

## Challenges in Planning and Scheduling for the Imaging X-Ray Polarimetry Explorer (IXPE)

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### Abstract

The IXPE mission is a science observatory that carries three identical telescopes that are used to measure the polarization of X-rays originating from celestial objects. Throughout the mission, the observatory gathers data for different astrophysical objects at different times during the year and for different durations. This variation in targets and observation durations creates interesting and complex planning and scheduling challenges. While there is usually a 6-9 month schedule for what objects will be observed and when, the plan is often fluid and can quickly change due to a variety of reasons. These reasons include, but are not limited to, a request to conduct coordinated observations of a specific target with other observatories, change in the level of X-rays being produced by an object, or a target of opportunity (TOO) where an observer from the science community requests to point at a specific target because it is actively doing something interesting (ex: a gamma ray burst). The planning team must remain flexible in order to accommodate these last-minute requests that can require a turnaround time of less than 48 hours. There are also few ground stations available along the equator and the IXPE program has only two options: the Malindi ground station in Kenya (operated by the Italian Space Agency) and the Singapore ground station (operated by KSAT). NASA's Direct to Earth Scheduling Office works with KSAT to schedule contacts at Singapore while the Italian Space Agency (ASI) located in Fucino, Italy, schedules the contacts for the Malindi station. These two stations have very different scheduling timelines and cadences. Schedules are requested and delivered at different times during the week and cover different time ranges. This makes it difficult to condense the planning process into one or two days and, instead, must span a week and be carefully timed. The planning process needed to be designed in such a way that multiple people can work on it with minimal coordination. In addition, the number of ground contacts needed to downlink all of the science data varies depending on how bright the observed celestial target is and how long IXPE is observing said object. Bright objects produce a lot of X-rays/data (ex: the Crab Nebula) and require more contacts to downlink all of the data, while dimmer objects generate less X-rays and require less ground contacts. Because of this, the nominal planning cadence requires the Science Operations Center (SOC) to send the planning team a three-week activity plan, one week before the plan is set to begin. This allows the planning team ample time to calculate exactly how long IXPE will be observing various targets and schedule the correct

number of contacts. However, this can present challenges when a faint object is planned for but a TOO for a bright object comes in and the planning team must reschedule everything within 24-48 hours. In addition to ground contact scheduling, the planning team is responsible for generating and sending Two-line elements (TLEs) to multiple parties. They must also schedule spacecraft and instrument activities around antenna nulls, the South Atlantic Anomaly, and eclipses. Antenna nulls have been particularly impactful on IXPE and the planning team has updated the planning process and developed ground autonomy to help mitigate the impact of nulls and any necessary retransmits of data. The IXPE team has put a lot of effort into streamlining the process while also maintaining flexibility to handle short-turnaround changes and requests made by the SOC and science community as a whole. This paper will provide an overview of the planning and scheduling process, how the planning team works with two different ground stations that are managed by two different agencies, and how TOOs and other urgent requests are handled. It will also talk about the spacecraft and ground automation implemented to increase efficiency and minimize work load as well as touch on the role of the University of Colorado students.

## 1. INTRODUCTION

The Imaging X-Ray Polarimetry Explorer (IXPE) observatory is a NASA Small Explorer mission developed and flown in collaboration with the Italian Space Agency (ASI). It is managed by the Marshall Space Flight Center (MSFC) in Huntsville, Alabama and operated by BAE Systems and the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP), both of which are located in Boulder, Colorado. It is NASA's first mission dedicated to the study of polarization of X-rays and seeks to support NASA's science objective in astrophysics to discover how the universe works.



*Figure 1 Illustration of NASA's Imaging X-ray Polarimetry Explorer (IXPE).*

IXPE carries three identical X-ray telescopes that are used to measure the polarization of X-rays originating from celestial objects. During IXPE's prime two-year mission, IXPE observed over 40 different pre-planned X-ray sources including black holes, magnetars, and pulsars. During extended mission, IXPE started a Guest Observer program and began taking requests for observations from the entire astronomical community. This program has been very successful and IXPE has observed many new, exotic phenomena in space.

IXPE launched on December 9, 2021 into a low-Earth orbit (LEO) on a Falcon-9 from the Kennedy Space Center in Florida. The observatory was launched into a near circular, equatorial orbit at 600km altitude. IXPE has a downlink rate of 2Mbps and uses two ground stations. The primary station is located in Malindi, Kenya and is operated by the Italian Space Agency. The secondary station is located in Singapore and is operated by the Kongsberg Satellite Services (KSAT). Contact scheduling for Malindi is handled by the ASI scheduling office in Fucino, Italy. NASA's Direct-to-Earth Scheduling Office (DTESO) works with KSAT's Tromsø Network Operations Centre (TNO) to schedule contacts with Singapore.

## **2. PLANNING AND SCHEDULING REQUIREMENTS, CONSTRAINTS, AND CONSIDERATIONS**

The science of IXPE creates many interesting planning and scheduling challenges. There are numerous requirements, constraints, and considerations that need to be considered in order for IXPE to collect science data and downlink said data in an efficient and effective manner. This section provides details on the major planning factors and the challenges of each.

### **2.1 Variable Data Rates:**

IXPE observes a variety of objects in space, and each object produces a different volume of X-rays. Brighter sources, such as the Crab Nebula, produce a large number of X-rays and have data record rates of about 40-60 KBytes/sec. Dimmer targets, such as the Perseus Cluster, generate relatively few X-rays and have data record rates of about 0.2 to 10 KBytes/sec. In addition, each target is observed for a different amount of time. For example, the Crab Nebula is typically observed for only 24-48 hours because the data it generates fills up the on-board data recorder quickly. A longer observation runs the risk of the Mission Operations Center (MOC) not being able to schedule enough contacts to transmit the data to the ground before the first recorded is overwritten and overflowing the onboard recorder. Conversely, IXPE can observe low-rate targets, such as the Perseus Cluster, for multiple weeks without risk of data loss since they do not generate data quickly.

There is also the chance that these nuanced targets can suddenly brighten without warning. Prior to an observation, the Science Operations Center (SOC), located at MSFC, monitors the object closely for changes in activity. If an object spikes unexpectedly in brightness, the SOC will notify the IXPE team and adjust the assumed data rate on the ground accordingly. The planning process needs to be flexible enough to handle these changes.

The varying data collection rates and observation times means that the number of contacts required per day to get the new science data downlinked can range from 3 to 30. Given IXPE's LEO altitude, it only sees the Malindi and Singapore ground stations 14-15 times per day each (for a total of 28-30 possible contacts per day). It is unrealistic and unreasonable to schedule the maximum possible contacts per day every day in the event IXPE happens to be observing a high-rate target. Therefore, the planning team requests only the number of contacts necessary to downlink new science and Spacecraft State of Health (SSOH) data and monitor the health and safety of the observatory. For low-rate targets, the planning team will schedule 6-7 total contacts per day (spread across both ground stations) and up to 12-14 contacts for high-rate targets. This ultimately means that the number of contacts scheduled varies from week to week and contact scheduling is an extremely important part of the planning process. If the planning team fails to schedule enough contacts, the mission risks losing valuable science data.

## **2.2 Ground Station Availability:**

As stated in the Introduction, IXPE is in an equatorial orbit. Equatorial orbits are not very popular and thus there are few ground stations along the equator available for IXPE to use. Malindi ground station support was supplied by ASI as part of their contribution to the IXPE mission. The Singapore ground station was also selected to supplement Malindi support. These stations are just far enough apart geographically that IXPE can take contacts on both stations on the same orbit without any overlap. This is extremely useful when doing critical activities and during high-rate target observations.

## **2.3 Ground Contact Scheduling:**

During the development phases, the IXPE Planning and Scheduling Team thought that the Malindi schedules would be generated and delivered on a similar cadence to the DTESO schedules for Singapore and cover the same period of time. The team had expected a Malindi predicted forecast schedule to be delivered three weeks in advance and a final operational schedule delivered two weeks in advance. The schedules would run for one week from Monday-Monday (similar to DTESO schedules). Singapore forecast schedules were expected to be delivered from DTESO two weeks in advance and the operational schedules to be delivered one week in advance. This cadence would have allowed for multiple days of schedule negotiations with both ground stations. The team designed the entire planning and scheduling philosophy around this cadence.

However, during a routine test shortly before launch, the planning team found out that Malindi schedules would be delivered only one week in advance. There would be no separate forecast and operational schedules, and the schedule would cover approximately 13 days from Tuesday to Sunday. While this presented additional challenges and complications, the planning team quickly pivoted and came up with a new planning process.

The Malindi ground station is IXPE's primary ground station: 90% of passes are scheduled on one of its three antennas. Schedules are delivered weekly on Tuesday mornings (Mountain time) and run from that day (Tuesday) for 13 days to the second Sunday. The first six days (Tuesday through the first Sunday) overlap the previous schedule delivery, (delivered the previous Tuesday) and maintains the contacts granted in the last schedule. The other seven days (Monday through the following Sunday) are newly granted contacts. As stated above, this was a large departure from the scheduling cadence that the IXPE planning and scheduling team was originally expecting. Given the actual schedule delivery timeline, the amount of time the planning team has to negotiate and request additional or alternate contacts shrank to only one to two days.

The Singapore ground station is the secondary ground station and is largely used to supplement the Malindi schedule during observations of bright objects, anomalies, and anomaly recoveries. It is also used as a backup in case the Malindi ground station has issues and one or more antennas are unavailable.

DTESO works with TNOC to schedule the Singapore antenna. IXPE sends schedule requests to DTESO, which then passes the requests on to TNOC. Forecast schedules are delivered every Friday and cover the week after next (Monday through Sunday). Both the IXPE MOC and TNOC receive this schedule; however, TNOC does not review the schedule and confirm any of the requested contacts until the next week. Operational schedules are delivered to the MOC every Thursday and cover the upcoming week (Monday through Sunday). For these schedules, TNOC reviews the schedule and deletes any IXPE requested contacts that conflict with high priority missions. Once TNOC has finished deconflicting the schedule, they send the updated schedule to DTESO and DTESO sends the MOC the operational schedule. Contacts in the forecast schedule are typically granted, however, there are times when TNOC has had to delete one or two of IXPE's requested contacts in

the operational schedule. When this happens, the planning team must review the current schedule and target observations and determine if replacement contacts are needed.

The two different cadences of schedule requests and delivery can make it challenging to determine and schedule the necessary contacts. For high-rate targets, the planning team must often complete two rounds of scheduling. Initial schedule requests with all desired contacts spread across both stations are sent to Malindi and DTESO. Malindi schedules are delivered first, but the team then must wait two to three days for the Singapore operational schedule to be delivered before knowing the full scope of the combined, granted, Malindi and Singapore schedules. Once the MOC receives the Singapore schedule, the planning team can begin any necessary negotiations. If one or more Singapore contact requests are declined, the team will try and schedule alternative Singapore passes. If those are also declined, then they must try to schedule additional Malindi contacts in order to ensure all data for the current science target is downlinked in time.

## **2.4 Coordinated Observations and Targets of Opportunity**

Target observations are typically planned 6-9 months in advance by the SOC. However, the plan is often fluid and can quickly change for multiple reasons. The primary reasons for observation changes are coordinated observations with other space telescopes (such as Chandra and/or NuStar) and Targets of Opportunity (TOOs).

In the event of a coordinated observation, the timing of the slew to the target of interest needs to be optimized to ensure as much overlap in data from the different telescopes as possible. This can result in a shift in slew start time from the original plan. The SOC usually needs to adjust the slew start by only a few hours, which is negligible from a planning and scheduling perspective. However, a change of 1-2 days is not unheard of and when this occurs, the planning team must review the updated target schedule and determine if changes to the current contact schedule are necessary. In some cases, additional contacts on different or multiple days are required to compensate for the slew time changes and general target observation time. It is important that these changes are caught quickly so that the planning team can send updated ground contact schedule requests as soon as possible. Any newly scheduled passes will need to be folded into the upcoming command load. These coordinated events increase the complexity of the planning cycle but can be incorporated via the nominal planning process.

IXPE also allows observers from the science community to request an immediate observation of a specific target to observe an interesting new behavior (ex: the brightest gamma ray burst every observed, GRB 221009A). These TOOs can be last minute requests that require a turnaround time of 48 hours from receipt of the request at the MOC. The planning and scheduling system must be flexible enough to accommodate these rapid, turnaround TOOs. Depending on the timing and brightness of a TOO, additional contacts may be required, and a new command load may be necessary to observe the target as soon as possible. TOOs such as these require the planning team to use special processes to incorporate the TOO and still ensure all the data has time to be downlinked and maintain the health and safety of the observatory.

## **2.5 Command Loads**

Routine command uploads with time-tagged commands are required for IXPE to downlink data and complete its science objectives. The planning team considered several options for how frequently to schedule these uploads. Loading every two to three days would make it easier to accommodate TOOs and other last minute target observation or ground contact schedule changes as well as reduce the number of potential command reloads due to any changes. However, this would require additional staffing to not only generate multiple loads per week, but also to execute

the real-time commanding and complete the uplink of new commands. Given IXPE's limited staffing, this was not desirable.

Creating time-tagged sequences that last for a longer period of time, 7 to 14 days, was also considered but loads longer than ten days were quickly dismissed. While it would require less real-time commanding to upload the time-tagged commands, the team would lose much of its flexibility when it comes to observation and contact schedule changes. It would result in the need to regularly clear and reload the time-tagged commands on board. The Malindi schedule, being only 13 days long, also limited the length of command loads to 10 to 11 days maximum.

The IXPE team concluded that a command load containing seven days of time-tagged commands was the optimal length. It allows for some flexibility and only requires one command load per week, which is a reasonable workload from both a real-time commanding, planning, and scheduling perspective.

### **3. PLANNING AND SCHEDULING ACTIVITIES**

The planning process is broken down into seven major steps. The planning team has one week to complete all the necessary planning and scheduling activities and upload a new time-tagged command load. The order of these activities was carefully considered and chosen to optimize the planning flow. This section provides an overview of these activities.

#### **3.1 Instrument Activity Ingest:**

The Instrument Activity Plan (IAP) is delivered weekly from the SOC and contains all the information necessary to start the planning process. It starts one week from delivery and covers a three-week time span (21 days). It includes details on the science targets to observe during these three weeks, the expected data rates and observation durations, and any calibrations the SOC wishes to execute. Once it is received by the MOC, the planning team ingests the file into the LASP Operations and Science Instrument Support – Planning and Scheduling (OASIS-PS) system and populates the database with the next targets to observe, calibrations to execute, and the time windows these observations and calibrations can take place.

#### **3.2 Two-Line Elements and Orbit Events:**

Two-line elements (TLEs) are used for antenna tracking, ground contact scheduling, and science planning. To ensure accuracy for all these activities, TLEs are generated three times per week using GPS data downlinked from IXPE. They are sent every Monday, Wednesday, and Friday to the Malindi and Singapore ground stations for antenna tracking and DTESO and the SOC to aid with science observation planning. They are also delivered to the Malindi and Singapore schedulers for contact scheduling. Schedulers use TLEs to ensure that acquisition and loss of signal (AOS/LOS) times are accurate.

IXPE planners ingest the TLEs into Systems Tool Kit (STK) as part of planning process. Orbit events such as South Atlantic Anomaly (SAA) crossings, ascending and descending nodes, Earth eclipses, ground station antenna visibility, and antenna null predictions, are generated using STK. These events are ingested into the planning database and used to schedule many items such as target observations, calibrations, slews to various targets, antenna null commanding, and ground contacts.

During periods of low solar activity, the publicly available TLEs were accurate enough to meet mission requirements. However, as the solar cycle approached its maximum in late 2023 and 2024, the operations team found that they needed a new TLE every one to three days to avoid issues with antenna tracking and inaccuracies in contact schedules (i.e. shifts of AOS/LOS times greater than one minute). Solar activity turned out to have a significant impact on IXPE's orbit and TLE accuracy would drop greatly after a major solar event such as a coronal mass ejection. This caused the ground antennas to have difficulty tracking IXPE and often resulted in a temporary loss of signal from the spacecraft.

Fortunately, by this time, the Navigation team at LASP had developed a process for using the spacecraft GPS data to create a seven-day predicted ephemeris file to be used by NASA's Conjunction Assessment and Risk Analysis (CARA) team. Since these files were being automatically generated on a daily basis, the planning team quickly capitalized on this new process and started ingesting the ephemeris files into STK and fitting a TLE to them. These LASP-generated TLEs are currently in use for planning, contact scheduling, and antenna tracking and have improved the short-term (seven to ten days) accuracy of these activities.

### **3.3 Observation and Calibration Scheduling:**

The observation time is the total time spent observing a target and does not include the time when the target is not visible by IXPE due to the earth being between the target and the observatory, or when IXPE is flying over the SAA. The SAA poses a risk to the instrument hardware. To mitigate the risk of damage, the instrument is configured to a special mode when flying over the SAA. In this mode, the instrument does not collect science data. OASIS-PS tracks the total observation time and once that time reaches the requested observation time, OASIS-PS moves on to scheduling the next target. This means that it can take over two weeks to complete an observation request of only nine days due to target Earth occultations or SAA entries. The exact duration of a target observation is not known until the OASIS-PS completes the observation and calibration scheduling.

To maximize target observation time, calibrations are scheduled daily and during the time periods when a target is not visible by the telescopes.

### **3.4 Slew Planning:**

Once OASIS-PS knows when observations change from one target to the next, the IXPE planning team can schedule and generate the appropriate attitude slews for the timeframe of the IAP. Each slew is analyzed and reviewed to verify that no Flight Rules or mission constraints, such as solar array to sun angle or instrument boresight to sun angle are violated. If there are any violations, the operations team is notified, and the planning process is paused until the violation can be resolved.

If the violation occurs at the start or end of the slew, then the slew itself is not the issue – it is the pointing to a target itself that is the problem. When this happens, the SOC has the option of adjusting the observation period so that IXPE points to the offending target at a more favorable time and avoids all flight rules and constraint violations. Depending on the situation and degree of the violation, the SOC may need to replace the target with one that has better visibility. Both options require the SOC to adjust the plan, re-deliver an IAP, and the planning team must restart the planning process.

If the violations occur during the slew, then the SOC must either re-arrange the order of observations to change the slews or select an intermediate target for IXPE to slew to before pointing at the desired observation target. The requirement for this intermediate target is that it provides a slew path that does not violate any flight rules or constraints. Once again, both options require a complete replan.

It should be noted that the operations team has a process for considering the waiver of a flight rule if the violations are deemed acceptable and pose a low enough risk for a specific scenario.

Final slew times are sent to the SOC so that they can adjust observation times for future targets if the current plan has IXPE slewing to a new target sooner or later than desired.

### 3.5 Ground Station Scheduling:

The slew times allow the planning team to know which targets IXPE is observing and when. They use this information to calculate how many ground contacts are needed per day and send schedule requests to Malindi and DTES0 for the upcoming weeks. Schedules are delivered based on the cadence described in Section 2.3. Once they are received at the MOC, they are ingested into the planning database.

### 3.6 Antenna Nulls:

Due to the design of the communication system, IXPE experiences at least one antenna null per contact. Prior to launch, the IXPE team expected to see some nulls, but they did not anticipate their true frequency and magnitude. During a null, the data is 'ratty' and there are lots of small gaps in the downlinked data. In the interest of data continuity and to reduce the number of data retransmissions, the planning team was able to utilize STK to predict these antenna nulls beforehand and command the spacecraft to pause data playbacks during the nulls.

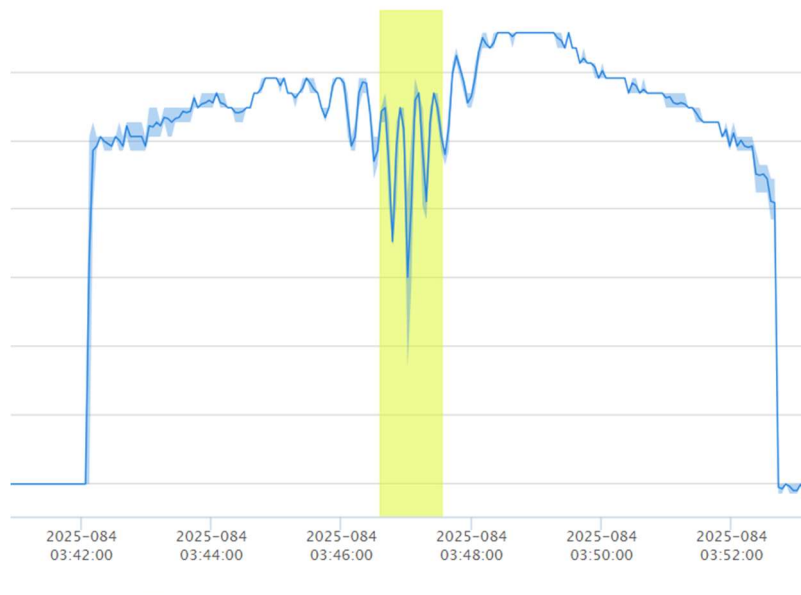


Figure 2 Antenna Signal Strength. Antenna null highlighted in yellow

Antenna null scheduling is optimized to pause stored-data downlink only during the worst parts of the null. Pausing for any longer risks losing valuable good downlink time and increases the need for extra contacts to make up for the lost time. Figure 2 is an example plot of the signal strength (as seen at the spacecraft) and the highlighted section is the successfully predicted antenna null. The planning team also designed the null scheduling logic to handle nulls that occur during AOS and/or LOS and contacts with multiple nulls.

After the ground contact schedules have been delivered and ingested into the database, the planning team schedules the predicted null activities for each contact. Overall, nulls reduce the amount of time during contact to downlink stored data by about 20% and the plan went from scheduling four to five contacts per day to six to seven to make up for this loss.

### 3.7 Command Load Generation:

Once all requests and activities have been scheduled in OASIS-PS, the planning team can build the seven-day, time-tagged command load. This command load contains all the necessary commanding for science and contact activities for the next week. It is reviewed by the operations team and assigned to the Flight Controller (FC) and student Command Controller (CC) to uplink.

## 4. NOMINAL PLANNING CYCLE

Given all of the requirements, constraints, and considerations mentioned in Section 2, the IXPE team developed a three-week planning cycle that is structured enough for multiple people to work on but also flexible enough to handle TOOs and other last-minute changes to observation and contact schedules.

### 4.1 Weekly Planning Cycle

A general overview of the weekly planning flow is depicted in Figure 3 below.

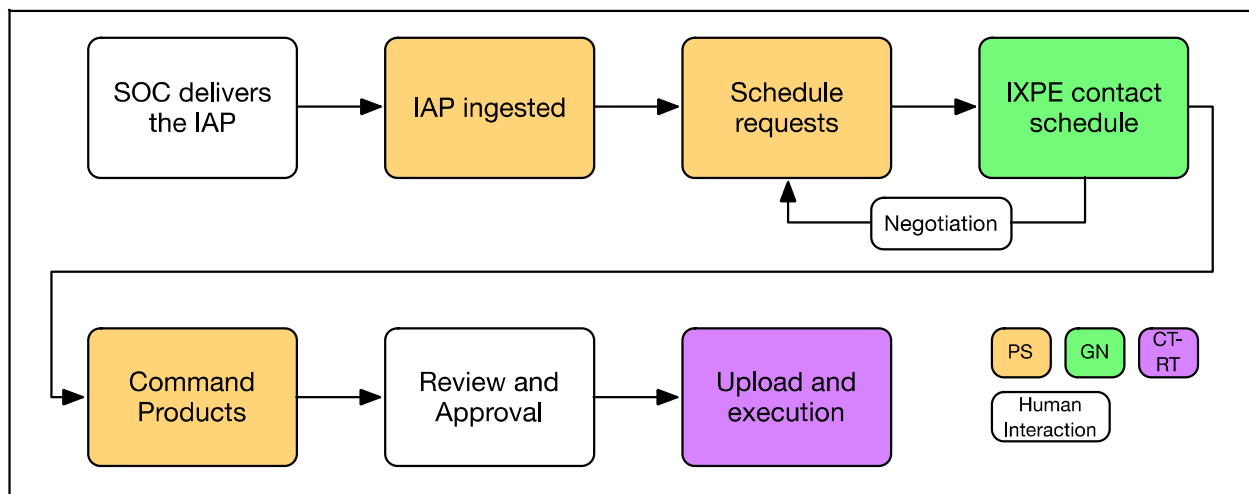


Figure 3 Planning Cycle General Flow

Planning kicks off with the delivery of the IAP from the SOC. As stated earlier, the IAP starts one week from delivery and covers a three-week time span (21 days). The planning team ingests the IAP, calculates the number of contacts required based on each target's data rate and observation duration, and works on the contact schedules and requests that cover the next three to four weeks.

Malindi and Singapore receive the requests and deliver contact schedules to the MOC. The planning team reviews these schedules and confirms if the required contacts have been scheduled. If more contacts are needed, the planning team negotiates with the ground stations to schedule additional contacts at different times and/or on different days.

Once the schedules are finalized, the planning team builds the command products to load the time-tagged commands needed for the next week. These loads are then reviewed, approved, and uploaded to the spacecraft.

This one-week cycle is repeated three times to complete a full, three-week planning cycle. The three-week cycle is necessary because ground contact schedule requests must be made at least one to two weeks in advance.

## 4.2 Full Three-Week Planning Cycle

Figure 4 is an example of a planning calendar and shows which planning and scheduling activities are performed to generate a 7-day time-tagged command load and when these activities typically occur. This schedule focuses on the process for generating the command load for days 26-33. Note that there are other activities occurring throughout the entire planning cycle and command loads are being uploaded on days 5, 12, and 19, but for simplicity's sake, those activities have been removed from this example calendar.

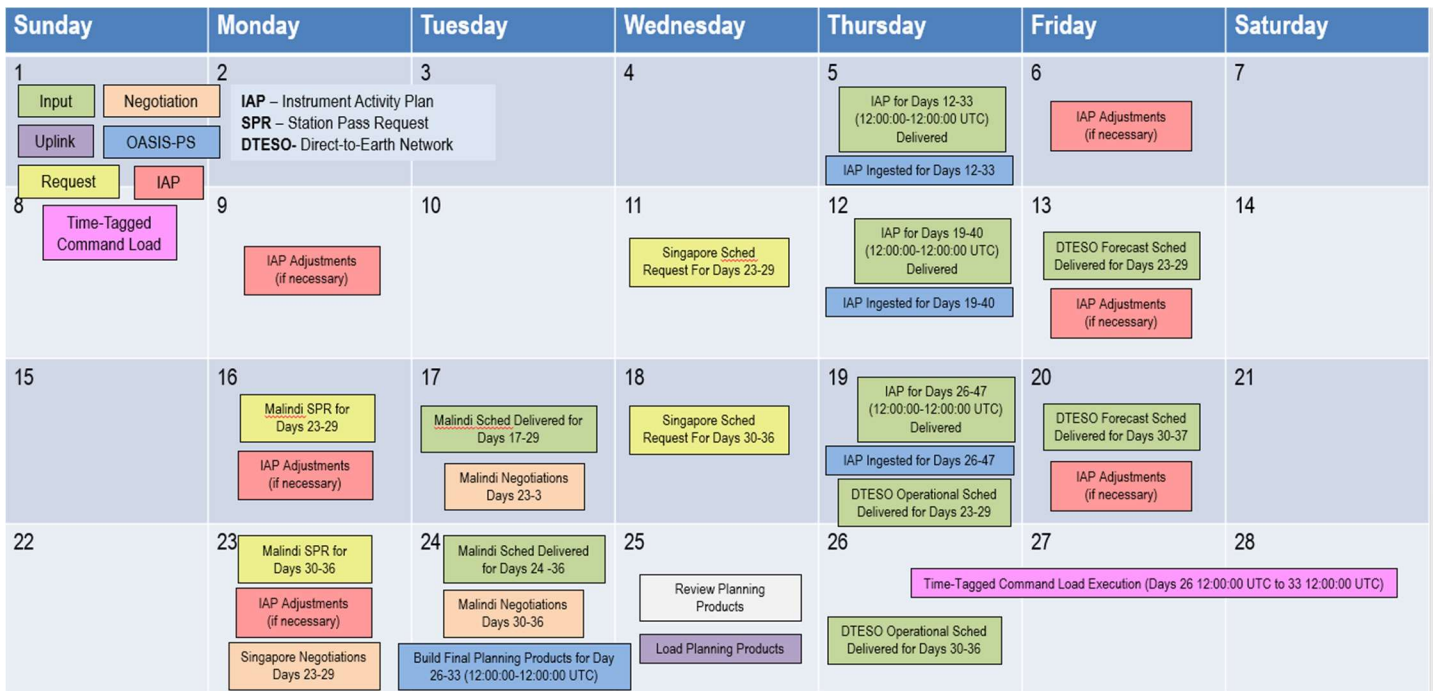


Figure 4 Full, 3-Week Planning Cycle

The planning required to prepare, build, and upload the time-tagged commands for days 26-33 (highlighted in pink in Figure 4) begins three weeks earlier on day 5 with the delivery of the IAP that covers days 12-33 (green IAP box on day 5). The IAP is delivered to the MOC on Thursdays and is ingested into OASIS-PS by the planning team. Observations and calibrations for days 26-33 are included in the third and last week of the IAP. The planning team reviews the IAP for any major changes in weeks one and two (days 12-26), verifies any attitude slews to new targets, and checks the data rates and contact schedule to ensure that the number of contacts is still sufficient. If there are any questions or concerns, the planning team works with the SOC to resolve any issues.

Once the IAP has been verified and the observation schedule confirmed, the planning team can send the initial Singapore pass request for days 23-29, which is noted in Figure 4 in the yellow box on day 11.

On day 12, a new IAP is delivered that covers days 19-40 (green IAP box on day 19). The observations for days 26-33 mentioned previously, are now in the second week of the IAP. Again, the planning team ingests the IAP and reviews it for any major changes. Once it has been confirmed, the planning team can now submit a Malindi pass request for days 23-29 and the Singapore pass request for days 30-36, indicated by the yellow boxes on days 16 and 18, respectively.

The Singapore forecast schedules that covers days 23-29 is delivered on Friday (green box on day 13), and the Malindi schedule covering days 17-29 is delivered that following Tuesday, day 17 (also noted by a green box). The planning team reviews both schedules as they come in and verifies that all requested passes have been scheduled. If there are any passes that were declined, the team works with each ground station to find alternate passes.

Another three-week IAP is delivered on day 19. It covers days 26-47. At this point, the observations for days 26-33 are in the first week of the IAP and there should be no major changes to these observations. This IAP is ingested, reviewed, and confirmed. The Singapore operational schedule is also delivered on day 19 and the forecast schedule for days 30-36 is delivered on Friday, day 20. These schedules are also reviewed to ensure that all passes in the forecast schedule have been granted by TNOG. And once again, if there are any changes, the planning team works with DTESO to schedule alternate passes.

After the Singapore operational schedule and IAP have been verified, the planning team can send out pass requests to Malindi for days 30-36. At this point, the planning team also starts running the planning tools to schedule target observations and calibrations for the time-tagged command load for days 26-33.

Malindi will deliver a schedule that covers days 24-36 on Tuesday, day 24. Once the MOC receives this schedule, the planning team has the remaining information it needs to build all the load products for the command load that covers days 26-33.

These products are built and reviewed on Tuesday and Wednesday and the command load is uplinked on Wednesdays. The Thursday to Thursday time range of the command load was chosen to optimize the overlap between a Singapore operational schedule and Malindi schedule. The MOC is confident in the first seven to ten days of the Malindi schedule and does not expect contacts scheduled during those days to change. The planning team avoids building command loads that cover the last few days of the Malindi schedule to provide flexibility and margin for potential schedule changes. Figure 5 below shows the overlap of the Malindi and Singapore schedules. The Malindi schedule is represented in the orange boxes and Singapore operational and forecast schedules are shown in teal boxes.

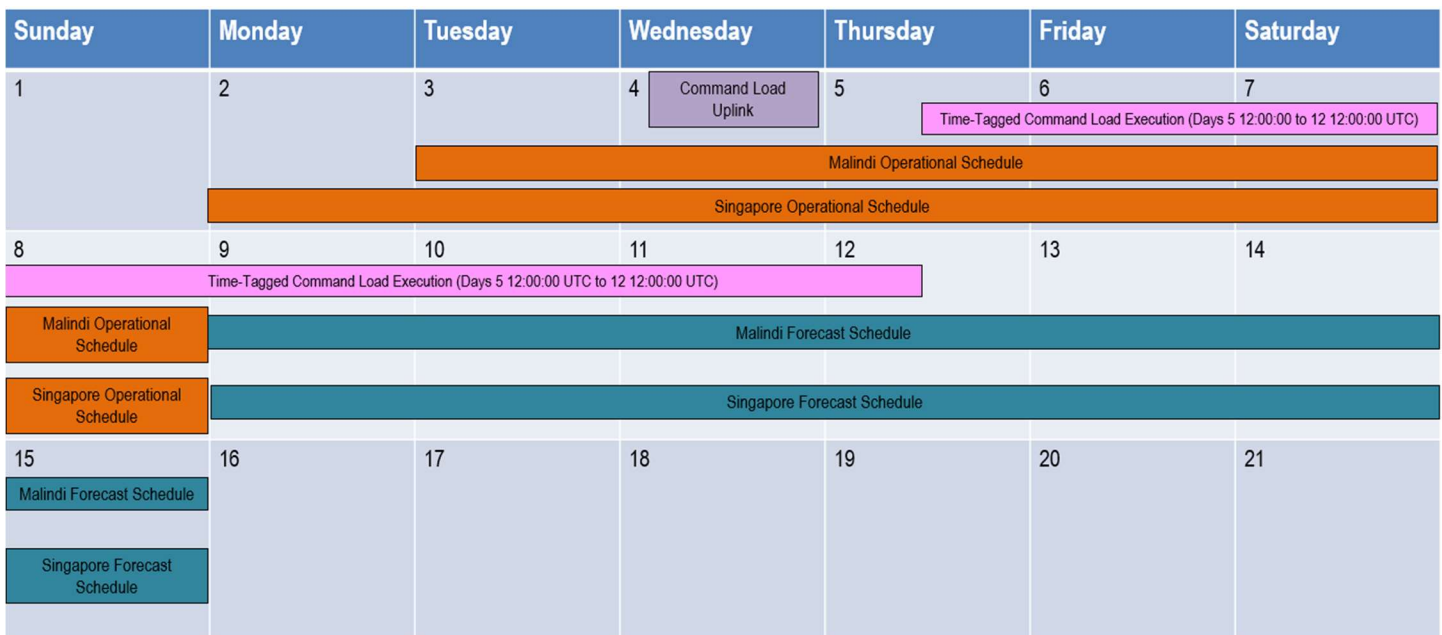


Figure 5 Malindi and Singapore Schedules at Time of Command Load Uplink

The planning team needs to allot two days for the build and review process. This gives the team time to address and issues, questions, or concerns before the time-tagged commands start on Thursday.

The final Singapore operational schedule for days 30-36 is delivered on Thursday, day 26. Note that this is after the command load has begun executing on the spacecraft. The planning team relies on the accuracy of the forecast schedule to build the weekly time-tagged commands. The final step in the planning process for a command load is to review the operational schedule and compare it to the forecast schedule to ensure all contacts in the forecast schedule were granted by TNOC and are in the operational schedule.

Despite careful planning, losing Singapore passes in the operational schedule is still a risk and there are usually one to two passes per month that are requested in the forecast schedule but do not end up in the operational schedule. Most of the time the planning team has scheduled enough Malindi contacts that the deleted Singapore contacts are not required to get all the new science data downlinked. In these cases, the team accepts the loss and does not try to schedule alternate passes nor build and upload new command loads to remove the deleted pass. Instead, the team has developed automation that detects data gaps from a lost pass (and also antenna nulls) and sends commands to re-downlink the data.

If replacement contacts are needed, the planning team will first work with Singapore to see if any alternate contacts are available. If Singapore cannot provide the necessary support, the planning team turns to Malindi to request the additional passes needed. The challenge of these negotiations is that by the time the operational schedule is delivered, the time-tagged commands that cover the first half of the operational schedule (Monday to Thursday 12:00:00 UTC) have already been uploaded to the spacecraft. To prevent having to reload the commands, the planning team focuses on scheduling the replacement contacts on Thursday through Sunday.

## **5 TARGET OF OPPORTUNITY PLANNING**

Targets of opportunity can come in at any time during the week including weekends and holidays. While they can sometimes be folded into the nominal planning cycle, they often require quick turnaround outside of the nominal planning cycle. In these latter cases, the planning team has as little as 48 hours from receipt of the new IAP containing the TOO to point the observatory at the new target. The planning cycle for this type of TOO becomes a highly-compressed version of the one and three-week planning cycles (see Figure 6).

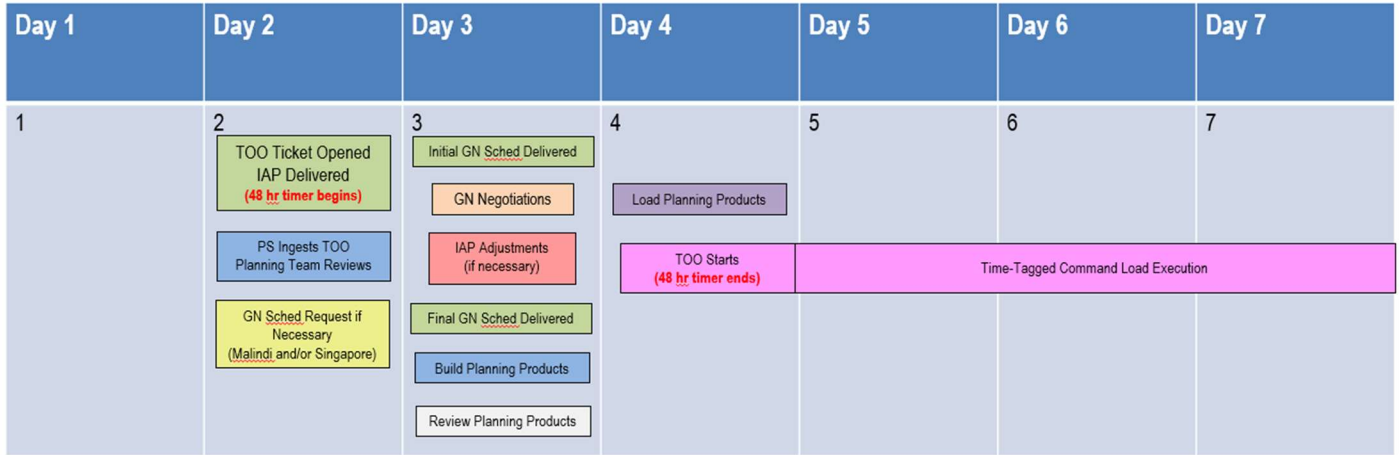


Figure 6 TOO Planning Cycle

The IAP containing the TOO is delivered via a special IXPE Change Request Ticket (XCR) and ingested into OASIS-PS. The planning team reviews the TOO data rate and duration and determines if additional contacts are needed. If no new contacts are required, planning can continue immediately, and the activities outlined in Section 3 can be completed within 24 hours. This leaves another 24 hours for the command loads to be reviewed and uploaded and the observatory to slew to the new target.

The primary challenge for TOOs comes when additional contacts are necessary to get all the new science data down. Due to the seven-hour time difference between Boulder, CO and Fucino, Italy, it is often the middle of the night for the Malindi schedulers when a TOO comes in and thus there is little scheduling support during the MOC working hours. The same is true for Singapore scheduling. Even though DTESO is in the same time zone as the MOC, TNOC is in the same time zone as Fucino and their schedulers do not confirm passes until their working hours, which is late evening for the MOC. This means that the IXPE planning team needs to get schedule requests out to Malindi and DTESO quickly in order to make sure that the Malindi, DTESO, and TNOC have time to update and deliver new schedules. The compressed timeline also needs the planning team to get as much planning done on the first day as possible. Once the schedules come in on day two, the planning team must work quickly and diligently to complete the remaining planning activities and get the command load approved. Since the planning team does not actually upload the command loads – that task is handled by the FC and CC, additional coordination with the FC and CC is required to ensure the new command load with the TOO is uplinked in time.

## 6 STAFFING AND TASK MANAGEMENT

Planning and scheduling is a constant process that requires the planning team to focus not only on the activities and products required for the immediate command load, but also the collection of target observations and schedules for the next three weeks. LASP employs a team of University of Colorado students to help support each of the missions operated by LASP. The IXPE team has

leveraged this opportunity of student availability and built a dedicated planning team consisting of three professional engineers and four to five students.

Weekly tasks are broken down as much as possible to allow for maximum flexibility as students are usually only available for a few hours each day. In order to work with their schedules, the planning team separated the weekly planning items into an organized checklist of tasks to be completed every day. These checklists are created, stored, and worked via Confluence so that planners can access them remotely at any time. This allows for one student to begin the daily planning and get as far as they can before they need to leave. The next student reviews the checklist, notes how far the previous student got, and picks up where they left off. Any questions, comments, or concerns are communicated via a specific planning thread in Slack. Important notes or off-nominal activities are also discussed in the Slack chat and then documented in the checklist to ensure everyone has access to all pertinent information. This process has proven very effective and ensures all tasks are completed on time.

## **7 CONCLUSION**

IXPE's science, its use of ground stations operated by two different entities, and its need for flexibility, results in a complicated planning and scheduling cycle. The IXPE planning team has worked diligently to streamline and optimize the process. It has had great success utilizing a combination of professional planners, student planners, and automation. LASP plans to leverage the strategies developed by IXPE and apply them to future missions.

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## **Acronyms**

AOS	Acquisition of Signal
ASI	Agenzia Spaziale Italiana (Italian Space Agency)

CARA	Conjunction Assessment and Risk Analysis
CC	Command Controller
CT-RT	Command & Telemetry, Real-time Monitoring
DTESO	Direct-to-Earth Scheduling Office
FC	Flight Controller
GN	Ground Network
IAP	Instrument Activity Plan
IXPE	Imaging X-Ray Polarimetry Explorer
KSAT	Kongsberg Satellite Services
LASP	Laboratory for Atmospheric and Space Physics
LEO	Low-Earth Orbit
LOS	Loss of Signal
MOC	Mission Operations Center
OASIS-PS	Operations and Science Instrument Support – Planning and Scheduling
PS	Planning and Scheduling (i.e. OASIS-PS)
SAA	South Atlantic Anomaly
SOC	Science Operations Center
SSOH	Spacecraft State of Health
STK	Systems Tool Kit
TLE	Two-Line Element
TNOC	Tromsø Network Operations Centre
TOO	Target of Opportunity
XCR	IXPE Change Request