Global Connectivity to Aerospace Forces Via SATCOM

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Abstract

There is an evolving need in the commercial markets for low cost airborne receive antennas and potentially, low cost steerable antennas for 2-way fixed satellite service. These requirements are initially emerging from the slowly developing Ku-band pay-per-view TV market for commercial airlines. In the early 2000's, Low Earth Orbit (LEO) based satellite systems will be providing initial service for wideband 2-way communications at 30 and 20 GHz. One such system, Teledesic, will primarily offer fixed satellite service, however there are tentative plans on providing 2-way communications service for commercial aircraft. The baseline plan is to use phased array antennas on commercial aircraft to provide this connectivity. Spaceway NGSO is also planning on the use of phased arrays antennas for ground terminals earmarked for many home and business sites. This paper will discuss some Ku-band mechanical and electrically steered aircraft antennas currently being developed for commercial applications. The paper will also discuss the differences between the commercial and military aircraft antenna requirements and what steps should be taken to leverage the commercial antenna developments.

Recent Commercial/Military Mechanical Antenna Developments

As discussed above, there is an evolving market for pay-per-view TV to commercial aircraft. A mechanically steered antenna that is being pursued in this market is shown below in Fig 1. The antenna consists of a set of Luneberg hemispherical lenses with varying dielectric strength from the center to outer edge of the hemisphere. The lenses sit on a spinning ground plane and the antenna uses ground plane image reflection theory to achieve an effective doubling of the aperture and therefore doubling of the gain. This enables the designer to maintain a lower profile for a given gain and thereby reduces the aerodynamic drag associated with the antenna. This is obviously critical for minimizing fuel consumption for aircraft. All positioning hardware is external to the aircraft skin under a radome. A one-inch hole is all that is required to route the necessary RF and DC cabling into the aircraft. The Information Directorate of AFRL is working with the contractor, Datron/Transco Inc, to translate this design for MILSTAR and GBS receive applications at 20.2 to 21.2 GHz. MILSTAR operates Right Hand Circular Polarization (RHCP) on receive and GBS operates Left Hand Circular Polarization (LHCP) on receive.

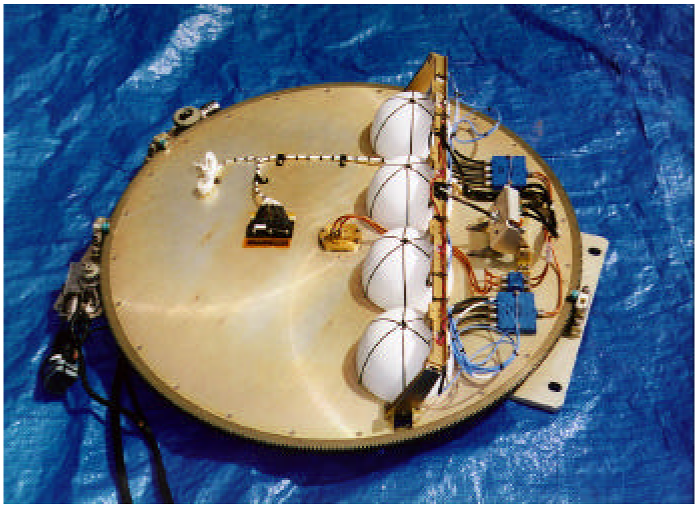

FIGURE 1. Ku-band Hemispherical Lens Antenna

It is of course of interest to the commercial airborne Ku-band application to have dual simultaneous polarization for the pay-per-view TV market. This capability can be obtained at 20 GHz as well but it is not critical for the military application, which will most likely only require switchable polarization. Sanford[1] has done research in the area of multiple shell lenses and has published a set of curves relating the relative efficiency of these lenses as a function of lens diameter, wavelength of operation, and the number of shells used to achieve the desired lens diameter. This is shown in Figure 2. While some have suggested less than quarter wavelength thicknesses for each shell, Sanford has shown through measurements that approximately 6 to 9 shells are sufficient for lenses less than 20 wavelengths in diameter. Performance issues include air gaps between shells and outgassing of the lens material at high temperatures (greater than 160 degrees F). The lenses are inherently wideband and a low profile feed horn is all that is needed for scanning in elevation. Greater than 2:1 bandwidths can easily be achieved. With this in mind, AFRL is working with Datron/Transco to develop a simultaneous 20/44 GHz feed for a lens antenna that will be used for both GBS receive (LHCP), and MILSTAR transmit (44 GHz) and receive (both RHCP).

The cost of the lenses is in the low hundreds of dollars for even small quantities. The expense of the antenna system primarily lies with the feed and combiner network, drive mechanisms, and beamsteering computer/controller. Current quotes for the commercial Ku-band system alluded to above are approximately $60,000. Installation time on commercial aircraft is targeted for a 4-hour shift. The radome recurring cost is approximately $10,000. Installation cost is a key cost driver for airborne antenna systems.

Previous airborne antenna efforts involving similar requirements focused on low profile reflector based systems, which required large openings through the fuselage. This procedure alters the structural integrity of the aircraft and includes extensive steps to ensure its airworthiness. Installation costs on military aircraft for these reflector antennas were typically over $1M.

[1] J. R. Sanford, “A Luneberg Lens Update”, republished in *IEEE Antennas and Propagation Magazine*, Vol. 37, No.1 Feb 1997

The relatively small hole needed for the Luneberg lens design will significantly reduce installation costs on military aircraft, but this cost will vary on a case by case basis and is somewhat unknown at this time.

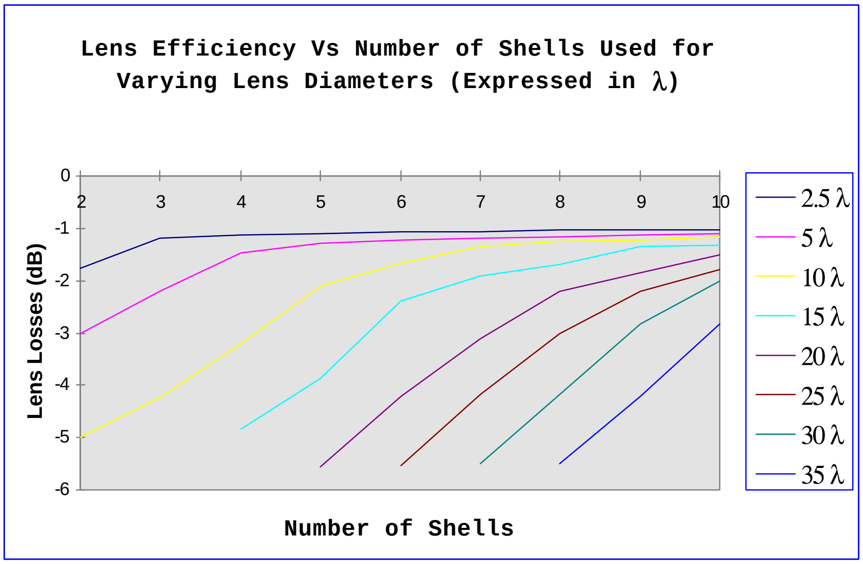

Figure 2 – Luneberg Lens Sizing/Efficiencies for Various Lens Thicknesses (expressed in wavelengths)

The Direc TV G/T specification for the commercial airline antennas is about 7 dB/K. Assuming a system temperature of about 100 K, this translates to an antenna gain of about 27 dBi. The scanning requirement is approximately 65 degrees for CONUS coverage of the Direc TV satellites.

For the 20 GHz GBS and MILSTAR receive applications, a gain of 35 dBi is desired. The amount of ground plane necessary for this antenna is a function of the height of the lens and how far the antenna needs to scan off zenith. The goal of the AFRL effort is to provide scanning 80 degrees off zenith. This translates to a ground plane of about 40 inches for an 8-inch lens (or a 4-inch high hemisphere). At 44 GHz, the graph shows that an 8-inch lens with 10 shells would have an efficiency of about 63%. Additional spillover losses may add another 1 dB of loss making the overall efficiency of the lens approximately 50%. The gain of each lens is approximately 36 dBi per lens with 4 lenses then providing about 41 dBi transmit gain. With a dual band feed, the gain at 20 GHz for the entire antenna would be approximately 35 dBi. With a modest power amplifier on transmit, the full MILSTAR MDR data rate could be realized if the aircraft is operating up above atmospheric turbulence. This is a reasonable assumption for many aircraft and results in a savings of 12 dB in the link budget for the 44 GHz uplink. For receive operation at 20 GHz, GBS requires approximately 35 dBi of gain.

For MILSTAR MDR receive, 35 dBi of gain will provide enough gain to close an MDR link of several hundred Kbps. The exact data rate is a function of the priority of the user and the number of downlink accesses available to the user.

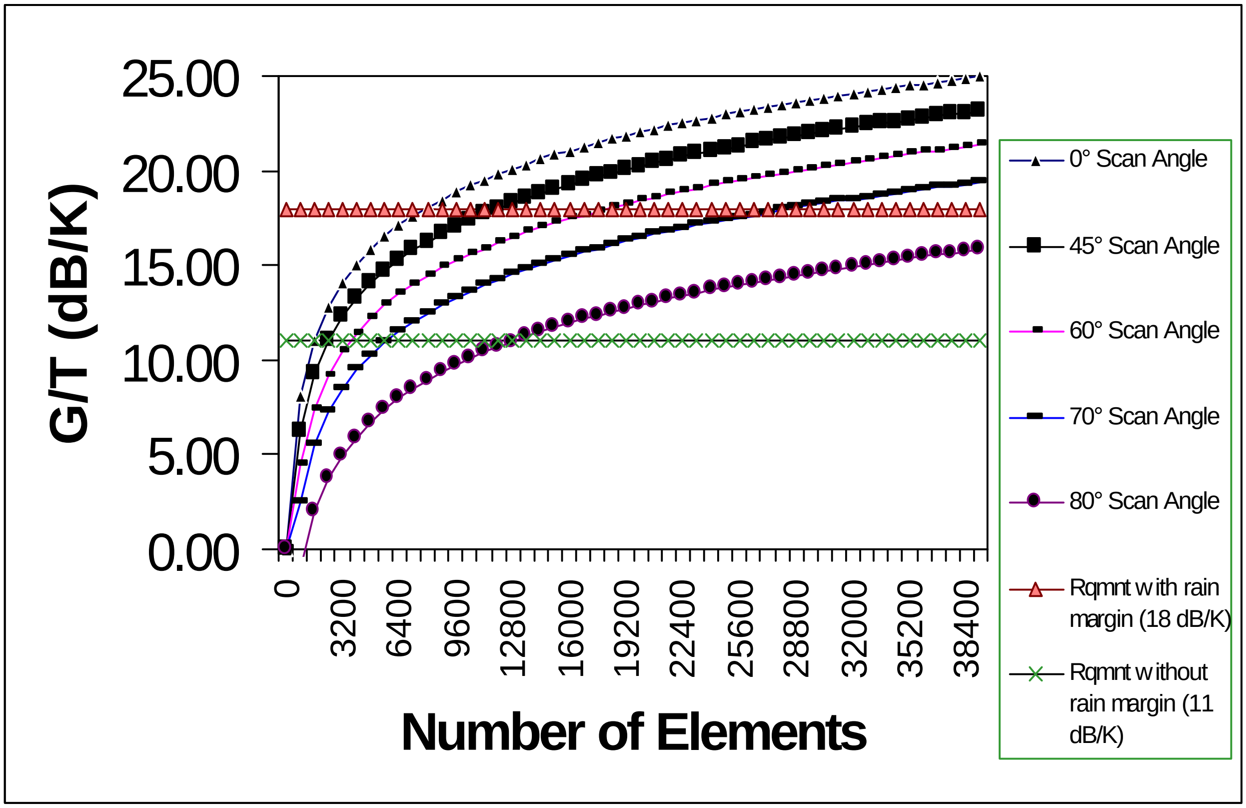

FIGURE 3. Phased Array Sizing Requirement for Various G/T and Scan Requirements

Present Day Phased Array Alternatives

If it was desired that the antenna be nearly conformal or very low profile, a 2-dimensional phased array is a possible candidate antenna design. The graph below in Fig 3 indicates the number of elements needed at 20 GHz to achieve a given G/T for a GBS receive application. It should be noted that the design of a phased array that scans 80 degrees off boresight is not practical due to cos theta losses

The following assumptions were made concerning array performance:

- Ohmic losses in radiator:	1 dB
- Tracking/Squint error:	0.35 dB
- Phase & amplitude errors:	0.13 dB
- Failed elements (5% margin):	0.22 dB
- Polarization mismatch (max scan):	0.6 dB
- LNA NF:	1.5 dB
- Sky Temp:	42^{o}

Once again, it is preferable (due to cost considerations) to assume that an operational aircraft needs to close the link to the satellite when it is up above the weather. As before, we need coverage from zenith to 80 degrees off zenith in elevation. The cosine theta roll-off of the gain as the beam is scanned down in elevation makes the design of a 2-D phased array impossible for this coverage. A modified design with truncated 4-sided pyramid and an array panel per each pyramid face would be more optimum. The scan requirement would be reduced to 50 degrees or so. This would require about 2800 elements per face to achieve a G/T of 11 dB/K. The total number of elements would then total to about 11,200. The array size is roughly 0.4 meters on a side. An estimate on today's cost would be about $100 per element. This is a reasonable cost number given the current status of LNA and phase shifter GaAs chips at 20 GHz. This indicates an antenna well over $1M given the fact that the production build of these arrays would probably be limited. This cost is unacceptable.

An alternative design would place the array on a tilted, spinning turntable. The array would be spun in azimuth and have a more limited electrical scan in azimuth and elevation. This would drop the cost of the antenna by a quarter and provide scanning which more closely approached the horizon. The tradeoff here is in reduced reliability with the introduction of a mechanically driven system in azimuth. A hybrid design would employ a 1-D scanning array. The antenna would mechanically be spun in azimuth and would electrically scan in elevation using row element phase shifting. This would involve 60 to 90 (depending on design concept) amplifier/phase shifter modules and a low loss beamformer to achieve the same performance in a low profile (less than 4 inches) configuration. Per element costs would be comparable and the entire antenna could probably be delivered for about $140K. Again, the lens antenna discussed above could be designed for both 20 GHz receive and 44 GHz transmit capability from one aperture. A phased array implementation calls for separate apertures. It's imperative to provide as much functionality as possible from the hardware as possible. Program offices such as JSTARS, AWACS, Rivet Joint, etc all have prime contractors that are responsible for the actual integration of equipment on to the aircraft. The intent is to minimize the effort involved in installation since this is often the dominating cost factor. The idea for the lens antenna is to include all LNA, downconverter, upconverter, and transmitter electronics with the antenna aperture, exterior to the aircraft skin. This will minimize the effort of installing the antenna. The cost savings for doing this is somewhat intuitive and has not been quantified at this time.

Very Low Cost Electrically Steered Antennas

There is much anticipation for the development of very low cost antennas via the commercial satellite market. Teledesic will be offering some mobile service. In particular, wideband 2-way service to commercial aircraft is being targeted. Operating frequencies will be 18.8 to 19.3 GHz on receive and 28.6 to 29.1 GHz on transmit. The proximity of the receive band to the military receive bands for MILSTAR and GBS (20.2 to 21.2 GHz) may provide substantial leverage for achieving much lower antenna costs for these military systems. Joint industry and Government programs are needed to pursue this technology so that industry may more quickly realize its low cost goals and to ensure that these commercial designs can undergo modest redesigns for the military frequency bands if not include the military bands. The 12 percent bandwidth to cover the Teledesic and military receive bandwidths is not completely out of the question in terms of design capability. New manufacturing/assembly technologies and significantly reduced RF chip cost must be realized to support the commercial cost goals. AFRL has been conducting research into low cost 20 and 44 GHz phased arrays for 15 years. Efforts with Boeing, Texas Instruments (now part of Raytheon), and Raytheon (Sudbury, MA) have recently come to completion. Some of the technical hurdles that have been addressed in the development of low cost arrays over the last 5 years include:

- Highly automated multilayer manufacturing technologies that can support high performance RF feedthroughs
- Good performance printed resistor technologies for RF distribution
- High yield, high performance GaAs amplifiers and phase shifters

The first area has advanced significantly in the last 2 to 3 years and there are a growing number of manufacturing facilities that are addressing low cost multilayer boards for microwave and millimeter-wave vertical RF interconnects. This includes conductive bump and vertical Z-axis material technologies. Alignment tolerances at higher frequencies (0.34 cm for half wavelength spacings at 44 GHz) has not been perfected but should increase in availability in the next 2 to 3 years.

Printed resistors eliminate the need for automated pick and place of drop in resistors which additionally require automated wirebonding techniques. It isn't clear that this is a significant contributor to cost, but manufacturing techniques for printed resistors are concurrently being developed with the advance of multilayer RF boards.

An optimistic estimate of the cost of GaAs per square millimeter would be about $3 to $4. With attention to minimizing GaAs real estate, phase shifters using lumped element designs have been realized in approximately 1.5 mm^2. A 20 GHz Low Noise Amplifier (LNA) may be similarly sized. This brings the receive chip pair cost to about $9 to $12. This is only for single polarization operation. A separate phase shifter would be required to have both polarizations thereby bringing the chip cost on receive to about $13.5 to $18. A 100 mW transmit chip at 44 GHz can be sized at about 3 mm^2. This brings the transmit chip pair cost to about $8 to $12 assuming identical yields as the 20 GHz LNA. However, the yields for power chips at 44 GHz are about one half that for 20 GHz LNA's. This brings the cost of the transmit chips to $16 to $24. The cost to distribute the RF, DC, and digital control lines to each element might introduce another factor of 3 to the cost. The additional array element costs, integration costs, and other assembly steps would additionally introduce another factor of 2 to 3 for the array. This brings the cost range for the receive function to $81 to $162 per element. The transmit element cost variation is from $96 to $216. This is a wide variation in cost but reflects the amount of unknowns and the dynamic environment that the world of phased arrays contends with.

The possible avenues for realizing lower cost arrays may include the following:

- The possible use of 1D arrays (depends on operational requirements)
- The evolution of high yield, low cost 6 inch GaAs wafer processes
- The use of SiGe in place of GaAs
- The use of Si based MicroElectroMechanical Systems (MEMS) for phase shifters

The first item involves the tradeoffs in using partially mechanically steered and electrically steered antennas for tracking LEO satellites. An azimuth only gimbaling system could be used to track satellites with elevation pointing being accomplished electrically. The cost of the positioning system has to be weighed against projected high volume costs for a 2D array.

There a number of companies transitioning to 6 inch GaAs wafers. The hope is that this will help bring down the cost of the chips used for the amplifier and phase shifter at each element. At 20 and 44 GHz, to obtain reasonable performance, gate lengths of a quarter micron and less need to be used. Gate lengths this size typically need to be defined by using electron beam lithography. This adds some expense and makes it hard to drive the cost of these chips to an affordable level.

Germanium has been introduced to dope standard silicon and brings its operating frequency up significantly. F_t's greater than 50 GHz have been reported for SiGe. In the future, there is a possibility of using SiGe for the 20 GHz receive function. Much of this will depend on how the SiGe processing will advance as a result of commercial applications at much lower frequencies. Cost estimates for SiGe have been ballparked at about an additional 30% over standard Si processes and about 5 times cheaper than GaAs.

MEMS technology has many applications. For phased arrays, there is near term interest in using MEMS for phase shifter applications. A standard phase shifter uses transistors to switch in the various phase bits. The transistors dominate the losses (typically about 10 dB at 44 GHz). These phase shifters need to be fabricated on GaAs. With MEMS, the transistors are replaced by a simple switch at the integrated circuit level. The possibility exists for realizing these switches on Si substrates. Losses are projected to be less than 2 dB. The drawback involved in using MEMS technology lies in the typically excessive pull down voltages needed to actuate the switches (anywhere from 10 to 40 volts). The switching time is limited to about 5 microseconds. Also, the power handling capability is limited to approximately 1 Watt. The latter two concerns are not limiters in the phased array designs being considered at 20 and 44 GHz. Also, pull down voltages are coming down as industry and Government invest more and more research dollars into this area. There have also been ideas for providing converter ASICS at the array element to upconvert the standard IC voltages to the voltages needed for the MEMS switches.

In general, for Si based processes, the potential is there to realize the amplifier, phase shifter, and control ASIC all on a single chip. The nonrecurring investment to do this may not warrant such a move. The advent of several Ka-band satellite terminals in the next 10 years will dictate the choice of 20 GHz LNA components and packaging concepts that will be used for MILSTAR and GBS receive functions. The phase shifter components will be determined by the ground and airborne antennas that will evolve and be fielded for systems like Teledesic.

Summary

Recent developments for wideband aircraft antennas in the pay-per-view television market mark the first attempts by the commercial world to develop low cost antennas at higher frequencies (Ku-band). These designs can be extended to 20 GHz (and potentially 44 GHz) for military applications with great savings in cost to the military. The primary cost savings is associated with a large reduction in installation costs which is derived from low profile designs such as a Luneberg lens which requires only small holes (less than 2 inches) to be drilled through the fuselage. Some technical challenges remain to convert these antennas for wideband use which might enable both receive and transmit functionality.

Low cost antennas with some degree of electrical steering are anticipated from the evolving wideband LEO satellite systems of the future. Low cost assembly and MMIC chip technology needs to be advanced in order for the commercial goals to be realized. The latter may be partially satisfied with the maturing of MEMS based phase shifters which can be fabricated in a batch mode on silicon substrates.

The proximity of the MILSTAR and GBS receive frequencies to the commercial receive frequencies of systems like Teledesic beckons for a concentrated effort between industry and Government. This will ensure that the military will be able to take advantage of the low cost technology that the commercial world will use to develop these antennas. Toward that end, AFRL, Rome Research Site, is investing in low cost array technology that seeks to cover these two bands. These efforts are relatively new and will be reported on in the future.