SATELLITE ANTENNAS

Antennas for satellite systems have developed and increased in performance over the last 40 years and greatly contribute to satellite capabilities. The preponderance of this antenna development has been for communication systems, and other development has been for remote sensing applications. Early satellite systems provided not only proof of concept but also a useful initial operating capability. The payload constraints of early satellites together with primitive attitude control systems limited antennas to simple narrow-bandwidth, broad-coverage designs, a far cry from today's sophisticated antenna systems with substantial throughput capabilities. Similarly, early users needed large ground terminal antennas to achieve the required link performance, and terrestrial links were provided to other system users. Today, systems are being developed to communicate to individual users with hand-held terminals (1).

Both spaceborne and user antenna systems have requirements and development issues that are unique to satellite systems. In addition, satellite system antennas have testing requirements and objectives that differ from other antenna applications. Antenna technology, requirements and development issues, and test methods and objectives are described.

SPACE SEGMENT ANTENNAS

Spaceborne antennas have unique requirements and development issues. Like all satellite subsystems, much design attention is paid to three important parameters: weight, power, and volume. Likewise, reliability is a key requirement because an anticipated lifetime exceeding ten years is expected without the possibility of repair or servicing. Spaceborne antenna designs must be sufficiently rugged to survive the rigors of launch environments. In addition to these physical requirements, the rf requirements differ from common antenna specifications. Spaceborne antennas provide performance over prescribed coverage areas containing the user segment; the pattern of the antenna projected on the earth's surface is referred to as its *footprint.* Antenna systems are specified by their minimum performance within the specified coverage area rather than their peak performance levels. This discussion uses different coverage area requirements to describe space segment antennas.

Earth Coverage Antennas

The simplest spaceborne antenna design is one that matches its coverage area with the available field of view from the satellite. These antennas are generally referred to as earth coverage designs, and their beamwidth subtends the field of view plus the angular uncertainties of the satellite's attitude stability. Early satellite attitude control systems had both limited attitude control and uncertain reliability so that simple antenna designs with broad coverage were used. However, today's attitude control systems provide stabilities on the order of one-tenth of a degree, so that earth coverage antennas can be essentially matched to the field of view. Thus, for geosynchronous satellites, an antenna with an 18° beamwidth is required; lower altitude LEO and MEO satellites require a correspondingly larger beamwidth for their larger field of view.

A typical earth-coverage design for geosynchronous altitudes is a corrugated horn antenna (2) which can be easily constructed and has a rotationally symmetric, low sidelobe pattern for an efficient fit to the design coverage area. These horns are typically wide flare designs chosen to maintain the same beamwidth and coverage over a wide bandwidth. Thus, a single horn together with a diplexer to isolate the receiver and transmitter can be used for both uplink and downlink frequencies. A design alternative at higher EHF frequencies is separate uplink and downlink horn antennas because these horns are very small and lightweight. Since the uplink and downlink frequencies are widely separated at EHF, the transmit diplexing filter is inherent because the transmit waveguide is cutoff at the receive frequencies and a modest physical separation may provide adequate isolation to meet the receive diplexing filter requirement of avoiding receiver saturation at the transmit frequency. Thus, the weight of a second horn antenna is offset because a diplexer is not required and performance is not degraded by the insertion loss of the diplexer.

At lower LEO and MEO altitudes, the broader field of view requirements can be met with an open-ended waveguide surrounded by corrugations to produce low sidelobes and beam symmetry. At these lower altitudes, the range differences between the subsatellite point and the edge of the earth become more significant and thus users at the edge of the coverage experience less sensitivity from the satellite antenna. In these cases, a shaped beam that provides more gain at the edge of the earth than the subsatellite point may be desired. Such

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shaped-beam antennas can be realized by an array of horns with properly selected excitation to meet the beam-shaping requirement. However, such shaped-beam designs have more design complexity than a simple horn, and weight and volume are important satellite parameters. A well-known example of shaped beam designs is the array antenna used by the GPS satellites to broadcast navigational information. The GPS satellites are in a 12-h orbit, and the antenna array (3) is designed to deliver a uniform flux density to users within the earth's field of view.

Tracking, Telemetry, and Command Antennas

Every satellite requires a TT&C (tracking, telemetry, and command) subsystem to assist in determining the satellite's orbital position, reporting the satellite's health and status to the ground-based satellite control segment, and providing a means to command and validate changes to the satellite's operation. The TT&C antennas have two distinct coverage requirements. One requirement is to provide complete spatial coverage during launch operations so that corrective commands or, in the worst case, a command for destruction can be delivered irrespective of the satellite's orientation. The second requirement is to provide coverage over the earth's field of view once on-orbit so that different terminals within the ground-control network can access the satellite. TT&C antennas must be both simple in design and highly reliable since the control of satellite operation is critical.

The broad coverage requirements of the TT&C antennas provide several design challenges. Aside from the impossibility of an ideal isotropic antenna with uniform sensitivity in all directions, the presence of the spacecraft blocks the antenna coverage. As a result, two antennas that strive for hemispheric coverage are used with one hemisphere being earth facing and the other hemisphere facing away from the earth. During launch operations, the antenna having the higher signal strength is used and once the satellite is stable in its orbital position, the earth facing antenna is used. In principle, somewhat better on-orbit performance could be achieved with an earth-coverage antenna, but the additional antenna and required switching increase weight and volume and add switch reliability risks. Since TT&C data rate requirements are low, ample link performance is readily achieved by ground-based control terminals.

Achieving and quantifying the performance of hemispheric coverage antenna elements remain challenges. Satellites have irregular shapes and appendages such as solar arrays whose positions vary to *sun track* and maximize their power output. The hemispheric coverage required by TT&C antennas is degraded by blockage and diffraction effects from the satellite structure. Controlling wide-angle sidelobes and backlobes of a simple, electrically and physically small antenna is difficult to do but is needed to minimize antenna interactions with satellite structure. Extending the antenna from the spacecraft to reduce interactions results in deployment risk. Analytic projections of the antenna coverage in the presence of the spacecraft are challenged by the design complexity and the wide variety of satellite designs. Measurements of the antenna performance have all the problems of testing broad coverage antenna designs. Certainly, measurements using flight hardware not only have practical limitations such as the inability to deploy solar arrays but also moving and positioning flight hardware for the measurements have unacceptable risks. Generally, these problems are addressed by a combination of selecting a satellite antenna location with a clear field of view, analytic estimates of the effects of nearby satellite structure, scale model measurements, and ample margin in the ground segment.

Typically, TT&C systems operate at the lower microwave frequencies. Generally, a single uplink and downlink antenna is used to minimize weight and volume and avoid mutual blockage. The difference between uplink and downlink frequencies often spans a significant percentage bandwidth. These considerations typically result in selecting a frequency independent antenna design such as a spiral to achieve the broad coverage requirements.

Spot Coverage Antennas

Spot coverage antennas service only a portion of the available field of view. These antenna designs provide higher gain levels than earth coverage antennas because of their narrower beamwidths. This higher gain performance may be traded for higher data rate transfer, reduced user antenna dimensions, or increased link margin. In addition, spot beam antenna designs can provide coverage that is confined to geographical areas (4) and avoid worldwide licensing requirements. Thus, these designs are widely used to serve national or regional requirements. Several different design implementations have been developed to satisfy these needs.

The easiest design solution is to select a sufficiently large antenna so that its beamwidth matches the required coverage area and any variations caused by attitude uncertainty. Such a design might consist of a reflector whose size is selected to meet the desired beamwidth and a single feed horn, a simple design approach. In such a design, any variations in coverage requirements during the satellite lifetime can be accomplished by mechanically repositioning the antenna to serve a different coverage area. Such a capability is commonly used in military satellites so that coverage to different geographical areas within the field of view can be provided to service changing political needs.

A wide variety of designs has been developed to service more irregular coverage areas. These coverage areas may be bounded by geopolitical borders, different time zones, etc. A standard means of providing such coverage is to synthesize the coverage area by combining different beams generated by a cluster of feed elements in the focal region of a reflector antenna. Each feed has its own pointing direction and the collection of beams subtends the desired coverage area. The individual beams being combined are required to have a common phase center so that grating lobes do not degrade coverage characteristics. Thus, the collection of beams is generated by a common aperture. The arrangement of individual beams and their corresponding feed elements mimic the desired coverage area. The reflector antenna size is much larger than that needed to provide coverage over the composite area. When active devices are used in the feed elements prior to combining, design attention must be paid to their amplitude and phase tracking. The precision of fitting to the design coverage area can be increased by using a larger number of beams at the expense of design complexity and a larger overall aperture size.

In addition to the complexity of the additional number of feeds and the larger reflector required by this approach, the design complexity also increases because the individual feeds are no longer located at the focal point of the reflector but instead are distributed within the focal region. The off-axis feeds are not ideally focused, and suffer gain loss and pattern degradation. These problems are shared with multiple beam designs and, as will be discussed, result in dual reflector designs to limit beam degradation when a large number of beam are combined.

Another design approach has developed in recent years to provide coverage over irregular areas. This design uses a single feed, and the irregular coverage area is generated by deforming the reflector surface (5). Synthesis procedures have been developed (6) to specify the required deformation of the reflector surface. This design approach has the advantage of a simple feed design rather than a cluster of feed elements and combining, but requires developing and maintaining controlled reflector surface distortion. If the coverage requirements change, a new surface deformation is required. This approach also precludes changing the coverage areas on-orbit by using beam switching techniques.

A final design alternative for spot coverage is an adaptive uplink antenna. The pattern within the coverage area is adaptively controlled to service desired users within the design coverage area to the extent practical while reducing received interference by forming pattern nulls in the direction of interference sources. This capability is principally required for military systems whose users desire protection from intentional interference. When interference is not present, a quiescent pattern provides coverage over the design region. When interference is initiated, the antenna responds under adaptive control to form pattern nulls.

Adaptive antennas require a means to distinguish desired signals from interference, to detect the initiation of interference, and to determine a set of complex weighting values that combine antenna elements to satisfy an optimization criteria. Several different discriminates have been employed to distinguish desired signals from interference: spectral characteristics, power levels, and signal arrival directions. When systems also use spread spectrum modulation for additional interference protection, the properties of the spread spectrum codes provide a basis to distinguish interference from desired signals. Interference initiation can be detected by increased received power levels that do not have spread spectrum modulation components; correlation processes are normally used to indicate interference power. An optimization criterion such as maximum SINR (signal to interference plus noise ratio) is used to establish complex weighting coefficients to combine antenna elements. Generally, a recursion relation based on measured correlation values and the optimization criteria is derived to form a control algorithm. The combination of the complex weighted antenna elements produces a pattern containing null in the direction of interference, and equivalently, the received interference power is minimized.

Two types of antenna designs have been investigated for these adaptive systems (7,8). One approach uses a thinned array where the elements are combined to generate pattern nulls when interference is present and a set of weighting coefficients for interference-free cases. The potential advantage of this approach is that the resolution between desired users and interference is enhanced by increasing the array element spacing. However, the separation between array elements produces additional nulls within the coverage area referred to as grating nulls that degrade coverage characteristics. The separation of the array elements results in the inherent frequency scanning properties of an array creating dispersion that limits cancellation performance over the required bandwidth. In addition, the coverage of the array elements generally extends beyond the desired coverage area resulting in susceptibility to interference beyond the coverage area. Finally, the thinned array design generally results in reduced G/T performance within the coverage area.

The second design approach uses an offset reflector with a cluster of feeds in the focal region. In interference-free conditions, a set of quiescent weighting values for the individual feeds maintains performance over the design coverage area. The initiation of interference produces correlation products associated with the interference that are used to derive complex weighting values. The advantage of this design approach is that all beams generated by the feed cluster have the same phase center location so that the dispersion inherent in array designs is not present and broad bandwidth cancellation performance is achieved. The resolution between interference and desired signals is limited by the beamwidth of the individual beams. This resolution depends on the amount of G/T margin that the user can sacrifice and the interference source's location on the earth, as illustrated in Fig. 1. A comparison between the performance of a thinned array design and a multiple feed design is presented in Fig. 2. The grating nulls are apparent in the thinned array contours, which reduces the coverage available to users.

Several performance measures are used with adaptive antenna designs. The threshold SNIR establishes a bound for acceptable communication performance that can be measured using BER (bit error rate) values by injecting both desired signals and residual interference into the receiver. The null depth performance and its variation over the required bandwidth as measured between the quiescent pattern and the pattern after adaption are sometimes used to judge nulling performance. The amount of time the adaptive process takes to convert the quiescent pattern to the nulled pattern is referred to as the convergence time and measures the transient performance of the system. Finally, for this uplink application, the amount of the design coverage area that exceeds the threshold SNIR value is another measure for space segment antennas. These performance measures depend on the number of interference sources and their locations, and their power levels and spectral characteristics; this description of the interference is referred to as a scenario. Adaptive systems are commonly developed using a simulation that varies the scenario parameters on a Monte Carlo basis to provide statistical measures of the performance parameters. The simulation is then validated by using hardware measurements on a limited number of scenario cases in order to avoid the impractical amount of time required to test on a Monte Carlo basis.

Multiple Beam Antennas

Multiple beam antenna systems (MBA) (9) greatly increase the on-orbit satellite capabilities. These antennas simultaneously produce more than one antenna beam from a single aperture. For space applications, a single aperture is a significant savings in space required on the satellite and the overall

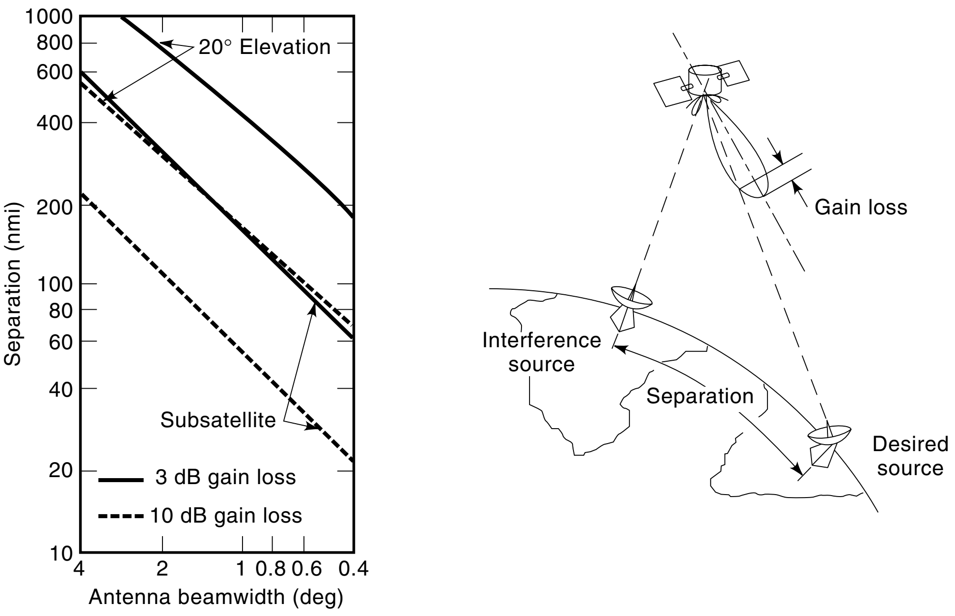


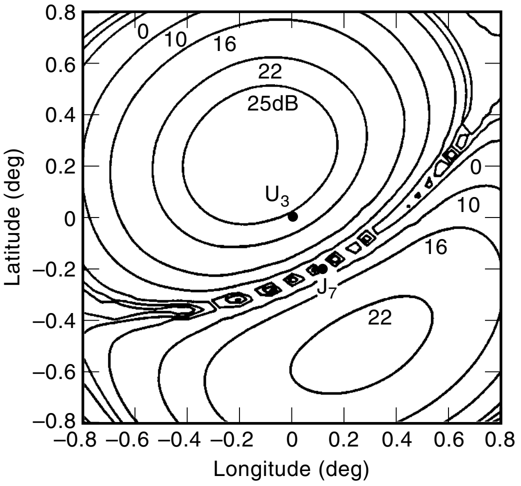
Figure 1. Adaptive antenna resolution (after Ref. 8).

weight compared with multiple aperture alternatives. When the coverage area is subdivided by different beams, the gain available to users increases permitting higher data rates or reduced user terminal performance. A further advantage of multiple beam antennas is that beams directed to different geographic locations are isolated by their spatial separation. Thus, the same frequency bands can be used simultaneously at both beam locations increasing the information that can be transferred by a single satellite. These advantages are the reasons for the wide application of multiple beam antennas.

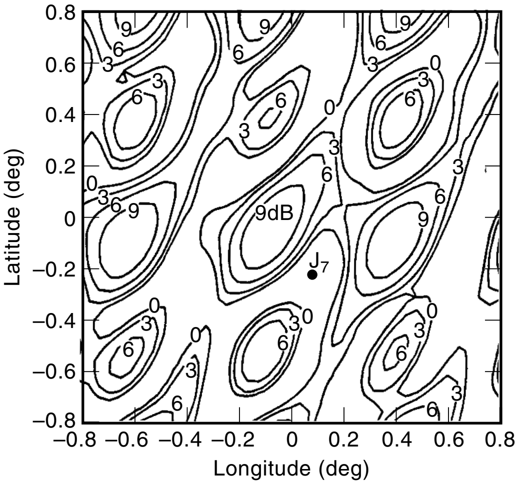
The antenna design has several different requirements. Independent beams must be efficiently generated with high pattern fidelity and minimal gain degradation over the required field of view. Isolation between different beams must be maintained so that signals using the same frequency subband are not degraded by cochannel interference. Beam-forming networks that combine signals from the antenna beam outputs to and from the satellite transponder must be developed. The transponder must provide a means to map the uplink information in each beam position to the downlink beam positions.

One design issue is to efficiently generate independent beams with high pattern fidelity over the required field of view. When optical designs (i.e., reflector and lens antennas) are used, each feed produces an independent beam in a different direction, but not all of the feeds are ideally focused. As a consequence, some of the feeds experience phase distortions that degrade the pattern characteristics and reduce the gain compared to the feeds that are well focused (10). Several different techniques in the design of the optics are used to minimize the degradation. One technique is to select a long *f*/*D* ratio to reduce off-axis phase distortions. The popularity of dual reflector designs in these applications results in part from their increase of the effective *f*/*D* and careful attention to the optics can produce excellent results (11,12). The dual reflector designs in an offset configuration also provide the ability to achieve very good polarization purity. Other techniques have been applied to selecting lens surface contours (13).

In addition to achieving good pattern and gain performance over the required field-of-view for an individual feed,



(**a**) Multiple beam contours



(**b**) Thinned array contours

Figure 2. Comparison of multiple beam antennas and thinned array performance (after Ref. 8).

another set of design challenges exists with the cluster of feeds. The problem is a conflict among beam isolation, the crossover level between adjacent beams, the sidelobe levels of the beams, and the antenna efficiency. On the one hand, low sidelobe patterns are desired to enhance the beam isolation which requires the feed to produce an amplitude taper over the aperture resulting in a relatively large feed. The physical interference between large adjacent feeds results in a relatively low tangential crossover level (the pattern level relative to the beam boresight at an equal distance between beam centers) between beams. The consequence of the low crossover level is that the minimum gain within the field of view is reduced. On the other hand, high beam crossover levels result a higher minimum gain level within the field of view, but beam patterns with high sidelobes having reduce beam isolation. High beam crossover levels also result in beam coupling loss (14) that degrades antenna efficiency.

These conflicts have resulted in several different design approaches. One technique is to couple signal samples from adjacent feed elements (15) to achieve high crossover levels, low sidelobe patterns, and reasonable antenna efficiency. Another technique (16) uses a underilluminated aperture with the feeds displaced from the focal region. This approach requires a somewhat larger reflector than the focused case, but at EHF frequencies where compact antennas result from the small wavelength, the size increase may be unimportant.

The required isolation between beams depends on the susceptibility of the signal modulation to cochannel interference and the dynamic range of the system users. Thus, the required isolation level must be derived for each application. Isolation between adjacent beams can be achieved in two ways. One way, referred to as frequency reuse, divides the allotted bandwidth into subbands. A frequency plan is devised to adequately separate the beams using the same subband to meet the isolation requirement. Since the same frequency subband is simultaneously used in different beam positions, the plan is referred to as a frequency reuse plan.

A second way of increasing isolation referred to as polarization reuse uses orthogonal polarizations together with frequency subbands in applications requiring high isolation. Orthogonal polarization is also used in applications demanding as much capacity as possible because the same beam position can transfer twice the information. These techniques require antennas with high polarization purity; a typical requirement is to suppress cross polarization levels at least 27 dB lower than the principal polarization. Generally, satellite systems use circular polarization so that the user does not have to align to a linear polarization. However, inclement weather can cause coupling between polarizations reducing the isolation. This effect is less severe for linear polarization, so that orthogonal linear polarization is sometimes used. This combination of polarization and frequency reuse is commonly used by commercial systems to obtain as much capacity as possible from a single satellite.

Multiple beam antennas are generally considered as designs covering the available field of view. As the beamwidth of the individual beams decreases, the required number of beams greatly increases as shown in Fig. 3, larger aperture sizes are required and the complexity of beam routing increases. In some applications, multiple beams are used in a limited geographical region (4,17). The Ka-band multiple beam system described in Ref. 17 has such small beamwidths that active tracking of a ground beacon is required to compensate for satellite attitude variations.

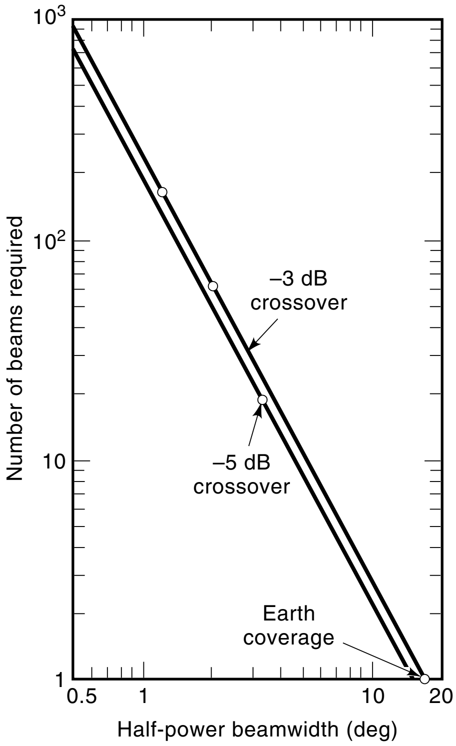


Figure 3. Number of beams to cover FOV (after Ref. 9).

The ability to process and direct the information on the collection of multiple beams requires beamforming networks that separate information on the uplink beams and combine information on the downlink beams. A wide variety of beamforming networks has been developed. The simplest design is a fixed beam-former network that simply combines beams in a fixed pattern. This beam former together with transponder channelization maps the uplink beam patterns into the downlink patterns. other beam-former designs use cascaded networks on switches or variable power dividers so that the beam patterns can be changed on-orbit. Still other beam formers use adaptive processing on the uplink beam former to negate interference. Yet other systems route the uplink information to a terminal on the ground, referred to as a *gateway,* where the uplink beams are mapped into the downlink collection.

The beam formers have different requirements for the uplink beams and downlink beams. The system noise temperature on the uplink can be established by preamplifiers which are followed by the beam formers. In this way the system sensitivity is not degraded by the insertion loss of the beam formers, and lightweight networks and diode switching can be used in the beam-former implementation. The downlink beam-former network must be placed between the transmitters and the beam ports, so that power handling and insertion loss are important design parameters. In addition, switching for redundant transmitters is also required. These requirements depend on the application.

The development of multiple beam antenna systems has been principally pursued for geosynchronous satellites, and future design challenges exist to develop multiple beam designs for LEO and MEO satellites. While offset reflector antennas are commonly used in geosynchronous satellites, these antennas are examples of limited scan antennas (14), that are not appropriate for the wider field of view at the lower altitudes. These lower altitudes also need wider beamwidths than geosynchronous designs to maintain reasonable footprint dimensions, and thus the overall antenna size is electrically smaller. Array antennas are commonly used to meet performance requirements for these orbits. With their smaller electrical size compared with geosynchronous designs, a reasonable number of array elements is required.

The trend toward using digital technology in the transponder also naturally leads to considering digital beam-forming techniques in the array design. On the uplink, the received signal at each element is preamplified, downconverted to baseband, and transformed into the digital domain by an analog-to-digital converter (ADC). Digital samples from each array element are combined using a complex matrix multiplier containing the complex coefficients that perform the beam steering. Parallel complex multipliers are required to form multiple beams. The same constraints on beam isolation exist for multiple beam operation. The downlink antenna follows the same procedure in reverse. The input digital data stream is complex matrix multiplied to obtain the properly weighted samples for each array element for the beam steering, and a digital-to-analog converter (DAC) provides conversion to the analog domain. This analog baseband is upconverted to the transmit frequency and suitably amplified to the required element power level. Experience with digital array designs is described in Ref. 18; an adaptive array using digital technology to increase beam isolation is described in Ref. 19.

The downlink array designs for multiple beam operation also present challenges in transmit power control. The element transmit power is shared with each of the beams transmitted by the array. The relative amplitude and phase between the array elements must be maintained to achieve the desired downlink pattern. In addition, the total power in the array elements must be maintained near saturation to achieve the design ERP performance and maximum power efficiency. However, the total power must not extend into the transmitter's nonlinear region that would degrade performance by producing intermodulation products and signal suppression. The challenge is to maintain the required amplitude and phase excitation for each beam while allotting each beam an equable share of the downlink transmit power.

Remote Sensing Antennas

Satellite antennas also include designs for remote sensing applications. Two types of sensors are used: active, or radar, and passive, or radiometric, sensors. These systems are used in low-orbiting satellites to provide both global coverage and high resolution of terrain features.

Radar sensitivity is commonly measured by the power aperture product of the design, and thus, in addition to high peak power levels, a physically large aperture size is required (20). Antenna designs for active applications generally require deployment to achieve the required aperture size. A conflict exists in these designs. Large apertures can be obtained from low frequency arrays where a reasonable number of elements are required and the mechanical tolerance is not overly stringent, but the resolution of these systems is lower than higher frequency designs. The better resolution of the higher frequency designs is accompanied by the requirements of additional array elements and more stringent mechanical tolerance. The size, weight, and prime power requirements for these sensors make their development an ambitious effort, but future systems designs, particularly those using synthetic aperture processing, can be anticipated.

Passive sensors are commonly used for both meteorological and terrain remote sensing (21). Two types of antenna designs are used in these applications. One type of antenna, generally an offset reflector, is mechanically rotated at a constant angle from the satellite's nadir to generate a conical trace on the ground at a constant elevation angle. As the satellite proceeds in its orbit, a swath on the ground is swept out. The requirements for these antennas include design attention to minimize insertion loss to achieve high sensitivity, good polarization purity to discern the radiometric contrast for oblique incidence angles used by these sensors, low sidelobes so that the emission received by the main beam is not degraded by sidelobe returns, and a narrow beamwidth to obtain good resolution of terrain features. Commonly, these antennas are specified by their solid beam efficiency performance. This parameter is defined by the power received for the specified polarization over a required angular region to the total power received from all space assuming the antenna is uniformly illuminated from all directions. This parameter is defined to provide a means to quantify the degree to which the power received by the sensor is isolated to its specified coverage area. This system design commonly operates at several different frequency bands using the same aperture.

A second type of antenna has a much simpler design and is used in sensors referred to as *sounders*. In this design, the antenna boresight is aligned with the satellite nadir. These designs operate at frequencies selected from peak of molecular absorption resonances, which occur at EHF frequencies. Several different IF bandwidths are used in these designs. As the bandwidth straddles more of the molecular resonance, the absorption toward the bandwidth edges reduces from the peak value at the resonant frequency. This reduced absorption at the bandwidth edges permits the sensor to view emission closer to the earth's surface. Thus, by examining the emission received at different IF bandwidths, a profile for different altitudes may be observed. The antennas used in these sounder designs are generally corrugated horn designs selected for their low insertion loss and rotationally symmetric, low sidelobe patterns.

USER SEGMENT ANTENNAS

User segment antennas also have requirements specific to satellite applications. In addition to meeting G/T and ERP requirements for link closure, the user antennas generally need to align their main beams with the appropriate satellite. Other design issues include the control of interference to and the reduction of interference from other systems. With the increased number of satellite users, terminal costs including the antenna, transportability to alternative locations, and in future personal communication systems, techniques to reduce interactions with the surrounding environment form the principal development issues.

Radio Frequency Issues

The most common user antenna is a reflector design capable of reasonable RF performance with a modest cost. Other antenna technologies, such as phased arrays, have more complexity which results in higher manufacturing costs, and therefore are used when compelling reasons exist for their design. For example, aerodynamic constraints for high performance aircraft may dictate the development of conformal array designs.

The trend toward increased numbers of users results in the terminal costs having a significant fraction of the total system costs. This trend in turn requires sufficient performance from the satellite to minimize terminal performance requirements. An excellent example is provided by direct broadcast satellite TV services where both the user terminal size and costs have dramatically shrunk. More generally, the present development of systems for VSATs (very small aperture terminals) illustrates this trend. A very important part of system planning is to insure that adequate satellite performance is available to minimize user performance requirements, and thereby control the total system cost as well as provide a minimum amount of equipment, particularly for those users with mobility requirements.

The increased number of satellites on-orbit has also resulted in additional requirements for the antennas. Concern regarding interference to and from satellites that are closely spaced in orbit has resulted in sidelobe envelope requirements to reduce interference levels. These requirements are mandated on antenna manufacturers. A typical example of these requirements has been levied by the CCIR [International Radio Consultative Committee, technical branch of International Telecommunication Union (ITU)] (22), which results in a sidelobe envelope constraint that depends on the electrical size of the antenna.

Sidelobe control is one antenna technique that reduces interference for both reception and transmission. Another technique for reducing received interference is to construct an adaptive cancellation system. A typical design for ground terminal applications called a *sidelobe canceller* (23) assumes the desired signal is received by the main beam and that the interference arrives through the antenna sidelobes. The antenna hardware consists of a main reflector antenna and a set of auxiliary antenna elements which are combined with complex weighting values with the main reflector antenna to cancel interference. The principal issue for this design approach is the dispersion inherent in the main reflector's sidelobe response. The sidelobe response of reflector antenna includes radiation from edge diffraction, direct feed radiation and spillover, scattering and blockage contributions, and leakage from the panels composing the reflector surface. The complex sum of these individual radiation mechanisms varies over the operating bandwidth so that effective cancellation requires frequency-dependent weighting values. Such frequency-independent weighting values can be achieved by adaptive equalization circuitry using a transversal filter with adaptive weighting coefficients at each time delay tap. An example of this interference reduction approach may be found in Ref. 24, which describes the design and the measured results of a demonstration of cancellation capabilities.

The trend toward increased microwave users and systems extends beyond satellite applications. This trend also increases the possibility of interference to user terminals from nearby terrestrial systems. A particular concern is the possibility of out-of-band receiver compression from high-level pulse systems such as radars which suppresses desired signal levels and creates intermodulation products degrading receiver performance. Design attention must be paid to the receiver's dynamic range and RF filtering to protect the receiver from high-level interference. However, RF filtering while necessary has insertion loss that degrades sensitivity by reducing the received signal and increasing the system temperature.

Inexpensive, low noise receiver front ends and relatively low sky temperature values (25) provide the potential of low system temperatures that increase system performance and reduce the required antenna size. Controlling antenna spillover and wide angle sidelobe levels by both efficient rotationally symmetric feed designs and reflector geometry choice produces low antenna temperature values (26). Low antenna temperature values also require minimizing feed and transmission line losses. Filter loss even in a high Q media becomes the dominant insertion loss, but such receiver protection is necessary. These steps permit development of terminals that meet the required G/T with a minimum size antenna. These factors result in the popularity of offset reflector antennas for user applications. The efficiency of offset reflectors is enhanced by the absence of feed blockage, their high level spillover lobes are directed toward the lower sky temperature instead of the ambient earth temperature, and their low sidelobe levels minimize the antenna temperature while also complying with sidelobe envelope requirements.

User antennas for future personnel communication systems face additional challenges. These antennas must provide broad coverage so that antenna pointing is not required, particularly since the LEO and MEO orbits used in these systems produce ever-changing angular positions between the user and the satellite. One problem inherent in broad-coverage antennas, as previously discussed for TT&C antennas, is the sensitivity of the antenna performance to the environment surrounding the antenna. For the personal communication application, there exists a wide variety of environments with varying degrees of multipath (i.e., scattering from humanmade and terrain features). In addition, link performance can be degraded by foliage attenuation and blockage from terrain features. These development issues are being actively pursued for both satellite systems and terrestrial cellular networks that operate at somewhat lower frequencies. Development of techniques to mitigate these degradations is also being actively pursued; techniques such as Rake receivers that provide adaptive diversity combining and equalization are being evaluated.

Antenna Pointing Techniques

User antennas must also be aligned with the desired satellites for signal reception. The satellite's orbital position is specified by its ephemeris which describes the satellite's altitude, eccentricity of orbit, inclination, longitude of ascension, and time of epoch. The satellite ephemeris and the user location are required to determine the antenna pointing angles. Typically, this information is transferred to the antenna control unit where the required pointing angles are computed and the necessary commands to the antenna positioner are issued. The requirements for antenna pointing depend on the antenna beamwidth, the uncertainty in the satellite's location, and the orbital dynamics. For communication applications, a pointing accuracy of one-tenth of a beamwidth is typically specified to minimize signal loss caused by pointing errors.

In some cases, antenna pointing is trivial. For example, the antennas for personal communication systems are purposely designed with broad coverage antennas so that the user has no pointing requirements. Another common example is a small user antenna for direct broadcast satellite reception from geosynchronous satellites. These antennas are roughly aligned using the user's geographic location, verified by signal peaking techniques, and rigidly secured. The combination of the relatively wide beamwidth from the small antenna and the stationary position of the geosynchronous satellite and its station keeping results in a fixed pointing requirement.

In other applications where satellites have inclined orbits or orbits that are not geosynchronous, the satellite undergoes dynamic motion with respect to the user, and a means must be provided to follow the satellite in orbit. For users with relatively broad beamwidths compared to the orbital uncertainty, the knowledge of the satellite ephemeris and the user location may be adequate to simply command the user's antenna position. This open loop procedure is commonly referred to as *program tracking*.

If some uncertainty exists in the antenna pointing, such as ephemeris data that are not current, another open loop technique referred to as *step track* is commonly used to verify correct alignment with the satellite's position. The user's antenna is pointed at the nominal position of the satellite as might be obtained from program track. The antenna is then commanded to move in equal and opposite angular positions from this nominal pointing direction. If the antenna is correctly aligned with the satellite, the received signal level should be reduced by the same amount at both angular offsets. If the signal levels at both positions are not identical, the difference in the power level provides the angular correction to the nominal position. This process is repeated in the orthogonal plane to properly position the antenna in two angular coordinates.

These two open loop antenna pointing techniques are commonly used together. The step track procedure is periodically exercised to validate the correctness of the program track pointing. A significant advantage of these techniques is that minimal equipment is required. The antenna positioner is required and simple software commanding is needed to execute the angular offsets. The power measurements at the different angular offsets may be obtained from a simple measurement of the receiver's automatic gain control (AGC) voltage with the appropriate calibration and linearity verification.

When user antennas have beam widths that approach ten times the uncertainty in satellite position or a significant amount of orbital dynamics exist, closed loop tracking techniques are required. These techniques are commonly used in radar systems to locate targets and are referred to as *monopulse* designs. This term is derived from radar applications because the tracking information is obtained from each radar pulse. In radar applications, the received signal level varies as the target changes aspect angle and typically has a significant dynamic range. Thus, tracking information is derived from each radar pulse so that the dynamics of the target return do not degrade antenna pointing performance. Monopulse systems for communication applications have easier requirements than those for radar systems. The received signal level has a relatively constant amplitude, so that the monopulse signals can be sequentially sampled reducing hardware requirements. The antenna pointing accuracy depends on aligning the antenna with sufficient accuracy to minimize signal loss as compared to locating a radar target with the maximum precision practical.

Monopulse systems operate by forming two types of antenna beam shapes: a sum beam that receives the desired signal and a difference beam that has a null on the antenna boresight axis. The signal power in the sum beam is maximized by positioning the antenna to the null of the difference pattern. The ratio of the signal levels in the sum and difference beams is independent of the power density of the received signal, and provides a measure of the angular displacement from the antenna's axis. This ratio can be used in a closed loop system so that the antenna will align to the received signal and will follow any variations in the signal location.

Two different types of feed designs are commonly used to generate the sum and difference beams. One feed design (27) uses a conventional feed for the sum beam and an additional four small feed elements to produce the difference beam. The second design (28) uses a higher order waveguide mode to produce the difference beam which is sampled by couplers. In both cases, the difference beam outputs are coupled into the sum channel and switched sequentially. The resulting AM modulation on the sum signal is processed to derive the antenna pointing measurements.

SATELLITE ANTENNA TESTING

While antenna testing is widely developed for many applications, satellite antenna systems pose some unique testing challenges. Rigorous testing is required for spaceborne antenna systems because of their reliability requirements and the inability to service on-orbit antennas. This discussion illustrates the trends toward increased integration of antennas with payload electronics, and testing where the antenna performance depends on both the antenna hardware and system electronics further increases testing complexity. The user segment also follows the trend of increased integration with terminal requirements. Finally, the demands for capacity also result in more stringent than normal testing requirements, such as validating the polarization purity requirements for systems using polarization reuse.

Spaceborne antenna testing generally has three distinct phases:

Development testing that demonstrates design compliance with system specifications

Qualification testing that ensures flight hardware not only meets the RF performance demonstrated in development testing but also is capable of surviving the launch and on-orbit environments and meets weight and power requirements

On-orbit testing that validates system compliance with system specifications and provides diagnostic evaluation of system shortfalls during the orbital lifetime.

These three test phases have a scope that greatly exceeds the normal testing to define the component level performance of antennas. This situation is particularly true with the trend toward incorporating payload electronics into the antenna system which results in the antenna system performance that depends not only on the antenna components but also the electronics performance.

The development testing has the objective to demonstrate the designs fully comply with the system specifications. The testing in this phase of the program is most closely related to conventional antenna testing and quantifies gain values, pattern characteristics, polarization purity, impedance properties, bandwidth variations, etc., as is typically performed. These RF characteristics can generally be performed using conventional RF test facilities and general purpose instrumentation. The antenna components are designed on a prototype or engineering model basis, so that weight projections and compliance with thermal and mechanical requirements for launch can also be evaluated.

The qualification testing has the objective of determining whether or not the flight hardware is capable of the performance established for the design whose compliance has been demonstrated in the development testing. An important part of the program test planning is a requirements' flowdown that identifies the testing necessary to demonstrate overall system compliance and assurance of flight worthiness. The principal concern in this phase of the testing is how to perform the testing without risk to flight hardware. Moving flight hardware to conventional antenna test facilities poses an unacceptable risk in many cases. Testing very lightweight antenna designs may be precluded because they can be destroyed by wind or become contaminated and the effects of gravity can degrade the ability to project on-orbit performance. The development of portable near field test facilities is viewed as a need to permit detailed antenna testing in payload assembly areas. Another important part of the test planning in the early part of the program is the identification of test ports for system evaluation and the required development and calibration of any specialized test fixture. Qualification testing must also evaluate performance variations in the thermal variations and vacuum conditions, and the ability to survive the shock and vibration levels experienced during launch. Other issues such as the reliability of deployment mechanisms if used must be demonstrated.

On-orbit testing is conducted using specialized test terminals, which are often a part of the satellite control networks. The testing at this phase is generally conducted shortly after the satellite arrives at its orbital location. This testing generally concentrates on system level performance parameters, such as uplink G/T, downlink ERP, and payload antenna pointing alignment, to establish overall performance compliance. After this initial performance evaluation, these test facilities are used to periodically assess on-orbit performance, and together with the telemetry information provide a means for on-orbit diagnostics. An important part of the test planning is an examination of the adquacy of the telemetry and test terminal information for identifying failed components and their potential substitution with redundant components.

Satellite systems also have some specialized testing requirements peculiar to their environment. One problem with satellite systems is the static charging of components on-orbit. Typically, this charging occurs on dielectric materials used for thermal protection not only for the antenna but also other satellite subsystems. The charge builds up on these components until discharge occurs. This phenomenon is referred to as ESD (electrostatic discharge), and the spectral components of the discharge may have sufficient intensity to interfere with payload receivers. The ESD spectral content is typically measured by embedding a sample of the material in an electron beam and using a pickup probe antenna and a spectrum analyzer or very wide bandwidth oscilloscope.

Another problem which results from high power operation in vacuum conditions is multipaction. In this case, the RF energy may be sufficient to strip electrons from the surfaces of materials exposed to the high power, which will damage the component. The potential for multipaction is typically evaluated by testing the components associated with high power in an evacuated bell jar and using a spectrum analyzer to observe any RF noise associated with multipaction. Such testing can also evaluate any power handling and microarcing limitations of the components by examining the components after the test for damage. Temperature increases from high-power operation can also be measured.

A third problem is also associated with high-power operation and is referred to as PIM (passive intermodulation). This problem results from exposing junctions with high power. Dissimilar metals or contamination forms weak diode junctions whose nonlinearity generates intermodulation products. Such junctions can occur in transmission line components, filters and diplexers, and joints within the antenna structure. Those components exposed to high power are tested by injecting two tones at high-power levels (higher power transmitters than the operational ones are sometimes used to insure the observed intermodulation does not result from products generated by a saturated transmitter) and observing any intermodulation products generated by the components under test with a spectrum analyzer.

User antenna testing also has some unique issues for satellite systems (29). One problem results from testing on ground terminal antennas, where the physical size of the antenna precludes testing in conventional antenna test facilities. A test technique using the emission from astronomical sources is used to measure the G/T (30). The flux density of these emissions has been well established, and a variety of sources exist. The emission from the sun has a high level, but the angular width of the solar disk limits this technique to relatively wide beam widths. Other sources such as the moon and radio stars such as Cassiopeia A are used for narrower beam widths. The positions of these sources are also well known, and thus, the opportunity to validate the accuracy of the antenna positioning systems is also available. The antenna gain in the transmit bandwidth can also be established by connecting a low noise preamplifier in place of the transmitter, measuring the G/T, separately measuring the system temperature, and multiplying to obtain the transmit antenna gain. While this technique was developed for large ground terminal antennas (31), with the available low noise preamplifiers, useful measurements can be made on much smaller antennas. This technique is particularly useful for those antennas that follow the trend of integrating the antenna feed and receiver front end without connectors for test purposes.

Other electromagnetic measurements are required in the development of both user and spaceborne systems to validate EMI/EMC (electromagnetic interference/electromagnetic compatibility) issues. Part of the system planning for satellite systems involves frequency planning to avoid such problems; measurements at the assembly level are performed to assure on-orbit performance will not be degraded by interference between subsystems. User terminal designs are also evaluated to insure the design is not susceptible to outside interference as well as not creating interference to other systems that may be located nearby.

SUMMARY

Satellite antenna development is a significant part of present day antenna technology. Much progress in antenna systems for both the space and user segments has been made. However, future requirements such as the development of satellite systems for personal use provide a rich opportunity for further development and challenges to meet the increased performance levels demanded in future systems and applications.

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