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TECHNIQUES FOR LEO CONSTELLATION DEPLOYMENT AND PHASING UTILIZING DIFFERENTIAL AERODYNAMIC DRAG

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The Cyclone Global Navigation Satellite System (CYGNSS) mission is a recently selected NASA Earth Venture investigation seeking to improve tropical cyclone (TC) modeling and prediction through remote sensing observation of the ocean surface winds in the TC inner core with a LEO constellation of 8 micro-satellites. An initial study investigated trades and techniques for the deployment, initial phasing, maintenance, and collision avoidance of the satellite constellation, using differential drag as the only means of orbit modification, to reach an evenly spaced coplanar configuration for the 8 satellites in a circular orbit. This paper reviews these trades and outlines the current CYGNSS mission design.

INTRODUCTION

The CYGNSS mission enables a more in-depth measurement of the strength of tropical cyclones, including hurricanes, by using direct and reflected Global Positioning System (GPS) signals to precisely locate each satellite and measure the ocean surface roughness with high time resolution, providing a detailed look at the wind speeds in a developing cyclone. Feeding these new measurements to models of atmospheric dynamics enables the study of the air-to-sea boundary interactions in the inner core of these rapidly changing storms. Analyzing the integrated dynamics will resolve the mission science goals: to determine how tropical cyclones form; whether or not a storm will strengthen; and if so, by how much, leading to advances in forecasting and tracking methods.

The constellation consists of 8 nadir-pointed microsatellites orbiting along a coplanar 500 km orbit with a 35-degree inclination, covering the most active latitudes for cyclone development. The altitude provides an orbit period of about 95 minutes, and gives at least 75% coverage of the entire latitude band every day. Each satellite measures four simultaneous GPS reflections per second, resulting in 32 wind measurements every second as the constellation covers the globe. This paper reviews the current CYGNSS mission design and requirements, and examines the trades

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and analyses that are underway to further define the deployment sequence, constellation phasing and maintenance via differential drag, and collision avoidance considerations.

CYGNSS MISSION DESIGN REQUIREMENTS

The current design of each microsatellite provides for a mass of 22.2 kg (current best estimate without margins) with foldout solar panels. The attitude determination and control system (ACS) consists of a combination of two horizon sensors, a magnetometer, three orthogonally positioned torque rods, and a momentum wheel for pitch control. The satellites have no propulsion system, and rely solely on pitching the spacecraft with the solar panels deployed to create drag for orbit adjustments, also known as the differential drag technique.

Launch is expected no earlier than October of 2016, with a 2-month commissioning period before the first science observing period begins. The satellites can be released individually or in pairs from a common deployment module with configurable release angles and initial velocities. The deployment trades investigate the optimum deployment angle and velocity for every satellite that minimizes the probability of collision through the initial commissioning phase of operations, assuming no means of orbital adjustment is available in case of launch anomalies.

The mission science and lifetime requirements, and instrument measurement capabilities, dictate an orbit altitude of 500 km +/-25km at beginning of life. Above 525 km, science coverage decreases due to longer propagation delays, and below 475 km, the worst-case lifetime starts being reduced below the desired 2 years. Further lifetime analysis has shown that even at 475 km, the lifetime could be as much as 5 years, giving some extra room to lower the minimum altitude. The inclination of 35 degrees was chosen to maximize the percentage of storms that could be imaged, based on historical records, while maintaining the minimum science requirement of at least 70% coverage over 24 hours. This requirement drives the number of satellites, and the constellation can meet it with only 7 satellites in case one is not operational.

After successful launch and release, the satellites must be positioned in the constellation configuration that meets these science requirements. Three constellation configurations have been chosen for preliminary analyses: an evenly spaced arrangement where all eight satellites are placed in a coplanar orbit 45 degrees apart in phase from each other; a train of satellites that are that provide higher time resolution data over an active TC; and an option of no active satellite management, allowing the constellation to drift. The evenly spaced configuration is primarily investigated in this paper for the establishment of the constellation.

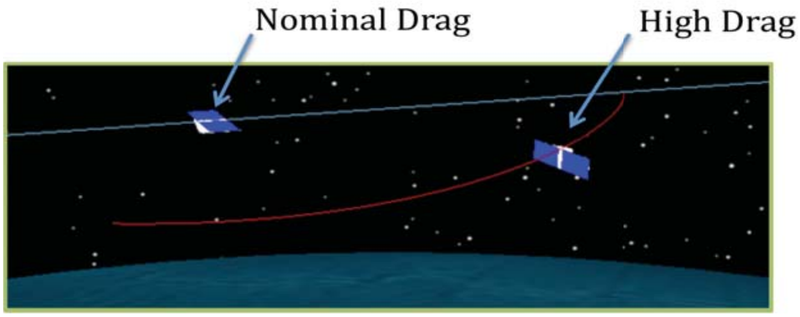

Figure 1. CYGNSS, High Drag vs. Nominal Drag Maneuvering

The loose pointing requirements of 5° control and 2.7° knowledge, both 3-sigma values, during science operations allowed the ACS to be designed without needing propulsion. Long settling times of up to three orbits are allowed for maneuvers, and during deployment, tip-off rates of less than 5 deg/sec are recoverable within 3 orbits. The ACS performs maneuvers by pitching the spacecraft up to 81 degrees to enter the "high-drag" configuration, where the solar panels face the ram direction, in its LVLH (Local Vertical, Local Horizontal) Relative Attitude mode. These driving requirements for the ACS have been met with the current design.

Once deployed, the satellites are slowly phased into their respective locations in the constellation by the differential aerodynamic drag technique. Nominally the solar panel wings face in the zenith (-Z) direction. Pitching the spacecraft into the high-drag attitude, so the undersides of the solar panels face the ram direction, increases the drag profile of an individual satellite, as seen in Figure 1. This configuration causes the satellite to drop in its orbit slightly, speeding up relative to the rest of the constellation. Returning to a nominal attitude after a specific duration stops the descent, but leaves the satellite in a new, lower orbit. By performing this sequence for all eight satellites, the constellation can slowly be phased into the equally spaced configuration with all the satellites ending up at the same baseline orbit altitude.

The use of differential drag as a means of satellite control is not well established. The concept has existed in the literature for decades[1,2], but details on flight applications are difficult to find. The CYGNSS team recognized that the mission design would be a challenge and launched a detailed analysis to understand the planning and constraints using the differential drag technique. The slow maneuvering capability and limited control authority are the primary concerns with this system.

The phasing algorithms that have been developed solve for the optimal duration in the high-drag configuration for each satellite and in the combined constellation. Constraints for the phasing trade study are to minimize the overall altitude loss and to minimize the total time required for phasing. Preliminary results give about a 95-day commissioning period needed to position all eight satellites. The algorithms and results are discussed in the Constellation Maintenance section.

Once science operations begin, the pointing requirements are tightened to meet the science requirements. Maneuvers are only performed if the health and safety of the satellite is at risk, as in a collision avoidance scenario, or for constellation position maintenance, and can be timed to minimize impact to any ongoing science operations.

Finally, this paper examines collision avoidance over the constellation lifetime. Conjunction analyses are performed both for close approaches between the deployed satellites, and conjunction probability and frequency between the constellation satellites and non-constellation objects. A feasibility study reviews the previously developed phasing strategies for use as methods of collision avoidance.

For each of these studies, primary optimization considerations include: 1) maximizing control authority; 2) minimizing altitude loss; and 3) maximizing required time between maintenance maneuvers. These trade studies addressing methods of deployment from a single launch vehicle deployment module configuration, orbit phasing, maintenance, and collision avoidance reveal optimal input parameters and orbit adjustment methods.

DEPLOYMENT

The eight satellites are attached to a deployment module (DM), which is permanently attached to the launch vehicle (LV) upper stage, and are released at the deployment altitude of 500 km, +/-25 km including launch injection uncertainties. They are organized in two rings with 4 satellites on each ring, with 45 degree spacing, and can be deployed from the DM in any order with an initial velocity change (delta-V) up to 1.6 m/s using tunable separation springs. Figure 2 shows the stack configuration for the satellites on the DM.

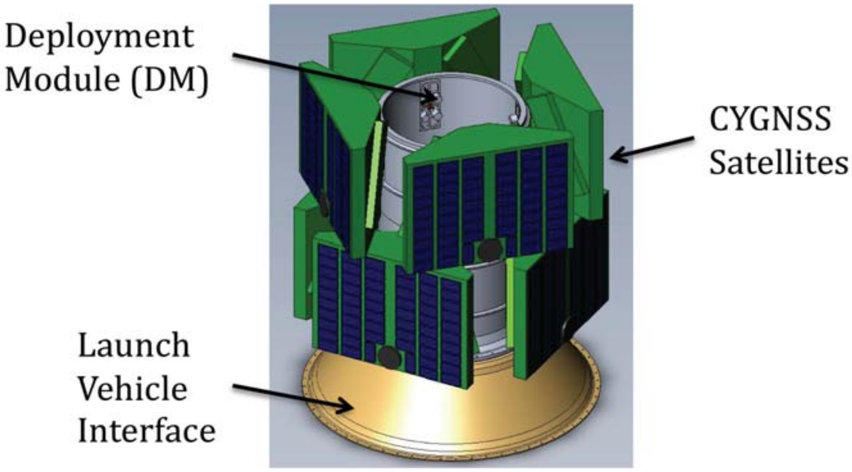

Figure 2. Deployment Module Stack Configuration

The primary deployment aim is to maximize the distance from one satellite to its nearest neighbor and the DM as the satellites separate from the DM. The deployment analysis measures the separation distance over the first half orbit. A secondary consideration is to maintain a minimum separation distance of 500 m over at least 2 months in case of anomalies and for initial commissioning activities. Finally it is desirable to use an initial delta-V that is as low as possible while still achieving comfortable separation distances at ½ orbit, because a larger delta-V at separation will require a longer constellation commissioning time. Once the nearest neighbor requirement is met, the satellites are propagated out for 6 months to verify the separation distance is acceptable.

The satellites could be deployed individually or in pairs. If deployed individually, the launch vehicle upper stage must fire thrusters to compensate and regain its original attitude for the next separation. To maintain stability of the DM and minimize the wait time between deployments, the CYGNSS team selected a deployment strategy where opposing pairs are released at the same time. In order to cover this critical phase during a single communications ground track, there is a requirement to complete all the separations within 5 minutes.

The DM, with the satellites mounted for release in the X-Y plane (Ram - Cross-track), can be rotated around its nadir vector, so that the angle of separation, or clock angle, is at any desired cross-track angle, with a 3-sigma pointing error of 3 degrees. An initial study of the release angle that maximized the half orbit separation distance, ranging from 0 to 45 degrees, showed a separation clock angle of 11.25 degrees was optimal if all the satellites separated simultaneously.

These results then fed more detailed sensitivity and Monte Carlo analyses using the Systems Tool Kit (STK) software, including separations in pairs instead of simultaneously. The sensitivity study investigated sequencing the pairs, separation velocity, clock angle, timing between successive pairs, and separation timing accuracy.

The DM rotates by the clock angle once only due to the limited propulsive capability of the DM as well as the desire to finish deployment during one communications pass. Therefore the separation angle for each satellite is set by its position on the DM and the clock angle. Figure 3 gives the satellite sequence numbering. The separation pair sequencing evaluated 24 permutations of satellite pair release sequences. The study showed that the minimum half-orbit miss distance tended to occur between the vehicles with the most similar in-track velocity components, i.e., between satellites 1 and 8 or satellites 3 and 6. To achieve the largest overall spread of the constellation at half-orbit, the pair with greatest in-track velocity component should be released first with the remaining pairs released in order of decreasing in-track velocity: 1-3, 6-8, 5-7, 2-4.

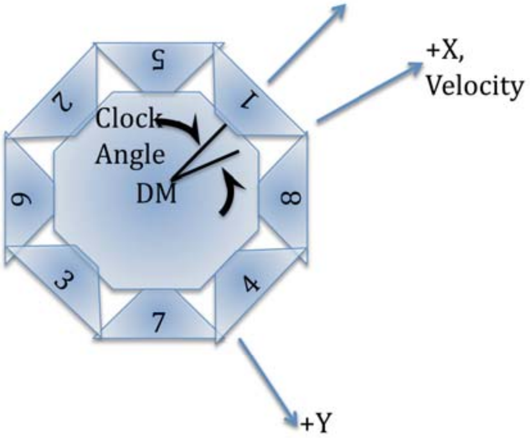

Figure 3. Deployment Module Positioning and Deployment Sequence

In the study of separation velocities it was confirmed that half-orbit miss distances tend to increase with increased separation delta-Vs. The velocity was limited to a max of 1.25 m/s accounting for possible errors, and looking at 2 pairs at a time, it was found that reducing pair 6-8 to 1.1 m/s provided a decent increase in miss distance of 500 m at half an orbit. Scaling the separation velocities up or down by a common factor provided for a predictable increase or decrease in miss distance independent of clock angle. Looking again at the clock angle range using the chosen separation sequence and velocities, the analysis showed that an optimal angle of 15.35 degrees gave a minimum half-orbit miss distance over the constellation of 3.06 km.

Adding in 3-sigma error distributions for separation azimuth and elevation (+/- 3 deg), delta-V (+/- 0.05 m/s), and separation timing (+/- 5 sec), and reducing the overall delta-V's by a common factor of 2.5 to 0.5 m/s for pairs 1-3, 5-7, and 2-4, and to 0.44 m/s for 6-8, yielded an average minimum miss distance of 1064 m over 50,000 runs, as shown in Figure 4. The delta-V reduction allows a shorter commissioning time and a lower risk separation from the DM because of easier separation recovery.

Over 6 months, with this deployment strategy, the constellation will slowly spread out. Eventually the satellites start clumping back close to each other, but not close enough to be less than the minimum requirement for miss distance. This behavior is advantageous in case of any anomalies where the constellation could not be phased as planned. For instance, if the launch injection altitude does not leave enough room for the altitude drop required for active phase control, the satellites would not be in any danger from each other, and the mission science return would still meet minimum requirements. This deployment strategy is the current baseline for CYGNSS.

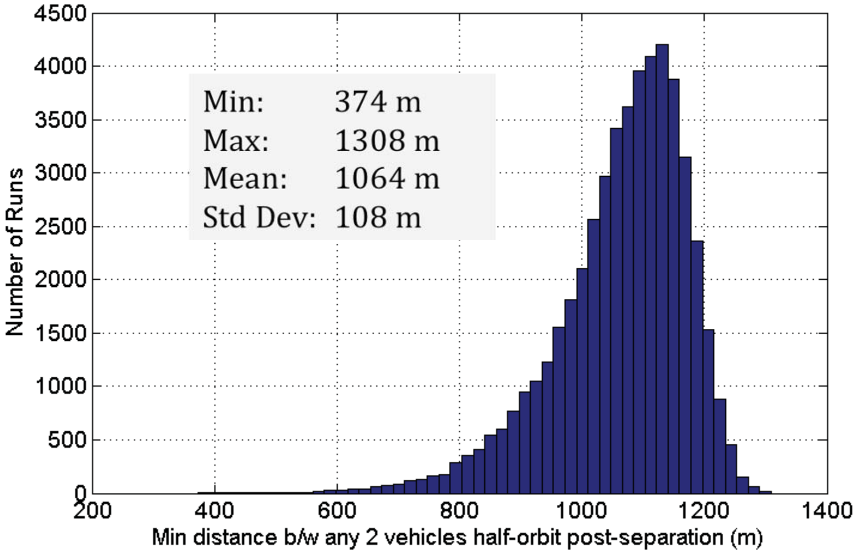

Figure 4. Close Approach Distance Results after a Half Orbit

CONSTELLATION ESTABLISHMENT

The initial plan for constellation establishment allowed the satellites to drift following deployment without any attempt to change the orbits further. In this case the satellites have varying orbital altitudes from the different deployment angles and velocities, and they drift apart then regroup as they approach each other from the other direction as a regular behavior of the constellation. This approach is simplest but it does not meet the baseline science requirement of 70%, averaging 5-10% less. It remains a backup option in case of an anomaly. Active control to reach an equally spaced constellation exceeds the coverage requirement with margin of 10%.

By using differential drag the constellation can be carefully controlled to provide the desired spacing between the satellites, and each satellite can be steered to approximately the same altitude to stabilize the constellation and minimize any drifting between satellites. It is helpful to think about the maneuvering for the constellation in terms of the relative phasing and phase drift between satellites and not absolute phasing around the orbit. The orbit altitudes also are relative. During the lifetime of the constellation, all satellites are constantly losing altitude due to nominal drag, however satellites in the high drag orientation will lose altitude at a higher rate than those in the nadir pointing orientation. Altitude becomes a budgeted resource since the constellation altitude loss that occurs for any maneuver is included in the evaluation of the maneuver risk.

Actively controlling the phasing of the constellation assumes a way to define and measure the phasing so a convention is established as follows. The first pair of satellites to be deployed (1 and 3) are deployed with the greatest delta-velocity (delta-V) in the direction of the velocity (minus the clock angle) for Satellite 1 and in the opposite direction of the velocity for Satellite 3, which by definition makes them the highest satellite in the constellation and the lowest satellite in the constellation, respectively. After the deployment, all of the satellites in the constellation will appear to move away from Satellite 1 in the same direction so the position of Satellite 1 is defined as the reference of zero degrees around the orbit for the phase angle. A satellite with a phase angle of 180 degrees would be located on the opposite side of the orbital circle relative to Satellite 1. The phase rate of a satellite is the rate in degrees/day that it is moving around the orbit relative to Satellite 1.

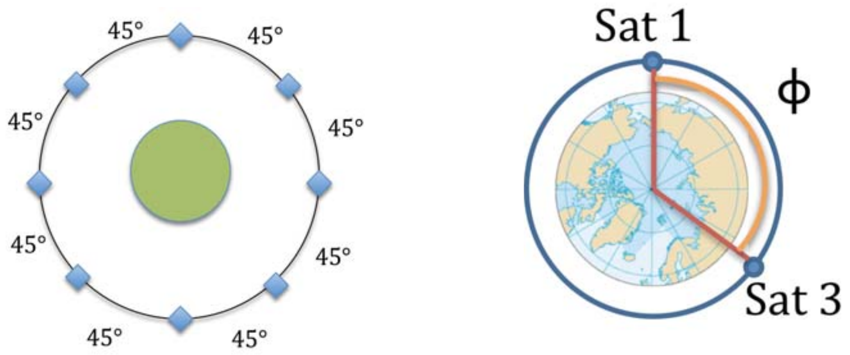

Figure 5a: Equally Spaced Constellation, 45° Separation; b: Satellite Phase Angle, ϕ, Relative to the Reference Satellite 1.

The target constellation configuration has all satellites separated at 45-degree intervals around the orbit with a phase rate of 0 deg/day such that the constellation remains fixed over time. Figure 5 shows the desired configuration along with a definition for the phase angle.

The differential drag maneuver for only two satellites is examined first. One satellite (the maneuvering satellite) performs an attitude maneuver to increase its drag area relative to the other satellite (the reference satellite). This attitude change causes the satellite to experience a higher drag force relative to the other satellite, which in turn causes it to drop in altitude at a faster rate. The lower altitude in turn causes the satellite to have a higher orbital velocity (and shorter orbit period), which will cause the satellite to move faster along the orbit than the reference satellite.

Once the maneuvering satellite establishes the desired drift rate between itself and the reference satellite it returns to the low drag orientation while it continues to drift away from the reference satellite. When the maneuvering satellite reaches a desired phase separation from the reference satellite the roles are reversed, and the reference satellite moves into a high-drag orientation. Once the reference satellite has dropped to the same altitude as the maneuvering satellite, the relative position between them becomes fixed and both satellites return to the low drag orientation.

For any pair of satellites the process is straightforward, but to simultaneously maneuver eight satellites into a desired configuration is complicated by the fact that any time one satellite maneuvers, its phase position and rate will change relative to the other seven satellites. A few approaches were developed to solve this problem.

Drawing on approaches used in control system development, the satellites are viewed on a phase plane with the error in phase, ϕ_{Err}, drawn along the x-axis and the phase rate, $\dot{\phi}$, drawn along the y-axis. Once a satellite is moved from its initial state to the origin, it has achieved its desired state. Figure 6 shows the maneuver sequence on the phase plane. The satellite has an initial low phase rate due to deployment tipoff. The satellite maneuvers to increase this rate and then returns to the low drag orientation. At a precisely calculated time, the reference satellite (Satellite 1) then performs a maneuver to decrease the phase rate between the satellites down to zero (by maneuvering to the same altitude) at a time when the phase error will be at zero.

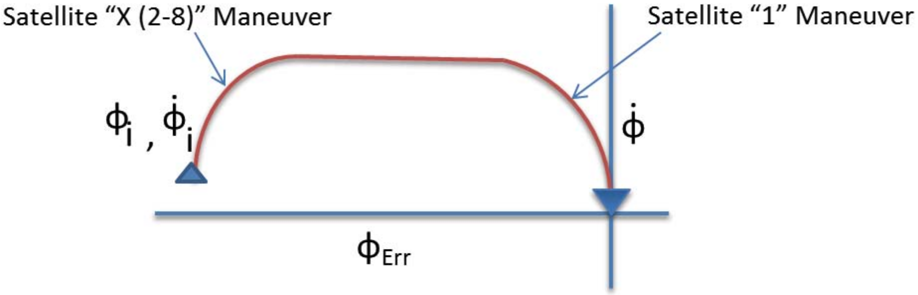

Figure 6: Phase Plane View for Maneuvering Only Two Satellites

The maneuver depicted in Figure 6 represents the simplest case and the fastest way to maneuver a satellite to its desired state. Other cases increase the complexity of the maneuver but also introduce degrees of freedom that allow the simultaneous maneuvering of multiple satellites into position, including a Delayed Start, an Overshoot, and a General Case.

The initial phase rate after deployment for a given satellite is $\dot{\phi}_i$, and the phase rate relative to the reference satellite is $\dot{\phi}_M$, and is the maximum phase rate difference between the phasing satellite and the reference satellite. The phase acceleration, $\ddot{\phi}$, is a constant, determined by the difference in drag between the high drag and nominal drag attitude of the satellite divided by the mass. For all cases, once the constellation is completely phased, the difference in the phase rate between the reference satellite and the phased satellite should be zero.

For the Delayed Start maneuver, there is a delay time between the initial state and the first maneuver as shown in Figure 7.

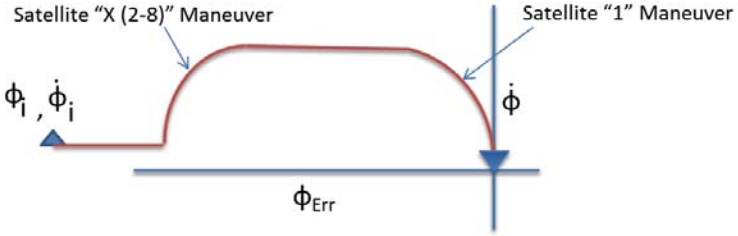

Figure 7: Delayed Start Maneuver

In the Overshoot case, the satellite drifts past the target state and the reference satellite maneuvers below the maneuvering satellite causing the maneuvering satellite to drift back towards the target phase and necessitating a third maneuver to fix the phase, shown in Figure 8.

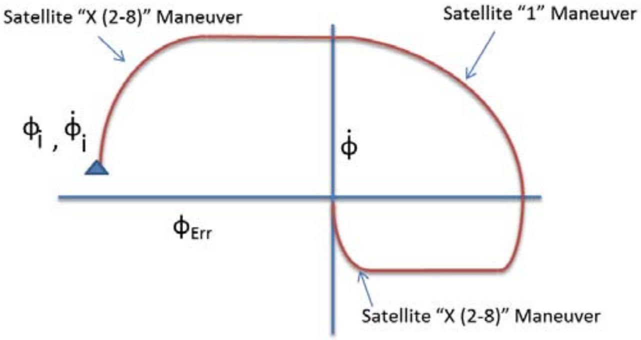

Figure 8: Overshoot Maneuver

Considering both of these cases together a General Case was developed which includes a delayed start along with an overshoot maneuver, as seen in Figure 9.

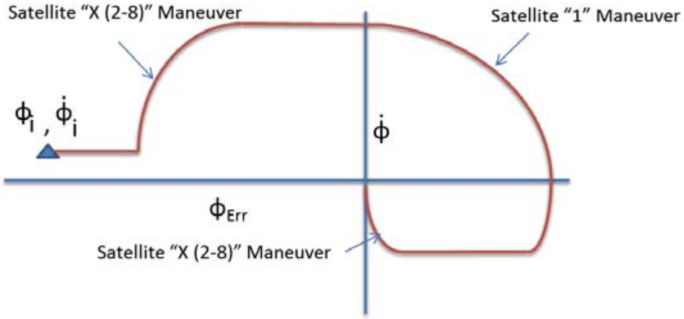

Figure 9: The General Case Maneuver Sequence

In order to establish a timeline for the maneuver sequence and to determine the required maneuver durations, a set of equations were developed, based on the equations of motion, that define the phase position and the time for each phase. For the General Case, the problem can be split into six parts (0-5) for each operational segment. Figure 10 shows the General Case with each phase of the maneuver sequence annotated in terms of the change in phase. For any given sequence, the change in phase of all phases should total the initial phase error so that the satellite ends up at the desired phase position.

Some variables are defined as inputs available to the mission planner to adjust the timeline to meet operational constraints. For example, the initial time delay prior to starting the first maneuver is a user input. Other variables became the terms that are solved to compute maneuver times to yield the desired end state.

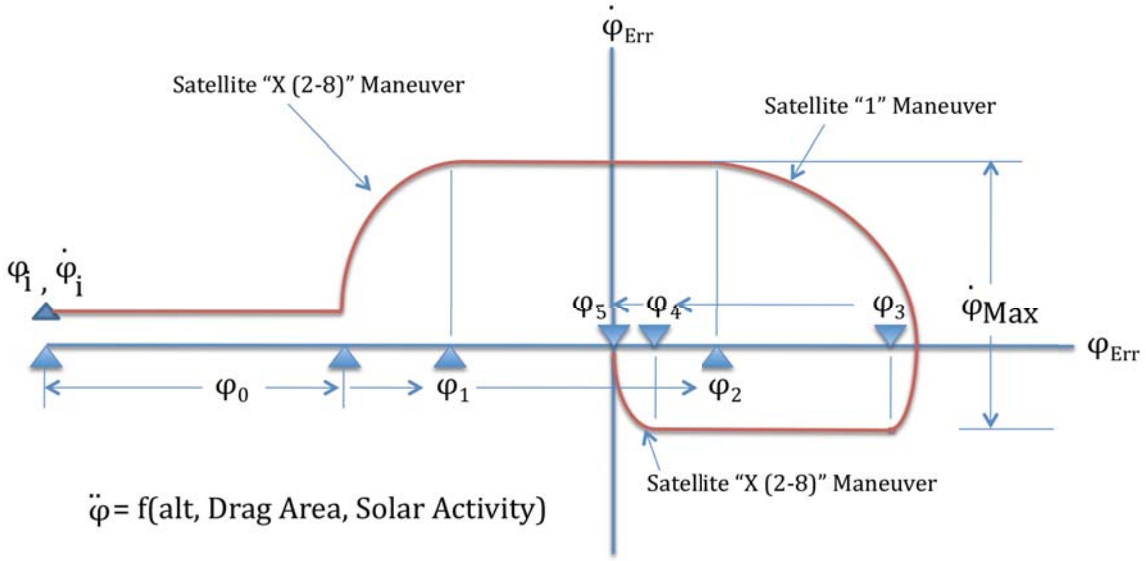

Figure 10: General Case: Phase Plane

The phases are defined as follows:

- Phase 0 is for a possible delayed start.
- Phase 1 is the first maneuver, where a phasing satellite (one of Satellites 2 through 8) enters a high-drag configuration, drops to a desired altitude that is lower than the reference satellite, then returns to the nominal attitude. This maneuver allows the phasing satellite to orbit faster than the reference, so the relative drift rate is high.
- Phase 2 is the phase change due to drift of both satellites.
- Phase 3 is the overshoot maneuver for the reference satellite, Satellite 1. It enters a high-drag configuration, drops below the phasing satellite, and then returns to nominal attitude. Now it is moving slightly faster that the phasing satellite with a negative relative phase drift rate.
- Phase 4 is the phase change due to drift of both satellites.
- Phase 5 is where the phasing satellite performs a final maneuver to match the altitude and drift rate of the reference satellite, setting the relative phase angle between them.

Working through the math yields the set of equations 1 through 12 to define the phase and time changes between each phase (0 through 5) of the maneuver sequence. The times, t_0 through t_5, correspond to the phase differences, ϕ_0 through ϕ_5, for a given maneuvering satellite.

As an example, to phase Satellite 3 to a relative angle of 315 degrees, the ϕ_{Err}, first select a $\dot{\phi}_M$ of 4.5 m/s to limit the overall altitude loss to 3.55 km. For the first phased satellite, in the simple Two Satellite case, this velocity is also equal to the desired reference satellite rate. Then the satellite has a $\dot{\phi}_i$ of 4.2 m/s from initial deployment, and the total maneuver time, t_{TOT}, is set to 78 days.

$$\phi_0 = \dot{\phi}_i t_0 \tag{1}$$

$$t_1 = (\dot{\phi}_R - \dot{\phi}_i)/\ddot{\phi} \tag{2}$$

$$\phi_1 = (\dot{\phi}_R{}^2 - \dot{\phi}_i{}^2)/2\ddot{\phi} \tag{3}$$

$$t_2 = \frac{1}{(\dot{\phi}_R - \dot{\phi}_i)}(\phi_{Err} - \phi_0 - \phi_1 - \phi_3 - \phi_4 - \phi_5) \tag{4}$$

$$\phi_2 = \dot{\phi}_R t_2 \tag{5}$$

$$t_3 = \dot{\phi}_M / \ddot{\phi} \tag{6}$$

$$\phi_3 = (2\dot{\phi}_R\dot{\phi}_M - \dot{\phi}_M{}^2)/2\ddot{\phi} \tag{7}$$

$$t_4 = \frac{1}{(\dot{\phi}_R - \dot{\phi}_M)}\left(\phi_{Err} - \phi_0 - \phi_1 - \phi_2 - \phi_3 - \phi_5\right) \tag{8}$$

$$\phi_4 = (\dot{\phi}_R - \dot{\phi}_M)/\ddot{\phi} \tag{9}$$

$$t_5 = (\dot{\phi}_M - \dot{\phi}_R)/\ddot{\phi} \tag{10}$$

$$\phi_5 = -(\dot{\phi}_R - \dot{\phi}_M)^2/2\ddot{\phi} \tag{11}$$

For the Two Satellite case, a direct phasing approach is used, so t_4 and t_5 are zero, allowing an initial solution for t_2. Once t_2 for Satellite 3 is found, the total reference satellite maneuver time, t_{RefTot}, is known, and t_2 for the subsequent satellites can be calculated working backwards.

$$t_2 = t_{RefTot} - t_1 - t_0 \tag{12}$$

For this example, a final phasing plot that shows the commissioning times for each satellite, the output of this process, is shown in Figure 11.

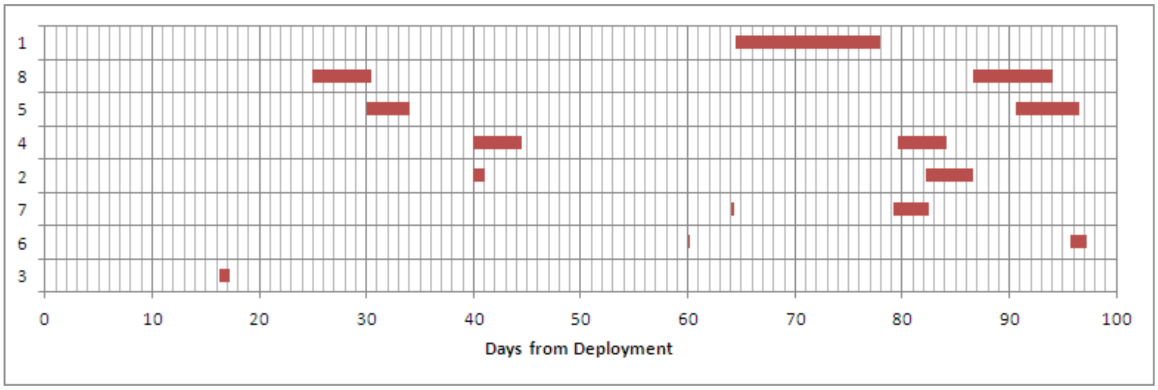

Figure 11: Satellite Maneuver Times vs. Days from Deployment

There are a number of practical benefits of approaching the maneuver using the General Case:

- Each satellite can begin its maneuver at a chosen time (operational flexibility).
- Each satellite can adjust its own phase rate based on the initial rate and error.
- All satellites share a common Satellite 1 reference maneuver at the same time.
- Each satellite can then wait the appropriate time and perform a final maneuver to synchronize with the reference satellite at the final altitude and lock in the phase separation.

Figure 12 portrays these maneuvers in the time domain, which shows a constellation of satellites spaced as four groups of two satellites. The two satellites with the farthest distance to travel used the more efficient Delayed Start while the rest of the satellite used the General Case maneuver to establish their final phase position.

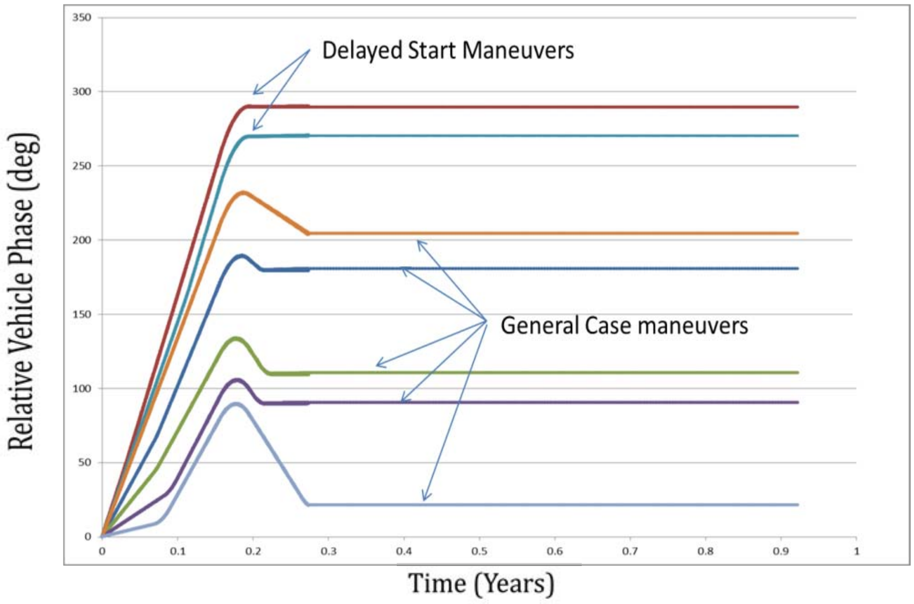

Figure 12: Constellation Maneuvers in the Time Domain

CONSTELLATION MAINTENANCE

Once the constellation is established, there are a few scenarios where the phasing may need to be readjusted. While a relative drift rate of zero is targeted between all the satellites, there are residual errors from commissioning plus minor variations in the environment that cause drift. A need for higher time resolution over a particular storm could spur a reconfiguration of the constellation into a more closely spaced "train" of satellites. Finally a high probability debris conjunction could cause the whole constellation to lower its altitude slightly for collision avoidance.

Addressing the drift rate, possible configurations were tested against the science coverage requirement of 70% over 24 hours. Table 1 shows the approximate minimum angular spacing for a particular configuration before it no longer met the baseline coverage. Inspecting the results, for the more likely cases of two or three satellites drifting close together, a separation closer than 7 degrees would have science implications. Giving this value some margin, a 10° error was chosen for further analysis of drift rates.

Table 1. Minimum Angular Spacing Before Loss of Science Coverage.

Configuration	Description	Min. Angular Spacing (deg)
1	1 Satellite drifts close to a neighbor	None - no impact to baseline
2	2 Sets of 2 Satellites Each	7
3	1 Set of 3 Satellites	7
4	4 Sets of 2 Satellites	14
5	2 Sets of 4 Satellites	28

Table 2. Relative Drift Rates and Time to Reach a 10° Drift vs. Delta Altitude.

Delta Altitude (m)	Relative Drift Rate (deg/day)	Time to Reach 10° Spacing (days)
5	0.006	1673
10	0.012	837
20	0.024	418
50	0.06	167.3
100	0.12	84

To understand how often the satellite orbits may need to be adjusted due to drift, the relative drift rates and the times to reach this 10° error, for a given range of small altitude differences, were calculated and are shown in Table 2. One benefit of the slow maneuvering using differential drag technique is that once the in-flight behavior is characterized, altitude can be carefully controlled, keeping drift rates low. Constellation maintenance caused by the need for a collision avoidance maneuver could be more common than a maneuver to correct drift and is described further in the next section.

CONJUNCTION ANALYSIS AND COLLISION AVOIDANCE

After the setup of the constellation completes and science operations begin, the primary CYGNSS mission operations concern is performing regular conjunction analyses and evaluating the risk of any identified close approaches. An initial study of the CYGNSS constellation, shown in Figure 13, within the crowded space of low earth orbit at altitudes of 500 km and 400 km, found that for 500 km, the time between possible conjunction events closer than 0.5 km was an average of 40 days.

Any close approach that comes within 500 m will be closely watched, especially along the in-track direction. Depending on the probabilities as the uncertainty estimates improve, a decision is made whether to perform an avoidance maneuver. The effect of a short maneuver was examined because often there are only days between learning that a conjunction may be a serious threat and when that conjunction is supposed to occur, but differential drag is a relatively slow control method.

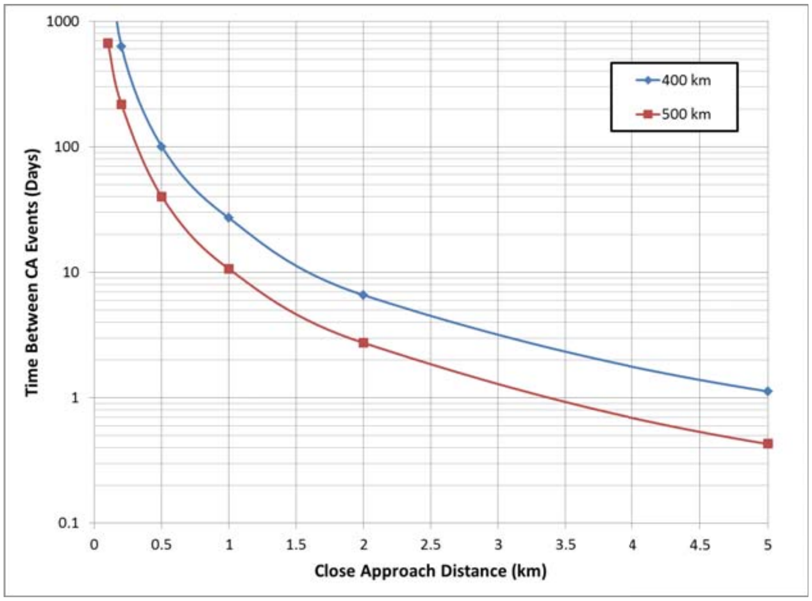

Figure 13: Time Between Close Approach (CA) Events vs. Distance

Three maneuver times of 1.5, 3.0, and 4.5 hours with a high solar flux (giving the highest drag capability), and the equivalent maneuver times in case of minimal solar flux, are shown in Figure 14. The shortest maneuver time of 1.5 hours accomplishes an in-track position change of 2 km given a 2-day notice.

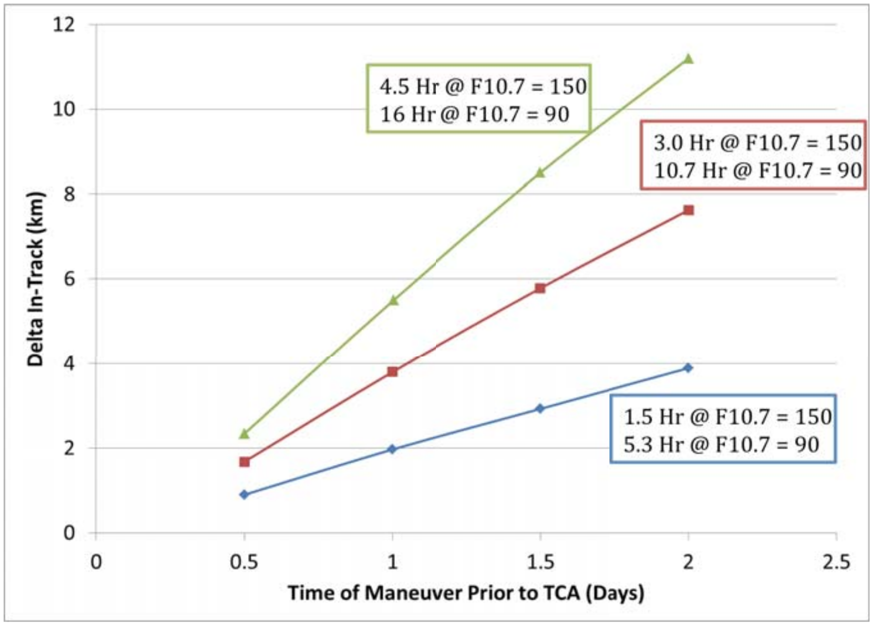

Figure 14: In-Track Position Change vs. Maneuver Times for High and Low Solar Flux (F10.7) Values

With maneuver plans in place, the differential drag technique with this maneuver timing can successfully avoid a near-term collision for a given satellite. These are preliminary studies and the next steps are to run more cases with a greater parameter variation and to examine the altitude loss per close approach maneuver to determine the effect on mission lifetime.

CONCLUSION

The CYGNSS mission is in the early stages of development and the design is evolving. This paper has reviewed the current state of the requirements and the preliminary analyses that have been performed to help guide the mission design and operations concepts.

The use of differential drag to establish a constellation requires carefully timed maneuvers, and a key trade in the final design is minimizing constellation altitude loss while completing constellation phasing within the commissioning period. A phase-space method for accomplishing differential drag maneuvers, based on the relative phase drift rate, is presented. The analyses show that even with the slow rate of maneuvering, phasing with this method meets requirements and is achievable for the CYGNSS constellation.

The initial conjunction analysis found the collision avoidance frequency estimates and the maneuver timing requirements that can be used in the planning for COLA events, and verified that, while collision avoidance events should be carefully tracked, the maneuverability of the satellites is adequate to perform COLA maneuvers.

Throughout the analyses, the effects of parameter variations have been tied to science coverage and the sensitivity of the design with respect to the coverage requirement. More work remains to increase the scope of the deployment and constellation establishment studies to include higher resolution environments to improve the drag estimates, and to examine sensitivities to other uncertainties, such as the attitude control pointing.

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REFERENCES

[1] Leonard, C. L., Hollister, W. M., & Bergman, E. V. (1989). Orbital Formationkeeping with Differential Drag. Journal of Guidance, Control and Dynamics, Vol. 12, No.1, pp. 108-113.

[2] Mishne, D. (2004). Formation Control of Satellites Subject to Drag Variations and J2 Perturbations. Journal of Guidance, Control and Dynamics, Vol. 27, No.4, pp. 685-692.