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Roy A. Axford, Jr.

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This paper describes a K/Ka-band ("two-way Ka") active phased array antenna and mobile terminal technology development project co-sponsored by the Office of Naval Research (ONR) Future Naval Capability (FNC) Program and the Defense Advanced Research Projects Agency (DARPA) Future Combat Systems Communications (FCSC) Program. The objective of the ONR/DARPA 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 converters to provide wideband satellite communications on the move (COTM) capabilities for mobile vehicles. By using a mechanically augmented phased array (MAPA) antenna, USAT demonstrates these technologies in a prototype that requires one transmit array and one receive array to achieve full-hemispherical coverage.

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ULTRA SMALL APERTURE TERMINAL (USAT) PHASED ARRAY TECHNOLOGY DEMONSTRATOR

Roy A. Axford, Jr.
Space and Naval Warfare Systems Center
San Diego

ABSTRACT

This paper describes a K/Ka-band ("two-way Ka") active phased array antenna and mobile terminal technology development project co-sponsored by the Office of Naval Research (ONR) Future Naval Capability (FNC) Program and the Defense Advanced Research Projects Agency (DARPA) Future Combat Systems Communications (FCS-C) Program. The objective of the ONR/DARPA 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 converters to provide wideband satellite communications on the move (COTM) capabilities for mobile vehicles. By using a mechanically augmented phased array (MAPA) antenna, USAT demonstrates these technologies in a prototype that requires one transmit array and one receive array to achieve full-hemispherical coverage.

INTRODUCTION

Active phased array antennas (PAAs) are candidates for satellite communications on the move (COTM) applications when the vehicle in question has requirements for streamlining and/or low radar cross section (RCS). Furthermore, the high EIRPs and *G/T*s of the K/Ka-band portion of the Wideband Gapfiller Satellite (WGS) System allow useful data rates to be achieved using relatively small apertures in the mobile terminal. This paper describes a K/Ka-band active PAA and mobile terminal technology development project called Ultra Small Aperture Terminal (USAT). USAT aims to demonstrate new PAA and miniaturized frequency converter technologies in an affordable prototype terminal that is suitable for installation in a variety of mobile vehicles. USAT's mechanically augmented phased array (MAPA) antenna, shown in Figure 1, uses a combination of mechanical and electronic steering to achieve full-hemispherical coverage with one transmit array and one receive array. The MAPA approach thus allows the PAA technologies to be demonstrated in a prototype that costs less than a terminal that employs multiple panels.

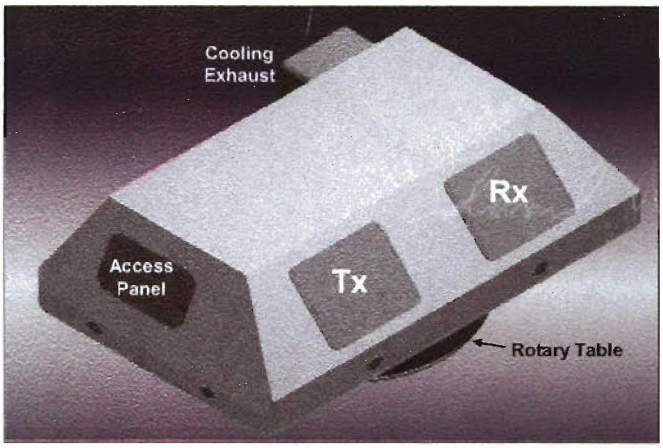

Figure 1. In the USAT MAPA, one transmit array and one receive array are mounted on a rotary table. The arrays steer electronically in the same manner they would if hard mounted. The rotary table compensates for the heading of the vehicle while the electronic steering tracks out faster variations in roll, pitch and yaw.

THE USAT PROJECT - BACKGROUND

The Space and Naval Warfare Systems Center, San Diego (SSC SD) is the lead technical agency for the ONR/DARPA USAT Project. From July 1996 through August of 1997, SSC SD and NASA Jet Propulsion Lab (JPL) conducted a proof-of-concept demonstration aboard USS *Princeton* (CG 59) using JPL's Advanced Communications Technology Satellite (ACTS) Mobile Terminal (AMT) [1]. This demonstration and other earlier development work [2] provided the basis for SSC SD Solicitation N66001-98-X-6901, "Ultra Small Aperture Terminal (USAT) Advanced Technology for Mobile SATCOM" on 4 February 1998. The USAT technical evaluation board (TEB) consisted of government personnel from SSC SD, JPL, Naval Research Lab, NASA Lewis Research Center (LeRC), the German Ministry of Defense, SPAWAR PMW 176 (Navy SATCOM Program Office), Naval Undersea Warfare Center (NUWC), Naval Air Warfare Center Aircraft Division (NAWCAD) and ONR. From a large number of white papers and subsequent proposals, the TEB selected only two proposals for contract awards, one each from Boeing Phantom Works of Seattle, WA and Hittite Microwave Corporation of Chelmsford, MA. Boeing proposed to build a MAPA, while Hittite proposed to build a miniaturized K/Ka-band frequency converter unit (FCU). SSC SD awarded both contracts in 1Q FY1999. As of this writing, the FCU has been completed and the MAPA is in the final stages of assembly.

Figure 2. USAT MAPA with cover removed. The arrays are tilted back at a fixed angle of 45°. A self-contained liquid-to-air heat exchanger for cooling the arrays is visible behind the foreground array. The rotary table on which the arrays are mounted can be programmed to move in step sizes ranging from 1° to 45° per step, subject to the restriction that the selected step size is a divisor of 360.

BOEING'S USAT MAPA PAAs

The transmit phased array in Boeing's USAT MAPA uses 512 elements to achieve a design effective isotropic radiated power (EIRP) of 48 dBW at 45° scan from boresight. The polarization of the transmit beam is selectable between right hand circular and left hand circular (RHCP and LHCP). The transmit array supports signals in the frequency range from 29 to 31 GHz.

The receive phased array uses 384 elements to achieve a

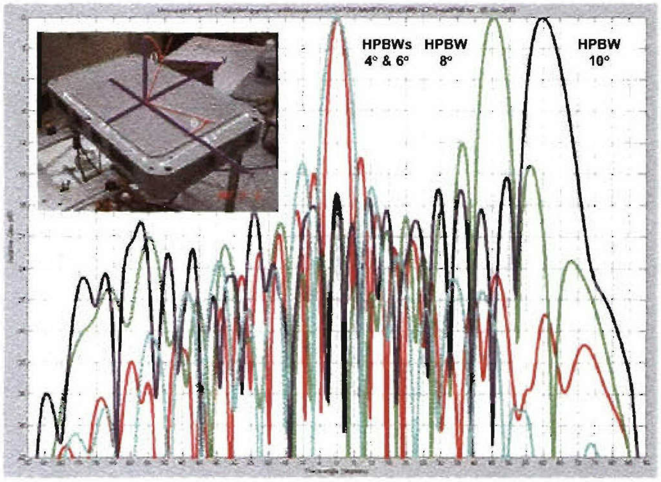

Figure 3. Receive array LHCP far field directivity patterns. Red: $\theta = 0°$, $\phi = 0°$; Light blue: $\theta = 0°$, $\phi = 90°$; Green: $\theta = 45°$, $\phi = 90°$; Blue: $\theta = 60°$, $\phi = 90°$.

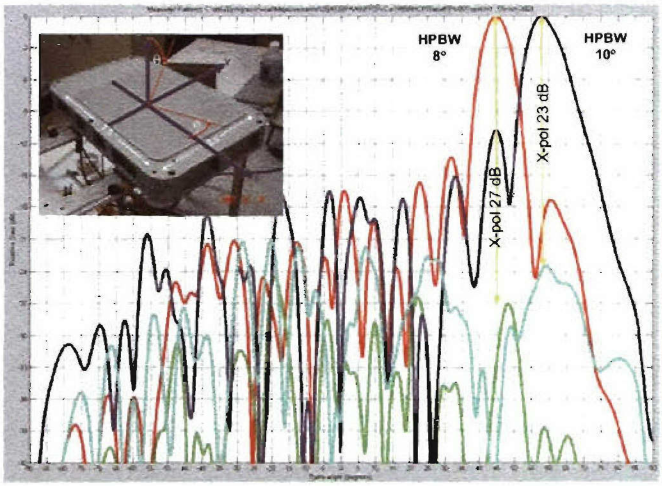

Figure 4. Receive array RHCP far field directivity patterns with cross-polarization isolation from the LHCP signal.

design G/T of 0 dB/K at 45° scan from boresight. The receive array can support two independently steerable beams simultaneously, one RHCP and the other LHCP. (The FCU, which was specified before Boeing embarked on a dual-beam receive array design, only has one receive channel and therefore can only support one polarization at a time.) The receive array can accommodate signals in the frequency range from 19.2 to 21.2 GHz.

The USAT Project's EIRP and G/T design objectives were based on the specifications and performance of the AMT deployed in [1], which routinely achieved a full duplex T1 data rate using the ACTS steerable beam to serve the mobile terminal, and an ACTS fixed beam (named "East 18") to serve a 2.4-meter fixed terminal on the other end of the hop (located at JPL).

Boeing has completed assembly of the receive array and generated a compensation table at 19.85 GHz using a near field planar scanner (NFPS). Figure 3 shows LHCP far field directivity patterns for beam scan angles of $\theta = 0°$, 45° and 60° in the $\phi = 90°$ plane, as well as $\theta = 0°$ in the $\phi = 0°$ plane. Note that the beam directivity is narrower at boresight in the $\phi = 0°$ plane than in the $\phi = 90°$ plane. This is simply because the array aperture is wider in the $\phi = 0°$ plane. Figure 4 shows measured cross polarization isolation $\geq$23 dB at $\theta = 45°$ and 60° in the $\phi = 90°$ plane.

Boeing's 512-element USAT MAPA transmit array is still under construction as of this writing. The performance of a 16-element proof-of-concept transmit array with elements that will populate the full size array was very promising in terms of achieving the design objective EIRP.

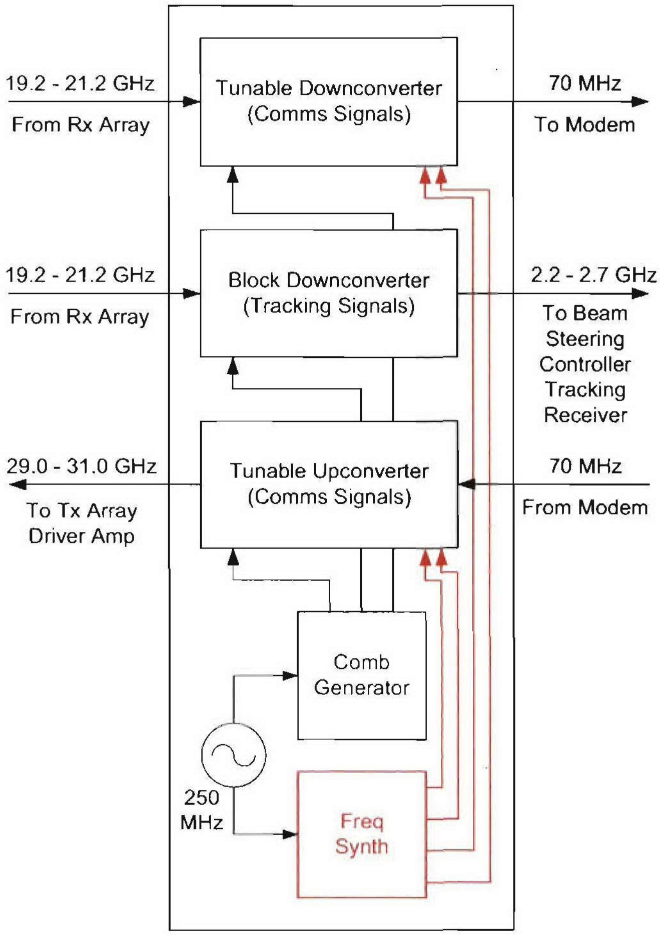

Figure 5. FCU functional block diagram (simplified).

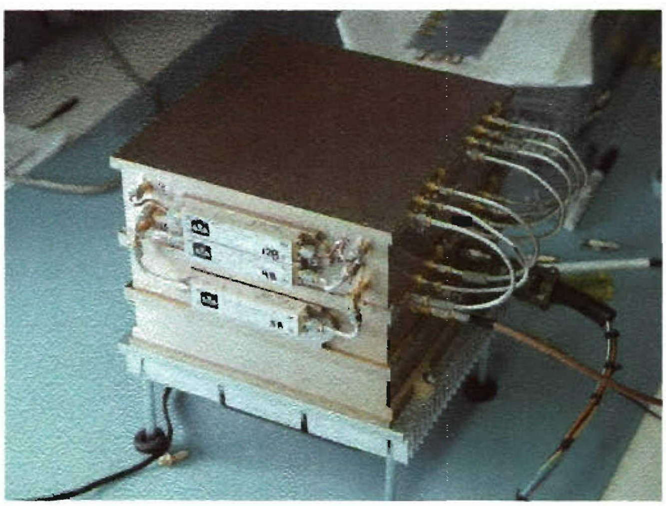

Figure 6. Completed FCU. As shown, heat fins are used for cooling when operating in the lab. When installed in the USAT MAPA, the FCU is mounted on a cold plate.

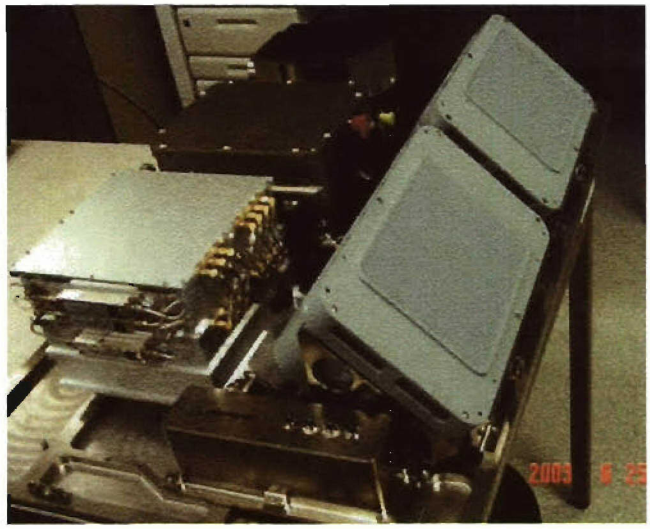

Figure 7. FCU shown mounted in the USAT MAPA.

FREQUENCY CONVERTER UNIT (FCU)

Figure 5 shows a functional block diagram of the FCU with the supported radio frequency (RF) ranges. The tunable converters, with a tuning step size of 125 kHz, support transmitted and received communications signals. The block downconverter provides received signal energy to Boeing's beam steering controller for closed-loop acquisition and tracking.

Figure 6 shows a photograph of the completed FCU. The final packaging was performed by JPL. Figure 7 shows the FCU installed in Boeing's USAT MAPA. Because the FCU resides on the MAPA turntable, the lengths of the 20- and 30-GHz RF cable runs can be kept to a minimum. The 70-MHz transmit IF signal uses one RF channel of the turntable rotary joint, while the 70-MHz receive IF signal and the 2.2-2.7 GHz tracking signal share a second RF channel. The isolation between these two RF channels was specified at 50 dB and has been measured at >60 dB.

A lesson-learned from the USAT Project was that the FCU development turned out to be a greater challenge than originally anticipated. For instance, each blue trace in Figure 5 from the comb generator to a converter subsystem represents the coarse-tuning local oscillator (LO) frequency that determines which one of the four 500-MHz segments of the relevant RF band is addressed. Hittite Microwave Corporation had originally intended to select the needed frequencies from the comb with electronically tunable active filters. When this approach proved to be unachievable with available funding, our fallback position was to perform this tuning with passive filters that, necessarily, must be physically removed and replaced to change from one 500-MHz RF segment to another. For the purposes of the USAT Project, this approach is satisfactory because the frequency plan of any field demonstration would be limited to a single 500-MHz RF segment. The three filters in question are mounted on the exterior of the FCU housing as shown in Figure 6. They can be serviced by removing the access panel shown in Figure 1. Considering recent advances in monolithic microwave integrated circuit (MMIC) technology, the Hittite Microwave Corporation believes that a follow-on FCU effort could produce a smaller unit with greater flexibility.

USAT MAPA SYSTEM ARCHITECTURE

Figure 8 shows a block diagram of the entire USAT MAPA system. The inertial navigation system (INS) provides assistance to the antenna control unit (ACU) for initial acquisition. Once signal acquisition has been achieved, tracking relies on a classic four-point closed loop algorithm; the INS serves only to confirm the power tracking algorithm's center point after initial acquisition. An algorithm that uses INS-provided attitudes and attitude rates in addition to the four-point signal-power algorithm in order to track through signal outages (e.g., due to blockage) was beyond the scope of Boeing's USAT MAPA effort, of which the primary focus was to develop high-performance 30/20 GHz phased array module technologies suitable for mass production. This closed-loop tracking algorithm is expected to be adequate for demonstrating the phased arrays in realistic field trials.

EXPECTED COMMUNICATIONS PERFORMANCE

In preparation for field trials of the USAT MAPA, SSC SD has procured the commercial-off-the-shelf (COTS) 2.4-meter K/Ka-band antenna system shown in Figure 9 [3]. This system has two swappable antenna feeds with frequency coverage as follows:

- Linearly Polarized Feed
  - Tx: 29.0 to 30.0 GHz
  - Rx: 19.2 to 20.2 GHz
- Circularly Polarized Feed
  - Tx: 30.0 to 31.0 GHz
  - Rx: 20.2 to 21.2 GHz

The EIRP and G/T of the 2.4-meter system are nominally 68 dBW and 27 dB/K, respectively, subject to verification by a 4Q FY03 characterization effort.

When determining the data rate capabilities of any SATCOM earth terminal with a transponded satellite, it is necessary to consider the characteristics of the earth terminal at the other end of the hop (the "hub" here). Because the USAT MAPA apertures are as small as they are, it is interesting to plot the achievable hub-to-USAT and USAT-to-hub data rates versus the hub earth terminal aperture diameter. Figure 10 shows such a plot in which the satellite is ACTS, configured as used in [1]. The hypothetical hub earth terminal is the one shown in Figure 9, with EIRP and *G/T* scaled by aperture size according to the abscissa in Figure 10. (In performing the link budget calculations, the following assumptions were made regarding ACTS: (1) saturation flux density = -110 dBW/m^2 at maximum transponder gain, (2) for flux densities <-110 dBW/m^2 incident upon ACTS, the OBO/IBO = 1 dB/dB.) In any future field trials with ACTS, it should be possible to achieve T1 data rates.

SUMMARY

The 30/20 GHz portion of WGS provides DoD opportunities to make available wideband services to smaller aperture mobile terminals. The USAT MAPA is a prototype terminal that enables COTM trials on a variety of mobile platforms. After delivery to SSC SD, the USAT MAPA antenna patterns will be fully characterized at antenna range facilities at NASA's Glen Research Center, Cleveland, OH (test plan in progress). The first planned USAT MAPA field demonstration is on an Army HMMWV in support of DARPA's FCS-C Program (schedule to be determined). Afterwards, SSC SD will pursue a demonstration of the USAT MAPA on a small surface combatant (e.g., the FFG 7 Class). Upgrading the USAT MAPA's INS, ACU and acquisition and tracking algorithm may be pursued if warranted. A follow-on 30/20 GHz FCU technology development effort is recommended because of the miniaturization advances that could be achieved.

ACKNOWLEDGEMENT

Thanks to Greg Bostrom of SSC SD, who performed the link budget calculations presented in Figure 10.

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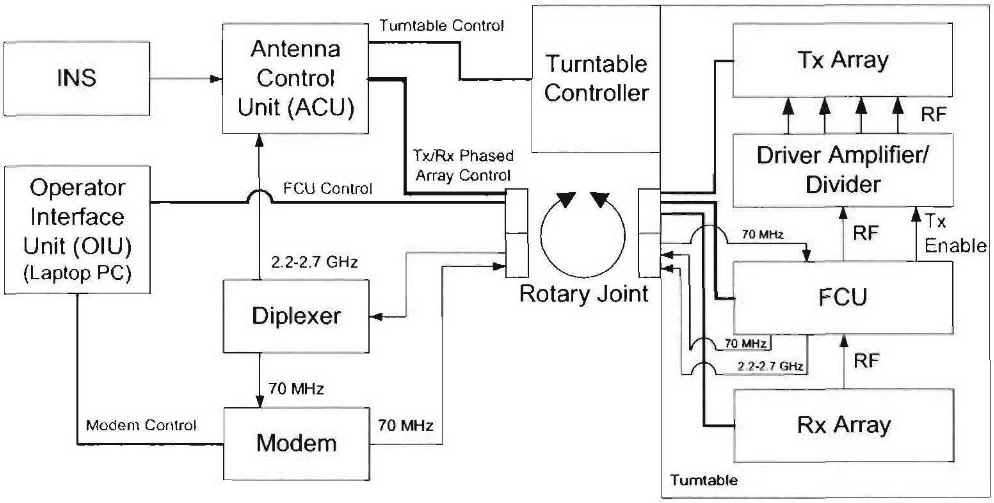

Figure 8. USAT MAPA architecture. The modem could be any with a 70-MHz IF.

Figure 9. 2.4-meter transportable terminal. VertexRSI 240 DMVO antenna system mounted in a 240 AT trailer by Shook Mobile Technologies.

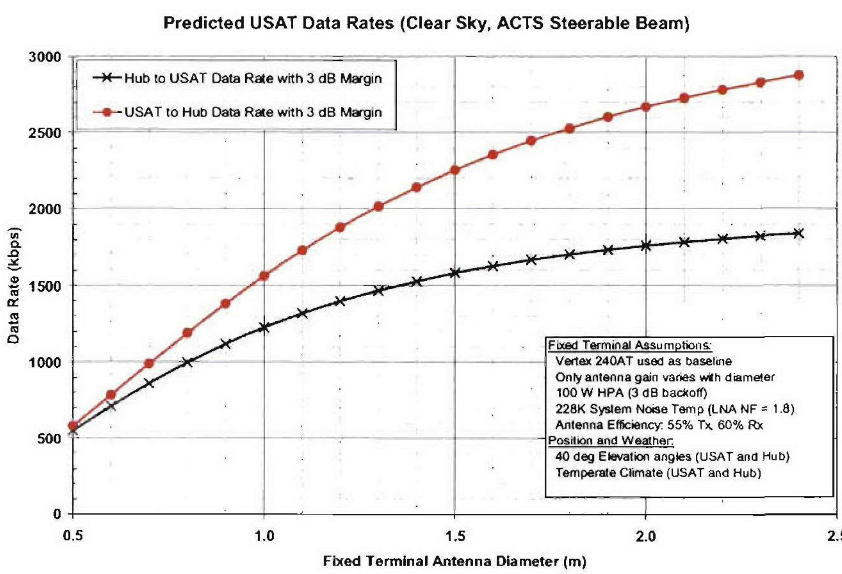

Figure 10. Link budget calculation results. Data rates vs. hub antenna diameter.