A High Gain Antenna System for Airborne Satellite Communication Applications

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ABSTRACT

A high gain antenna for commercial aviation satellite communications is discussed. Electromagnetic and practical design considerations as well as candidate system implementations are presented. An evaluation of these implementation schemes is given, resulting in the selection of a single top-mounted aerodynamic phased array antenna with a remotely located beam steering unit. This concept has been developed into a popular product known as the Canadian Marconi Company CMA-2100. A description of the technical details is followed by a summary of results from the first production antenna.

INTRODUCTION

The commercial aircraft industry has a rapidly growing requirement for an aeronautical satellite communication (SATCOM) system to provide data and voice services to airline fleets. These services will allow safer, more efficient air travel throughout the world.

The SATCOM system is comprised of an Aircraft Earth Station (AES), a Satellite, and a Ground Earth Station (GES). The AES portion of the system for commercial aviation is defined by Aeronautical Radio Incorporated (ARINC) Characteristic 741 and is comprised of a Satellite Data Unit (SDU), A Radio Frequency Unit (RFU), a Diplexer/Low Noise Amplifier (DIP/LNA), a High Power Amplifier (HPA) and a High Gain Antenna (HGA) with its associated Beam Steering Electronics. Refer to Figure 1.

Canadian Marconi Company has developed the CMA-2100; a High Gain Antenna System which conforms to the ARINC industry specification.

INDUSTRY REQUIREMENTS

Due to the complexity of the airborne system, coordination with many parties was necessary to allow successful development of the antenna system. The following identifies the major organizations with which Canadian Marconi Company has interfaced during product development.

Service Providers. Initially, the system will utilize the International Maritime Satellite Organization (INMARSAT) constellation of satellites. The INMARSAT requirements are outlined in their Aeronautical System Definition Manual (SDM).

ARINC. ARINC Characteristic 741 provides guidance on the form factor and pin assignments for the Line Replaceable Units (LRU) that make up the AES.

RTCA. Special Committee SC-165 of the Radio Technical Commission For Aeronautics is currently in the process of defining the Minimum Operational Performance Standards for Aeronautical Mobile Satellite Services.

Airworthiness Agencies. The involvement of the Federal Aviation Administration and Transport Canada is necessary to ensure compliance with industry airworthiness requirements.

Airlines. The input of the ultimate end users was considered to ensure development of a marketable product.

Airframe Manufacturers. The major airframe manufacturers were consulted to ensure structural compatibility of the antenna with the host airframes.

Avionics Manufacturers. The manufacturers of the complement of the AES were consulted to ensure compatibility of the communication protocols between the LRUs.

PERFORMANCE REQUIREMENTS

The ideal High Gain Antenna coverage volume required by ARINC 741 is defined as 12 dB of circularily polarized gain in the upper hemisphere for all normal aircraft flight attitudes. Electromagnetic characteristics, however, are not the only criteria that must be considered during product development. The CMA-2100 development team considered many other parameters during the design of the antenna system. These are listed below along with the electromagnetic considerations.

Gain. Practical antennas will result in the specified gain value over approximately 75% of the ideal coverage volume. The achieved gain should be aircraft direction independent to allow for routing flexibility.

Multipath Rejection. Flight tests performed to date have shown multipath fading to be a problem[1,2]. An antenna whose gain falls off at the horizon would be ideal to maximize multipath rejection.

Axial Ratio. The axial ratio (AR) specification has been chosen to prevent excessive gain loss due to cross polarization with an elliptically polarized satellite feed antenna.

Sidelobe Level. To provide satellite discrimination in future constellations, sidelobe levels greater than 45° from the satellite direction should be minimized.

Beam Switched Phase Error. The phase error induced across the HGA aperature when switching from one beam to an adjacent beam should be kept to a minimum to satisfy SDU modem requirements and prevent demodulation synchronization loss.

Input Impedance. The input Voltage Standing Wave Ratio (VSWR) at the RF connector of the HGA should be minimized to prevent HPA overloading.

Airworthiness. There are many factors to consider to ensure the antenna conforms to airworthiness standards, however good engineering practices can ensure that most of these requirements are met.

Equipment Cost. Initial cost plays a large part in an airlines decision to outfit their fleet with SATCOM capability. For obvious reasons, this cost should be kept to a minimum.

Installation Cost. Depending on the design approach taken, installation of the antenna system can range from easy to very difficult. To minimize the installation effort and cost, the antenna system should employ simplicity. Ideally a single antenna with flexibility as to where the associated control electronics can be placed would meet this requirement. This would avoid the need for switching relays, microwave splitters/combiners and extra wiring.

Operating Cost. Any increase to the operating cost of the aircraft such as fuel burn penalty should be minimized. By implementing a low profile aerodynamic design, this can be accomplished.

Maintenance. Aircraft downtime is of major importance to airlines. A system that minimizes downtime when equipment replacement is necessary is desired. The antenna should be replaceable with access to only the exterior of the aircraft and the associated control electronics should be rack mounted to allow easy replacement.

Reliability. To prevent aircraft downtime, the antenna system should be reliable. In the event of a failure, the system performance should degrade gracefully. An electronically steerable phased array is ideal for meeting this requirement.

CANDIDATE SYSTEM CONFIGURATIONS

Four different design approaches were considered during the development of the CMA-2100 antenna system.

Mechanically Steered Antenna. This approach consists of a top mounted mechanically steered array of antenna elements enclosed in a large radome. Reliability aspects and fuel burn penalty make this approach unattractive.

Side Mounted Conformal. This antenna type consists of a number of crossed slot or microstrip patch antenna elements configured in a package conforming to the aircraft fuselage. ARINC 741 defines an antenna system which would incorporate two such antennas mounted on either side of the aircraft at 45° from the horizontal. System complexity, poor multipath rejection and aircraft direction dependent gain due to scanning limitations of the patch elements are significant disadvantages of this antenna design.

Multifacetted Top Mounted. This design approach incorporates a number of microstrip patch antenna arrays, each pointing in a different direction. The group of arrays is housed in a single radome mounted on the top of the aircraft fuselage. The elements used will suffer from the same limited scanning characteristics and multipath problems as the conformal sidemounted antenna and will not maintain the low profile, conformal form factor, resulting in increased drag.

Top Mounted Wide Scanning Antenna. This design approach incorporates an array of elements mounted at a height which is a significant fraction of a wavelength above the aircraft fuselage. This array implementation will allow the antenna beam to be scanned to very low elevation angles allowing aircraft independent gain coverage, very good multipath rejection as well as a mechanical package with very desirable attributes. The fuel burn penalty is kept low by minimizing the radome height above the antenna elements.

CMA-2100 DESIGN APPROACH

Trade-off analysis has shown the top-mounted wide scanning antenna to be the approach needed to develop a marketable SATCOM antenna with good electrical performance that fulfills the industry reliability, maintenance, and cost requirements. Canadian Marconi Company adopted this approach in the development of the CMA-2100 High Gain Antenna System.

The CMA-2100 is configured in two line replaceable units; The High Gain Antenna (HGA) and the Beam Steering Unit (BSU). The HGA is housed in a single mechanical package and mounts on the top of the aircraft fuselage. The BSU is mounted in a standard avionics rack up to 100 ft. from the HGA. Only two cables are required to penetrate through the aircraft skin: one for the BSU/HGA digital communication, and one for the RF cable. Replacement of the HGA is accomplished from the exterior of the aircraft while replacement of the BSU requires access to the equipment rack inside the aircraft.

High Gain Antenna

The HGA is an electronically steerable phased array antenna which provides +12 dBic nominal gain with near hemispherical coverage. The major components of the HGA are the radiating elements, 3-bit phase shifters, 32-way power divider/combiner, antenna interface card, and mechanical package. Refer to Figure 1.

Radiating Elements. The antenna array is comprised of 32 crossed dipole elements configured in a 4 x 8 planar array. Utilization of element feed structures with negligible cross sectional area help to minimize scattering and improve low elevation angle antenna performance. Individual elements are fabricated by intersecting two microwave circuit cards, each containing the printed radiating structure and balanced feed network.

3-Bit Phase Shifters. Antenna beam steering is performed utilizing 32 phase shifters which provide the necessary electrical phase shift to each antenna element. The design is a 3 bit implementation that allows for 45° phase steps. Included in the circuit is an orthogonalization network for circular polarization. Each phase shifter is constructed on a printed microwave circuit card using conventional surface mount components and then bonded to the radiating element to form an antenna element module. The phase shifter is manufactured to high reliability standards with no plated through holes.

32-Way Power Divider\Combiner. This assembly is a bidirectional power divider/combiner circuit that feeds 32 equal phase and amplitude signals to/from the phase shifters. The design is based on a modified Wilkinson coupler power divider which compensates for the array impedances that vary with scan angle.

Antenna Interface. This circuit receives digital words from the BSU and sets the appropriate phase shifter bits, as well as communicates antenna status information back to the BSU. The design incorporates parallel circuitry dedicated to each antenna element resulting in only one element being affected by a failure (a negligible degradation of antenna RF performance). The antenna interface includes built-in-test circuitry to monitor the phase shifter operation, EMI surge protection for the digital and power busses penetrating the aircraft skin, and on board power conditioning of the d.c. power fed from the BSU. One double sided digital/analog printed circuit card with conventional leaded components controls all 32 phase shifters.

Mechanical Package. The antenna electronics are housed in an aerodynamic radome/baseplate integrated enclosure. The radome is constructed of honeycomb sandwich while the baseplate is milled aluminum. The bottom of the HGA is flat and adapts to the curved aircraft fuselage with an airframe dependant adapter plate. The approximate dimensions of the HGA are 67" x 18" x 5".

Beam Steering Unit

The BSU is used to translate antenna beam position data and beam change commands received from the SATCOM Satellite Data Unit (SDU) in a standard digital format into signals needed to select phasing of the antenna elements. This results in the antenna beam pointing at the desired satellite. The major components of the BSU are the processor card, software, BSU interface card, power supplies and the enclosure. Refer to Figure 1.

Processor Card. This circuit provides interfaces to the SDU as well as the DIP/LNA. The design utilizes surface mount components on a multilayer printed circuit card. The processor is an INTEL 80C86.

Software. The software translates the azimuth and elevation satellite coordinates from the SDU into HGA phase shifter settings. In addition, the software also communicates with the SDU and HGA, and performs self test for the BSU and HGA. The software is written in Pascal and has been developed to RTCA DO-178A flight essential standards.

BSU Interface card. This circuit provides the RS-422 interface to the HGA, monitors the HGA DC power, and provides EMI/surge protection to the power and signal lines that penetrate the aircraft skin. This double sided printed circuit card utilizes both leaded and surface mount components.

Power Supplies. The BSU incorporates a 115 volt 400 Hz in/ 28 volt DC out power supply assembly. It also utilizes two high reliability DC to DC converters to provide the operating voltages. The BSU power supplies provide power to the HGA.

BSU Enclosure. The BSU is enclosed in an avionics industry standard 2 MCU ARINC enclosure utilizing an ARINC 600 connector. The enclosure can be rack mounted in the aircraft equipment bay and requires no forced air cooling.

CMA-2100 TEST RESULTS

Extensive measurement of the CMA-2100 electromagnetic characteristics has been performed utitilizing a fully automated roof top range. All measurements were taken on the Antenna Under Test (AUT), which is defined as the HGA mounted in a manner to simulate service usage on a 7 ft. X 9 ft. curved ground plane. The radius of curvature of the ground plane is 127 in. The measurement coordinate system is illustrated in Figure 2. A brief summary of these results follows.

Figure 3 shows the nominal boresight pattern of the AUT at 1.545 GHz. The antenna is orientated such that the scan occurs in the azimuth=135° plane. The elevation angle for this pattern is set to 90° (boresight). The 12 dBic line is superimposed upon the plot.

Figure 4 illustrates the same pattern cut as Figure 2, but the AUT beam has been electronically steered to 10° elevation. This figure shows that multipath signals arriving to the AUT at -10° elevation will be strongly attenuated by the sharp pattern rolloff beyond the 10° elevation point.

The composite scan, shown in Figure 5, of the antenna performance is a dynamic measurement that illustrates the peak gains and beam switching of the AUT. For this measurement a complete elevation scan was taken in the azimuth=135° plane while the computer utilized open loop steering to monitor the positioner location and updated the AUT beam selection to keep it pointed at the source antenna. The irregular pattern shape illustrates the beam switch points.

Extensive axial ratio measurements were performed over the full frequency range. In general the AR was < 6 dB (typically 3-4 dB) with worst case performance occurring with the antenna scanned towards the horizon. This phenomenon was expected since a semi-infinite ground plane (the aircraft fuselage) cannot support a horizontally polarized wave.

Due to the finite antenna beam width and phase quantization of the phase shifters to 45°, a finite number of beams were selected to cover the antenna coverage volume. When switching between beams, it is a requirement to maintain a minimum phase disruption. Adjacent beam switch point phase error measurements have been taken for all possible beams and over the full frequency range with the aid of automated testing. The phase errors are typically 2°-3° and in over 99% of the cases are below 10°.

REFERENCES

1. **Makita, F. 1988.** Air-ground Satellite Communications Test By Japan. *Proceedings of the 1988 RTCA Assembly.* pg 111.

2. *Mobile Satellite Reports*, January 19, 1990 pg 4.

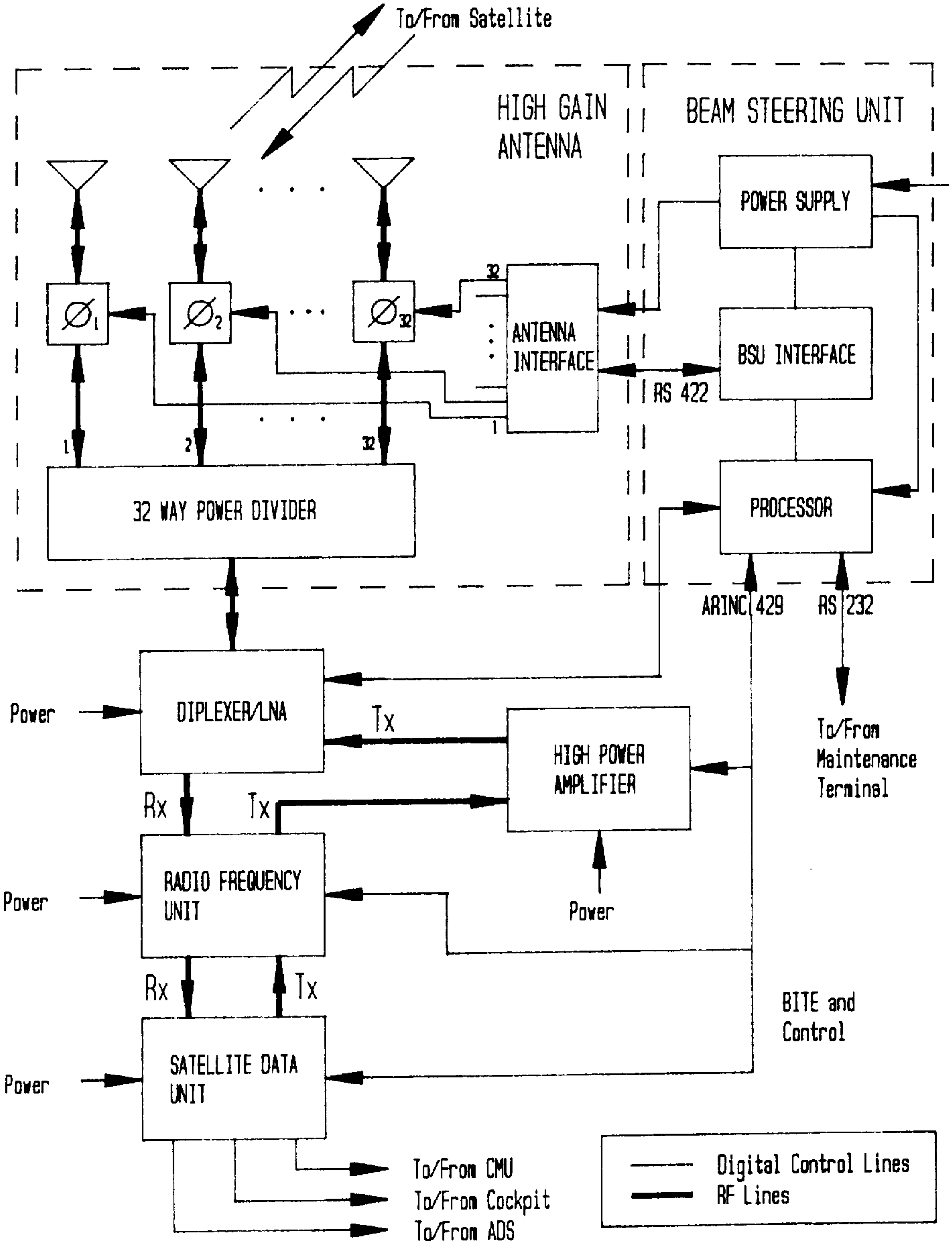

Fig 1. Typical CMA-2100 Application and Block Diagram

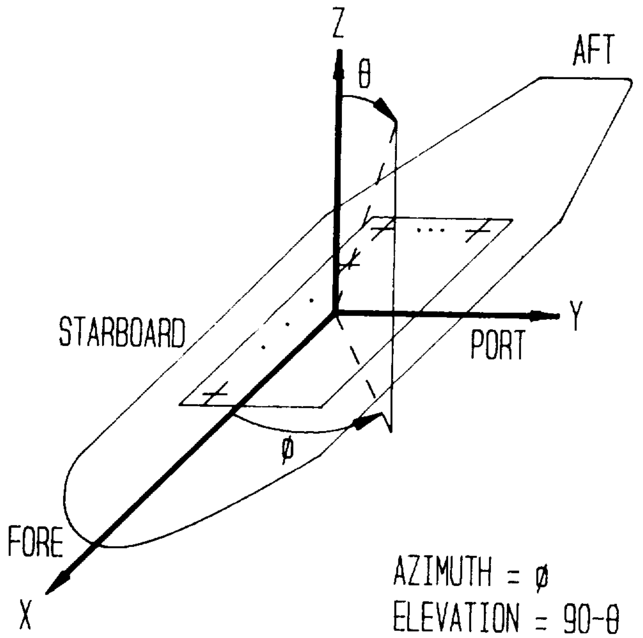

Fig. 2. Definition of AUT Coordinate System

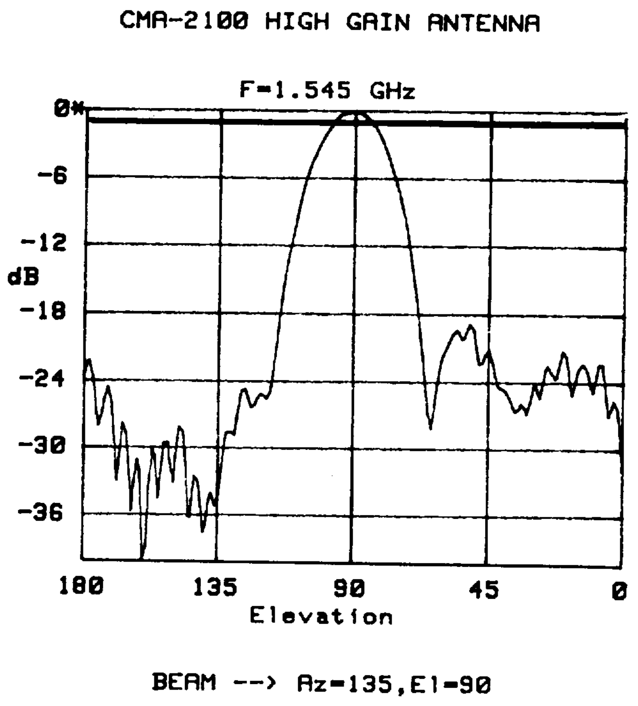

Fig. 3. Boresight Antenna Radiation Pattern

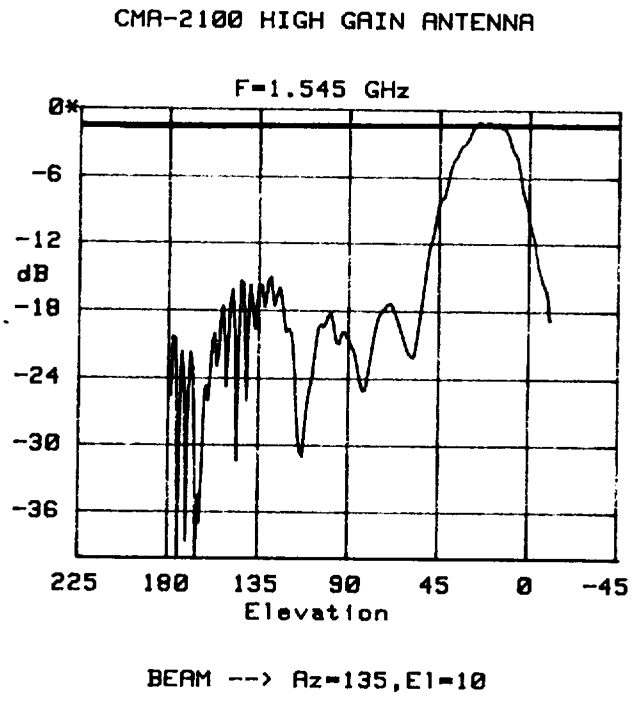

Fig. 4. Low Elevation Antenna Radiation Pattern

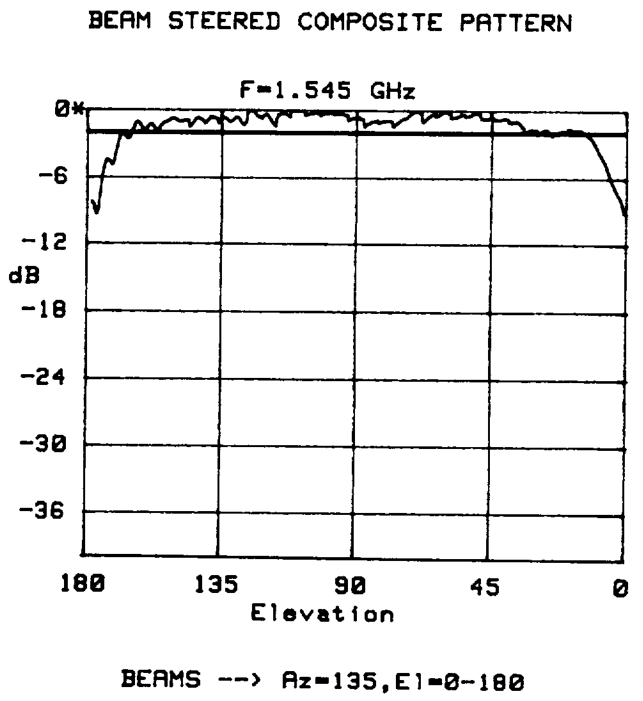

Fig. 5. Composite Scanned Antenna Radiation Pattern