Open Research Institute

Minimum Viable Product

Amateur Radio Satellite Service

9 July 2021 (JAK, MDT, AM)

Battle of Jericho by Julius Schnoor von Carolsfeld (1794–1872)

Introduction

The Amateur Radio Satellite Service is non-profit, profoundly amateur (in the most positive sense of the word), and highly experimental in nature. It was the high-risk non-commercial work of the amateur satellite community which enabled the SmallSat and CubeSat revolution. And, in like manner, it can be the high-risk non-commercial work of the amateur satellite community that can contribute in significant, systematic ways with respect to Debris Mitigation and Remediation.

High-risk non-commercial and experimental work needs to be protected from inadvertent regulatory destruction in order to fulfill this promise. High-risk non-commercial activities will not thrive if exempted to death. Amateur activity in particular cannot be left to rot in single-payload LEO orbits that do not serve the entirety of the global amateur community.

This does not mean that single-payload LEO missions are bad or should not be done. Such missions have high educational value and benefit a significant part of the community. However, a regulatory framework which assumes simple LEO missions are all that amateur radio does or wants to do will not result in long-term success for the service. In particular, long-range international communication as envisioned by many members of the Amateur Radio Satellite Service is simply not practical by means of 500-600 km altitude circular-orbit communications satellites.

This presentation outlines a Minimum Viable Product (MVP) approach. Open Research Institute, Inc. believes that the Amateur Radio Satellite Service must achieve this minimum level of service to the community in order to participate in the “New Space Age.”

The MVP approach provides value by delivering minimal features that early adopters will use. Better communications services and superior user experience follow because real-world feedback from real-world operators is collected without excessive delay. MVP does not repeat previous work, although it builds upon the significant foundation of work done internationally within the ARSS. MVP delivers features and services that were not previously provided, as simply and quickly as possible. This gives the best possible chance for innovation in high-risk environments.

The innovative process in amateur radio has shifted from the personal development of relatively large and power-intensive antennas and radio systems, to smaller, higher-precision antenna pointing systems and radio systems. These modern amateur systems are most often derived from technologies originally intended for GSO-FSS and 4 and 5 G cellular markets. They are modified to meet the needs of the ARSS.

We emphasize that this kind of contribution, as a significant portion of the Amateur Radio Service, will continue to provide the same positive benefits to the public as they have since the beginning of the radio era. Amateur satellite operators are continuing to innovate and demonstrate ever-newer technologies. This innovation is by private citizens who have keen interest and active curiosity. They want to know, “How does it all work, anyway?”

The Situation With “Shells”: How a Change in the FCC “Mandate” Changed Frequency Management

The United States Federal Communications Commission (FCC) has licensed at least 13 different entities that all have the goal of deploying large commercial constellations in space. Operating within the FSS and MSS services, the number of NGSO spacecraft from these various entities could exceed 100,000. The original target orbits were 800 - 1200 km in altitude, but almost all of these constellations have modified their plans and moved down to lower altitude orbits.

These moves are to increase capacity, not for visibility (communications range of individual satellites). System liability is lower because at a lower altitude spacecraft can be removed from orbit more easily and quickly.

What has developed in this era of the “New Space Race'' is a proprietary approach to orbital altitudes. “Shells'' around the earth are created by taking all points at a specific altitude and treating that spherical layer of space as if it was owned. These layers are populated by a constellation. The constellation owner does not want to share their shell with others. The constellation owner does not want their shell crossed by others. These shells are like spectrum allocations or analogously, leased real estate. The concept of constellations “owning orbits” is now largely codified in FCC regulatory framework. This is ironically, not by virtue of the FCC’s authority to regulate just spectrum, but by the added authority to regulate debris mitigation, coupled with their power to manage the spectrum. This has been born out by applications put out for Public Notice. Commenters have, on numerous occasions, combined spectrum issues with debris mitigation issues in such a manner as to reinforce the notion of shells defended by commercial applicants.[1]

There are some useful similarities between treating orbits in space as if they were spectrum to be licensed. However, there are some stark and inescapable differences. Spectrum can, on relatively short notice, be re-used if the allocation is expanded or changed. Orbital shells in space are much more like real estate development and code enforcement. Once built out, the land cannot be instantly re-used. It takes some amount of time, which can be many years, to make a change in space. If orbital debris becomes excessive, in some simulations the models show that we can be denied access to space for a very long time, indeed. Most importantly, the LEO orbital resource is not just to be shared by FSS/MSS/BSS NGSO operators but by many other space services as well, and one of those is the ARSS. It is patently unfair for commercial operators to occupy shells in any sort of uncontested way, just because they are revenue-earning entities. The Commission has long recognized that there are many more services which make up the whole of the Public Interest. These services should have access to this “shell game” on the same equal basis as spectrum-managed “categories of service.”

These shells should not be specific to any particular category of service.

A conservative approach to space with sustainability as a goal would require all spacecraft missions to be as short as possible and demand inactive spacecraft be deorbited as soon as possible. This is the stated goal of Debris Mitigation. “Short as possible” also improves access and increases innovation because new spacecraft can be deployed more quickly into previously occupied shells.

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[1] JFCC IB Notice 18-313, Mitigation of Orbit Debris in the New Space Age, Reply Comments of Iridium Communications, Inc., pp 4-5. filed April 16, 2020

We assume that large commercial constellations will continue to be deployed. We assume large commercial constellations will "own" shells of altitude and those shells will be protected under regulatory frameworks. We assume Debris Mitigation rules will be applied to almost all missions. We assume there will be some exemption for government, experimental, amateur, and educational missions. We assume the exemptions will apply primarily to LEO, and that the missions will be either single payload or very small constellations or perhaps less formal formations.

Useful LEO orbits, regardless of inclination, range in altitude from 400 km to 1200 km. Above this altitude, long lived LEO missions encounter significant radiation damage issues and the delta-V required of on-board propulsion systems for de-orbit become more problematic. As will be explained in more detail below, for the MVP the perigee of any Amateur Radio Satellite Service payload with an elliptical orbit needs to be above the highest dense NGSO commercial shell. That number is approximately 1250 km. Following this procedure assures that an ARSS spacecraft will not intersect or pass through the shells of commercial NGSO operators or the lower altitude orbits of manned space flight missions.

Amateur missions should keep perigee above 1250 km.

The Situation With Launches: The ARSS has Requirements and Means that Vary from Other Users/Operators in the Small Satellite Community

For LEO

Amatuer Radio Satellites using LEO orbit were once the "King of the Small Satellite world" but now compete for increasingly desirable orbit space. For all small satellite systems there are now fairly regular opportunities to launch to orbits from 400-600 km altitude and most of these opportunities are to sun-synchronous orbits (SSOs). We believe we can continue to favorably compete for these launch opportunites and that ARSS missions should comply with the debris mitigation procedures now being adopted by the Commission. We acknowledge that higher altitude LEO missions may require some form of ΔV, whether that is provided by a small propulsion system or by some form of drag modification device on-board the satellite. If ARSS missions are low enough in altitude, then they may re-enter within a few years (we argue a 6-year lifetime for an ARSS mission could be quite acceptable)

For HEO

For the MVP, we value highly eccentric orbits with perigees above 1250 km as a quality approach to long-range communications services (both experimental and quasi-operational) for the ARSS.

A geosynchronous transfer orbit or geostationary transfer orbit (GTO) is the best way to get to this orbit.

Secondary payload opportunities to GTO are currently reasonably available to the small satellite community and are price competitive with LEO mission secondary payload space. GTO missions are available via multiple launch vehicle companies from several countries. Hence, such missions are not currently cost prohibitive for our very cost-constrained user base. HEO missions using GTO starter orbits have been a primary focus of the non-profit organization AMSAT, who has launched four (4) modified GTO orbit spacecraft during the period 1980-2005. AMSAT has been an international organization in which up to 14 countries have cooperated in the design and development of these HEO mission spacecraft. Three of these satellites provided long distance communications services in the amateur bands from 145 MHz to 24 GHz during the entire period from 1983 – 2006.

ARSS pioneered the use of this orbit class. The only other space systems to use this orbit class operationally, were the Russian Molniya class FSS/MSS spacecraft. It is worth noting here that these AMSAT HEO spacecraft utilized bipropellant kick motors capable of producing more than 1500 m/sec of ΔV. In particular, the mission AMSAT-OSCAR-13 executed it's two-burn orbit transition flawlessly after producing 1589 m/sec of ΔV.

Burn #1 delta-V: 275.7 m/s

Burn #2 delta-V: 1313.6 m/s

TOTAL delta-V: 1589.3 m/s

See Technical Addendum 1 for a summary of AO-13 400N Motor Performance. This is the largest delta-V produced by any small satellite (commercial or amateur) by a very large margin. See results of 2nd burn for accuracy of 2nd burn and a comparison to NORAD's orbit determination (via TLEs).

MVP orbits, as we are defining them here, do have some additional requirements in order to satisfy the spirit of the debris mitigation requirements for all satellites. These can be summarized here:

MVP missions with limited propulsion systems ($\Delta V \approx$ 100-150 m/sec) are anticipated to be used to modify the initial GTO in three ways:

a) ΔV will be applied by the spacecraft at apogee (35,800 km) in order to increase the perigee of the orbit to 1250 km or slightly higher. Details of this requirement are provided in Technical Addendum 3.

b) The MVP orbits, even at 1250 km perigee altitude, are mathematically characterized as "chaotic" with respect to their orbital elements and require occasional ΔV as a means of ***maintaining*** their perigee altitude at 1250 km. The details of this requirement are also provided in Technical Addendum 3: Nominal Sequence of Orbit Modifications for an Operational ARSS Sustainable Mission with a [6-year] Lifetime.

c) MVP mision satellites must be removed from orbit at the end of their useful missions and the maneuver required to do this will be planned to de-orbit the spacecraft either during a single perigee passage after the re-entry burn (applied at apogee) or within two or three orbits at most. Once again the details of the typical ΔV required to remove the satellite from orbit are given in Technical Addendum 3.

NGSO-FSS/MSS/IoT LEO constellations provide communications services for humans and things (IoT). The use case is, fundamentally, global Internet access. Will these constellations do more over time than provide internet access? In other words, will the demand for GEO missions slowly go away based on market force adjustments? If there is a large reduction in GEO missions, then the MVP launch assumption that "GTO launches will continue to be available" falls into doubt. While this could occur over time, the GSO asset base is 180 spacecraft (assuming 2 degree orbit spacing) times the number of frequency bands in use for these services. While we foresee that many MSS markets and some FSS GSO markets could fall prey to the NGSO market evolution, we believe that high speed data services and broadcasting services, that are fully entrenched within the GSO market now, will assure a reasonable flow of launches to GTO into the foreseeable future. Each of the launches of these individual spacecraft potentially has sufficient excess payload capacity to support ARSS small satellite launch needs.

An alternative source of launches to GTO potentially exists and is currently emergent. Small launch vehicles capable of launching a dedicated small satellite to LEO are now a reality. The best example of such a capability is the Rocket Labs Electron launch vehicle; a US/New Zealand corporate partnership. Other companies, operating globally, are fully expected to complete their L/V technical developments within the next few years. What is even more contemporary, is the technology being developed by these launch vehicle companies, which utilizes restartable upper stage capabilities to take reasonable payload masses (10-50 Kg) to HEO orbits. Thus, "payloads" may then be separated from these "tug" vehicles or the stage may continue to be operated as a stand-alone spacecraft.[2] In the latter case, the on-board payloads could be thought of as host payloads. The cost of such payload opportunities are envisioned to

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[2] Rocket Labs Electron launch vehicle will shortly have a "tug" upper stage (called Photon) that can deliver small payloads to higher orbits or act as an ultimate spacecraft in its own right. Momentus, Inc. and SpaceFlight, Inc. are both finalizing similar upper stages that may even be used on multiple launch vehicles, but certainly they will be carried on the Space-X Falcon-9 rocket.

be in the $0.5M to $5.0M class, depending on the SwaP of each payload. This scenario places such an opportunity within the reach of an MSV ARSS provider organization.

If it is assumed three to six Amateur Radio Satellite Service payloads spaced apart in a useful manner constitute an ARSS constellation, then such a system can provide global coverage and can support links as long as 164 degrees of great circle distance. For example, three payloads at 120 degrees spacing in longitude of Right Ascension of Ascending Nodes (RAAN) will provide global longitudinal coverage. If within each plane there are two satellites (spaced 180 in Mean Anomaly (MA)) then global coverage occurs also in latitude (except at the poles), given the initial orbit inclinations typically achieved by GTO launches. For a sustainable system, with minimum three to five year payload lifetimes, and $350,000 to $500,000 per launch (here a 6U CubeSat mass of 10-11 Kg is assumed), at one launch per year, with donated labor and grant-funded hardware, we can calculate the annual cost expectations.

<u>For GEO</u>

For GEO MVP missions, “Direct To Graveyard” debris disposal is a proposed strategy.
See Technical Addendum 2: Direct-to-Graveyard Orbit Study for details on achieving this orbit.
This strategy dramatically reduces the risk of creating Debris in GEO and allows testing of open source propulsion techniques that cannot yet comply with GEO slot requirements. The ΔV requirements for GEO removal to their graveyard orbits is well known and, it is clear that ARSS operators would have to comply with this FCC orbit disposal requirement. We note that the most likely means for ARSS systems to utilize the GEO orbit is by becoming a “hosted payload” on a regularly scheduled and licensed mission. Thus, the debris associated with an ARSS payload would be a small portion of the responsibility of the GEO operator of that satellite.

GEO hosted and secondary payloads should be pursued whenever the opportunity is offered or developed, however we understand this almost always will result in amatuer spacecraft volunteers being left out of most of the integration and development due to insurance risks and other logistical reasons. Having a commercial solution in space is part of the mix, but we should not fall back to this being the primary way the amateur satellite service survives.

The Situation With Communications Technology

Microwave, digital, broad-band, multi-user, and open source are the MVP requirements for the communications payload.

The system must fail gracefully, and not be rendered inoperable in the event of an in-orbit hardware failure. Standard modern failure mitigation techniques are required for such systems. We assume there will be a non-commercial version of a service agreement present so that users of the MSV system can “count on'' such a service. Indeed, if the ARSS is to fulfill any of its emergency service directives, the service must not only be accessible but also must be available using portable equipment Earth stations and during times of disaster or during emergency conditions. Capacity targets for MVP transponders will range from 100-1000 simultaneous users per payload, with each user sourcing from 5,000 to 50,000 bps. These are sustainable and realistic technology goals for the communications payload.

Source for a detailed link budget can be found in Technical Addendum 4: Link Budget Showing Typical Capacity of a 6U GTO Orbit using mmW Spectrum. This link budget shows a link budget using mmW technology and demonstrates that such systems are well within reach.

DVB-S2 and DVB-S2X for the downlink, separated by coding to eliminate interference, is the technology roadmap for Open Research Institute. This roadmap, of using DVB-S2/S2X/T2, has been widely adopted across amatuer radio. Uplinks for Open Research Institute are generally FDMA 4-ary MSK digital signals and include the open source M17 Project protocol. The payload can accommodate legacy amateur analog modes with a configurable polyphase filter bank and the regenerative capabilities of the digital multiplex transponder. Channels are digital pipes. Any mode can be supported, from keyboard to video, because these choices are made at the application layer as an interface provided by the user equipment on the ground. For example, an embedded device running a web browser.

In the amateur service, to date, most of the space segment systems have used linear analog transponders using the amateur 144-146, 435-438, 1260-1270 and 2400-2417 MHz frequency bands. The transponders have been linear (bent pipe) systems and narrowband methods such as A1-CW (Morse Code), A3J-SSB and various narrowband FSK modes have been used. Some hard-limiting demod/remod transponders have been employed to relay traditional narrowband FM (NBFM) signals for specialized missions. Multiplexing has been largely single channel per carrier (SCPC) or equivalent and the ARSS does not typically employ full duplex links, hence there is no formal forward and return spectrum separately used. Rather, half-duplex methods have routinely been employed. The “over” method of swapping emitters is still held sacred by many radio amateurs, even when space technology is involved.

But, in the New Space Age, while Morse Code via Satellite will still exist for some users, big transitions are happening. In this new age, small 6U-class CubeSats can provide multiple Mbps of capacity at GEO altitudes (yes, with 41,000 km link connections) but, only if the ARSS also operates at or near the state-of-the art and if we use, to good measure, the millimeter wave (mmW) bands, which we have been given to use as a public trust. Indeed, it can be put much more definitely: We can only make the MVP architecture work IF we use our mmW bands and use them effectively. These bands are enabling the future of the ARSS. And, we know it.

We can describe and even demonstrate by analysis how this can be done. The primary advantage of using a modern capable standard like DVB-S2(X) is that it performs essentially at the Shannon Limit. As there are no forward and return links used in the ARSS, we only need to support all simultaneous uplink users (transmitting within a single band) and then re-transmit those users on a single downlink.

The uplink problem is much harder as these users are fully uncoordinated. However, multiple solutions exist. It is possible to use a relatively narrow band version of DVB-S2(X)[3] and assign frequency division multiple access (FDMA) channels to each user. This would be accomplished using demand assignment methods (DAMA) similar to those used by existing mobile satellite systems like Inmarsat. Alternatively, one single wideband channel could be used and Code Division Multiple Access (CDMA) methods could be used to allow the users to be separated by Gold Coding or even Walsh codes. Various other TDMA/FDMA/CDMA methods exist. The paramount operating condition is that the uplinking users need to use a form of high performance forward error correction (FEC) coding, such as the double coding method used in DVB-S2(X). This will reduce the RF power level of the individual uplinking user to a very small value (approximately 2-3 watts).

The Situation with Debris: We Assume the FCC has the Lead; We Believe the FCC is NOT the Only Interested U.S.Federal Agency; We Don't Know What the ITU's Role Will Be

Dealing with Debris MItigation rules means being able to modify an orbit. And, there are two known ways to modify an orbit:

1) Utilize Propulsion, or

2) Utilize a means or drag modification (temporary or permanent) .

Both ways require 3-axis attitude control. It is possible to implement a permanent drag increasing device (such as a tether or small inflatable device (balloon) which does not require attitude control in order for the device to function, but we do not recommend it.

Precise attitude control is non-trivial. Applying ΔV in a directive manner to raise or adjust orbits on short notice, essentially requires a 3 axis attitude control system, although a single axis "spinner" system would be viable. We have seen amateur spacecraft (such as AMSAT-OSCAR-13 (using "spinner technology") flawlessly execute a 2-burn modification of a GTO orbit and control it's attitude during its entire 8 year lifetime. We have also seen both amateur and "professional" payloads fail to properly implement attitude control. However, time is once again changing the "technology game" in which the Amateur Satellite Service is participating. Very small reaction wheels (e.g., having total angular momentum storage as small as 30 mNsec) and small star trackers with 10's of arc-sec pointing accuracy are now common-place technology on small space missions. Even with this degree of evolution, however, the cost of these components for amateur radio satellites is constraining, if not prohibitive. Indeed,

[3] We note that the terminology, DVB-S2(X) implies the use of both standards DVB-S2 and DVB-S2X in combination; in particular the MODCOD steps of both can be incorporated into the flight FPGA code employed.

the cost of the propulsion system must be added to the cost of the ACS components. However, the ACS components dominate the budget of small space systems, both commercial and amateur. We acknowledge that a 3 axis ACS system is essential if we are to achieve the benefits of directive antennas needed to achieve the promises of high speed mmW communications. Hence, the ACS tasks associated with the communications system are equally demanding to those required to execute precision motor burns and so the ACS software tasks are not solely driven by the debris mitigation requirements of our space systems. This is true for orbit raising/lowering events as well as responding to conjunction notices that may be received by amateur radio spacecraft operators. We do believe it is important to make this point. Simpler attitude control means were acceptable for amateur satellites used in earlier times as a means to start the service, however, those days have changed for our service as much as it has for the industry, in general. We would note that amateur satellites have been using active propulsion systems (with very significant ΔV) since the early 1980s. So, propulsion systems are not a novel concept to the small satellite world, and particularly not so to the amateur satellite community.

Therefore, active propulsion and relatively precise attitude control technologies are required components for the MVP. We further would expect to be required to control debris from amateur radio satellites, to the extent that there is any uncertainty that they will decay and be removed from orbit by natural drag effects within a reasonable performance lifetime (5 to 6 years in our estimation). For spacecraft in HEO orbit, we believe it is reasonable to be able to respond to conjunction warning events as are routinely issued by CSpOC, however, we certainly expect the issuance of such notices to be very infrequent, given our strategy for avoiding the LEO shells now being created by the NGSO-FSS and NGSO-MSS operators.

Conclusion

We radio amateurs have been given a special blessing. For the cost of passing a relatively straight-forward technical examination, we are allowed to experience the many wonders (and they are true wonders) of the radio world. Citizens from hundreds of countries around the world, in this manner and by their administrations, are allowed to share in this special opportunity. We, non-profit radio operators have a place to experiment and marvel at the physics of the electro-magnetic spectrum. Among those privileges is the opportunity to use radio systems in space and such “space stations” have always been built with our own hands. But, we *know* that we are fortunate and we respect the rights and the responsibilities that come with this participation. We, the amateur radio community, know and abide by the radio regulations adopted by the United Nations, via the International Telecommunications Union (ITU) in a way that no other citizens do. Virtually all radio amateurs know and understand the most important portions of the ITU Radio Regulations. Most citizens of the world have never even heard of the ITU. We radio amateurs can still in the 2020s, spread the message of spectrum stewardship - through doing and learning - better than any other radio service that exists. The amateur community can appreciate the special responsibilities that come along with orbiting one’s own spacecraft. Those creating such objects can and must calculate that such objects travel at velocities from 7 to 10 kilometers per second – and we learn, first hand, how to get them “up there." When it comes to sustainability, we get it. Our service will likely never have more than one to two dozen operating space vehicles in orbit at any one time. Other individual spacecraft operators may have responsibility for more than 20,000 satellites worth of future orbit debris – and that is, arguably, a lot of responsibility for one single entity. While this imbalance between the services seems unfair on its face, we accept this reality. However, we would expect to be able to continue to carry out the mandates of our service - the ARSS. We've shown here how we can co-exist within this level of emerging mayhem and still respond to our service responsibilities. We continue to move forward, advancing technology in a world where Silicon Valley has passed us by. We'll do this, not by doing the same thing as other services but, by doing it differently. And, we will educate and demonstrate to new-comers to the radio world some of its wonders and magic. We intend to continue to use the higher frequency bands, allocated at the ITU to our service - back at a time when all wondered how we'd ever achieve the development of a 10 to 100 GHz transmitting or receiving radio device. These frequency bands will make small spacecraft "powerful little tools" that will demonstrate and repeat in a new way that same magic that Hiram Percy Maxim demonstrated every time he completed an HF communications contact across the Atlantic Ocean back in 1914. It's clear to some that the radio spectrum is a very valuable resource and we all appreciate that, however, we also know as well, that a visit to a National Park can't be replaced by all the revenue of FaceBook, Inc. (to put a contemporary spin on the argument). So, herewith, we again commit that we'll keep doing our part. And, this presentation is how we propose to go about being a good neighbor. We'll commit to staying "out of their way" but, please, help us keep them out of our way.

Relatively precise attitude control of small spacecraft will be required for new amateur satellites using microwave and millimeter wave communications so, this same capability can and will be used for accurate burn maneuvers performed by high Isp electric (ion or plasma) propulsion systems and this class of propulsion system can be fitted to spacecraft as small as a 6U CubeSat.   Such propulsion systems are emerging abundantly, thanks to the technological progressions taking place in the small space community. The total ΔV requirements of ARSS missions to HEO orbits, for all orbit debris adjustments and mission phasing requirements is less than 300 m/s per spacecraft and such propulsion capabilities are within the scope of the small space community technology base and, hence, within the range of the ARSS. We foresee an evolving ARSS, which uses a combination of LEO platforms flying below 600 km mixed with MVP missions providing global communications services, and both classes of system operating sustainably within an internationally shared global space environment. If good fortune abounds as we go forward, the ARSS will also have our own MVP GSO space systems – scaled to the needs and expectations of the Amateur Radio Satellite Service operating in the New Space Age.

Presentation Outline

Presentation Outline

The Amateur Satellite Service in the Modern Era

I. Summary of the Performance of the Amateur Satellite Service since 1961

II. The Impact of Government Regulation and the Evolution of Space Services

A. The International Traffic In Arms Regulations

B. Orbital Debris Mitigation Regulations

III. Technological Adjustments and Adaptations of the ARSS Over the History of the Service

A. Changes in Solar Cell Efficiency, RF Device Efficiency, Specialized S/C Technologies (e.g. HELAPS)

B. Micro-miniaturization of Electronic Devices

C. The Use of Millimeter Wave Spectrum

D. The Evolution of the Small Satellite World the Amateur Satellite Community Initiated

E. Doing More with Less

IV. More Adaptations Necessary

V. The Notion of “Orbit Shell Ownership (OSO)…(Caused by the Mingling of Spectrum and Orbit Debris Federal Management)

VI. The ARSS Adaption to the “Orbit Shell Ownership” Problem

A. Maximize Coverage by means of Increased Orbit Altitude(Also Minimizes Number of S/C Required for a Sustainable Service Offering)

B. Minimize Propulsion Requirements

1. For Orbit Raising
2. For Orbit Phasing
3. For Spacecraft EOL Disposal

C. Minimize Risk of Spacecraft Failure by means of Proper Orbit Selection (If Spacecraft Fails due to Infant Mortality Spacecraft Quickly Re-enters Atmosphere Due to Low Perigee).

D. Minimize Launch Costs by Picking a Very Commonly Used Orbit Type

VII. Why Geostationary Transfer Orbits (GTOs) are the Right Choice (Satisfies VI-A through VI-D Completely)

VIII. Members of the ARSS Acknowledge the Ultimate Need for Orbit Debris Removal by means of Propulsion + Atmospheric Drag

XI. The ARSS Community Needs Our Millimeter Wave (mmW) Spectrum Now

A. Minimizes Spacecraft SWaP (Size, Weight & Power)

B. Increases Service Capacity

C. Minimizes Terminal Size in Crowded Urban Environments (a Modern Era Problem that did not exist a generation ago)

1. ARSS Earth Station for Condominium & Apartment Living

2. New Technology Enables “Cheap” Precision Pointing Antennas for Ultra Low Cost Earth Stations

3. Standards such as DVB-S2X make HSD Cheap

4. 5G Cellular Technology Enables mmW Amateur Radio Spectrum

X. Conclusion: The Amateur Satellite Service (ARSS) Can Still Provide Citizen-Based Technology Evolution and Support STEM-based Student Learning…but, It must be done Differently…this is the Modern Era.

NOTE: The ARSS community (and Open Research Institute, in particular) still supports the Manned Space Flight Initiatives we continue to work on (using ISS and working with NASA. This presentation is in addition to that capability that we have.

Technical Addendum 1: Confirmation of delta-V produced by AO-13

AMSAT-OSCAR-13 was the third spacecraft in the satellite series called Phase-3. Before launch it was referred to as Phase-3C. This series of satellites was designed to deliver the satellite from a Geostationary Transfer Orbit (GTO) to an orbit that approximated the Molniya orbit used by the former Soviet Union for their communications satellites. The first two satellites in this series did not achieve their objective regarding orbit modification. Phase-3A was lost in 1980 due to the Ariane-L02 vehicle first stage failure. Phase-3B (which became AMSAT-OSCAR-10, in orbit, completed its first burn (see below) but failed to perform it's second burn due to a small leak in the He pressurant system that occurred during the first burn.

A GTO, used by Ariane V-22 (the first Ariane-4) that launched this spacecraft was approximately:

hp = 210 km

ha = 36,300 km

i = 7.0 °

The rocket motor used for this mission was a 400 N bi-propellant motor using N2O4 oxidizer and Aerozine 50 as propellant. AZ-50 is a 50%/50% mixture of UDMH and Hydrazine (by weight). The motor in this case completed the mission successfully in two steps:

1) The first burn modified the orbit from GTO to one with the following properties:

hp = 2545 km

ha = 36,265 km

i = 17°

The ΔV imparted by this first burn was 276 m/sec.

2) The second burn further modified the orbit to give a final one with the orbital elements shown in this table. The AMSAT developed Ranging System gave one solution shown here and North American Air Defence gave us their solution from the Millstone Hill radar in Connecticut. NORAD confirmed both our orbit precision and our ranging system precision. Both are noteworthy when compared against the resources spent to achieve the results.

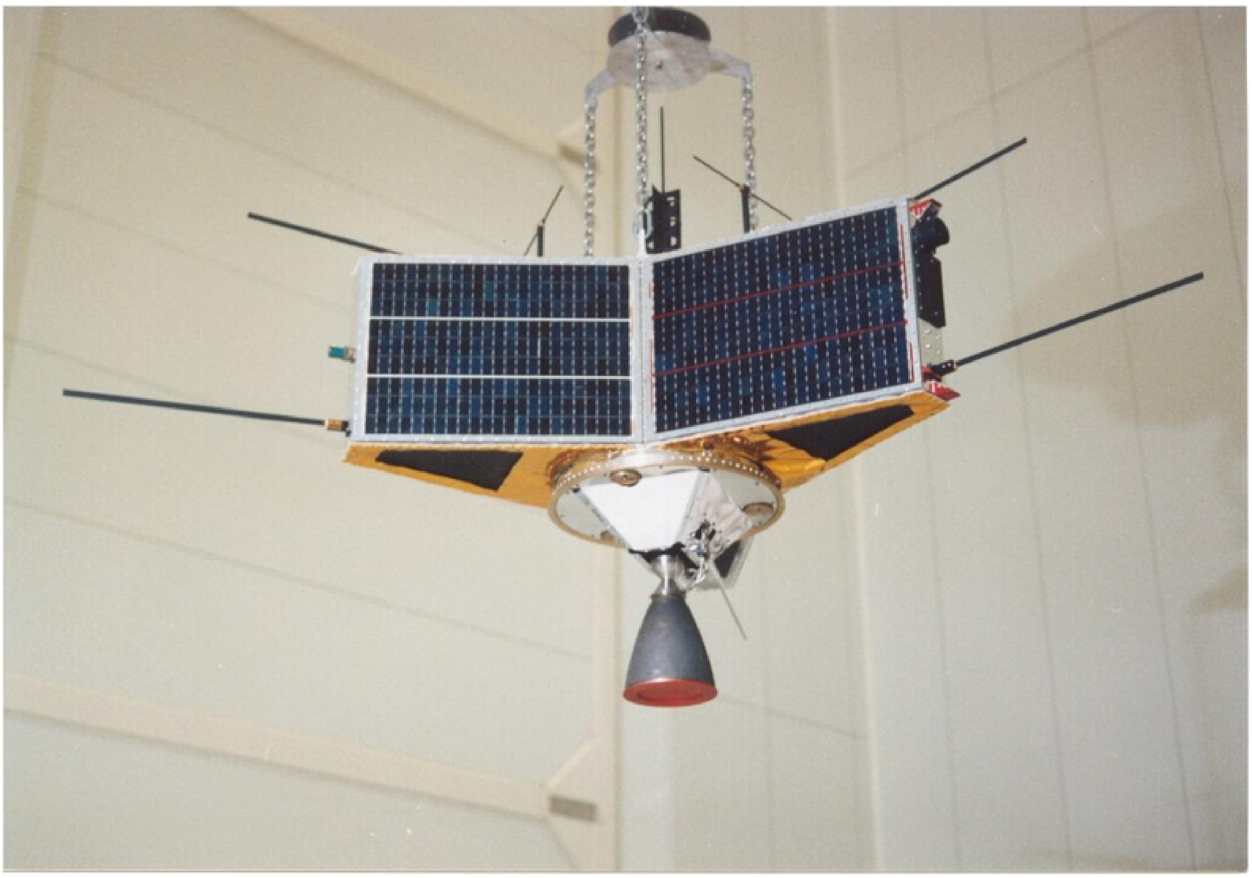
This mission was carried out in 1988. As of this writing in 2009 no other amateur or professional small satellite mission of this size class has ever performed a propulsive manoeuvre of this magnitude and precision. This mission has definitely been the high water mark for the AMSAT organization, involving both AMSAT-NA and AMSAT-DL as well as other assisting countries.

The total ΔV produced by the 400N motor was 276+1313 m/s = 1589 m/sec.

Photograph of satellite below.

Jan A. King/ W3GEY

AMSAT-NA Project Manager



Technical Addendum 2: Direct-to-Graveyard Orbit Study

By Anshul Makkar

Senior Engineer
Open Research Institute, Inc.

Introduction: A Geostationary satellite is launched into space on a rocket, and once there it is inserted into the geostationary orbit and is maintained in that orbit by means of thrusters onboard the satellite itself.

Propellant budget calculation is an important analysis for sizing of a geostationary satellite in the preliminary design phase (PDR). Propellant budget defines the lifetime, mass of the satellite, propellant tank volumes and dimensions.

Aim:

In this study, a guideline is presented for the calculation of the propellant budget of a geostationary satellite and its subsequent maneuver direct-to-graveyard orbit. This is proposed to meet the requirements for Debris Mitigation while providing compelling experimental amateur radio communications services.

Study GTO to GEO:

In the case of a geostationary satellite, the satellite must perform a critical maneuver at the apogee of the transfer orbit at the synchronous altitude of 35,786 km to simultaneously remove the inclination and circularize the orbit. The transfer orbit has a perigee altitude of about 200 km and an inclination roughly equal to the latitude of the launch site. To minimize the required velocity increment, it is thus advantageous to have the launch site as close to the equator as possible

Velocity change required for orbit raising depends on the launcher selection. Launcher leaves the satellite at Geostationary Transfer Orbit (GTO) and the satellite performs several apogee maneuvers to go to Geostationary Orbit (GEO). Here for my calculation, I will be using a Falcon 9 rocket with below details.

Launcher	Inclination (degree)	Perigee (km)	Apogee(km)
Falcon-9	28.5	185	35,786

Velocity of the satellite on elliptic orbit is given by

$$v = \sqrt{GM\left(\frac{2}{R} - \frac{1}{a}\right)}$$

where

GM: Earth Gravitational Constant, 398600.4418 km3/s2

R : Distance of the satellite to the center of the Earth, km

a : Semi-major axis of the satellite orbit, km

Apogee maneuvers circularize the elliptical GTO orbit to GEO orbit and correct the inclination between these two orbit planes. These maneuvers are performed at apogee of the GTO orbit to have minimal velocity change

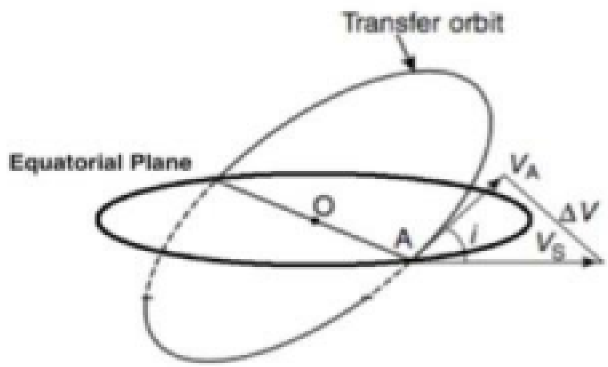


Figure 1. GTO to GEO orbit maneuver

Semi-major axis for the GEO orbit is 42164km and the velocity at GEO orbit can be calculated using

Vs = sqrt(GM/2a)
V_S = sqrt(398600.400/42164)

V_S = 3074.7 m/sec

Radius of earth can be assumed to 6378 km.

Semi-major axis of the GTO for Falcon-9 can be calculated by using the altitude of apogee and perigee.

a = (185 + 35786)/2 + 6378

a = 24363.5 km

V_A = sqrt(GM(2/R - 1/a))

V_A = sqrt(398600.4418(2/(6378+35786) - 1/24363.5)

V_A = 1595.80 m/sec.

ΔV = sqrt(sq(V_A) + sq(V_S) - 2* V_A * V_S * cos(i))

ΔV = sqrt(sq(1595.80) + sq(3074.7) - 2*1595.80*3074.7 *

cos(28.5)) **ΔV = 1840.40 m/sec from GTO to GEO**

Study : GEO to graveyard

ΔV for graveyard orbit is calculated using (1) with the assumption of Hohmann transfer to graveyard orbit. ITU recommends a multiple maneuver strategy for orbit raising. First maneuver is performed to go from GEO orbit to a graveyard transfer orbit with apogee 42514 km, perigee 42164 km and semi-major axis 42339 km. Second maneuver is performed to circularize the graveyard orbit with a 42514 km radius.

$\Delta V_1 =$ sqrt(GM(2/42164 - 1/42339)) - V_S

$\Delta V_2 =$ sqrt(GM/42514) - sqrt(GM* (2/42514 - 1/42339))

$\Delta V_{grave} = \Delta V_1 + \Delta V_2$ = 12.7 m/sec from GEO to graveyard.

The above case study aims to help in mission planning. It shows that if carefully planned, with a minimal set of Δ**V** and propellant budget, the missions can be made FCC compliant for Debris Mitigation paving the way for future missions and collision avoidance.

Technical Addendum 3: Nominal Sequence of Orbit Modifications for an Operational ARSS Sustainable Mission with a [6-year] Lifetime.

ΔV Required for ARSS Modified GTO Mission

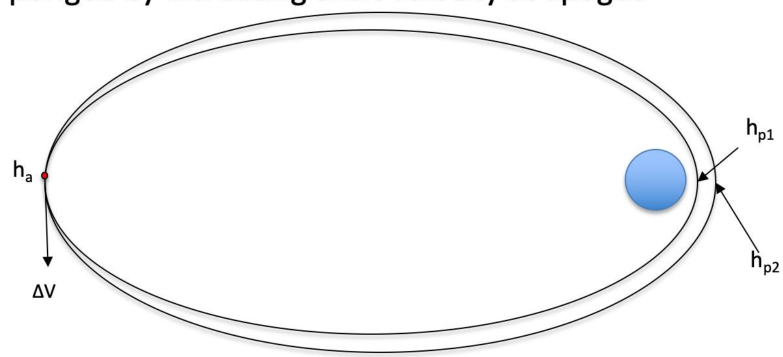
Calculations by:

Jan A. King/W3GEY

Rev 2.0

Phase 1: Orbit Raising

- This step can be achieved by a Hohmann Transfer Manouver
  - Start Burn Immediately after Launch (within first 10 apogees)
  - A single burn may be used: Fire at apogee to raise perigee
  - Or alternatively, multiple burns may be employed if low-thrust electric or plasma propulsion is used: fire multiple times at apogee to more slowly raise perigee.
  - Raise perigee by increasing orbit velocity at apogee



Phase 1 Orbit Raising:

Initial Orbit:

- h_{a1} = 36,000 km
- h_{p1} = 250 km
- V_{a1} = 1595.081 m/sec
- V_{p1} = 10,198,428 m/sec

Mission Orbit:

- h_{a2} = 36,000 km
- h_{p2} = 1250 km
- V_{a2} = 1693.987 m/sec
- V_{p2} = 9410.947 m/sec

$\Delta V = V_{a2} - V_{a1} =$ **98.9**01 m/s

Phase 2: Orbit Maintenance

(After Orbit Raising and During Operational Lifetime)

- Eccentric orbits, including GTOs are marginally unstable, and exhibit chaotic behavior in terms of the forward propagation of most of their orbital elements, including eccentricity and semi-major axis.
- This means that the orbit apogee and perigee will rise and fall as a result of solar and lunar tidal effects.
- A modified GTO of this type could increase or decrease its perigee by more than 1000 km over the course of many months-to-years.
- If the perigee decreases the S/C could prematurely re-enter the atmosphere.
- If the perigee increases the S/C attitude control system may no longer be able to dump angular momentum accumulated by the reaction wheels. Torquer coils are no longer effective at 2000 km.

Phase 2: Orbit Maintenance (2)

- This instability is a strong function of the angle between the Earth-sun line and the orbit major axis. The parameter, Right Ascension of Ascending Nodes (Ω) or RAAN, best reflects this condition.
- The Following Table shows the instability of a well-studied orbit quite similar to a GTO. It is called a Molniya Orbit. Very similar orbits were used by earlier Amateur Satellites and hence we are familiar with this instability property from our work with these missions.
- The orbit studied here, had a perigee of 1000 km and an apogee of about 39,000 km. It had an inclination of 63.4°.
- Its stability was tested against the initial RAAN value.
- We notice that for initial orbit RAAN (Ω) values near 45° and 315° the orbit perigee increases significantly during the observation period, while for orbit RAAN values starting near 180° the perigee decreases unacceptably. In-between RAAN starting values were best.

Instability of a Well-Studied Eccentric Orbit with Properties Similar to a Geostationary Transfer Orbit (GTO)

Orbit Stability Summary - 12 Hour Period Sidereal Resonant Orbit - 5 Year Orbit Integration						
	- Perigee Height Variation -			*- Argument of Perigee Variation -*		
Starting RAAN:	*Highest in 5 Yrs:*	*Lowest in 5 Yrs:*	Δh_p	*Highest Value in 5 Yrs:*	*Lowest Value in 5 Yrs:*	$\Delta\omega$
0°	1912.0 km	951.0 km	961.0 km	90.82 deg.	87.09 deg.	3.73 deg.
30°	1836.0 km	890.0 km	946.0 km	90.61 deg.	87.03 deg.	3.58 deg.
60°	1651.0 km	768.0 km	883.0 km	90.04 deg.	86.77 deg.	3.27 deg.
90°	1406.0 km	569.0 km	837.0 km	90.03 deg.	86.89 deg.	3.14 deg.
120°	1144.0 km	363.0 km	781.0 km	90.04 deg.	87.60 deg.	2.44 deg.
150°	1001.0 km	198.0 km	803.0 km	90.03 deg.	88.16 deg.	1.87 deg.
180°	1004.0 km	118.0 km	886.0 km	90.03 deg.	87.25 deg.	2.78 deg.
210°	1088.0 km	144.0 km	944.0 km	90.03 deg.	86.18 deg.	3.85 deg.
240°	1270.0 km	239.0 km	1031.0 km	90.04 deg.	85.33 deg.	4.71 deg.
270°	1506.0 km	464.0 km	1042.0 km	90.04 deg.	85.24 deg.	4.80 deg.
300°	1720.0 km	827.0 km	893.0 km	90.17 deg.	85.81 deg.	4.36 deg.
330°	1851.0 km	987.0 km	864.0 km	90.44 deg.	86.67 deg.	3.77 deg.
Largest Value:	1912.0 km	987.0 km	1042.0 km	90.82 deg.	88.16 deg.	4.80 deg.
Smallest Value:	1001.0 km	118.0 km	781.0 km	90.03 deg.	85.24 deg.	1.87 deg.
Mean Value:	1449.1 km	543.2 km	905.9 km	90.19 deg.	86.67 deg.	3.52 deg.

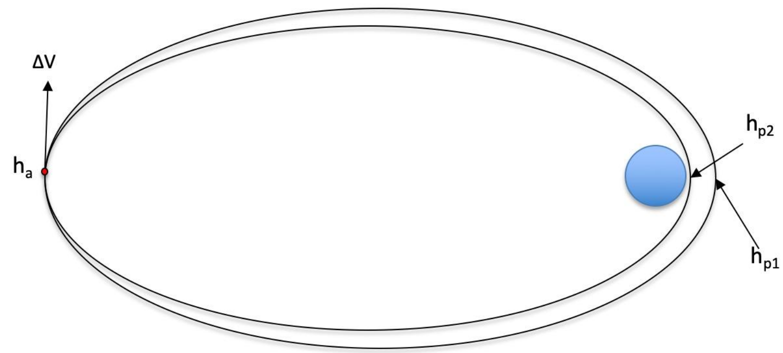
Phase 2: Orbit Maintenance (3)

- The solution to this problem is to occasionally adjust the orbit perigee altitude during the mission lifetime in order to maintain it within an acceptable boundary altitude, as shown in the table below.
- The orbit is allowed to drift between perigee altitudes of 1050 and 1500 km during its lifetime. If the perigee of the orbit exceeds these boundaries a ΔV maneuver is executed to return the altitude of perigee to 1250 km.
- The cost of maintaining these altitude limits is less than 24 m/sec per event.
- Such events, based on orbit modeling, suggests one to two such maneuvers will occur per spacecraft lifetime of 5 years.

Perigee Altitude:	*ΔV to Restore:*	*Action Taken:*	*Limit:*
1000 km	23.810 m/sec	Orbit Not Allowed	
1050 km	19.002 m/sec	Increase Altitude of Perigee to 1250 km	LOWER LIMIT
1100 km	14.217 m/sec	Monitor Altitude	
1200 km	4.716 m/sec	Monitor Altitude	
1250 km	0.000 m/sec	NOMINAL ALTITUDE	NOMINAL ALT.
1300 km	-4.694 m/sec	Monitor Altitude	
1400 km	-14.014 m/sec	Monitor Altitude	
1500 km	-23.248 m/sec	Decrease Altitude of Perigee to 1250 km	UPPER LIMIT
1600 km	-32.396 m/sec	Orbit Not Allowed	

Phase 3: Orbit Lowering

- This step can be achieved by a Hohmann Trasfer Manouver
  - Prior to Mission End-of-Life
  - A single burn may be used: Fire at apogee to lower perigee
  - Or alternatively, multiple burns may be employed if low-thrust electric propulsion is used: fire multiple times at apogee to more slowly lower perigee.
  - Lower perigee by decreasing orbit velocity at apogee



Phase 3 Orbit Lowering

Mission Orbit:

- h_{a1} = 36,000 km
- h_{p1} = 1250 km
- V_{a1} = 1693.987 m/sec
- V_{p1} = 9410.947 m/sec

Final Decay Orbit:

- h_{a2} = 36,000 km
- h_{p2} = 150 km
- V_{a2} = 1584.621 m/sec
- V_{p2} = 10,286.743 m/sec

$\Delta V = V_{a2} - V_{a1} =$ **-109.36**6 m/s

Total ΔV Required for an ARSS Spacecraft Using a Modified GTO Orbit

Mission Element:	Mission Phase:	ΔV:	Comment:
Orbit Raising (BOL)	Phase 1	98.9 m/sec	Increase Velocity at Apogee
Orbit Maintenance	Phase 2	2 X 24 ≈ 48 m/sec	Increase or Decrease Velocity at Apogee as Required.
Orbit Lowering (EOL)	Phase 3	109.4 m/sec	Decrease Velocity at Apogee
TOTAL MISSION ΔV:		**256.3 m/sec**	Add 10% Reserve

Typical 6U Spacecraft Propellant Calculation:

Calculating the *Critical Mass* (Maximum Allowable Mission Mass), Given Required ΔV and Rocket Motor I_{sp}

$$m_c = m_{fuel}\left(\frac{e^{\Delta V / g_e I_{sp}}}{e^{\Delta V / g_e I_{sp}} - 1}\right)$$

m_c = Critical Mass … Combined Mass of Spacecraft + Mass of Fuel that Can Achieve the Desired Modified Orbit by Meeting Mission ΔV Requirements.

Parameter:	Symbol:	Value: Unit:	
Spacecraft Useful (Expendable) Fuel Mass	m_{fuel} =	0.4687 Kg	
Rocket Motor Effective Specific Impulse	I_{sp} =	600.0 sec	Small Plasma Thruster Typical I_{sp}
Mission Required Total ΔV	ΔV =	256.30 m/sec	
Mission Critical Mass	m_c =	11.00 Kg	6U Spacecraft Allowable Mass
Spacecraft Maxium Dry Mass	$m_{s/c}$ =	10.53 Kg	
Motor Average Thrust (during burn)	F =	0.5 N	Small Plasma Thruster Avg. Thrust
Mass Flow Rate	$\dot{m}$ =	0.0000850 Kg/sec	
Motor Total Burn Time at Constant Thrust	t_{burn} =	5515.65 sec	
Total Impulse Available	I_T =	2,758 N-sec	

Technical Addendum 4: Link Budget Showing Typical Capacity of a 6U GTO Orbit using mmW Spectrum

Please visit

https://github.com/phase4ground/documents/tree/master/Engineering/Link_Budget/Jan-King-Link-Budgets

to download the current version of this spreadsheet.

A video walk-through of the spreadsheet as of 12 May 2021 can be found at the following link:
https://youtu.be/sClk7Kd_rQI