SSC16-IX-08

A novel pedestal geometry – optimized for large diameter Ka-band antennas

Hubert Fröhlich, Tomaž Rodič
SPACE-SI, Slovenian Centre of Excellence for Space Sciences and Technologies
Aškerčeva 12, 1000 Ljubljana, Slovenia; +38612000444,
hubertf@space.si

Jeff Hertig, Paul Ward
Dynamic Antenna Systems Corporation
11165 Madrigal Street, San Diego CA 92129, USA

ABSTRACT

A very unique and efficient pedestal design, that has been optimized for tracking LEO satellites on frequencies up to and including Ka-band, is presented. It has a novel three axis geometry that not only provides for full hemispherical coverage but also assures that during tracking, the system never comes closer than 45 degrees to a keyhole. This results in the lowest possible axis speeds and accelerations while enabling the system to track the satellite very accurately. With the trending of the space industry towards big constellations of LEO satellites that produce huge amounts of data, Ka-band is gaining momentum. To serve large constellations of satellites we need significant contact time which translates into a large network of antennas distributed globally. Add to this requirement the low power capabitlities of small satellites and we end up with the demand for large dish diameters to provide an adequate link budget. With traditional pedestal geometries, the cost of a system to meet the demands for LEO Ka-band tracking with large dish diameters becomes prohibitively expensive. So one of the main goals, while designing the the antenna system around our novel predestal, was a minimum lifecycle cost.

INTRODUCTION

Companies have been making satellite tracking antennas for LEO satellites since the late 50’s and, except for the use of modern electronics, haven’t changed much. However, with recent changes in the small satellite industry [1] and the rapid growth of NewSpace economy [2-3] the requirements for the ground segment are changing too. As satellite constellations are trending towards a large number of small cost-efficient satellites producing huge amounts of data, the ground segment will have to follow with networks of cost-efficient, high availability, groundstations that will be able to provide enough contact time to download all the data. Considering the low power budgets of small satellites and the need to employ higher frequency bands, the requirements for NewSpace ground station will include large aperture, high precision tracking and an ability to operate at Ka/Ku-band. To move forward with larger apperture sizes for these frequencies the following problems need to be addressed:

- Large numbers of ground stations will require interoperability and central control;
- Faster relative angular velocities are needed to track lower and decaying orbits and present a unique challenge, near keyholes where axis velocities increase exponentially;
- Reduced beam widths of higher frequencies coupled with larger apertures require higher pointing accuracies;
- Smaller wavelengths require tighter requirements on reflector geometry as well as on deformation of the reflector caused by weight, wind loading and uneven thermal gradiants;
- Smaller wavelengths have an increased sensitivity to moisture and require much greater margins to compensate for its effects;
- Specialized custom components result in higher cost, longer MTTR and frequently, lower reliability;
- Complex multi-motor drive systems to control backlash result in higher complexity and cost while reducing reliability;
- Many customers locate antennas in areas which require protection of the antenna system from extreme environments;
- The high volume of small satellites and the corresponding demand for additional ground stations require that both initial cost and day-to-day operating costs be driven down.

Our goal was to design a positioner that supports complete interoperability, can maintain pointing accuracies suitable for Ka-band over a full range of motion while remaining scalable to support larger apertures of up to 10 m. Such a goal called for some basic design decisions:

- To build a system for use with or We had to keep the component count to a minimum. This not only reduces the original cost but also the life-cycle cost as well;

- We needed to support the highest level of integration possible;
- Components need to be readily available COTS components with multiple potential manufacture sources to the maximum extent possible;
- Components should be modular and interchangeable, avoiding “custom fit”;
- A full range three axis system is needed to avoid keyholes to the maximum extent possible;
- The use of a radome is needed to support all-weather use and to maintain dish geometry.

without a radome is usually a big decision, but not in this case. Along with recent revolutionary advances in radome technology, the advantages of not having to deal with wind loadings on large reflectors and environmental considerations while maintaining a high degree of pointing accuracy, far outweigh the minimal signal loss.

Recent study presented in [4] shows that the weather will, in any case, be a decisive factor when building a network of groundstations for Ka-band or above. The radome losses compared to losses resulting from bad weather are negligible on high frequencies. Thus, the main disadvantage of a radome does not significantly affect the system perfomance. But all the benefits of the radome are still present. Especially when the loss resulting from the use of a radome can be offset by substantially better pointing accuracies or simply the potential to use a larger aperture. Structures inside a radome only have to take into account gravity, axis accelerations, and harmonic frequencies when considering stiffness. A well balanced system allows a servo system to be tuned for accuracy, only having to compensate for varying gravitational effects. It also keeps the center of gravity over the center of rotation which helps keep the system orthogonal when small amounts of flexing do occur.

While keeping these goals in mind, the ground station needs to support state-of-the-art technologies and protocols to the maximum extent possible. Additionally, pedestal environmental control is required. By controlling the internal pedestal environment, uniform and predictable action can be assured while increasing the life expectancy of the components. This is more reliable and less expensive than regulating the complete environment inside of a radome. These design goals are of little value without a way to realize them. It took some significant new initiatives by Dynaso and Space-SI to do it:

- A new pedestal geometry which allows use of a single mode of operation while never approaching a keyhole to within 45 degrees, minimizing requirements for axis velocities and accelerations;
- A single motor zero-backlash gear reduction system which allows a single motor per axis to control each axis;
- Due to it's lean design it has to be protected by a radome. A special very low loss radome construction was developed;
- Ultra-high integration;
- State-of-the-art network communications.

Beside these innovations we considered how to improve the rest of the major groundstation components, namely servo drives, parabolic reflector, the feed, and, last but not least, the control software. The result is a completely new and innovative ground station that can handle the accuracies necessary for current as well as future needs in almost any weather conditions, and with the lowest possible life-cycle cost.

THE POSITIONER

First tracking antennas relied on Az-El geometry which has a keyhole in the zenith. This presented a problem for tracking a high elevation passes. In order to overcome this, new geometries were introduced. X-Y geometry moved the keyholes to the horizon and thus often had problems tracking at low elevations. X-Y over Azimuth is a geometry that acts as X-Y or Az-El depending on a pass geometry but adds a lot of complexity and cost to the system. Other geometries such as Az-El-Tilt or Az-El-crosslevel which enables the Az-El type of positioner to avoid the zenith keyhole, but only by af few degrees which is far from optimal and again adds a lot of complexity and cost to the system.

Our new antenna positioner geometry works like a two axis X/Y antenna with a Z axis for programmatically optimizing the X/Y geometry. The significant difference is that the X axis is tilted at a 45 degree angle from the horizontal. Thus the Y axis angle operates in a range between -45 to 45 degrees perpendicularly to the X axis. This results in the elevation angle transitioning from 90 degrees (the zenith) down to zero(the horizon) when the X axis angle is zero (see Fig. 1). This is not nearly as straight forward when the X angle deviates from zero and makes for some interesting math in resolving pointing angles [5]. The result is that the X-axis keyholes are 45 degrees below the horizon and 45 degrees past the zenith. This means that when tracking a satellite, the positioner never gets within 45 degrees of a keyhole.

Since the velocities increase exponentially as a keyhole is approached, this results in significantly lower axial maximum velocities.

For normal polar or weather satellites, this translates to a typical maximum axis velocity of under 0.7 degrees per second. For a CubeSat about to re-enter the atmosphere it can be as high as 1.2 degrees/second. To put it another way, in the worst case situation while tracking a typical LEO satellite, the X-axis will accelerate from 0 to 0.7 degrees per second and back again over a period of more than 10 minutes. These very low velocities and associated accelerations virtually eliminate the need to consider dynamic effects, allowing the servo loops to be finely tuned for very high accuracy and precision. As velocities are reduced, even time precision becomes slightly less important. This results in a big advantage if TLE's ever become "stale", because time is normally the parameter that drifts the most as TLE data becomes old. As an added advantage, the new geometry is structurally very "stiff". It has very little counter levered mass resulting in a stiffness approaching that of a classical AZ/EL design. Add the high use of Carbon fibre, which is over twice as stiff as aluminum by volume and the result is a very stiff design.

The third major advantage of this design is that, by using the Z axis, it keeps the Y displacement at a minimum angle, i.e. as orthogonal as possible, which minimizes axis velocities and maximizes the effectiveness of auto-track. In our system, these auto-track vectors are always applied to just the X and Y axis. The Azimuth angle is always controlled programmatically based on the orbit of the satellite with the objective of minimizing the Y angle. In addition, the pointing accurcies of this design are so precise that collected error data during auto-track can be used to propagate the TLE's for times where updates are unavailable.

ZERO BACKLASH GEAR REDUCTION

Backlash is a major problem for tracking antennas when using gear reduction and causes havoc on servo loops. This is usually handled by the use of two motors that apply a "bias" to the movement to keep the pinion gears tight on the spur gear. Although commonly used, this is a very problematic solution since it not only doubles the hardware and communications used to drive each axis but also produces a control "nightmare" over varying velocities with high gear ratios. This is because the required load to back-drive a gear system varies greatly as velocity changes.

This is to such a degree that bias-drive and high gear ratios can be safely considered mutually exclusive. The concept seems simple but in practice, the cost and reduced reliability of such systems always has a major impact on performance, mean-time-between-failure, and life-cycle cost of a ground station. For this reason we decided to develop an alternative to the dual motor system.

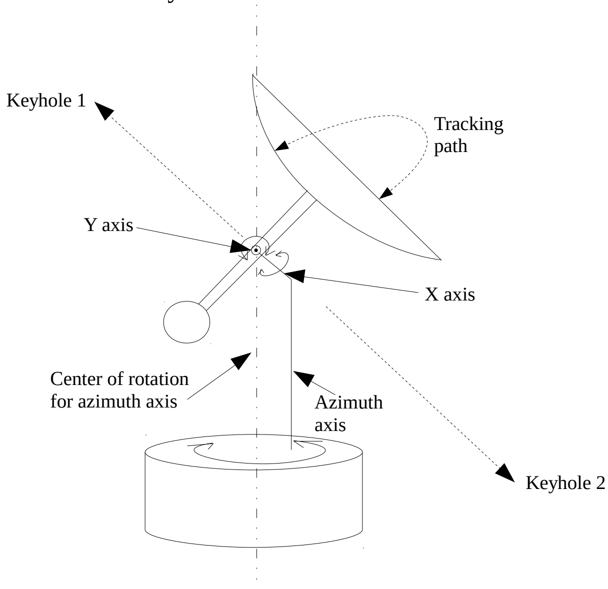

Figure 1: New pedestal geometry shown with both keyholes. The geometry assuress that each point of the tracking path is at least 45 degrees away from the keyhole.

High gear reduction is desirable because drive and measurement errors on the input are divided by the gear ratio. This enables very high precision and control on the output shaft. Classical direct and belt drive systems with zero backlash exist but cannot yield the very high gear ratios and resulting precision.

Our solution is to cascade two different drive systems into each other. The final drive is a zero-backlash worm gear. These drives have the great advantage of not only being zero-backlash but providing a self-contained bearing and perform an axis translation all in one package. The big disadvantage of worm gears is that they yield low efficiency and require a high static load to turn. To solve this issue, we first use a harmonic drive system. These drive systems turn the high velocity output from the motors into the high torque needed to drive the worm gears. This cascading of drive systems results in high gear ratio with outstanding control, with insignificant backlash and with the fewest number of moving components. It must be remembered that the reason for our very high gear reduction is not for high drive torque but for very fine motion control and measurement. The precision of the motor shaft encoder is essentially multiplied by the gear ratio and any errors in positioning are divided by it. By using this system, we can achieve levels of accuracy and precision that are not achievable by using direct drive or belt drive systems. And because it is a single motor system, the high gear ratio does not result in the control problems that would normally plague a bias drive system.

RADOME

The use of radomes is often a controversial issue. The G/T value obtainable by an outdoor antenna on a clear, cold, calm day under perfect conditions will be greater than the same antenna in a radome. No amount of "tuning" can prevent some loss by a radome. But most users want to use their antennas in less than perfect weather. It is the typical or even the worst case performance with which they are concerned, not the optimal.

By far, the biggest problem using an antenna without a radome is that of wind loading. A dish has a very large "sail" area and it travels through quite a few orientations with respect to the prevailing winds during a satellite pass. The dynamics of wind gusts play havoc on the servo loops and support structures while trying to maintain very precise pointing. Other concerns are the ice and snow as well as the thermal effects of direct sunlight which cause unequal heating and expansion along with feed and RF issues.

By comparison, an antenna designed without concern for wind or ice loading and with the only concern being gravitation, can be very lightweight. Such an antenna may look frail by comparison but with the use of high precision bearings and when tuned for accuracy, it is not only much less expensive to build with a much lower life-cycle-cost but also can easily outperform its more robust, "clunky" counterparts. While classical radomes make very poor thermal insulators they do allow for some control of temperature and humidity and thus provide protection of components, resulting in longer life.

However, we have developed an inovative radome design, that is currently under full operational test and is quite different from classical radomes. It is designed of specially selected materials where the walls are constructed as a double, thin-wall, membrane with air pockets between the layers. This gives the radome much better insulation properties and since the signal only travels through two very thin layers of material with very low electric permitivity, the signal loss is below 0.2 dB at frquencies through 40GHz. Actual measurements of sample material on X-band showed loss of 0.05 to 0.15 dB in the frequency range from 7.8 GHz to 8.4GHz . Another big advantage of such a uniquely constructed radome is that there is no need for frequency tuning of the wall thickness. It will work up to 40 GHz without tuning. Being flexible, one might think it is prone to colapse under wind. However, extensive testing of similar structures, which have been installed around the world, have proved them to withstand winds up to 250 km/h without any structural damage.

Figure 2: Innovative two-layer thin membrane radome on test location.

HIGH GEAR RATIOS

The Dynaso-Space-SI antenna uses high gear ratios (6800:1 in the case of the Azimuth) to achieve the required precision. This means that a small angular displacement error on the motor shaft is insignificant on the output axis. Because Servo systems and DC brushless motors are easier to control with appreciable motion, even at the very low axis velocities, our antenna employs motors such that they can maintain a "stable" rotational velocity.

BALANCED ANTENNA

High gear ratios also mean available high torque output. Thus, balancing the antenna is not that important from the perspective of being able to point it. However, balance is still important for the structural stiffness of the antenna. With such high demands on pointing accuracy, it is important that any elastic deformation of the structure that may exist, be held to a minimum and that it be quantifiable. Any amount of displacement is undesirable but, no matter how stiff, all things deform under load. By balancing the antenna, the load is kept centered around the center of rotation and thus helps to keep it orthogonal throughout its range of motion. Without compensating, any amount of deformation will create a pointing error and hence must be minimized by building a light and stiff antenna with minimal external effects.

HIGHLY INTEGRATED BRUSHLESS MOTORS

Normally, each axis on an antenna positioner requires switches, digital I/O control and monitoring devices, encoders, decoders, servo amplifiers, communications devices and all the wiring associated with them. For protection, servo amplifiers are usually located inside the antenna control unit (ACU) which greatly increases the wiring. In our antenna, highly integrated motors, which contain almost all of those requirements are in a single device. Not only do they provide a strong brushless DC motor but also they provide a very integrated control system complete with digital I/O, encoder, servo system, servo amplifier and communications device. Only the external switches remain and thus the use of these motors reduces the electronic requirement for each axis to a single motor, three switches and the necessary wiring to support them. Communication and power to the motor is done with a single RS485 connection and a power cable. Such a low wiring and component count has a major effect on reliability and life-cycle cost.

The integrated servo motors run an 8KHz PID servo loop with optional Velocity Feed Forward, maximum acceleration and target velocity inputs. This offers a level of control that can't be approached using external servo amplifiers. With a 40 Hz position update rate and at maximum tracking velocities, this could mean as much as 0.015 degrees of movement between position updates but as accelerations are held at such low values, the high Velocity Feed Forward and Integral terms can be used in the PID to maintain a much better accuracy. This is something that a positioner, which doesn't have such low dynamics, cannot claim. The motors are equipped with a multi-turn shaft encoder, with essentially 14 bit resolution, equating to a precision in azimuth of 0.000005 degrees per count and similar for the X and Y axis which is far more than is needed.

INTERNAL PEDESTAL ENVIRONMENTAL CONTROL

While radomes offer the ability to control the environment, especially ours, it is often impractical to control it well enough or uniformly enough to maintain precise control throughout the whole volume. Nor does radome environmental control guarantee keeping electronics, grease, and bearings within operating temperature ranges in extreme cases. To alleviate this problem, a positive pressure airflow system was built into the positioner where air is injected into the base of the pedestal and flows through the electronics before being directed up through the pedestal to escape around the gear boxes and motors. This makes it possible to ensure that all components are kept within specified temperature ranges. It also regulates thermal expansion of structural parts between axes to minimal levels. It should be noted that for medium and larger aperture antennas, we can build a 19" rack into the base of the antenna where the ACU, signal distribution unit (SDU) and support equipment can be located. This rack provides additional environmentally controlled space for redundant ACU and/or customer equipment. It is anticipated that many customers will locate receivers or transmitters in this space to avoid transmitting RF data through cables for long distances. Even in the harshest of environments, when the radome is kept at or above -20C, commercial grade equipment can reliably operate in this rack.

USE OF COMPOSITES AND OTHER LIGHTWEIGHT MATERIALS

Space-SI is employing carbon composites in their reflectors and reflector support structure. Carbon composites offer a great stiffness/weight ratio which is necessary to reduce deformation due to gravitational effects and for which are extremely hard to compensate during tracking. As deformation of the reflector can have devastating results, initially, the reflector was built from carbon composite structure.

USE OF MOTOR SHAFT ENCODERS INSTEAD OF AXIS SHAFT ENCODERS

It was previously mentioned that the encoders being used are integrated into the motors. This is actually a beneficial coincidence of the highly integrated motors but was also a design objective from the beginning. The typical approach of locating the encoders on the axis shaft of the antenna seems to make sense since as that is what you are trying to measure. However, the problem is, that in all cases, it eventually causes issues. Even with a system that is supposed to have zero-backlash in the gear system, in reality, they still have a certain amount of torsional or structural "flexing" which results in a discontinuity in the servo-loops. As systems age, this has been known to cause serious issues. Of course the other thing, that is supported by the theory, is that the precision of the motor shaft encoder is multiplied by the reduction rate. By using a multiturn motor shaft encoder you can get greater accuracy than by using a very expensive shaft encoder with more bits of resolution.

CNC FINAL MACHINING

Most antennas are designed and built on a limited production run with the final components being put together, aligned and tested at the factory or on a range. The components are then disassembled and shipped to the customer site for re-assembly. Once re-assembled at the customer site alignment must be re-done. And if for some reason, parts must be swapped, all bets are off at how good the final performance will be. This is because the parts are manufactured and "tuned" to work together. Space-SI takes another approach. We build all our parts and then use a CNC machine to do final cutting of mating surfaces with interlocking joints or pins so there is no possible movement between pieces. All pieces are machined to the highest tolerances and are interchangeable between antennas. When a Dynaso-Space-SI antenna is assembled in the factory it can be tested and the orientation aligned. When it is then taken apart, shipped and reassembled, it only needs to be realigned to its new orientation. The antennas only go together one way with each section "locking" into the previous one. The bolts only hold pieces together as the construction assures the exact, repeatable alignment each and every time. The prototype pedestal is shown in Fig. 3.

MINIMIZING COMPONENT COUNT

To design a cost effective reliable system, the strategy of keeping the component count as low as possible was employed. Although some of these components are initially costly, the lifecycle is quite low. For example, the cost of the motors seems a bit high. But realizing the amount of hardware, cabling and assembly that a single motor eliminates, brings the overal cost down significantly. The positioner is really only made up of its structure, three sets of worm gears, harmonic drives, motors, and switches, the SDU, the ACU, and a few cables and wires. The ACU is actually just a ruggedized rack-mounted PC and the SDU a few power supplies, network controller, USB or network to serial hub. Add to that a radome, reflector feed, LNB, receiver, router, GPS, camera system and you have a complete ground station.

We prefer to use the Space-SI high quality auto-tracking feed but we can install any RF system desired by a customer. With the Space-SI feed, all we need to receive and process tracking vectors is a serial port and cable which is already available through our SDU. No other RF connection is necessary, eliminating the need for additional components. We use COTS components whererever possible and can even provide a Bill Of Material for users so they can buy their own spare parts should they decide to do so.

Figure 3: Antenna positioner during installation.

Even the ACU which is a ruggedized PC, could be replaced with any rack mounted PC with at least modest performance and two separate drives. The provided software installation disk will install the LINUX OS, ACU code and configure the system on any such PC.

USE OF OPEN SOURCE SOFTWARE, WHENEVER POSSIBLE

The software itself is designed to use "Open source" software whenever possible. It runs on CentOS, a Red Hat derivative that it is readily available from the Net. The Web server used is Mongrel 2 and is also readily available. A number of other key component libraries like Sqlite3, Jansson, Zeromq, Boost, and WebSocketpp are all open source libraries, but the critical parts of the code are proprietary. However, API's have been released enabling complete interoperability with the code.

MAXIMIZE THE USE OF SOFTWARE vs HARDWARE

Software is flexible while hardware is not. And hardware to run the software gets cheaper by the day. Therefore, it has been our philosophy to do anything and everything possible in software to make hardware easier. Nowhere is this philosophy demonstrated more than in the use of the “Slant-X” design of the positioner. This may make the hardware motion more straight forward but the axis translations are much more complex to say the least. The software in general is written as a group of shared libraries and five separate applications which can reside on multiple hardware platforms, if necessary.

DESIGNED FOR INTEROPERABILITY

Sometimes a single antenna might be used for tracking satellites by a customer; however, there are efforts being made to use an array of antennas to track satellites, all controlled by a single application. Our scheduling application can support such functionality but frequently a customer will want to use their own software to manage multiple antennas. As no dominant standard has been developed, in cases like this, a third-party driver will need to be written to talk to the antenna. To facilitate this an Application Program Interface (API) has been published describing how to communicate with the antenna control software.

CONCLUSION

We have developed an innovative antenna positioner by redesigning all of the crucial parts with a clear goal to make it future proof, flexible, easy to install and inexpensive to maintain. The ground station built around our positioner can be used autonomously or intergrated in any existing network through our published API. The positioner is designed from the ground up to achieve very high accuracy in a cost efficient way. It is designed to maximize operational availability with an extremely high MTBF and have the lowest possible MTTR. This was achieved by use of a modular design and extremely low component count. Use of COTS components means that a complete set of spares can be obtained for minimal cost.

REFERECES

[1] N.H. Crisp, K. Smith, P. Hollingsworth, *Launch and deployment of distributed small satellite systems,* Acta Astronautica, vol 114, pp. 65-78, 2015

[2] B. Holz, *OneWeb Satellites – a new approach to satellite production*, Proceedings of Small Satellite Systems & Service Symposium 2016, Valletta, Malta

[3] R. Horn, N. Frischauf, I. Baumann, O. Heinrich, *NewSpace – New Business Models at the Interface of Space industry and Digital Economy*, SpaceTec Partners, Report for the German Government, May 2016

[4] P. Hyvönen, *Operations of Optical Ground Networks for Small Satellites*, Proceedings of Small Satellite Systems & Service Symposium 2016, Valletta, Malta

[5] J.B. Kuipers, *Quaternions and rotation sequences*, Princeton University Press, ISBN 0-691-05872-5, 1999