Low Profile Tracking Ground-Station Antenna Arrays for Satellite Communications

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Low Profile Tracking Ground-Station Antenna Arrays for Satellite Communications

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The paper presents a new concept for application of low-profile antenna arrays as two-way terminals for mobile ground stations for high-throughput satellite communications with small satellites. Three types of tracking antenna systems have been described and compared: with pure electronic or mixed (electronic-mechanical) beam steering with flat antenna arrays or with one or multi-panel antennas. The principle of satellite tracking has been described. Several design examples have been given for illustration of the different types of mobile low-profile terminals (on the base of Ku band operation).

Key Words: Antenna arrays, Antenna tracking, ITU regulations, Small satellites, Broadband communications

1. Introduction

The properly working ground station/stations (GSs) are key elements of any small-satellite mission. They have to track the flying LEO satellites as long as possible and have to ensure as much as possible data throughput from and, in some cases, to satellite, not to consider the ordinary telemetry, tracking and command, and data-handling services. Nevertheless, that this is a locally-based component of the missions, its purposes and functionality usually exceeds the frame of the place, where the GS is situated. Unfortunately, universal solution for an ideal ground station of type "one-fit-all" does not exist. The options for the small-satellite operators could be as follows: "to build own GS" (for a single use), "to rent (remote control) GS" (for many missions), or to "co-operate" (dedicated GS networks). Therefore, three common GSs concepts can be formulated[1]: 1) "Single site" (purchased and installed GS at low-cost often in a single facility of the corresponding satellite operator; 2) "Global sites" with dedicated mission antenna network (the single satellite operator installs and operates GSs at multiple location around the Earth globe) and 3) "Global multi-mission GSs networks" (the satellite operators buy/rent capacity on an existing GSs network, owned, operated and maintained by a service provider). The first two concepts have been more or less preferred for the ordinary cost efficient VHF/UHF/S-band GSs, which need medium required initial investment. But for missions, based on constellation architecture and especially for missions with communication systems, operated at higher frequencies, the third option for Global multi-mission GSs networks is more appropriate.

In the last several years we indicate serious efforts of ITU (International Telecommunication Union) to recommend[2] allocation of new higher frequency bands for communication with small satellites for primary and secondary services – in the X, Ku, K and Ka bands. In a short time period the preparation of obligatory ITU documents API (Advance Publication Information) for small satellites increased exponentially[3] (from 10-11 to 80-85/per year); this fact clearly indicates that there are needs for high-frequency communications with small satellites and probably they will start to be rapidly implemented soon. This paper is dealing exactly with these new possibilities, describing a new type of low-profile high-frequency tracking antennas for fixed or mobile service, working in the X, Ku, K and Ka bands.

Nowadays communications are an important part of the fast developing satellite technologies. It concerns not only dedicated communication satellites, but also the space missions with micro and nanosatellites, which rely on communications. The fast growing demand of higher date rate transmissions, capable to support for example live video or high definition images transmission, requires high gain GS antennas in order to ensure the proper carrier-to-noise ratio. Such antennas usually work in higher frequency bands and are able to concentrate the radiated electro-magnetic energy in a sharp beam, which needs to point exactly the direction toward the satellite during communication session. In some scenarios, when as satellite, as well as GS are on-the-move, the GS antenna needs to track the satellite in order to ensure the exact antenna beam pointing. Such typical scenarios can be defined as follows:

- Fixed GS communicating with moving satellite; typical case is communication with non-geostationary satellite: for example LEO (Low Earth Orbit) MEO (Medium Earth Orbit) or HEO (High Elliptic Orbit) satellite;
- Mobile GS communicating with geostationary satellite;
- Mobile GS communicating with continuously moving LEO, MEO or HEO satellite.

The known high gain tracking antennas can be generally divided into two main types. One type utilizes a reflector or lens antenna with fully mechanical steering. Another type uses so called antenna arrays comprised of a plurality of radiating elements. In this paper we compare the both solutions and share our viewpoint, experience, and obtained results for the concept, architecture, realized solutions, performances, advantages and some applications of antenna systems, based on low-profile antenna platforms.

2. New ITU Frequency Bands Allocated for SmallSats

ITU demonstrates a good vision for the small satellites. The Prague declaration[4)] "open the window" for more flexible utilization of the spectrum for the purposes of the growing small-satellite missions, taking in mind the specific nature of small satellite space stations in the amateur-satellite service and the frequency coordination and registration process within the International Amateur Radio Union (IARU) to avoid harmful interference to amateur and amateur-satellite stations and compliance with the space debris mitigation guidelines.

From our point of view, the ideas of the Prague declaration mean more intelligent utilization of the spectrum using the advantages of the higher frequency bands, applying antennas with narrower beams and better directivity to avoid accidental interferences and more accurate steering. The already established bands, which cover several relatively narrow bands, are in the dm wavelength range (HF, VHF, UHF, L, S) 144-146 MHz, 435-438 MHz, 1.26-1.27 GHz (Earth-to-Space), 2.40-2.45 GHz, in the cm range (C, X, K) 5.65-5.67 GHz (E-S), 5.83-5.85 GHz (S-E), 10.45-10.5 GHz; 24-24.05 GHz (some of them coincide with the license-free ISM bands) and in the mm range (30-250GHz) 47-47.2GHz, 76-77.5, 77.5-78; 78-81, 134 -136; 136-141, 241-248, 248-250 GHz. ITU started to allocate also new frequency bands for amateur satellites, most of them for broadband applications (for EESS, Earth Exploration Satellite Services, and SRS, Space Radio- communications Stations); for example, 1.675-1.71 GHz, 2.025-2.11 GHz, 2.20-2.29 GHz, 8.025-8.40 GHz (S-E), 25.5-27.0 GHz (S-E), 28.5-29.1 GHz (E-S), 29.5-29.9 GHz (E-S), etc.

3. Antenna Arrays versus Reflectors at High Frequencies

The pure mechanically steerable reflector antenna (standard dish) has a relatively large sweep volume and accommodated under protective radome for mobile use, may have too large and undesirable height for mobile applications, especially when installed on ground vehicles – see Fig. 1. The alternative, antenna arrays, from a certain number of radiating elements arranged in planar or conformal lattice can be built with appropriate shape and size. They typically take the form of conformal or flat panels and utilize the available space more efficiently than the reflector solutions providing a lower profile with comparable performances. In certain cases the mentioned panel arrangements can combine two or more panels in order to reduce the height further. The third efficient solutions for steerable antennas are the reflect arrays, which are not considered in this paper.

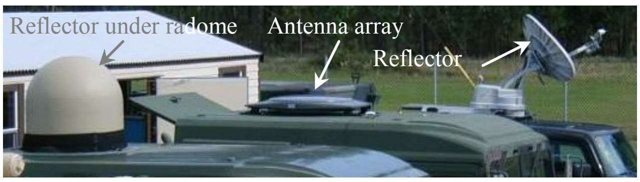
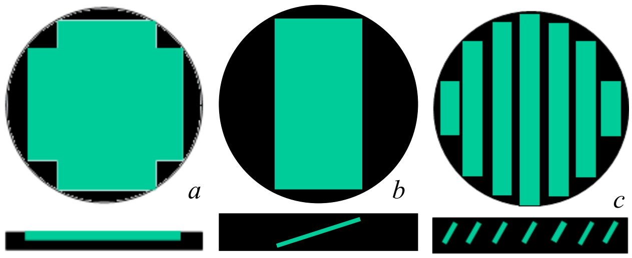


Fig. 2. Visible importance of the low-profile antennas for ground vehicles

4. Low Profile Antenna Arrays

Using flat panel antenna with good efficiency can be designed even when highly asymmetrical shape is desired, that is not feasible for reflector antennas. From another side controlling the phase and amplitude of the signal fed to any element of the antenna array it is possible to shift beam position without moving antenna panel mechanically (it is so called electronic beam steering). Such type of antennas is known as *phased array*. Therefore, depending on the specific application the antenna array technology it considered as more flexible to provide variety of options for beam pointing, antenna form factor and performance optimization. Fig. 2 shows three possible flat panel's arrangements.



Zenith-type panel | Tilted-panel antenna | Multi-panel antenna

Fig. 2. Three flat-panel antenna configurations: top and side views

The first variant, called "Zenith panel", is typical for antennas with full electronic or mixed (electronic-mechanical) beam steering. It gives the possibility to achieve extremely low profile (antenna height of 2-3 inches, 5-7.6 cm) and to make antenna invisible or even embedded into the vehicle roof. This configuration could be expensive and complex in case of relatively large panels. Such types of antennas also suffer from performance degradation at low elevation angles (below 25 deg). Second option "tilted panel" gives more freedom for antenna performance optimization with respect to form factor and performance at low elevation angles. Fully mechanical or mixed (mechanical in azimuth and electronic in elevation) beam steering configurations are possible. The third option "Multi-panel antenna" optimizes antenna performance with respect to the occupied volume. Fig. 1 clearly illustrates the advantage of low profile antenna form factor. Mechanical steering and electronic phase compensation between panels are usually applied in this variant of antenna implementation. Multi-panel configuration also allows to dedicate some of the panels for transmit and some for receive in case of two-way communication antennas for ground stations.

All of the described above antenna configurations have been used in the RaySat BG Ltd. products design [5-8] allowing system integrator or customer to select most proper antenna solutions for any specific application, including GSs for small-satellite tracking and communication sessions.

5. Control and Tracking of Satellite Terminal Antennas

Targeting the most complicated case of the antenna communicating with LEO satellite, when the both segments are moving, exact pointing is essential for good quality of mobile connection. Any deviation, even small, means that antenna beam don't point exactly to the satellite, which is equivalent to reducing its gain. Taking into account that the width of high-gain antenna beam at the level of -3 dB is typically of the order of a few degrees, and the speed of rotation of the mobile platform may be up to more than 60 degrees per second, the complexity and importance of the problem immediately becomes apparent.

The control and guidance of the antenna include sensors for determination of the movement parameters (gyroscopes and inclinometers), GPS receiver, detectors for the received signal strength RSSI (Receive Signal Strength Indicator), processor (CPU) with integrated specialized software and devices directing the antenna beam: motors or system of high-frequency control devices (for antennas with electronic beam-steering). The connection to the satellite passes through three stages: initial targeting, identification and switching on to tracking mode. For initial antenna pointing, GPS information has to be used for the exact location of the mobile station and the position of the satellite using the preliminary flight parameters. With this information CPU calculates the satellite elevation; the actuators guide of the antenna to the required elevation and rotate it azimuthally until it receives a signal. Then a procedure for identification is switched on based on the specific code that emits each satellite. If the signal does not belong to the desired communication satellite antenna rotation continues until once again a signal is received and the procedure is repeated until the desired satellite is found out. Using the GPS receiver allows to significantly reduce time initial finding and recognizing that usually does not exceed 20 to 30 s. Once the satellite is identified, the tracking mode is switched on and the actuators start to compensate the rotation of the mobile platform by CPU commands using signals from the sensors of the parameters of movement and the RSSI detector. Gyroscopes, which are used to measure the platform rotation angles, are miniature semiconductor COTS devices; which drift over time is significant. Therefore, the information from these sensors is used to compensate the rapid changes only and their drift is adjusted using the information from the tracking system with feedback, including RSSI detectors. The exact direction of the satellites is determined by measuring the difference in the levels of the received signals from the so-called tracking beams of the antenna, which have maxima diverted from the main antenna maximum a specific acute angle, as shown in Fig. 3. These beams can be generated by mechanical movement of the antenna or electronically tunable RF devices in case of antenna with electronic beam steering.

The Fig. 3 illustrates the operation of the monitoring system with feedback,comprising RSSI detectors. The tracking beams in elevation plane are shown, which are diverted at ±0.5 deg to the main antenna beam direction.When the antenna is directed exactly to the satellite, the signal levels received from the pair of tracking beams coincide. In case of deviation of the main beam from the exact direction of the satellite, a difference appears between the tracking signals levels, which is proportional to the deviation. Then the information about registered difference has been used by the processors for generating of commands to the actuators to compensate the variations in the elevational plane. Similarly, the deviation is compensated in the azimuthal plane by using information about the RSSI detectors received by the azimuthal tracking beams.

The pointing accuracy of the on-the-move antenna to the satellite is an important parameter of mobile broadband satellite terminals. Usually it is defined for the maximum speed of mobile platform rotation and depends on the response time of the system for monitoring and the actuators. In the link budget for mobile satellite system must take into account the reduction in the gain of the antenna due to inaccurate targeting (tracking error) and the actual extension of the main beam of the antenna diagram, which must be entered in the regulatory mask. The achievable accuracy of practical guidance is typically in the range between ±0.3 and ±0.5 deg at a maximum speed 60 deg/s of mobile platform rotation.

In many cases of fixed antenna communicating with small satellite the simpler open-loop tracking system has been implemented. The information for beam pointing can be provided by software determining the time and position of the satellite passes over. In the case of high-gain antenna working in higher frequency bands (Ku, K, Ka and above) in order to decrease the tracking error, it is better to combine the open-loop system with the closed-loop system described above.

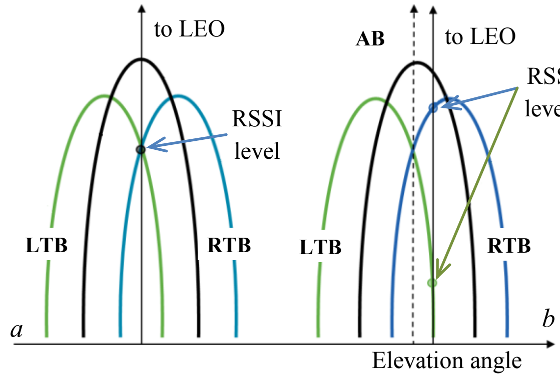


Fig. 3 Determination of the exact LoS direction to the satellite using information for signal strength received by tracking antenna beams (AB – main antenna beam; LTB, RTM – left and right tracking beams). Cases: *a*) antenna beam is along the LoS to LEO; *b*) antenna beam is diverted

6. "On-the-Move" Antenna Systems and Design Examples

Practical design of broadband satellite mobile terminals faces many challenges. Most important of them can be defined as follows:

- Form factor: Low profile is highly desirable especially for land mobile applications;
- High antenna efficiency;
- Satellite acquisition and tracking;
- Line-of-Sight problem. Satellite shadowing and fast link recovery;
- Reliability. Tough operation environment;
- Complexity and manufacturability;
- Cost.

In this paper we will present several examples, which illustrate how these challenges are addressed in the RaySat SOTM (Satcom-On-The-Move) antennas [8]. Only Ku-band examples have been given, but there are antenna systems implemented in all other neighbor bands – X, K, Ka [9, 10].

6.1 Multi-panel Tx/Rx Antenna Terminals. First design example is related to multi-panel antenna architecture (Fig.2*c*). Antenna comprises four panels. Multi-panel approach allows for optimization of antenna performance versus occupied volume. In the particular design the overall height of antenna terminal is limited to less than 150 mm. In the receive-only version of the system (such as SpeedRay® 1000 – see [8]) all four panels work in receive mode, while for mobile VSAT (Very Small Aperture Terminals) application (e.g. EagleRay®

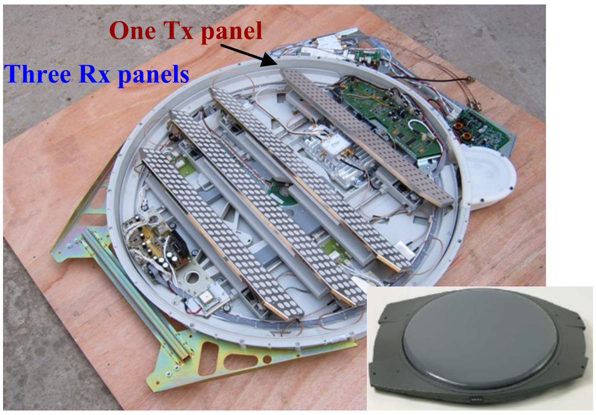


Fig. 4 Design example: EagleRay® two-way antenna system [7]

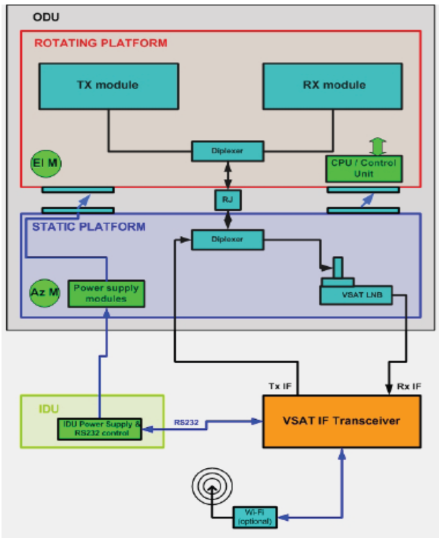


Fig. 5. Block diagram of two-way mobile antenna system

antenna family) three panels are receive and one is dedicated to transmit. Picture and block diagram of the two-way antenna terminal version is shown on Fig. 4 and Fig. 5, respectively.

Antenna terminal ODU (Outdoor Unit) parts are situated on static and rotating platforms. The antenna panel, combining circuits, diplexer devices, gyro sensors, CPU and elevation motors are located on the rotating platform, while the azimuth motor, power supply unit, LNB device and interface with IDU (Indoor Unit) and VSAT transceiver are located on the static platform. The functional connection between the both platforms is accomplished by rotary join and slip ring devices for RF, power supply and digital signals transferring.

Antenna panels are designed as arrays of dual port radiating aperture elements, arranged in rectangular lattice. Size of the elements and array grid are optimized in order to achieve minimal number of antenna elements and to simplify combining networks. Two independent fed layers are used to combine signals from vertical and horizontal polarization ports. By proper summation of the corporate vertical and horizontal signals at the panel outputs required polarization control is achieved.

The signal combining inside the antenna panel is done on two stages. First stage is combining of radiating elements per panel quarters trough air-filed strip line combiners. The second stage combining employs air-filed rectangular waveguides in order to achieve lowest possible losses and good antenna efficiency. Two-stage low-noise amplifiers are integrated directly at the panel's backs to keep the antenna system noise temperature low. Panel's construction is built using cost effective and light weight components – punched aluminum grids, foam layers, thin printed circuit boards and metalized plastic parts. Special design of the panel's box ensures effective suppression of surface waves. Exploded view of antenna panel is shown on Fig. 6.

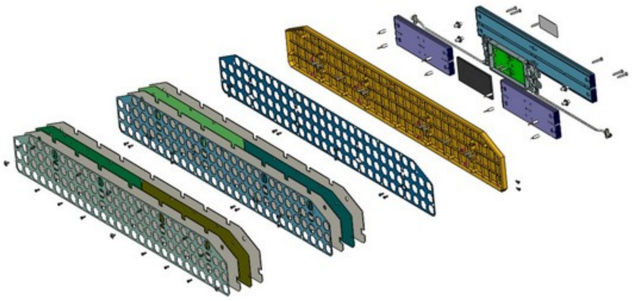


Fig. 6 Exploded view of the antenna panel

Finally two linearly polarized H and V signals from the antenna panel's outputs are summed together by final combiners, comprising electronically controlled phase shifters and attenuators, in order to compensate phase shifts between panels dependently of the elevation angle and at the same time to ensure required polarization control. A custom design highly integrated MMIC comprising four channels including amplifiers, four-bit phase shifters and attenuators are used for this purpose. Typical measured four-panel antenna panel patterns in azimuth and elevation plane are shown on Fig. 7.

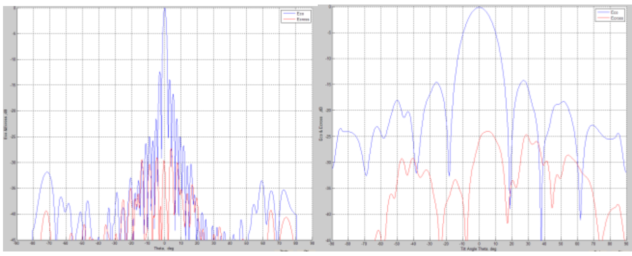


Fig.7 Measured SpeedRay antenna patterns in azimuth and elevation plane (blue curves – CoPol; red curves – CrossPol)

Fast satellite acquisition is obtained using information for the current position of the antenna terminal provided by integrated GPS receiver. Implemented dual stage tracking algorithm (see 5) allows for fast and reliable tracking and quick link recovery even after long time interruptions. The platform movement is compensated trough open-loop INS (Inertial Navigation System) comprising CPU, motion sensors (accelerometers) and rotation sensors (gyroscopes). The required INS correction data is obtained through adaptive signal strength detector and mechanically or electronically generated tracking beams. General parameters of EagleRay antenna shown on Fig 4 are systematized in Table 1.

Typical application of the described above antenna is to provide one-way (TV and radio programs) or two-way (real time video, Internet and data transfer) communication to mobile platforms, such as cars, buses, trains, recreation vehicles, boats etc. Antenna system is successfully used in various scenarios including news gathering (DSNG), first responders or defense and security communications (Fig. 8). This antenna is fully applicable for small-satellite tracking.

Table 1. Parameters of the Antenna System from Fig. 4

General	
Function	Two-way satellite communications; mobile VSAT
ODU dimensions	1130 x 880 x 147 mm
ODU weight	30 kg
Tracking speed	60 deg/s
Antenna Field of View	
Azimuth	360 deg continuous
Elevation	30 – 70 deg
Return Link (Transmit; Tx)	
Tx frequency	14.0-14.5 GHz
Polarisation type	Ortogonal linear with adjustable orientation; Automatic Polarization Control
Cross-pol isolation	>30 dB
Uplink data rate	Up to 2 Mbps (with optional external BUC)
Uplink EIRP	32 dBW (with internal 3-Watts BUC)
Forward Link (Receive; Rx)	
Rx frequency	11.7-12.7 GHz
Rx G/T	7.6 dB/K @ 30 deg

Fig. 8 EagleRay antenna applications: first response, military vehicle, boat

4.2 One-panel Tx/Rx Antenna Terminals. Another design example concerns dual band inclined single panel antenna configurations. Such types of antennas are designed to provide two-way communication using one and the same antenna array aperture. The main design challenge here is to ensure broadband operation in order to cover standard FSS receive and transmit frequency bands in Ku or Ka bands. This requirement calls for development of wideband antenna element and combining circuits as well as proper array arrangement. As an example S200 dual band inclined panel antenna [8], working in Ku band, is shown on Fig. 8.

S200 antenna panel has a multilayer construction – a combination of radiating aperture and stacked patch antenna elements in order to ensure the required 38% operational bandwidth 11-14.5 GHz band. The cavity layers embedded in panel construction help to suppress the surface waves and to increase the efficiency of the aperture. Exploded view of panel construction is shown on Fig. 10.

Independent broadband low-loss air stripline combining circuits are used to sum the signals from the pair of ports of the radiating elements. Receive and transmit bands are separated

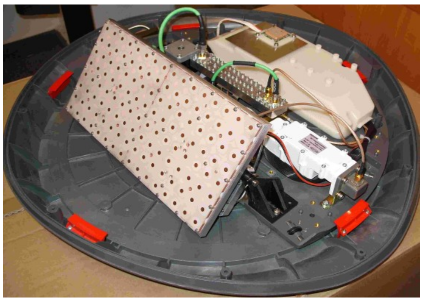


Fig.9 Dual band inclined panel antenna S200

by two diplexers providing four independent antenna outputs: for Rx/Tx vertical polarization and for Rx/Tx horizontal polarization. The signals from these four outputs are used for control of the polarization offset. Polarization control is electronic for the receive band including first stage of low noise amplifier and mechanical for the transmit band. Block diagram of this type of antenna panes is shown in Fig. 10. Fig. 11 shows two measured S200 antenna patterns at 11.7 and 14.2 GHz.

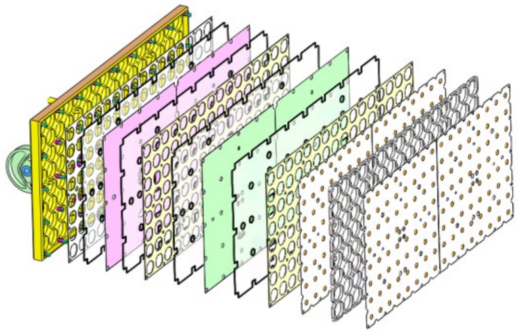


Fig. 10 S200 antenna panel construction – exploded view

Fig.11 Block diagram of the dual band panel construction

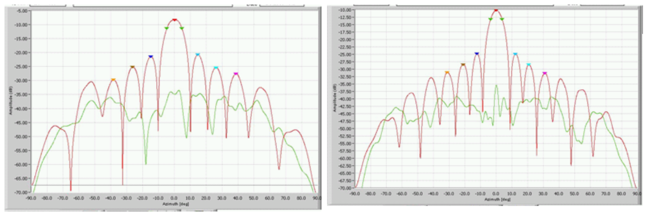


Fig.12 CoPol and CrossPol S200 antenna pattern at 11.7 and 14.2 GHz

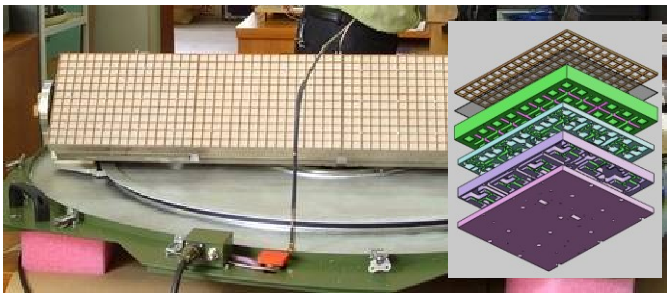


Fig 13 EagleRay7000 full size antenna panel and view of quarter panel

RaySat's EagleRay7000 antenna (see Fig. 13) represents another example of inclined panel solution. Antenna design now is based on array of dual polarization square horn. The horns are arranged in an equilateral Cartesian lattice. Desired uniform phase and amplitude distribution at the aperture is achieved by adding a grid layer in front of the horn's array. Vertical and horizontal polarizations are separated by a compact ortho-mode transducer and then the corresponding signals are summed using independent waveguide feed combiners.

Antenna panel has modular structure and in full size version consists of four identical modules built out of metallized molded plastic parts (see the inset in Fig 13). This is a quite flexible solution for building of different size antenna panel.

4.3 Flat-panel Tx/Rx Antenna Terminals. Electronic beam steering antennas or so-called phased-array antennas (PAA) are usually associated with extremely expensive military radar antenna solutions, comprising a large number of radiating elements and Tx/Rx microwave modules. Recently the advancement in Monolithic Microwave Integrated Circuit (MMIC) technology makes feasible some other applications such as communication antennas. PAA technology is very attractive especially for mobile broadband satellite service antennas mainly because it can offer extremely low profile and beam pointing agility. Something more, full electronically beam steering is the only possible option for antennas embedded into the vehicle's roof allowing to maintain the appearance unchanged, to avoid acoustics noise from mechanically driven antenna and to improve the system reliability. From another side a dedicated service specially tailored for mobile users can afford significantly lower size antennas, hence reducing the price and complexity of the subscriber's terminal. Fig. 14 shows comparison between the sizes of elements in flat antenna arrays at different frequencies from Ku to Ka bands.

Full electronically steerable antennas require ability for phase control of each radiating element in the array. Moreover, in order to compensate the polarization offset a dual port elements must be used and phase and amplitude control of each port is necessary to be provided. Therefore the number of phase-shifters may exceed the number of array elements. Not to entering in details, some practical examples have been given below. Fig. 15, 16 presents two RaySat flat antennas in Ku band and measured pattern. Table 2 includes systematized data for the RaySat antenna T9 [10].

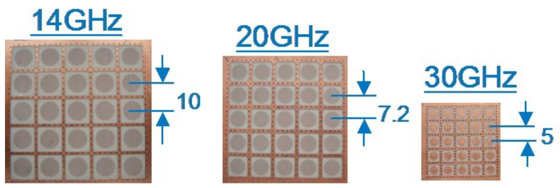


Fig. 14. Required distance in mm between antenna array elements for full electronically beam steering operation for different frequency bands

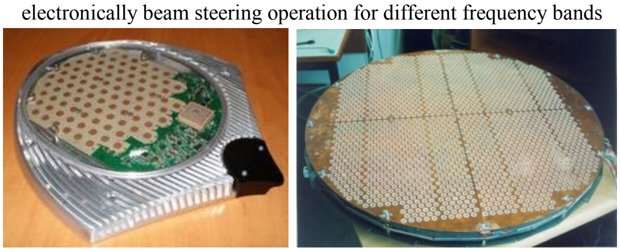


Fig. 15. Examples for two RaySat flat antenna arrays (T9, T2)

Table 2. Parameters of the T9 full electronically tunable antenna

General	
Function	Receive-only antenna
Frequency range	11.7 – 12.2 GHz
Overall terminal sizes	240 x 250 x 20 mm
Antenna weight	1.5 kg
Tracking speed	120 deg/s
Antenna Field of View	
General	
Azimuth	360 deg continuous
Elevation	30 – 90 deg
Antenna array panel parameters	
Antenna directivity at 11.95 GHz	24.8 dB at boresight 21.9 dB at 60 deg elevation
Side lobe level	< -14dB within the field of view
Cross-pol isolation	>18 dB within the field of view
G/T	0.9 dB/^{0}K at boresight; -3.2 dB/^{o}K at 60 deg. tilt

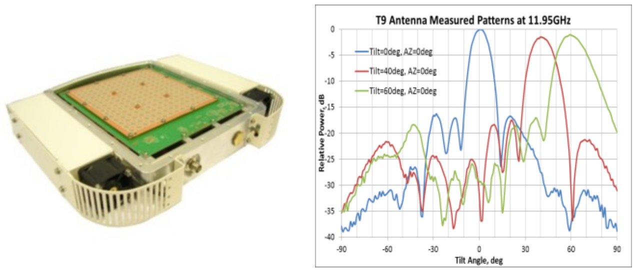


Fig.16 Tx Ku-band electronically steering prototype and its pattern

8. Conclusion

Different antenna technologies described above allow to provide mobile antenna terminal solutions, that could be optimal to various applications requiring low profile, high efficiency and affordable cost products. These applications can include also the communication with low earth orbit small satellite missions from fixed or mobile GS. All these solutions are successfully implemented in RaySat Company products, showing good performance and reliability.

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