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Modern Communication Satellite Antenna Technology

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1. Introduction

Satellite antenna design is a challenging task for design engineers because it differs in many aspects from classical antenna design. Satellite antennas are designed for point to multipoint (or vice versa) operation as opposed to point-to-point operation for conventional ground station antennas. The design objective for the ground station antennas is to achieve highest gain in the boresight direction while for satellite antennas every point within the coverage area is important. Satellite antenna parameters even at the edge of the coverage are very important to be ensured. Monotonic (unshaped) beams are circular or elliptical and follows natural roll off of an antenna aperture providing highest gain at boresight of the coverage. Normally it does not fulfill the stringent requirements imposed on satellite payload. To meet high performance of satellite payload these days contoured beam (shaped) antennas are used. Satellite antenna designer at least must be well conversant with payload performance parameters, satellite platform, satellite launch vehicle and international regulations. The choice of any antenna parameter is likely to affect several other system parameters both inside and outside the antenna subsystem. Satellite antenna designer comes across a variety of factors and feels ousted from heaven of classical antenna design. At the same time, he finds himself confronted with great concern to achieve more general system objectives.

This chapter will present an overview of antenna design and its related issues for a typical geostationary communication satellite. The discussion may be useful for non-geostationary satellites as well but author(s) will focus on geostationary satellite unless stated otherwise. State-of-the-art satellite antenna technology and future trends are subjects of the chapter. Satellite antenna design drivers used to perform trade offs, selection of antenna related parameters, analysis techniques, industry standard softwares, various antenna configurations, contoured beam antenna implementation, and remotely configurable satellite antenna design will be discussed.

For a design to be declared flight proven, it needs to undergo a myriad of critical qualification tests and experimentation. Set of space standard procedures are strictly followed at every stage including design, manufacturing, testing etc. of a flight standard hardware. Satellite once launched is to operate for a certain period usually 10 - 15 years and if a fault occurs, it has to be corrected by onboard computer(s) or telecommand otherwise it may lead to satellite's malfunctioning. Satellite systems needs to be very rugged and reliable

so that satellite can operate and provide the desired services satisfactorily throughout its life. In satellite industry, best does not necessarily mean fit to the requirements and a common term used is KISS (Keep It Simple, Stupid!). This chapter will introduce the reader with tests performed on satellite antennas to ensure that it can withstand the worst-case environment and its performance at least meets the requirements.

2. Satellite Orbits

The commonly used satellite orbits are
1. LEO: Low Earth Orbit
2. MEO: Medium Earth Orbit
3. GEO: Geosynchronous Earth Orbit
4. HEO: Highly Elliptical Orbit (Molniya)
5. SSO: Sun Synchronous Orbit

The choice of the orbit depends upon the mission objectives and characteristics. The effects of space environment in different orbits are different and play a major role in selecting the orbit and mission parameters. Every orbit has perturbations which results in changing the orbital parameters i.e. osculating orbit. Even in the same orbit the perturbation and space environment can be different for different orbital locations. To find an orbit which can exploit the perturbations and require less spacecraft attitude & orbit maintenance is a research issue.

3. Communication Payload

The communication payload can be broadly divided into two sections
1. Repeater section
2. Antenna section

The signal is received by the receiving antenna and is processed by the repeater. The repeater can be transparent or regenerative. Mostly repeaters used for public communication are transparent and regenerative repeaters are used for military purposes. After processing the signal in repeater it is transmitted by the transmitting antenna. Communication antennas used in geostationary satellites are normally reflector antennas to overcome the high loss due to height of GEO orbit. The receiving and transmitting antennas can be the same hardware unit or different depending upon many factors that will be discussed in the coming sections. To decide the configuration of satellite antennas is very challenging task and is affected by many factors to be explored in the subsequent sections.

4. Payload Performance Parameters

In mission planning phase the service zones (called coverage regions or coverage polygons hereafter) and performance parameters for all the coverages are decided. The main performance parameters are operating frequency band(s), antenna polarization(s), EIRP (Effective Isotropic Radiated Power), G/T (Figure of Merit) and XPD (Cross Polarization Discrimination). Different polygons can have different performance parameter values depending upon many factors considered in the planning phase based on need and market survey e.g. intended application, predicted transponder usage, revenue generation and user equipment's size & cost.

From EIRP value, it is to decide the gain of transponders and the gain of antenna considering the feeder losses. The transponder power is a strong function of availability and choice of technology for high power devices like TWTAs (Travelling Wave Tube Amplifiers) and SSPAs (Solid State Power Amplifiers). The satellite thermal design is a strong function of heat generated by high power devices. Higher the operating power of a device; higher is the probability of its failure and higher risks to the mission. To satisfy the system's reliability criterions, the design becomes more complex when dealing with high power devices. So to make the design simpler and more reliable, it is tried at best that the power of the transponder is kept minimum and high gain is achieved using larger antennas to meet the EIRP requirements while satisfying the mass, launch vehicle fairing accommodation and other related system constraints. Gain distribution between antenna and transponder may require several iterations and trade offs.

While considering the G/T parameter, satellite antenna designer need to know the coverage region characteristics to find the antenna noise temperature. If satellite antenna is looking towards ocean, it will have less noise temperature; on the other hand, if antenna is looking at the hot earth its noise temperature will be high which will finally affect the G/T of satellite. Normally worst case is considered and antenna noise temperature is taken to be 290K. We also need to know the noise generated by satellite receiver to find the system noise temperature. It is tried to get a receiver with lower noise but low noise receivers are costly. Once system noise temperature is known, the focus is shifted to receive antenna gain and correspondingly its size. An optimum antenna size is selected bearing in mind the performance required and constraints.

To transmit and receive the signals faithfully high value of XPD is required. Normally XPD for satellite antennas in coverage polygons ranges from 27 to 30 dB. It is hard to satisfy the XPD requirements especially for wider coverage regions. XPD performance requirements can lead to different antenna configurations.

The selection of frequency band(s) and polarization(s) is complex issue and will be discussed separately in coming sections.

At the end of above exercise antenna designer at-least have operational frequencies, antenna polarization, values for gain and XPD of transmit & receive antennas in different coverage polygons.

5. Frequency Band Selection for Communication Payload

The frequency is a limited natural resource. ITU (International Telecommunication Union) has allocated different frequency bands to different regions of the world for different services. The frequency resource is shared among various satellite operators. When a new operator is planning to have a satellite to provide some service in a particular region and there already exist some satellite(s) with footprint in that region, ITU is contacted for the available frequencies in the intended service zone. The satellite operating frequencies and power levels are negotiated with existing operator(s) to limit the interference to an acceptable level. Existing operator(s) have preference over the new operator. ITU plays the role of moderator to resolve the outstanding issues among satellite operators. It is very important to resolve the issues with other satellite operators and it should be completed during the mission planning phase. If there is no frequency bandwidth available for a

certain orbital slot, it will be useless to put a satellite in such a slot because it cannot be operated due to international regulations.

Sometimes frequencies used by TT&C (Telemetry Tracking & Command) subsystem falls in the communication frequency band, so we have to be very careful in selecting the frequencies in order to minimize the interference between TT&C subsystem and communication payload.

For an antenna designer it is important to know the uplink and downlink frequency bands to be used by the intended satellite to design the antennas accordingly and to perform PIM (Passive Inter Modulation) analysis & decide the number of antennas.

6. Polarization Selection

Due to limited frequency bandwidth available, satellites make use of multiple polarizations to enhance the communication capacity. Multiple polarizations can be either linear or circular but not both together (in the same service area) as they cannot be separated. Satellite can have high capacity by using two orthogonal linear polarizations namely horizontal and vertical polarization. On the other hand, if choice is circular polarization then Left Hand Circular Polarization (LHCP) and Right Hand Circular Polarization (RHCP) can be used. Because users of satellite are many so while choosing antenna polarization, the availability of commercial communication equipment is considered. To avoid interference, existing satellite operators can impose binding on new operators to not to use certain polarization. ITU (International Telecommunication Union) plays key role to make the negotiations between operators successful. Satellite can have polarization switch on board to switch the required polarization in case of conflict between operators or due to some other reason. But this may lead to many complications (regarding reception & transmission as the satellite is already in use) and should be planned well in advance. Another factor considered during polarization selection is rain as it behaves differently for different polarizations as explained below (Johnson, 1984).

1. Differential attenuation: Due to non-spherical shape of falling rain droplets, horizontally polarized wave (polarization vector parallel to major axis of rain droplet ellipsoid) suffers higher attenuation than vertically polarized wave (polarization vector parallel to minor axis of rain droplet ellipsoid). The differential attenuation is about a decibel.

2. Differential phase: When waves with horizontal and vertical polarizations propagate through anisotropic medium they suffer differential phase shift. Below 10GHz, differential phase is more dominant and above 30GHz, differential attenuation is more dominant. In between these frequencies dominance depends upon tilt angle of link and the climate (Pratt, Bostian et al. 2003).

3. Depolarization: A linearly polarized wave whose polarization is in between vertical and horizontal can be resolved in vertical and horizontal components. These components will propagate through the rain with their polarizations unchanged but horizontal component is more attenuated than vertical component. If these components are recombined to reconstruct the wave, result will be rotation of polarization towards the vertical and a cross polar component will be present.

There is not much margin available in onboard transponder power while on the other hand the power of uplink from earth can be controlled. So rain is important to be considered

when deciding the polarization for uplink and downlink. However, normally rain's effect on polarization is paid less attention due to other dominant effects e.g. limitations imposed by other satellite operators. It is a usual practice to have about 2 to 3 dB higher antenna gain in regions with high rain as compared to regions with less rain.

7. Satellite Antenna Design Drivers

Mission statement defines almost all of the system level parameters. Communication payload parameters are extracted form mission statement and lay down the foundations for antenna subsystem parameters. The payload need to comply mission requirements, International Telecommunication Union (ITU) regulations, interference with neighbouring satellites, frequency coordination issues, and frequency bands of interest. Satellite antenna is designed for specific coverage(s) on earth. The satellite intended to operate in a specific location in geostationary orbit directly impacts on the coverage area in terms of look angles of earth antennas.

Broadly speaking antenna performance design drivers can be divided into following categories

1. Electrical performance
   a. High Effective Isotropic Radiated Power (EIRP), which results in high gain requirements of transmit antenna (downlink antenna of satellite)
   b. High Gain/system noise Temperature (G/T), results in high gain requirements of receive antenna (uplink antenna of satellite)
   c. Cross Polarization Discrimination (XPD) requirements for both uplink and downlink antennas resulting in selection of antenna configuration(s)
   d. Frequency band(s) of interest
   e. Intended Polarization and switching ability (if required)
   f. Passive Inter Modulation (PIM) analysis and necessary measures to avoid
   g. Loss in antenna subsystem
   h. Interference of TT&C with communication band
   i. EMC and EMI (Electromagnetic Compatibility & Interference) issues of platform and payload
   j. Stability of antenna parameters during the entire service life

2. Others
   a. Accommodation and mass constraints of satellite platform
   b. Antenna pointing requirements and satellite platform's attitude stability
   c. Thermal and mechanical interfaces of satellite platform
   d. Thermal stability during the service life to ensure the electrical performance of antenna
   e. Antenna deployment mechanism
   f. Antenna materials and manufacturing technology
   g. Launch vehicle fairing accommodation constraints and dynamic launch environment
   h. Natural frequency of antenna structure to avoid the resonance
   i. Space Environment, temperature variations, vacuum cold welding, zero gravity environment
   j. The geopolitical and geographical factors can cause stringent coverage requirements and may have an impact on antenna manufacturer(s) selection, testing etc.

An antenna designer should be well conversant with other relevant systems so that final product is compatible with the whole system without any flaws. Some of the above factors are coupled to each other e.g. antenna placement and feeder link loss. Keeping in view the interactions of antenna system with other systems, we will discuss satellite platform, satellite launch vehicle and space environment briefly to develop a feeling about the factors that antenna designer have to consider during the design process. After developing a feel about constraints that other systems put on antenna system, the focus will be shifted to electrical performance of antenna and ways to achieve it.

8. Satellite Platform and Antenna

Satellite can be divided into two basic units namely the payload and the platform (bus). The payload is to fulfil the mission objectives and the platform is the basic unit to make the payload operational throughout the satellite's service life. The payload characteristics like mass, size, electrical power, configuration, pointing requirements, and operational life defines the abilities of platform. On the other hand, if an organization wants to use the existing platform (which is the normal case for commercial purposes) then the payload characteristics are limited by available platforms. Normally it is an iterative process to choose a platform to meet the payload requirements.

Satellite platform consists of all the supporting subsystems to support the payload so that it can work normally. Following are major subsystems of the platform

1. Structure Subsystem
2. Electrical Power Subsystem (EPS)
3. Attitude and Orbit Control Subsystem (AOCS)
4. Telemetry, Tracking and Command Subsystem (TT&C)
5. On Board Data Handling Subsystem (OBDH)
6. Propulsion Subsystems
7. Thermal Subsystem

The optimum placement of subsystems inside the platform is a challenging task and a lot of factors need to be considered e.g. accommodation space, structural stiffness, satellite balance, thermal requirements, clear field of view, EMI & EMC requirements, RF (Radio Frequency) power loss, power loss in harness network etc. The payload is placed such that

1. The received signal's G/T and transmitted signal's EIRP is maximized by minimizing the feeder links loss between antennas & repeater.
2. TWTA generated heat can be dissipated easily to maintain the temperature within specified limits.
3. Mass distribution is such that platform can be kept balanced.

In three axis-stabilized spacecrafts, the antennas can be mounted on earth deck, east, and west panels. The earth deck may contain TT&C antennas along with communication antennas. The sidewall antennas are deployable and are in stowed position during launch. The deployable antennas can be deployed while spacecraft is in GTO (Geosynchronous Transfer Orbit) or in final orbit depending upon the mission. It is better to deploy antennas in GTO to ensure the successful deployment in early stages. It is a general practice to mount solar arrays on north and south panels so that it can face the sun to generate the maximum output power. Rest of the subsystems need many optimizations to get proper place in the platform.

It is required that the communication antennas should point to the earth all the time to provide coverage to the service zone satisfactorily. The pointing accuracy of platform has direct influence on satellite's communication performance. The pointing accuracy is expressed by a statistical parameter 3σ (3 Sigma) which indicates that almost 97% of the time, the pointing will be as desired. The desired pointing is normally 0.1 degree in roll & pitch axis and about 1 degree in yaw axis. During design, pointing error need to be considered with a great concern and communication payload is designed such that it can fulfil the requirements in presence of specified pointing error. Every platform specifies number, size, configuration, and mass of antennas that can be supported. Therefore, antennas should be designed to be compatible with the platform.

9. Satellite Launch Vehicle (SLV) and Antenna

To put the satellite in orbit launcher is used. Satellite is placed in launch vehicle's fairing and acts as payload for it. Mostly launch vehicles consist of multiple stages in order to achieve high mass ratio. The satellite is designed and tested keeping is view the launch and in orbit environment. The capabilities of launch vehicle, e.g. fairing size and supported mass put an upper limit on satellite. Various launchers are available in the market. Some SLVs can put the satellite directly in orbit & most of the SLVs put the satellite in GTO. From GTO apogee engine of satellite is usually fired multiple times to reach to the final orbit. Some available launch vehicles are Ariane, Atlas, Delta, Long March, GSLV, Athena, Beal BA, H-IIA, Taurus, Zenit, [{Titan and Proton}(capable of direct to GEO)]. Details can be found at (Space and Technology, 2009). The satellite launch can be dedicated or piggyback. Factors considered while choosing a launch vehicle are its fairing size, cost, reliability, launch heritage, location of launching site, on time availability and political relations etc. Location of launch site is important because putting the satellite in equatorial orbit may require additional fuel consumption to correct the inclination. A typical launch vehicle fairing is shown in Figure 1 (ILS, 2004). It is important to have specified clearance inside the fairing after the satellite is placed in it.

Launch vehicle manufacturer is contacted in very early phases of satellite contract signing to make sure that satellite interface is compatible with the launch vehicle. It is a general practice to make the satellite compatible with multiple SLVs. The important informations required by satellite antenna designer about SLV are fairing dimensions, natural frequencies and the launch environment loads. Fairing dimensions decide the maximum allowable antenna size and natural frequencies & launch environment tells about the antenna structural requirements so that antenna can withstand the highly dynamic environment created during the launching phase. The launch environment includes acoustic noise, vibrations, acceleration, and mechanical shocks, etc. Launch vehicle manufacturer provides such data to the users and a coupled load analysis is performed to ensure a successful mission.

10. Space Environment and Antenna

The space environment is different from the environment on earth. The outer space temperature is about 4K (Kelvin), pressure is extremely low normally considered as vacuum moreover, there is no gravity (0 g). There exists undesired phenomenon e.g. vacuum cold

welding that can result in antenna deployment failure. There are so many factors in space, which are beyond the scope of this chapter. Normally there is team for design & development process and antenna designer should have the knowledge of space environment but there are other people around him to assist.

At this stage this is enough to know that on front side of antenna there are thermally stable paints that do not effect the communication much and on back side of the antenna there are MLIs (Multi Layer Insulations) for thermal stability.
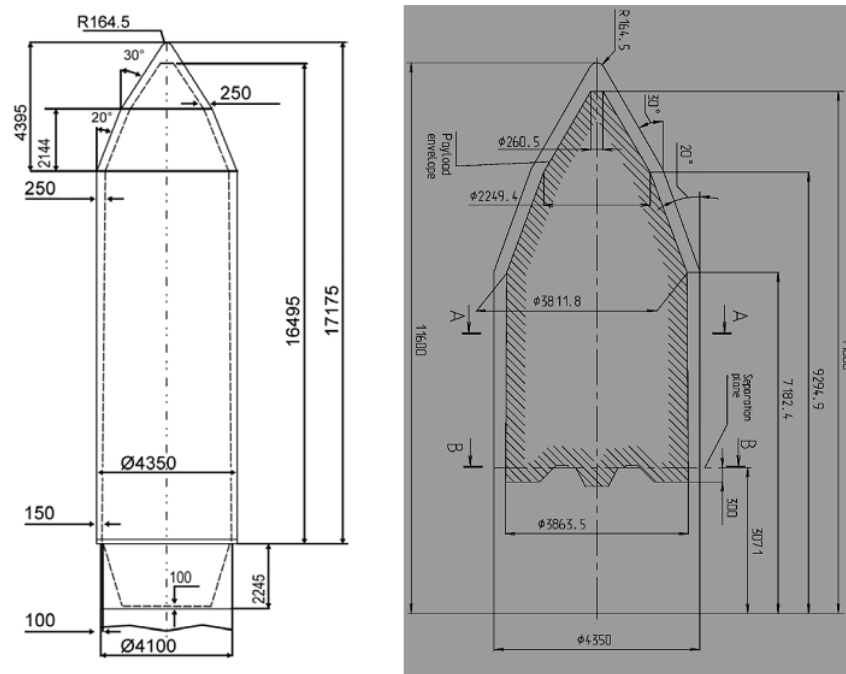
(a) Fairing   (b) Payload accommodation inside fairing

Fig. 1. A typical launch vehicle fairing (mm) (ILS, 2004)

11. Passive Inter-Modulation (PIM) Analysis

Passive inter modulation is becoming an increasing concern in satellite design due to its debilitating effect on the communication performance. When more than one frequency encounters a non-linear electrical junction or material, PIM is generated. PIM results in undesired signals that are mathematically related to original frequencies. In multicarrier environment, the PIM analysis is performed to know whether some inter-modulation harmonic(s) of transmitted signal are falling in the receiving band or not. If such harmonic with enough high power exist, they are likely to damage the satellite's receiver or make it oscillate and may cause communication failure if necessary measures are not taken. PIM analysis is so important that full conferences have been focused on it (ESTEC, 2003). PIM analysis is performs in advance to avoid such failures. The analysis can be performed using following formulation

$$PIM_{freq} = N_1 f_1 + N_2 f_2 + N_3 f_3 + ... + N_n f_n \tag{1}$$

where $N_1, N_2, N_3, ..., N_n$ are integers.

Order of PIM is given by $\quad N = |N_1| + |N_2| + |N_3| + ... + |N_n|$ \hfill (2)

Lower order PIMs has higher power associated with them and band edge frequencies generate lowest order PIM. These days softwares are available to perform PIM analysis (GL Communications Inc., 2009) & (F-Intermod, 2009). Many satellite manufacturers use their own custom made softwares. PIM issue is so important that it has to be considered with intense attention at every stage including design, manufacturing, integration, and maintenance. Currently there is no complete mathematical modelling available that can ensure PIM free design. Only the precautions, experience and testing are in use. Following measures can be taken to suppress the level of PIM.

1. Avoid using ferrous metals, avoid dissimilar metals in direct contact, avoid any type of dust; pollution and contamination of parts, minimize the number of contact junctions, apply sufficient pressure on junctions, properly align the parts, solder the junctions, avoid oxidation by uniformly plating the surfaces and pay attention to bending of cables & torque applied to connectors (Summitek Instruments, Inc., 2009).

2. Use a filter in transmit path to suppress the received band frequencies and use low PIM feed horn(s).

3. Use different antennas for receive and transmit bands. It is very crucial decision to be made by antenna designer along with other subsystem designers because additional antenna will increase the mass and will occupy accommodation space, limiting the space that might have been used for some other payloads.

12. Satellite Antenna coverage (footprints)

For a satellite to provide services to a certain area it is required that targeted area is within field-of-view of satellite and earth station antenna can point to satellite with a certain elevation. To account for atmospheric effects it is required to use higher values of elevation angle. The atmospheric attenuation is frequency dependent and different elevation angle values for different frequency bands are required. The typical values are 5° for C band, 10° for Ku band and 20° for Ka band. Higher the elevation angle of earth station antenna better is the system performance. The requirement of increased elevation angle value reduces the coverage area that can be served by the intended satellite. Now a days many softwares like Satellite Tool Kit (AGI STK, 2009), SatSoft (SatSoft, 2009) etc. are available to find view angles. A comprehensive mathematical detail can be found in (Pratt, Bostian et al. 2003).

Due to different performance requirements in different coverage polygons, to avoid interference with existing satellite operators, international regulations, geographical and geopolitical reasons these days the footprints of satellite antennas are highly shaped according to requirements rather than just using circular coverage. Inside the coverage of a transmit antenna there can be many polygons with different levels of EIRP and XPD. Similarly, for a receiving antenna the G/T and XPD values can be different in different polygons. High levels of EIRP and G/T are required to meet high data rates and to mitigate the rain effects.

The plots of constant EIRP or G/T levels are called contours. To generate the shaped contours, contoured beam antennas are used. For understanding purposes let us take the following example, please bear in mind that this is just an example and practical cases can be far complex. The coverage area to be served in Ku band by a satellite (at 56 degree east orbital slot) is shown in Figure 2.
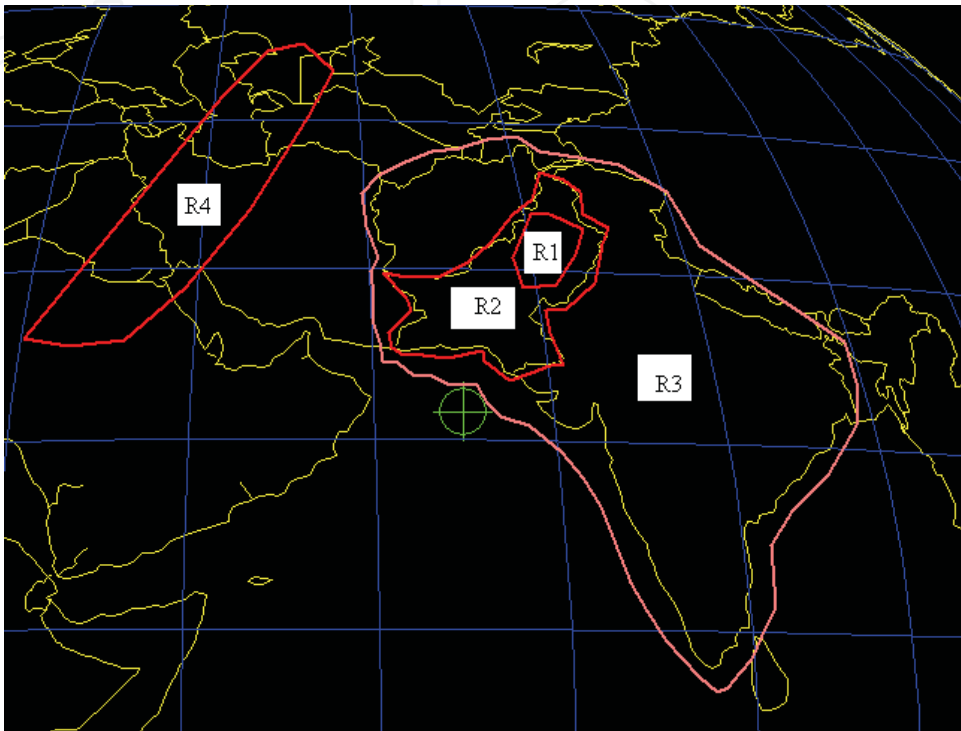

Fig. 2. Satellite coverage

Coverage consists of four polygons R1 through R4 covering various areas on the earth. It is required to maximize the EIRP and G/T levels in polygons R1 through R3. The polygon R4 is the region where it is required to suppress the EIRP and G/T levels below certain value due to various restrictions imposed on the system. The performance requirements can be as listed in Table 1.

Region	Purpose	EIRP (dBW)	Transmit XPD	G/T (dB/K)	Receive XPD
R1	Maximize	51	30	5	30
R2	Maximize	49	30	4	30
R3	Maximize	47	27	3	27
R4	Suppress	20	Not applicable	–5	Not applicable

Table 1. Performance requirements

The above example provides an insight of satellite coverage and related performance parameters in different polygons.

13. Contour Beam Implementation

The design objectives for satellite antennas are to enhance the performance over entire designated area and at the same time conform to the frequency re-use and beam roll off requirements. The simple analysis characterizing only beam peak area is thus not applicable for on board satellite antennas. The shaped beam is tailored so that edge of beam matches the shape of desired earth area as seen from the satellite. The gain within beam is enhanced where required and roll off is controlled as dictated by the orbital coordination agreements. Figure 3 shows the monotonic and shaped (contour) beams gain and roll off characteristics.
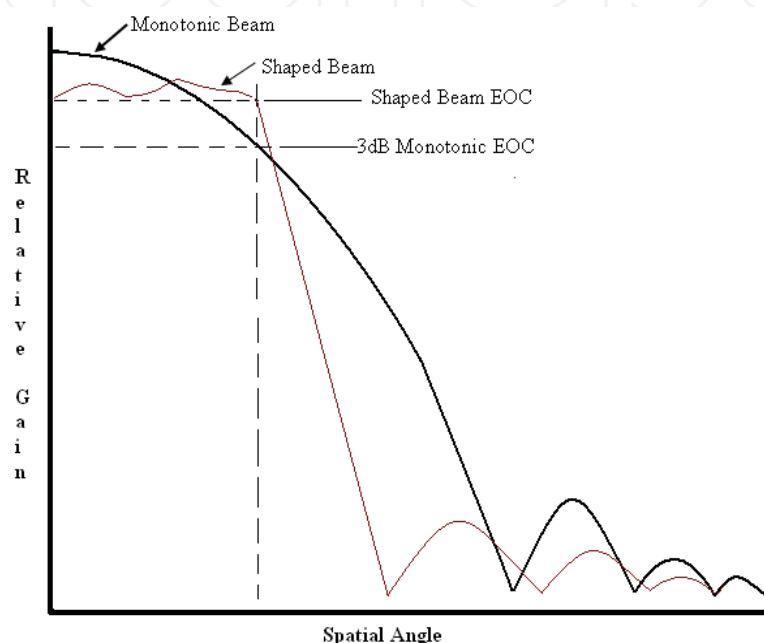
Fig. 3. Monotonic beam and shaped beam roll off

The shaped footprints can be achieved by the following ways.

1. <u>Direct Radiating Array</u>: The method is very versatile and is quite flexible. Excitation coefficients (power and/or phase) of individual elements of array are controlled to get the required coverage. The coverage can be changed by changing the excitation coefficients of the array elements on the run time. Due to control of individual element's radiation pattern, the technique is good for achieving spot beam coverage for high data rates. In cases where onboard processing capability is available, different adaptive coding and modulation schemes can be applied in different spot beams for efficient utilization of satellite resources. The excitation coefficients control circuitry is very complex and there are high spill-over losses associated with this technique as compared to shaped antenna with single feed, so it is not widely used technique in commercial satellites.

2. <u>Multiple Feeds:</u> in this technique, single reflector is illuminated by multiple feed horns resulting in shaped footprints. This method employs beam-forming network to control excitation coefficients of individual feeds. By controlling the excitation of individual feeds, the illumination of reflector surface is controlled which results in shaped footprints. Many feeds along with beam forming network increase the overall mass of antenna subsystem,

adds complexity to the system and there are high spill-over losses as compared to shaped antenna with single feed. Therefore, it is also not a very efficient method.

3. Surface Profile Shapping: This is the most widely used technique these days for commercial communication satellite. Here a single feed is normally used to illuminate the reflector surface, which is no more plane surface. It is shaped to meet the desired performance and satisfies shaped coverage requirements. This technique define a base surface which is typically a paraboloid, ellipsoid, hyperboloid or just plane surface and then add an "adjustable" surface to this as shown in Figure 4. The adjustable surface is created by mathematical functions; Splines and Zernike etc.
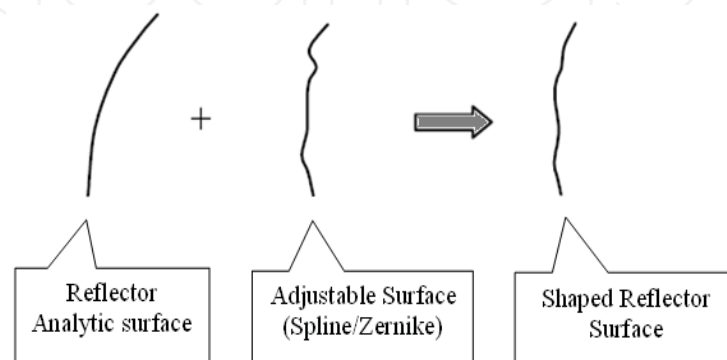
Fig. 4. Adding adjustable surface to reflector antenna to get shaped antenna

The solution is simple, much reliable as compared to above techniques and have good flight heritage. The drawback of this technique is that the highly shaped beam may correspond to large surface gradients that may not be feasible to get manufactured even at increased cost. In the coming sections we will discuss more about this technique with the help of softwares used in satellite industry.

14. Satellite Antenna Analysis Techniques

Usually a scattering problem consists of a known incident field, scatterer(s) with known geometry and electrical surface properties. The goal is to compute the total radiated field. Various techniques are available to be used for reflector antenna analysis. The choice of a particular technique for a specific application is dependent upon its validity in the angular region of interest around scatterer and computational time required. Following techniques are widely used for satellite antenna analysis. The details can be found in (Godara, 2001), (Samii, 1984), (Philips & et al, 1996), (Ahmad, 2008) and (Ahmad & Mohsin, 2009).
1. GO: Geometrical Optics
2. GTD: Geometrical Theory of Diffraction
3. PO: Physical Optics
4. PTD: Physical Theory of Diffraction

14.1. Geometrical Optics
The key features of GO are listed below
1. GO fields behave locally as plane waves and are discontinuous at shadow boundaries. Zero field is predicted in shadow region.

2. It is a good candidate for large reflector antennas as the computation time is almost independent of reflector size.

3. It is less accurate at lower frequencies and accuracy increases with the increase in frequency

4. It exhibits caustic while predicting the field at or near the regions of rays convergence.

5. It is more accurate than PO at far-out sidelobes.

6. The field prediction by GO is less accurate at edges of the scatterer. To increase the accuracy at edges GO is supported by GTD.

14.2. Physical Optics (PO)
The key features of PO are listed below

1. PO is wave based technique and overcomes the GO caustics.

2. The PO technique is only accurate near and within the specular reflection region (main beam region and near–in sidelobes) and becomes erroneous farther away from this region (far–out sidelobes).

3. As the PO currents needs to be integrated over the surface to calculate the scattered field, the computation time for PO increases with the size of scatterer.

4. The endpoint contributions along the edges contribute to the PO diffracted fields.

5. To enhance the accuracy of PO for far–out sidelobes the PTD was introduced.

15. Satellite Antenna Design Tools

Here we introduce some commercially available satellite antenna design softwares to equip the antenna designer with state-of-the-art tools.

1. Softwares provided by TICRA (electromagnetic radiation) Engineering
Consultants, Copenhagen, Denmark (TICRA Engineering Consultants ,2009).
    a. GRASP9
    b. COBRA
    c. POS
    d. CHAMP and etc.

2. SATSOFT (SatSoft, 2009), HFSS (Ansoft HFSS, 2009) and others.

15.1. GRASP9 (General Reflector Antenna Software Package (version 9))
The key features of the GRASP software are listed here, more details can be found at (Pontoppidan, 2005). A student version with limited functions is also available from (TICRA Engineering Consultants, 2009).

1. The GRASP9 software is a very versatile tool for electromagnetic analysis of reflector antenna, antenna farms and scatterers.

2. It supports various antenna configurations used for satellite applications and can calculate electromagnetic radiation from systems consisting of multiple reflectors with several feeds and feed arrays.

3. Various reflector types are supported e.g. triangular & rectangular plates, parallelograms, paraboloids, ellipsoids, hyperboloids, plane, sphere and general second-order polynomials, all with general rim shapes.

4. It has numerous built in feed models and user can also define feeds through input files, either as pattern cuts or spherical wave coefficients.

5. It helps the user to calculate electromagnetic scattering from circular as well as polygonal struts used to support the feed and / or subreflectors.

6. Analysis methods supported by GRASP are PO, PTD, GO/ GTD, multi-reflector GTD. The MOM (method of Moments) is also available and can be used for small objects like feed and sub-reflector.

7. Analysis can be carried out for points in the near field as well as in the far field of the antenna, in planar or spherical cuts and two-dimensional grids.

8. Reflectors need not be perfect conductors and can have electrical properties like polarization grids, dielectrics, frequency-selective or lossy materials.

9. The interaction between various antenna systems used in the satellite can be analyzed e.g. communication's antennas and TT&C antennas.

10. In the *post processor* part of the software antenna contours from satellite orbital positions can be plotted to see the footprints on the earth.

15.2. COBRA (Contoured Beam Radiating Antenna software)

COBRA is front-end software for antenna optimizing softwares. A limited evaluation version of COBRA can be downloaded from (TICRA Engineering Consultants ,2009). The key features are given below

1. It is used to generate data for satellite coverage. This data represents the specified coverage area and antenna performance parameters required for each coverage area.

2. For a defined antenna geometry, it generates required files used by optimizing softwares (for example to be used as input to POS) to generate contoured beam for defined coverage.

3. COBRA serves as front-end software for optimization for following types of contoured beam antennas:

    a. Single reflector (paraboloid) antenna illuminated by an array of horns

    b. Direct-radiating array of feeds

    c. Single or dual reflector antenna illuminated by a single feed.

In case of (a) and (b) the contoured beam is generated by adjusting the excitation coefficients (powers and phases) of the feeds. In case of (c) the surface profile of the reflector(s) is adjusted to achieve the optimal contoured beam. In this chapter case (c) will be discussed only and reader can reffer to (Rolf, 2000) for details of other cases.

15.3. POS (Physical Optics-based Shaped Reflector and Phased Array Design Tool)

The key features of POS satellite antenna design software are listed below with more details at (Viskum, 2006) & (Stig, 2006).

1. POS is state-of-the-art industry standard, object-oriented design software for reflector shaping and phased arrays. Currently almost all the satellite industry uses POS for contoured-beam antenna design.

2. User need to specify satellite antenna coverage(s), performance requirements (antenna gain(s) minimum levels in coverage and maximum levels in suppression regions, XPD, polarization parameters etc.) and initial antenna configuration.

3. POS uses highly advanced and tailored min-max optimization algorithm to adjust the design variables.

4. Spline or Zernike mode expansions can be applied to reflector adjustable surface to adjust the expansion coefficient variables during optimization process.

5. Array coefficients can be optimized in amplitude and phase, and the position of any feed or reflector involved in a design can also be included in the optimization.

6. Additional constraints can be imposed on the variables, e.g. to limit the curvature of a reflector surface. This might be necessary because optimization may result into surfaces which might not be feasible for manufacturing.

7. All field calculations involving one or more reflectors are based on Physical Optics to reduce the computation time.

8. To reduce the computational cost POS implements an active set strategy which limits the calculations to the most crucial residuals thus speeding up significantly the design of large shaped reflectors.

9. POS comes with the same graphics interface as that of GRASP, and the common object description enables a seamless interchange of design files between POS and GRASP.

10. Similar post processor as that of GRASP.

15.4. CHAMP (Corrugated Horn Analysis by Modal Processing)

CHAMP is software for feed horn design and analysis. Main features of CHAMP are listed below details can be found at (TICRA Engineering Consultants ,2009).

1. CHAMP software package is used for accurate analysis of corrugated and smooth-walled horns with circular cross section to be used for satellite applications.

2. CHAMP analysis is based on a full-wave modal expansion of the field in each elementary module into cylindrical waveguide modes.

3. Mode matching at interfaces between the different elementary modules is performed.

4. Evanescent modes are carefully considered.

5. The overall generalized scattering matrix for the horn inner structure (throat to aperture) is obtained by cascading the scattering matrices of all modules.

6. The feed can be decomposed into elementary modules that facilitate easy modification and reusability.

15.5. SATSOFT (Satellite Antenna Design and Systems Engineering Software for Windows)

SATSOFT is software by *Satellite software incorporated* for quick realization of satellite antenna parameters. The key features are listed below and details can be found at (Satellite Software Incorporated, 2004) & (SatSoft, 2009). A limited evaluation version can be downloaded from (SatSoft, 2009).

1. SATSOFT is used for communication satellite antenna design, analysis, and coverage planning.

2. User can quickly assess antenna coverage and gain, conduct antenna trade studies, develop shaped beam and multibeam antenna designs, and perform other satellite payload engineering tasks.

3. SATSOFT Professional adds multiple composite beam shaping (SATSOFT Standard can shape only a single beam), pointing error expansion and reduction of polygons, plotting of pointing error loci at polygon vertices, and conversion of polygon viewpoint to multiple spacecraft locations.

4. SATSOFT/PRO also provides for maximum and minimum parameter variation due to pointing error, axial ratio, and C/I in performance tables.

5. Various coordinates display options, earth map, city tables and performance tables are available for the user to make the design process easy.

6. SatSoft supports following key models

    a. Analytic Reflector Model for an offset-paraboloidal reflector fed by an array of small, fundamental mode circular or rectangular horns.

    b. Dual-Mode Optimizer for dual-mode feed network optimization for non-contiguous output multiplexer.

    c. Analytic Phased Array Model to handle phased arrays

    d. Physical Optics Model for reflector antenna modeling

15.6. HFSS (High Frequency Structure Simulator)

HFSS is software from Ansoft Incorp. for electromagnetic analysis of passive 3D structures. The software is very versatile and here we will be limited to its use within our scope of antenna design. Further details can be found at (Ansoft HFSS, 2009).

1. HFSS utilizes a 3D full-wave Finite Element Method (FEM) to compute the electrical behavior of high-frequency and high-speed components.

2. HFSS user can extract parasitic parameters (S, Y, Z), visualize 3D electromagnetic fields (near- and far-field), and generate Full-Wave SPICE™ models to effectively evaluate signal quality, including transmission path losses, reflection loss due to impedance mismatches, parasitic coupling, and radiation.

3. HFSS is able to simulate very complex geometric models, including models imported from 3D CAD environments.

4. HFSS can be applied to design

    a. Linear wire, slot, horn, patch antennas.

    b. Phased array antenna including array-to-radome interaction.

    c. Antenna feed and feed network structures.

Numerous softwares for antenna design are commercially available in the industry and some of the satellite manufacturers use their custom build softwares. Here due to limited space we have introduced most widely used softwares to just give an idea to satellite antenna designer to get started. Authors recommend antenna designer to get hands on training from authorized trainers whenever buying a particular software. Training is highly necessary to use the software accurately and efficiently.

16. Reflector Antenna Configurations

Following configurations are available for reflector antennas

1. Single reflector antenna system

    a. Center fed antenna

    b. Offset fed antenna

2. Dual reflector antenna

    a. Gregorian antenna

    b. Cassegrain antenna

3. Dual gridded antenna

Due to over all thickness of center fed reflector antenna, normally is cannot be used as

deployable sidewall antenna of satellite. Its use is only restricted to earth deck. It can save mass but its power handling capability is restricted and directivity loss is high due to feed blockage. Single offset reflector antenna can solve the accommodation constraints; have lower mass and no feed blockage. It is a standard concept and is used in the satellites. Due to high XPD requirements, normally reflector antennas with long focal length are required. This might put accommodation constraint on single offset reflector antenna. In such cases, our choice is to use dual reflector antenna systems.

Cassegrain dual reflector antenna system is not a standard practice used in satellite due to its restricted XPD capabilities and accommodation space requirements. Gregorian dual reflector antenna configuration is good candidate for achieving high XPD values.

When very high XPD values are required, we can use dual gridded antenna configuration. In this configuration, we can rotate the reflectors to move the cross polarization component out of our coverage region or even away from the earth. Dual gridded configuration is also useful when two beams with orthogonal polarization are required and there is no accommodation space available for two different antennas.

17. Feeds and Feeding Mechanism

Here we will discuss very briefly about the reflector antenna feeds, feeding mechanism (technique) and commonly used hardware for this purpose. Wide variety of feeds is available to be used. In reflector software simulations, we can use Gaussian beam model for initial assessment of radiation pattern. The circular symmetric corrugated feeds represents Gaussian beam model closely. Feeds are simulated using CHAMP, HFSS or some other electromagnetic simulation software. Reflector edge taper, polarization(s), XPD, VSWR (voltage standing wave ratio), PIM levels, multipaction effects (ESA, 2003) are considered when designing feed for a particular reflector system.

The feeding mechanism or feed network for a reflector antenna system can be considered as all the hardware used in between transponder input/output and feed itself. The feeding mechanism can include OMT (ortho-mode transducer), diplexer, hybrids (for combining/splitting polarization signals), polarization switch, and waveguides etc. We try to minimize the losses associated with feed network to enhance the communication performance. In receive chain low loss is required to achieve high G/T values while in transmit chain we require low loss to meet high EIRP vales. In the transmit chain another consideration is the design for low PIM as there exists high power handling units in this chain.

18. Antenna Surface Shaping for Optimum Contours

A typical antenna optimization process is shown in Figure 5. The optimization starts with defined performance specifications required for a particular service in a particular coverage area. These performance specifications decide design goals; which act as an input to the optimizing software along with the antenna geometry and feed model. The reflector surface is deformed by the software using distortion functions like Bi–cubic splines or Zernike modes. Using software it is now easy to compute surface variations applied to theoretical parabola to achieve the desired coverage. The computer controlled manufacturing technology makes it possible to precisely manufacture shaped reflector

surface profile. The resulting contours due to antenna deformation are plotted and checked to satisfy the goals. In case design goals are not satisfied, they are updated and optimization is started again. Once the goals are met, the Performance contours are plotted and discussed with customer for his acceptance. If the customer is satisfied then the antenna optimization is completed. In case the customer is not satisfied or wants changes in performance specifications then the whole process need to be repeated until the customer is satisfied.
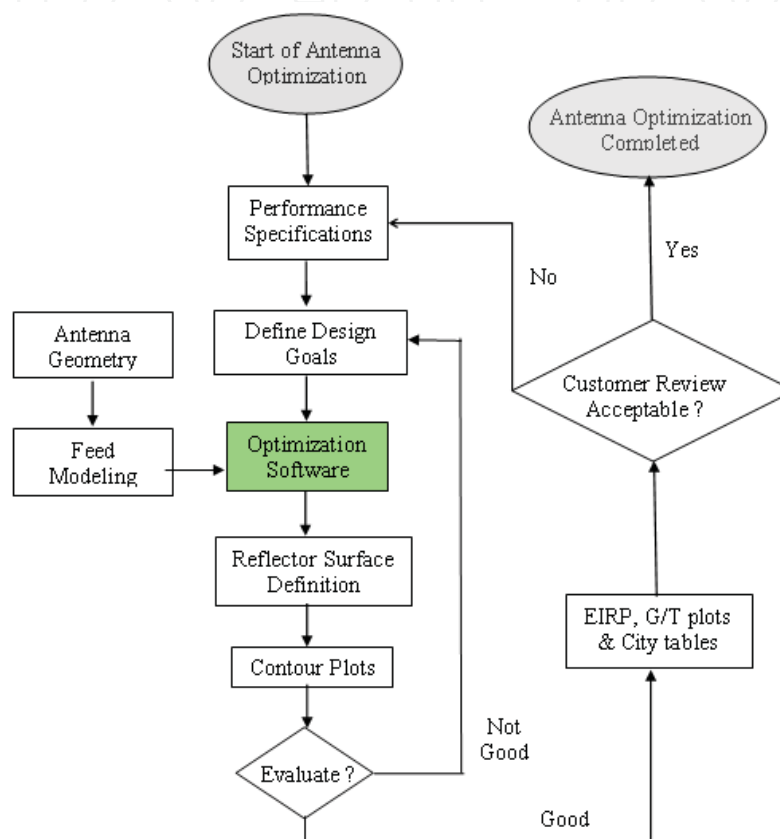
Fig. 5. Typical antenna optimization procedure

18.1. Activities Performed in COBRA
The main activities to be performed in COBRA are listed below
   1. Orbital location of satellite
   2. Coverage polygons
   3. Antenna pointing to coverage and antenna pointing error
   4. Generation of station file (*sta file*)
   5. Contoured beam generation technique (direct radiating array, multiple feeds with single reflector, or shaped surface reflector (single or dual reflector system)) and initial defocusing ellipse generation.
   6. POS project settings (number of iterations, splines; surface; grid files, feed and reflector coordinates etc.)
Here we select an example of Ku band, 1m offset dual reflector antenna on a geostationary satellite in 38 degree East orbital slot. The coverage plygons are drawn according to the

requirements and antenna is pointed towards the coverage area as shown in Figure 6(a). The antenna pointing accuracy is entered accordingly as shown in Figure 6(b). The important of all steps is to generate the station file contating the coverage data and performance parameters for each station in the coverage. The station sampling density in coverage area depends upon the antenna aperture diameter measured in wavelengths. Due to the approximate Fourier transform relationship between the field from a finite aperture and the radiated far field, a rule of thumb based on the Nyquist criteria (Rolf, 2000) states that the coverage must be sampled at intervals Δ along u and v coordinates,

$$\Delta u \text{ and } \Delta v \leq 0.5 \, D \, / \, \lambda$$

where D is reflector diameter and λ is the operating wavelength. A conservative practice is to use a sampling distance of half of this value.

The format of station file (*sta file*) is given below (Stig, 2006).

U V GOAL WEIGHT IPOL ROT ATT ID

The U and V indicates station coordinates, GOAL is the required goal for antenna gain or XPD etc., WEIGHT indicates the weighting factor during optimization; higher the weight of station(s) more consideration will be given to that during optimization process, IPOL indicates the polarization of field or XPD component, ROT is polarization rotation, ATT is distance attenuation and ID field is an optional field for identification of the station(s). As shown in Figure 6(c), user is required to input the desired values for the paramters for each polygon.

(a) Coverage and antenna pointing   (b) Antenna pointing accuracy

(c) Station file generation   (d) Initial defocusing ellipse and contoured beam antenna type selection
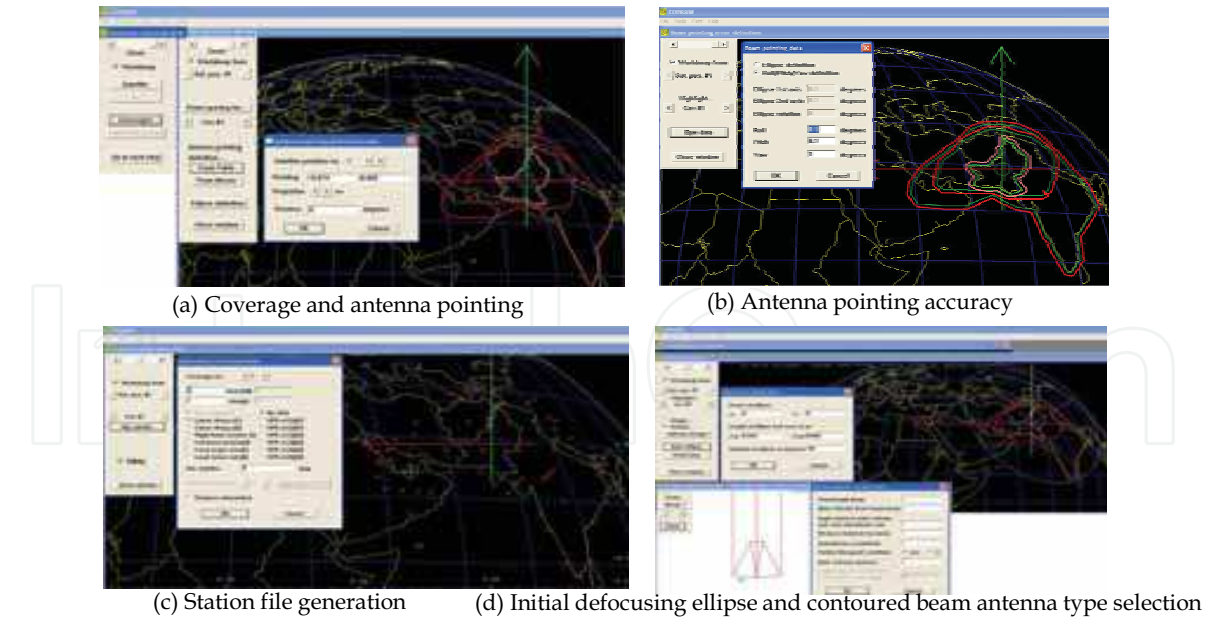
Fig. 6. Activities in COBRA

POS, min max optimizer requires initial defocusing of reflector antenna to avoid optimizer trap if some station is located at peak of antenna sidelobe. The user specifies an object of the "Initial Surface" class with two attributes. One specifies the focal length and the diameter of

the parabolic main reflector, the other gives information about the coverage region. It is specified as an ellipse where the centre (antenna pointing) and the axes are given in (u, v) coordinates. POS will then create an initial defocusing by using user specified spline or Zernike coefficients to modify the main reflector. The initial defocusing ellipse is generated in COBRA which approximately encampuses the coverage area where gain of the antenna is required to be maximized. The important step is to select the contoured beam antenna type, here we select shaped surface dual reflector configuration. User is required to input the parameters for the antenna as shown in Figure 6(d). Finally user generates the data for POS as shown in Figure 7. The generated data including the POS project with necessary files is imported in POS for starting optimization.

Station file (*sta file*) can be generated from SatSoft (*stn file*) with little modifications. The POS objects can be generated inside the POS software as well in case user don't have COBRA software.

Fig. 7. POS data generation

18.2. POS Optimization

POS (Physical Optics reflector Shaping) is a tool for shaping reflector surface to user specified far field coverage goals. Coverage Pattern is defined by a set of synthesis stations where the specific antenna directivity is desired. The technique that POS5 uses to shape a surface is to define a base surface, which is typically a paraboloid, an ellipsoid, a hyperboloid or just a plane, and then add an "adjustable" surface to this as was shown in Figure 4. Through approximation, an initial reflector surface is created with a Zernike-function or Bi-Cubic Spline function series expansion that roughly provides a far field response in the shape of the desired far field contours. Through subsequent PO iterations, the surface coefficients are further optimized to produce a far field pattern that matches the

initial goals closely. The optimization is based on minimizing the maximum deviation from the specified requirements of the synthesis stations. In practice several iterations are attempted in order to obtain an optimum and acceptable performance.

The input and output files for POS are shown in Figure 8(a). Stations file defining the coverage and performance goals (*sta file*) acts as input to optimization object in Object file (*tor file*). The *tor file* (containing antenna geometry data and adjustable surface object) along with command file (*tci file*) acts as input to POS software. The software optimizes the antenna surface and calculates residues by comparing required goals to achieved results.

18.2.1. POS Min Max Optimizer

When the coverage area, the initial geometry and the optimization details have been defined the optimization can be started. POS calculates residual function as defined below (Stig, 2006).

$$f_i(\overline{x}) = \omega_i(d_{goal,i} - d_i(\overline{x}))$$ (3)

Here the subscript i refers to the station number, $d_{goal,i}$ (dBi) is the requirement on the station number i and $d_i(\overline{x})$ (dBi) is the directivity at station i. The vector $\overline{x}$ contains all the variables involved in the synthesis e.g. surface coefficients. The weights ω_i are normally + 1 for stations where gain is to be maximized and – 1 for isolation stations. By adjusting the weight it is possible to change the balance between achieving the desired gain and desired isolation. A min max optimization method minimizes the following function.

$$F(\overline{x}) = \max\left\{f_1(\overline{x}), f_2(\overline{x}), f_3(\overline{x}), ..., f_k(\overline{x})\right\}$$ (4)

(a) Antenna optimization in POS   (b) Successive optimization in POS
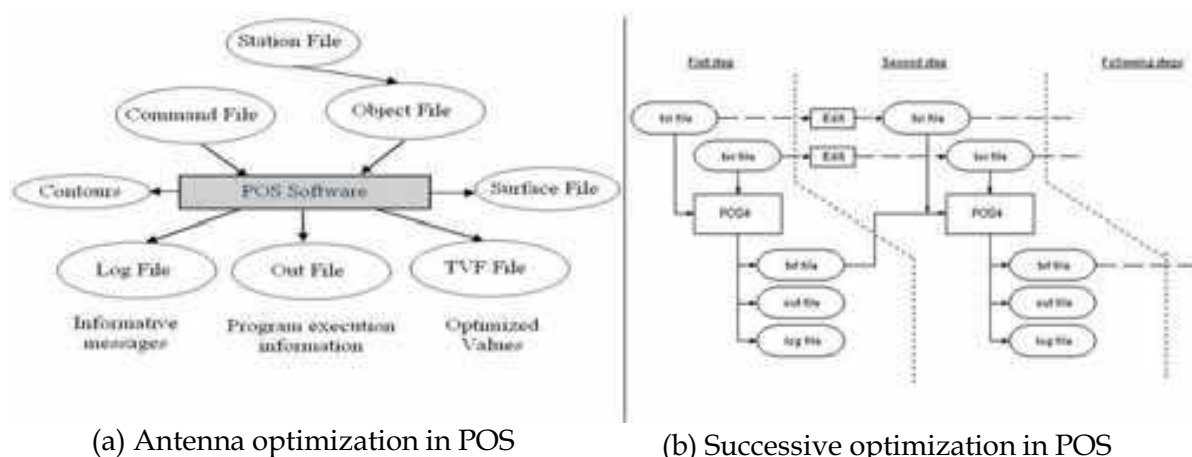
Fig. 8. POS optimization process

If the residue is positive the optimization continues until the residue becomes zero or negative. Figure 8(b) shows successive optimization process in POS. The files generated by one optimization step are used as input to the next optimization step. During optimization

steps user may need to check for performance by observing *out file* and / or plotting the contours and as a result the user may need to increase the density of adjustable surface coefficients to achieve more shaping of reflector surface and to ultimately reach to the goals.

18.2.2. POS Commands

The commands used in POS to optimize the reflector are shown in Figure 9. The antenna is defocused initially; the optimization is performed by taking no input *tvf file* (Ticra Variable File) and generating a *tvf file* in optimization. The *tvf file* is updated and reflector geometry is written to surface (*sfc*) file. The simulation is started, residues and contours plots are observed, the successive optimizations are performed by inputting the *tvf file* generated by the previous optimization step to the next step. Mean while the density of spline coefficients can be increased. The optimization is continued until the residues become negative. If after successive optimizations, required results are not acheived then user might need to change the antenna size, configuration ect.
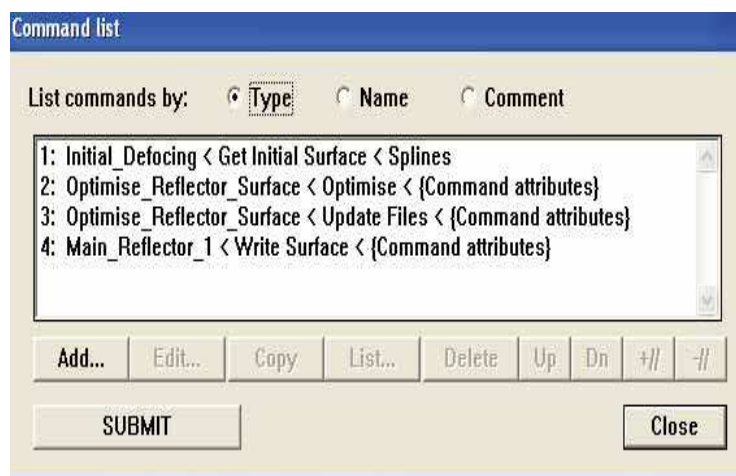
Fig. 9. Commands in POS for optimization

18.2.3. Optimized Antenna Contours

After optimization is complete, final contours of EIRP, G/T, and XPD are plotted. Here only EIRP contours are shown in Figure 10 using a 100W TWTA.

Sat. lon= 38.0,lat= 0.0,height= 35786 km. Created on: Fri Sep 05 (
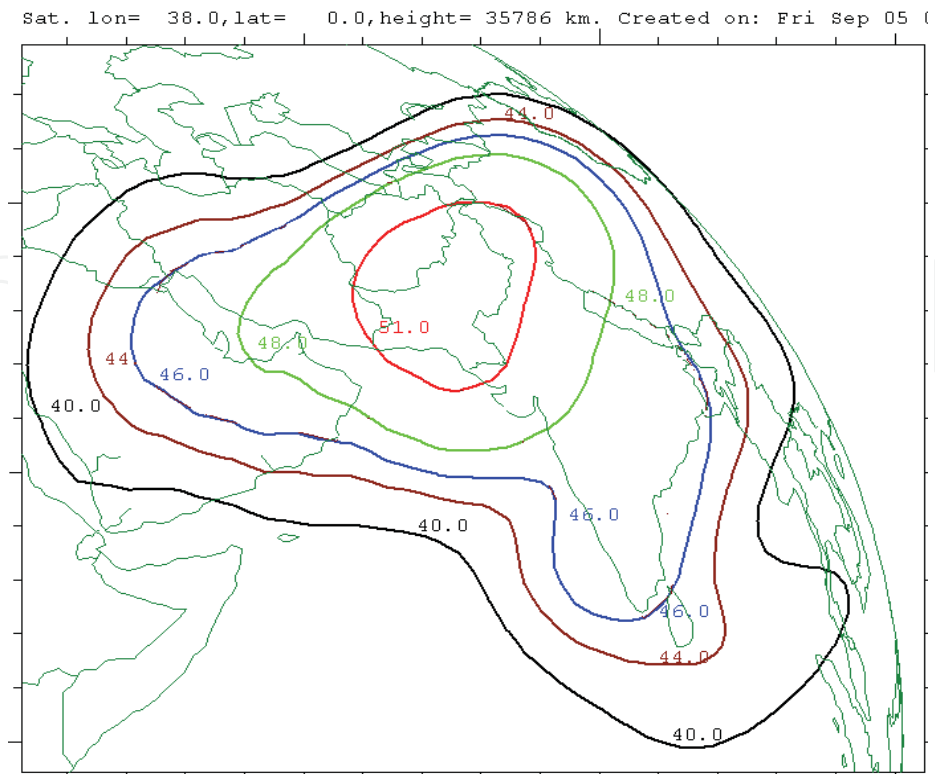
Fig. 10. Optimized contours in POS

18.2.4. Radiation Pattern

The optimized antenna geometry can be imported in GRASP to perform radiation pattern analysis. The comparison of Shaped and Unshaped antenna radiation patterns is shown in Figure 11. The shaped radiation pattern depicts that the antenna gain is no more focused only along the boresight. The near in and far out side lobes has increased considerably in case of shaped antenna as compared to the unshaped antenna. The radiation pattern is modified from unshaped antenna radiation pattern in such a way that it fulfils the performance requirements as is clear from the contours plot.
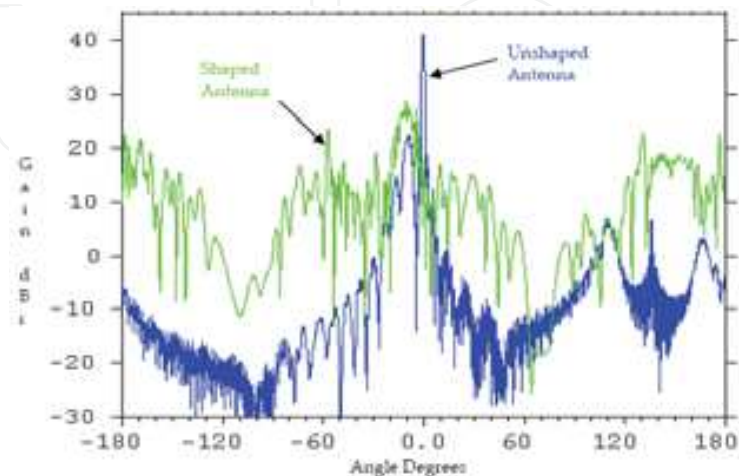
Fig. 11. Shaped and unshaped antenna radiation pattern

18.2.5. Rays Plot

The ray plot is shown is Figure 12 (a&b) for unshaped and shaped antenna system respectively. The rays reflected from shaped reflector antenna are no more parallel.
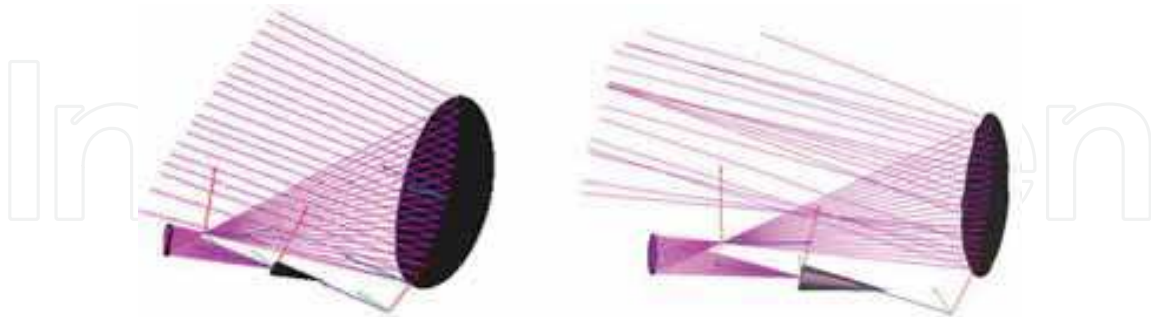
(a) Unshaped antenna rays plot   (b) Shaped antenna rays plot

Fig. 12. Unshaped and shaped antenna rays plot

18.2.6. Shaped and Unshaped Antenna Surface

The reflector antenna surface geometry are plotted before and after shaping using post processor as shown in Figure 13 (a&b) respectively.
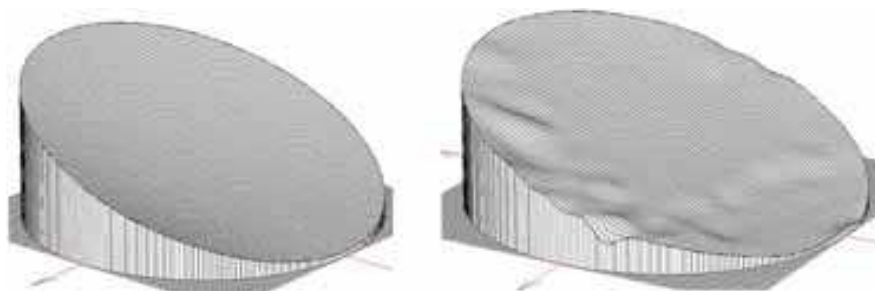
(a) Unshaped antenna surface   (b) Shaped antenna surface

Fig. 13. Unshaped and shaped antenna surface

19. Satellite Antenna Tests

The surface file(s) generated by POS is provided to manufacturer to get the antenna manufactured using an appropriate & available material and manufacturing process intended for space use. After the antenna has been manufactured the next step is to test its performance. Normally satellite antenna tests can be classified into following types

1. Electrical performance test

    Radiation pattern test normally carried out in a CATR facility equipped with standard measurement hardware and software. Radiation pattern is measured and antenna footprints on earth map are calculated and plotted using softwares.

2. Mechanical performance tests

    The mechanical tests include all the tests conducted to make sure that antenna can withstand the dynamic environment during launch.

3. Thermal tests

Thermal tests are conducted to make sure that antenna can survive and do not deform due to temperature variations when in orbit. It is highly necessary to check the variation in surface profile due to temperature changes because the changed profile might change the coverage area significantly.

4. Deployment tests

Deployment tests are very important to make sure that the antenna can fully deploy to required position because there are multiple antennas and pointing to respective coverage area is very important. The deployment tests are conducted using zero gravity apparatus. The hold and release mechanism holds the antenna during launch and releases it using pyrotechnic devices when we want to deploy it. The antenna can be deployed using springs or deployment motors.

5. In Orbit Tests

In orbit tests are performed to verify that communication payload is healthy, capable of performing required functions properly and EIRP, G/T values etc. are within tolerance limits when compared with test data on ground.

20. Remotely Configurable Satellite Antennas

Currently we are limited to satellite antennas which are shaped before the satellite is launched. Such antennas are not so flexible and once the satellite is launched, we can not change foot prints dynamically. The limitation tends to sustain because use of new technology is highly risky and commercial satellite manufacturers don't want to take any kind of risks due to high costs involved. The reliable technologies with years of space heritage (although less advance) are always preferred. But to make the satellite footprints dynamically changeable by using ground commands it is required to perform some experimentation and accept the risks due to complex nature of remotely configurable antennas.

The key concept behind remotely configurable satellite antennas is to change the surface profile of reflector antenna using onboard actuators controlled by telecommand. The actuators can be arranged in rows and columns, the surface deformation amount can be predicted by ground simulations and then corresponding actuators can be controlled to deform the surface of reflector antennas. POS can be used for calculating amount of deformation. Each coefficient of adjustable surface can be mapped to an actuator. More actuators placed on board; more flexible is the reflector shaping.

The cost of such antenna is high, TMTC system is complex (as every actuator is to be controlled and monitored), power requirement is high, control electronics and associated mechanisms are complex. Presently this is an immature technology so high risk is involved which is a major constraint in using such antennas. Remotely configurable antennas are still in research and we can expect their use in future satellites after going through myriad of tests and verification process.

21. Conclusion

We have presented here the technology of communication satellite antennas with a focus on contoured beam antennas using surface profile shaping. It is hoped that this material will

provide a quick insight of satellite antenna design and its related issues to the reader in a unified way. Our opinions are based on literature survey and experience. However, user is required to fully investigate the technology and its related issue before implementation as space related systems are very complex in nature. Authors are not responsible for any kind of loss or damage caused by use of the material covered in this chapter.

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The techniques of computer modelling and simulation are increasingly important in many fields of science since they allow quantitative examination and evaluation of the most complex hypothesis. Furthermore, by taking advantage of the enormous amount of computational resources available on modern computers scientists are able to suggest scenarios and results that are more significant than ever. This book brings together recent work describing novel and advanced modelling and analysis techniques applied to many different research areas.

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