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REAL-TIME TACTICAL SPACE ASSET RETASKING

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ABSTRACT

It is well known that the value of satellite imagery to the warfighter dramatically decreases with age and that this is particularly true for more tactical operations where battlespace situational awareness is paramount. Reducing the length of the kill chain, the time from target selection to neutralization, is important to maximize not only the safety of the warfighter but also to minimize the potential for targets to morph and collateral damage.

Successful missions such as ORS-1 have shown that it is possible to get tactically useful information into the hands of the warfighter. To minimize the complexity of the pathway from image request to image delivery, future mission concepts such as the DARPA SEE-ME program have aimed to launch a large constellation of low-cost spacecraft that could be tasked via a tablet application. However, even this system suffers the drawback that assets cannot be always immediately retasked for image request in real-time.

Together with DARPA and others, Moog has led the development of a terminal allowing low latency Low Earth Orbit (LEO) spacecraft communications with the internet via existing Inmarsat ground and space assets. Under an Air Force Research Laboratories research effort and inspired by architectural visions long advocated by the Operationally Responsive Space (ORS) Office, Orbit Logic has developed a software suite able to import the user requests and mission constraints and process to develop an optimized set of spacecraft directives on orbit in real-time.

In this paper, Moog and Orbit Logic describe how such developments in real-time Low Earth Orbit (LEO) communications and intelligent on-board scheduling software can be used in three diverse applications. A tactical military application is described that could accelerate battlefield awareness as well as a simplified command and control architecture for large LEO constellations and a Space Situational Awareness application.

REAL-TIME LEO COMMUNICATIONS

The last decade has seen exponential growth not just in the interest and use of small satellites (smallsats) but also an increase in the value of data that can be obtained from them. Commercial investor interest in LEO smallsat technology is clear with Google recently investing nearly $1 billion in a large constellation of Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class (<300kg) spacecraft to be built by Space Exploration Technologies Corporation (SpaceX) and companies such as Planet Labs Inc. and Spire Global Inc.winning tens of millions of dollars in venture funding to field cubesat class space systems[1].

Given their orbit geometry, typical LEO spacecraft have discrete contact sessions with the ground lasting on the order of 10 minutes per pass, compared to an orbital period (where data can be collected) of roughly 100 minutes. Depending on the ground infrastructure available (the geographical distribution of terminals), spacecraft may also have as few as two ground contacts per day. Additionally, geopolitical and cost constraints typically limit the ability for mission designers to set up additional ground assets. To truly capitalize on the exponential value increase of LEO smallsat data, LEO/ground low-latency data links would have to be available at acceptable cost.

SB-SAT CAPABILITY

Moog and COM DEV have collaborated with Inmarsat to develop the capability to provide and receive near-real-time and continuous communications from LEO. SB-SAT seeks to offer small satellite customers connectivity via a simple secure Internet connection. SB-SAT can be thought of as a terrestrial Inmarsat satellite handset that would be operated in space on a LEO spacecraft. As seen in Figure 1, the LEO spacecraft would carry an SB-SAT terminal that would employ an antenna-pointing mechanism to acquire and maintain a link with Inmarsat geostationary Earth Orbit (GEO) assets that in turn would route the communication link through Inmarsat’s existing Broadband Global Area Network (BGAN).

The SB-SAT terminal was conceived and designed specifically for small satellite applications. The high-reliability radiation-tolerant terminal is designed for a five-year mission life at LEO. The terminal uses a modified version of proven terrestrial and aircraft software to account for the effects of orbital velocity on terminal operations. The compact terminal can be incorporated into spacecraft on the order of 75 kg and above. The SB-SAT terminal cost is on the order of currently available gimbaled X-band smallsat solutions and offers both near real-time communications as well as the ability to leverage existing Inmarsat assets. Customers would be merely required to purchase and operate a compact low-power terminal on their LEO spacecraft.

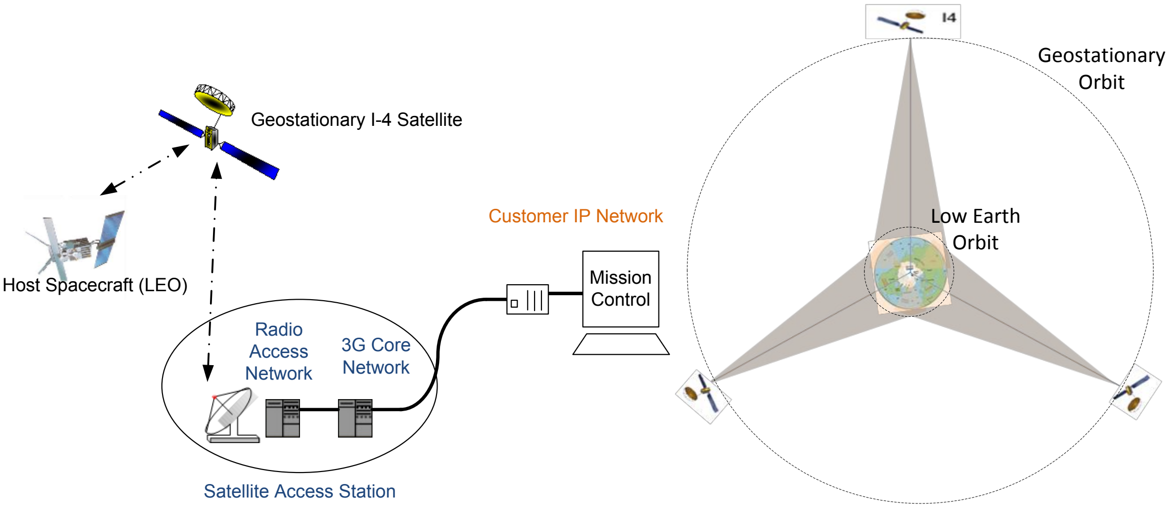
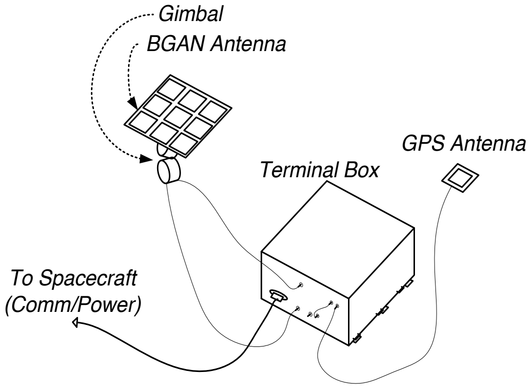


Figure 1: SB-SAT seeks to offer near zero latency communication with LEO assets

Figure 2 shows the major mass elements of SB-SAT. The LEO asset employing SB-SAT would also include a small, gimballed L-band terminal that would allow uplink and downlink to the Inmarsat I-4 constellation operating in GEO. As the LEO spacecraft orbits the Earth, the terminal would be able to both maintain a link with individual GEO spacecraft as well as seamlessly handover between the different GEO spacecraft that appear and disappear from view due to Earth shadowing. The GEO assets would offer continuous connectivity to the Inmarsat ground network so that a LEO-to-ground link would be nearly continuously available. Each SB-SAT customer would become another user on the Inmarsat network in the same way that a hand held cell phone becomes just another user on an existing network. Communication to the LEO satellite would be enabled through a simple virtual private network (VPN) connection on the Internet. Depending on the speed of the customer's terrestrial Internet provider, the latency of SB-SAT would be a few seconds (typically less than 3 seconds).



Item	Mass
Terminal Box	8 kg
Gimbal	1.9kg
BGAN Antenna	1.1kg
GPS Antenna	0.1 kg
TOTAL	**11.1 kg**

Artist's concept

Figure 2: SB-SAT configuration and mass elements

SB-SAT customers would purchase a data plan, similar to that used by satellite phone customers. There would be several options including a background service that would provide the maximum data rate and a streaming service that would provide a guaranteed data rate. SB-SAT can provide a maximum data rate of approximately 475 kbps, which would provide roughly 2500 Mb per orbit.

SB-SAT LEO TERMINAL

SB-SAT was designed to minimize hosting requirements on small satellites. The miniature dual-axis gimbal antenna would be housed on the LEO asset to provide visibility to GEO spacecraft. For typical nadir pointing LEO spacecraft, this is on the zenith face. A single electronics box would control the gimbaled antenna and provide power, as well as provide data interfaces between the Inmarsat network and the LEO spacecraft. Using the signals from the Global Positioning System (GPS) system, spacecraft position is determined so that, together with attitude information provided by the host, the SB-SAT electronics could command the antenna to acquire and track the currently visible Inmarsat GEO asset. Several times per orbit, the terminal would automatically perform a handover from the current GEO satellite to the one coming into view. This handover has been designed to maximize link performance with less than forty seconds required to release the current GEO asset and re-establish the connection with the new spacecraft. Once position information becomes available, normal operation would be enabled in less than a minute after initial power-on.

The mass of all SB-SAT terminal elements is 11.1 kg and spacecraft packaging is simplified by the fact that the electronics box and antenna can be separated by a meter before signal losses become an issue. The SB-SAT requires a standard small-satellite 28V unregulated power supply from the host and has a typical power consumption of 37W when tracking and receiving information. During transmission sessions this power level rises to only 60W, which is important because power is a valuable commodity for small spacecraft and drives cost and mass-heavy components such as solar arrays and batteries. In addition, the relatively wide field of view of the SB-SAT antenna ensures that host pointing requirements would continue to be driven by that of their payload. In terms of spacecraft platform simplification, the use of SB-SAT should also ease data storage requirements through SB-SAT's ability to stream high capacity payload data.

SB-SAT TECHNOLOGY READINESS

The SB-SAT concept has been developed by both public and private stakeholders since fall 2010. In the United States, DARPA provided development funding to Inmarsat who then contracted Moog to develop and build the terminal. Additionally, in Europe, the United Kingdom division of COM DEV developed technology employed in the RF front end of the SB-SAT terminal. Inmarsat, also of the United Kingdom, has been intimately involved in the project from the beginning to ensure seamless system compatibility with both the GEO ground and LEO segments. Particular focus areas for Inmarsat have been performing the ground station updates required and developing the battery of tests required to ensure SB-SAT operation on the BGAN.

The SB-SAT team has made great progress with the technology and is now nearing readiness for spaceflight. Multiple terminal breadboard and engineering models have been fabricated and tested to prove key elements of the SB-SAT system. In terms of Technology Readiness Levels, SB-SAT is currently at a level 6 with "system/subsystem model or prototype demonstration in a relevant environment" having been successfully performed. The end-to-end functionality of SB-SAT has been proven with ground-based connection to the GEO spacecraft achieved together with successful operation on the BGAN (see Figure 3).

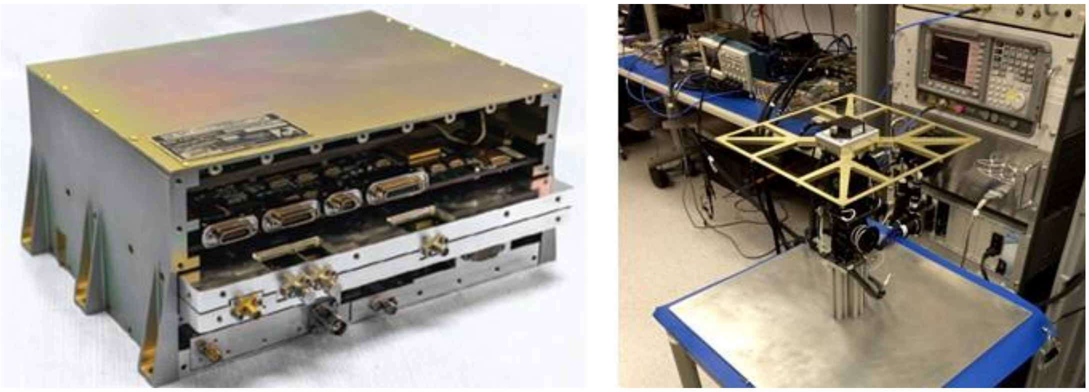


Figure 3: SB-SAT terminal (left) and antenna (right)

ONBOARD AUTOMATED RETASKING

Almost all spacecraft planning and scheduling is currently performed on the ground, with resulting plans uplinked to the spacecraft for execution. This process has inherent time delays that can cause a loss of critical mission opportunities or in worst-case scenarios even cause the loss of the spacecraft.

In traditional satellite operations, data from onboard sensors are sent to the ground, where processing is performed to extract information. This information may indicate a condition that requires additional action on the part of the satellite. The planning that incorporates an action in the satellite's execution schedule (or the schedule of other satellite assets) is performed on the ground and then uploaded at the next opportunity the satellite has contact with a ground station. This cycle takes significant time, especially when constrained by the schedules of humans required to be in the loop. Clearly, this widely distributed decision loop could be effectively compressed to a "point" if the necessary software process components are hosted onboard. In such a system, when opportunities are detected onboard, the spacecraft could react immediately without the need for communications coverage or the need for ground-based planning response. Logically, faster response times would lead to better responses and thus enhanced mission success.

Orbit Logic has developed a modular planning system that can run aboard a satellite's in-flight software and respond in real-time to onboard and external events to meet the planning/scheduling requirements of a variety of missions. The modular architecture allows planning systems to be assembled from individual planning components and quickly configured (and reconfigured as necessary) to meet initial and dynamic mission goals.

The Autonomous Planning System (APS) is comprised of Specialized Autonomous Planning Agents (SAPAs) that address specific planning needs (data recorder management, sensor collection, orbital maneuvering, etc.), applying suitable (and potentially distinct) algorithms for each planning domain. This approach is unique and contrasts with the current state-of-the-art for planning systems which generally try to apply a single algorithm type (often state-based and rules-based for flexibility) to multiple planning domains, often very inefficiently and beyond the processing capability of onboard resources. For nominal mission planning (namely the determination of an optimized solution within physical and resource constraints), APS employs a "rolling planning timeline" to reduce the planning window timeframe. Reactive SAPAs employ expert-system-type approaches to make rapid decisions about responses based upon system conditions and events. The application of multiple SAPAs to distinct subsets of the overall planning problem manages the complexity of the planning space so that solutions are more readily computable. This strategy has resulted in a collection of planning software that runs very effectively within the relatively constrained (compared to terrestrial computers) processing and memory resources of contemporary space processors such as the Moog BRE440.

Plans generated by multiple SAPAs are integrated by a Master Autonomous Planning Agent (MAPA) that de-conflicts global resources and forwards the final plan to the onboard task executive for implementation. Communication between components of the APS architecture is facilitated by a transport agnostic, cross subnet messaging service called Aspire (Adaptive, Scalable, Portable Infrastructure for Responsive Engineering) that can execute on a variety of processing platforms (operating systems and processor architectures). Aspire uses a common message wire protocol to pass data and configuration information between components. Aspire maintains a dynamic registry of components in the architecture and supports queries by data consumers for providers of data sources. This includes providers that deliver periodic or event messages (publish/subscribe) as well as services (request/reply). Aspire also supports named "domains". Although many Aspire components may reside on a single physical data network, domains allow for fine control over the visibility of, and access to, data between those components.

APS atop the Aspire complements the SB-SAT capability because the native Aspire transport is Internet Protocol (IP) compliant. As such, an APS-based planning solution could be supported out of the box on a satellite with SB-SAT equipment installed. Furthermore, a networked APS solution could be distributed among multiple SB-SAT hosting satellites and supporting IP-based ground infrastructure. This would naturally extends to other mission-enabling asset configurations - such as satellites in a federated constellation or cooperating clusters of satellites. The fact that the architecture is modular as well as distributable would also allow systems to be highly resilient. If a networked node in the system were compromised, the architecture components that reside on that node could be reinstated on another (or multiple other) nodes in the system to restore full capability. In AFRL-sponsored research, APS has been applied to a variety of distributed space system planning/orchestration use cases, most notably sensor tipping and asset cueing in which on-orbit sensor processing algorithms provide event triggers with metadata that result in action by other remote assets.

One of the most tangible benefits of the APS Architecture is how it streamlines the software life cycle. Initial integration is significantly eased by the use of XML-described data interface control documents (ICDs) delivered by the software components themselves. This ensures that components maintain an agreement on exchanged data formats. Perhaps more significantly, ground-support software meeting the Aspire messaging protocols can obtain the XML descriptions of any or all components and interact with them. This capability could yield significant dividends for command/control systems (or disadvantaged users in the field) as they could dynamically obtain the capabilities of deployed system elements and immediately interact with them. The modular aspect of the architecture would allow for straightforward upgrade late in the integration process or even post-deployment. Later in the service life of a mission, these same features could facilitate the complete repurposing of assets through the upload of an entirely new collection of autonomous software.

The next sections discuses some of the envisioned mission applications of an APS-based planning configuration on SB-SAT-enabled spacecraft for several relevant domain examples.

EXAMPLE APPLICATIONS

EXAMPLE APPLICATION: SEEK & REPORT

One example is based on DARPA's SeeMe program aims to enable the lowest echelon members of the U.S. military in remote locations to obtain satellite imagery in a timely manner for tactical operations and planning.[2] The constellation of satellites would be comprised of 24 spacecraft spread out in a common LEO orbit. Spacecraft would be tasked directly from the ground by users and requests are fulfilled on a First In First Out (FIFO) basis.[3] If the receiving satellite is unable to fulfill the task, the request would be passed on to subsequent spacecraft in the constellation via crosslink until fulfilled. Once the request is fulfilled, data would be sent to the ground user.

Recent potential applications of interest include imaging. Such constellations of imaging satellites could employ orbits inclined to some degree that precess slowly compared to the Earth's rotation (underneath), providing intermittent opportunities for ground users to post requests. A constellation of satellites would operate at an altitude of 300 km, giving a best case (0 degree elevation) horizon-to-horizon access time of approximately 8.7 minutes for each spacecraft. Assuming the orbit would be filled with enough spacecraft to ensure there would always be an asset in view as the orbit plane passes overhead, this access time would increase by a factor of one divided by the sine of the inclination as shown in Figure 4.

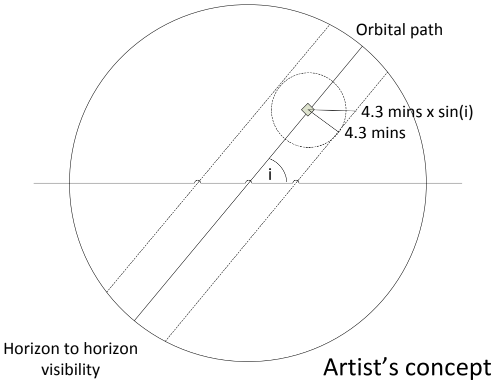


Figure 4: Maximum time of constellation visibility

For demonstration purposes, an orbital inclination of 45 degrees would result in a maximum constellation visibility of approximately 12.25 minutes. Each orbit should give two opportunities for contact (north and south-bound orbital portions) so that the maximum time (for a 45 degree inclination system) a user would wait to make a request should be in the order of 33 minutes. Given SeeMe's goal of taking 90 minutes or less to provide imagery at the mission level, this suggests that a maximum of roughly an hour would be required to ensure a request has sufficient priority for execution and that an asset is overhead to take an image and send it to the warfighter.

If one or more spacecraft in a SeeMe-like constellation were outfitted with SB-SAT terminals, then using the existing crosslink capability requests from warfighters could reach the entire constellation nearly immediately and without outage. Combining this capability with the facility to prioritize imaging requests continually on board the spacecraft (not in a simple FIFO fashion) should result in a net improvement in mission effectiveness for the warfighter. Lower priority requests might still take 90 minutes but the highest-priority requests would be improved immediately reducing the maximum time for image receipt to around 35 minutes as the constellation would come into view, take an image and send it.

It should be noted that this estimate does not take into account the fact that true spacecraft visibility times are less than 8.6 minutes, as the satellites rising over the horizon are not immediately visible to ground terminals. In addition, the ability for spacecraft to slew and take imagery off nadir (meaning imagery could be taken before spacecraft are in direct communications with the warfighter) has also not been considered. Both these factors suggest a further improvement in imagery delivery time with a system employing SB-SAT compared to current technologies.

EXAMPLE APPLICATION: GEO SSA

The United States has shown an increasing interest and commitment to effective space situational awareness (SSA) over the last decade. Of specific interest here is a potential way to use LEO assets to reduce potential risk to GEO assets. Figure 5 shows a envisioned system of LEO spacecraft monitoring GEO areas of interest, occupied by key assets. Given a constellation of three LEO spacecraft spread around an equatorial orbit, an area of the GEO belt could be continually monitored for evidence of objects of interest such as orbital debris from inoperative spacecraft or other space "junk" that could present potential risk to operational GEO assets.. To allow the LEO assets to remain small and low-cost in order to enable a quickly deployable system, it is envisioned relatively coarse sensors would be employed. It is beyond the scope of this paper but depending on the precise sensor characteristics and the number of GEO threat boxes to be continuously monitored, additional spacecraft could be added to the system to ensure, with effective handover operations, sufficient observational capability.

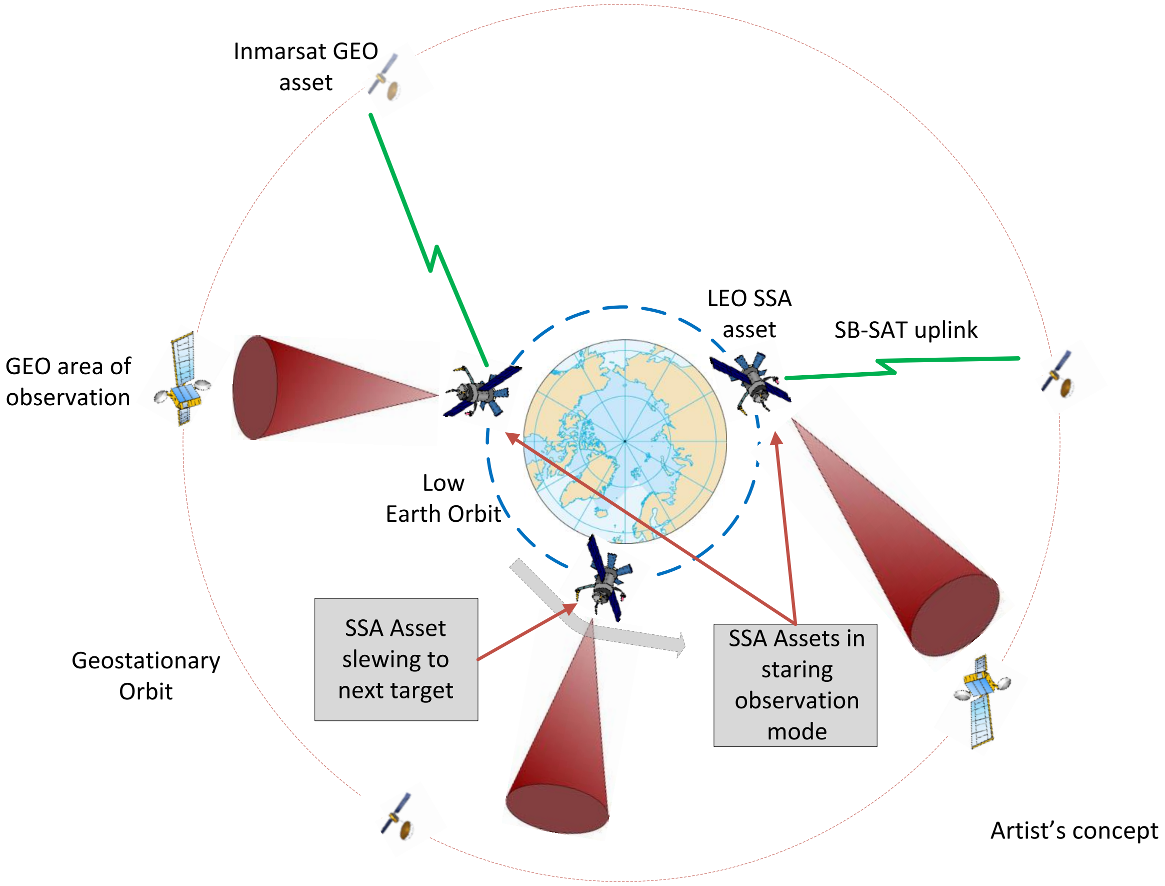


Figure 5: Envisioned LEO constellation for continual real-time monitoring of potential risks to GEO assets

To sum up, the SB-SAT would offer the GEO observation system a LEO-GEO-Earth link that would not employ GEO military communications spacecraft but instead use assets of a publicly owned company (Inmarsat). It should also be noted that the continual near-real-time uplink access to LEO assets allows immediate retasking. Such capability could be of value in the event of the loss of availability of other SSA assets or discovery of potential risks in unexpected GEO locations.

EXAMPLE APPLICATION: COMMAND AND CONTROL SIMPLIFICATION

There is currently great interest in the deployment of so-called LEO 'megaconstellations' that would consist of hundreds or even thousands of satellites[4,5] (Figure 6). Such systems are seen by some as the best way to connect the estimated more than three billion people around the world who do not have a reliable, accessible internet connection.

The potential of reduced latency of LEO communications compared to GEO communications could enable a wave of mobile satellite applications. In contrast, maintaining data connectivity with LEO assets that move across the sky requires handover capability as well as potentially complex payload operations to ensure LEO spacecraft do not interfere with existing GEO assets.

A potential application of SB-SAT is the command and control of large constellations. It is expected that as much autonomy as possible will be built into future spacecraft to reduce dependence on ground assets. However, for network assurance, it is expected that system operators will wish to receive regular telemetry from spacecraft both to understand and quickly resolve network outages and prevent such outages through trend analysis. Given the billions of dollars of investment required to set up these operational constellations, the value of the orbital domains used by these megaconstellations would force operators to minimize the creation and cascading effects of orbital debris. Indeed, NASA has already identified such constellations as posing a challenge for debris mitigation, especially given the expected orbits will prohibit natural orbital decay within the 25-year limit specified in U.S. Government standard practices[6].

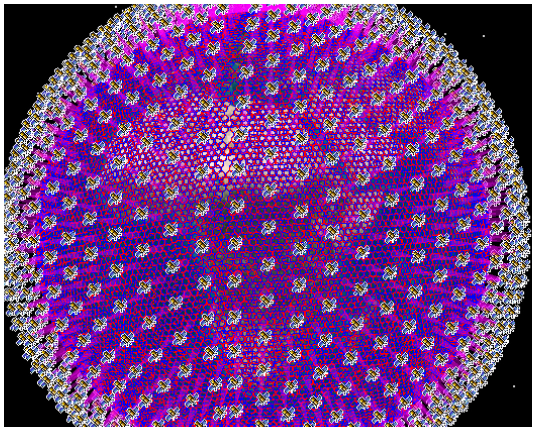
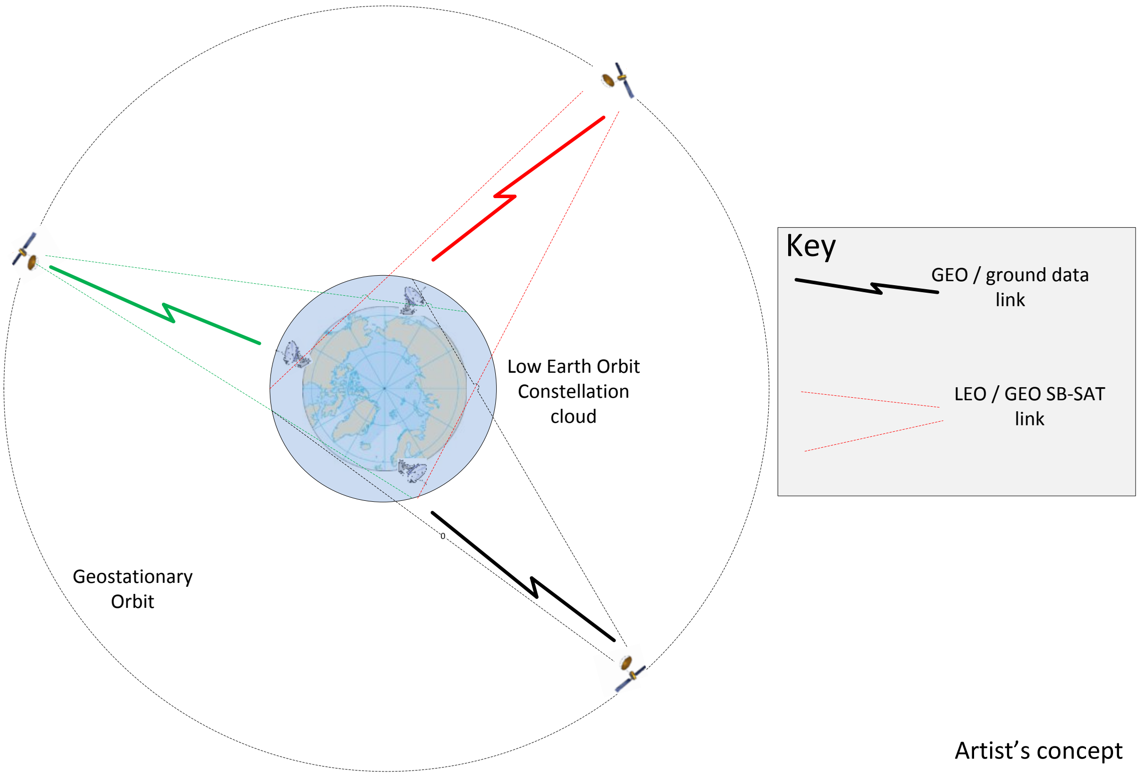


Figure 6: Command and control of large LEO constellations would be challenging

In order to ensure that spacecraft can be reliably tracked with the most up-to-date positional data to predict orbital collision hazards, and command satellites to make avoidance maneuvers, an assured data link is required. Traditionally LEO spacecraft rely on a network of ground stations and for polar orbits (planned for these megaconstellations) terminals are sited near the poles to give regular contacts through the day. Given that the multiple planes of the megaconstellations would all come together near the poles, the sheer number of ground assets required and their resource management would be challenging. Constellations could plan to utilize internet payload connectivity for command and control but this could add the risk of not ensuring communications in the event of a payload anomaly or internet outages.



Artist's concept

Figure 7: Envisioned on demand command and control for a large LEO constellation

Figure 7 shows how, with terminals placed on every LEO asset, SB-SAT could be used to both simplify spacecraft command and control in megaconstellations and potentially make them more robust. From LEO, SB-SAT could ensure nearly continuous and zero-latency command and control capability via GEO assets.

In addition to the command and control of spacecraft, Moog has explored the use of SB-SAT by the launch vehicle community. Typically, during ascent significant cost and complexity is required to ensure a reliable link between ground controllers and boosters. Typically, rockets employ Tracking and Data Relay Satellite System (TDRSS) links for this purpose and there is widespread interest in upgrading range operations (using systems such as automatic flight termination systems) to move all infrastructure onto the launch sites. The use of SB-SAT, plugged into an existing architecture, would take this a stage further and offer an uplink capability that currently is unavailable once launchers are out of range of ground radars. This uplink capability will become more and more valuable as rideshare launches[8] make more use of upper stage multiple-restart capabilities and even the re-use of first stages as explored by multiple launch providers[7].

CONCLUSION

The potential uses of nearly-real-time and continuous low-bandwidth communications from LEO are only just being realized and considered as SB-SAT nears flight readiness. New capabilities provided by SB-SAT could open up both entirely new mission applications and the ability to decrease cost and complexity of existing commercial and government systems.

From a resiliency point of view, this capability would allow a more dynamic and responsive systems that could both identify and use LEO assets to reduce potential risk to GEO assets. More tactically, remote warfighters could employ the new capability, together with in-orbit mission planning, to improve battlefield awareness, maximize safety and minimize the potential for inaccurate prediction of target behavior.

Potential commercial uses of the capability include a simplification of the command and control of very large LEO constellations or even launch vehicles to decrease operational complexity and ground asset cost.

The views, opinions, and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government

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