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Modified mission planning schemes for the aging CYGNSS mission with expanding scientific pursuits during high beta angle seasons

Amanda M. Alexander[a,b]*, William Wells[c], Richard Medina[a], Jillian Redfern[a]

[a] *Southwest Research Institute, 1050 Walnut St. Ste 300, Boulder, Colorado, USA, 80301,*
amanda.alexander@swri.org
[b]*Department of Geological Sciences, University of Colorado at Boulder, UCB 399, Boulder, Colorado, 80309*
[c]*Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas, USA 78238*
* Corresponding Author

Abstract

The eight-microsatellite constellation, CYGNSS (CYclone Global Navigation Satellite System), launched in late 2016, has been a widely successful first NASA Earth Venture mission. CYGNSS was proposed to estimate ocean surface roughness and windspeeds to inform on the intensification of tropical cyclones using a Delay Doppler Mapping Instrument (DDMI). In the six years since launch, CYGNSS has also informed mapping soil moisture content, freeze/thaw transitions, and tracking of ocean microplastic concentration and distributions.

Now in the extended mission phase, operations of the CYGNSS mission are busier than ever. Nominal weekly science collects have increased, with the addition of weekly high-resolution science collects all year long (no longer just during peak hurricane season). With the aging of these spacecraft, operations and planning have had to adapt and define new protocols to balance spacecraft health and science activity.

In this work, we will present on how the CYGNSS Mission Operations team has used Systems Tool Kit (STK) predictions of beta angle and umbral timeframes to roll spacecraft (+/- 10-16 degrees) during certain times of the year to maintain battery state of charge and prevent loadshed. Further, we have designed software to provide weekly monitoring using STK-exported data and Python scripting which automatically notifies the mission planning team of an upcoming roll season and generates the necessary roll commands for review. As a result, we introduced and enable a beta angle flag in our mission planning software to prevent loadshed and consequently, science collection and operation interruptions. Downlinks are then automatically throttled to a limited frequency of no more than once per three orbits. We also discuss the implementation of another mission planning software update that spaces out the final downlink for any special science collect.

Our mission planning software modifications allow the CYGNSS constellation to continue collecting and downlinking valuable high-resolution data of the Earth’s surface, without further straining the battery in high beta angle seasons.

Keywords: CYGNSS, mission planning, spacecraft operations, planning and scheduling

Acronyms/Abbreviations

ATS – Absolute Time Sequence
CYGNSS – CYclone Global Navigation Satellite System
DDM – Delay Doppler Map
DDMI – Delay Doppler Mapping Instrument
FM – Flight Model
GNSS – Global Navigation Satellite System
IF – Intermediate Frequency
LEO – Low-Earth Orbit
MOC – Mission Operations Center
NASA – National Aeronautics and Space Administration
SC – Spacecraft
SIMPL – SwRI Mission Planner
SoC – State of Charge
SOC – Science Operations Center
SSC – Swedish Space Corporation
STK - Systems Tool Kit®
SwRI – Southwest Research Institute

1. Introduction

The CYGNSS mission [1,2] successfully launched eight microsatellites in December 2016 into an orbital inclination of 35 degrees from the equator with the intent to collect space-based measurements of surface wind speeds over tropical cyclones. Each satellite has a four-channel bistatic radar receiver onboard which measures GPS signals reflected and scattered by the Earth's surface. GPS signals operate at a very low microwave frequency and can penetrate thick clouds and precipitation (which allows for remotely measuring inner-core wind speeds of tropical cyclones).

While the original goal of the CYGNSS mission was to study the formation and intensification of tropical cyclone (e.g., 3,4), additional scientific pursuits over land and water have been of increasing interest. In the six years since launch, CYGNSS ocean applications have expanded to include studies on ocean surface heat flux [5], tropical meteorology [6], and extratropical cyclones [7]. Over land, the constellation has provided data on soil moisture content (e.g., 8-11), freeze/thaw transitions [12], and flood inundation [13]. CYGNSS measurements were also used to detect the breeding grounds for a major locust outbreak in East Africa [14]. Most recently, global maps of ocean winds and ocean surface roughness generated from CYGNSS data were used to estimate annual mean microplastic distributions [15]. Now well into the extended mission phase, demand for CYGNSS data is at an all-time high. In this paper, we will discuss the effect of increased special science demand and the aging of the spacecraft power— and how we have modified existing practices and implemented new software to prevent scientific interruptions.

1.1 CYGNSS Special Science

The spacecraft constantly collect data in the form of windowed Delay Doppler Maps (DDMs) at a frequency of 2 Hz, resulting in approximately 100 flash blocks (256-KB each) of engineering data and 1000 blocks of science data to downlink each day during a ten-minute contact. Nominally, each CYGNSS spacecraft downlinks data once per 24 hours via one of three ground stations operated by SSC in Australia, Chile and Hawaii. The MOC receives data files within four hours of each contact and immediately processes the data which is uploaded to a shared server for the SOC team (located at the University of Michigan in Ann Arbor, Michigan) to access.

In addition to the ongoing 2 Hz DDM collections, SOC requests for special Raw IF and Full (non-windowed) DDM collects are uplinked weekly for non-cyclone activities as well as when cyclones develop. Raw IF and Full DDM collects were previously used exclusively for cyclone activity but have since been used for a variety of non-cyclone research purposes (such as soil moisture content, microplastics, and more, as described in the previous section). The extended research possibilities have led to an additional 4-6 Raw IF and/or Full DDM collects per week (for the entire constellation). **Figure 1.1.** shows how special science collections have increased dramatically, and in turn, so too have Raw data downlinks (**Table 1.1**) from 2018 through 2022. Each Raw IF collect is usually 60 seconds over the area of scientific interest producing ~2750 blocks of data. Given that ~800 blocks of data are downlinked per ground contact, four additional special "Raw downlink" contacts are added to the schedule for each Raw IF collection. With this extra load from the SC transmitter, the early-mission estimations for average battery use per orbit is no longer accurate and the spacecraft average battery SoC is lower.

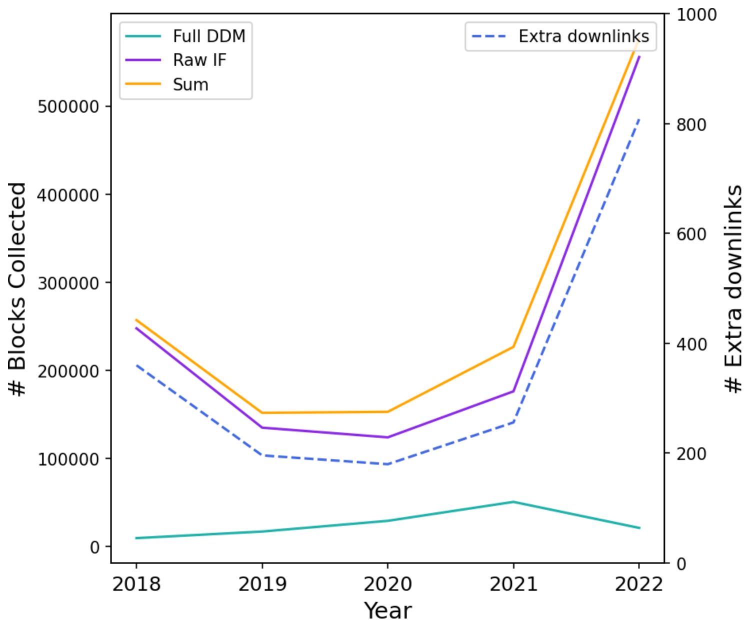

Figure 1.1 (left). The amount of data collected by special science from 2018 through 2022. Full DDM (in light blue) collections increased steadily 2018 until a peak in 2021 but decreased in 2022. Raw IF collections decreased slightly in the early years of the mission but have since increased exponentially since non-cyclonic research from CYGNSS data became in demand. For every 60 seconds of Raw IF data, approximately 2750 blocks of data is recorded, and an additional 4 downlinks are needed (extra downlinks over time shown in the dark blue dashed line).

Table 1.1. Breakdown of normal science and special raw downlinks for the past five years. As non-cyclonic research became popular, special raw downlinks increased significantly. Note: the nominal downlink cadence increased from once per 48 hours to every 24 hours in 2019 when the default rate of DDM production was increased from 1 Hz to 2 Hz, effectively doubling nominal science data volume.

Year	Normal science downlinks	Special Raw downlinks
2018	1733	272
2019	3187	85
2020	3061	192
2021	3013	287
2022	3095	790

1.2 The effects of beta angle on CYGNSS satellites

CYGNSS SC are eclipsed by the Earth for part of each orbit given their relatively low altitude (~520 km) and inclination (35 degrees). The time spent in eclipse depends on the tilt of the orbital plane with respect to the Sun. This tilt, called beta angle (β) changes throughout the year (**Figure 1.2**) to affect solar power generation. More significantly, for larger magnitudes of beta angle, the average sun incidence angle on the spacecraft solar arrays becomes shallower due to the spacecraft attitude being fixed relative to the Earth, resulting in lesser orbit-average solar power generation.

Spacecraft battery usage and solar array power generation were estimated initially via pre-launch analysis and testing and later confirmed with empirical data after launch. Similarly, the threshold beta angle (max | β |) for when to roll spacecraft was determined from pre-launch testing, STK analysis of beta angles for the mission, and minimum predicted battery SoC for a given beta angle. When the predicted beta angle would result in a battery SoC less than a minimum value, we would plan to roll the spacecraft toward the sun to increase energy input to the solar arrays. Now, later in the mission, the beta angle threshold is based on empirical data as we go through beta angle seasons. We continue to monitor and predict battery SoC as a function of beta angle to determine timing for spacecraft roll and unroll.

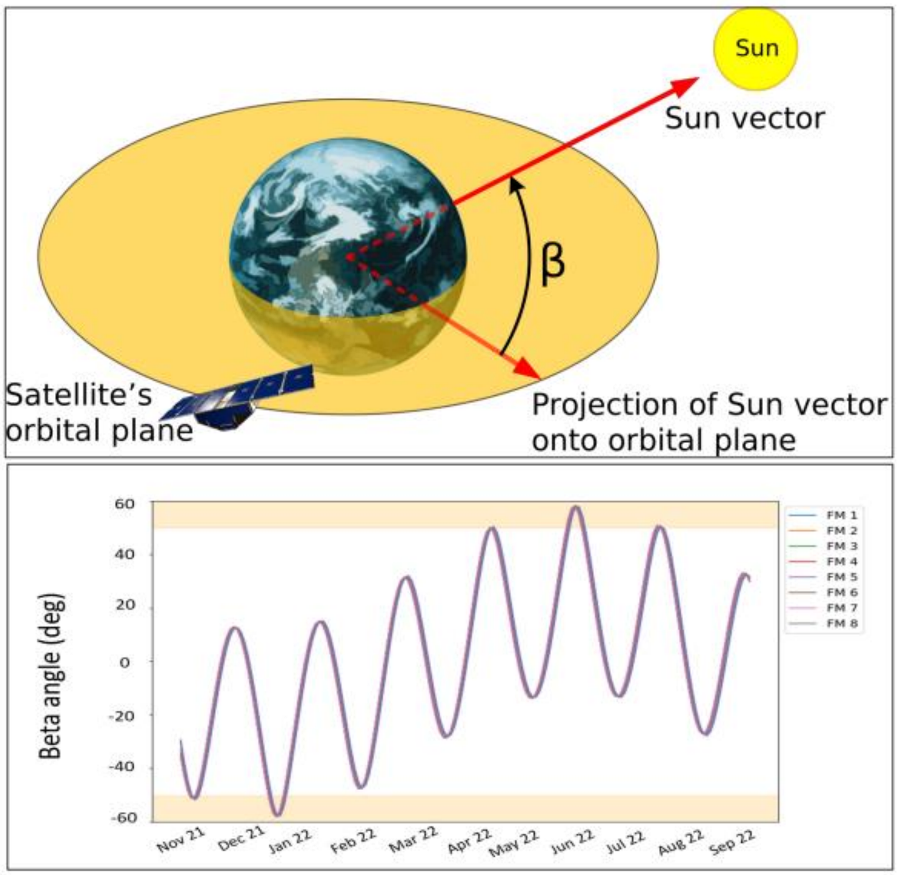

Fig 1.2. Top*:* Illustration of beta angle: the angle between the spacecraft orbit plane and the solar vector. **Bottom**: beta angle for each spacecraft over time for 2022. The yellow shaded region denotes a high beta angle season, which means spacecraft would roll to increase power generation from the solar arrays.

2. Material and methods

The CYGNSS mission operations team utilizes the following software for mission planning: SIMPL, STK and Orbit Logic Scheduler. In addition, several Python-based scripts run automatically on daily, weekly and monthly bases to aid in file transfer, data processing and data trending. In this section, we will describe how we use data trending to determine beta angle thresholds and roll angle (Section 2.1), detail a Python script we have developed to check for upcoming beta angle seasons (Section 2.2), and introduce updates to our mission planning software, SIMPL (2.3) in response to aging spacecraft batteries and increased science collects and downlinks.

2.1 The beta angle threshold and roll angle

To account for the aging spacecraft solar arrays and batteries, we have revised the beta angle thresholds that were in place since the beginning of the mission. Originally, the beta angle threshold was determined from pre-orbit estimations and instrument experiments to be 50.8 degrees for each spacecraft, except FM1. FM1 experienced a pre-launch anomaly that results in out-of-family high power dissipation and thus its battery being consistently more depleted than the other spacecraft, so the beta angle threshold was set to 40.8 degrees for this spacecraft (**Table 2.1**).

We updated the beta angle threshold for roll by comparing beta angle and the minimum battery SoC of the spacecraft. We looked at data for each spacecraft when the Earth-Sun distance is maximum (i.e., northern hemisphere summer) such that the spacecraft SoC will not drop below 53%. This value for minimum battery SoC provides 5% margin above the default loadshed threshold of 48%. The 48% loadshed threshold corresponds to energy in the battery required to reliably achieve sun-pointing safe mode attitude for 99.7% of cases in pre-launch Monte Carlo simulations. To provide more margin against inadvertently transitioning to safe mode, the loadshed threshold is temporarily reduced to 43% to provide 10% separation between predicted minimum battery SoC and the threshold. From the aphelion data, we determined beta angle limits of 34.5 degrees for FM1 and 47.0 degrees for the other seven spacecraft (**Table 2.1**).

We have also determined how much a spacecraft will need to roll to increase energy input to the solar panels. Initially, we had four roll schemes for a high beta angle season: +/- 10 and +/- 22 degrees. The more extreme roll case was used only for FM1 and FM2 early on until the MOC and SOC teams agreed that it was preferred to be in a less-rolled state for the quality of science data. For five years, rolling just +/- 10 degrees for all spacecraft was sufficient. However, we reassessed these roll angles following an annual operations review for FM1 and determined that for | β | > 52 degrees, FM1 should roll to +/- 16 degrees to maintain SoC above the 53%. This angle allows for adequate solar array power generation on FM1 with less degradation to science data compared to rolling +/-22 degrees.

Table 2.1. Old and revised beta angle threshold for the eight CYGNSS spacecraft. The beta angle threshold was updated to maintain battery SoC above the SoC loadshed threshold, with margin, (and subsequently a spacecraft safing event) on aging spacecraft.

FM	Old beta angle threshold (+/- deg)	Revised beta angle threshold (+/- deg)	Roll amount (-/+ deg)
1	40.8	34.5 (52.0)	10 (16)
2	50.8	47.0	10
3	50.8	47.0	10
4	50.8	47.0	10
5	50.8	47.0	10
6	50.8	47.0	10
7	50.8	47.0	10
8	50.5	47.0	10

2.2. Weekly check for an upcoming beta angle season

Each week, a CYGNSS team member would output STK files that predict beta angle and eclipse timings for the next month in CSV format based on attitude and ephemeris data. Historically, a user would then have to look through each file and determine a date and time when the beta angle would be higher than an accepted value. Then, CYGNSS mission planners would have to manually write commands to adjust the spacecraft attitude and battery SoC loadshed threshold (meaning if the SoC drops below a certain value the spacecraft will transition to safe-mode, sun-point to fully recharge; this prevents the onboard battery from ever becoming fully depleted). We have developed a Python script to parse the STK-generated CVS files and generate the roll command files (if necessary). Our servers operate in Python 2.7.11 and utilize the following libraries: *os, glob, pandas, smtplib, email.mime, logging* and *numpy.*

The Python script reads through each beta angle and eclipse file to determine if the maximum | β | over the next month exceeds the threshold and if so, which spacecraft will roll to compensate. If any spacecraft require a roll maneuver, the script calls a function to determine the timing of the roll period and writes out command files for each spacecraft that will be processed through SIMPL to create MOC tasks. **Figure 2.1** shows a flow chart of how this script works.

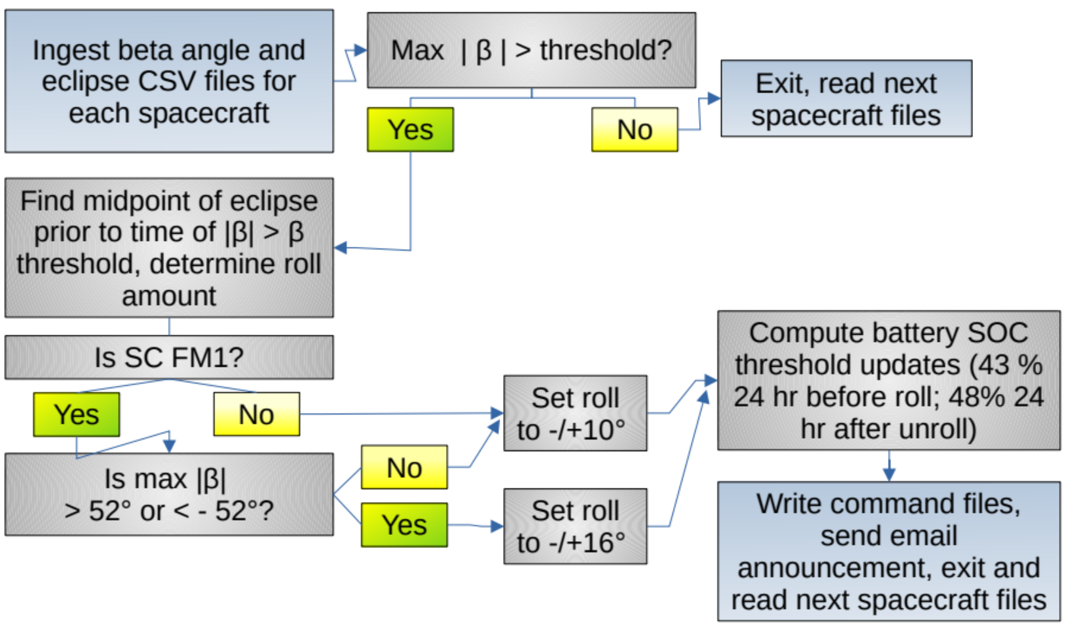

Figure 2.1 (above). Flowchart illustrating the script process to write out command files for rolling spacecraft and updating onboard battery SoC threshold for a beta angle season.

Command files generated include timing for the following: adjust the SoC threshold on board the spacecraft to 43% (instead of the nominal 48%) 24 hours before the beta threshold is exceeded, roll the spacecraft the specified degree amount one orbit prior to the beta threshold during eclipse, unroll the spacecraft one orbit after the beta angle drops below the beta threshold (again, during eclipse), and finally, return the spacecraft SoC to 48% one day after unroll (**Figure 2.2** shows an example email output from the beta angle check script which includes a full table of timings for all commands). The command files are then reviewed by the mission planning team and ingested into SIMPL, our mission planning software for scheduling. Once approved, the commands are uploaded to the spacecraft via ATS, an onboard file containing all actions (such as reset, special science collect, turn on or off the transmitter, etc) the spacecraft should perform for the next 14 days.

Subject **[CYGNSS_MOC] Automated notification of upcoming BA season**

[CYGNSS] Automated Message....

	BA Season Start	BA Season End	Max BA	Roll Type	SOC to 43	Roll time	Unroll time	SOC to 48
F7	12-04-2022 21:00:00	12-21-2022 18:30:00	-58.116	16	12-03-2022 20:14:13	12-04-2022 20:14:13	12-21-2022 20:21:28	12-22-2022 20:21:28
F9	12-06-2022 09:30:00	12-16-2022 22:00:00	-58.000	10	12-05-2022 09:06:21	12-06-2022 09:06:21	12-16-2022 23:43:05	12-17-2022 23:43:05
2B	12-06-2022 03:30:00	12-16-2022 15:30:00	-57.975	10	12-05-2022 02:03:24	12-06-2022 02:03:24	12-16-2022 16:40:53	12-17-2022 16:40:53
2C	12-06-2022 02:00:00	12-16-2022 14:30:00	-57.965	10	12-05-2022 01:32:21	12-06-2022 01:32:21	12-16-2022 16:09:31	12-17-2022 16:09:31
2F	12-07-2022 15:30:00	12-18-2022 05:30:00	-58.094	10	12-06-2022 14:04:40	12-07-2022 14:04:40	12-18-2022 06:22:21	12-19-2022 06:22:21
36	12-06-2022 05:00:00	12-16-2022 17:30:00	-57.985	10	12-05-2022 03:51:32	12-06-2022 03:51:32	12-16-2022 18:28:23	12-17-2022 18:28:23
37	12-06-2022 01:30:00	12-16-2022 13:30:00	-57.964	10	12-05-2022 00:30:45	12-06-2022 00:30:45	12-16-2022 15:08:14	12-17-2022 15:08:14
49	12-06-2022 22:00:00	12-17-2022 11:00:00	-58.031	10	12-05-2022 21:11:47	12-06-2022 21:11:47	12-17-2022 11:51:47	12-18-2022 11:51:47

Command files written to: */home/cygnss/PlanningPersonnelInterface/SIMPLCode/Input/*

Command files: ['CYGNSS_F7_MOC_CMD_2022_318_16_53_25.txt', 'CYGNSS_F9_MOC_CMD_2022_318_16_53_25.txt', 'CYGNSS_2B_MOC_CMD_2022_318_16_53_25.txt', 'CYGNSS_2C_MOC_CMD_2022_318_16_53_25.txt', 'CYGNSS_2F_MOC_CMD_2022_318_16_53_25.txt', 'CYGNSS_36_MOC_CMD_2022_318_16_53_25.txt', 'CYGNSS_37_MOC_CMD_2022_318_16_53_25.txt', 'CYGNSS_49_MOC_CMD_2022_318_16_53_25.txt']

Figure 2.2 (above). Example email which is sent automatically after running the Python script from the December 2022 high beta angle season. The email includes a table detailing the start and end of the high beta angle season, when to update the SoC threshold to 43% and back to 48% and when to roll and unroll the spacecraft. The email also includes paths to where the command files are written for other CYGNSS MOC members to review before ingesting into SIMPL for scheduling.

2.3 Modifications to mission planning software, SIMPL

We perform weekly mission planning on Mondays wherein timings are refined for previously scheduled ground station contacts for each spacecraft for the following 14 days as well as a new week of ground station contacts are added to the schedule for four weeks from the current date. The SOC also sends any special science commanding on Monday mornings that is scheduled with the 14-day update. If Raw-IF commanding was requested, an additional four contacts per 60 second collect for the relevant spacecraft will be added to the schedule for that week.

For planning, we utilize the SIMPL software coupled with STK and Orbit Logic's STK Scheduler (see [16,17] for a detailed description of how SIMPL, STK and Orbit Logic's STK Scheduler interact as well as for a more detailed description of the CYGNSS mission planning architecture). The SIMPL software is presently configured to create schedule files containing a week's worth of spacecraft contacts during local business hours with the click of a button. A schedule request file is generated and each spacecraft activity (e.g., downlink, science collect, spacecraft reset) is called a task and assigned a unique task number. The schedule request file is ingested into STK Scheduler; tasks are deconflicted and assigned based on allocated resources (e.g., ground station antenna, lighting, communication spacing, etc.), stored attitude and ephemeris files and availability within the SSC schedule file.

2.3.1 Increased spacing between contacts on individual spacecraft in high beta seasons

To space out contacts during high beta angle seasons and alleviate burden on the spacecraft battery and SoC, a new column was added to the SIMPL database titled "BETA_ANGLE" that is flagged when generating a schedule request file. If the beta angle flag for a task is on when a new week of contact requests is generated, the communication spacing constraint resource, "BETA_ANGLE-SPACING-CONSTRAINT", is applied to the task which modifies the spacing between consecutive spacecraft contacts for the same satellite from a minimum of 1 orbit to a minimum of 3 orbits.

2.3.2 Additional spacing before final Raw downlink pass

Moreover, many downlinks result in some gaps in data due to occasional glitches in connectivity between the spacecraft transceiver and ground station antenna, masking of the ground station antenna, or inclement weather conditions at the ground station. As a result, we have an automatic script that runs every hour to check processed data files for gaps (that is, a non-sequential jump in the sequence count of packets received intact on the ground). If any gaps exist, a procedure file, "proc", is generated for the affected spacecraft to replay the flash block containing the missed data. The proc is called automatically in every nominal downlink pass two minutes before the scheduled end of pass.

To allow for replays of any missing Raw data, we modified the SIMPL software to add a delay of 8 hours before the final special Raw downlink. Since a Raw IF collect typically records ~2750 blocks of data and four additional downlinks are added which playback approximately 800-900 blocks per downlink, the final downlink for that Raw IF collect does not require the full 8–10-minute duration that is scheduled and the remaining time should be used to replay any missing data. However, even the three-orbit buffer between contacts was not long enough for data to arrive and be processed (typically 4-6 hours after the end of the contact). To resolve the spacing and allow time for data processing to finish and gaps and replays to be estimated, we have added task ID tracking to raw downlink passes so that the 4th raw downlink pass after each raw collect should be eight hours after the third one.

3. Results and Discussion

We have developed a Python script that checks for upcoming high beta angle seasons, computes necessary roll and unroll timings, generates command files, and emails the CYGNSS MOC team to alert that an upcoming high beta season is approaching, and command files will need to be reviewed and scheduled. In addition, we have revised the beta angle thresholds and roll angles for all spacecraft to account for aging of the SC power system. Finally, the SIMPL software was modified to automatically space out spacecraft contacts from once per orbit to once per three orbits during high beta seasons as well as delay the last raw downlink in a set by 8 hours to allow for data processing to complete and compute gaps in data and replays.

3.1 Python script improves planning duration and accuracy in high beta angle seasons

The creation and implementation of the Python script which reads in STK-generated CSV files and generates command files if any spacecraft will need to roll to accommodate a high beta angle season has significantly improved mission planning for CYGNSS. In the past, a mission planner would spend several hours looking through CSV files and manually estimating and writing out command timings; now, the planner spends less than ten minutes to generate the beta angle and eclipse files on STK, run the Python script and ingest into the SIMPL database. In addition to reducing the time spent on planning for a high beta angle season, the Python-generated command files are more reliable as the formatting is consistent and without typos, timing is based on carefully constructed logic and an email receipt is sent to the mission planning team with the command file locations for others to review automatically.

3.2. New beta angle thresholds

We have revisited the beta angle thresholds and roll angles for all spacecraft and revised where necessary. This particular change was motivated by a three-satellite safing event that occurred in Spring 2022. Between 30 April and 1 May, three of eight spacecraft safed due to loadshed (that is, the battery SoC dropped below 48%, **Figure 3.1**). The beta angle was just below the roll threshold

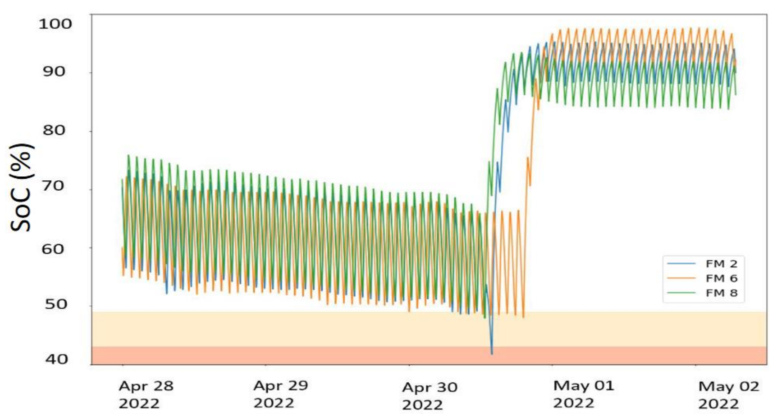

Figure 3.1 (above). *The SoC of three spacecraft (FMs 2, 6 and 8) dropped below the threshold of 48% (shown in the yellow shaded region on the plot) between 30 April and 1 May 2022.*

value for FMs 2-8 (~50 degrees) and so only FM1 was rolled at the time. The triple safing event prompted revisit of expected minimum battery SoC as function of beta angle. We found that all spacecraft were nearing the default loadshed threshold of 48% for the beta angle on these dates and the three SC that safed had touched the threshold (**Figure 3.2**). Loss of the 5% margin between minimum predicted battery SoC and the default loadshed threshold established early in the mission is attributed to aging of the SC power system over several years without taking corrective action. In response, we have determined new beta thresholds for rolling, and updated FM1's roll angle during high betas seasons, as shown in **Table 2.1**. **Figure 3.2** highlights the effect of rolling per updated beta thresholds on minimum SoC; the beta angle season in May had a peak beta angle of 50.1 degrees for FM2 and the minimum SoC dropped to 47% since the spacecraft did not roll. In August when the peak beta angle was larger at 51 degrees, FM2 maintained battery SoC above the desired 53% by rolling when beta reached the update value of 40.8 degrees.

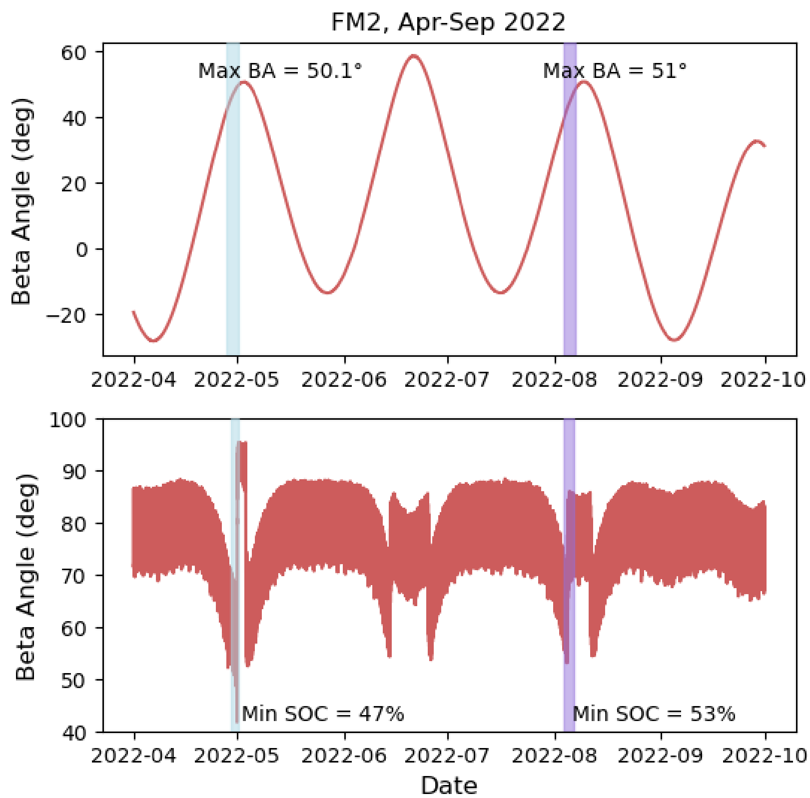

Figure 3.2 (left). *Top plot shows beta angle variation in red from April to September in 2022. Bottom plot shows spacecraft FM2 SoC for the same date range in red. The blue (left) shaded regions highlight a maximum beta angle of 50.1 degrees and minimum SoC of 47% before the beta angle threshold modifications which resulted in a safing. The purple (right) shaded regions highlight the effect of rolling sooner; the maximum beta angle of 51 degrees in August with a minimum SoC of 53% since the spacecraft rolled -10 degrees on 4 August 2022.*

3.2 SIMPL modifications auto-space contacts

The SIMPL software has been revised to have a beta angle flag and raw downlink resource. The beta angle flag alerts the software so that all spacecraft contacts should be spaced three orbits apart at a minimum when spacecraft are rolled. The increase in spacing reduces burden on the battery SoC which in turn reduces risk for a safing event, particularly immediately prior to rolling and immediately after un-rolling when power margin is lowest. In addition, we have added a constraint to delay the final raw downlink pass by 8 hours to allow for data processing and gap estimations to be computed such that the latter half of the final raw downlink pass can be used to pick up any missing data.

4. Conclusions

The CYGNSS spacecraft continue to sample the Earth's oceans and land over a tropical latitude. Extended mission and science operations have resulted in increased data collection benefiting scientific analysis for a variety of environmental and climate purposes. The mission operations team has since revised existing mission planning software with supplementary scripting to monitor and predict high beta angle seasons when the spacecraft batteries will be strained more than usual. To prevent loadshed and consequently, science collection and operation interruptions, we have re-determined the maximum beta angle before spacecraft are required to roll and have added an additional roll state of +/- 16 for FM1. Downlinks are now automatically throttled to a limited frequency of no more than once per three orbits in a high beta angle season. To avoid the same pitfall that led to the May 2022 safings, revisit of beta angle thresholds to account for power system aging is now performed at least once per year as part of the annual operations review. These updates will allow the CYGNSS mission to operate for years to come.

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