay control. Phase control is preferable if possible (for single narrowband MDR channel) due to the relatively small amount of hardware required for adequate resolution for a given scanning field of regard. For example, simultaneous coverage over 1 GHz bandwidth could be accomplished with a 24 subarray antenna structure, while coverage over 4 GHz bandwidth would require a much larger number of subarrays to achieve the same performance and levels of beam squint.

Table 17. Airborne Receive Performance Goals.

Item	Requirement	Source
Number of Beams	> or = to 4	Aggressive SOW
Beam Shape	spot	SOW
Frequency	see spectrum figure below	Aggressive SOW
Polarization	adaptable ⇒ dual cp	SOW
Coverage	70^0 cone	SOW, Milstar
G/T (@ max scan	5dB	SOW
Beam Update Rate	20kHz	Milstar, Advance EHF
Beam Settling Time	<0.9 microseconds	Milstar, Advance EHF
Sidelobe level (first)	not specified	
Spot beamwidth	not specified	
Additional Requirements	Target Search Capability. Flat, thin, compatible with C-17, E-3, UAV, Fighter	SOW

8.35.1. Performance
SOW goals consistent with Milstar and Advanced EHF

8.35.1.1. Multiple Beam Downlink
Full coverage of COMM assets with single consolidated aperture

8.35.1.2. Multichannel or Wideband Operation
Aggressive performance goal relative to current Milstar
Necessitates Subarray TTD

8.35.1.3. Applications
Simultaneous COMM channels from single or multiple COMM assets
HDR COMM

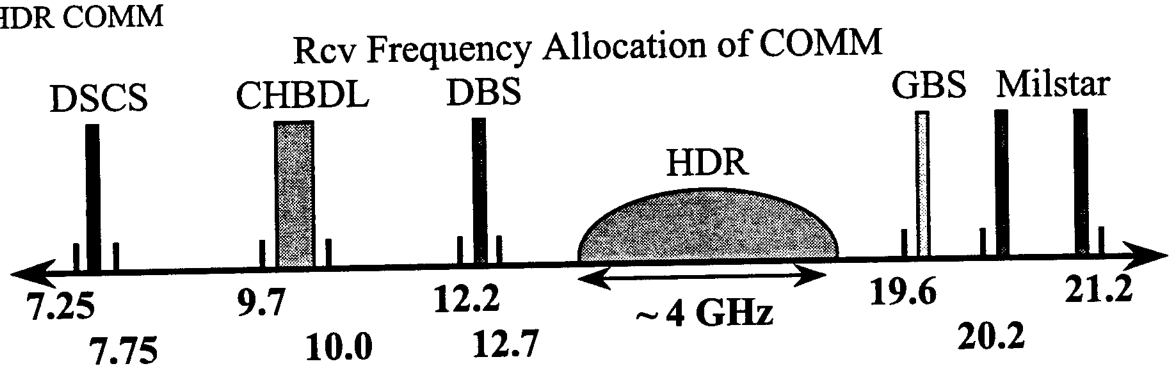


Figure 99. Airborne Receive Performance Goals.

8.36. Receive Antenna G/T and LNA Front End Design

The driving design requirement for the airborne receive antennas is a G/T = 5 dB/K at 70° scan angle. A common wideband crossed notch element and wideband InP LNA module are assumed for all architectures with both RF and photonic beamforming. Each candidate architecture is designed to meet this performance requirement before comparisons such as size, weight and power are made. By assuming a common antenna element and RF pre-amplifier for both the RF and photonic *scanning arrays*, we employ a fair comparison of RF and photonics (i.e. we don't assume different pre-amp gain or noise figure which would skew the comparison). Antenna gain values were determined with a combination of measured pattern data and loss estimates based on existing hardware (e.g. polarizer and radome loss). Other considerations such as end of life degradation (assumed to be 95%) and pointing loss were factored into the G/T budget calculation. The pre-amplifier performance is based on projected estimates of the performance of wideband InP pre-amplifiers currently under development at TRW.

MBA's will generally use different antennas than the scanning arrays. Although we have examined a hybrid MBA scanning array in the architecture trade, we do not provide a direct performance comparison with the RF scanning array. However, the hybrid architecture would enable wideband beamforming and would require use of the wideband preamplifier. As such the preamplifier considered is that used for the wide aggregate bandwidth scanning arrays considered. For the MBA module antenna pattern, analysis is provided in the trade that describes the relative performance to sufficient precision so as to judge which architecture is most feasible and useful for the desired application. The preamplifier gain and noise figure is assumed the same for all cases examined.

Provided in the figure below is the antenna array layout and representative radiation pattern for the scanning arrays. We have determined that an approximately square array of elements situated on a hexagonal lattice will provide adequate array gain margin from the design goal and enable appropriate partitioning of the array for true time-delay control and optical power distribution (for the photonic scanning arrays). Note that although the dimension of the array is 54x60 elements, the physical dimensions for an element separation of (s meters) is given by 54s x 52s m^2 which is very nearly square.

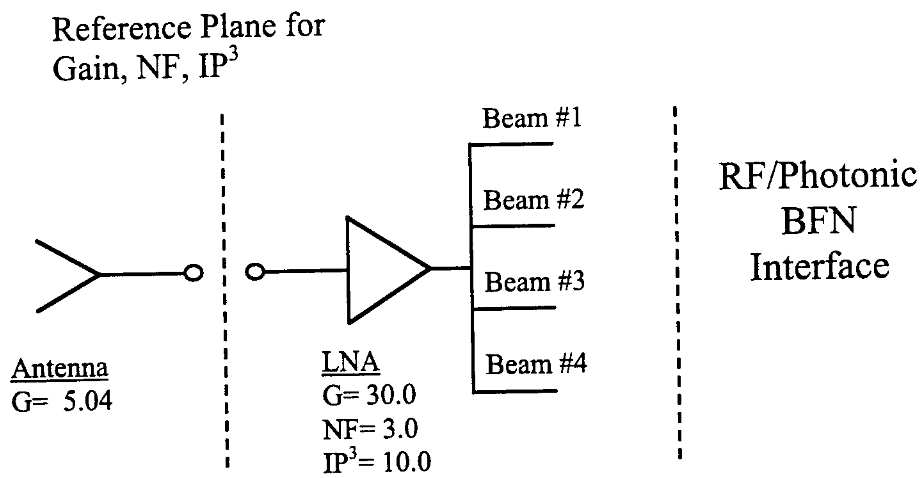


Figure 100. LNA Front End Design.

8.36.1. Scanning Antennas designed for 5 dB G/T at 70°scan => Requires 2992 wideband RF elements

- Link budgets for traded designs are provided in Supporting Analysis Package

8.36.1.1. Crossed Notch Elements - Provides single CP channels

8.36.1.2. Hexagonal lattice - 0.5 λ spacing

8.36.1.3. Wideband InP LNA (3.0 dB NF) - Consistent with TRW Projections

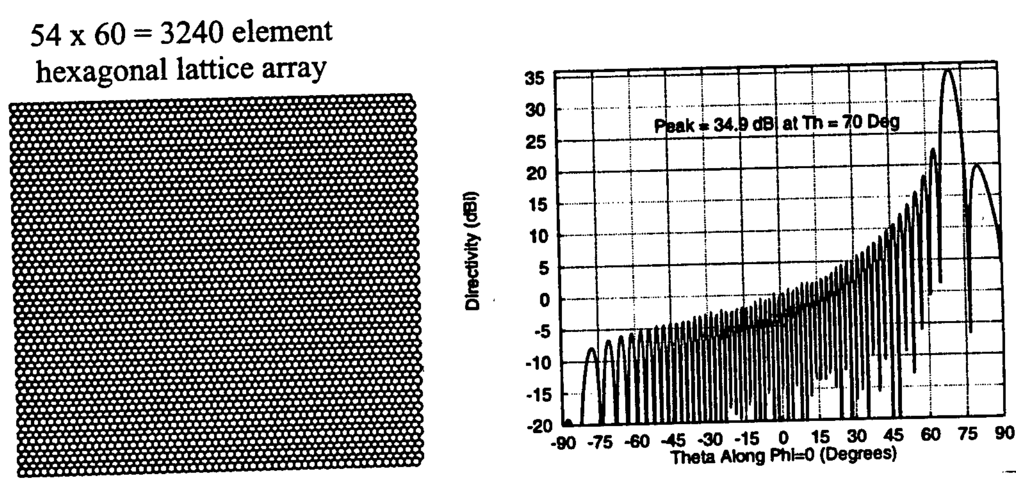


Figure 101. Receive Antenna G/T.

Note: Antenna element and gain calculation based on measured data and software analysis..

8.37. Airborne Receive Antenna Array Configuration

For the airborne receive antenna design and configuration, we employ phase steering at the antenna element level. Four bits of phase quantization provide a sufficiently stable beam as indicated in the figure below. The figure indicates that although grating lobes are slightly increased they are still at lower levels than the first sidelobes (uniform amplitude weighting is assumed). An additional bit of phase resolution is easily accomplished with photonics and will result in an antenna pattern nearly identical to that formed with infinite phase resolution. The figure shows the antenna pattern for 70° scan angle at an RF frequency of 20.7 GHz. For the crossed notch wideband elements, we estimate an element scan loss of 7 dB at 70° scan angle. The formed beamwidth is estimated to be 1.633°x1.674° at the 0.5 dB position and 2.571°x2.646° at the 1 dB position. If full coverage of the 70° conical field of view is assumed, then approximately 44,926 beams are required for 0.5 dB crossovers and 18,072 beams are required for 1 dB crossovers. This is assuming that infinite phase and time delay quantization are available so that every individual beam location can be accessed.

For multi-channel or wideband coverage, true time delay will be required minimally at the subarray level. The level to which the array must be partitioned can be determined by defining and acceptable level of beam squint penalty allowable for a given frequency span. We use 20.2 to 20.7 GHz as the required coverage frequency and note that the squint penalty is symmetric around the array design frequency (here chosen to be the center of the band i.e. 20.7 GHz). We find that if the array is subdivided into 6x4 = 24 subarrays each consisting of 9x15 = 135 elements it is possible to realize a maximal squint penalty of 0.31 dB along the direction parallel to the vertical dimension of the array. This penalty is within the designed G/T margin of the array.

A final issue is time quantization of the true-time delay beam steering. Unlike phase quantization, where the range of phases is always limited to 0°-360°, time quantization is based on a range depending on the array aperture size. The maximum time delay is dependent on the array size and level of subdivision. The impact of quantization also depends on whether or not the time delays are generated in a separable or unseparable manner. Separable time delay generation is utilizing two cascaded time elements, one for the horizontal scanning followed by one for the vertically scanning. Unseparable time delay is where each single time delay is used to steer the beam to a single position in the field of view. As some time delay elements are more easily configured in a separable configuration and some are more easily configured in an unseparable configuration, this issue is critical in implementing time delay control of the array. We use the number of bits of time resolution to describe the beam positions from boresight to the edge of scan so that with a separable time delay configuration, 4 bits means there are $(16x2)^2 = 1024$ possible individual beam positions. As described in the figure below, at least 6 bits of time resolution are required to adequately form the beam with low sidelobes. The number of individual time states for this level of quantization are significant and represent a substantial challenge in the implementation of this antenna architecture.

8.37.1. Phase steered at elements
4 bit quantization (see figure below)

@ 70° scan pattern

Quantized closely matches ideal pattern

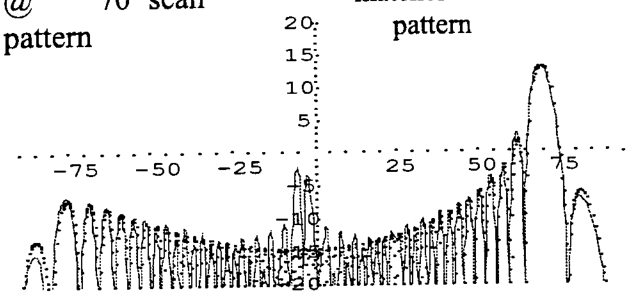


Figure 102. Four Bit Quantization.

8.37.2. Scan loss at 70° = 7 dB from measured element pattern

8.37.3. Vertical (Horizontal) Beamwidth
1.633° (1.674°) for 0.5 dB crossover
2.571° (2.646°) for 1.0 dB crossover

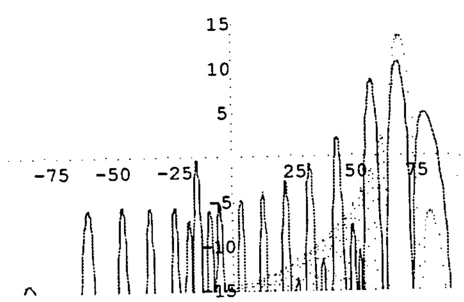
8.37.4. Beams for full coverage (approximate)
44,926 for 0.5 dB crossover
18,072 for 1.0 dB crossover

8.37.5. Time delay steered at subarray Squint loss at 70° (dB)

	Horizontal	(# subarrays)		Vertical	(# subarrays)
	6.24 dB	(1)		5.70 dB	(1)
⇒	0.15 dB	(6)	⇒	0.31 dB	(4)
	0.06 dB	(9)		0.20 dB	(5)

Separable (H) configuration
$\tau_{max} = 1.021$ ns
5 bits _ (3.37 dB penalty)
6 bits _ (0.83 dB penalty)

Separable (V) configuration
$\tau_{max} = 0.884$ ns
5 bits _ (5.58 dB penalty) 4096 states
6 bits _ (1.32 dB penalty)
16,384 states



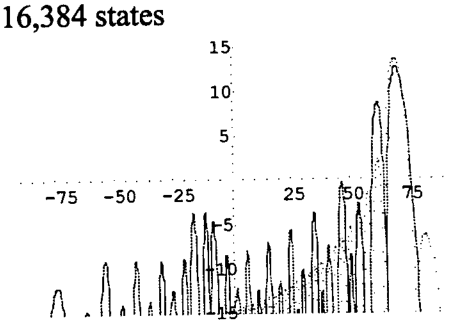


Figure 103. Time Delay Quantization (H) and (V) Configurations.

8.38. Airborne Receive Candidates

Three candidate architectures were traded for the airborne receive antenna: RF and photonic scanning arrays, and a hybrid scanning array of MBA elements. The lens MBA provides a controllable element pattern which can be selected to maximize element gain in the scan direction. This approach mitigates scan loss at the edge of scan (because the element pattern can be pointed to that location) and as such represents an approach worthy of consideration. As the number of required elements for adequate G/T performance is large, the required aperture size of the antenna is relatively large. In addition, the antenna must have a depth consistent with airborne platforms, and the cover a wide scanning field or regard. These factors preclude quasi-optical MBA systems and confine our baseline architecture trades to scanning arrays. Since a relatively large number of direct radiating elements are required, circuit MBA's are not feasible as well and are excluded from the trade analysis. Since the receive frequency is near 20 GHz, RF and photonic Rotman lenses will be too large and are impractical for this application as well. As demonstrated elsewhere, Butler matrices exhibit high complexity and will not meet even moderately wide bandwidth requirements.

The RF scanning array was used as a baseline of comparison. To access the several desired SatCom assets, several individual antennas are required. The S/W/P estimates are given for 4 antennas while the S/W/P estimates for the photonic scanning array is for a single 4-beam antenna. As the hardware and power associated with TTD is only a small fraction of the total structure, there is little difference in the S/W/P of time delay based and all-phase steering based photonic architectures. The data presented for the candidate hybrid scanning antenna consisting of lens MBA "elements" is for an antenna that forms a single beam. A relatively small amount of hardware could be added to enable multiple beam operation, but with significantly increased complexity.

As seen from the data presented for our S/W/P estimates, the multi-beam photonic scanning array provides for aperture consolidation that results in significantly less size than for the 4 RF receive antennas. This size reduction is provided with moderately less power than the multiple RF antennas, but at a cost of increased beamformer weight. It should be noted however, that photonics enables remoting of a majority of the beamforming hardware and for the photonic scanning array, only 30 kg of weight is located at the front end. The expectation is that by consolidating the apertures and utilizing a single wideband aperture, it is possible to significantly reduce the cost of the resources required to fully utilize multiple military COMM systems.

Table 18. Airborne Receive Candidates.

	Scanning Array (RF)	Scanning Array (Photonic)	MBA Array Hybrid
Element Number	(4-aperture) 3240	4 beam single aperture 3240	1 beam single aperture 1024 (4x4 module)
G/T @ EOS Antenna Gain System NF System Gain System IP3 G/T @ BS	5.35 -1.94 dB 2.01 dB 90.1 dB 24.6 dBm 12.34	5.35 -1.94 dB 2.7 dB 93.8 dB 24.6 dBm 12.34	5.00 1.04 dB 2.71 dB 11.99
Size	91,604 cm^2	16,456 cm^2	29,353 cm^2
Weight	139 kg	259 kg (30 kg at front end)	66 kg
Power	6496 W	5906 W	655 W
Complexity	MMIC Stripline	Optical Stripline	Large number of wavelengths
Comments	Multi-aperture required for coverage	Subarray TTD	TTD control for multi-beam

Note: Key challenge is enabling multi-beam for aperture consolidation

8.38.1. Photonic Scanning Array Enables

⇒ Remoted electronics (structure) ⇒ Consolidated Apertures

⇒ Reduced component count ⇒ REDUCED COST

8.39. Scanning Array (RF)

The architecture for the RF scanning array presented in the chart below represents a straightforward configuration for a 4 beam phased array antenna. Although not included in the design, additional amplification may be required to compensate for the insertion loss and splitting loss of the 1:4 splitters at the front end used to enable the formation of the multiple beams. The significant portion of the beamforming hardware consists of the power combining networks used to form the beams. The combining is accomplished at the RF frequency rather than at the IF frequency. As RF combiners whether waveguide or stripline are designed based on the signal wavelength, combining at 20 GHz frequency can be accomplished with smaller devices that comprise significantly less weight. With RF combining it is necessary to retain short transmission lengths if possible and consequently, nearly none of the beamforming hardware may be remoted from the antenna array. As the technologies required for implementation of the RF scanning array are standard for this application, there are no identifiable technologies that would be critical to the implementation of this architecture or would require significant development.

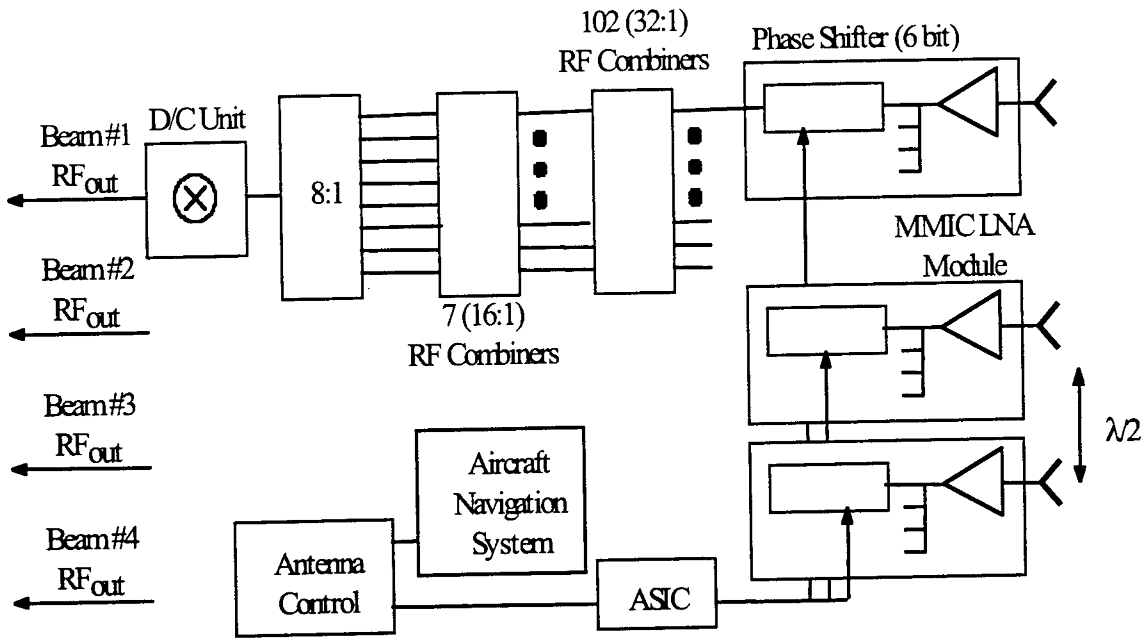


Figure 104. Scanning Array (RF).

Note: RF scanning array design is based on design incorporating standard 20 GHz MMIC components

8.39.1. Trade Considerations

(+) Moderate size, weight, power
(-) No hardware remoting
(-) Narrowband operation

8.39.2. Critical Technologies

Packaging conformality

8.40. Scanning Array (Photonic)

The architecture for the photonically implemented scanning array is presented in the figure below. The front end element, LNA, and 4-way RF splitter is the same circuit as that used with the RF scanning array design. As the signals are phase weighted and transported to the subarray combining structure with fiber optics, the only other component required to be located at the antenna array is the optical modulator. Electroabsorption modulators are a useful device for this purpose as they are very small and could be incorporated into a MMIC front end with the LNA and splitter. Semiconductor MZ modulators could also be used if the linearity performance goal was difficult to achieve. The optical signals are distributed in a heterodyne configuration using some passive, but mainly active splitting. The phase weights are also established on the optical heterodyne signals to facilitate beamforming at the subarray level. We employ IF power combining and true time-delay steering of the subarrays as illustrated in the block diagram. As the true time delay beamforming is done at the IF frequency, some consideration must be made to implement the correct delays so as to minimize the impact of squint that can result from IF beamforming. Given the aperture consolidation that results from the multi-beam capability, we find the weight and power estimates to be competitive with the RF implementation. The use of optical fiber for hardware remoting and the incorporation of signal downconversion are also attractive features. The critical technologies identified for the successful implementation of this architecture include the optical heterodyne source, the MOSAIC optical splitting device and the DBR based tunable semiconductor laser employed in the true time-delay implementation.

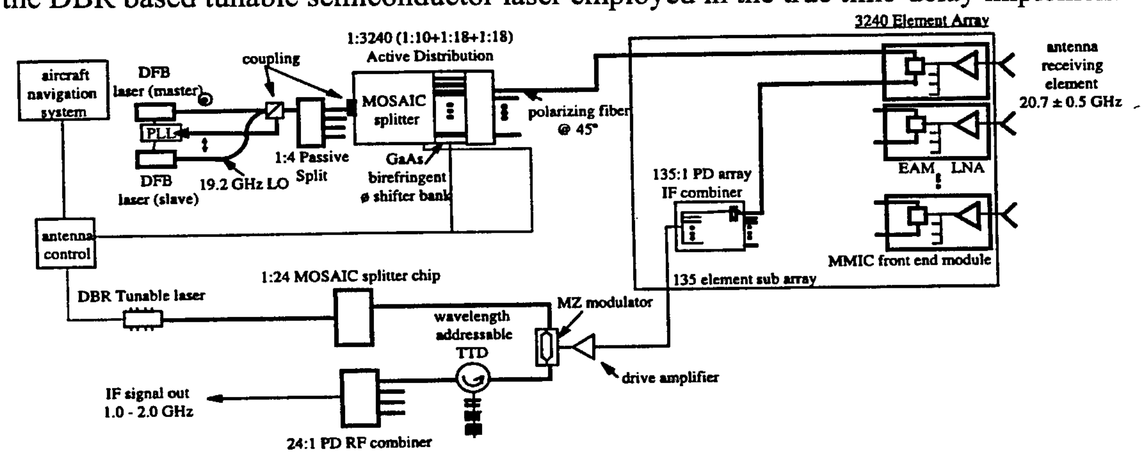


Figure 105. Scanning Array (Photonic)

Note: Multibeam capability incorporation leads to aperture consolidation

8.40.1. Trade Considerations

- (+) Downcovnersion incorporated
- (+) Multiple beam operation
- (+) Moderate Weight (≈ 2x RF)
- (+) Lower DC power required

8.40.2. Critical Technologies

Heterodyne laser source	DBR Tunable Laser
MOSAIC	

8.41. Hybrid MBA/Scanning Array

For the airborne receive antenna, we have also developed the beamforming architecture for a hybrid scanning array consisting of MBA elements. The idea is to utilize the MBA structures to provide several selectable wide coverage patterns and then array them to provide a narrow scannable beam. The MBA elements could comprise either a constant dielectric layered lens or a butler matrix module. Selection of the feed port is equivalent to selecting an antenna element pattern steered to a given region in the field of view. If a single feed is selected from each MBA module and these selected signals appropriately delayed and combined, a narrow beam is formed in the desired scanned direction. Selection of the feed port and photonic combination of the received RF signals is accomplished with multiple optical wavelengths.

As illustrated in the figure below, a tunable laser device and optical WDM demultiplexer is associated with each MBA module. Tuning the laser wavelength routes the optical signal to a modulator located at the desired feed element. The WDM demultiplexers are configured so that when the same feed element is accessed on each module, each laser has tuned to a single wavelength distinct from the lasers associated with the other MBA modules. In configuring the architecture in this manner, all of the signals from the same feed port on different modules can be optically combined. The combined signals from each feed element are then photodetected and summed with an RF power combiner to form a single electronically steerable beam. Proper assignment of wavelengths to feed element ports as illustrated in the figure enables the time delay and signal combining functions to be accomplished together. As seen in the figure, some of the signal combining is accomplished with optics and some is accomplished in RF.

True time delay steering is accomplished with either a single wavelength time delay element (such as a switched grating device) or with a multiple wavelength TTD element (such as FBG device). Multiple wavelength TTD steering will increase the complexity of the WDM demultiplexers and the modulators. Multiple-beam operation is challenging to implement with this architecture, but could be accomplished with increased beamforming complexity. Although not illustrated in the figure, signal downconversion can be accomplished with the complex weighting technique. Critical technologies associated with this beamformer are the DBR tunable lasers, the Mux/DeMux devices, and the TTD technology.

In assessing this beamforming architecture, it must be noted that although the wideband operation is attractive for some applications, it is considered excessive for typically conceived Milstar applications. Additionally, as will be shown in the next figure, it is difficult to obtain acceptable coverage with this antenna architecture. The MBA elements enable wide scanning of the array, but at the expense of rather nonuniform coverage over the field of regard. These principal factors are what move us away from selection of this architecture for detailed design.

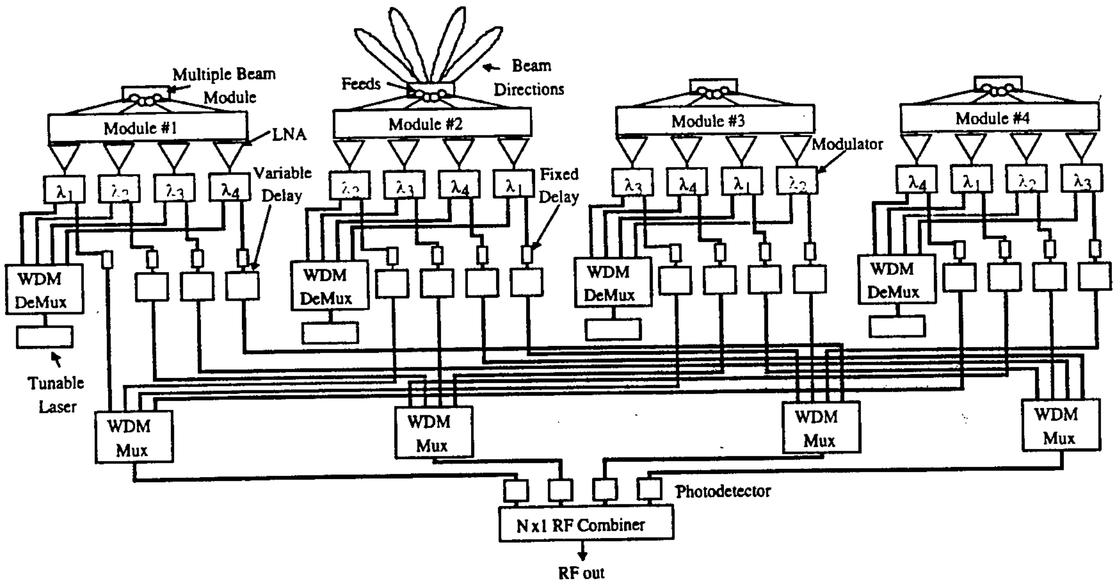


Figure 106. Hybrid MBA/Scanning Array.

Note: Hybrid architecture provides a useful structure for wideband applications.

8.41.1. Trade Considerations

(+) Wideband operation

(-) High complexity with TTD

8.41.2. Critical Technologies

DBR Tunable Laser

WDM Mux/DeMux

TTD technology

8.42. Hybrid Array Patterns Show High Crossover Losses

The key performance challenge with implementation of the hybrid MBA/scanning array is the nonuniformity of the array pattern. At the crossovers between the multiple beam positions there can be deep gain transitions. The variation in the array gain can be as much as 7 dB depending on the desired scan angle. The figure below illustrates this point by showing the array pattern for a hybrid array incorporating an 8x8 array of 4x4 butler matrix MBA elements. The array gain varies significantly with scan angle and would require prohibitively many modules to provide enough gain margin for acceptable performance. The array pattern crossover depth is a function of the MBA element crossover depth and cannot be modified with array geometry (since the butler matrix inherently provides 3 dB crossovers). Using the constant dielectric lens element may provide additional design flexibility to mitigate the impact of the nonuniform array pattern.

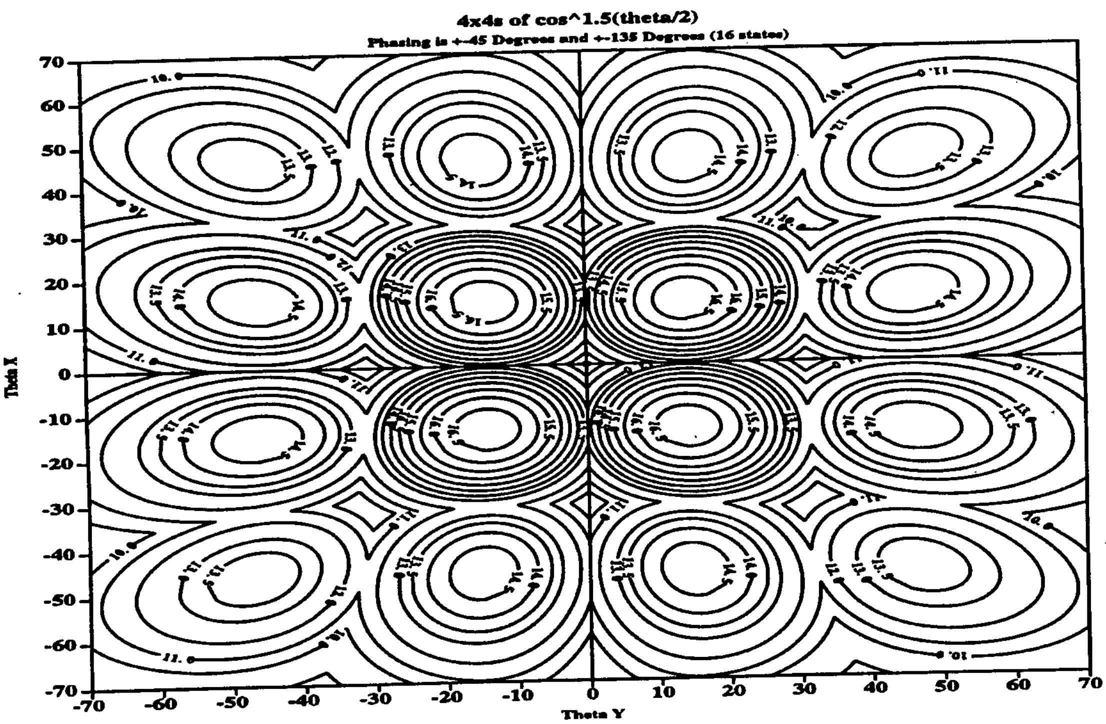


Figure 107. Hybrid Array Patterns Show High Crossover Losses.

Note: Crossover losses can be eliminated by combining adjacent module beams
⇒ Increased complexity in photonic beamformer design

8.43. Photonic Scanning Array Selected for Airborne Receive

Our design selection is a photonically implemented phased array antenna that facilitates coverage from 7 - 20 GHz. The design relies on the use of wideband phased array crossed-notch elements. The wideband cross-notch element array is illustrated below. These elements support dual polarization operation and typically are individually machined and assembled. As there are two feed points for each element (one for each orthogonal polarization), some additional electronics at the front end are required to support arbitrary circular sense polarization. The two feed outputs from the element, are input to a printed circuit 90° hybrid and an RF switch between the two outputs enables the collection of LH or RH sense circularly polarized signals. The additional electronics would add complexity to the receive module, but the cost penalty is expected to be less than implementing multiple beamformers for each frequency band. TRW has demonstrated satisfactory operation over approximately a 20 GHz bandwidth with these devices, which will support the airborne multi-frequency antenna array application.

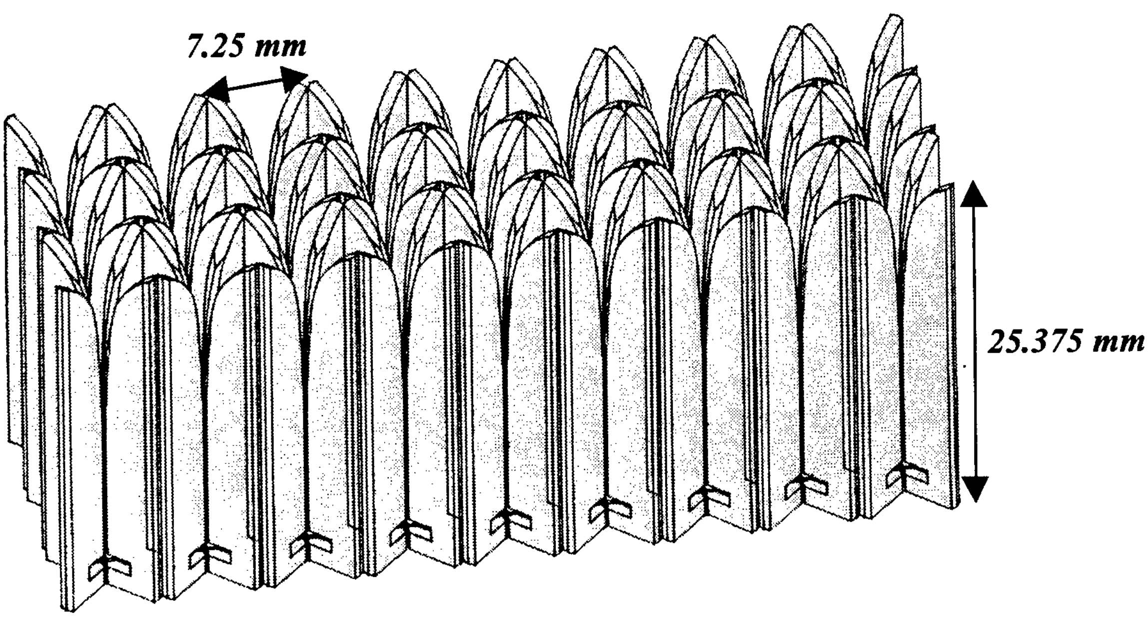


Figure 108. Photonic Scanning Array Selected for Airborne Receive.

8.44. Airborne Receive Conclusions

During our development of alternate beamforming architectures for the airborne receive antenna, it has become clear that performance and cost requirements of the current Milstar system favor the implementation of RF based beamforming for a scanning array. Photonics provides little leverage when there is no requirement of true time delay steering or no requirement for multiple beam operation. It is also difficult to incorporate the favorable features of quasi-optical and other types of MBA antennas for multiple beam applications as the requirement of conformality to the aircraft surface precludes their utility.

However, if we examine photonically implemented scanning arrays for use in enabling multi-beam operation for aperture consolidation and multi-channel operation in the MilSatCom downlink band, we find that photonic beamforming provides the desirable features of significant reduction of the total antenna size, moderate reduction of the DC power requirement, and significant remoting of the antenna hardware from the surface of the aircraft. Such aperture consolidation can have significant impact on reducing the invasiveness of the apertures to the aircraft and on reducing the cost of incorporating these systems into modern fighter aircraft. Photonics can provide these benefits while retaining the current level of COMM resource availability utilized by today's warfighter.

8.44.1. Requirements preclude use of quasi-optical MBAs for airborne receive antenna

8.44.2. Single beam requirement favors RF scanning array with no TTD (i.e. band hopping)

8.44.3. Photonics BFN for multi-beam enables aperture consolidation

- Frequency coverage of all desired space based COMM assets
- Significantly reduced antenna size
- Moderately reduced DC power
- Increased total antenna weight, but almost **90%** is remoted from front end
- Reduced number of antenna elements leads to REDUCED COST
- Aperture consolidation enables conformal configuration

8.44.4. Photonic BFN enables multi-channel for Milstar COMM (FBG TTD)

- Ultra wideband provides little leverage

Appendix 1
Size, Weight, Power Tabulation

Spaceborne Receive Antenna Candidates

RF Fed Spaceborne Receive Direct Radiating Phased Array

Component	Size	Weight	Power	Quantity	Manufacturer
TOTAL 512 element array	54,537 cm^3	34.02 kg	243 W	1	TRW IR&D
TOTAL 547 element array	72,831 cm^3	45.43 kg	325 W	1	10-beam, Scaled of above

Photonic Fed Spaceborne Receive Phased Array

Component	Size	Weight	Power	Quantity	Manufacturer
DFB Laser @ 30mW	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	20	ORTEL 30 mW High Power DFB Laser
Polarization Beam Splitter	22.2 x 44.5 x 66.8 (65,992 mm^3)	150 g	0 W	10	OZ optics packaged device
Phase Locked Loop Assembly	38.862 x 16.764 x 10.668 (6,951 mm^3)	36.9 g	0.120 W	10	For the Photodetector, there is also the electronics
1:550 Active Splitter - ϕ Shift Chip (0.5 g/mm^3 Density)	137.5 x 11.951 x 4 (6,574 mm^3)	3,287 g	181.5 W	10	MOSAIC Splitter Device (1:5+5(1:10)+50(1:11))
Antenna Element	34.52 x 15.24 d (6,297 mm^3)	0.355 g	0 W	550	TRW IR&D
LNA/10-beam split/Booster	15.24 x 13.2 x 83 (16,697 mm^3)	10.41 g	0.5941 W	550	TRW IR&D estimate
EAM	0.4 mm length added to LNA	2 g	0.012 W	5500	Estimated for TRW device
2:1 WDM Combiner/Splitter	105 x 4 (d) x 1 units (1,320 mm^3)	3 g	0 W	2750	1 MZ FBG MUX (Innovative Fibers)
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	2750	Estimate for Traveling Wave Photodetector
36:1 RF Power Combiner	114.3 x 57.2 x 1.6 (10,461 mm^3)	18.35 g	0 W	80	TRW IR&D
4:1 RF Combiner	12.7 x 6.35 x 1.6 (129 mm^3)	.453 g	0 W	20	TRW IR&D
IF splitter	0 mm^3	0 g	0 W	20	Use 0 as estimate
Booster Amplifier	0 mm^3	0 g	0.0147 W	80	Booster for adequate NF
Electronically Tunable DBR Laser	58.9 x 8.7 x 12.7 (6,508 mm^3)	30 g	1.66 W	10	NEL KELD1575BTF 2 mW (1550nm) SSG-DBR laser
1:4 Passive Splitter Chip	55 x 10 x 6 (3,300 mm^3)	10 g	0 W	10	PIRI Tree Coupler
4.5 GHz MZ Modulator (Quadrature Biased)	140 x 22.9 x 10.2 (32,702 mm^3)	50 g	0.058 W	20	UTP APE Microwave Analog Intensity Modulator, 1550nm
11.0 GHz MZ Modulator (Quadrature Biased)	140 x 22.9 x 10.2 (32,702 mm^3)	50 g	0.058 W	20	UTP APE Microwave Analog Intensity Modulator, 1550nm
TTD (primarily circulator)	57.5 x 25 x 11 (15,813 mm^3)	42 g	0W	40	Kaifa Fiberoptic circulator

Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	40	Estimate for Traveling Wave Photodetector
4:1 RF Combiner	12.7 x 6.35 x 1.6 (129 mm^3)	.453 g	0 W	10	TRW IR&D
TOTAL	20,194 cm^3	66.59 kg	2,245 W		

Photonic Fed Spaceborne Receive MBA

Component	Size	Weight	Power	Qty.	Manufacturer
Reflector Hardware		9702 g		1	
Antenna Element	34.52 x 15.24 d (6,297 mm^3)	0.355 g	0 W	331	TRW IR&D
LNA	15.24 d x 8.3 (1,514 mm^3)	0.944 g	0.0245 W	331	TRW IR&D estimate
EAM/ or SMZM	0.4 mm length added to LNA	2 g	0.012 W	331	Estimated for TRW device
Routing Hardware	(24,264,240 mm^3)	28938 g	42 W	1	estimate
DFB Laser @ 30mW	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	90	30 mW High Power DFB Laser
3:1 WDM Combiner/Splitter	105 x 4 (d) x 1 units (1,320 mm^3)	3 g	0 W	30	1 MZ FBG MUX (Innovative Fibers)
EAM and RF LO for D/C	~ 0	6 g	0.5 W	30	Estimated for TRW device
SG S	100 x 50 x 50 (250,000 mm^3)	600 g	1 W	29	Estimated
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	210	Estimate for Traveling Wave Photodetector
21:1 RF Power Combiner	57.2 x 28.6 x 1.6 (2,617 mm^3)	4.6 g	0 W	10	TRW IR&D Estimate
TOTAL	(35,250 cm^3)	59.541 kg	145 W		

Airborne Transmit Antenna Candidates

RF Fed Airborne Transmit Direct Radiating Phased Array

Component	Size	Weight	Power	Qty.	Manufacturer
Input RF Amplifier	included	included	2 W	1	TRW IR&D
Power Divider Network	79.4 x 79.4 x 10.72 (67,583 mm^3)	43.24 g	0 W	1	TRW IR&D
Decoder/1:4 Divider	3.97 x 3.97 x 4.8 (75.6 mm^3)	.048 g	0 W	100	TRW IR&D
Variable Phase	3.97 x 3.97 x 11 (173 mm^3)	.111 g	0 W	400	TRW IR&D
Drive and Power Amplifier	3.97 x 3.97 x 9.2 (145 mm^3)	.093 g	1.6	400	TRW IR&D, 30% eff. 0.48W
Antenna Elements	3.97 x 3.97 x 7.62 (121 mm^3)	.077 g	0 W	400	TRW IR&D
Polarizer and Radome	79.4 x 79.4 x 11 (69,305 mm^3)	44.34 g	0 W	1	TRW IR&D
Mounting Harness	4 x 15,803 mm^3 (63,211 mm^3)	40.44 g	0 W	1	TRW IR&D
Thermal Hardware	646,998 mm^3	414 g	0 W	1	Estimated
TOTAL 400 element array	1,023 cm^3	0.659 kg	642 W		

Photonic Fed Airborne Transmit Direct Radiating Phased Array

Component	Size	Weight	Power	Quantity	Manufacturer
DFB Laser @ 30mW	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	3	ORTEL 30 mW High Power DFB Laser
2.5-4.5 GHz IF Mach Zender Modulator (Low-Biased)	140 x 22.9 x 10.2 (32,701 mm^3)	50 g	0 W	1	UTP APE Microwave 8 GHz Analog Intensity Modulator, 1550nm
Polarization Beam Splitter	22.2 x 44.5 x 66.8 (65,992 mm^3)	150 g	0 W	4	OZ optics packaged device
Optical Circulator	57.5 x 25 x 11 (15,813 mm^3)	42 g	0 W	2	Kaifa Fiberoptic circulator
SGTTD	100 x 50 x 50 (250,000 mm^3)	600 g	1 W	1	Estimated
Integrated Splitter/Biref. ϕ chip (1:100)	6.568 x 25 x 4 (656.8 mm^3)	328.4 g	31.5 W	4	Estimate for MOSAIC Type device (1:5+5(1:20))
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	400	Estimate for Traveling Wave Photodetector
Drive and Power Amplifier	3.97 x 3.97 x 9.2 (145 mm^3)	.093 g	1.6	400	TRW IR&D 30% eff. 0.48W
Antenna Elements	3.97 x 3.97 x 7.62 (121 mm^3)	.077 g	0 W	400	TRW IR&D
Polarizer and Radome	79.4 x 79.4 x 11 (69,305 mm^3)	44.34 g	0 W	1	TRW IR&D
Mounting Harness	4 x 15,803 mm^3 (63,211 mm^3)	40.44 g	0 W	1	TRW IR&D
Thermal Hardware for Heat	646,998 mm^3	414 g	0 W	1	TRW IR&D
TOTAL	1,504 cm^3	3.310 kg	769 W		

Hybrid Photonic/RF Airborne Transmit Direct Radiating Phased Array

Component	Size	Weight	Power	Qty.	Manufacturer
DBR Laser @ 30mW	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	2	ORTEL 30 mW High Power DFB Laser

2.5-4.5 GHz IF Mach Zender Modulator (Low-Biased)	140 x 22.9 x 10.2 (32,701 mm^3)	50 g	0 W	1	UTP APE Microwave 8 GHz Analog Intensity Modulator, 1550nm
Phase Locked Loop Assembly	38.862 x 16.764 x 10.668 (6,951 mm^3)	36.9 g	0.120 W	1	For the Photodetector, there is also the electronics
Polarization Beam Splitter	22.2 x 44.5 x 66.8 (65,992 mm^3)	150 g	0 W	1	OZ optics packaged device
Integrated Splitter/Biref. φ chip (1:40)	5.596 x 10 x 4 (223.8 mm^3)	112 g	13.5 W	4	Estimate for MOSAIC Type device
AWG Delay lines	5 x 100 x 55 x 20 (550,000 mm^3)	500 g (Heater)	.05 W	40	PIRI 16x16 AWG (shared heater = 2 devices @ 2 W)
SGTTD	100 x 50 x 50 (250,000 mm^3)	600 g	1 W	1	Estimated
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	640	Estimate for Traveling Wave Photodetector
RF Rotman Lens	79.375x79.375x1.98 (12,502 mm^3)	30 g	0 W	40	Estimate
Drive and Power Amplifier	3.97 x 3.97 x 9.2 (145 mm^3)	.093 g	1.6	400	TRW IR&D 30% eff. 0.48W
Antenna Elements	3.97 x 3.97 x 7.62 (121 mm^3)	.077 g	0 W	400	TRW IR&D
Polarizer and Radome	79.4 x 79.4 x 11 (69,305 mm^3)	44.34 g	0 W	1	TRW IR&D
Mounting Harness	4 x 15,803 mm^3 (63,211 mm^3)	40.44 g	0 W	1	TRW IR&D
Thermal Hardware for Heat	646,998 mm^3	414 g	0 W	1	TRW IR&D
TOTAL	2,317 cm^3	3.749 kg	699 W		

Photonic Fed Aperiodic Airborne Transmit Direct Radiating Phased Array

Component	Size	Weight	Power	Quantity	Manufacturer
DFB Laser @ 30mW	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	3	ORTEL 30 mW High Power DFB Laser
2.5-4.5 GHz IF Mach Zender Modulator (Low-Biased)	140 x 22.9 x 10.2 (32,701 mm^3)	50 g	0 W	1	UTP APE Microwave 8 GHz Analog Intensity Modulator, 1550nm
Polarization Beam Splitter	22.2 x 44.5 x 66.8 (65,992 mm^3)	150 g	0 W	4	OZ optics packaged device
Optical Circulator	57.5 x 25 x 11 (15,813 mm^3)	42 g	0 W	2	Kaifa Fiberoptic circulator
SGTTD	100 x 50 x 50 (250,000 mm^3)	600 g	1 W	1	Estimated
Integrated Splitter/Biref. φ chip (1:50)	5.946 x 12.5 x 4 (297.3 mm^3)	148.65 g	16.5 W	4	Estimate for MOSAIC Type device (1:5+5(1:10))
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	200	Estimate for Traveling Wave Photodetector
Drive and Power Amplifier	3.97 x 3.97 x 9.2 (145 mm^3)	.093 g	3.2	200	TRW IR&D 30% eff. 0.96W
Antenna Elements	3.97 x 3.97 x 7.62 (121 mm^3)	.077 g	0 W	200	TRW IR&D
Polarizer and Radome	79.4 x 79.4 x 11 (69,305 mm^3)	44.34 g	0 W	1	TRW IR&D

Mounting Harness	4 x 15,803 mm^3 (63,211 mm^3)	40.44 g	0 W	1	TRW IR&D
Thermal Hardware for Heat	646,998 mm^3	414 g	0 W	1	TRW IR&D
TOTAL	1,448 cm^3	2.577 kg	709 W		

Spaceborne Transmit Antenna Candidates

RF Fed Spaceborne Transmit Direct Radiating Phased Array

Component	Size	Weight	Power	Quantity	Manufacturer
Power Splitter/element	38.2 x 38.2 x 14.7 (21,451 mm^3)	324.65 g	4.6x4 W	270	TRW IR&D
4 beam variable phase/Amplifier Module	38.2 x 38.2 x 7.62 (11,120 mm^3)	16.95 g	1.7 W	270	TRW IR&D 45% eff.
Antenna Elements	38.2 x 38.2 x 147 (214,509 mm^3)	12.08 g	0 W	270	TRW IR&D
TOTAL	66,712 cm^3	95.494 kg	477 W		

Photonic Fed Spaceborne Transmit Direct Radiating Phased Array

Component	Size	Weight	Power	Quantity	Manufacturer
DFB Multi-λ Laser @ 30mW (4 wavelengths)	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	8	ORTEL 30 mW High Power DFB Laser
1.5-2.5 GHz IF Mach Zender Modulator (Low-Biased)	140 x 22.9 x 10.2 (32,701 mm^3)	50 g	0 W	4	UTP APE Microwave 8 GHz Analog Intensity Modulator, 1550nm
Polarization Beam Splitter	22.2 x 44.5 x 66.8 (65,992 mm^3)	150 g	0 W	4	OZ optics packaged device
Phase Locked Loop Assembly	38.862 x 16.764 x 10.668 (6,951 mm^3)	36.9 g	0.120 W	4	For the Photodetector, there is also the electronics
1:272 active splitter - φ shift chip (0.5 g/mm^3 density)	9.583 x 68 x 4 (2,607 mm^3)	1,304 g	86.4 W	4	Estimate for MOSAIC Type device (1:16+16(1:17))
Wavelength Mux (4:1)	105 x 4 (d) x 3 units (3,960 mm^3)	9 g	0 W	271	3 cascaded MZ FBG MUX (Innovative Fibers)
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	271	Estimate for Traveling Wave Photodetector
Driver Amplifier	total for both amplifiers is below		0.08 W	271	From EHF SB Tx IR&D
Power Amplifier	38.2 x 38.2 x 7.62 / 2 (5,560 mm^3)	8.475 g	1.7 W	271	TRW SB Tx IR&D, VP is 1/2 device area
Antenna Elements	38.2 x 38.2 x 147 (214,509 mm^3)	12.08 g	0 W	271	From EHF SB Tx IR&D
Overhead Packaging (20% of size and weight)	320,538 mm^3	1,770 g			Calculated from Photonics
TOTAL	61,562 cm^3	16.19 kg	813 W		

Photonic Fed Butler Matrix Direct Phased Array

Component	Size	Weight	Power	Quantity	Manufacturer
DFB Multi-λ Laser @ 30mW (4 wavelengths)	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	5	ORTEL 30 mW High Power DFB Laser

1.5-2.5 GHz IF Mach Zender Modulator (Low-Biased)	140 x 22.9 x 10.2 (32,701 mm^3)	50 g	0 W	4	UTP APE Microwave 8 GHz Analog Intensity Modulator, 1550nm
Polarization Beam Splitter	22.2 x 44.5 x 66.8 (65,992 mm^3)	150 g	0 W	4	OZ optics packaged device
Phase Locked Loop Assembly	38.862 x 16.764 x 10.668 (6,951 mm^3)	36.9 g	0.120 W	4	For the Photodetector, there is also the electronics
1:256 active splitter - φ shift chip (0.5 g/mm^3 density)	7.164 x 64 x 4 (1,834 mm^3)	917 g	81.6 W	1	Estimate for MOSAIC Type device (1:16+16(1:17))
SGTTD	100 x 50 x 50 (250,000 mm^3)	600 g	1 W	2	Estimated
Butler Matrix (16 x 16)	20 x 5 x 4 (400 mm^3)	200 g	0 W	32	Estimated for Butler Matrix
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	256	Estimate for Traveling Wave Photodetector
Driver Amplifier	total for both amplifiers is below		0.08 W	256	From EHF SB Tx IR&D
Power Amplifier	38.2 x 38.2 x 7.62 / 2 (5,560 mm^3)	8.475 g	1.7 W	256	TRW SB Tx IR&D, VP is 1/2 device area
Antenna Elements	38.2 x 38.2 x 147 (214,509 mm^3)	12.08 g	0 W	256	From EHF SB Tx IR&D
Overhead Packaging (20% of size and weight)	199,516 mm^3	1.928 g			Calculated from Photonics
TOTAL	57,535 cm^3	16.83 kg	523 W		

Airborne Receive Antenna Candidates

RF Fed Airborne Receive Phased Array (4 beam)

Component	Size	Weight	Power	Quantity	Manufacturer
Antenna Element	8.52 x 8.52 x 16.35 (1,187 mm^3)	0.534 g	0 W	3240	TRW IR&D Est From Tx
LNA	8.52 x 8.52 x 4.21 (305.6 x 2 mm^3)	0.47 x 2 g	0.5 x 4 W	3240	TRW IR&D Est From STx
Variable Phase Shifter 6-bit	38.2 x 38.2 x 7.62 / 2 (5,560 mm^3)	8.475 g	0 W	3240 x 4	From STx Module
32:1 RF Power Combiner	203.2 x 101.6 x 1.6 (33,032 mm^3)	58.08 g	0 W	102 x 4	TRW IR&D
16:1 RF Power Combiner	101.6 x 50.8 x 1.6 (8,258 mm^3)	14.52 g	0 W	7 x 4	TRW IR&D
8:1 IF Power Combiner	50.8 x 25.4 x 1.6 (2,064 mm^3)	3.63 g	0 W	1 x 4	Estimate
Downconverter	17.04 x 17.04 x 8.42 (2,444 mm^3)	3.76 g	3.76 W	1 x 4	Estimate
TOTAL	91,604 cm^3	139 kg	6496 W		

Photonic Fed Airborne Receive Phased Array (TTD)

Component	Size	Weight	Power	Quantity	Manufacturer
DFB Laser @ 30mW	34.54 x 35.24 x 9.9 (12,050 mm^3)	22.7 g	0.75 W	2	ORTEL 30 mW High Power DFB Laser
Polarization Beam Splitter	22.2 x 44.5 x 66.8 (65,992 mm^3)	150 g	0 W	1	OZ optics packaged device

Phase Locked Loop Assembly	38.862 x 16.764 x 10.668 (6,951 mm^3)	36.9 g	0.120 W	1	For the Photodetector, there is also the electronics
Passive Splitter (1:4)	55 x 10 x 6 (3,300 mm^3)	10 g	0 W	1	PIRI Tree Coupler
1:3240 Active Splitter - φ Shift Chip (0.5 g/mm^3 Density)	810 x 19.669 x 4 (63,728 mm^3)	31,864 g	1029 W	4	MOSAIC Splitter Device (1:10+10(1:18)+180(1:18))
Antenna Element	8.52 x 8.52 x 16.35 (1,187 mm^3)	0.534 g	0 W	3240	TRW IR&D Est From Tx
LNA	8.52 x 8.52 x 4.21 (305.6 mm^3)	0.47 g	0.5 W	3240	TRW IR&D Est From STx
EAM	0.4 mm length added to LNA	2 g	0.012 W	12,960	Estimated for TRW device
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	12,960	Estimate for Traveling Wave Photodetector
128:1 IF Power Combiner	812.8 x 406.4 x 1.6 (67,105 mm^3)	929.28 g	0 W	96	Estimate for 135:1 Combiner
Electronically Tunable DBR Laser	58.9 x 8.7 x 12.7 (6,508 mm^3)	30 g	1.66 W	4	NEL KELD1575BTF 2 mW (1550nm) SSG-DBR laser
1:24 Passive Splitter Chip	3.75 x 6 x 4 (90.048 mm^3)	45 g	0 W	4	MOSAIC Splitter Device
1.0 - 2.0 GHz MZ Modulator (Quadrature Biased)	140 x 22.9 x 10.2 (32,702 mm^3)	50 g	0.058 W	96	UTP APE Microwave Analog Intensity Modulator, 1550nm
TTD (primarily circulator)	57.5 x 25 x 11 (15,813 mm^3)	42 g	0W	96	Kaifa Fiberoptic circulator
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm^3)	0.238 g	0 W	96	Estimate for Traveling Wave Photodetector
32:1 RF Power Combiner	203.2 x 101.6 x 1.6 (33,032 mm^3)	58.08 g	0 W	4	TRW IR&D
TOTAL	16,456 cm^3	259 kg	5906 W		

Photonic Fed Airborne Receive Hybrid

Component	Size	Weight	Power	Quantity	Manufacturer
Tunable Laser (2 mW)	58.9 x 8.7 x 12.7 (6,508 mm^3)	30 g	1.66 W	64	NTT Tunable 1550 nm DBR laser
WDM Demux	100 x 55 x 20 (110,000 mm^3)	100 g (Heater)	2 W	64	PIRI 16x16 AWG (shared heater = 2 devices @ 2 W)
Lens Element	28.3 x 28.3 x 42.45 (33,998 mm^3)	6.535 g	0 W	64	TRW IR&D Est From Tx
Feed Element	7.08 x 7.08 x 16.35 (211 mm^3)	0.369 g	0 W	1024	TRW IR&D Est From Tx
LNA	7.08 x 7.08 x 4.21 (305.6 mm^3)	0.47 g	.5 W	1024	TRW IR&D Est From STx
EAM	0.4 mm length added to LNA	2 g	0.012 W	1024	Estimated for TRW device
TTD (primarily circulator)	57.5 x 25 x 11 (15,813 mm^3)	42 g	0W	1024	Kaifa Fiberoptic circulator
EAM for DownConvert	8.89 x 10.16 x 13.28 (1,200 mm^3)	9.4 g	0.012 W	1024	Estimated for TRW device

WDM Mux	100 x 55 x 20 (110,000 mm³)	100 g (Heater)	2 W	16	PIRI 64x64 AWG (shared heater = 2 devices @ 2 W)
Waveguide Photodetector	0.425 x 0.28 x 4 (0.476 mm³)	0.238 g	0 W	16	Estimate for Traveling Wave Photodetector
16:1 IF Power Combiner	101.6 x 50.8 x 1.6 (5,161 mm³)	14.52 g	0 W	1	Estimate
IF MMIC Amplifier	17.04 x 17.04 x 8.42 (2,444 mm³)	3.76 g	3.76 W	2	Estimate
TOTAL	29,353 cm³	65.905 kg	655 W		

Appendix 2
SOW Cross Reference

SOW Task	Refer to Page
4.0 TASKS/TECHNICAL REQUIREMENTS: The Contractor shall:	FR ⇒ Final Report DP ⇒ Design Plan
4.1 Investigate, analyze, and develop a Design Plan for implementing photonically-based true time delay RF beam formation and RF beam steering as well as photonically-based beam nulling in an RF phased array antenna for EHF satellite communications (SATCOM) applications (43.5 - 45.5 GHz uplink; 20.2 - 21.2 GHz downlink with the downlink expandable to 19.7 to 20.2 GHz).	FR DP
4.1.1 Conduct an investigation that addresses: Photonic Component	
4.1.1.1 The use of a nominal 1.3 micron (1300) nanometer) or 1.55 micron optical wavelength for all photonic circuits.	FR: 63, 70
4.1.1.2 The use of a reconfigurable photonic based RF signal distribution system in both the airborne and space based platforms.	FR: 122-199
4.1.1.3 Methods of beam formation and beam steering control and configuration directly at the antenna or remotely located elsewhere within the platform. This part of the investigation shall also address the methods of information transfer of both control data and signal between the antenna(s) and the terminal and controller.	FR: 62-199 DP: 8
4.1.1.4 The use of integrated photonics, bulk photonic devices, and hybrid technology in the true time delay beam steering and beam forming system.	FR: 62-199
4.1.1.5 The issues of common vs. multiple aperture for each selected platform and of transmit/receive reciprocity and whether a full duplex system can use a common antenna with photonic methods.	FR: 128
4.1.1.6 The issue of RF and optical losses.	FR: 62-84
4.1.1.7 Size, weight, and power issues.	FR: 137, 159, 175, 191
4.1.1.8 The use of various photonics devices including optical sources, detectors, integrated photonic waveguide, and modulators over temperature range, shock, vibration, and other environmental factors.	FR: 62-121
4.1.2 Conduct tradeoff studies to examine:	

4.1.2.1 Methods to use photonic interconnects between the terminal and active aperture radiating elements and determining whether hybrid methods shall be used to implement the RF feed systems (transmit and receive).	DP: 8
4.1.2.2 Hybridized methods of RF phase/photonic time shift vs. all optical time shift vs. all photonic phase/time shift for RF beam formation and steering.	FR: 72, 74, 75, 137, 159, 175, 198
4.1.2.3 Ways to minimize photonic conversion loss in optoelectronic integrated devices, photonic based RF links, and photonic based time delay/phase shifters.	DP: 8
4.1.2.4 Methods to provide low noise figure and high spur-free dynamic range for the SATCOM antenna receiver systems, particularly in the uplink antennas on the spacecraft.	FR: 62-120
4.1.2.5 Reliability and producibility of photonic devices	FR: 62-120, DP
4.1.2.6 The ease and maturity of fabrication techniques for photonic, integrated photonic, and hybrid devices.	FR: 62-120, DP
4.1.2.7 Whether the beam formation and beam steering subsystem shall be remoted from the surface of the array in order to minimize the physical size (depth) of the array.	FR: 122-199, DP
4.1.2.8 An analysis of frequency generation topologies to determine if direct frequency operation or up/down frequency conversion techniques are more desirable.	FR: 74, 75
4.1.2.9 If photonic control of individual radiating elements, subarray, or a combination of these beamforming methods are best suited to beam formation and beam steering.	FR: 99, 135, 156, 173, 189
4.1.2.10 Various methods to implement photonically-based true time delay beam formation including both coherent and non-coherent methods of beam formation and control including multiple beam formation, optically based main beam and sidelobe beam nulling, and optically based beam steering.	FR: 72, 89, 99, 101, 106-121
4.1.2.11 Maintenance/log support concepts for the airborne platform antennas. For example, examine possible methods for performance verification, maintenance concepts and ease of repair in an effort to improve design, minimize "downtime," and lower other maintenance action costs.	DP: 25

4.1.3 Based upon the results of the investigation and tradeoff studies, develop designs for optically implemented RF phased array antennas that use photonics technology for true time delay beam formation and beam steering, as well as for data control.	FR: 122-199 Design Plan
4.1.3.1 Design photonically implemented RF phased array antennas for the EHF SATCOM frequencies to be installed on an airborne platform. Photonic time delay shall be implemented in both the transmit and receive arrays within the parameters determined during the tradeoff study and investigation.	FR: 122-199 Design Plan
4.1.3.1.1 The airborne platform phased array design shall be based upon the airborne phased array with 45 dBW EIRP (effective isotropic radiated power) at a 70 degree scan angle.	FR: 155
4.1.3.1.2 The phased array design shall be based upon the receive system G/T for the airborne terminal greater than 5 dB at a 70 degree scan angle based on local ambient temperature.	FR: 185
4.1.3.1.3 The airborne phased array antennas shall be a flat thin array for SATCOM applications such as for C-17, E-3A, or similar airborne platform sized application and conformal for use in a UAV or fighter type platform.	FR: 153, 185
4.1.3.1.4 The airborne phased array shall be designed to minimize airframe drag and platform penetrations.	DP: 24 - 25
4.1.3.1.5 The airborne array design shall use true time delay methods for circularly polarized beam formation and steering in a single beam with 70 degree steering capability in a circular direction from the normal to the antenna.	DP: 10
4.1.3.1.6 The airborne receive array design shall be adaptable for polarization changes to meet the requirements of a SATCOM downlink as well as the GBS requirements.	DP: 24
4.1.3.1.7 The airborne arrays shall be designed to have active reconfiguration during operation so as to maintain the link operation during normal platform maneuvers.	DP: 7, 24

4.1.3.1.8 The airborne platform receive array link acquisition subsystem shall be designed to have a target search capability which is tied into the platform navigation system. This subsystem shall provide an apriori pointing and then scan of the antenna beam pointing system within the beamwidth of the antenna for spacebased platform signal acquisition prior to establishment of the communications link.	DP: 24
4.1.3.1.9 The airborne antennas shall be based upon a phased array with 256 (16 x 16) elements for receive applications and 100 elements (10 x 10) for transmit applications.	FR: 153, 155, 156, 185, 187, 189
4.1.3.1.10 The antenna control (beam formation and beam steering) subsystem for the airborne platform shall receive data from the aircraft navigation system (including GBS) for aircraft position and orientation and shall have active reconfiguration during operation so as to maintain the link operation during normal platform maneuvers.	DP: 7, 24
4.1.3.1.11 The airborne array design shall address issues related to pattern distortion of the arrays based upon airframe configuration	DP: 25
4.1.3.1.12 The airborne array design shall use photonic control to enhance the acquisition process and assess various search methods for signal acquisition.	DP: 7, 24
4.1.3.1.13 The airborne array antenna designs shall maximize the use of integrated photonic techniques.	DP: 8
4.1.3.2 Design photonically implemented RF phased arrays for use on a space based platform.	
4.1.3.2.1 Photonic based RF phase shifters shall be implemented in both the transmit and receive arrays within the parameters determined during the tradeoff study and investigation.	Design Plan
4.1.3.2.2 The space-based transmit RF phased array application shall be based upon multielement arrays with circularly polarized elements on a two-wavelength spacing. Each beam to be formed during transmit operation shall be capable of 50 dBW EIRP in each of the four independently controllable beams.	FR: 124-128

4.1.3.2.3 The Satellite array receive terminal shall have a maximum noise figure of 3.2 dB based on local ambient temperatures	FR: 131
4.1.3.2.4 The space-based receive antenna shall form up to ten independent simultaneous beams for communications from airborne and ground based terminals. Photonically implemented Butler Matrices, Rotman Lenses, or other methods of multibeam formation shall be investigated.	FR: 106-121, 131
4.1.3.2.5 The space-based platform beam forming and control system shall be designed for active reconfiguration for forming and controlling the independent beams for both spot coverage and for full earth coverage. Each of the spot beams shall be independent pointing and reconfiguration anywhere within the full earth field of view from the space-based platform.	DP: 9, 15, 20
4.1.3.2.6 The space based antenna shall use photonically based beam formation and control, consistent with the photonically based receiver beam nulling and multibeam formation.	DP: 15
4.1.3.2.7 Design optically based receiver nulling that shall be implemented in the SATCOM receive array at an RF level.	FR: 86-105 Design Plan
4.1.3.2.8 The spaced based antenna designs shall maximize, where practical, the use of integrated photonic techniques.	DP: 7
4.1.3.3 The antennas shall be designed to meet the full environmental requirements for the required platforms and for shipping and handling requirements for these antennas.	DP: 13, 22
4.1.4 Verification Experiments	
4.1.4.1 Conduct experiments to verify unique photonic implementation concepts developed during the design tradeoff studies	FR: 56
4.1.5 Design Plan	
4.1.5.1 Based upon the design of the photonically implemented EHF SATCOM RF Phased Array antennas developed under paragraph 4.1.3 prepare a design plan for fabrication of the airborne and spaceborne antennas	Design Plan

4.1.5.1.1 The RF phased arrays design shall possess stability, reliability, and maintainability to be suitable for the proposed platforms. A Reliability and Maintainability (R and M) assessment shall be performed to indicate R and M weaknesses and suggestions to improve the R and M with emphasis on electro-optic (photonic) components.	Design Plan
4.1.5.1.2 As part of the Design Plan, prepare suggested approaches for proof of concept Exploratory Development Models EDM(s) See Note 1, and a rough order of magnitude (ROM) for costs for the EDM(s).	FR: 61and DP: 26 - 27

EHF SATCOM ARRAY DESIGN
(ESAD)

DESIGN PLAN

Brent Toland, James Leight, Alon Barlevy

Sponsored and Monitored by
Air Force Research Laboratory, Rome Laboratory
Contract #: F30602-96-C-0026
James Nichter, COTR

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1. INTRODUCTION

The following document describes a TRW design recommendation for the five (5) photonically implemented antenna terminals that comprise an EHF SATCOM system for MILSTAR type applications. Of the five terminals, two would be located on an airborne platform such as an F-16, F117A, E-3A or Unmanned Aerial Vehicle for wide scanning narrow spot beam transmit and receive operation. The remaining three terminals would be located on a space based platform providing agile spot multi-beam transmit and receive operation and nulling receive operation capability.

The design recommendations incorporate photonics technologies and techniques where appropriate and in ways that maximize the leverage from photonics insertion to positively impact system performance and/or cost. The design recommendations for photonically implemented beamforming and signal distribution are based on the results of extensive photonic component, beamforming concept, and architecture trades conducted during the execution of the investigation and development period of performance of the ESAD contract.

For each antenna, we provide the system performance requirements derived from Milstar, Advanced EHF, and the ESAD program SOW. We then provide the architectural block diagram for the design recommendation, as well as artwork that depicts the individual beamforming or signal distribution subsystems and a conceptual drawing of the antenna terminal. An explanation of the design and operation of each antenna subsystem and discussion relevant to issues of operation, control, fabrication, integration and test, maintenance and performance verification is provided. A brief description for three proposed exploratory development model (EDM) demonstration activities relevant to the highest leverage subsystems is presented as a motivation for future work leading to the insertion of photonics in practical EHF SATCOM systems.

The artwork and conceptual drawings associated with each antenna architecture should not be taken to represent the antenna design to exacting detail as mechanical, thermal, packaging, fabrication and assembly considerations have not been fully subjected to a design review process (i.e. incorporating the usual milestones of system, preliminary, and critical design reviews). The drawings are also not drawn to scale and should not be represented as such. However, the artwork provided does provide an adequate physical representation of the construction of the beamforming or element array hardware and insight to many of the practical considerations associated with fabrication, integration and test of the various subsystems and antenna architectures.

2. AIRBORNE TRANSMIT ANTENNA

2.1 System Requirements

The system requirements for the airborne transmit antenna are summarized below in Table 2-1. The key performance drivers are the 70° conical scan for a single beam delivering 45 dBW of equivalent isotropic radiated power (EIRP). These requirements directly impact the extent of true time delay (i.e. the size of the subarrays), the number of elements in the array, and the radiated power for each element. A secondary requirement is the RF power delivered by the photonic beamforming network to the transmit module input port.

Table 2-1 System Requirements for Airborne Transmit Antenna

Item	Requirement	Source
Number of Beams	1	SOW
Beam Shape	spot	SOW
Frequency	43.5 - 45.5	SOW
Polarization	single, circular	SOW
Coverage	70° cone	SOW, Milstar
EIRP (@EOS)	45 dBW	SOW
Beam Update Rate	20 kHz	Milstar, Advanced EHF
Beam Settling Time	< 0.9 microseconds	Milstar, Advanced EHF
Sidelobe level (first)	not specified	
Spot beamwidth	not specified	
Carrier to Noise	15 dBC	Assumed (SB Tx)
Additional Requirements	Flat, thin, compatible with C-17, E-3A, UAV, Fighter	SOW

The link budget and antenna array designation that achieves the 45 dBW EIRP requirement is presented in paragraph 8. Typical loss mechanisms for phased array antennas such as aperture efficiency, RMS error, scan loss, radome and polarizer losses, end of life degradation and pointing losses are all accounted for in the analysis. The 0.96 W transmit module output power is consistent with 44 GHz devices developed and fabricated at TRW with IR&D funding. Careful design of the antenna elements result in adequate element gain to enable the use of 200 elements to achieve the EIRP goal.

2.2 Design Recommendation

2.2.1 Antenna Architecture

The figure below (Figure 2.1) illustrates the architecture of the airborne transmit antenna design recommendation. The design is for a 200 element phased array antenna oriented on an aperiodic lattice. The aperiodic spacing allows for the suppression of grating lobes in the antenna pattern while spreading the elements out over a larger area, thereby reducing the thermal density across the antenna aperture. The RF transmit signal is modulated onto one of two optical carriers injection locked at a 43 GHz offset frequency and oriented in orthogonal polarizations. The two optical signals (one modulated) are evenly combined and split to two stages of time delay elements consisting of switched grating devices to establish the subarray level time-delay steering. The four time-delayed outputs are input to optical distribution and phase weighting units that incorporate amplified optical splitter devices (MOSAIC) and birefringent phase sections. The two coherent orthogonally polarized optical signals acquire equal and opposite optical phase delays that upon polarization at 45° and photodetection will impose a phase weight profile on the transmitted RF signals. As indicated in the figure, the antenna control electronics receive information from the aircraft navigation system pertaining to the platform location and orientation, determine the appropriate beam steering direction to maintain the SATCOM link, and transmit the beam steering control signal to the ASIC decoders which set the appropriate time and phase weights for each subarray and element.

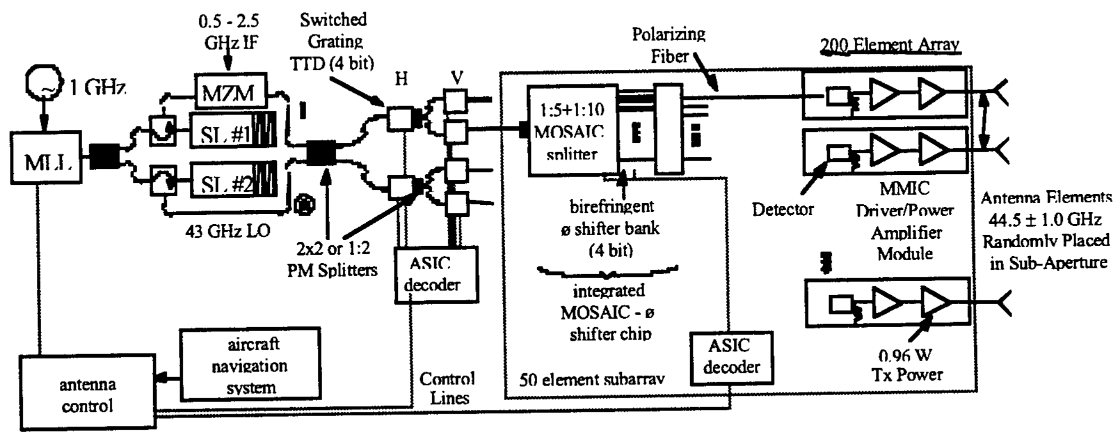

Figure 2.1 Airborne Transmit Aperiodic Phased Array Antenna Architecture

2.2.2 Subsystem Modules

Figure 2.2 shown below illustrates a conceptual brassboard exploratory development module (EDM) of the optical source and true time delay subsystem.

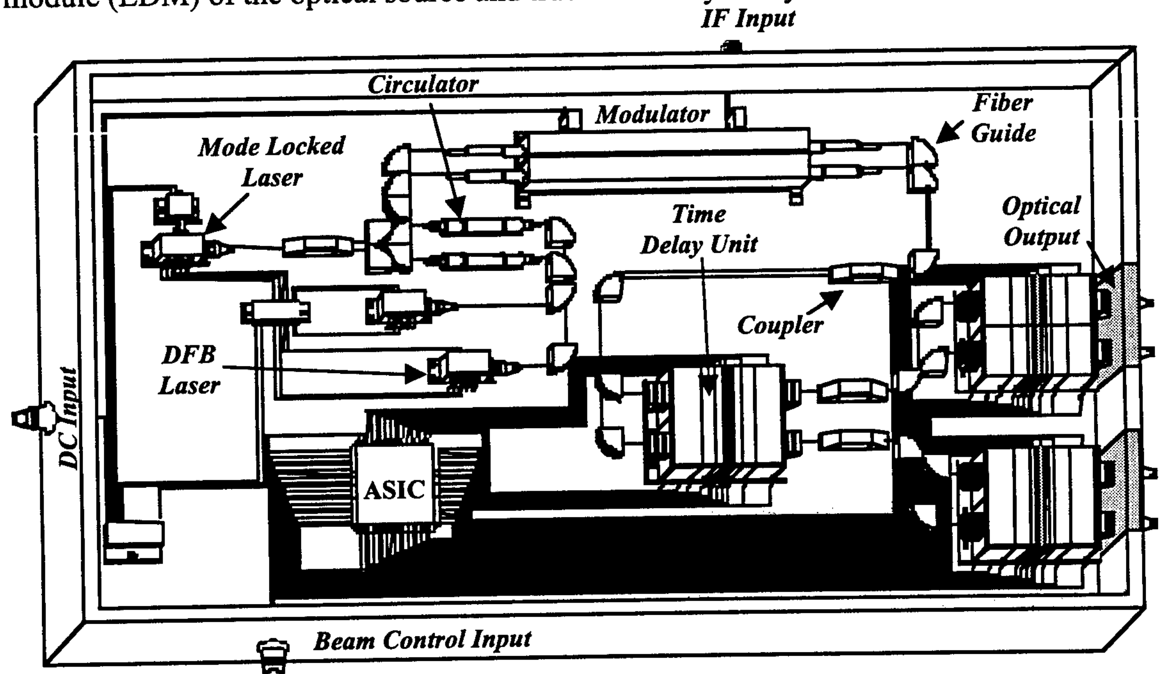

Figure 2.2 Airborne Transmit Optical Source and Time Delay Module

The brassboard EDM primarily consists of commercial off the shelf (COTS) devices with the exception of the mode locked laser, the modulator package, the switched grating time delay units, the ASIC decoder circuit, and the DC power distribution circuit. The modulator package consists of two sections. One section contains the IF band modulator and the second is a through path (possibly with a phase calibration capability) section that enables the two optical signals to propagate over an equivalent path length so as to maintain phase coherence up to the 2x2 optical coupler. The assembly would comprise one slice of the photonic beamformer structure. As many of the devices are fiber pigtailed, some structure is required to guide the fibers throughout the assembly as indicated in the figure.

Figure 2.3 below illustrates a two channel optical distribution and phase weighting module.

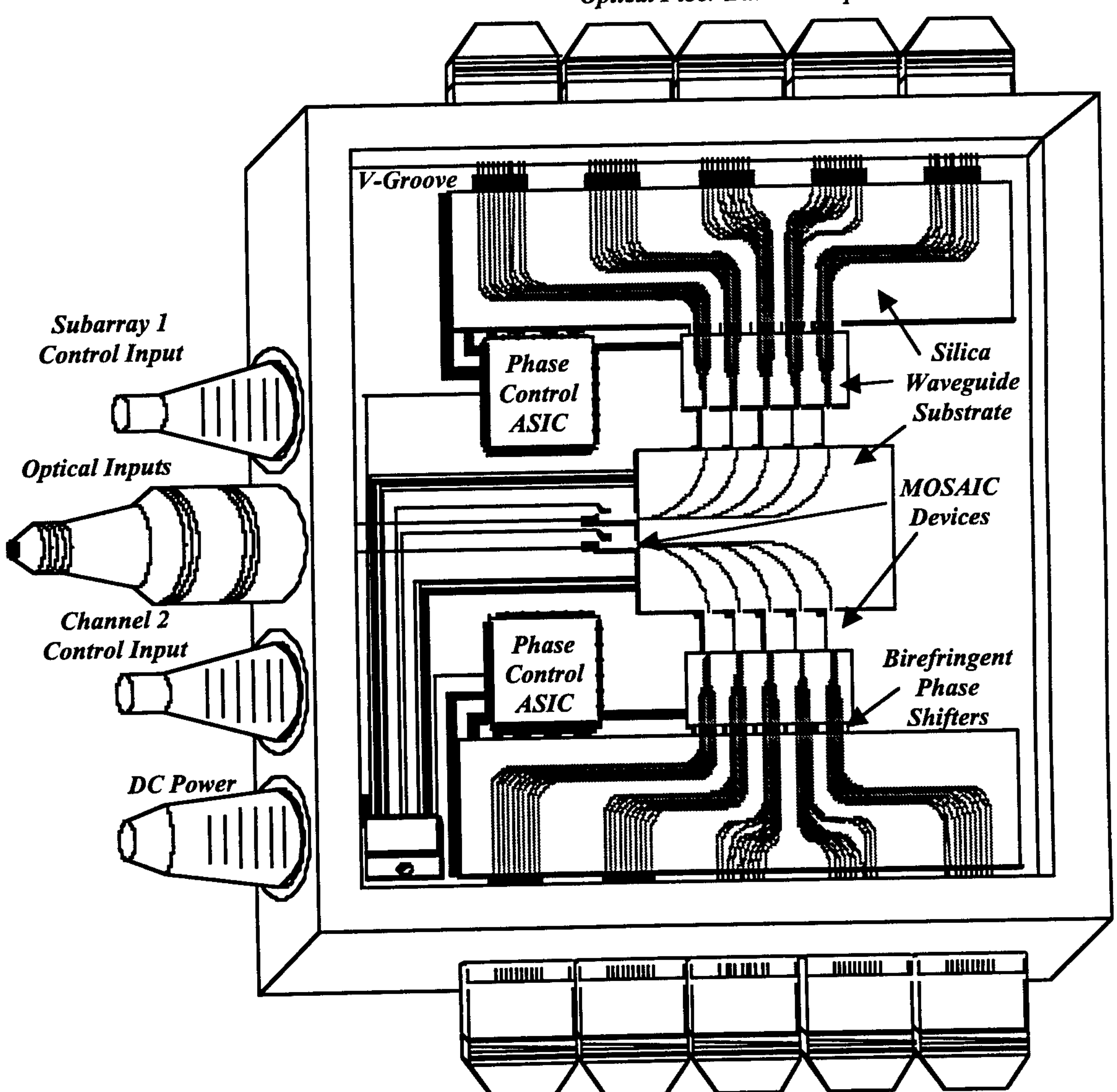

Figure 2.3 Airborne Transmit Antenna Two-Channel Optical Distribution Module

This unit consists of MOSAIC type optical amplifier splitters, silica waveguide routing circuits, birefringent phase shifting arrays, electronic control circuits, and 10-fiber bundle output cables. Two of these units would be required to enable optical distribution and phase weighting for the four subarrays.

2.2.3 Fabrication of Optical Distribution Units

Our recommendation is to fabricate the assembly and other optical distribution units as a multi-chip module rather than an optoelectronic integrated circuit. Given that typical yields for the fabrication of active optoelectronic devices (i.e. lasers and amplifiers) can be rather low, it is more likely to be cost effective in the near term to select individual MOSAIC devices rather than attempting to fabricate arrays of optical amplifier devices. A second consideration is optical losses in the fanout waveguides. The use of silica based waveguides can result in significantly lower propagation losses when compared to III-V materials such as Gallium Arsenide or Indium Phosphate. This becomes most important in the fanout to the optical fiber array where the pitch is expanded from 6 μm at the Talbot output waveguides to 250 μm at the fiber output array, which can require long waveguides. The phase modulator chips could most likely be fabricated in large arrays, as the yield for these devices can be much better. We have placed a silica waveguide distribution circuit between the amplifier outputs and the phase control sections, this could possibly be a single integrated unit, depending on the loss and yield of these amplifier/phase shifter units. For optical coupling from III-V based devices to silica waveguides, the use of expanded mode waveguides may be necessary. Expanded mode techniques enable mode matching between optical devices characterized by significantly different mode field profiles. By matching the optical mode from the semiconductor waveguide to the silica waveguide, it is possible to significantly reduce the optical coupling losses. Flip chip bonding and other passive alignment techniques could also be used to more effectively couple light from the amplifier chips to the silica waveguides. Silicon V-groove bench techniques could be utilized to enable the fiber pigtail coupling, although active alignment and laser hammering techniques may be required for the pig-tailing most critically impacting system performance (e.g. at the amplifier inputs).

2.2.4 Beam Steering Control

The use of photonics for RF signal distribution in a phased array provides several ancillary, but substantial reductions in beamformer complexity. RF implemented phased arrays require a control line and sub-decoder ASIC at each transmit or receive module. The implementation of photonic distribution and phase-time control allow a single or very few control signals to be transmitted to a single or few ASIC decoder circuits. The control lines that would normally be distributed to each element module and the decoder circuitry at each element are eliminated which results in additional hardware savings and reduction of antenna complexity. Single point beam control can also possibly lead to faster beam steering and the adaptation that will be necessary for the airborne transmit antenna in order to maintain link operation during airborne combat platform maneuvers.

2.2.5 Transmit Module and Antenna Front End

A conceptual drawing of the transmit modules and antenna aperture is provided in Figure 2.4 shown below. A facing view of the antenna element array is provided following in Figure 2.5.

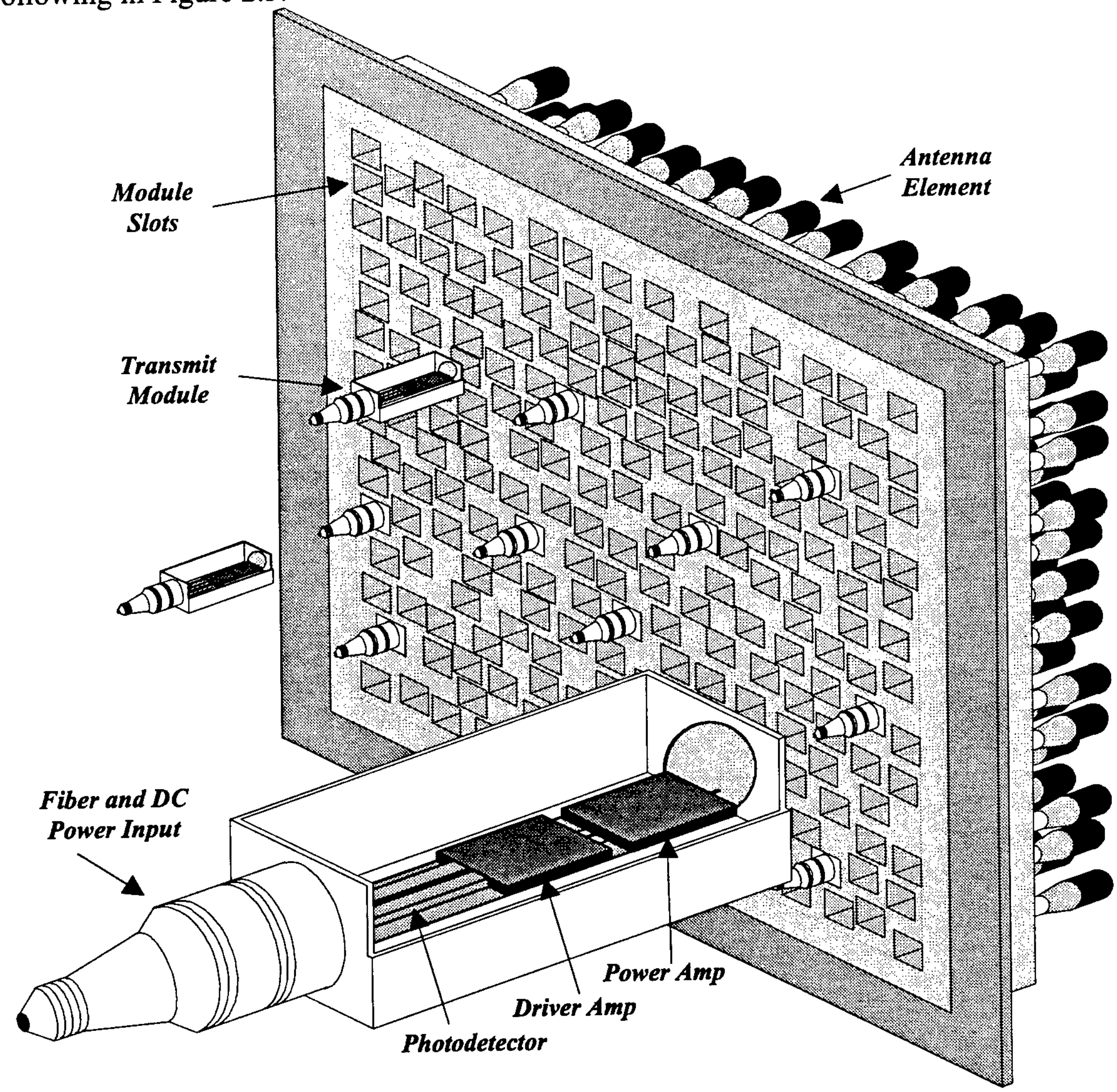

Figure 2.4 Airborne Transmit Antenna Aperture

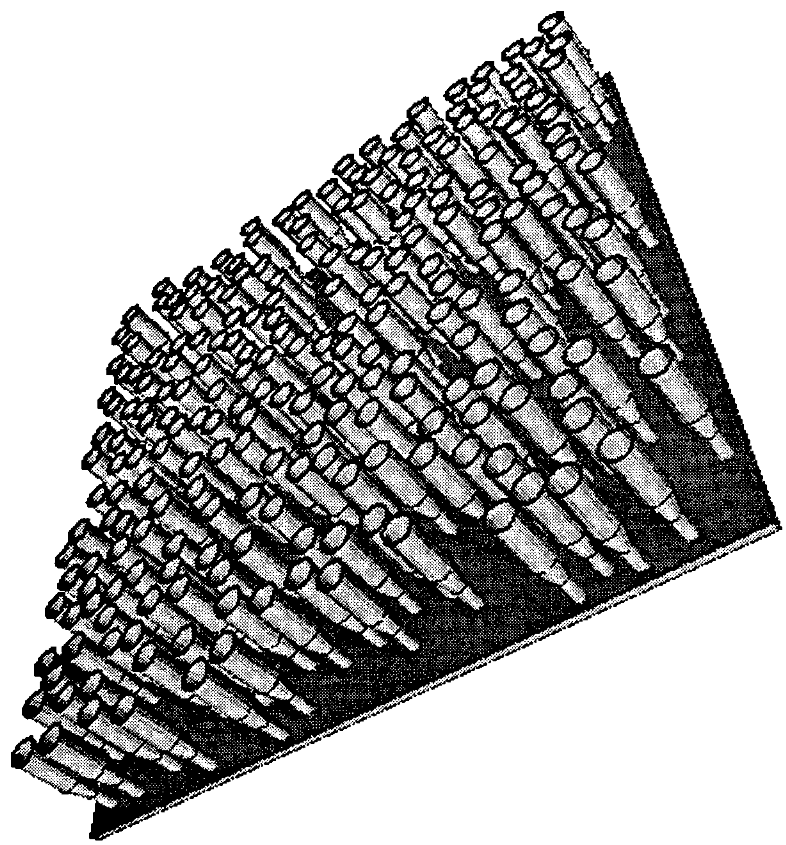

Figure 2.5 Airborne Transmit Antenna Element Array

The aperiodic element spacing requires a novel concept for packaging the array. A thermal structure is fabricated with rectangular sections removed in the aperiodic pattern. The transmit modules fit into the slots and the antenna element attaches to the front end of the module. The transmit module, an enlarged version of which is illustrated in Figure 2.4 consists of a fiber input, a photodetector, the driver and power amplifier. Although not indicated in the figure, DC power is fed to each module for biasing the photodetector and amplifiers. Also not shown in the illustration of Figure 2.4 is the vein polarizer and radome. The vein polarizer converts the linear polarization of the 44.5 GHz horn radiation mode into a single sense circular polarization for the uplink channel. This polarization technique is consistent with that previously proposed for EHF airborne transmit phased arrays and finds equivalent use for this design recommendation.

3. Spaceborne Agile 10 Beam Receive Antenna

3.1 System Requirements

The system requirements for the spaceborne receive antenna are summarized below in Table 3-1. The driving requirements are the 10 beam spot electronically scannable coverage, 9.3° conical scan (field of view of Earth coverage), and 10 dB G/T (NF specification was provided in SOW, but G/T specification is more consistent in performance characterization of MILSATCOM systems). There is a requirement for full Earth coverage that we would suggest establishing with a separate single feed consistent with the current MilStar configuration. The principal secondary requirement is the noise figure performance of the beamforming network as it directly impacts the relative Gain/Noise performance of the overall antenna system.

Table 3-1 System Requirements for Spaceborne Receive Antenna

Item	Requirement	Source
Number of Beams	10	SOW
Beam Shape	spot and full Earth coverage.	SOW
Frequency	43.5 - 45.5GHz	SOW
Polarization	single, circular	SOW
Coverage	$\pm$ 9.3°	SOW, Milstar
Noise Figure	< 3.2 dB	SOW
Beam Update Rate	20 kHz	Milstar, Advanced EHF
Beam Settling Time	< 0.9 μs	Milstar, Advanced EHF
G/T (spot beam)	10 dB*	Advanced EHF
Sidelobe level (first)	25 dB below peak	Advanced EHF
Spot beamwidth	1.0°	Advanced EHF
Jammer Cancellation	40 dB	Advanced EHF
Additional Requirements	Design compatible with space environment	SOW

The link budget for a receive MBA has been determined so to achieve the 10 dB G/T based on the reflector size, operation frequency, and field of view. The calculation is straightforward compared to that for the phased arrays, depending only on the reflector geometry and as such is not included in the Antenna Design Link Budgets.

3.3 Design Recommendation

The design recommendation for the spaceborne 10 agile beam antenna is a dual reflector multiple beam antenna (MBA) with array feed. Figure 3.1 below illustrates the photonically implemented beamforming architecture for this antenna. The array feed works through the combination of 7 element clusters oriented on a hexagonal lattice. The combination of a 7 element cluster with the appropriate amplitude weights results in the formation of a beam in a predetermined direction. The photonically implemented beamforming network is configured to enable the selected collection of signal from a desired beamforming cluster. This architecture is derived from some TRW proprietary concepts for the routing function.

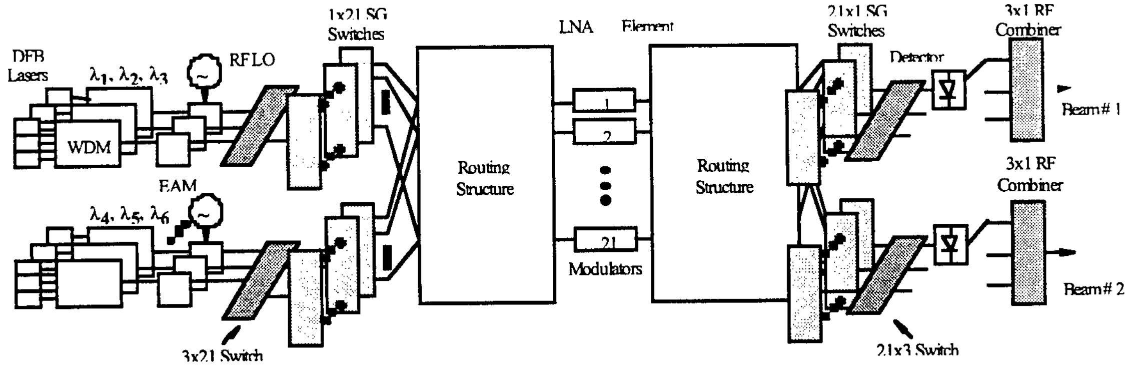

Figure 3.1 Spaceborne Receive Array Feed Beamforming Architecture

To form a single beam, the signal from 7 DFB lasers must be routed to the modulators associated with the cluster of 7 elements and combined at the beam output. Seven lasers at distinct wavelengths are combined with WDM multiplexers. The optical signals are modulated by a RF tone that acts as a local oscillator for downconversion of the incident RF signal. These outputs are optically switched to the inputs of a routing structure that routes the signals to the optical modulators associated with the 7 element cluster. The signals are modulated by the input RF signals and the optical outputs are combined and routed back to the appropriate switch output. This routing occurs for the other sets of combined wavelength signals corresponding to other beams as well after which the signals are switched back to corresponding optical detectors and electronically combined resulting in the summed beam output. Other beams are simultaneously formed in the same structure using other optical wavelengths. Multiple optical wavelength signals pass through the routing network simultaneously, thus enabling the multiple beam operation. We have identified switched diffraction grating based optical switches as an attractive candidate for the optical switching technology. This technology offers the possibility of low insertion loss, rapidly reconfigurable, and highly compact optical switching for this application.

Figure 3.2 below illustrated an EDM brassboard of the optical source, heterodyne, switching, and combining module. Most of the components could be fiber pigtailed for convenience of assembly and packaging. Not shown in the figure is the heat sinking hardware that would be on the backend of the lasers and local oscillator source unit. Shown in the figure is the majority of the control, bias and DC power electronics that would be required for operation of the module.

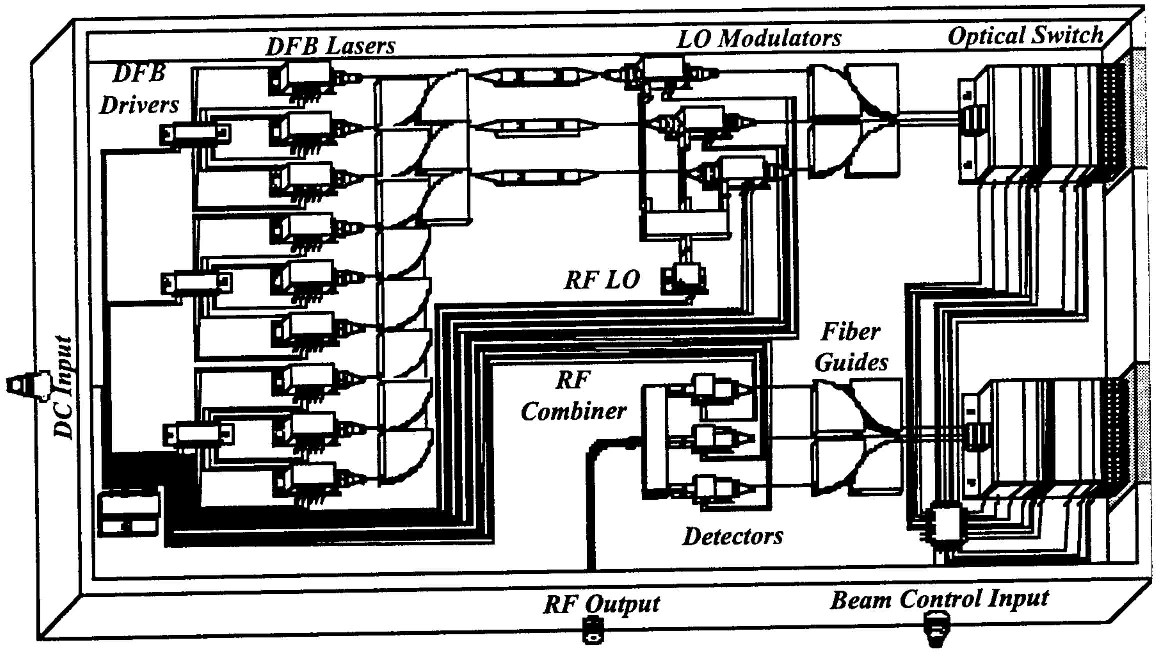

Figure 3.2 Optical Source Module for Spaceborne Receive Antenna

Many of the fiber optic devices would require further packaging development and stabilization for space qualification. Packaging large numbers of similar devices as arrays will result in reduced packaging size, and weight requirements. Radiation hardness qualification will be required, but is out of the scope of this work.

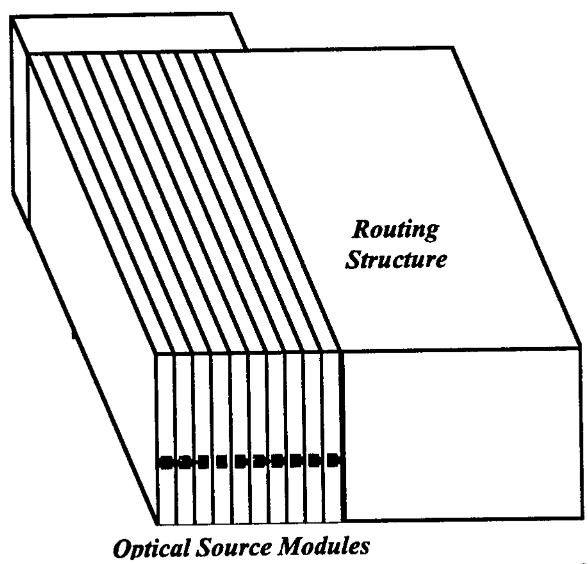

Figure 3.3 Spaceborne Receive Assembled Beamformer

Figure 3.3 illustrates the assembled photonic beamformer. Multiple optical source slices are shown for each of the 10 beams. The remaining hardware represents the routing structure and is shared between all of the beams so that the size is nearly independent of the required number of beams. The beamformer is compact and could be remoted to the most convenient part of the spacecraft if necessary.

The feed horns and receive module structure are illustrated below in Figure 3.4. A semiconductor Mach-Zehnder, or an Electroabsorption Modulator is packaged with the LNA and DC power circuit in a multi-chip fashion. Aside from the input and output fiber cables, the only other required connection is the DC power source. No beam control lines are required as the beam steering and control is accomplished remotely from the antenna. Some packaging techniques on the modulator are required to enable easy access to the fiber inputs. TRW is currently developing packaging concepts for establishing LNA modulator assemblies that could be directly applicable to building this antenna hardware.

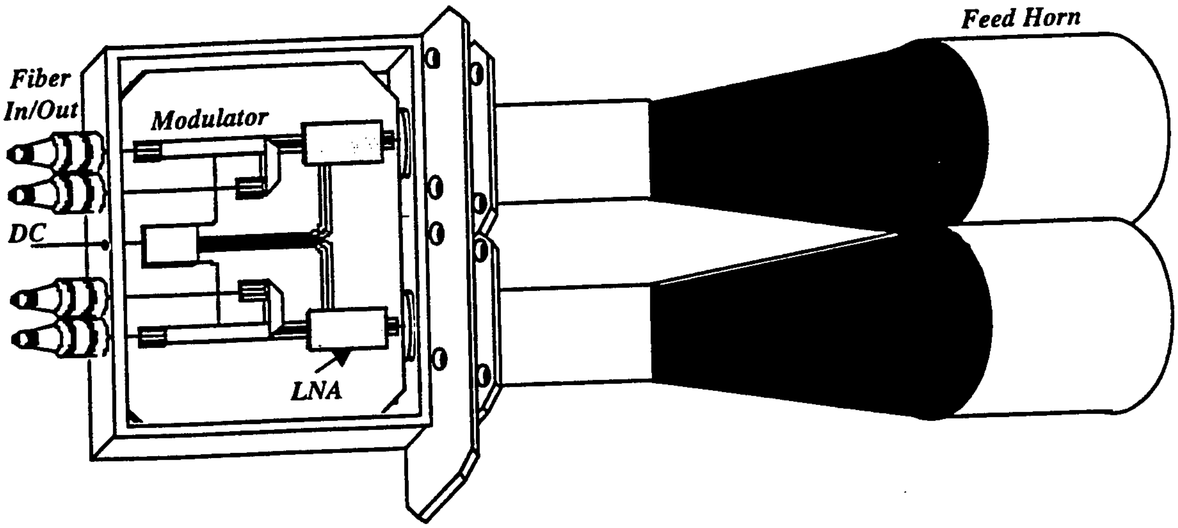

Figure 3.4 Spaceborne Receive Feed Horn/ Receive Module

The full antenna system from a top-down view and from a side profile is illustrated in Figure 3.5. The main and sub reflectors are suspended over the array feed in such a way as to allow the ±9° scanning field of view. The antenna would be oriented on the spacecraft so to point towards the earth at the correct angle and the aperture would possibly be covered by a radome not shown in the figure. The mean mission lifetime of seven years would be the standard design goal for this antenna. A full space qualification procedure would be required for the photonic components and subsystems in order to ensure this level of reliability. The key components of this beamforming architecture that would have to be qualified are the optical modulators, the routing structure, and the optical switches. There has been some moderate work on radiation testing of these or similar types of components, but to our knowledge, none of these components have been subjected to a full space qualification process. For integration and testing of this antenna architecture, we expect that existing test sets designed for spaceborne EHF receive antennas can be modified to accommodate this photonically implemented architecture. Since MBAs are notorious for reliability considerations, we do anticipate that some redundancy should be incorporated at the front end and for critical beamformer components. Some of these issues have been directly addressed in reliability of photonic components for telecommunication applications and can be directly applicable to space applications.

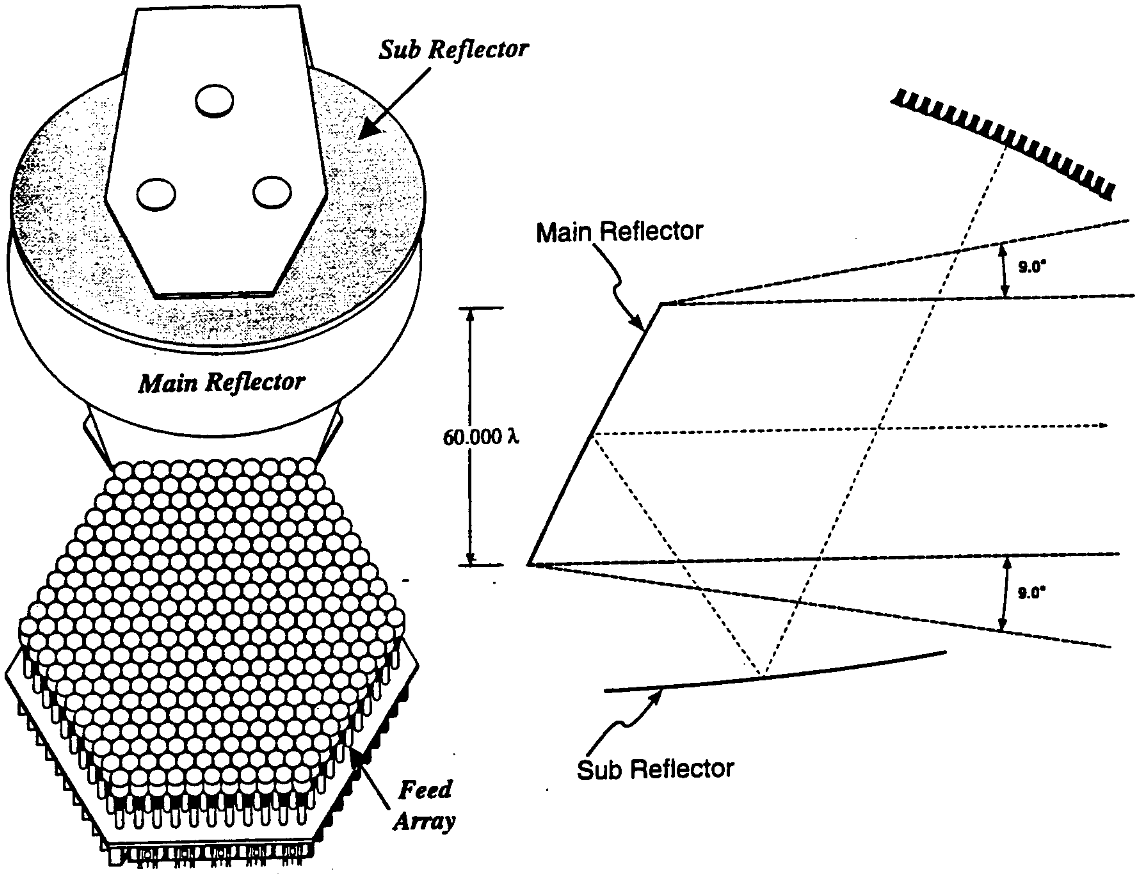

Figure 3.5 Spaceborne Receiver Agile Multiple Beam Antenna

4. SPACEBORNE NULLING ANTENNA

4.1 System Requirements

Specific system requirements for the nulling antenna were not specified in the ESAD SOW and many nulling performance system requirements are classified. However, the criteria we have used during the performance of the contract are based on reasonable assumptions of performance in terms of such metrics as percent coverage area, nulling convergence time, and nulling bandwidth. The most favorable approach seems to indicate the use of a MBA based architecture similar to the current MILSTAR configuration as illustrated below in Figure 4.1.

4.2 Design Recommendation

There are several key modifications to this antenna architecture that we make for our design recommendation. They include an increase of the reflector size and the number of feed elements (to at least 19 elements), the use of photonic based signal correlation for determination of the adaptive beamforming weights, and (for larger reflectors and more feeds) the use of photonically implemented tapped delay line beamforming for maintenance of nulling bandwidth.

MILSTAR NULLER

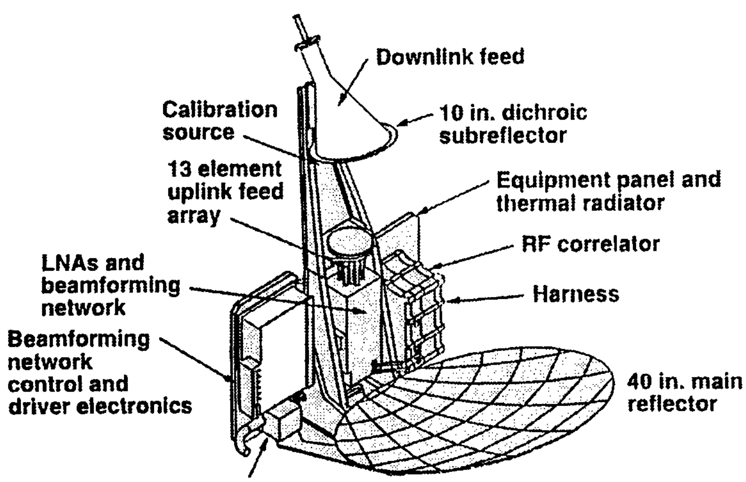

Figure 4.1 Spaceborne Receive Nulling Antenna

The beamforming and processing architecture is presented in Figure 4.2. The detected signals at the feed elements are phase and amplitude weighted and summed to form the received beam signal. No full Earth coverage is required for the nulling antenna, so there is no need for beam spoiling or a separate wide coverage antenna. The individual feed element signals and the summed beam signals are tapped, downconverted to a fixed IF bandwidth and input to the correlation processor. Each of the signals modulates a common optical carrier, is filtered so as to remove the unwanted sideband (the rejected sideband can be detected to form a power estimate of the individual feed signal). The modulated sum signal is again split and correlated with each individual feed signal in a 4x4 Talbot optical correlator. The outputs are differentially detected, integrated for the prescribed dwell time, sampled and quantized. The sampled and quantized outputs are then used to determine the modification of the complex weights so to maximize the signal to noise ratio of the set of received COMM signals. Our recommendation is that even the expansion of the antenna scale to 19 feed elements will result in significant performance improvement and can clearly benefit from the incorporation of photonics in the signal processor. Consequently, we see a need for tapped delay line beamforming only in the long term and not for next generation hardware.

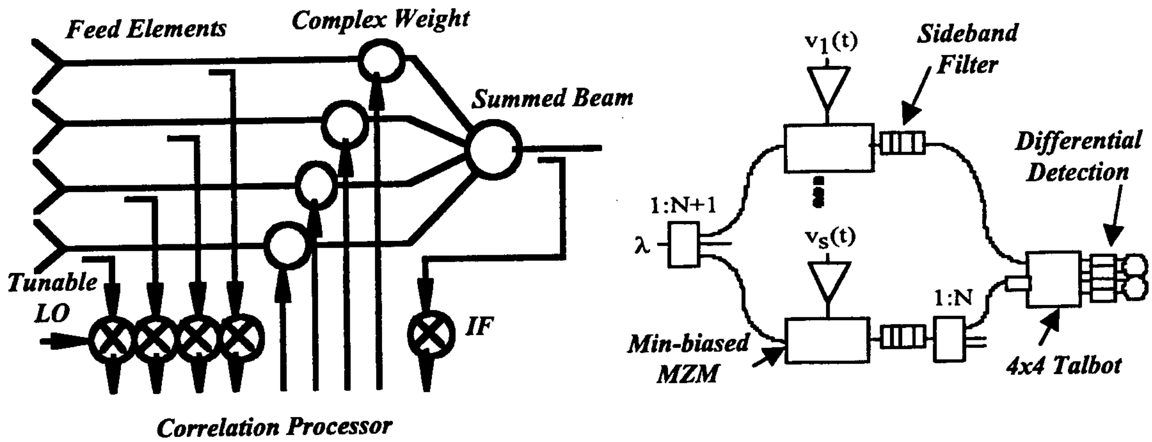

Figure 4.2 Nulling Beamformer and Correlation Processor

The photonic correlation processor and associated support electronics is illustrated below in Figure 4.3. The RF inputs are routed to the photonic correlation unit that is configured as a multi-chip module. A DC bias ASIC provides the necessary modulator, laser, and amplifier bias for proper operation. The differentially detected output currents are integrated on a charging capacitor that is sampled/quantized and then discharged in preparation for the next integration time. The adaptive weights are updated and the necessary commands sent to the beamforming network thereby forming a null on those jammers in the service area.

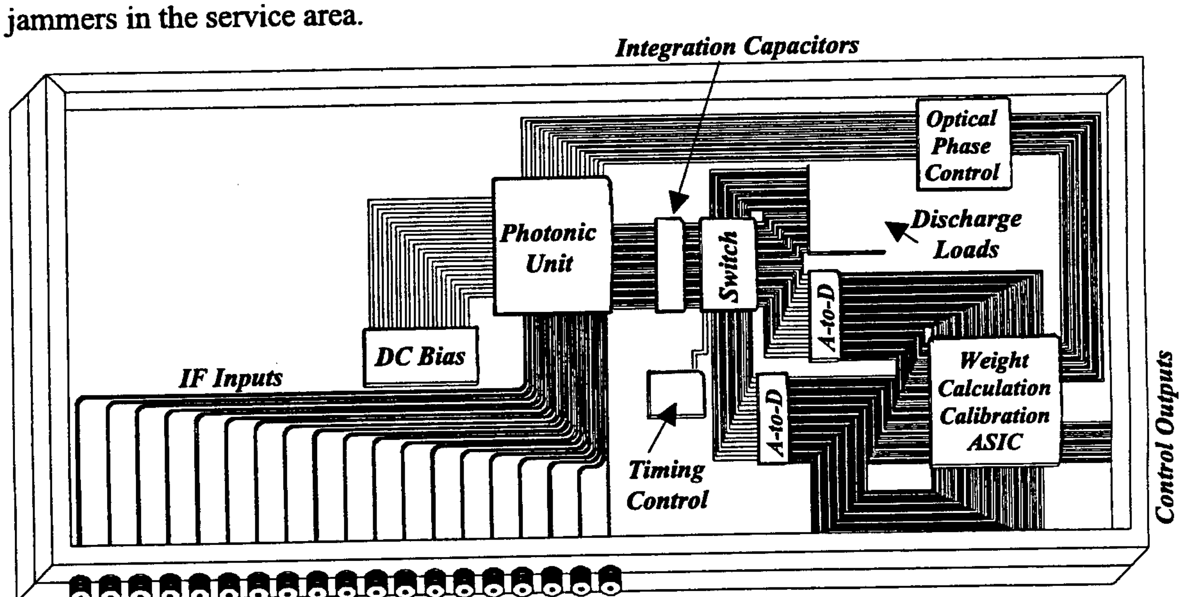

Figure 4.3 Photonically Implemented Correlation Processor

The photonic correlation unit that is constructed as a multi-chip module unit is illustrated in Figure 4.4 below. The DFB laser, MOSAIC type optical amplifier/splitters, modulators, phase compensation sections, and detector array could all be fabricated as individual devices (see Figure 4.5), placed and aligned in the multi-chip module package using active or passive alignment techniques. The routing waveguides could be fabricated using passive silica waveguide, or polymer technology resulting in relatively compact, stable, and low loss signal routing on the chip. The optical phase compensation sections are required to equalize the optical path lengths between the numerous channels, a necessary requirement for optical correlation. The 4x4 Talbot optical correlators could be fabricated with the waveguides in an entirely passive structure. For a processor compatible with the current MILSTAR configuration, the IF inputs would require an approximate bandwidth of 150 MHz, which could be achieved in this type of package. The bending radius of the passive waveguides would have to be large enough to minimize optical bending losses and is the determining factor on the module size. For 1 mm bending radius, the entire package would be about 2 inches square. Waveguide bending radii or 1 mm is not reasonable with most manifestations of planar lightwave circuit technology, but recent developments in high-Δ silica waveguides can provide 1.5 mm bending radii with only 0.1 dB/cm propagation loss. Such a "correlator on a chip" could provide adequate performance in an extremely small package, which is desirable for next generation nulling antenna systems.

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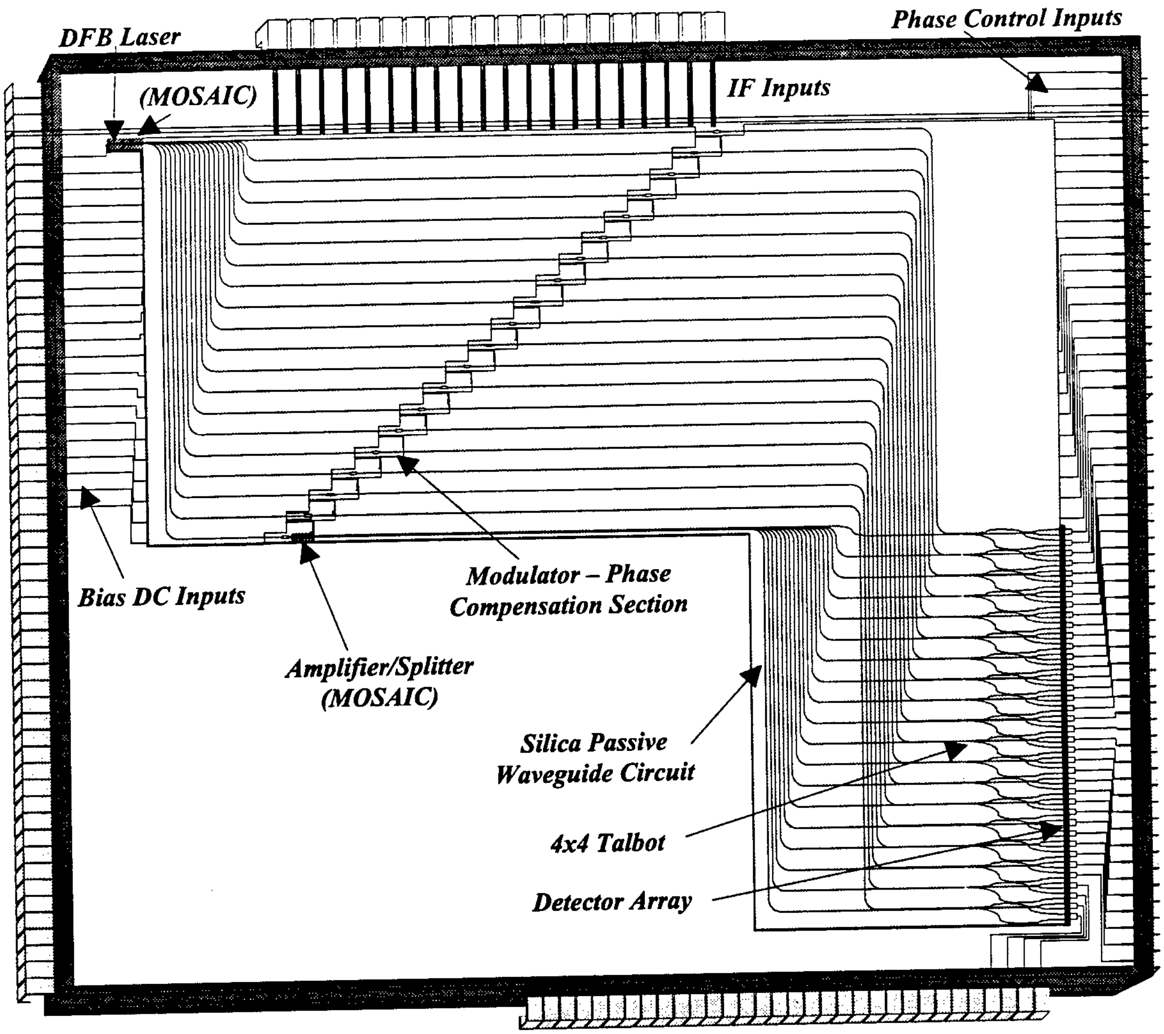

Figure 4.4 Photonic Processor Multi-Chip Module

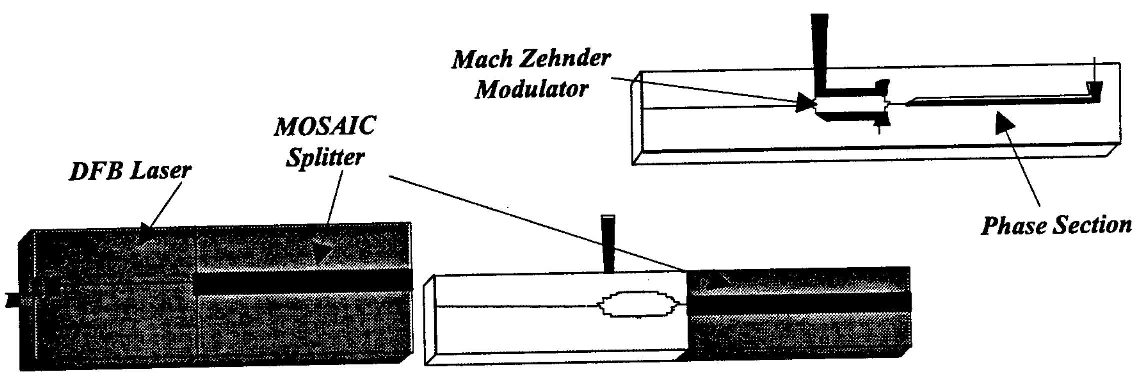

Figure 4.5 Photonic Processor Components

5. SPACEBORNE AGILE 4 BEAM TRANSMIT ANTENNA

5.1 System Requirements

System requirements for the agile 4 beam spaceborne transmit antenna are presented below in Table 5-1. Requirements are derived from the ESAD SOW, Milstar, Advanced EHF and the TRW proposed Multiple Beam Phased Array (MBPA). The driving requirements are operation of 4 simultaneous beams, spot and full earth coverage over the visible Earth (9.3° conical field of view), and 50 dBW EIRP. A secondary requirement is the RF power delivered to the 20 GHz transmit module to achieve the specified EIRP requirement.

Table 5-1 System Requirements for Spaceborne Transmit Antenna

Item	Requirement	Source
Number of Beams	4	SOW
Beam Shape	spot and full-Earth coverage	SOW
Frequency	20.2 - 21.2, 19.7 - 20.2 for GBS	SOW
Polarization	single, circular	SOW
Coverage	9.3° cone (Visible Earth)	SOW, Milstar
EIRP (spot beam at EOC)	50 dBW	SOW
Beam Update Rate	20 kHz	Milstar, Adv. EHF
Beam Settling Time	< 0.9 microseconds	Milstar, Adv. EHF
Sidelobe level (first)	not specified	
Spot beamwidth	1.0°	Advanced EHF
Carrier to Noise	15 dBC	Tx MBPA
Additional Requirements	Design compatible with space environment	SOW

The link budget and antenna array designation is provided in paragraph 8. As with previous designs, typical loss and error mechanisms for phased arrays are incorporated in the EIRP calculation. The transmit power amplifiers are designed to provide up to 0.26 W of output power to be evenly distributed among the four beams. A total of 271 elements arranged on a hexagonal lattice is required to meet the stated EIRP design goal.

5.2 Design Recommendation

5.2.1 Antenna Architecture

The direct radiating phased 271 element phased array antenna architecture is illustrated in Figure 5.1 and represents our design recommendation.

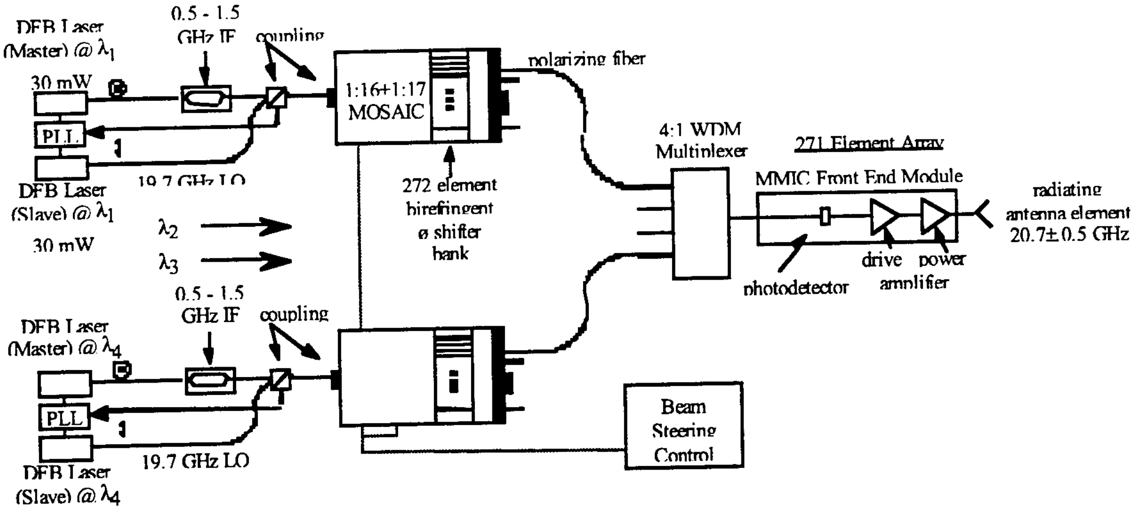

Figure 5.1 Spaceborne Agile 4 Beam Transmit Antenna Architecture

An optical heterodyne source consisting of two lasers oriented in crossed polarizations are phased locked at a 19.7 GHz offset frequency are combined through a polarization beam splitter. This heterodyne source is equivalent to the mode locked laser source illustrated for the airborne transmit array in Figure 2.1 and should only be considered an alternate implementation that may or may not be more practical depending on the state of the technology at the time of EDM development. The crossed polarization signals are amplified and split and phase weighted in a manner identical to that described for the airborne transmit antenna. This structure is repeated and implemented at distinct wavelengths for each simultaneous beam. A WDM multiplexer combines the optical wavelength signals at each element for each beam to be transmitted. The signals are remoted to the array via optical fiber and detected by a high current photodetector subsequent to amplification and radiation from the horn element. The radiated signal is polarized and transmitted through a protective radome thus establishing the downlink signal.

5.2.2 Subsystem Modules

Figure 5.2 illustrates a conceptual brassboard EDM for the optical heterodyne source module. The assembly could be constructed with primarily off the shelf components. Fiber spools and guides allow packaging of fiber pigtailed components. Although not shown in the figure, heat sinking hardware would protrude from the back end and facilitate thermal stability of the assembly. A single optical source module would be required for each transmit beam.

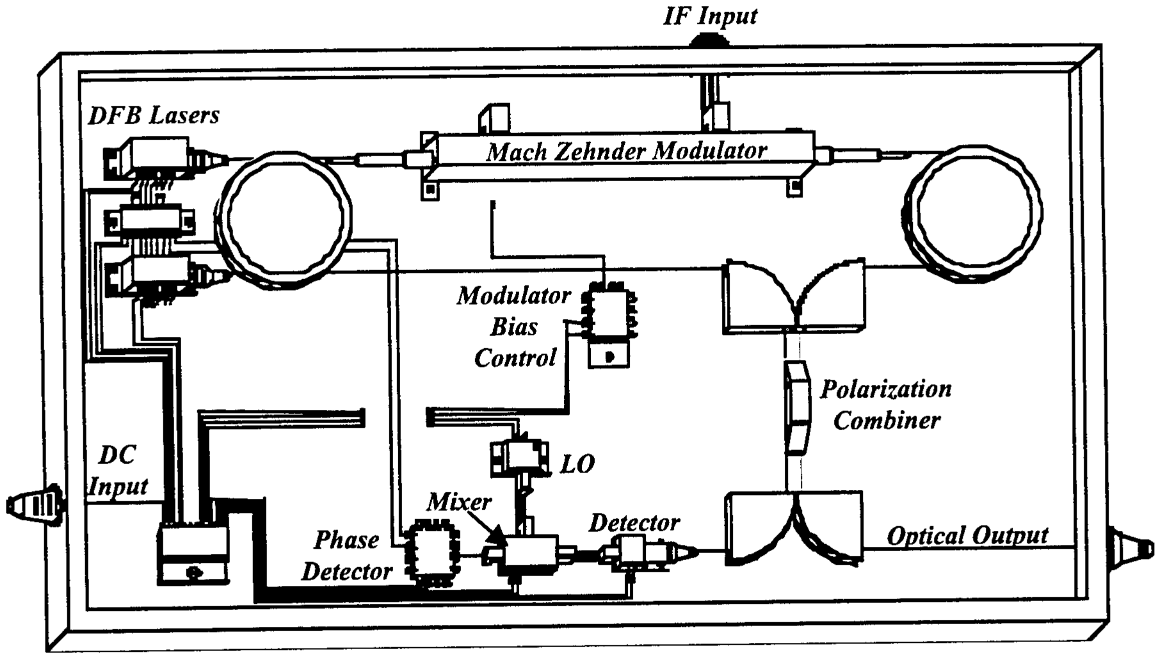

Figure 5.2 Spaceborne Transmit Optical Source Module

The 1:271 optical distribution and phase steering module is illustrated below in Figure 5.3. A single optical input (comprising the modulated and heterodyne optical signals) is first amplified and split 16 ways by an input MOSAIC device. Silica waveguides fanout the signals each to a 1:17 MOSAIC type splitter and birefringent phase shifting section. Silica waveguides are again used to distribute the optical signals to optical fibers oriented on a 250 μm pitch and aligned with silicon bend v-groove components. The 17 fiber polarizing bundles extend off of three sides of the module to be routed to the WDM combiner elements packaged in a manner similar to that of Figure 3.3. Single point beam steering control is again possible because the phase weighting occurs at the module, thus eliminating the harnesses and hardware associated with phase control at each individual element. Additionally, because the optical phase shifters are analog devices, the bit phase resolution of the beamformer is not limited by the RF frequency. Only the output levels of the phase control decoder ASIC limit the phase accuracy of the beamforming. Full Earth coverage can be accomplished through a single spoiled beam state that establishes a low gain beam over the entire field of view of the transmit antenna.

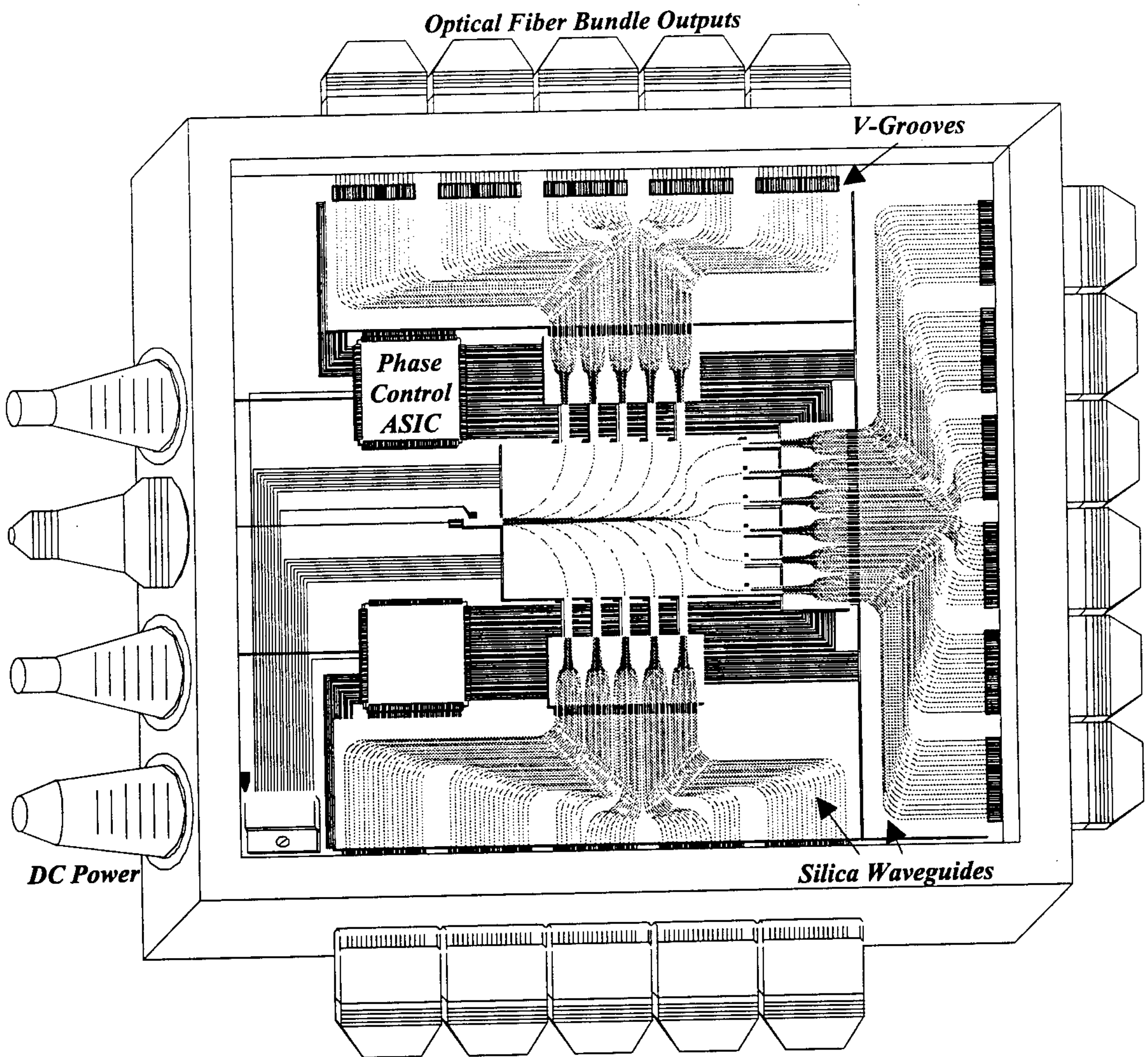

Figure 5.3 Spaceborne Transmit Antenna Optical Distribution Module

The optical source and distribution modules can be assembled on a compact structure as illustrated in Figure 5.4 shown below. One source module slice and optical distribution – phase weighting slice is required for each beam. Additional structure is required for optical fiber routing and the WDM multiplexers. The beamforming structure is rather modular to support additional beams by adding more optical source and distribution cards and modification of the WDM multiplexer devices. The beamforming structure can be conveniently located on the spacecraft and remoted from the antenna element array if necessary.

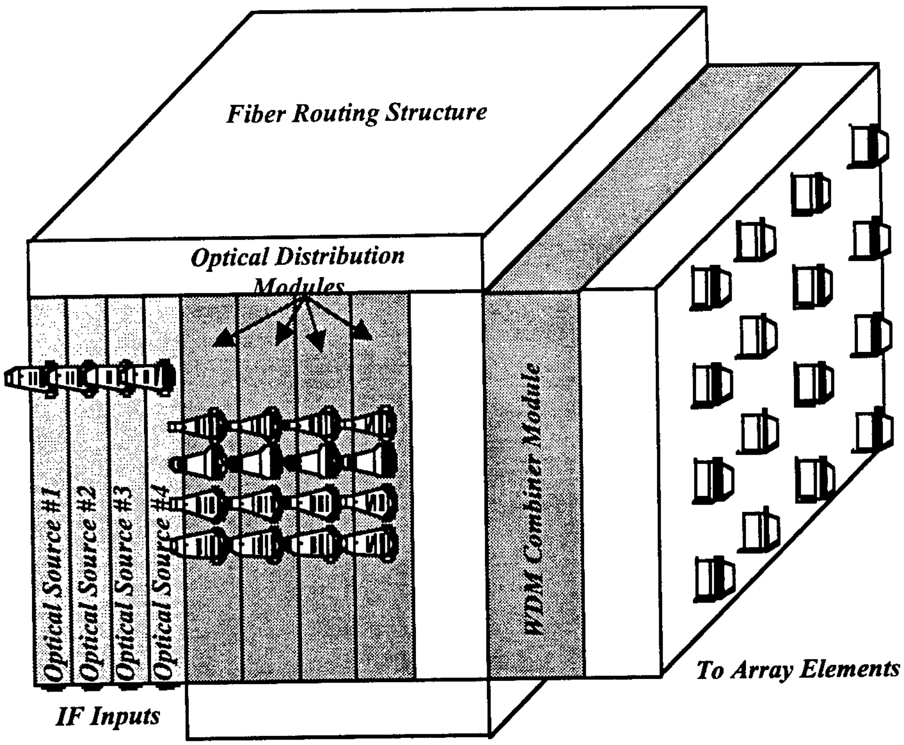

Figure 5.4 Spaceborne Transmit Beamformer Assembly

The spaceborne transmit module and horn element is illustrated in Figure 5.5. A DC bias ASIC is required at each unit to provide DC power to bias and operate the photodetector and amplifiers.

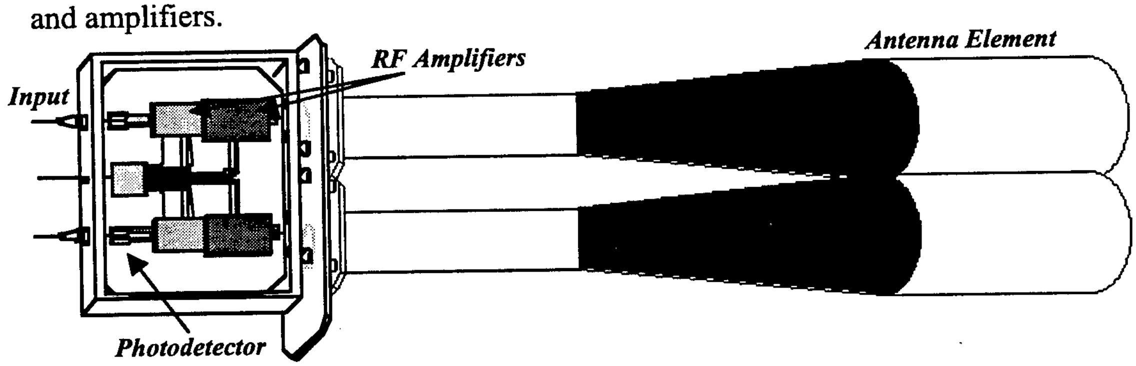

Figure 5.5 Spaceborne Element Horn and Transmit Module

The two element modules can be arranged together to form the radiating structure illustrated in Figure 5.6 without the polarizer and radome. The antenna element array structure is the same design as the RF phased array with the exception that the phase shifter hardware is removed from the transmit module and the photodetector is incorporated.

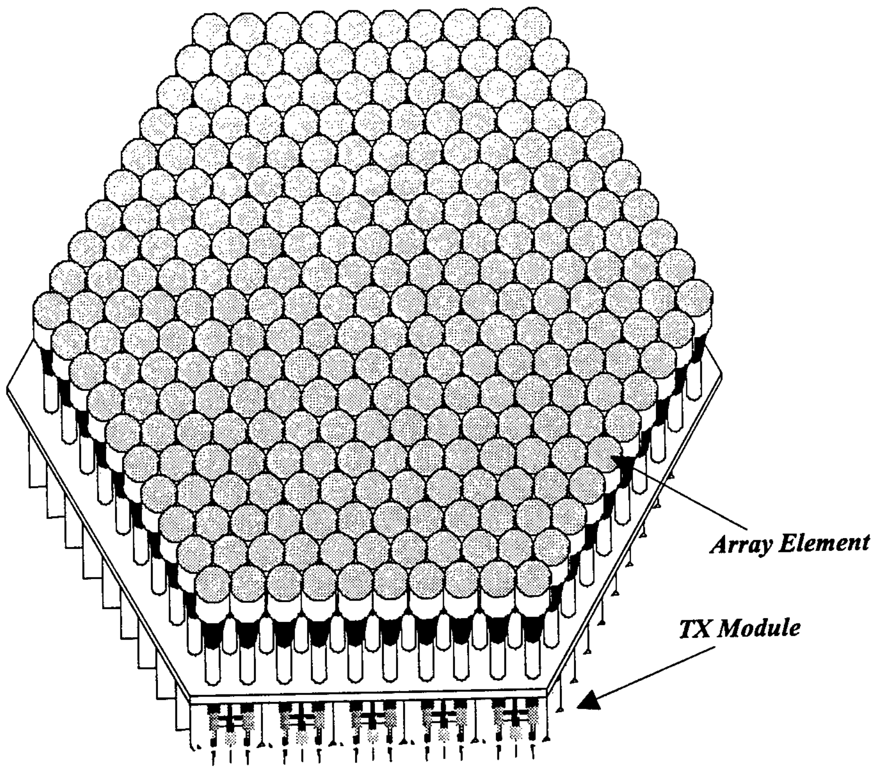

Figure 5.6 Spaceborne Transmit Antenna Element Array

Fabrication, integration and test of the spaceborne transmit array would follow the well establish design processes representative of other spaceborne EHF antenna array programs. The antenna would be designed and fabricated for the typical mean mission lifetime of seven years. The phased array architecture would enable graceful degradation at the array level. Some redundancy may be required in the beamforming system so to enable adequate reliability and performance over the lifetime of the system.

6. AIRBORNE MULTI-BAND RECEIVE ANTENNA

6.1 System Requirements

The system requirements for the airborne receive antenna are provided below in Table 6-1. We have promoted aggressive requirements relative to the ESAD SOW and other sources. The driving requirements are multi-frequency coverage from 7.25 to 21.2 GHz (so to provide access to SATCOM resources from DSCS to MilStar), dual polarization support, 70° conical field of view, and 5 dB G/T noise performance. The primary goal in the multi-frequency coverage is to enable the consolidation of antennas to a single aperture that can access all current military COMM space assets. We believe that this is a strong motivation for the use of photonics to enable the beamformer remoting that is necessary for multi-band beamforming and operation.

Table 6-1 Airborne Receive Antenna System Requirements

Item	Requirement	Source
Number of Beams	≥ 4 (multi-frequency)	Aggressive SOW
Beam Shape	spot	SOW
Frequency	see spectrum plot in Final Report	Aggressive SOW
Polarization	adaptable ⇒ dual cp	SOW
Coverage	70° cone	SOW, Milstar
G/T (@max scan)	5 dB	SOW
Beam Update Rate	20 kHz	Milstar, Adv. EHF
Beam Settling Time	< 0.9 microseconds	Milstar, Adv. EHF
Sidelobe level (first)	not specified	
Spot beamwidth	not specified	
Additional Requirements	Target Search Capability. Flat, thin, compatible with C-17,E-3A, UAV, Fighter	SOW

Our design recommendation for the airborne receive antenna is a phased array of 3240 elements using a cross notch wideband element, band multiplexers, and a wideband LNA consistent with TRW projections. The link budget for this antenna system is provided in paragraph 8 and demonstrates the array configuration that meets the 5 dB G/T design requirement.

6.2 Design Recommendation

6.2.1 Antenna Architecture

The architecture of our design recommendation is presented in Figure 6.1. The optical heterodyne source, distribution, and phase weighting are consistent with previously described beamformer designs. Multiple beamformers are required for each receive band, but the antenna array aperture is shared for all COMM channels. The Electroabsorption modulators and band multiplexers can be integrated into the antenna element receive module in a compact manner. Subarray level true time-delay is required at a rather extensive level if wideband operation is required (i.e. for HDR communications). In Figure 6.1, we indicate true time-delay steering of 24 subarrays that is adequate HDR COMM with moderate squint penalty. For narrowband frequency-hopping operation, phase only beam steering may be adequate for acceptable performance.

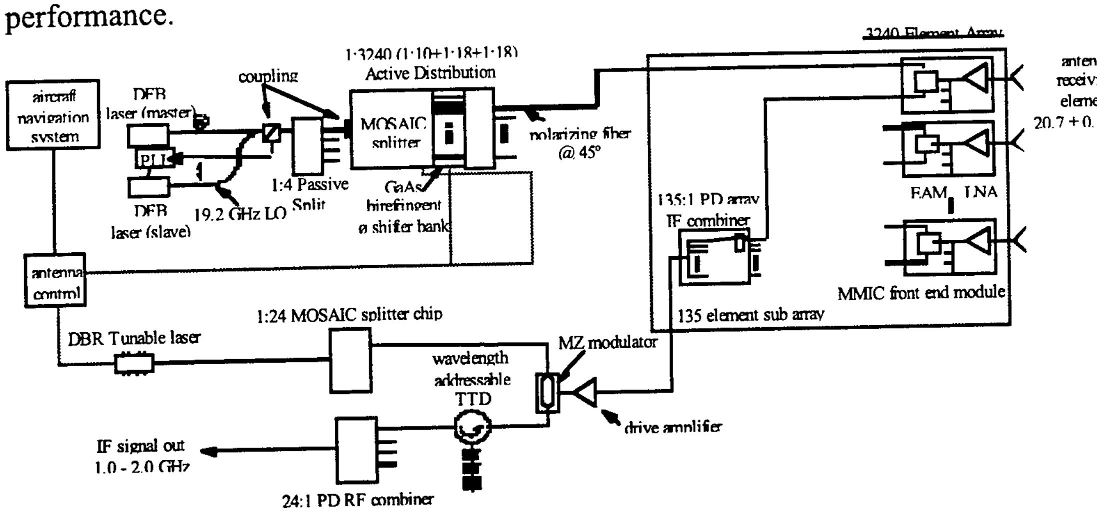

Figure 6.1 Airborne Receive Antenna Architecture

The wideband cross-notch element array is illustrated in Figure 6.2. These elements support dual polarization operation and typically are individually machined and assembled. As there are two feed points for each element (one for each orthogonal polarization), some additional electronics at the front end are required to support arbitrary circular sense polarization. The two feed outputs from the element, are input to a printed circuit 90° hybrid and an RF switch between the two outputs enables the collection of LH or RH sense circularly polarized signals. The additional electronics would add complexity to the receive module, but the cost penalty is expected to be less than implementing multiple beamformers for each frequency band. TRW has demonstrated satisfactory operation over approximately a 20 GHz bandwidth with these devices, which will support the airborne multi-frequency antenna array application.

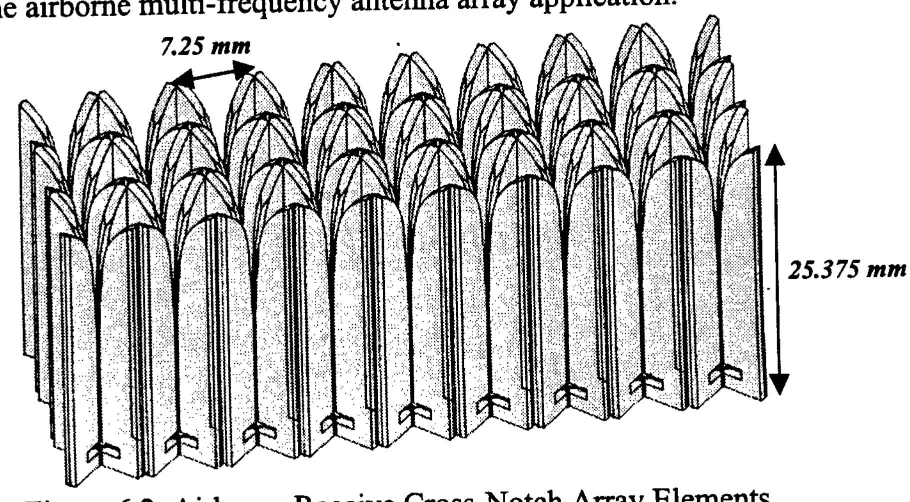

Figure 6.2 Airborne Receive Cross-Notch Array Elements

The airborne receive antenna is expected to support acquisition and auto-track operation for the maintenance of acceptable performance on the downlink channel. We propose the use of electronic con-scan techniques for link acquisition and maintenance just as is implemented in other airborne receive COMM antenna systems. Based on aircraft implemented in other airborne receive COMM antenna systems. Based on aircraft navigation information, the receive beam is initially scanned over a set of grid points so that the satellite target falls from 0.5 dB to 1 dB down from the direction of peak gain and performance. The beam position is dithered at a higher resolution at a 1 μs refresh rate and the mean beam position modified in a closed loop fashion to minimize the dither on the signal resulting in optimum pointing accuracy during operation of the downlink. The 1 μs refresh rate equates to 1 MHz modulation on the phase weighting sections and operation of the ASIC control circuits. This level of performance for the phase weighting sections is trivial to accomplish with moderate RF packaging of the birefringent phase sections. The single point beam control that is enabled with photonics and the possibility of high levels of phase resolution also enabled by photonics make the complexity associated with this functionality less restrictive to the antenna architecture scale and design.

6.2.2 Mechanical, Electromagnetic, Issues of the Airborne Arrays

As illustrated in Figure 6.2 as well as Figure 2.4, the antenna elements for both the airborne transmit and receive antennas are not expected to protrude significantly from the aircraft surface. The antenna array structures will be designed so to be "conformal", which by our definition is that the antenna does not protrude more than 6 inches from the aircraft surface. Such limited protrusion will result in minimal impact from airframe drag so that the operation of the aircraft will not be affected by the introduction of the transmit and receive antenna arrays. Fiber optic remoting of the beamformer could also help in minimizing platform or hull penetrations. The small size and weight of the optical fibers would facilitate the transportation of the signals to the remote antenna terminal and should be considered significantly advantageous over RF implementations. Of course, the metallic surface of the aircraft might be expected to impact even slightly the beam pattern formation of the antenna array. The effects of pattern distortion due to the airframe are difficult to model for both the transmit and receive antennas, and also depend on the exact placement of the antenna arrays on the aircraft. As such, the effects due to airframe structure and pattern distortion would be measured during the EDM - Brassboard design process. This would be accomplished by moderate electromagnetic modeling, construction of an airframe mockup, and direct electromagnetic measurement.

6.2.3 Test and Maintenance of the Airborne Arrays

Photonics can also enable the test and maintenance of the airborne arrays. Testing select subarrays or parts of the array are possible simply by disconnecting fiber optic connections and selectively illuminating or powering parts of the array. There are several techniques developed for testing active RF arrays, many of which can be directly applied to the photonically implemented arrays. Selectively powering portions of the optical distribution module will enable test and performance verification for the antenna systems. The conformal nature of the photonically implemented phased arrays also enable ease of access to the antenna structure which will work to reduce maintenance and performance verification costs and complexity.

7. EXPLORATORY DEVELOPMENT MODELS (EDM) – BRASSBOARD DEMONSTRATION

As a recommendation of future work in developing photonically implemented antennas for SATCOM applications, we propose the construction of EDM or brassboard demonstrations for three specific structures. They include the photonically implemented spaceborne receive MBA beamformer (Figures 3.1, 3.2, and 3.5), the nulling antenna signal correlation processor (Figure 4.4), and the airborne transmit antenna aperiodic array (Figures 2.2, 2.3, and 2.4). Due to the perceived novelty and high risk of photonics, we recommend that the following design development path be undertaken from EDM to flight qualification (for the spaceborne systems). Subsequent to construction of the EDM unit for concept definition and demonstration, a brassboard unit be constructed that incorporated the necessary support electronics and systems to demonstrate full flight level operation. A qualification model would then be established, possibly from the brassboard that would be subjected to full, environmental, functional, and accelerated life testing. These EDM and brassboard models could be incorporated into existing RF units for flight level RF testing and characterization. Such a development path would serve to accomplish several objectives. Risk reduction and demonstration of perceived novel photonic concepts will do much to demonstrate the feasibility and viability of photonic beamforming and processing approaches. Environmental testing would lead to establishing a basis for the reliability of photonic components and subsystems, especially for space applications. Finally, such testing and demonstration of these components and subsystems will enable the generation of new ideas for application of photonic to military and defense communication architectures.

8. ANTENNA DESIGN LINK BUDGETS

Airborne Transmit Antenna

Frequency (GHz)	44.50
Wavelength (m)	6.74E-03

Item	Unit	Value		
1. Antenna Element Gain	**dB**		**0.00**	
Directivity	dB		1.31	
Antenna Area	m^2	1.80E-05	6.98	cosine q_e=0.75, q_h= 0.75
Aperture Efficiency	%	78.00	-1.08	
Axial Ratio	dB	4.00	-0.22	
RMS error	mils	10.00	-0.24	12 ° phase error
Scan angle	°	70.00	-4.13	q= 0.443
Antenna Losses	dB		-1.31	
Radome	dB	0.30	-0.30	
Polarizer	dB	0.20	-0.20	
Insertion Loss	dB	0.30	-0.30	
Active VSWR	ratio	2.00	-0.51	
2. SSPA module	**dB**		**-0.18**	
Power Out	W	0.96	-0.18	
Insertion loss	dB	0.00	0.00	past SSPA
Net EIRP per Element	**dBW**		**-0.18**	
4. Array Level	**dB**		**45.33**	
Number of Elements		200	46.02	power combining gain + antenna gain
End of Life	%	95.00	-0.45	
Pointing Error	°	0.00		
Half Power Beamwidth (of array)				
Pointing Loss	dB	0.25	-0.25	
EOC loss	dB	0.00	0.00	
5. Number of beams		1.00	**0.00**	
Array EIRP	**dBW**		**45.14**	

Spaceborne Transmit Antenna

Frequency (GHz)	20.70		
Wavelength (m)	1.45E-02		

Item	Unit		Value		
1. Antenna Element Gain	**dB**		**14.64**		
Directivity	dB		15.32		
Antenna Area	m^2	1.00E-03	17.78	conical pattern	
Aperture Efficiency	%	78.00	-1.08		
Axial Ratio	dB	2.00	-0.06		
RMS error	mils	20.00	-0.21	12 ° error	
Scan angle	°	9.00	-1.11	q=10.3	
Antenna Losses	dB		-0.68		
Radome	dB	0.10	-0.10		
Polarizer	dB	0.10	-0.10		
Insertion Loss	dB	0.30	-0.30		
Active VSWR	ratio	1.50	-0.18		
2. SSPA module	**dB**		**-6.20**		
Power Out	W	0.24	-6.20		-50.20
Insertion loss	dB	0.00	0.00	past SSPA	
Net EIRP per Element	**dBW**		**8.45**		
4. Array Level	**dB**		**47.71**		
Number of Elements		271	48.66	combining gain + antenna gain	
End of Life	%	95.00	-0.45		
Pointing Error	°	0.00			
Half Power Beamwidth (of array)					
Pointing Loss	dB	0.50	-0.50		
EOC loss	dB	0.00	0.00		
5. Number of beams		4.00	**-6.02**		
Array EIRP	**dBW**		**50.14**		

Airborne Receive Antenna

Frequency (GHz)	20.70
Wavelength (m)	1.45E-02
Element Temp. (K)	300

Item	Unit	Value	Gain	
Incident Intensity	dBm	-74.25		$Pt*Gt*(1/4pR)^2$
Background Noise Temp.	K	100		
(assumes isotropic noise)				
1. Antenna Element Gain			**-1.94**	
Antenna Directivity	**dB**		**-1.27**	Q of aperture
Antenna Area	m^2	8.40E-05	7.02	cosine , $q_e = q_h = 0.75$
Aperture Efficiency	%	78.00	-1.08	
Axial Ratio	dB	4.00	-0.22	
RMS error	mils	0.00	0.00	
Scan angle	°	70.00	-6.99	q= 0.75
Antenna Losses (La)	**dB**		**-0.68**	
Radome	dB	0.30	-0.30	
Polarizer	dB	0.10	-0.10	
Insertion Loss	dB	0.10	-0.10	
Active VSWR	ratio	1.50	-0.18	
T_{ae}	K	128.9		
$T_{sys} = T_{e1} + T_{e2}/A_1 + T_{e3}/A_1A_2 + etc..$	K	374.1		
$T_{eq} = T_{ae} + T_{sys}$	K	503.0		
ELEMENT T_{eq}	dB	**27.02**		
ELEMENT G/Teq	dB	**-28.96**		
ARRAY GAIN	**dB**		**34.305**	
Number of Channels		3240	35.11	
Random Amp. & Phase Errors	dB	0.3	-0.3	
Quantization Loss	dB	0	0	
Pointing Loss	dB	0.5	-0.5	
EOC loss	dB	0	0	
ARRAY G/T (dB)	**5.35**			

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