CubeSat ISR Constellation Mission Tailoring

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***Abstract*—This paper presents a modeling framework for the Intelligence, Surveillance & Reconnaissance (ISR) CubeSat constellation that combines optical payload and Software Defined Radio (SDR). The concept satellite is 8-16U depending on the payload resolution and the presence of warm-gas propulsion allowing for orbital changes and station keeping extending the operational time. Deployed in 500-km Sun-Synchronous Orbit (SSO), the system targets various mission profiles including ground target surveillance, maritime awareness, disaster response, and space object tracking.**

Evaluations use 30 deg deflection from the nadir pointing for ground imaging and 15 deg elevation SDR thresholds, incorporating realistic orbital transfer vehicle (OTV) deployment for idealized displacement and propulsion for station-keeping, collision-avoidance, injection phasing, and end-of-life de-orbit to counter drag. Single satellite benchmarks establish 5-day ground track repeats with dual day/night camera passes for change detection (crop health, target movement, mining) and about approximately 15 minutes of SDR observation per day for spectrum mapping.

Multi-satellite scenarios are optimized for revisit time, aiming to minimize the number of required satellites while maintaining the information domain dominance. Camera coverage achieves 12-hour windows with 5 satellites for diurnal tracking (e.g., shipping routes, border flows) and 6-hour with 10 satellites for intra-day events (e.g., convoys, wildfires). SDR configurations deliver 3-hour gaps via 4 satellites for broad awareness (e.g., interference detection) and 1-hour with 13 satellites for tactical bursts, all with global fallback despite diminishing returns on scaling.

With the today's market offering about 10-14 months from order-to-launch and vertical integration from level 0 data to fully evaluated outputs shows CubeSats hold a solid stake at the future of constellations.

***Index Terms*—CubeSat, Spacemanic, ISR, SIGINT, Constellation, Revisit, Coverage, SDR, Optical payload, Radio Spectrum mapping, SSO, Multi Domain Awareness**

I. Introduction

This paper presents a modeling framework for rapid first-iteration analysis of small-satellite constellation needs. The key parameter, the revisit time, quantifies how frequently targets of interest can be observed. The required revisit time directly affects the target orbital parameters and the number of satellites needed to fulfill the mission. In the case of the intelligence, surveillance, and reconnaissance (ISR), including signal intelligence (SIGINT), revisit times may need to be as short as hours or minutes, leading to the need for a quick first-iteration analysis framework.

The framework enables quick assessment of satellite configurations, orbital parameters, and payload capabilities to determine minimum constellation sizes for the desired coverage.

Three Spacemanic product satellites — built on the CORVUS Platform developed under the ESA Pioneer Programme — serve as realistic baselines: an 8U SIGINT PRO with Software Defined Radio (SDR) (Fig. 2), 16U ISR with multispectral camera (Fig. 3), and 12U ISR PRO combining SDR, hyperspectral camera and propulsion (Fig. 4). These enable diverse ISR/SIGINT tasks like Satcom surveillance, GNSS interference detection, maritime awareness, and disaster response (Fig. 1). We apply the framework to model SDR/camera coverage in Sun-synchronous orbit (SSO), determining minimum N_{sat} for revisits over a region of interest.

II. Satellite System Concepts

All three satellites consider a complete set of core subsystems. The design builds on the flight heritage components and the CORVUS platform developed under the European Space Agency (ESA) Pioneer Programme. This includes a scalable power harvesting and distribution system, redundant data handling unit for data collection and automated operations, communication modules in UHF, S-band and X-band, an advanced attitude control system for operations in sunlight and eclipse conditions. The ”PRO” satellites also include a propulsion for collision-avoidance, orbit maintenance, correction and adjustments which can positively affect the constellation design by ensuring orbital parameters more predictable.

The 8U SIGINT PRO (Fig. 2) and 12U ISR PRO (Fig. 4) integrate a SDR for Radio Frequency (RF) monitoring and signal collection. The envisioned design applications include (Fig. 1 shows the relevant bands):

- Radio Spectrum Monitoring
- Communications Mapping
- GNSS Interference Detection
- Radar Monitoring
- Satcom Surveillance

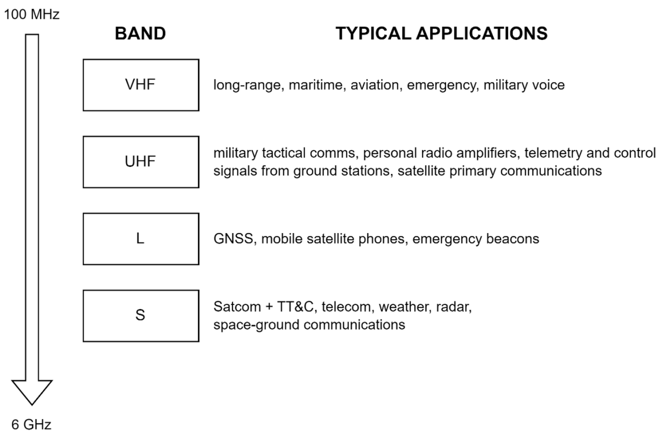

Fig. 1. Typical Bands of Interest in Signal Intelligence

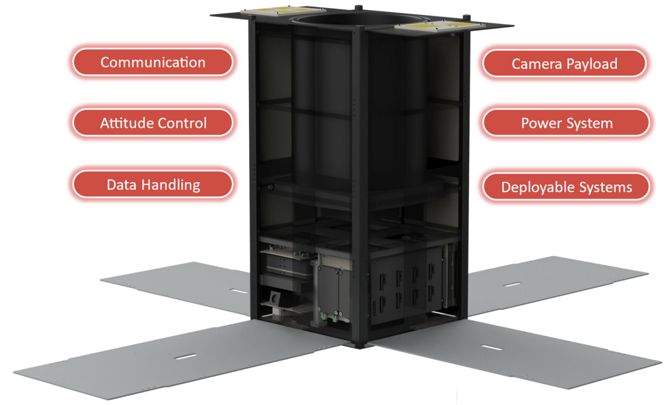

Fig. 3. 16U ISR by Spacemanic with a Multispectral Camera

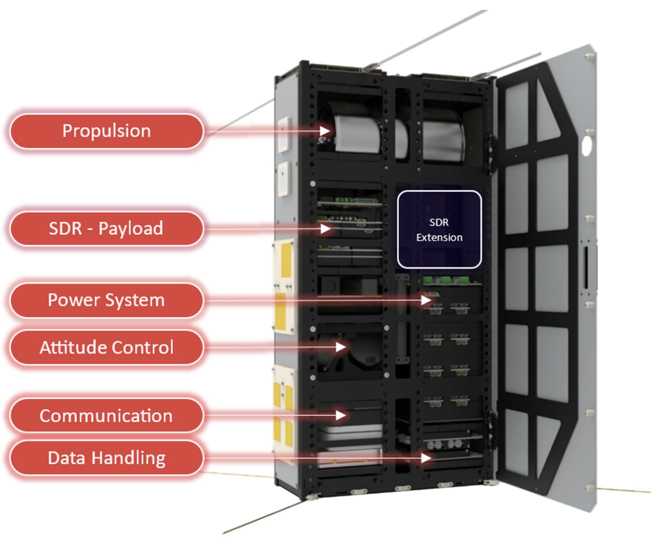

Fig. 2. 8U SIGINT PRO by Spacemanic with a Software Defined Radio (SDR) and Propulsion

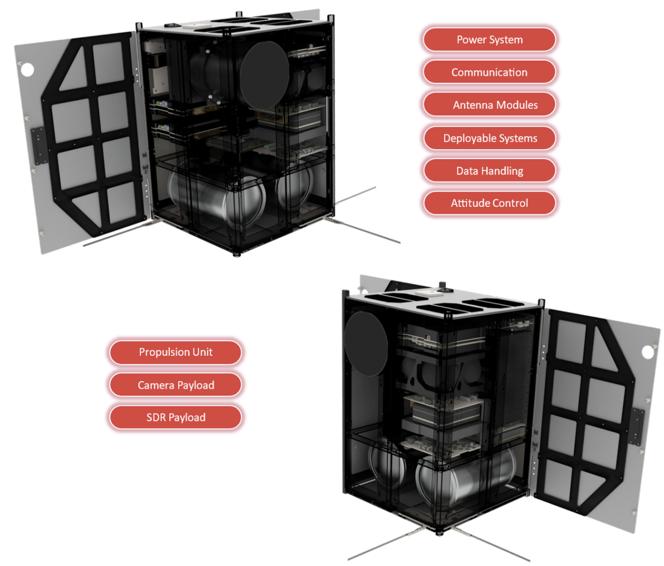

Fig. 4. 12U ISR PRO by Spacemanic with a Hyperspectral Camera, Software Defined Radio (SDR) and Propulsion

The 16U ISR (Fig. 3) integrates a multispectral camera with up to 1.5 m ground sample distance (GSD) at 500 km orbit altitude. The 12U ISR PRO (Fig. 4) integrates a smaller hyperspectral camera with up to 4.75 m GSD at 500 km orbit altitude. In both cases, the camera payloads can be utilized for wide range of applications, including:

- Ground Target Surveillance
- Space Object Observation
- Maritime Domain Awareness
- Disaster Response

III. Modeling Framework

The SDR and Camera coverage are analyzed separately. The real-world performance may vary depending on the detailed mission design, exact altitude of the satellite deployment and displacement of multiple satellites. Deployment through an Orbital Transfer Vehicle (OTV) may achieve the coverage and revisit times closer to the ideal scenario. The exact orbital parameters are usually subject to launch vehicle selection and OTV capabilities in case of small satellites deployment.

Satellite is assumed to be deployed to an ideal SSO with altitude of 500 km (justified by the availability with the SpaceX Rideshare missions, thus lower cost). The ground track of selected orbit repeats every 5 days and allows for a minimum of 2 visits to the same spot on Earth surface during this time period. Additionally, the place of interest can be covered not only from directly above but also during near-passes at an angle. During each pass the satellite has limited time window to collect data over a specific area. This naturally limits the amount of information that can be gathered from any single area during one pass.

The included propulsion unit providing the station-keeping ability extends the optimal operations lifespan by countering the orbital decay.

To evaluate revisit and coverage time of the SDR payload, an elevation of at least 15 degrees above horizon was chosen (typically about 10 degrees above horizon is used for S-band link). This choice is made to maintain line of sight from satellite to signal sources without the terrain mask obstruction and ensures a reliable detection of targeted signals. The Filed of View (FOV) of the antenna itself is not as wide to cover the whole area, but any targets within it can be observed by the satellite.

The camera coverage was estimated using a 30-degree cone. This is not representing FOV of the camera mounted on the satellite but rather the allowed deflection from the nadir pointing axis due to impact on picture quality and clarity, not only but primarily GSD. Other attitudes could be considered at the later detailed design phases at the cost of reduction in the final image resolution parameters to decrese the revisit time.

The simulations themselves were conducted using SaVi. Theoretical basis for the chosen constellation is variant of Walker-Delta also known as rosette [1], but due to SSO having comparatively small difference from polar orbit it is functionally less dissimilar to Walker-Star than for other families of orbits. The core approach was focus on optimizing the revisit time of sparsely populated constellations.

While most work is currently typically performed on complex large constellations with global coverage and near-zero local downtime, our focus is on investigating smaller scale, more affordable, and attainable constellations. The resulting constellation usually trends towards global coverage [1] with shortening revisit times, there are certain approaches that focus on equally utilizing both visits to target area. The natural spacing of the two visits by the same satellite heavily depends on the latitude of the target area, and additionally one occurs on the day side of the planet and one during the night. This can present challenges disqualifying one of the visits from being utilized by payloads either due to technical limitations or observation target being time dependent (eg. light pollution is observable only at night, thermal islands are also better observable shortly after sunset).

Further specialized optimization can be made by adjusting the orbit, which in certain cases can lead to shortening the operational lifespan due to early fuel depletion or drastic increase in cost of the constellation as dedicated launches become necessary. This has to be evaluated on case by case basis as every mission is slightly different and even with a finished product, enough space needs to be left for sufficient tailoring for the specific purpose.

A. Propulsion Considerations

By maintaining the satellite at a chosen orbital height, the mission can preserve the performance it was originally designed for. Even small changes in altitude will alter orbital period [2], revisit time and overall operations planning, so the ability to hold the orbit translates into more stable data quality and predictable mission behavior.

As an illustration, a nominal altitude of around 500 kilometers gives the satellite an expected passive lifetime of roughly 5 years, with performance drifting as the orbit decays (Fig. 5). When propulsion is used for station keeping, the satellite can maintain its intended orbit for a far longer period, keeping sensors and payloads operating in optimal conditions and only initiating a final de-orbit when the mission ends.

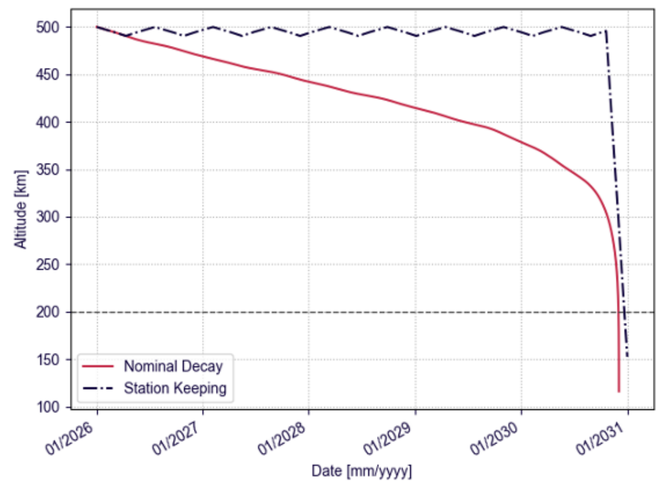

Fig. 5. Natural vs. Station Keeping Decay (Ideal Case Scenario)

IV. Model Scenarios

Applying the framework to 500 km SSO baselines reveals how payload constraints drive constellation scaling. We target European coverage (Brno-centric, lat 35–70°N) for SDR (15° elevation) and camera (30° nadir cone), evaluating single satellite baselines against 1 h or 3 h, and 6 h or 12 h revisit time goals for SDR and camera, respectively.

A. SDR Coverage

A single 8U SIGINT PRO yields $\sim$ 3x15 min observations per day of the Brno area (Fig. 6) with the visit of every global location on Earth at least once per day. With a single satellite, the time between revisits is inconsistent and will change depending on latitude of the target area observed, which makes it suitable for applications accepting infrequent data updates (e.g. continuous period mapping of RF spectrum in the target area).

However, tailoring to 3 h maximum revisit time requires just 4 satellites (Fig. 7), balancing the cost for spectrum monitoring constellation deployment with frequent data update. A satellite configuration of this type is well suited for missions that require frequent situational awareness across a broad region but do not require continuous presence. The constellation can support applications such as border activity monitoring, maritime domain awareness, tracking of communication patterns across large regions or regular verification of areas of interest.

For 1 h revisit time (e.g., radar/Satcom detection), 13 satellites ensure ground target near-constant cover with global coverage leading to revisit of any point of Earth within 1 hour (Fig. 8). This type of constellation can support rapid identification of e.g. newly active transmitters, detection of

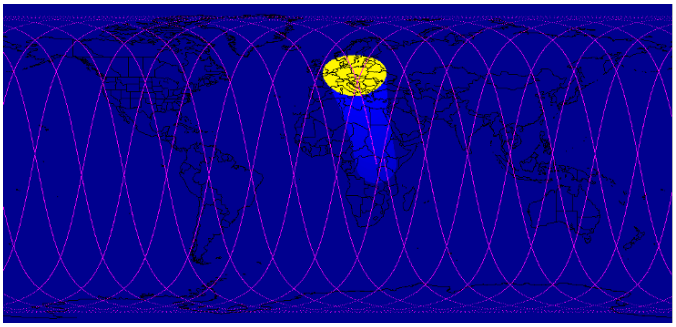

Fig. 6. Simulation of Single Satellite with SDR and its Ground Track over 24 Hours

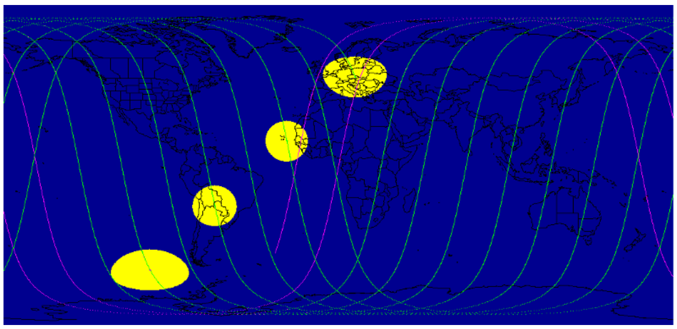

Fig. 7. 3-hour Projection of a 4-Satellite SSO Constellation with SDR with 3 h Revisit over Brno

short signal bursts, confirmation of interference events, observation of activity around critical infrastructure or monitoring of military communications during evolving situations.

B. Camera Coverage

Single 16U ISR offers 2 visits in a 5-day repeat (day/night) for the Brno area, latitude-dependent, driven by FOV and target pointing (Fig. 9). The end user can collect imagery to track slow or medium paced changes, such as construction progress, movement of large equipment, environmental conditions, changes in coastline features, activity around facilities, or verification of known points of interest. The mix of daylight and night time passes also enables observation of lighting patterns, thermal signatures, energy use indicators and detection of activity that is more visible after dark. This makes a single

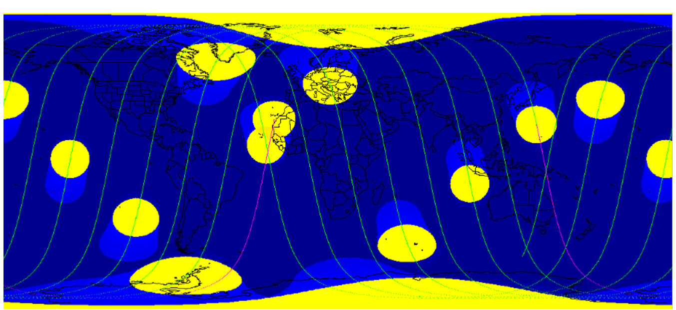

Fig. 8. 3-hour Projection of a 13-Satellite SSO Constellation with SDR with 1 h Revisit over Brno

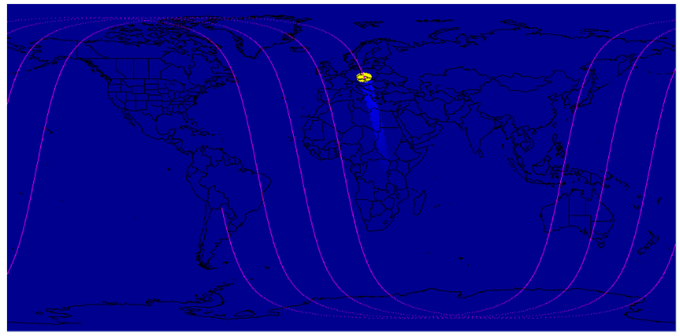

Fig. 9. Simulation of Single Satellite with a Camera and its predicted ground track over 24 hours

satellite useful for broad area awareness, change detection and long-term monitoring tasks.

5 satellites achieve revisit every 12 hours (Fig. 10), ideal for tracking day-to-day rhytm of the target area. Orbits not only provide coverage of chosen location but of any location globally every 12 hours. With one imaging opportunity roughly every twelve hours, an end user can follow developments that evolve on a day-to-day rhythm. This includes tracking movement of ships or ground convoys, monitoring activity around key facilities, observing infrastructure operations, watching changes in terrain conditions or verifying events reported through other channels. Because the constellation also provides a global 12-hour revisit pattern, users can extend their monitoring to additional regions when needed. The local time of each pass will differ outside the primary area, but useful imagery can still be collected for situational awareness, anomaly confirmation or rapid checks of emerging points of interest.

With 10 satellites, the revisit time reduces to 6 hours (Fig. 11)., despite diminishing returns beyond.This configuration is well suited for missions that need frequent updates on activity in a specific region. With an imaging opportunity every six hours, the end user can monitor changes that occur within a single day, follow short lived events, track movement patterns, assess developments around sensitive sites and respond more quickly to emerging situations. Naturally, the constellation can offer this coverage globally, although with an important caveat. As the time distance between the day and night visits depends heavily on the target latitude, it is possible that areas outside of the primary target's latitude will experience irregularities in revisit times at certain points.

V. Discussion

The main constraint of the methodology is the positioning of the satellites in SSO. While the SSO does posses a certain set of drawbacks, most impactful of which is inability to directly observe poles, the benefits do certainly outweigh them in case of sparse constellations with longer revisit times.

Additionally, for most payloads, observation of poles is possible albeit at reduced performance as no passes are directly over the pole. With considerable time spent outside of areas

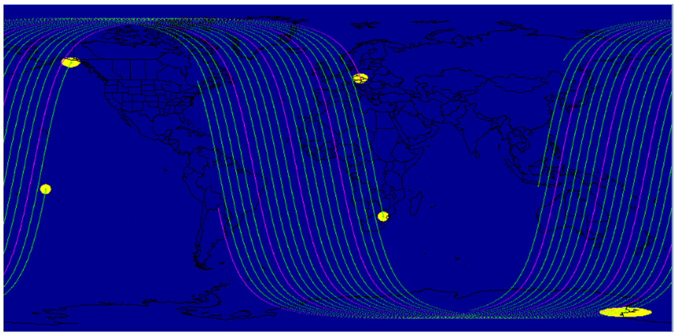

Fig. 10. 6-hour Projection of a 5-Satellite SSO Constellation with Cameras with 12 h Revisit over Brno

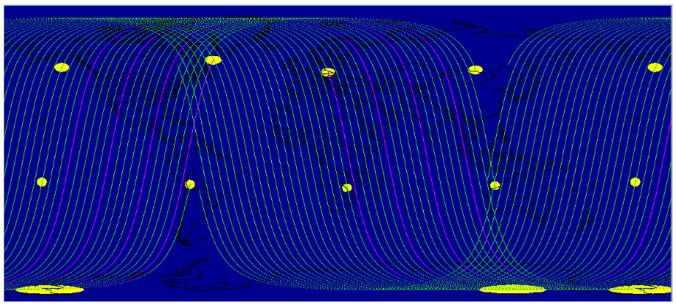

Fig. 11. 6-hour Projection of a of 10-Satellite SSO Constellation with Cameras with 6 h Revisit over Brno

of interest in lower latitudes it is prudent to consider other orbits. While those were not at the core of interest for now, as attaining those orbits often means a dedicated launch which vastly increases the cost of the mission, it is undeniable that they can offer big advantage in the scope of the current global events. Nevertheless, the presented model scenarios may serve for ITU regulatory compliance verification, disaster management in remote areas [3], support future urban planning and management by providing periodical information on heat islands over time [4], and many other. Additionally the platform itself can support varied payloads even further expanding the optional applications.

The combined operation of the 12U ISR PRO enables the user to exploit both optical and RF coverage of target area, only affecting the revisit time by increasing the number of satellites in the constellation. The combination of the SDR and camera enables Automatic Identification System (AIS) tracking through SDR coupled with optical imagery for maritime vessel tracking.

To prevent extensive drift of the ground track, the parameters (for example inclination and eccentricity) of the orbit need to be balanced, which can lead to more eccentric orbits which are not ideal for measurements at all altitudes that spacecraft will achieve or will yield data of diminished quality. Additionally, need for precise orbit insertions using an OTV and maintenance past insertion even further exacerbates the need for propulsion system for station keeping.

SSO allows us to combine almost circular orbit with frequently repeating ground track. But constellation consisting only of satellites on various SSOs follow a trivial rule of decreasing revisit time. Doubling the amount of satellites roughly halves the revisit time, which allows for simple back-of-the-envelope calculations at the initial stages of design, supporting rapid prototyping of possibilities for the end-user.

VI. Conclusion

This paper demonstrates a first-principles modeling framework for sizing CubeSat constellations based on revisit time, applied to Spacemanic's 8U SIGINT PRO, 16U ISR, and 12U ISR PRO product satellites. Key results show SDR requires 4 satellites for 3 hour or 13 satellites for 1 hour revisits, while cameras need 5 satellites for 12 hour revisit and 10 satellites for 6 hour revisits, with propulsion enabling stable long-term operations and a long-term reliability of the coverage performance (Tab. I).

TABLE I
Model Scenarios Summary (500 km SSO)

Sensor	**Area of Interest**	**Revisit Time [h]**	**Satellites Needed** N_{sat}
SDR	Brno, Czech Republic	12 to 24	1
		3	4
		1	13
Camera		60 to 120	1
		12	5
		6	10

The framework proves effective for NewSpace mission planning in spectrum monitoring, area monitoring, target surveillance, maritime awareness, and disaster response. Future extensions include multi-payload synergies, dynamic target area selection, propagators with increased fidelity incorporating atmospheric drag and solar radiation pressure, optimization of Walker-Delta phasing especially for non-SSO allowing for improved coverage with lower number of satellites.

References

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