An Aeronautical-Mobile 20/30 GHz Satellite-Tracking Antenna for High Data Rate Satcom

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INTRODUCTION

Access to the information superhighway has been extended to aircraft in flight. This was made possible by the recent development of an aeronautical-mobile, high gain satellite-tracking antenna.

The main objective of the antenna development was to provide a demonstration of aeronautical satellite communications that might be deemed commercially viable. This implies a number of related objectives. Video or full graphic applications (common uses of new "information super highway") are the most attractive form of entertainment or computer communications and require a high data rate. A high data rate requires a high-gain antenna with a narrow bearnwidth, and that requires a precise satellite tracking system. Installation on an aircraft implies that the antenna must present a minimal aerodynamic impact, so it must not protrude much outside the fuselage. Furthermore, any modifications to a commercial aircraft require a formal, tedious FAA approval, and commercial airliners desire a quick installation so that aircraft down-time is minimized. An antenna design that accommodates a simple installation is very desirable in those regards. An attractively low cost is certainly an objective for commercially viability. We believe that we have achieved all these objectives with the antenna system summarized in this paper.

During flight tests in October 1995 the antenna successfully tracked the NASA ACTS satellite and enabled 20/30 GHz communications reliably at a rate of 512 Kbps throughout takeoff, cruise and landing between California and Texas -- with no flight restrictions imposed for the sake of the new antenna. The antenna enabled, for the first time ever, a two-way (interactive) PBS-TV children's educational program to be broadcast live across the country from a NASA jumbo jet research aircraft. Children at selected schools across the country teleconferenced live questions to the scientists on the aircraft and remotely controlled a telescope on the aircraft with computer commands sent through the Internet, all via the new antenna. More information about the televised educational program is found on the World Wide Web at "http: //quest. arc.nasa.gov/livef rem/stratosphere. html. " The antenna has also been installed and operated on a small business jet. This paper discusses the antenrna used to provide the high data rate digital satellite communications from aircraft.

SYSTEM OVERVIEW

The antenna is installed on the top of the aircraft fuselage, where it has a nearly unobstructed view of the geostationary ACTS satellite (100 deg West longitude) while in flight in the Western hemisphere. The radome has a diameter of two feet and a height of less than 7 inches. The aerodynamic impact of the radorne on the aircraft flight stability was verified with test flights to be negligible on a C-141 (jumbo jet) anti was found to impose only a minor flight speed restriction on a Sabreliner 50 (small business jet). Installation requires a hole in the fuselage of only 3.5 inch diameter for cable routing. The installation intrudes very little into the cabin, since nearly the entire antenna assembly resides outside the fuselage, under tile radorne. The radome is designed for low loss at both 20 and 30 GHz frequency bands with the mechanical integrity to withstand the aerodynamic load of the air stream at jumbo jet flight speeds.

The antenna incorporates two slotted waveguide arrays situated side-by-side, one each for receive and transmit. The separate receive and transmit arrays both provide more than 30 dB directivity, and thus narrow beamwidths. High speed receive and transmit communications is enabled respectively by the high sensitivity and gain of the antenna. 1 he antenna's narrowest beamwidth of 2 1/2 deg requires accurate tracking as the aircraft turns. The antenna positioner utilizes an elevation-over-azimuth mechanism with a precision of a few hundredths of a degree. A low cost, three-axis, inertial turn rate sensor with 50 t lz bandwidth provides the majority of pointing information for the tracking system. A very low bandwidth (1/2 Hz), small displacement (1/2 deg) conical scan feedback control system completely cancels (in the steady state), and continually adjusts to any changes in, the three axis inertial sensor offsets and drift rates. The overall tracking system accommodates tracking rates anti acceleration up to 60 deg/sec and 30 deg/sec/sec azimuth, and 30 deg/sec and 15 deg/see:/sec elevation. T he antenna system provides full hemispherical coverage.

ANTENNA DESIGN

Several preliminary trade-off studies were conducted to establish the final antenna and positioner architectures. A two-axis, mechanically steered positioner was chosen over electronic scanning for the lower cost and low risk required by the one-year development schedule. The low loss, slotted waveguide array architecture was selected for both receive and transmit because of the lower profile compared to a reflector antenna and lower loss compared to a microstrip array.

Uniform array element excitation was chosen to minimize aperture size. Both array apertures are rectangular except for a staircase-trimmed corner which maximizes use of the volume beneath the curved radome. Both arrays consist of two layers of power division feeding eight subarrays (4 in azimuth and 2 in elevation). These first two layers contain a total of 15 reactive, H-plane Tee power dividers. Power is transferred between the layers through E-plane bends. The final eight Tees feed into the edge walls of eight resonant cavities which contain series slots feeding into the third layer. Each series slot feeds a resonant cavity in the forth layer. Shunt slots in each of the forth layer cavities make up the radiating elements. Designs for the waveguide transitions, E-plane bends and H-plane "1 ees were perfected using an EMS generalized scattering matrix, mode-matching code. Series slot resistances and shunt slot conductance were optimized for minimum across-the-band VSWR using an EMS circuit analysis code. Slot geometries were designed using HP's HFSS finite element code. Both antennas proceeded from design to fabrication without breadboard components.

The four array layers are constructed from a sandwich of 5 CNC machined plates of aluminum. The components are machined to 0.001" tolerance, precisely pinned together and vacuum brazed. Post machining trims the arrays to their final aperture shape, removes excess aluminum from the back sides and provides threaded holes for mounting. The post machined arrays are cleaned and anodized for corrosion protection. Both transmit and receive apertures are approximately 4 x 8 inches, and the arrays are approximately 0.5 inches thick. The meanderline polarizers add another 0.3 inches to the total antenna thickness.

Polarization tracking of the linearly polarized ACTS is obviated by linear-to-circular polarizers mounted in front of the flat plate arrays. Each polarizer consists of three meanderline layers designed using an EMS moment method code using triangular current patches. Array faces were included in the model. The meanderline layers are etched onto copper clad Kapton and are spaced using Rohacell foam.

The radome design required five layers to provide low loss at both K and Ka-band over a O to 60 deg range of incidence angles, and to meet the mechanical requirements of flight. From the inside out, the layers are: 1) 0.010" epoxy/spectra, 2) 0.067" foam, 3) 0.148" epoxy/spectra, 4) 0.067" foam, 5) 0.01 O" epoxy/spectra, and 6) 0.005" polyurethan paint. An EMS radorne code was used to optimize layer dimensions and materials to achieve minimum loss, reflection and polarization distortion. The refraction of the circularly symmetric radome varies as a function of elevation angle. The elevation refraction is a maximum of about 1 deg upward, nearly identical for both 20 and 30 GHz bands, at an elevation angle of 15 deg (through the knee of the radome). The azimuth refraction is in opposite directions for the 20 and 30 GHz bands and is a maximum of about 0.2 deg at the lowest elevation angles. 1 he elevation refraction is compensated in a feed-forward fashion by the antenna controller, and the azimuth refraction is small enough that it is neglected.

ANTENNA PERFORMANCE

The K-band frequency range is 5% centered at 19.7 GHz and the Ka-band frequency range is **40/.** centered at 29.5 GHz. Antenna performance was measured at a 100 foot outdoor antenna range at JPL.

The receive array has 161 elements with a directivity of 30.4 dB at band center. K-band, azimuth, 3 dB beamwidth is 4.0 deg and elevation beamwidth is 7,6 deg. T he transmit array has 366 elements with a directivity of 34.1 dB at band center. Ka-band, azimuth bearnwidth is 2.6 deg and elevation beamwidth is 5.0 deg. Both arrays were designed to have maximum in-band VSWR of 1.3:1 (1 .5:1 antenna system requirement) and Ist sidelobe levels below 13 dB.

An overall RMS tracking error of less than 1/2 deg was achieved. Only once was a short (5 see) outage experienced during the eight hours of televised flight during the PBS-TV special (flying from California to Texas and back). The one event was a "keyhole" outage -- when the direction to the satellite passed very near the positioner azimuth axis (zenith), temporarily requiring greater azimuth angle acceleration than the positioner capability. The outage occurred during a very steep turn (35 deg roll angle) just before landing in Southern Texas, where the satellite elevation look angle is about 55 deg.

The antenna system achieved excellent performance throughout all phases of flight, enabling the PBS-TV special to commence from inside the aircraft prior to the flight and continue through takeoff, cruise and landing. The flight patterns during several test flights were typical of any commercial flight. There were no restrictions at all placed on the aircraft maneuvers, and the tracking system performed flawlessly.

Table 1. Antenna Performance Summary

	K-band	Ka-band
Operational Bandwidth (GHz)	19,2 -20,2	28.9 -30.0
G/T, Room Temperature (dB) $	2.0	N/A
EIRP, maximum (dBW)	N/A	50.8
Min. Array Gain (dB)	29.4	32.5
1st Sidelobe Level (dB) *	10-13	12-15
VSWR, maximum	1.7	2.0
Axial Ratio, Polarizer+ Radome(dB)	1.0	1,5
Polarizer Axial Ratio (dB)	0.5	0.7
Radome Loss (dB)	0.5	0.6

* includes effects of radome and polarizer

$ a 2.5 dB noise figure LNA is mounted directly to the back of the receive array.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet ['repulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Adminstration, and by EMS Technologies, under contract with the Jet Propulsion Laboratory.

REFERENCES

M. Agan and A. Densmore, "ACTS Broadband Aeronautical 1 erminal," Proceedings of the International Mobile Satellite Conference, Ottawa, Canada, June 6-8, 1995.

Draft Artwork (Graphics preparing final version)

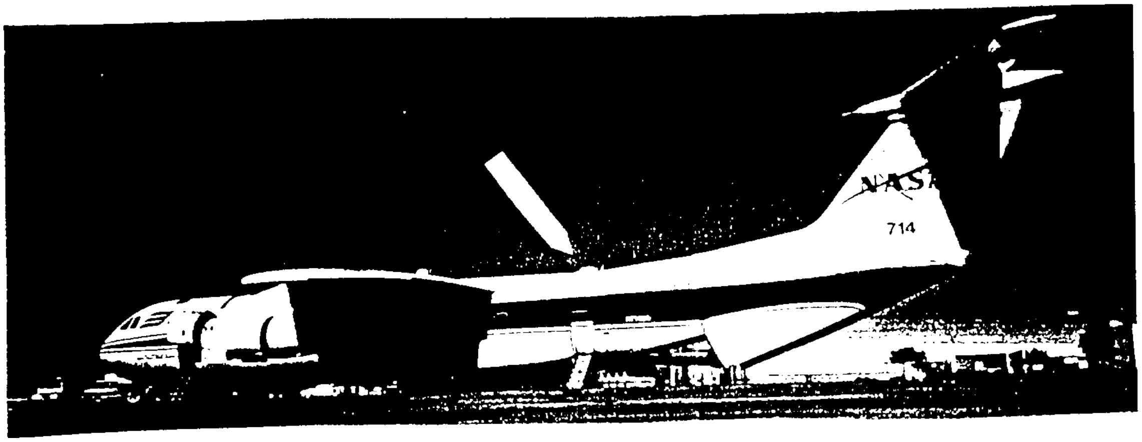

Fig. 1. C-141 KAO Installation

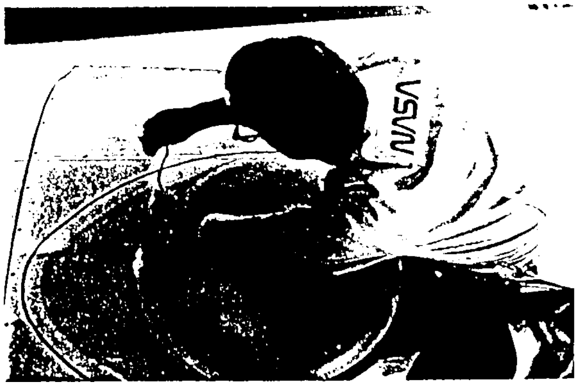

Fig 2. Radome Installation

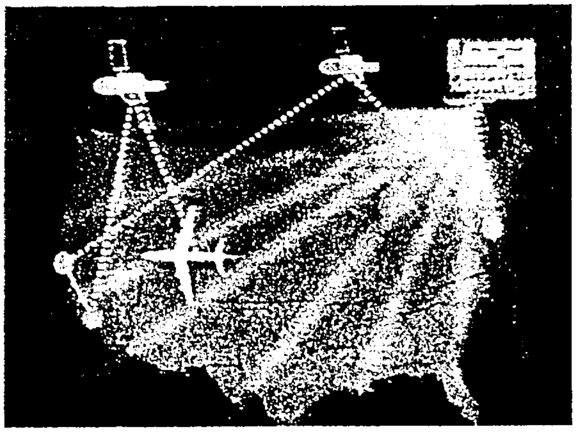

Fig 3. System Diagram

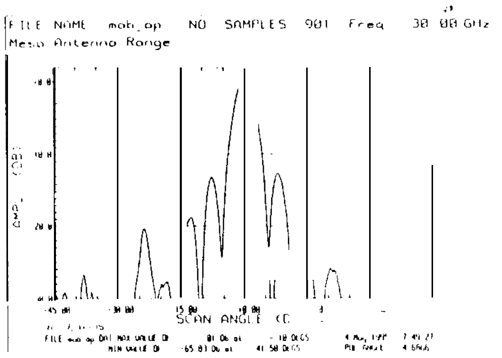

Fig 4. Antenna Pattern

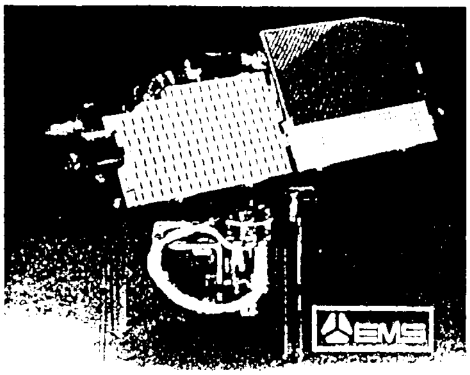

Fig 5. Antenna Assembly