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SIGINT: The Mission CubeSats are Made For

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ABSTRACT

The collection of radio frequency (RF) signals by means of interferometry is an area that shows great promise for small satellite applications and is a shared interest of business and the scientific and military community. SIGnals INTelligence or SIGINT is one of the oldest missions for satellites, especially for its subfield, ELectronic INTelligence (ELINT), the analysis and localization of RF-signals. Unfortunately, the accuracy that customers demand from such systems in order to merit their costs is often incongruent with detection techniques that rely on single nanosatellites (such as Angle of Arrival methods). Accuracy is strongly related to aperture size; rigid antennas are therefore limited to the available surface area of small satellites. Typical accuracies that can be expected of AOA-techniques range from 0.1° – 1°[1]. Factoring in orbital altitude, this results in geolocation accuracies of 10 km or more for RF-sources close to the satellite's nadir, increasing rapidly with distance from nadir for missions in LEO. Using a single CubeSat solution with rigid antenna systems limits the type of RF-emitters that can be geolocated with high accuracy (<0.1°) to X-band (or shorter wavelengths). Deployable structures and small satellites that do not adhere to the CubeSat standard offer a limited solution as there is limited volume available for deployment mechanisms.

One of the key benefits of using CubeSats is their lower unit and launch cost. This enables technical solutions that depend on distributing the desired functionality over many satellites, instead of investing in highly sophisticated single satellite payloads. This approach has in the past been studied for space-based interferometers like Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) enabling far larger diameter "apertures" than could be fitted on a single satellite while at the same time simplifying the development and deployment[2]. The same technologies that enable these scientific missions are at the heart of satellite formations for the purpose of identifying and geolocating RF-emitters on the Earth's surface, such as inter-satellite datalinks, station-keeping systems and precise avionics. The overlap is not limited to these enabling technologies but also extends to system level characteristics. One of the big obstacles for CubeSat missions beyond LEO is their reliability. CubeSat missions beyond LEO face two hurdles that amplify each other, on the one hand the radiation environment becomes significantly more hostile, complicating the use of COTS components and on the other hand the cost of replenishment increases drastically with distance from Earth. Missions such as OLFAR thus require a step change in the reliability of the subsystems in order for them to be affordable and cost effective. At the same time these same reliability improvements would further decrease the cost of ownership of LEO spectrum monitoring (or SIGINT) constellations.

INTRODUCTION

Recording and analyzing radio signals from space is one of the oldest applications of satellites. In June 1960 the US military launched its first ELINT satellite codenamed Tattletale, better known as Grab, for Galactic Radiation and Background Satellite (Tattletale's cover mission). Grab was a 20in sphere and had a mass of 18 kg[3]. By modern terminology a nanosatellite. It rode to orbit 'piggyback' fashion as secondary payload for the Transit 1B. Still to this day the standard way of launching nanosatellites.

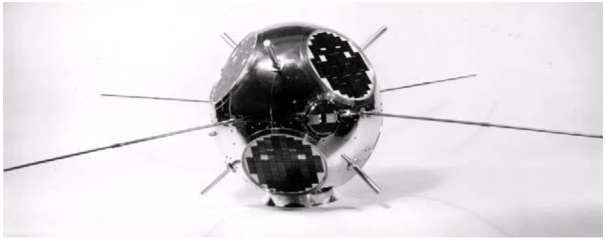

Figure 1: Grab satellite with deployed antennas (Photo courtesy of NRL).

Electronic Intelligence

Space-based ELINT systems have evolved significantly since Grab. Their accuracy, frequency range, signal characterization and ability to determine the location of the signal's origin have vastly improved. Their costs have, however, also increased dramatically. Full size constellations of these satellites are still strategic assets only the preeminent spacefaring nations can afford; US, Russia and China (with France to join their ranks soon).

Figure 2: Lotus-S ELINT satellite[4].

The prohibitive cost of such system has led several air forces and governments around the world to ask whether these systems can be miniaturized or distributed in order to benefit from the developments in small satellites.

Radio Astronomy

While the military and intelligence communities point their antennas at the Earth the science community has pointed theirs towards the heavens. In order to receive signals with a sufficiently high signal-to-noise ratio radio telescopes require much larger apertures (1 – 100 m) than their optical counterparts. Even these large diameter antennas have difficulties generating data with a sufficiently high level of detail. This has led to the development of radio interferometry, where large arrays of radio telescopes are used in conjunction.

Figure 3: The Westerbork Synthesis Radio Telescope (WSRT) consisting of 14 dish-shaped antennas.

For radio astronomy in frequency ranges down to as low as 20 to 30 MHz the Earth's atmosphere is completely transparent and therefore the benefits of space-based telescopes very limited. For HF radio astronomy, however, the ionospheric cut-off frequency, scintillation and time varying refraction impose fundamental limits on the performance of ground-based observatories[2].

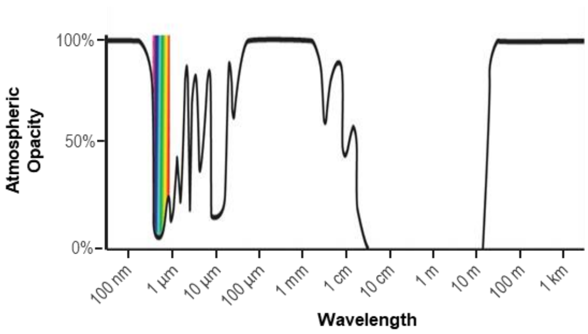

Figure 4: Atmospheric transparency of RF spectrum (image courtesy of Humboldt State University).

Thus, for HF radio astronomy space-based telescope are an obvious solution to the previously described challenges of ground-based observatories. The large aperture diameter that is required (10 – 100 km)[5], however, negates the option of using single satellite solutions. The largest single satellite launched by the US' National Reconnaissance Office[6] is rumored to be a SIGINT satellite with a foldable aperture of approximately 0.1 km.

Spectrum Monitoring

The third application of radiofrequency receivers that is of interest here is the ability to monitor manmade RF emissions by non-military sources. The fairly vague capture-all definition is indicative of the manifold reasons to carry out such missions. One of them is, for instance, verification of adherence to ITU regulations and frequency allocation.

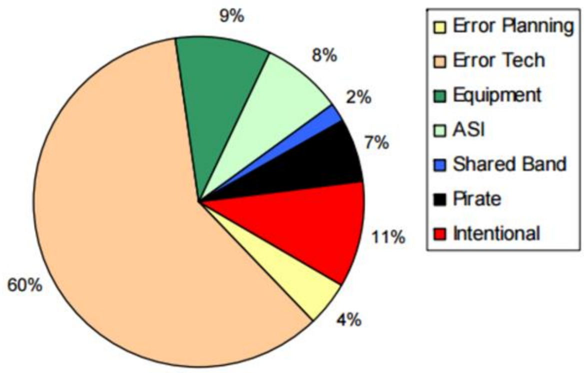

Figure 5: Sources of interference of Eutelsat satellites[7].

As can be seen 18% of the interference experienced by Eutelsat is intentional or due to piracy of the frequency bands.

The ability to locate the sources of this interference in space or on the Earth surface is of increasing importance, especially in combination with dynamic frequency allocation schemes under consideration by the ITU and the US government.

SINGLE SATELLITE LIMITS

When a single satellite is used to perform these missions, fundamental limits are quickly reached due to the physical size limits.

Radio Interferometry

For radio interferometry the array design (i.e. formation configuration) is determined by the angular resolution:

$$R = \frac{\lambda}{B} \quad (1)$$

where λ = wavelength of observation; B = the baseline (maximum physical separation between the individual telescopes in the array) and R = the angular resolution. Given the frequency range of interest (0.3 – 30 MHz) baselines of 0.1 – 100 km single satellite implementations are beyond those practical with today's technology and that in the foreseeable future[5].

Spectrum Monitoring & Signals Intelligence

For spectrum monitoring missions aiming at locating manmade RF sources on the Earth surface or in orbit the use of single satellite solutions is more feasible. Focusing specifically on the issue of localizing RF emitters Radio Direction Finding (RDF) systems have been around since the early 20th century[8]. By the end of WWII such devices had become part of the standard avionics suite for most military aircraft and would become the primary form of aviation and marine navigation until its replacement by GNSS like GPS. At the same time, as the use of RF equipment became more prevalent at the beginning of the 20th century, modern-day signals intelligence grew into an ever more important branch of intelligence gathering using many of the same technologies.

Mechanical solutions (that varied antenna pointing angles w.r.t. the emitter) gradually gave way to array signal processing techniques. Performance improvements in both antenna design and electronics led these systems to shrink significantly over time, however, physical limits resulting from the wavelength that is being monitored and sampling speeds result in a limitation in terms of the angular resolution that can be achieved with such RDF systems. For direction finding methods values of around 0.1° are typically mentioned in literature as the lower bound of what is achievable[1,9].

These estimates match up with declassified estimates for localization accuracies of Soviet space-based SIGINT platforms (which used a single satellite for this purpose). Geolocation accuracies of 8 to 220 km were estimated for the Tselina -D satellite in 1982[10]. Given the satellite's orbit and emitter-receiver geometry (elevation or distance from nadir) this would equal an angular error of between 0.2° and 0.7°. Similar angular accuracies (0.3°) were estimated for the EORSAT (the maritime space-based SIGINT component)[11].

Figure 6: Tselina-2 satellite from 1980's (payload mass 1120 kg) versus 6U CubeSat (payload mass 6 kg).

While it is obviously to be expected that these systems have seen a significant performance improvement since the '80's, the applicability of those improvements to CubeSats is doubtful without inflating the cost of these missions far beyond what typical CubeSat customers expect.

The main driver for moving towards CubeSat constellations is the ability to dramatically lower the cost of such missions. In the civilian domain this means essentially opening a new type of business, in the military domain it means lowering the cost of entry for countries seeking to acquiring SIGINT capabilities.

The physical size of CubeSats does impose limitations on the localization accuracy that can be expected from single satellite systems. Irrespective of the formfactor that is selected (6U, 12U or 16U) the maximum aperture diameter of a body-mounted antenna is 21.4 cm. Increases in diameter can only be achieved by deployable systems.

SQUARING THE CIRCLE

At first the notion that CubeSats are more suitable than traditional satellites to carry out a mission requiring large apertures than might seem contradictory. After all, the aperture size is dictated by physics, not manufacturing processes that can be changed to miniaturize payloads.

But CubeSats also offer the ability to make trade-offs between concentrated versus distributed systems. Miniaturization not only results from making components smaller while preserving their capabilities (i.e. the evolution of the cell phone over the past decades) but can also result from a reevaluation of the importance of certain capabilities. In a similar fashion the reevaluation of resolution versus coverage and persistence led a new market entrant (Planet) to use CubeSats to upset a market previously dominated by traditional satellites (DigitalGlobe).

A COMMON CORE

Despite the fact that the payloads for these three different missions differ significantly the overall space segment to achieve these goals would not look too dissimilar; therefore, the three communities can benefit from the co-development of a common mission architecture and satellite bus. A bottom-up analysis of the requirements that these three mission types would impose on a system led to the following three key aspects of a common satellite bus and mission architecture.

Reliability

Radio interferometry missions like OLFAR[2] aim to use the moon as a shield to block out the RF interference from Earth. Because launch opportunities into Lunar space are rare (and therefore costly), there is a profound impact on the replenishment strategy. The same is true for spectrum monitoring missions carried out in or around GEO. Current CubeSat missions, however, assume low cost replenishment due to the large number of launch opportunities to LEO and therefore prefer simple, cheap CubeSats that are easily replaced and offer the ability to update the space segment hardware frequently.

Spectrum monitoring or SIGINT missions also have an interest in increased reliability of CubeSats, but for different reasons. While currently CubeSats are often used for technology demonstration missions for MoDs around the world, where the risk of failure is higher but is compensated by the lower cost of the satellites, operational CubeSat missions will not have that luxury. Thus, operational CubeSat constellations will either require large numbers of redundant satellites or they will impose similar increased reliability requirements on CubeSats as the other two missions.

Station Keeping

For interferometric mission architectures, station keeping is required. For a SIGINT constellation of three or more satellites, such as the ELISA mission[12] typically formation flying is carried out by maintaining a relative position around a chief spacecraft by one or more deputy spacecraft (or around a virtual chief spacecraft).

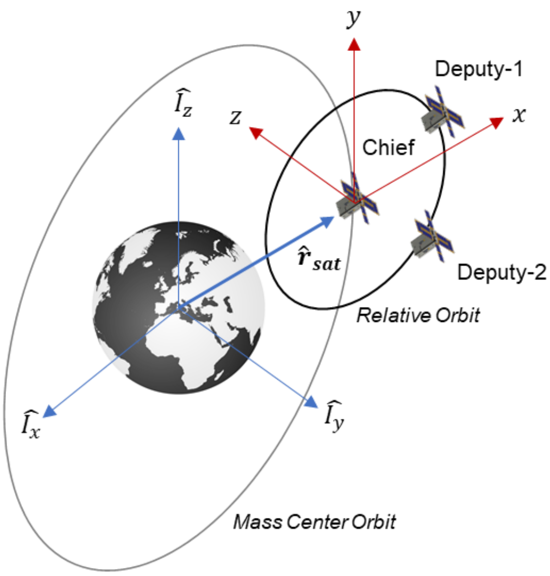

Figure 7: Relative motion described by Hill-Clohessy-Wiltshire differential equations[13].

The resulting unforced or "free" deputy spacecraft motion can be seen below. The 3D graph makes the typical "crock screw" motion of the deputy spacecraft apparent[14].

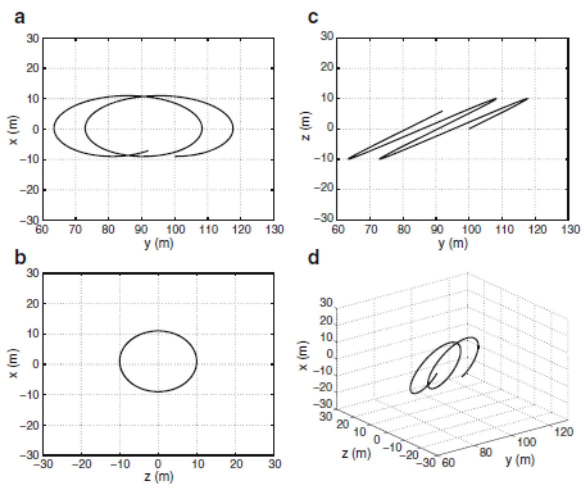

Figure 8: Unforced deputy spacecraft trajectory relative to the chief spacecraft[12].

In order to maintain formation and compensate for the perturbations encountered by the deputy spacecraft a low thrust bit, low total impulse propulsion system is a prerequisite for these missions, such as the one demonstrated during the CanX–4 and CanX–5 mission[15].

For missions away from LEO and with many more satellites, station keeping will need to be performed autonomously. Definition of control boxes and robust decision-making processes will need to be developed to ensure successful constellation maintenance.

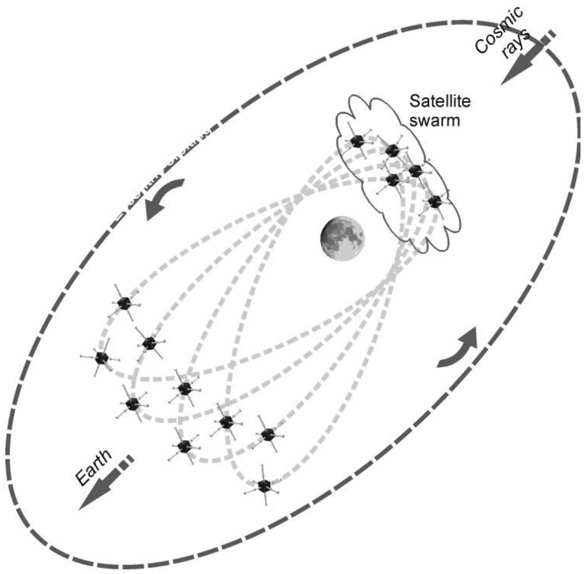

Figure 9: OLFAR concept for a satellite swarm in a highly elliptical moon orbit[16].

Intersatellite Links and Synchronization

Synchronization of the satellite formation for these missions is a key aspect of the design, as is position knowledge[17]. For missions beyond LEO the use of GNSS is no longer an option. Therefore, the formation will need to be able to independently determine the position of each satellite with sub-meter accuracy. Solutions for joint ranging and synchronization have been proposed that solve both problems in a single step[18].

The required ranging, time synchronization frequency and accuracy and data transfer volume between satellites will set requirements for the intersatellite links. Selection of the frequency band will also place requirements on platform attitude performance and power, which needs to be taken into account in system level design.

RECENT DEVELOPMENTS

The recognition of the potential of CubeSats for the missions described in this paper has not gone unnoticed. The CanX–4 and CanX–5 mission[15] completed a demonstration of precision formation flying in 2014. Several missions that aim to further the development of the required technologies are either in development or already in-orbit, though a coordinated international effort to develop an operational interferometric mission remains absent in the European context. The Danish Defence Acquisition and Logistics Organization (DALO) co-funded the GOMX-4A/B 6U CubeSats that experiment with inter-satellite communication and formation control[19] in a similar fashion as the CanX-4/5 mission (though equipped with significantly faster inter-satellite links than the earlier mission). Similarly, the SAMSON mission by Technion University set for launch in the fall of 2018 aims at using a formation of three 6U CubeSats to demonstrate formation flying, inter-satellite communication and synching of satellites for TDOA/FDOA-based localization of a distress signal[20].

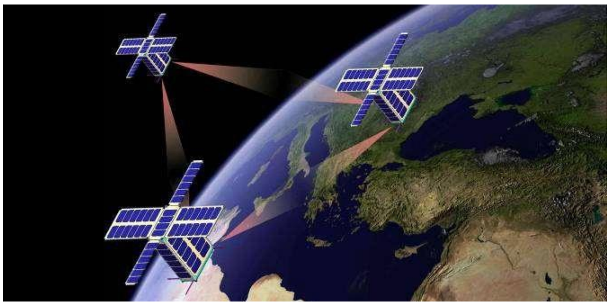

Figure 10: Space Autonomous Mission for Swarming and Geolocating Nanosatellites (SAMSON) mission (image courtesy of Technion).

On the payload side, the recent launch of the NCLE payload onboard the Queqiao relay satellite (Chang'e 4) placed in a halo orbit around the Earth-Moon L2 point (beyond Lunar orbit) is a precursor for the OLFAR observatory's payload[21].

Figure 11: Queqiao's nominal cis-L2 orbit.

Precursors to both military and commercial spectrum monitoring missions are set for launch in the near-term with the BRIK-II mission of the Dutch Air Force set for launch in the fall of 2019 (using a single 6U CubeSat)[22] and the US company HawkEye 360 launching its precursor triplet in the second half of 2018[23].

CONCLUSION

The entry cost for governments, institutes and companies seeking to perform spectrum monitoring (civilian and military) or radio astronomy missions have remained high due to the required mission and spacecraft designs. CubeSats are an attractive alternative to lower these costs thereby opening up business and science opportunities and providing capabilities previously reserved for only the preeminent space powers.

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