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Architecture and Characteristics of Antenna Systems onboard Inmarsat Spacecraft for Mobile Satellite Communications

Dimov Stojce Ilcev[1,*]

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ABSTRACT

This paper describes architecture and characteristics of special antenna systems onboard Inmarsat Geostationary Earth Orbit (GEO) spacecraft for Mobile Satellite Communications (MSC). These spacecraft provides satellite links for communications, tracking, monitoring and logistics solutions between mobile and personal units as a Mobile Earth Station (MES) and Gateways or Ground Earth Stations (GES) achieved via Geostationary Earth Orbit (GEO) satellite constellation. Inmarsat GEO MSS operator is deploying advanced technology and technique to deliver Voice, Data and Video (VDV) for all mobile applications worldwide, excluding Polar Areas. The Inmarsat organization received sufficient funds to implement at first solutions for maritime applications and in the next phase to develop additional services such as land (road and rail) and finally for aeronautical applications. The Inmarsat team overcame all the problems and challenges, gaining the attribute of only one global mobile satellite operator with a significant professional attribute. Regarding the improvement of the space segment and in particular the service for mobile and personal applications, antenna systems on the Inmarsat spacecraft are being considered. Modern spacecraft antenna characteristics and link performance with monobeam and multibeam antenna coverage are presented. Here are presented the possible basic types of antennas installed on board for MSC service.

1. Introduction.

The first commercial maritime GEO Mobile Satellite Communications (MSC) system was proposed and built by the International Maritime Organization (IMO) in London in 1979, known as the International Maritime Satellite Organization (Inmarsat). Inmarsat started out as a non-profit organization providing maritime satellite communications including distress and safety solutions. In subsequent phases, Inmarsat developed additional services for land (road and rail), personal and aeronautical applications. For the first decade of operation, Inmarsat leased the space segment from Comsat (three Marisat satellites F1, F2 and F3), from ESA (two Marecs satellites A and B2) and from Intelsat (three Intelsat V-MCS A, B and D).

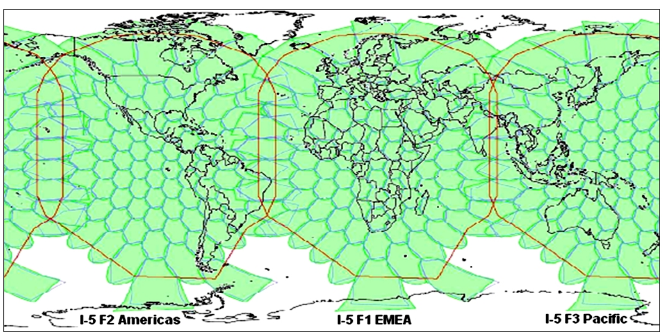
[1]University of Johannesburg, Johannesburg, South Africa.
[*]Corresponding author: Dimov Stojce Ilcev. E-mail Address: ilcev@uj.ac.za.

The Inmarsat GEO satellite constellations were originally configured in three oceanic regions: AOR, IOR and POR, each with an operational satellite and one spare in orbit. These satellite constellations are known as the first generation of the Inmarsat GEO network. Inmarsat was not responsible for TT&C, but operations were controlled by the Inmarsat Network Control Centre (NCC) in London. Inmarsat then operated with four 2nd generation Inmarsat-2 birds launched in 1990/92. with a capacity equivalent to about 250 Inmarsat-A voice circuits. These satellites were built to provide coverage of four oceanic regions: AOR-E, AOR-W, IOR and POR by British Aerospace's Space and Communications Division (Matra Marconi Space).

The US company Lockheed Martin has built a new spacecraft bus for the next generation of Inmarsat-3 spacecraft, based on the GE Astro Space Series 4000, with a height of 2.5 m and a radial envelope of 3.2 centered on the thrust cone. Thus, the Matra company built communication cargo, antennas, repeater and other electronic equipment. The payload and solar arrays are mounted on the N and S facing panels, while the receiver (Rx) and transmitter (Tx) L-band reflectors, mounted on the E and W panels, are powered by a cup array. Moreover, the navigation antenna is located on the panel facing the ground. A huge advantage of Inmarsat-3 satellites is to concentrate power on certain high traffic areas within the footprint.

These satellites can also reuse portions of the L-band for non-adjacent spot beams, effectively doubling the satellite's capacity. Responding to the growing demands of corporate mobile satellite users high speed Internet access and multimedia connections, Inmarsat built the fourth generation of Inmarsat-4 satellites as a gateway to a new mobile and personal satellite broadband network. Inmarsat has awarded Europe's Astrium a US$700 million contract to build three Inmarsat I-4 satellites, which will support the new mobile broadband and Broadband Global Network (BGAN).

Figure 1: Inmarsat-5 Global Spot Beam Coverage.



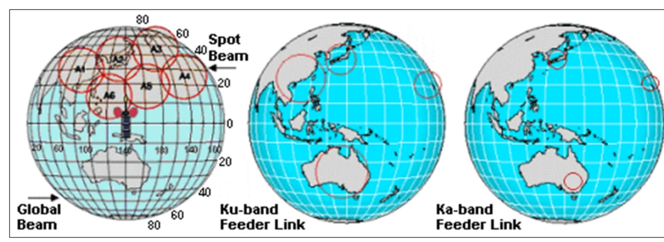
Source: Author.

The mobile broadband and BGAN for personal, fixed and mobile applications have to deliver fast Internet and Intranet content and solutions, video on demand, videoconferencing, facsimile, E-mail, phone and LAN access onboard mobile and at speeds up to 432 Kb/s worldwide, compatible with 4/5G cellular systems. Three Inmarsat I-4 F1 satellite launched March 11th 2005, I-4 F2 launched November 8th 2005, and I4 F3 anticipated launch in 2007 (POR) subject to business case and successful service introduction on IOR and AOR. All three spacecraft have the advanced technology to reduce service costs by 75%, compared to existing Inmarsat-M4 charges. They will be 100 times more powerful than the present generation and BGAN will provide at least 10 times as much capacity as today's network. The BGAN is model used to be designed maritime broadband known as FleetBroadband and aeronautical broadband known as SwiftBroadband.

Finally, Inmarsat has contracted the US Boeing, to build a constellation of new three multipurpose Inmarsat-5 satellites as a part of a global wireless broadband network Inmarsat Global Xpress. The first satellite Inmarsat-5 F1 entered in commercial service on dateMonth6Day30Year201430 June 2014. The second and third I-5 satellites are on course to launch by the end of 2014 and will provide global coverage during 2015. The spacecraft will provide radio spectrum on L/C and Ka-band for both communication and GNSS (navigation) facilities. The most important parts of Inmarsat spacecraft are antenna systems for satellite communications and navigation facilities. The I-5 spacecraft provided a new ground by transmitting in a portion of the radio spectrum never before utilized by the commercial operator of a global satellite system, which will be the extremely high Ka-band RF, in which global beam are situated many spot beams in rage with 3 LES terminals which is shows in **Figure 1.** Each I-5 will carry a payload of 89 Ka-band beams capable of flexing capacity across the globe and enabling Inmarsat to adapt to shifting subscriber usage patterns over their projected lifetime of 15 years.

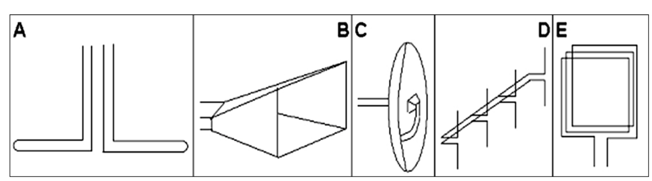
On the other hannd, the Japanese multipurpose GEO satellite MTSAT uses a minimum of seven spot beams and one global beam coverage, shown in **Figure 2 (Left),** a Ku-band feed link, shown in **Figure 2 (Middle),** and Ka-band feederl connection shown in **Figure 2 (Right).**

Figure 2: Japanese Multipurpose MTSAT Spot Beam and Feeder Links.



Source: Author.

Figure 3: Types of Spacecraft Antenna Systems.



Source: Author.

2. Basic Particulars of Spacecraft Antenna.

The spacecraft antenna radiates EM energy to the ground stations in both directions, efficiently and in desired path. Satellite antennas act as matching systems between sources of Electro Magnetic (EM) energy and space. The goal in using antennas is to optimize this matching. Here is a list of some of the properties of antennas:

1. Field intensity for various directions (antenna pattern);
2. Total power radiated when the antenna is excited by a current/voltage of intensity (Power Flux Density);
3. Radiation efficiency which is the ratio of power radiated to the total power (Radiation Pattern);
4. The input impedance of the antenna for maximum power transfer (matching); and
5. The antenna bandwidth or range of frequencies over which these properties are nearly constant.

However, spacecraft antennas can also be classified as electrical devices which convert electric currents into radio waves and vice-versa. They are generally used with a radio transmitter and receiver, which are broadly classified in two categories: Transmitting and Receiving antennas.

The difference is in the mode of operation, different functions etc. as the transmitting as well as the receiving antenna, and also difference is mainly in their environmental conditions which lead to their different designs.

Typically an antenna has an array of metallic conductors that are electrically connected. An oscillating current of electrons focused through the antenna by a transmitter creates an oscillating electric field. These fields are time-varying and radiate from the antenna into the space as a moving electromagnetic (EM) field wave. Certain properties of antennas such as directional characters result into reciprocity theorem.

The different types of spacecraft antennas are:

2.1. *Wire Antennas (Monopoles and Dipoles).*

The dipole is one of the most common used antennas. This spacecraft antenna consists of a straight conductor excited by a voltage from a transmission line or a waveguide and dipoles are easy to make, which is illustrated in **Figure 3 (A)**. Wire satellite antennas are used primarily at VHF and UHF-band to provide communications for the Telemetry, Tracking and Command (TT&C) systems. They are positioned with great care on the body of the satellite in an attempt to provide omnidirectional satellite coverage. Most communication satellites measure only a few wavelengths at VHF frequencies, which make it difficult to get the required antenna patterns, and there tend to be some orientations of the satellite in which the sensitivity of the TT&C system is reduced by nulls in the antenna pattern.

2.2. *Aperture Antennas (Horn Antennas).*

A horn is an example of an aperture antenna, which are used in Satellite spacecraft more commonly, shown in **Figure 3 (B).** Rectangular horn antenna is one of the simplest and most widely used antennas. Horns have been used for more than a hundred years, and today they used in radio astronomy, satellite communications, in communication dishes as feeders, in measurements, etc. Horn antenna is used at MW when for global coverage relatively wide beams are required.

A horn is a flared section of waveguide that provides an aperture several wavelengths wide and a good match between the waveguide impedance and free space. It is also used as feeds for reflectors, either singly or in clusters. Horns and reflectors are examples of aperture antennas that launch a wave into free space from a waveguide. It is difficult to obtain gains much greater than 23 dB or beamwidths narrower than about 10º with horn antennas. For higher gains or narrow beamwidths a reflector antenna or array must be used.

2.3. *Reflector Antennas.*

The parabolic reflector is a good example of reflectors at microwave frequencies, shown in **Figure 3 (C)**. In the past, parabolic reflectors were used mainly in space applications onboard spacecraft but today they are very popular and are used by almost everyone who wishes to receive the large number of television channels transmitted all over the globe.

Reflector antennas are typically used when very high gain or a very narrow main beam is required. Gain is improved and the main beam narrowed with increase in the reflector size. Large reflectors are however difficult to simulate as they become very large in terms of wavelengths. Reflector antennas are usually illuminated by one or more horns and provide a larger aperture than can be achieved with a horn alone.

For maximum gain, it is necessary to generate a plane wave in the aperture of the reflector. This is achieved by choosing a reflector profile that has equal path lengths from the feed to the aperture, so that all the energy radiated by the feed and reflected by the reflector reaches the aperture with the same phase angle and creates a uniform phase front. One reflector shape that achieves this with a point source of radiation is the paraboloid, with a feed placed at its focus.

The paraboloid, however, is the basic shape for most reflector antennas, and is commonly used for earth station antennas. Satellite antennas often use modified paraboloidal reflector profiles to tailor the beam pattern to a particular coverage zone. Phased array antennas are also used on satellites to create multiple beams from a single aperture, and have been used by Iridium and Globalstar to generate up to 16 beams from a single aperture for their Low Earth Orbit (LEO) satellite system.

2.4. *Array Antennas.*

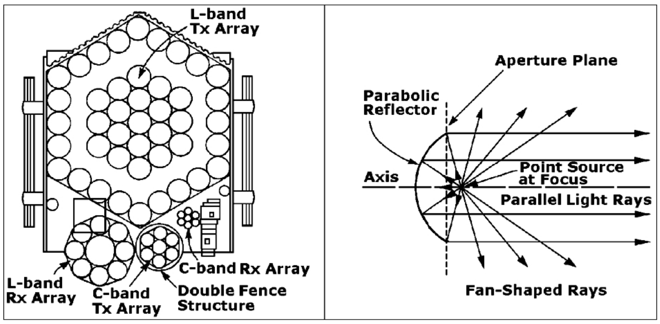
A grouping of several similar or different antennas forms a single array antenna, which is shown in **Figure 3 (D)**. The control of phase shift from element to element is used to scan electronically the direction of radiation. This array antennas are able to produce radiation patterns that combined, have characteristics that a single antenna would not. The antenna elements can be arranged to form a 1 or 2 dimensional antenna array.

A number of specific aspects and features of an antenna array will be stated using one-dimensional arrays for simplicity. This antenna array exhibits a specific radiation pattern, the overall radiation pattern of which changes when several antenna elements are combined in an array. In fact, the array factor quantifies the effect of combining radiating elements in an array without considering the element-specific radiation pattern. The overall antenna radiation pattern results in certain directivity and thus the gain associated with the directivity efficiency. Directivity and gain are equal if the efficiency is 100%.

2.5. *Loop Antennas.*

A wire loop antenna is used to radiate or receive EM energy. These antennas can also be used at home to record radio or TV channel signals, as illustrated in **Figure 3 (E).** The antenna pattern is a diagram of the field strength in the far field of the antenna infrastructure when the transmitter drives the antenna. At this point, antenna gain is a measure in dB of an antenna's ability to direct energy in one direction rather than all around. Thus, a useful principle in antenna theory is reciprocity, which means that the antenna has the same gain and pattern at any frequency, whether it is transmitting or receiving. The antenna diagram measured during reception is identical to the diagram during transmission.

Figure 4: Spacecraft Antenna Systems.



Source: Author.

As stated earlier, the antenna is providing global, spot and multiple beam coverages, but it can provide scanning and orthogonally polarized beams or coverage zones as well. The pattern is frequently specified by its 3-dB beamwidth, the angle between the directions in which the radiated (or received) field falls to half the power in the direction of maximum field strength. However, a satellite antenna is used to provide coverage of a certain area or zone on the Earth's surface, and it is more useful to have contours of antenna gain with maximum strengths of the signal in the middle of the coverage area and with decreasing of signals to the peripheries.

When computing the signal power received by an GES from the satellite, it is important to know where the station lies relative to the satellite transmit antenna contour pattern, so that the exact EIRP can be calculated. If the pattern is not known, it may be possible to estimate the antenna gain in a given direction if the antenna boresight or beam axis direction and its beamwidth are known.

All parts of spacecraft antennas, which have to be aligned normally are reflector (main reflector and sub reflector), feed and sometimes also support structures. These substructures allow a pre-assembly of reflectors and feeds subsystem level and an easier integration of the complete antenna onboard spacecraft. The goal of the alignment is to bring all the antenna components in a proper geometric configuration and to get the best or at least the designed RF antenna performance in the test facility and later on in the satellite orbit.

3. Satellite Antenna System onboard Spacecraft for Inmarsat MSS.

The antenna array system of Inmarsat-2 satellite for MSC is illustrated in **Figure 4 (Left).** The satellite antenna system mounted on the spacecraft structure, similar to the transponders, is composed of two main integrated elements: the C/L-band and the L/C-band antenna.

3.1. Inmarsat-2 C/L-band Array Antennas.

This uplink is actually the feeder link, which operates in the 6 GHz RF range. The signals sent by LES are detected by a C-band receiving array, comprising seven cup-dipole elements in the smallest circle. On the other hand, the L-band transmit antenna is the biggest segment of the whole system, consisting in 43 individual dipole elements, arranged in three rings around a single central element. Thus, this antenna is providing near-global coverage service downlink for MES in the 1.5 GHz RF spectrums.

3.2. Inmarsat-2 L/C-band Array Antennas.

These arrays are actually the service uplink and operate in the 1.6 GHz RF range. The signals sent by MES in adjacent global coverage region are detected by L-band receiving array, comprising nine cup-dipole elements arranged in a circle. Finally, the C-band transmit antenna consists in seven cup-dipoles for radiation of the feeder downlink to LES in the 3.6 GHz RF spectrum.

4. Characteristics of Satellite Antennas.

Both transmit antenna array systems are providing a global (wide) footprint on the Earth's surface. However, narrow circular beams from GEO or Non-GEO can be used to provide spot beam coverage. For instance, from GEO the Earth subtends an angle of 17.4^o. Antenna beams 5.8^o wide can reuse three frequency bands twice in providing Earth disc coverage. The directional properties of antenna arrays can be exploited to permit RF reuse in space communications, which is similar to several radio stations using the same RF being geographically far apart. Earth coverage by seven spot beams (six spots are set out around one spot in the centre) can be arranged by three pairs of beams: 1 and 4, 2 and 5 and 3 and 6, operating on frequencies f2, f3 and f4, respectively. Mutual interference within pairs is avoided by pointing one beam as far away from the other as possible. Coverage of the centre of the disc is provided by a single beam operating on frequency f1.

The main advantage with this spot footprint that is specific Earth areas can be covered more accurately than with wide beams. Furthermore, a greater power density per unit area for a given input power can be achieved very well, when compared with that produced by a global circular beam, leading to the use of much smaller receiving MES antennas. The equation that determines received power (P_R) is proportional to the power transmitted (P_T) separated by a distance (R), with gain of transmit antenna (G_T) and effective area of receiving antenna (A_R) and inverse proportional with 4π and square of distance. The relations for P_R and G_T are presented as follows:

$$P_R = P_T G_T \frac{A_R}{4\pi R}$$

$$G_T = 4\pi \frac{A_T}{\lambda^2} \quad (1)$$

Where G_T = effective area of transmit antenna and λ = wavelength. The product of P_T and G_T is gain, generally as an increase in signal power, known as an EIRP. Signal or carrier power received in a link is proportional to the gain of transmit and receive antennas (G_R) presented as:

$$P_R = P_T G_T G_R \frac{\lambda^2}{(4\pi R)^2}$$

or

$$P_R = \frac{P_T G_T G_R}{(L_P L_K)}[W] \quad (2)$$

The last relation can be derived with the density of noise power giving:

$$\frac{P_R}{N} = P_T G_T (\frac{G_R}{T_R})(\frac{1}{K L_P L_K}) \quad (3)$$

Where L_P = coefficient of energy loss in free space, L_K = coefficient of EMW energy absorption in satellite channels, T_R = temperature noise of receiver, G_R/T_R is the figure of merit and K = Boltzmann's Constant (1.38 x 10^{-23} J/K or its alternatively value is –228.6 dBW/K/Hz).

At any rate, P_R has a minimum allowable value compared with system noise power (N), i.e., the Carrier and Noise (C/N) or Signal and Noise (S/N) ratio must exceed a certain value. This may be achieved by a trade-off between EIRP (P_T G_T) and received antenna gain (G_R). If the receive antenna on the satellite is very efficient, the demands on the LES/MES are minimized. Similarly, on the satellite-to-Earth link, the higher the gain of the satellite transmit antenna, the greater the EIRP for a given transmitter power. Satellites often use parabolic dish antennas, though there are also other types, such as phased arrays. The principal property of a parabolic reflector is its ability to turn light from a point source placed at its focus into a parallel beam, as shown in **Figure 4 (Right).**

In practice the antenna beam can never be truly parallel, because rays can also be fan-shaped, namely a car headlamp is a typical example. In a microwave antenna the light source is replaced by the antenna feed, which directs waves towards the reflector.

The length of all paths from feed to aperture plane via the reflector is constant, irrespective of their angle of parabolic axis. The phase of the wave in the aperture plane is constant, resulting in maximum efficiency and gain. In such a way, the gain of an aperture (G_a) and parabolic (G_p) type of antennas are:

$$G_a = \eta(4\pi \frac{A_E}{\lambda^2})$$

$$G_p = \eta \frac{(\pi D)^2}{\lambda^2} \quad (4)$$

Where antenna values η = efficiency factor, A = projected area of antenna aperture, $A_E = \eta^A$ is effective collecting area and D = parabolic antenna diameter.

Thus, owing to correlation between frequency and wavelength, f = c/ λ is given the following relations:

$$G_p = \eta(\pi D \frac{f}{c})^2 = 60,7(Df)^2 \quad (5)$$

Where the second relation comes from considering that η ≈ 0.55 of numerical value. If this value is presented in decibels the gain of antenna will be calculated as follows:

$$G_T = 10.Log G_P \quad (6)$$

For example, a satellite parabolic antenna of 2 m in diameter has a gain of 36 dB for a frequency at 4 GHz and a gain of 38 dB for a frequency at 6 GHz. In such a way, satellite parabolic antennas can have aperture planes that are circular, elliptical or rectangular in shape.

Therefore, satellite antenna with circular shape and homogeneous illumination of aperture with a gain of –3 dB has about 47.5% of effective radiation, while the rest of the power is lost. To find out the ideal antenna characteristics it is necessary to determine the function diagram of radiation in the following way:

$$F(\delta_o) = s\frac{\delta_o}{s}\ (\delta_o = 0) \quad (7)$$

Where parameter s (δ_o) = flow density of radiation in the hypothetical satellite angle (δ_o) and s (δ_o=0) = flow density in the middle of the coverage area. Looking the Geometric Projection of Satellite the relation can be presented by the equation:

$$F(\delta_o) = \frac{d_o}{h} = cos\delta \sqrt{\frac{(k^2 - sin^2\delta_o)}{l - k}} \quad (8)$$

Where, as mentioned, k = R/(R + h) = sin δ and if δ_o = δ, the relation is defined by the following equation:

$$F(\delta) = k.cos\delta \quad (9)$$

For GEO satellite the value of ΔL is given as a function of angle δ, which is the distance from the centre of the coverage area, where the function diagram of the radiation is as follows:

F (δ) = ΔL = 20 log = 20 log R/(R + h) cos δ = 10

$$log\frac{R}{1 + \frac{2R}{h}}\quad [dB] \quad (10)$$

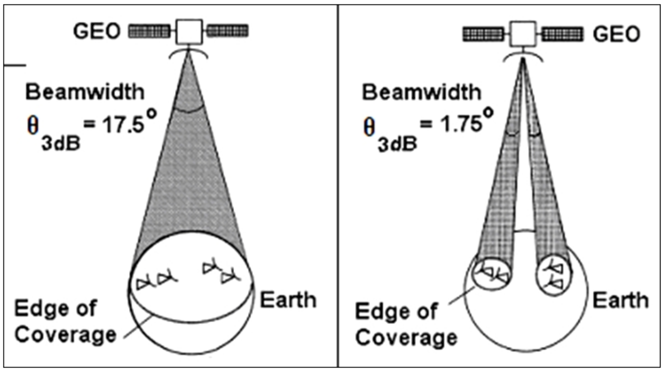
Therefore, in the case of GEO satellites the losses of antenna propagation are greater around the periphery than in the centre of the coverage area for about 1.32 dB. The free-space propagation loss (L_P) and the input level of received signals (L_K) are given by the equations:

$$L_P = (4\pi\ d/\ \lambda)^2$$

$$\frac{P_R}{S} = P_T \frac{G_T}{4\pi d^2} L_K \quad (11)$$

The free-space radio propagation loss is caused by geometrical attenuation during propagation from the satellite transmitter to the receiver.

Figure 5: Global Monobeam and Multibeam Antenna Coverage.



Source: Author.

5. Link Performance with Monobeam and Multibeam Antenna Coverage.

As stated earlier, the most important parameter of spacecraft transponder and the overall RF link quality depends on the gain of the satellite antenna. From equation (6), it can be seen that the satellite antenna gain is constrained by its beamwidth, whatever the frequency at which the link is operated. So the antenna gain is imposed by the angular width of the antenna beam covering the zone to be served. If the service zone is covered using a single antenna beam, this is referred to as single or monobeam beam satellite coverage, which displays one of these characteristics:

1. The satellite may provide coverage of the whole region of the Earth, which is visible from the satellite as a global coverage and thus permit long-distance links to be established, for example from one continent to another with 20 dB bandwidth. In this case, the gain of the satellite antenna is limited by its beamwidth as imposed by the coverage.
2. The satellite may provide coverage of only part of the earth (a region or country) by means of a narrow beam (a zone or spot beam), with 3dB beamwidth of the order of 1° to a few degrees.

With single beam antenna coverage, it is therefore necessary to choose between either extended coverage providing service with reduced quality to geographically dispersed GES terminals, or reduced coverage providing service with improved quality to geographically concentrated GES terminals.

Multibeam antenna coverage allows these two alternatives to be reconciled. However, satellite extended coverage may be achieved by means of the juxtaposition of several narrow beam satellite coverages, which each beam providing an antenna gain which increases as the antenna beamwidth decreases (reduced coverage per beam). The link performance improves as the number of beams increases; the limit is determined by the antenna technology, whose complexity increases with the number of beams, and the mass. The complexity originates in the more elaborate satellite antenna technology and the requirement to provide on-board interconnection of the coverage areas, so as to ensure within the satellite payload routing of the various carriers that are unlinked in different beams to any wanted destination beam.

In **Figure 5 (Left)** is presented that a satellite provides global coverage with a single satellite beam (monobeam) of beamwidth and in **Figure 5 (Right**) is illustrates that satellite supports spot beams with beamwidth of a consequently reduced coverage, known as multibeam satellite coverage. In both cases, all GES terminals in the satellite network are within the correspondent satellite coverage or in LOS with satellite. Multibeam coverage is providing the following advantages:

5.1. Impact on the Earth Segment.

The satellite communication link performance is evaluated as the ratio of the received carrier power C to the noise power special density N_0 and is quoted as the C/N_0 ratio, expressed in Hz. The expression for $(C/N_0)_U$ for the uplink (U) is given by the following equation:

$$(C/N_0)_U = (EIRP)_{station}(1/L_U)(G/T)_{satellite}(1/k) \quad [Hz] \quad (12)$$

Assuming that the noise temperature at the satellite receiver input is $T_{satellite}$ = 800 K = 29 dBK and is independent of the beam coverage (this is not rigorously true but satisfies a first approximation), let L_U = 200 dB and neglect the implementation losses. This equation becomes (all terms in dB) and can be presented as:

$$\left(\frac{C}{N_0}\right)_U = (EIRP)_{station} - 200 + (G_R)_{satellite} - 29 + 228.6 = (EIRP)_{station} + (G_R)_{satellite} - 0.4 \quad [dBHz] \quad (13)$$

Where value $(G_R)_{satellite}$ is the gain of the receiving satellite antenna in the direction of the GES transmitting terminals. This relation is represented by the two cases considered receiver:

1. Global coverage ($\theta_{3\ dB}$ = 17.5°), which implies $(G_R)_{satellite}$ = 29 000/$(\theta_{3\ dB})^2 \approx$ 20 dBi.
2. Spot beam coverage ($\theta_{3\ dB}$ = 1.75°), which implies $(G_R)_{satellite}$ = 29 000/$(\theta_{3\ dB})^2 \approx$ 40 dBi.

The expression for $(C/N_0)_D$ for the downlink (D) is given by:

$$(C/N_0)_U = (EIRP)_{station}(1/L_U)(G/T)_{satellite}(1/k) \quad [Hz] \quad (14)$$

Assume that the power of the carrier transmitted by the satellite is P_T = 10 W = 10 dBW. Let L_U = 200 dB and neglect the implementation losses. Thus, this equation becomes (all terms in dB):

$$(C/N_0)_D = 10 - -200 + (G_T)_{satellite} + (G/T)_{station} + 228.6 = (G_T)_{satellite} + (G/T)_{station} + 38.6 \quad [dBHz] \quad (15)$$

This relation is represented for the two cases considered transmitter:

1. Global coverage ($\theta_{3\ dB}$ = 17.5º), which implies $(G_T)_{satellite}$ = 29 000/$(\theta_{3\ dB})^2 \approx$ 20 dBi.
2. Spot beam coverage ($\theta_{3\ dB}$ = 1.75º), which implies $(G_T)_{satellite}$ = 29 000/$(\theta_{3\ dB})^2 \approx$ 40 dBi.

In case those values indicate the reduction in $(EIRP)_{station}$ and $(G/T)_{station}$ the transmission system is changing from a satellite with global coverage to a multibeam satellite with coverage by several spot beams. In this case, the multibeam satellite permits an economy of size, and hence cost, of the earth segment. For instance, a 20 dB reduction of $(EIRP)_{station}$ and $(G/T)_{station}$ may result in a tenfold reduction of the antenna size (perhaps from metricconverterProductID30 m30 m to metricconverterProductID3 m3 m) with a cost reduction for the GES terminal for more than 100 times. If an identical GES is retained (a vertical displacement towards the top), an increase of C/N_0 is achieved which can be transferred to an increase of capacity, if sufficient bandwidth is available, at constant signal quality in terms of Bit Error Rate (BER).

5.2. *Frequency Reuse.*

Frequency reuse consists of using the same frequency band several times in such a way as to increase the total capacity of the satellite network without increasing the allocated bandwidth (B). In the case of a multibeam satellite the isolation resulting from antenna directivity can be exploited to reuse the same frequency band in separate beam coverages.

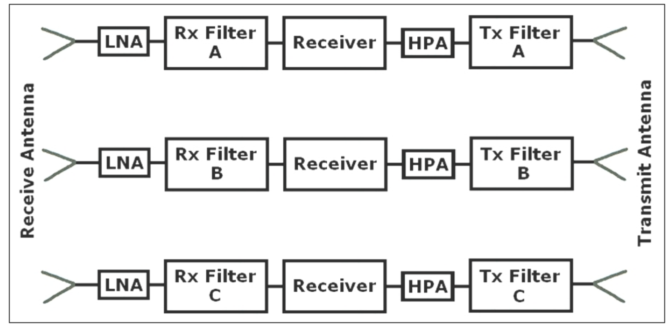
The frequency reuse factor is defined as the number of times that the bandwidth is used. In theory, a multibeam satellite system with M single-polarization antenna beams, each being allocated the bandwidth, combines reuse by angular separation and reuse by orthogonal polarization may have a frequency reuse factor equal to 2M.

This signifies that it can claim the capacity which would be offered by a single beam satellite with single polarization using a bandwidth of M x B. In practice, the frequency re-use factor depends on the configuration of the service area which determines the coverage before it is provided by the satellite. If the service area consists of several widely separated regions (for example, urban areas separated by extensive rural areas), it is possible to reuse the same band in all beams. The frequency reuse factor can then attain the theoretical value of M. In **Figure 5 (Right)** is shown an example of multibeam satellite coverage.

6. Multibeam Antenna Coverage.

Multi-beam antenna technology can effectively mitigate the impact of deep fading caused by multipath propagation on communication quality through spatial diversity and increase the reliability of the MSC systems. An advanced multibeam antenna configuration provides multispot coverage with a smaller number of apertures for Satellite Communications in the K and Ka-Bands. The multibeam antenna coverage is providing the following disadvantages:

Figure 6: Multibeam Antenna Coverage Transponder.



Source: Author.

6.1. *Interference Between Beams.*

In practical reality the interference generation within a multibeam satellite system is called self-interference. Thus, the effect of self-interference appears as an increase in thermal noise under the same conditions as interference noise between systems. At this point, it must be included the term $(C/N_0)_1$, which expresses the signal power in relation to the spectral density interference.

Taking account of the multiplicity of sources of interference, which become more numerous as the number of beams increases, relatively low values of $(C/N_0)_1$ may be achieved and the contribution of this term impairs the performance in terms of $(C/N_0)_T$ of the total link. As modern satellite systems tend to re-use frequency as much as possible to increase capacity, self-interference noise in a multibeam satellite link may contribute up to 50% of the total noise.

6.2. *Interference Between Coverage Areas.*

A satellite payload using multibeam coverage must be in a position to interconnect all network Earth stations and consequently must provide adequate interconnection of the entire coverage areas. The complexity of the payload is added to that of the multibeam satellite antenna subsystem, which is already much more complex than that of a single beam satellite. Different techniques, depending on the onboard satellite processing capability (no processing, transparent processing, regenerative processing, etc.) and on the network layer, are considered for interconnection of coverage:

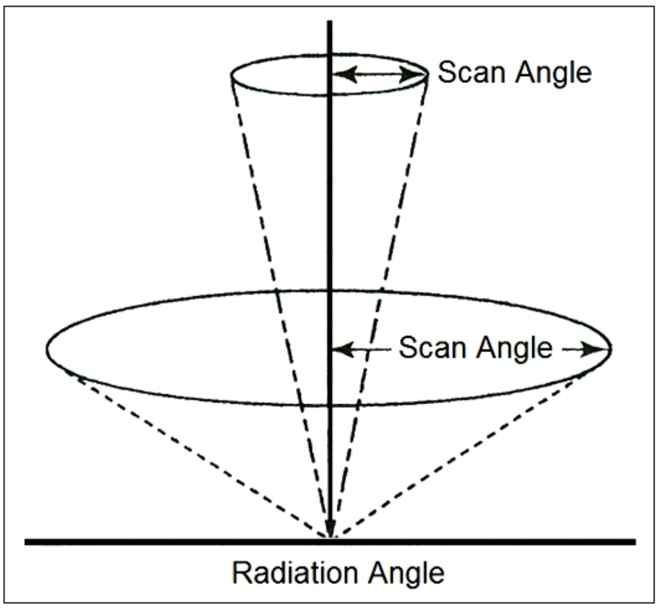
1. Interconnection by transponder hopping (no on-board processing);
2. Interconnection by onboard spacecraft switching (transparent and regenerative processing); and **–** Interconnection by beam scanning.

Multibeam satellite systems make it possible to reduce the size of GES terminal and hence the cost of the Earth segment infrastructure. Frequency reuse from one satellite beams to other permits an increase in capacity without increasing the bandwidth allocated to the system.

However, interference between adjacent satellite channels, which occurs between beams using the same frequencies, limits the potential capacity increase, particularly as interference is greater with earth stations equipped with small antennas.

The simplest form of a payload with multibeam antenna radiation is illustrated in **Figure 6.** Thus, a three-transponder payload uses one transponder per coverage circle. At this point, there is not connectivity between satellite coverage areas in this simple transponder.

Figure 7: Antenna Scan Angles.



Source: Author.

However, this payload could be designed so each transponder antenna illuminates three coverage circles and provide connectivity, but would cover three times area with just one-third the gain.

The relatively simple changes to multiple small beams have significant consequences as:

1. The area covered by each beam is much smaller, increasing the satellite antenna gain and allowing smaller and less expensive ground and mobile terminals;
2. The same total RF power can be used to carry more traffic, and/or reduce the RF power;
3. The same transponder bandwidth can be used multiple beam antennas, greatly increasing the available bandwidth: a) This allow the same bandwidth to be reused, increasing the amount that can be accommodated within the bandwidth; and b) A terminal has to be tuned to the correct RF to function and retuned if it is moved.
4. Connectivity between satellite beams, if required for the mission, must be provided by additional hardware on the satellite since a single uplink does not encompass the entire coverage area.

The satellite beams may be formed by individual feeds (circles) and by mechanical or electronic satellite beam former. However, mechanical beam formers use fixed wave-guide components to control the RF phase and amplitude. Usually there is one amplifier for each transponder in each composite beam. Electronic beam formers use electronic RF phase shifters, and sometimes provide electronic amplitude control, to produce the multibeam. There are many radiating elements and each usually has its own amplifier.

Satellite antenna radiators fall into two categories, reflector and direct radiating antennas. Reflector antenna uses a feed that indirectly radiates the energy towards the illuminated area of users, while direct radiating antenna radiates the energy direct to the coverage area. The satellite spot beam antenna can be pointed in various directions within a cone characterized by the scan angle, which illustrated in **Figure 7,** while a direct radiating array can radiate at large scan. Such arrays are attractive for LEO communication satellites because they operate over large scan angle than reflectors antenna, so they requires a scan angle of 63º to cover its field of view. In contrary, a GEO communication satellite requires a scan angle of 7º to cover the entire visible coverage circle on the Earth surface.

In addition to the fact that satellite antenna gain decreases as much the scan angle increases, and including polarization purity decreases as well. In such a way, the LEO satellite constellations require a direct radiating antenna. No commercial GEO satellite currently uses this antenna, while reflector antennas. At Medium Earth Orbit (MEO) satellite system the situation is less clear and both direct radiating and reflector antennas have been proposed for this orbit.

Conclusions.

The design and configuration of spacecraft antenna systems for MSS needs to be compact and robust especially for global coverage beam. Spacecraft mounted payloads usually require very accurate tracking performance capabilities for all mobile applications.

For example, a spacecraft mounted flexible antenna applies high accuracy and precision control to perform its mission serving ships, land vehicles (road and rail) and aircraft. The precision and accuracy is necessary to achieve the desired performance typically requires the use of a high gain feedback control system and accurate plant knowledge. On the other hand, the physical characteristics of antennas for ships and aircraft applications may be quite different, but both have to be designed compact for harsh environments and very extreme operating temperatures. These requirements will be difficult to achieve because the compact antenna has two major electrical disadvantages such as low gain and wide beam coverage, and because directional antenna has very heavy components for satellite tracking and getting satellite in the focus. However, a new generation of powerful satellite constellations with values of high EIRP and G/T performances should permit the design of compact and lightweight mobile satellite antennas.

The current Inmarsat-4 Spacecraft user link or mobile antenna system consists of a metricconverterProductID9 meters9 meters deployable reflector and a feed array with 120 helical elements. Over 220 simultaneous RF beams are created by applying vector weights to the feed elements under the control of the onboard Digital Signal Processor (DSP). The simultaneous transmission and reception requires the achievement of very low levels of Passive Inter-Modulation (PIM). The mission requires continuous coverage over fixed ground cells for orbital inclinations of up to 3°. This is achieved by uploading modified beam weights on a daily basis. This requires a large number of beam weights to be pre-synthesized.

In addition to the pervious, the Inmarsat team has placed a contract for the procurement of a fifth generation spacecraft system to fulfill the modern communications requirements of mobile terminal users worldwide into the 21st century. The system requirements for the Inmarsat-5 antenna systems onboard spacecraft is to service the projected communications capacity needs, focusing upon the L, C and Ka-band antenna system requirements which are one of the key technology development areas of the program. The critical technology aspects of the antenna design needed to provide efficient implementation of the system requirements such as global and spot coverages for Voice, Data and Vide (VDV) and VDVoIP transmissions over the globe up to 75^0 of Elevation angles on North and South latitudes.

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