Antennas...A Primer

A Cornerstone Issue for Airborne Broadband Communications

By Steve Cutbirth & Dennis Coombs

Introduction

When AVION Editor John White called to discuss the need for this basic article on aircraft antennas, he captured the broadband issue in one facetious question: "All I need to do to receive a signal is to add a dish to the side of my house...so, what's so complicated about aircraft?"

For many of us, it's difficult to understand antennas and their magical properties...even the recent passing of Ray Walston of *My Favorite Martian* fame reminds us that back in the 60s he could communicate with Mars using a built-in retractable antenna. Well, that's Hollywood. Even if it could work, the airline passengers probably wouldn't line up for antenna implants. Hmmn...or would they?

In the next few pages we'll visit some of the basic elements of radio frequency communications, especially via satellites, and how these elements impact airborne antennas, their design and complexity.

Uncle Martin's 6-inch rabbit ears looked simple enough, but would they be able to pick up BBC aboard a widebody on a transatlantic flight?

The Fundamental Issue... Data Rate

New multimedia applications (Mobile Internet Access, Email, Television/Video) are driving higher data rate requirements. Data Rate, information transported in a given period of time, is usually expressed in Bits Per Second (bps). Obviously it takes more information per second to deliver a channel of full motion video with audio than it does to relay a phone conversation or a simple burst of data advising the airline operations center that an aircraft has pushed back from the gate. ***Table 1*** below presents different types of communications and their typical data rates. As it pertains to aircraft communications links, the need for higher Data Rates generally equates to more Antenna Gain which drives Antenna Size. The term "gain" may not be familiar to everyone. *Gain* refers to the capability of a device to amplify, magnify or focus energy.

TABLE 1

Aircraft Communication	Typical Data Rates
Morse Code (dashes & dots)	Equivalent to 3 to 4 bps
ACARS*	300 to 1,200 bps
Voice Call	4,800 to 9,600 bps
Facsimile Transmission	2,400 to 9,600 bps
Stereo Music	32,000 to 48,000 bps[1]
Video with Audio	150,000 to 1,500,000 bps

**ACARS = Aircraft Addressing and Reporting System*

Using sunlight as an analogy, let's suppose the sun were shining through the window and illuminating this entire page. We'll refer to the light intensity as normal sunlight, no amplification, or a Gain of 1 (1 times normal sunlight). Using a magnifying glass you could redirect (focus) a portion of the sunlight into a small pinpoint that would contain far more energy than normal sunlight, perhaps an amplification or Gain of 10 (10 times the energy of normal sunlight). Antennas can be made to function in a similar manner, they can focus radio frequency (RF) energy to pick up smaller signals or to discern smaller pieces of information (higher bit rates) contained within the RF signal.

Here's another helpful analogy: an antenna is like a sail in the wind. Lower wind energy (lower satellite power or higher data rates) requires a larger sail (antenna) to catch and interpret the wind's energy. The larger the sail, the larger the gain. Keep this analogy in mind...we'll use it again later.

Radio Frequency and Inherent Data Rate

Suppose we have a piece of information digitally encoded at an appropriate data rate. One cannot directly transmit the digital stream of bits between a transmitter (satellite) and receiver (aircraft) without first combining it with RF energy. It's the RF energy that actually travels between antennas. Picture the information or bit stream as cargo and the RF energy as the train. In fact, the RF energy transmission is referred to as the *carrier*.

There is a direct relationship between the carrier frequency and the amount of information that can be imbedded into the transmissions. Generally, higher radio frequencies have greater information (data rate or bps) handling capacity. Details on a few of the frequency bands are contained in ***Table 2***. Realize, however, that the information in this table is an extreme oversimplification of the relationship between frequency and data rate. A true correlation would have to involve every aspect of what is referred to as *RF Link Budget, Modulation Scheme, Bandwidth*, etc.—all of which are too complicated for the intent and scope of this article. The point to remember is: higher frequencies, more data.

TABLE 2

Frequency in Hz*	Band Name	Data Rate Capability**
3 – 30 MHz*	HF	0.15 – 1.5 Mbps***
30 – 300 MHz	VHF	1.5 – 15 Mbps
300 – 3,000 MHz	UHF	60 – 600 Mbps
225 – 390 MHz	P	11 – 19.5 Mbps
0.390 – 1.550 GHz*	L	19.5 – 77.5 Mbps
1.55 – 5.20 GHz	S	77.5 – 260 Mbps
5.20 – 10.90 GHz	X	260 – 545 Mbps
≈ 10.9 – 20.0 GHz	Ku	545 – 1,000 Mbps
≈ 20.0 – 30.0 GHz	Ka	1,000 – 1,500 Mbps

** Hz = cycles per second, MHz = Mega (million) cycles per second, GHz = Giga (billion) cycles per second*

*** Assumes: BPSK Modulation and 5% Bandwidth. Note: Changing any aspect of the RF link, modulation scheme, bandwidth, etc. can greatly modify the data rate capability.*

**** Mbps = Mega (million) bits per second*

First The Chicken . . . Then The Egg

If the antenna is the egg, the satellite (or other communications link) is the prerequisite chicken.

A broadband service provider must first select a satellite, constellation of satellites, or a ground-to-aircraft communications path. Whatever is selected will have a unique set of performance characteristics: power output, receiver sensitivity, transmit/receive frequency, transmit/receive polarization and power footprint to the ground (or aircraft). Once known, the set of parameters for the communications link will drive the airborne antenna design.

The Design Impact . . . Antenna Size, Weight, Cost and Complexity

Obviously, for any mobile platform—especially an aircraft —size and weight of the antenna are critical features.

DEFINITION: ***Aperture*** is that portion of the antenna structure or surface that receives/transmits the RF energy (aperture excludes any motors, mounting hardware, or other electronics). Aperture is the "sail"...not the mast, boom or rigging.

The selected satellite and its RF parameters will determine what aperture size is needed on the airborne antenna. Aperture size becomes the most critical aspect of the aircraft antenna design. When aperture size increases, a host of other complexities and costs also increase. Key relationships between RF requirements/performance and their impact on the airborne antenna are as follows:

As transmit/receive frequency ⇧, antenna size ⇩ (good)

This particular relationship exists because antenna dimensions are in part related to the *wavelength* of the received or transmitted RF signal. As the frequency increases wavelength decreases and therefore the antenna can be made smaller.

DEFINITION: ***Wavelength*** is the distance (usually in centimeters or millimeters) between repeating cycles or phases of an RF signal, the distance before a signal repeats its wave shape. RF energy travels through space in a wave pattern similar to waves on the ocean. The wavelength of an ocean wave would be the distance between two consecutive peaks.

As satellite RF power ⇧, antenna size ⇩ (good)

In addition to wavelength, the RF power in the link is another factor which drives antenna size. If the satellite puts out a relatively weak signal then a larger antenna gain is required. Larger gain requires a larger aperture surface area to capture enough RF energy to detect and interpret the satellite signal. Conversely, as satellite technology has advanced, the RF power they transmit has increased. This has allowed the receiving antennas to decrease in size. Remember the satellite TV dish antennas that were 6′ to 8′ in diameter? Now you see mostly the 18″ to 20″ dishes on homes.

As communications data rate ⇧, antenna size ⇧ (bad)

A quick discussion on *compression*...***Compression*** is an encoding/decoding technique that allows us to beat the system and put 10 gallons of data into a 5-gallon container. Steady improvements in compression algorithms help all communications providers to get more data delivered at lower transmitted data rates.

EXAMPLE: The advances in MPEG (Motion Picture Experts Group) compression over the last several years now allow full motion video with audio to be transmitted at rates as low as 150 kbps without significant anomalies.

As receive/transmit beamwidth ⇩ (narrows), antenna size ⇧ (bad)

DEFINITION: ***Beamwidth*** is the measurement of how much spread exists in the main beam of focused RF energy (usually expressed in degrees).

Here's an analogy using light sources:

Laser Pointer = narrow beamwidth
Flashlight = wider beamwidth
Floodlight = widest beamwidth.

Antennas are designed to meet specifications in both receive beamwidth and, if applicable, transmit beamwidth.

As pointing/tracking accuracy ⇧, antenna complexity and cost ⇧ (bad)

DEFINITION: ***Pointing*** is the antenna's ability to mechanically or electronically center its beamwidth (highest gain) directly on the satellite source of RF energy. Pointing is generally done without monitoring the RF signal from the satellite. The antenna merely points toward the satellite location (very accurately calculated) and receives the signal. It does not hunt for the best signal.

continued on page 26

DEFINITION: ***Tracking*** is the antenna's ability to sense the satellite's RF signal and mechanically or electronically steer the antenna to keep the signal in the center of the antenna's beamwidth (highest gain).

Whether pointing or tracking, the accuracy is extremely important when communicating with a satellite. Operating at the center of antenna beamwidth is critical to maintain receiver gain and to prevent transmitted signals from overlapping to adjacent satellites.

As polarity correction requirements ⇧, antenna size, complexity and cost ⇧ (bad)

DEFINITION: ***Polarity*** is the direction in which the RF signal is transmitted into space from an antenna surface.

There are four different polarities used: *Vertical*, *Horizontal*, *Left Hand Circular* and *Right Hand Circular*. Let's go back to our wind analogy to understand this term. A fan is blowing into a sail on a model boat (RF energy to an antenna); move the fan up/down for vertical polarization, left/right for horizontal, clockwise for right hand circular, and counterclockwise for left hand circular. Depending on how the fan moves (transmits the RF energy), the sail needs to be designed for maximum performance for that specific motion (antenna designed to receive the specific polarity).

DEFINITION: ***Polarity correction*** is the ability of the antenna to correct for shifts in signal polarity.

Back to the model boat: the sail has been optimized for up/down fan movement (vertical polarization). If the boat were to sail up a steep wave, vertical to the boat is no longer vertical to the fan. Polarity correction in the sail would compensate for this shift (whether it took place at the fan or the sail). In the airborne/RF world this comes into play when the antenna is optimized for a specific polarity, geographic location and orientation to the satellite. If the aircraft is flown outside of the optimized area, there may be a significant shift in polarity between what the satellite is transmitting and what the antenna is expecting to receive. As with the sail analogy, polarity correction may be required whenever vertical to the aircraft is not vertical to the satellite. Got the mental picture?

If the antenna must receive and transmit, then antenna size, complexity and cost ⇧ (bad)

Beyond the additional antenna components necessary for transmitting, this feature will generally require a larger aperture (more size, weight and drag) to meet the transmit beamwidth, gain and sidelobe requirements to establish and maintain an acceptable satellite link.

As sidelobe performance ⇧, antenna size, complexity and cost ⇧ (bad)

DEFINITION: ***Sidelobes*** are the portions of RF energy that exist outside of the main beamwidth.

No antenna has a perfectly formed beam of energy; there are loss areas. These loss areas can be a significant problem when transmitting to a satellite. The lost energy may prevent the satellite from receiving the signal, or the sidelobes themselves may "paint" an adjacent satellite and interrupt a totally separate communications link.

As radome performance requirements ⇧, associated design and production costs ⇧, adding to the overall installed cost of the antenna system (bad)

DEFINITION: A ***radome*** is the housing over the antenna which provides an aerodynamic enclosure and environmental protection.

The radome must also be designed/tuned in its construction to minimize the energy loss as the RF signals pass through the radome material. If the radome is used with an antenna that both receives and transmits, then the material must be tuned for two different frequencies. As with all devices, the more complex the radome design, the higher its engineering and manufacturing costs.

Principal Antenna Solutions

There are literally thousands, if not millions, of different antenna designs serving a wide spectrum of frequencies and communications applications. For the purposes of this discussion on airborne broadband, just a few candidate antennas will be described. The intent of this section is to help the layman gain a basic understanding of antenna hardware and how the different designs point to and capture RF energy.

Dish Antenna, Mechanically Steered

The dish antenna is one of the easiest antennas to grasp. It functions in a similar manner to something we can all visualize—reflected light. RF signals can be reflected, focused or channeled along a pipe in much the same manner as working with light. Think of the dish antenna as a curved mirror that reflects light energy back to a single point; at that point there is a stronger concentration of energy than what exists anywhere on the dish itself. It employs the same optical logic as a magnifying glass, except that it uses reflection. The larger the dish, the more RF energy that can be captured and reflected back to the focal point.

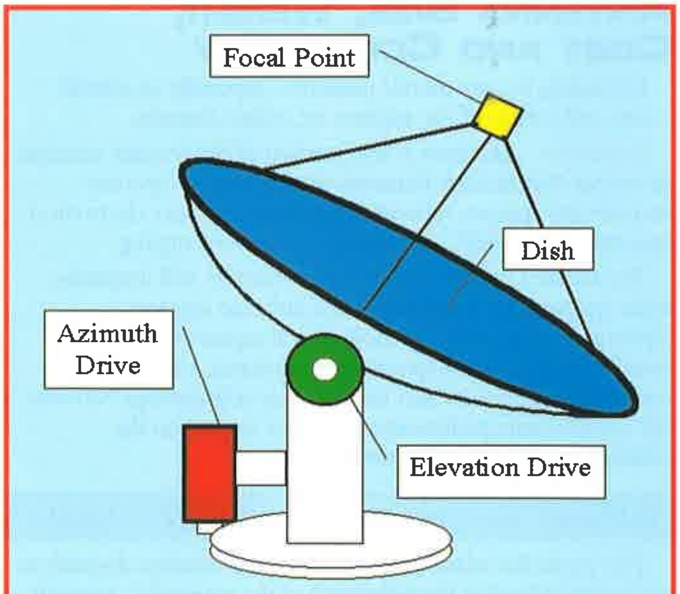

Illustration 1, Dish Antenna

continued on page 29

Unlike satellite dishes added to homes, an airborne dish antenna must have: (1) *azimuth* and *elevation drive motors* for pointing at or tracking the satellite to compensate for all aircraft locations and movement, (2) a *radome* to minimize drag and provide environmental protection, and (3) like all airborne equipment, the antenna must *meet stringent aircraft requirements* relating to operating temperature, altitude, Electromagnetic Interference (EMI), power utilization, etc. Also the airborne dish is smaller than the home version (11″ to 13″ in diameter versus 18″ to 20″). This design trade is made to reduce radome size/drag at the expense of antenna gain, the lower limit being a dish that becomes too small and can no longer pick up the satellite signals.

DEFINITION: ***Azimuth***, rotation in the horizontal plane (as in degrees of the compass).

DEFINITION: ***Elevation***, rotation in the vertical plane (from the horizon to directly overhead).

DEFINITION: ***Drag penalty*** can be thought of as the efficiency losses associated with disrupting/altering the airflow along an aircraft's fuselage or other aerodynamic surfaces. Any such disruption is less efficient than the original aircraft design and therefore has an impact on how easily the aircraft can move through the air. All antenna/radome designs that are placed on the fuselage or other locations cause additional drag (expressed in pounds or kilograms); the larger the drag, the greater the fuel costs to overcome the drag and maintain air speed. While the drag figure may be small, say 5 to 50 pounds depending on the antenna/radome size and shape, the additional fuel costs are perpetual, every hour of flight for the life of the aircraft.

DEFINITION: ***EMI (Electromagnetic Interference)*** is any RF energy disturbance that interrupts, obstructs, or otherwise impairs the performance of electronic equipment[2]. Meeting the FAA and aircraft manufacturers' EMI requirements has become increasingly difficult as concerns intensify over the multitude of new electronic devices built for passenger communications/entertainment, and preventing them from interfering with the aircraft's primary mission, flying safely!

Flat Panel Antenna, Mechanically Steered

The aperture of a flat panel antenna incorporates a collection of small tuned elements positioned across a planar surface. Each of the elements is actually a small antenna itself, with its size and geometric layout precisely engineered to respond to a specific frequency or range of frequencies. The element design, number of elements, how they are combined and their physical relationship to one another determine the antenna gain, frequency response, and beamwidth (receive and/or transmit).

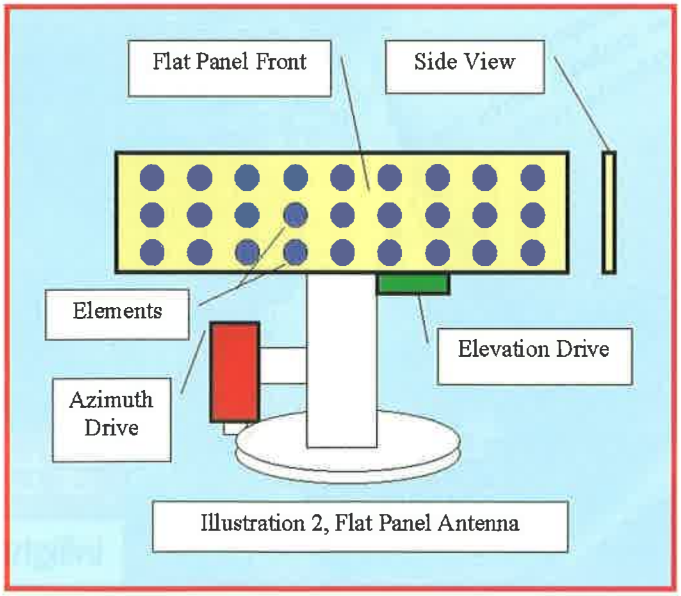

Illustration 2, Flat Panel Antenna

Azimuth and elevation drive mechanisms (same as used with the dish antenna) are responsible for keeping the antenna aperture at right angles to the source of RF energy, both horizontally and vertically. This right angle position ensures that the entire aperture receives the maximum amount of energy from the communications source (i.e. in this right angle position the physical aperture and *apparent aperture* are the same size).

DEFINITION: ***Apparent aperture*** is the size of the antenna as seen by the RF source.

Back to our analogy of wind (RF energy) and a sail (apparent aperture). Picture a 12″ × 12″ sheet of paper held directly in front of a fan. The paper is receiving the maximum wind energy on its 144 square inches. If the paper were tilted back at a 45° angle, the usable sail area (apparent aperture) would be reduced by half to 72 square inches. Only a 12″ × 6″ area is seen by the fan. This same result occurs in the relationship between an RF energy source and an antenna aperture; it is only the apparent aperture that can actually see/receive the RF signal. A large antenna with only its edge presented to an RF signal has virtually no apparent aperture. This is a very important issue, especially for phased array antennas which are steered electronically; their apparent aperture decreases as the antenna-to-satellite angle increases. More on this later.

Slotted Waveguide Antenna, Mechanically and Electronically Steered

This antenna is produced by joining sections of tuned *waveguide* to trap and then combine RF signals which are carried inside the channels of the waveguide.

DEFINITION: A ***waveguide*** is a rectangular or circular metal pipe that has a predetermined cross-section, specifically designed to guide or conduct high-frequency electromagnetic waves through its interior[2].

The antenna is made up of several sections of waveguide stacked next to one another. Each waveguide has several slots which allow the received RF energy to enter the waveguide at precise points. The energy can then be combined within each section, and combined section-to-section to give the antenna the required gain. The number and size of waveguide and the geometry of the slots determine the operating frequency and beamwidth of the antenna pattern. Slotted wave guide antennas can be steered mechanically for both azimuth and elevation (as done with the previous two antennas)… but let's discuss a hybrid approach.

continued on page 30

Antennas
continued from page 29

Mechanical pointing/tracking for azimuth is easily understood as swinging the antenna around to place it perpendicular to the RF source. However, electronically pointing/tracking the antenna for elevation is a bit more abstract. Without moving the antenna up or down physically, the phasing (or delay) of signals coming from each waveguide section can be changed so as to have the effect of looking up or down from the apertures primary plane.

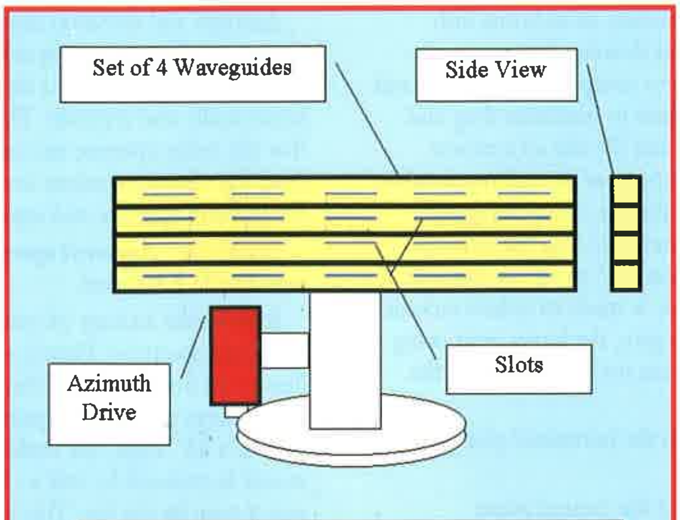

Illustration 3, Slotted Waveguide Antenna

This analogy may help: Imagine that you (the satellite) are sitting in an end-zone seat of a football stadium, looking out and down on 20 people (antenna aperture) positioned on the field. Five are equally spaced along the goal line, five on the 5-yard line, five on the 10-yard line, and the final five are on the 15-yard line. If you were to shout (RF energy) to them, the sound wave would first reach the listeners' ears (antenna elements/wave guide section) on the goal line, then the 5-yard line, then the 10-yard line and, finally, the 15-yard line. To combine the listening capability/sensitivity of all four rows of people (to realize gain in the satellite's direction) they would have to hear your shout at the same time. While this would be very difficult in the shout analogy, it can easily be accomplished in antenna/electronics design. There are electronic techniques which allow us to receive signals at various points, at different times, then delay each signal the correct amount so that they coincide in time. The individual signals are then combined to create one significantly larger received signal. This technique —delaying and combining signals from each waveguide row—would, in our analogy, be the equivalent of tipping the football field up so that each row of five listeners would be the same distance from your seat location (electronic pointing/tracking).

Luneberg Lens Antenna Array, Mechanically Steered

The Luneberg lens antenna array design is a bit of a hybrid between a lens and an array antenna. A Luneberg lens array uses several spherical dome lenses as the array element. Each spherical dome lens has a moveable focal point that is moved up or down across the dome to receive/transmit RF energy at various elevation angles. Unlike the dish antenna which must have its reflecting surface moved up or down in elevation, the Luneberg lens antenna element moves multiple focal points.

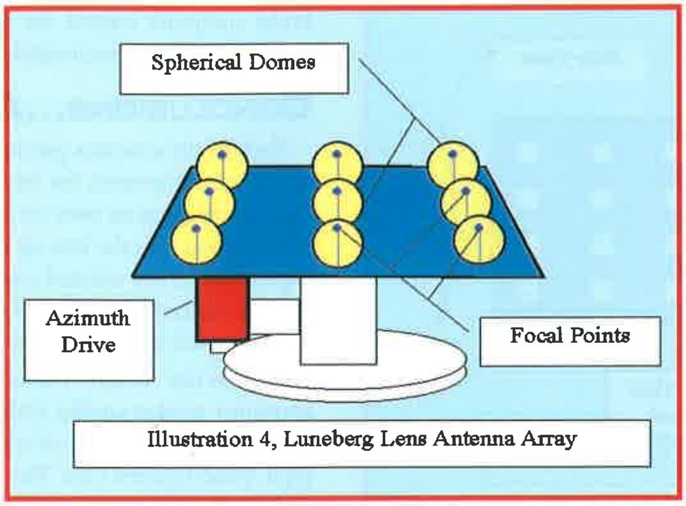

Illustration 4, Luneberg Lens Antenna Array

In this hybrid scan Luneberg lens array, azimuth steering is achieved by rotating the turntable that carries the lens elements. This azimuth rotation reduces the movement of the lens focal point collector elements to just one direction: elevation. Control is done in same manner as what was described for the other antennas. The planar surface, carrying the spherical domes, is rotated mechanically to position all of the focal points so they are pointed at the RF source.

Phased-Array Antenna, Electronically Steered

One of the most interesting antenna approaches is the Phased Array antenna—intriguing because it uses no moving parts. The Phased-Array antenna is constructed in a similar manner to the Flat Panel antenna discussed earlier. It is made up of several or even several hundred antenna elements populated in rows and columns on a planar surface, or a slightly curved surface to match the shape of an aircraft fuselage.

Its magic comes from accurately controlling the timing/phasing of RF energy that passes through each antenna element. Through this phasing the RF energy received or transmitted by the antenna is focused electronically in both azimuth and elevation. If you have a grasp of the electronic elevation control described for the Slotted Waveguide antenna, then understanding the Phased-Array will be a cinch.

continued on page 32

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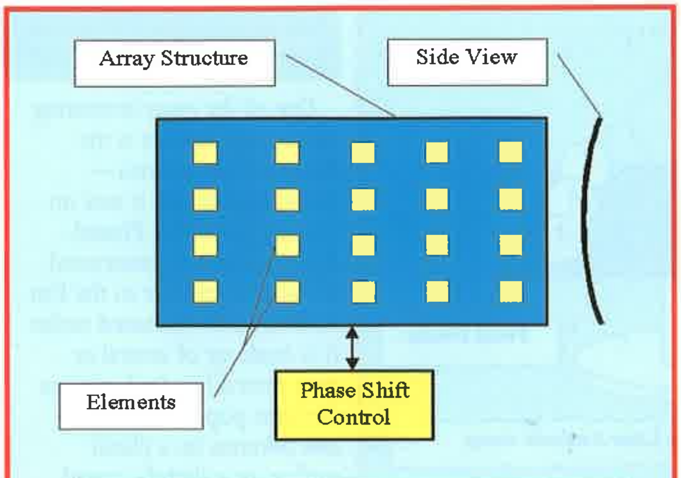

Illustration 5, Phased-Array Antenna

Imagine the same football stadium as used in our earlier analogy. Let's now have the 20 listeners position themselves over the entire field in evenly spaced rows and columns (elements on a flat panel). No matter where you choose to sit in the stadium (satellite location and relationship to the antenna) there is an appropriate delay (phasing) for each person on the field so that, whatever you shout, it will be heard and combined (gain) by all listeners at the same time. Also, if the people on the field were to shout (transmit) with the proper delays (phasing) you would hear and combine them all simultaneously.

DEFINITION: In a ***Phased-Array Antenna***, the radiation pattern of the fixed beam is determined by the phase relationships of the signals that excite the radiating elements. With adjustable phase shifters operating under computer control, the beam can be scanned in azimuth or elevation without mechanical movements[2].

Conclusions...Always Difficult

Each of the antennas previously described can meet the airborne requirements for broadband communications. Also, each antenna has its own set of strengths and weaknesses that will position it as the best or less than optimal design choice, depending on the selected communications link and the required over-all performance. *Table 3* presents some of the design trades and how well they are met by the various antennas.

Back to our AVION Editor's question relating to a simple consumer market satellite dish antenna: It can bring to your home multiple channels of television and/or one-way delivery of high speed Internet data. But your house doesn't have pitch, roll and heading changes. It isn't under a continental US satellite in the morning, an Atlantic Ocean satellite in the afternoon, and then a European satellite in the evening. And while you may be concerned about the cost to heat your home, you don't have to pay for fuel to move it around at 450 knots and be concerned about any increase in aerodynamic drag from a new antenna/radome and the subsequent fuel costs that go on for the life of the house, or let's say...aircraft.

References:

1 The MPEG AudioWeb Page, http://www.tnt.uni-hannover.de/project/mpeg/audio/
2 Electronic Dictionary, John Markus, McGraw-Hill Book Company

TABLE 3

Antenna Type: ⇧ = Strength ⇨ = OK ⇩ = Weakness

Parameter	Dish	Flat Panel Mechanical Scan	Slotted Waveguide Hybrid Scan	Luneberg Lens Array	Phased Array
Design Costs	⇧	⇨	⇧	⇨	⇩
Manufacturing Costs for Aperture Size	⇧	⇨	⇧	⇨	⇩
Gain and Data Rate	⇧	⇧	⇧	⇧	⇩
Beamwidth Control for Aperture Size	⇧	⇧	⇨	⇨	⇩
Sidelobe Performance For Aperture Size	⇧	⇧	⇨	⇨	⇨
Pointing and Tracking Accuracy	⇧	⇧	⇨	⇨	⇨
Incorporate Transmit and Receive	⇨	⇨	⇨	⇨	⇨
Incorporate Polarity Correction	⇧	⇨	⇨	⇧	⇨
Appropriate for Use Below 5.0 GHz	⇩	⇧	⇩	⇩	⇧
Appropriate for Use Above 5.0 GHz	⇧	⇧	⇧	⇧	⇩
Radome Size and Drag	⇩	⇨	⇨	⇨	⇧
Installed Weight	⇨	⇨	⇧	⇨	⇩
Satellite Coverage Area*	⇧	⇧	⇩	⇩	⇧

**Ability of some designs to steer down to and below the horizon to maintain satellite link.*

About the Authors...

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