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This paper describes the United States Office of Naval Research (ONR) Ultra Small Aperture Terminal (USAT) project. The objective of this project is to advance the state-of-the-art in 30/20 GHz active phased array antennas and miniaturized frequency converter technologies to support the wideband SATCOM requirements of future mobile vehicle construction.

To reduce costs, the ONR USAT project aims to demonstrate these technologies in a Mechanically Augmented Phased Array (MAPA) antenna that uses a combination of mechanical and electronic steerage. The MAPA can provide full hemispherical coverage (zenith to horizon) for one third to one fourth the cost of an equivalent terminal using multiple phased array panels. Furthermore, the cost of installing a single MAPA can be significantly less than the cost of installing multiple phased array panels.

A proof-of-concept experiment designed to demonstrate the MAPA USAT's performance is proposed to take place in Italy, using the Italian Space Agency's ITALSAT F1 and/or F2 satellite(s), and a P-3C Orion aircraft outfitted with the MAPA USAT as the mobile test platform.

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Ka-Band Mechanically Augmented Phased Array (MAPA) Antenna for Ultra Small Aperture Terminal (USAT)

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Abstract

This paper describes the United States Office of Naval Research (ONR) Ultra Small Aperture Terminal (USAT) project. The objective of this project is to advance the state-of-the-art in 30/20 GHz active phased array antennas and miniaturized frequency converter technologies to support the wideband SATCOM requirements of future mobile vehicle construction. To reduce costs, the ONR USAT project aims to demonstrate these technologies in a Mechanically Augmented Phased Array (MAPA) antenna that uses a combination of mechanical and electronic steering. The MAPA can provide full hemispherical coverage (zenith to horizon) for one third to one fourth the cost of an equivalent terminal using multiple phased array panels. Furthermore, the cost of installing a single MAPA can be significantly less than the cost of installing multiple phased array panels. A proof-of-concept experiment designed to demonstrate the MAPA USAT's performance is proposed to take place in Italy, using the Italian Space Agency's ITALSAT F1 and/or F2 satellite(s), and a P-3C Orion aircraft outfitted with the MAPA USAT as the mobile test platform.

1.0 Introduction

Italy's ITALSAT satellites, the United States' Advanced Communication Technology Satellite (ACTS) and Japan's Communication and Broadcasting Engineering Test Satellite (COMETS) have enabled the demonstration of new K/Ka-band technologies that have great potential for dual-use in government and non-government mobile satellite communications (SATCOM) applications. Active phased array antennas are attractive for many applications in mobile SATCOM. This is especially true when the mobile platform in question has simultaneous requirements for streamlining, low radar cross section and high maneuverability. Active phased array antennas have good potential for satisfying the first two requirements because they can be integrated into the skin of a mobile vehicle. On highly maneuverable vehicles, assuming that the electronic beam steering controller (BSC) has sufficient processing speed, phased array antennas can remain locked on the desired satellite through more stressing motion profiles than those which can be handled by purely mechanically steered antennas. Furthermore, the high *EIRP*s and *G/T*s of existing experimental, and emerging government and non-government K/Ka-band (30/20 GHz) SATCOM systems are highly attractive for mobile applications. This is because many vehicles (including aircraft, ships and submarines in addition to ground mobile vehicles) simply do not have sufficient space to accommodate large antennas to support wideband SATCOM requirements. SATCOM systems with high satellite *EIRP*s and *G/T*s can shift the burden of link margin (i.e., aperture size) away from the mobile terminal. Processing transponders in future 30/20 GHz SATCOM could further help to reduce mobile terminal aperture size requirements.

1.1 MAPA: A Cost-Saving Technical Approach

This paper describes a K/Ka-band active phased array antenna component and mobile terminal technology development project that is sponsored by the United States Department of the Navy (DoN) Office of Naval Research (ONR). The objective of ONR's Ultra Small Aperture Terminal (USAT) Project is to advance the state-of-the-art in K/Ka-band active phased array antenna components and miniaturized frequency converter technologies to help support the wideband SATCOM requirements of future mobile vehicle construction. The cost-saving programmatic approach employed in this project is to demonstrate these technologies in a prototype terminal that is suitable for backfit onto existing mobile platforms without integrating the antenna directly into the skin of the vehicle or

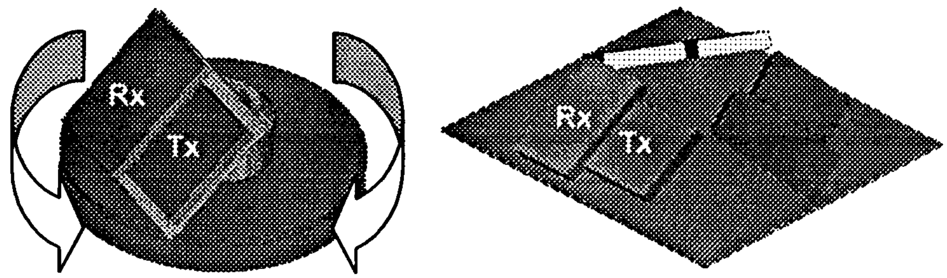

Figure 1 The MAPA approach (left) allows a capable mobile SATCOM terminal to be fielded with one-third the number of elements of an equivalent[1] static boresight approach (right). The trade-off is usually an increased vertical profile for the MAPA. At today's prices, the cost of the MAPA's mechanical turntable is insignificant compared with the cost of an additional four phased array panels (two each transmit and receive as shown on the right here).

requiring multiple phased array panels to achieve full-hemispherical coverage. The resulting technical approach, the mechanically augmented phased array (MAPA) antenna, shown in Figure 1, uses a combination of mechanical and electronic steering. The MAPA's ability to rotate the boresight of its phased array antennas through 360 degrees of azimuth allows a reduction in the number of active elements required to achieve full hemispherical coverage by a factor of 3 to 4 compared to approaches that hard-mount phased array panels on the skin of the vehicle. As a result, the MAPA approach allows the fundamental phased array component technologies to be demonstrated in a fieldable prototype that costs from one third to one fourth less than an equivalent terminal that employs multiple panels. This follows from the fact that the majority of the costs associated with today's state-of-the-art active phased array antennas are directly traceable to the gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) modules from which their active elements are constructed.

The remainder of this paper includes a discussion of planned and prospective DoD use of 30/20 GHz SATCOM, a description of the MAPA USAT currently under development, and a possible demonstration of the MAPA USAT aboard a P-3C Orion aircraft in Italy with the ITALSAT satellites.

2.0 The DoD and 30/20 GHz SATCOM

The DoD is currently defining the details of the architecture of a new three-satellite X/K/Ka-band military satellite communications (MILSATCOM) system named Wideband Gapfiller Satellite (WGS) [1]. The arrival of WGS, with its first launch scheduled for 2004, is timed to coincide with the expected end-of-life of a number of the current DoD Defense Satellite Communications System (DSCS) X-band satellites. However, instead of just maintaining the 500 MHz of government X-band bandwidth,[2] WGS will also accelerate DoD use of the 1,000 MHz of government K/Ka-band bandwidth, namely 30.0-31.0 GHz Earth-to-space and 20.2-21.2 GHz space-to-Earth. Furthermore, DoD plans an additional new X/K/Ka-band SATCOM system named Advanced Wideband Satellite (AWS) with launch scheduled for 2008. However, even with these planned increases in MILSATCOM capacity and coverage, many analysts have concluded that the total MILSATCOM capacity will continue to fall short of that needed by the DoD to carry out all of its missions. As a result, the entire DoD, and especially the DoN, have made, are making, and will continue to make significant use of commercial SATCOM services to fill the capacity gaps [2]. In the future, the authors expect that DoD will focus much of its commercial SATCOM interests on services provided in the 30/20 GHz band. The potential cost savings associated with the technical feasibility of mobile Earth terminal components common to the entire 3,500 MHz of contiguous government and non-government K/Ka-band SATCOM bandwidth explains our expectations [3]. Nowhere else in the spectrum is there a 3,500 MHz contiguous pair of government/non-government SATCOM allocations for which practical dual-use terminal component technologies will be available in the near-term.

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[1] The use of the word "equivalent" is based on the assumption that each of the 3 phased array pairs on the right can scan through ± 60 degrees of azimuth. If their scan range was ± 45 degrees, 4 pairs would be needed.

[2] 7.90-8.40 GHz Earth-to-space, 7.25-7.75 GHz space-to-Earth.

2.1 The DoD's Commercial Ka-Band SATCOM Acquisition ... ive

On 5 August 1998, the DoD SATCOM Senior Steering G... (SSG) tasked the DoN and the Defense Information Systems Agency (DISA) to co-lead, with j... articipation, the evaluation of commercial business cases for emerging commercial SATCOM ... ems in K/Ka-band. The DoD study team responsible for the resulting Commercial Ka-Band ... COM Acquisition Initiative is addressing:

- DoD's business case(s) for leasing commercial K/Ka-band ... COM services,
- technical specifications of emerging commercial K/Ka-ban... TCOM systems, and
- frequency management issues that could impact DoD (e.g., ... /MS frequency sharing).

DoN members of the DoD study team have published a p... [4] that summarizes their first year of work. Their observations thus far include the fact there is ... onsensus on what the potential total market is, let alone confident predictions of which particular ... mercial K/Ka-band SATCOM offerings may become profitable. Therefore, it is difficult to defend ... sions that might lock DoD into any particular commercial SATCOM venture that is unproven in ... marketplace. DoD is currently reluctant to enter into anchor tenancy agreements that would req... significant Government capital investments prior to the establishment of a sustaining commercial c... mer base.

2.2 Partnered DoD and Private Investment in Dual-Use Tech... gies for K/Ka-Band SATCOM

Despite the challenge of selecting individual "winners" f... the current field of commercial K/Ka-band SATCOM proposals, it is generally agreed that some ... them are going to be successful. Considering this, and that DoD's SATCOM capacity will co... ue to require augmentation by commercial systems, and that the DoD WGS and AWS systems d... bed above are virtual certainties (barring launch failures), it is defensible to invest in technol... s that apply simultaneously to commercial and military systems. This is why the USAT project ... andwidth specifications include both the government and non-government K/Ka bands.[3] This has ... bled the USAT project to take advantage of DoD funds that have been set aside for investment in ... nologies with high potential for "dual-use" in civilian and military applic... ions. The contractual a... gements in DoD's current Dual Use Science & Technology (DUS&T) Pro...ram r... quire that indus... partners contribute no less than 50% of the funds put towards an industry/DoD ... oint project. Fur... more, the return on investment obtained from the industrial contribution is ... pically increase... ecause the funds are internal reinvestment dollars, unburdened by gene...al an... dministrative (G...) costs. Thus, while the authors cannot predict DoD's near-term entrance into ... hor tenancy agr... ents with potential K/Ka-band SATCOM service providers, the viability of D... T is settled.

3.0 ONR's USAT Project

The Space and Naval Warfare Syste... Center, San Dieg... SSC-SD) is the lead technical agency for ONR's USAT Project. From July ... 6 through August ... 1997, SSC-SD and NASA Jet Propulsion Lab (JPL) conducted a major proof ... concept demonstra... on aboard USS *Princeton* using JPL's ACTS Mobile Terminal (AMT) [5]. Thi... monstration, other e... rlier civilian development work [6] and DoD's own experience in 44/20 GHz S... COM all provided v... luable lessons used by SSC-SD to issue Solicitation N66001-98-X-6901, ... ra Small Aperture Terminal (USAT) Advanced Technology for Mobile SATCOM" on 4 Febr... y 1998. The USAT te... hnical evaluation board (TEB) consisted of government personnel from SS... D, JPL, Naval Resea...ch Lab (NRL), NASA Lewis Research Center (LeRC), the German Minist... of Defense, SPAWAR PMW 176 (Navy SATCOM Program Office), Naval Undersea Warfare ... nter (NUWC), Naval Air Warfare Center Aircraft Division (NAWCAD) and ONR. From a larg... umber of white papers and subsequent proposals, the TEB selected only two proposals for contra... awards, one each from Boeing Information, Space & Defense Systems (ISDS) of Seattle, WA and H...ittite Microwave Corporation of Woburn, MA. Boeing proposed to build a MAPA, while Hittite p...posed to build a miniaturized RF/IF translation and amplification subsystem (RFTAS). Figure 2 shows the architecture of the MAPA USAT.

[3] 27.5-31.0 GHz Earth-to-space, 17.7-21.2 GHz space-to-Earth.

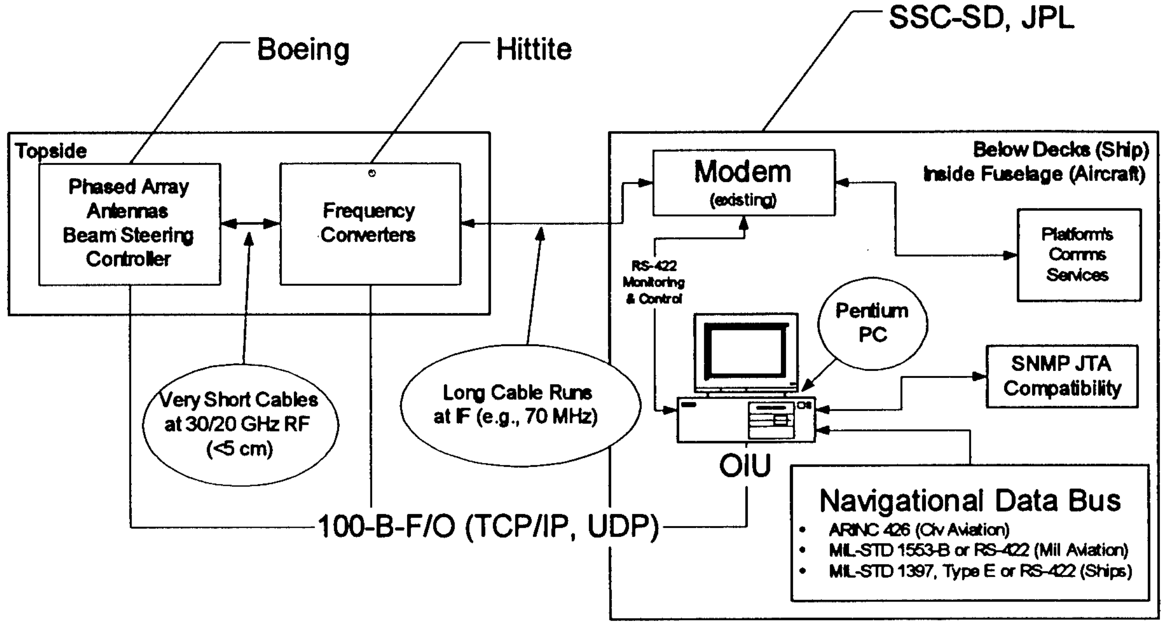

Figure 2 MAPA USAT system architecture diagram showing the division of responsibilities between the team members. The diagram also points out an important advantage of active phased array antennas for mobile SATCOM terminal applications. Namely, there is no separate high power amplifier (HPA). Instead, the HPA function is dispersed throughout the active elements of Boeing's transmitter phased array. This saves space and eliminates the HPA as a potential single point failure. Furthermore, note that Hittite's miniaturized IF/RF frequency converters are located immediately adjacent to the antenna array (<5 cm away). This allows the long cable runs to be at IF instead of RF, avoiding the need to run waveguide, thereby reducing installation costs. The operator interface unit (OIU) is based on a commercial off-the-shelf (COTS) portable PC with multiple PCI and ISA board slots. The OIU uses the User Datagram Protocol (UDP) to send vehicle navigational data at high speeds to the beam steering controller (BSC). In the reverse direction, the BSC sends samples of the received signal level (RSL) and electronic-beam/mechanical-turntable steering angles to the OIU for display and recording. This capability is a great aid during post-installation system operational verification and test (SOVT) procedures and for routine performance monitoring and troubleshooting. The OIU also provides compatibility with the Defense Information Systems Agency (DISA) Joint Technical Architecture (JTA) via a Simple Network Management Protocol (SNMP) capable interface.

3.1 Boeing ISDS' MAPA (by Jim Freeman of Boeing ISDS)

The USAT antenna system combines electrical and mechanical scan techniques to provide beam agility at low cost for mobile platforms. Phased arrays are desirable for mobile platforms because they can compensate for the platform motion by electronically adjusting the direction of the beam. At high scan angles, however, the projected area of the planar array drops rapidly and the array size must be increased to maintain adequate performance. This limits their practical usage to latitudes within ± XX degrees (for geosynchronous satellites) or to installations where multiple phased arrays can be accommodated at different boresight look angles on a platform.

On ONR's USAT project, the electronic agility of the phased array will be combined with coarse mechanical motion and a fixed tilt angle to reduce the scan angle losses and thus reduce the size and cost of the agile antenna. A turntable is used to provide approximate azimuthal positioning while the arrays themselves provide elevation and azimuth scanning of ± 40-50 degrees. The motor is only needed to remove macroscopic platform motions (e.g., heading changes) and thus moves infrequently. Tracking of a satellite and compensation of small platform motions is achieved electronically. This approach, called MAPA (mechanically augmented phased array), provides full hemispherical coverage, enabling application to GEOs from extreme latitudes (i.e., beyond ± XX deg), LEOs anywhere, and mobile platforms with large roll angles.

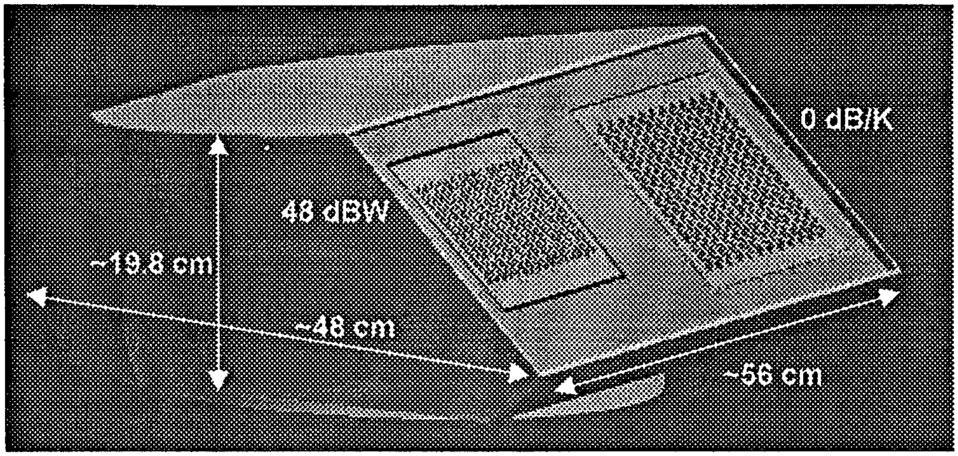

Figure 3 Boeing's current 30/20 GHz MAPA USAT packaging design. Objective 30 GHz *EIRP* & 20 GHz *G/T* specs. for the max. electronic scan angles are 48 dBW & 0 dB/K, respectively. In simulations, the array patterns shown have grating lobe free scan ranges of ±60° in elevation and ±45° in azimuth.

Our implementation of the MAPA antenna uses a 27.5-31.0 GHz, 512-element active-aperture phased array antenna mounted at a 45-degree angle as shown in Figure 3. This aperture is approximately 14 by 22 cm. before mounting on the tilted structure of the turntable. Each element of the array contains a compact MMIC phase shifter and power amplifier implemented in 0.25 micron PHEMT GaAs. The power is directly coupled into a circular-waveguide radiating element that, when combined with a wide-angle impedance-matching (WAIM) layer, exhibits nearly $\cos(\theta)$ scan loss (i.e., the minimum achievable scan loss). The polarization can be electronically selected as either left-hand-circular or right-hand circular (LHCP or RHCP, respectively). The *EIRP* is designed to be at least 48 dBW at scan angles up to 45 degrees. 60-degree scanning is possible in elevation to provide overlap directly overhead and to maintain the link during severe roll. The module technology is a fourth-generation design that builds upon similar communications arrays built by Boeing from 8 to 44 GHz [7], [8]. USAT will also include a 384-element 20 GHz receive phased array for the downlink, based on arrays already built by Boeing for DoD MILSTAR and Global Broadcast Service (GBS) reception. The two USAT arrays would be adjacent on the tilted platform and could be used with a shroud over the back of the arrays for low-speed platforms or an external radome if required.

3.2 Hittite's RFTAS (by Frank Paik of Hittite Microwave Corporation)

Hittite Microwave Corporation [9] is developing a miniaturized package of frequency converters for mobile Earth terminals operating at K/Ka-band known as the RF translation and amplification system (RFTAS). Figure 4 shows the top-level block diagram of the RFTAS which consists of tunable up/downconverters and a low noise block downconverter (LNB). The USAT Project plan has two phases. The RF ranges and IFs shown in Figure 4 will be available at the end of Phase II. For Phase I, the RFTAS RF range is limited to 19.2-20.2 GHz and there will be a single IF of

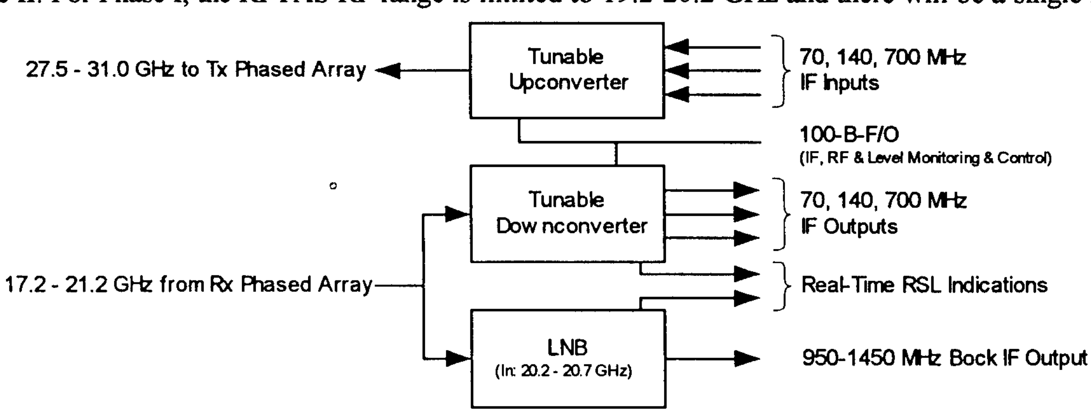

Figure 4 RF translation and amplification system (RFTAS) architecture (USAT Project Phase II).

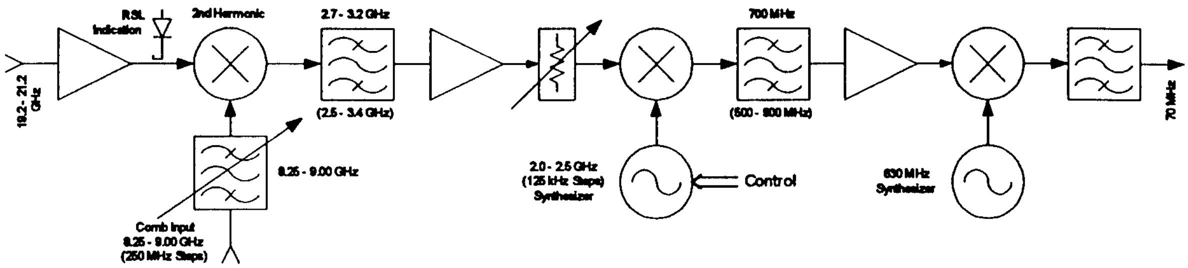

Figure 5 Tunable downconverter for Phase I of the ONR USAT Project.

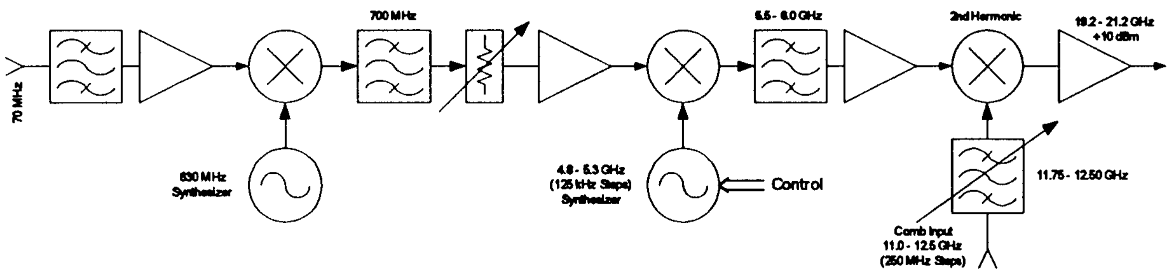

Figure 6 Tunable upconverter for Phase I of the ONR USAT Project.

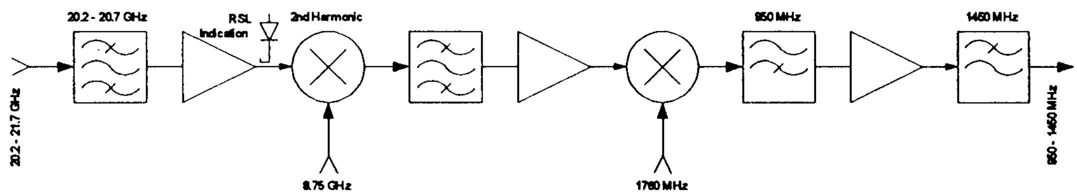

Figure 7 LNB for the ONR USAT Project.

70 MHz. The tunable downconverter (Figure 5) translates a selectable downlink frequency to an IF band, and the upconverter (Figure 6) performs the reverse operation to a selectable uplink frequency. In the chain of up/downconverters, there are several amplifiers and filters and a precision attenuator that controls the signal level with an accuracy of 0.25 dB. Tuning is accomplished by selecting the frequency of the second local oscillator, which is tunable in 125 kHz steps. The LNB is a dual conversion device that translates the 20.2-20.7 GHz RF block to the 950-1450 MHz IF block (Figure 7). All three converters will be implemented using MMIC chips for all mixers and amplifiers, including sub-harmonically pumped MMIC mixer chips, and commercial off-the-shelf (COTS) parts for frequency synthesizers. All three converters along with the associated digital circuits for amplitude/frequency monitoring and control and via UDP will be assembled into a miniaturized package sized 19 x 14.6 x 4 cm. (~1110 cubic cm.) using all passive filters. Hittite is also investigating the possibility of using emerging active filters with greatly improved phase noise performance. If this approach proves feasible, it could reduce the total package size by roughly 3/4 to ~278 cubic cm.

4.0 USAT Demonstration Possibility with ITALSAT

Because the ONR USAT Project is addressing the 30/20 GHz SATCOM terminal requirements of ships, aircraft and ground mobile vehicles, there are several possibilities for demonstrations of the MAPA USAT. One very likely demonstration would involve the P-3C Orion, a land-based aircraft designed for maritime patrol missions. The P-3C is widely deployed throughout the world and it is often the first reconnaissance asset on-scene. As such, DoD could benefit if P-3C crews were able to transmit video from their onboard camera systems in real-time to shore-based and shipboard command and control centers. The USAT MAPA is an option for providing this capability. ITALSAT provides an opportunity to demonstrate the capability in a region of high interest to DoD and NATO.

Alenia Aerospazio Space Division developed the ITALSAT satellites for the Italian Space Agency to support K/Ka-band propagation research and SATCOM technology testing. ITALSATs F1 and F2 were launched in January 1991, and August 1996, respectively. F1 has already lasted years past its expected end of life (EOL); F2's EOL is in 2004. Each has two payloads for point-to-point (multi spot beam (SB) payload) and point-to-multipoint (National beam (NB) payload). Figure 8 shows the ITALSAT SB and NB coverage maps.

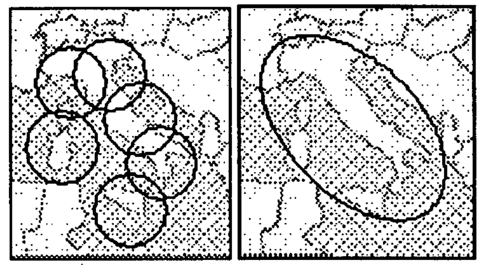

Figure 8 Left: SB, Right: NB [10].

Figure 9 and Figure 10 present USAT/ITALSAT link budgets for 97% availability and no-rain conditions, respectively, using the ITALSAT communications payload descriptions in [11] and [12], ITU meteorological data for Italy and the methods of [13] and [14]. These results predict that the link margin will (1) be greater than that shown in Figure 9 for 97% of the time and (2) never be greater than that shown in Figure 10. An aircraft can often obtain the best case performance (Figure 10) at will if link margin is limited by rain in the vicinity of the aircraft and it is possible to fly above the rain. Although these results must be considered preliminary until they are discussed in detail with the Italian Space Agency, there is clearly the potential to demonstrate a significant real-time airborne surveillance sensor data off-load capability using the MAPA USAT and ITALSAT. Future work will develop a detailed MAPA USAT demonstration plan using ITALSAT.

5.0 Summary

DoD interest in 30/20 GHz SATCOM can be expected to increase over the next 2-4 years. This paper introduced a dual-use technology development effort that anticipates this increased interest. The MAPA USAT project will advance the state-of-the-art in 30/20 GHz active phased array antennas and miniaturized frequency converter technologies, and deliver a multi-platform prototype terminal.

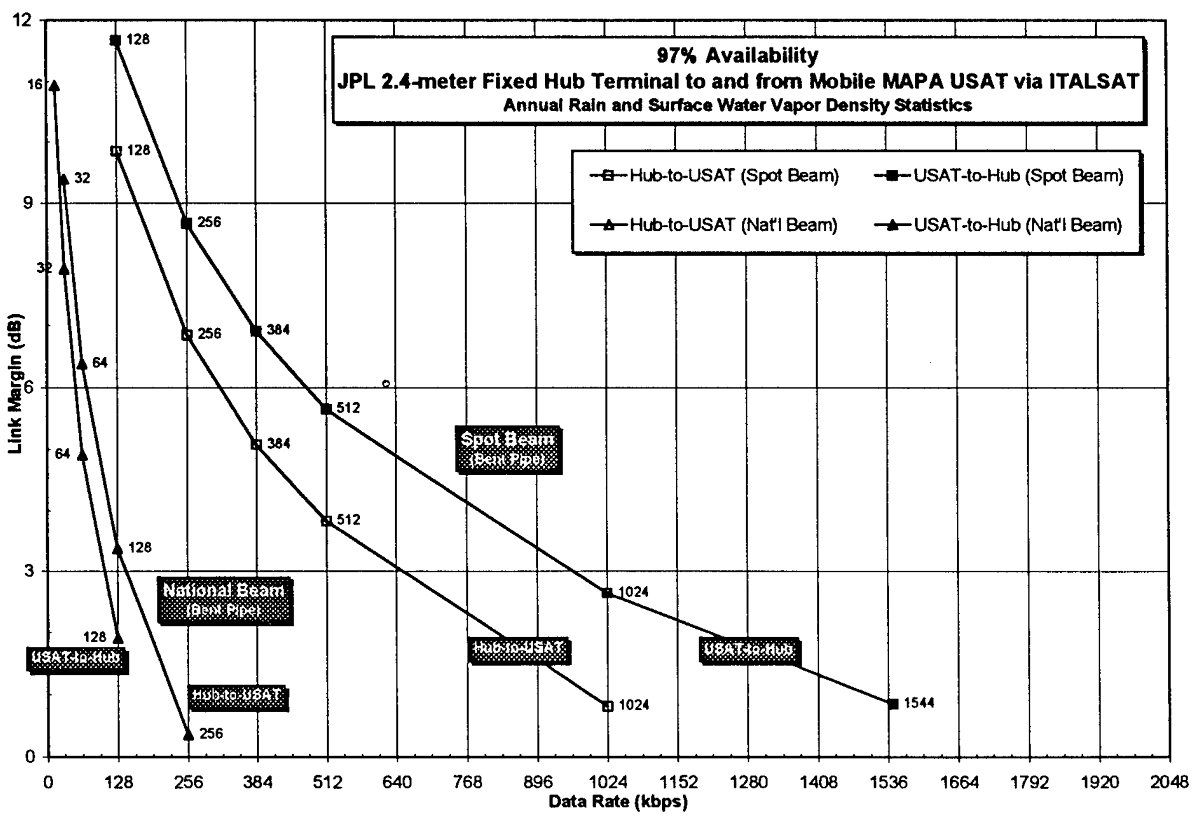

Figure 9 Link budget calculations for 97% availability of a full duplex hop between JPL's (portable) fixed 2.4-meter hub Earth terminal and the mobile USAT (performance parameters in Figure 3).

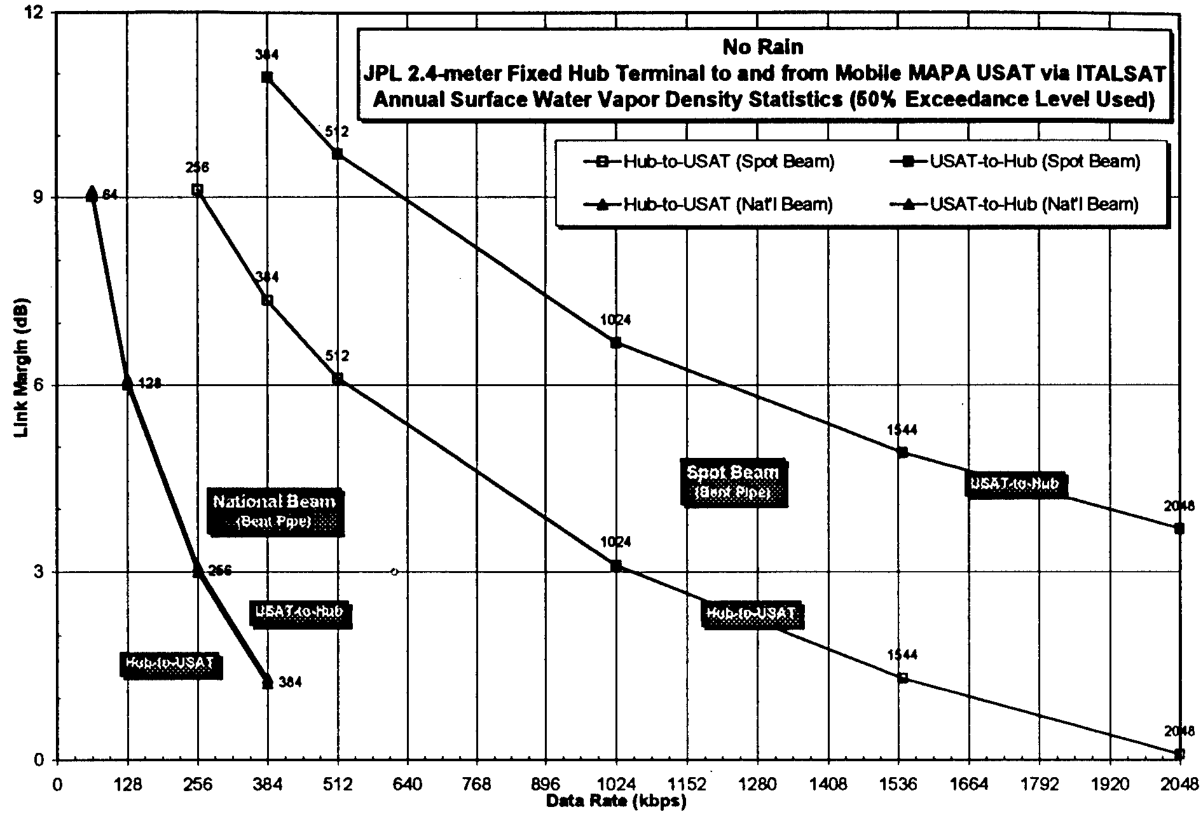

Figure 10 Link budget calculations for no-rain conditions. Full duplex hop between JPL's (portable) fixed 2.4-meter hub Earth terminal and the mobile USAT (performance parameters in Figure 3).

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