Ground Systems Software for Automatic Operation of the HYPSO-2 Hyperspectral Imaging Satellite

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ABSTRACT

HYPSO-1 was launched in January 2022, equipped with a novel hyperspectral imaging payload with the main objective of performing marine research. In 2024, HYPSO-2, with an enhanced capture capacity, will be launched. The satellites can point their cameras off-nadir, a capability that is used to achieve a high temporal resolution over target areas. HYPSO-2 will have over ten times increased downlink capacity compared to HYPSO-1. Therefore, the ground system needs to be adjusted in order to accommodate more data. The main obstacles to overcome are tied to target areas being in geographically close vicinity of each other, estimating when captures are downlinked, and data handling onboard the satellites. In this article, we describe the systems that have been developed to handle the payload operations of the HYPSO-1 satellite and show the technical advances made in the development of the HYPSO-2 satellite. The elements needed for the automatic operation of the HYPSO-2 satellite are introduced and a system to integrate most of these elements is proposed. The system that is designed is deemed to be implementable and can become a fully automated planning and uplink pipeline, but operators would still be required to monitor the satellites' health and perform troubleshooting.

Keywords: Satellite Operations, Mission Control Software, CubeSat, Payload Operation

1. INTRODUCTION

The HYPerspectral Smallsat for Ocean observation (HYPSO) mission successfully launched its first satellite - HYPSO-1 - into a near-polar sun-synchronous orbit in January of 2022.[1] The satellite is a 6U CubeSat and is fully operated by the academic team using a combination of software developed by the satellite bus manufacturer and in-house developed tools. The subsequent satellite with increased capabilities, HYPSO-2, is at the time of writing in its final stages of development and is scheduled for launch in Q2 or Q3 of 2024. As part of the preparation for the launch of HYPSO-2, the ground system software needs to be improved in order to accommodate the operation of two satellites in addition to utilizing the increased capacity of the HYPSO-2 satellite. This paper will only focus on the planning software, meaning operating the satellite and performing payload operation. The payload of the HYPSO satellites is developed by the HYPSO team and consists of a novel Hyperspectal Imager (HSI), an RGB imager, and an Onboard Processing Unit (OPU), with the primary objective of retrieving bio-geophysical parameters such as chlorophyll-a concentration. This can contribute to locating and monitoring of phenomena such as harmful algal blooms.[1–3]

There exist tools to reduce the resources necessary to operate satellites. These tools often concern satellite-bus operation and general tools that are required to communicate with the satellite since such functionalities are

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required for all satellites. Payload operation differs from satellite mission to satellite mission.[4] The existing tools found that have been developed by NASA are called generic inferential executor (GENIE), Generic Spacecraft Analyst Assistant (GenSAA), and Automated Scheduling and Planning Environment (ASPEN).[4] GENIE is a pass automation tool that performs scheduled tasks, GenSAA informs operators about potential issues and probable causes, and ASPEN is a tool that lets the operators use high-level wrapper functions instead of having to use all the low-level commands[4–7] available in the satellites. The HYPSO team already has such systems through their Mission Control Software (MCS), provided by the satellite bus manufacturer.[4] Another approach to making operations more efficient was proposed in the IntelliSTAR work structure that proposed what roles and responsibilities an operational team should consist of.[4,8] There also exists previous work on how other satellite projects have managed to perform agile maneuvers to cover specific areas and acquire images. One example is the *super-agile* maneuvers performed presented by Fan Guowei et al. in.[9] However, these systems, nor the state of art from identified literature, are concerned with how to automatically plan, schedule, and script the specific operation necessary to operate the satellite to carry out the payload-specific tasks. These commands are necessary to - for the purpose of the HYPSO satellites - acquire hyperspectral images of specifically targeted locations on Earth. This work will discuss and show how this has been done in the HYPSO mission.

2. HYPSO-1 OPERATIONS PLANNING SOFTWARE

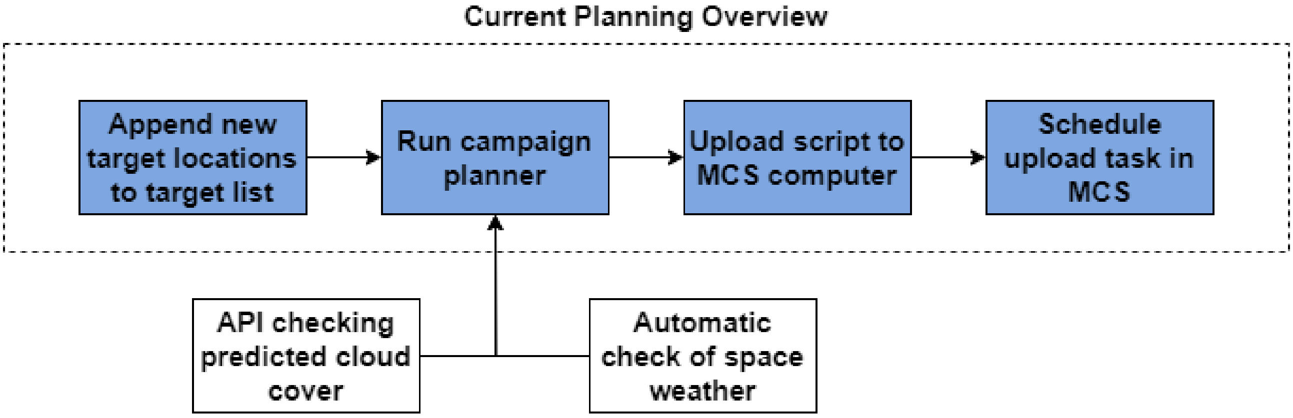

Figure 1. Overview showing the planning sequence for nominal operations of the HYPSO-1 satellite. The blue blocks indicate that the operator has to initiate the task manually, whilst the white blocks mean they are happening automatically.

The current planning software in use for the HYPSO-1 satellite consists of many tools covering different aspects of the operation. The software spans functions that warn about active space weather conditions and check predicted cloud cover over target areas in addition to generating the spacecraft scripts to point the satellite toward the specific imaging location and perform image acquisition. An overview of the process of planning captures for the HYPSO-1 satellite is shown in Figure 1.

The MCS schedules satellite passes and runs all scheduled tasks. The campaign planner iterates through all the capture targets that are given in a list of potential targets and outputs a user-specified list of the most suitable captures. The most suitable captures are defined as the highest priority targets that within acceptable with respect to the given criteria:

- within the user-defined off-nadir pointing angle,
- within the range of acceptable solar zenith angles,
- below the user-defined cloud cover probability forecast, and
- does not coincide with other higher-priority targets.

An overview of the campaign planner can be found in Figure 2. The output of the campaign planner is then input into a python script that generates the final spacecraft scripts that can be uploaded and run directly on the satellite to perform the imaging and data handling onboard. The manual step in between is to allow the operator to perform manual changes to the capture plan if desired.

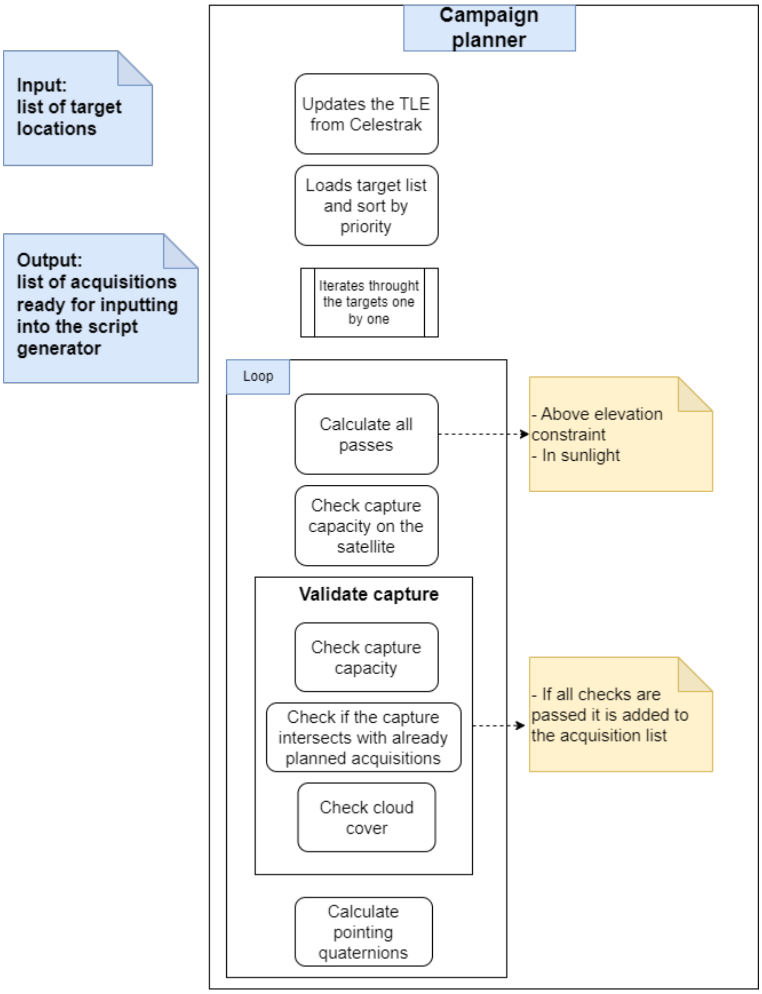

Figure 2. Overview of the campaign planner

For more information about the use of this system and the operation of the HYPSO-1 satellite, the reader is directed to the references[10] for information about the agile development of the HYPSO operational tool-chain and their effect on the operations of the HYPSO-1 satellite, and [11] for more information about a proposed method of introducing an onboard decision making of which captures to downlink and which captures to discard.

2.1 Spacecraft Scripts

The spacecraft scripts are running onboard the satellite with all commands timed and sequenced in a way to perform the imaging of the desired target. The scripts are separated into two different blocks; the *flight computer* script and the *payload controller* script. These can be seen in Figure 3. The flight computer scripts handle telemetry sample intervals and pointing of the satellite, whilst the payload controller scripts handle the imaging and onboard data handling. Each capture – in this type of flow – is seen as one single entry, meaning that the image acquisition and associated data handling happen sequentially with no other capture in between. This means that imaging two targets in close geographical vicinity of each other was not possible. Simplified, the system only allowed for the acquisition of one image per satellite orbit, which takes approximately 90 minutes.

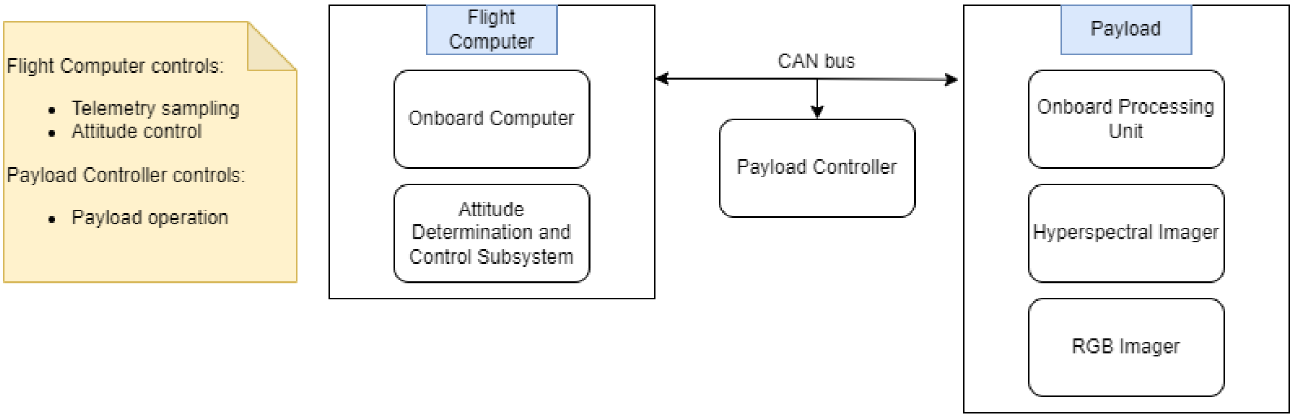

Figure 3. Communication and responsibilities for the *payload controller* and and the *flight computer*

The satellite is capable of performing closer image acquisitions and it has been tested. Close captures are currently not supported in the planning software and instead requires manual intervention in the spacecraft scripts to perform the data handling after all imaging is completed.

Spacecraft scripting also includes onboard processing of the captures, but will not be further discussed in this paper. For more information, the reader is directed to[12] where Jonas A. Røysland et al. performed in-situ classification of the hyperspectral images captured with the HYPSO-1 satellite, and,[13] where Corrado Chiatante et al. discusses how onboard classification can be used to enable in-situ georeferencing.

3. IMPROVEMENTS ON THE HYPSO-2 SATELLITE COMPARED TO THE HYPSO-1 SATELLITE

The HYPSO-2 satellite has technical improvements over the HYPSO-1 satellite that increases the overall capture capacity of the satellite. The capture capacity of the HYPSO-1 satellite is approximately six captures per day, limited by the downlink capacity[4].[11] The HYPSO-1 satellite is equipped with an S-Band radio for downlink, and two backup UHF radios for command, control, and emergency communication. HYPSO-2 uses the same communication sub-systems but has also an X-Band radio for faster downlink of payload data added. The X-Band radio will provide a throughput increase by a factor of at least ten compared to the S-Band downlink for HYPSO-1. There is also added a faster communication interface between the payload and the payload controller. Figure 4 shows an overview of communication interfaces from the payload to the ground system through the radios and payload controller. To match the potential increase in payload duty cycle, the HYPSO-2 satellite is also equipped with deployable solar panels that increase the solar power harvesting capacity. For more information about the HYPSO-1 satellite, the reader is directed to,[4],[1] and.[2]

Finally, the HYPSO-2 satellite has an upgrade to the payload controller subsystem. This upgrade includes data storage that allows an increased size of payload data.

Given these improvements, the capture capacity of the HYPSO-2 satellite could reach as high as 50 hyperspectral captures per day with a cube size of approximately 80MB per capture, compared to about 5 captures with HYPSO-1. The capture capacity will be limited by the power budget, something that is hard to estimate due to it being heavily affected by the imaging operations the satellite performs, which will determine the available onboard power based on the solar panels' orientation towards the sun during capture pointing. Bjørn A. Kristiansen et al. have discussed this problem statement in[14] and proposed a novel cost function that incorporates the incoming energy from the solar irradiance and the outgoing energy due to actuation that used HYPSO-2 as a simulation study.

4. NEW PLANNING APPROACH AND SOFTWARE

The main objective of the new planning software is not only to support a higher capture capacity but also to accommodate agile operation of the HYPSO satellites. Here, agility refers to the interval between when the

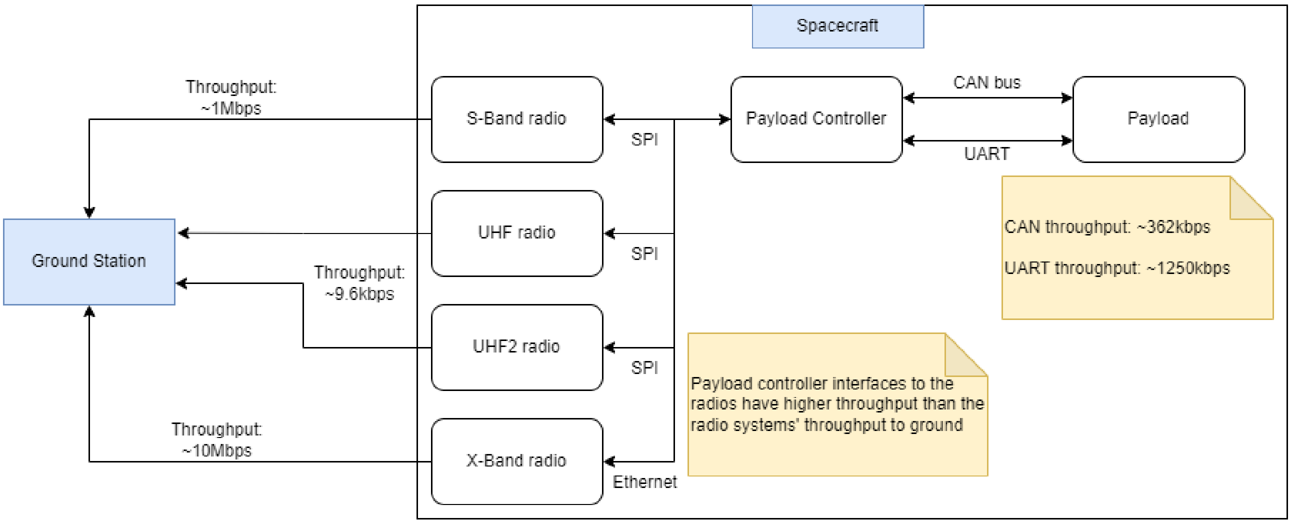

Figure 4. Overview of the communication interfaces from the payload to the ground station through the radios and payload controller.

satellite can acquire one image before pointing toward another target to acquire another image. As described in section 2.1, the current capture planning system is limited to having the image acquisition and the associated data handling as subsequent processes that do not allow for other image acquisitions in between. That leads to the satellite not being able to image targets in close geographical vicinity of each other during one single satellite orbit. Thus, the satellite cannot image all the highest-priority capture locations if they are coinciding with the data handling of the previous capture. The main objectives of the new planning software are:

- **Separating data handling from the image acquisition.** Image acquisition should be scheduled freely, then data handling associated with the captures should happen at times the satellite is not occupied with imaging. With this capability, one can achieve a higher temporal resolution over target areas that are in close geographical vicinity of each other.
- **Estimate when files are downlinked from the satellite.** With the X-Band radio capacity, the HYPSO-2 satellite has the capacity to downlink more captures than the allocated file storage capacity on the payload controller to store payload data. Additionally, one cannot image a lot of targets over a specific area during the daytime and downlink at night since the night-passes at the current ground station are poor. Therefore, it is required for the planning system to estimate when those files have been downlinked and can be overwritten with new captures.
- **Account for space weather.** With space weather being a potential threat to the satellites' health, the planning software should schedule the power-off of all non-essential subsystems when space weather is predicted to be above an acceptable threshold.
- **Prioritize Low latency captures.** Some imaging targets might be time sensitive and planning software should therefore have the ability to flag captures as low latency captures. A low latency capture would mean being prioritized to be downlinked as fast as possible, potentially after onboard data processing.

It is desirable to make this system scalable and replicable for others to use or build upon by making it an extension of the *pyorbital* library with *pass-* and *capture target* objects that have additional attributes such as space weather, Two Line Element (TLE), and cloud cover information. These will not be used as a library but as objects in the integration of bigger systems. At the time of writing, nothing is made open source but it is desired to build the system with a core that takes care of updating the satellite TLE, orbital calculations, space weather, capture targets list, and cloud predictions. Desired satellite-specific operations can then be developed and integrated by other users. The core is presented in Figure 5. This core would serve as a library containing functionality to easily access desired information needed for planning payload operations for other satellite missions. In general, there exist more tools for supporting satellite bus operation than supporting specific payload operation.[4]

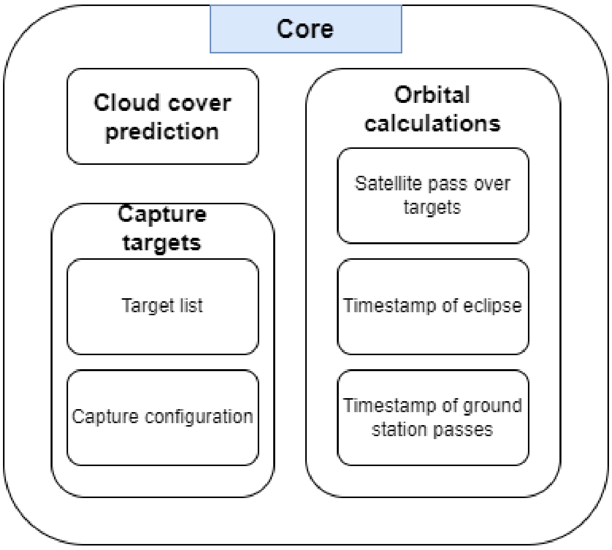

Figure 5. Overview of what the core of the planning software should include

In terms of the HYPSO planning software, this core needs to be developed and integrated with satellite-specific modules. Most of the core is already developed and in use in the existing system, with the exception of some minor functionality. The HYPSO teams also have to account for the differences between the HYPSO-1 and HYPSO-2 satellites. These differences are shown in Figure 6.

Implementation is challenging when planning the payload operation due to target locations changing from day to day, and the operation being heavily affected by external factors such as space weather and cloud cover. The *realizable* capture capacity is therefore not the same as the *theoretical* capture capacity. Thus, the system needs to have a validation of whether or not the current operational plan is realistic. In our proposed implementation, this is solved by making the system itself check if all captures are estimated to be downlinked in time, and recursively delete the lowest priority capture if it is not realizable. An overview of the proposed design is shown in Figure 7.

The design starts by updating the TLE of the satellite at hand and calculating eclipse timestamps and ground station timestamps. Then, it checks the space weather prediction and starts looking through the capture target list. It starts by validating all the possible imaging passes, and if they are all within the user-given requirements, they are accepted and put into the acquisition list. It is planned with a process to account for power budget constraints, but that has to be developed later when the team gains experience from operating the satellite. When the acquisition list has reached the inputted capture capacity, it goes into the data handling block.

In the data handling block, the planning system will be estimating the time to *buffer*, meaning transferring the image from the payload to the payload controller. Data transfer onboard the satellite is stable and a static throughput is experienced, but the image size is calculated based on the image configuration used.
Then, the system will find the timestamps between all image acquisitions before finding how large the timeslots are between all image acquisitions and space weather power-offs. It will continue by loading when all buffer files are expected to have downlinked previous captures such that new captures can be transferred to them. Before scheduling, the planning software will estimate when the image will be downlinked. The estimation algorithm should account for other scheduled capture downlinks. It calculates how many seconds the satellite has a minimum elevation of a to-be-determined threshold where the link is stable and can thus be assumed to have a static throughput. Then, a static offset needs to be subtracted to account for housekeeping tasks and telemetry downlink.

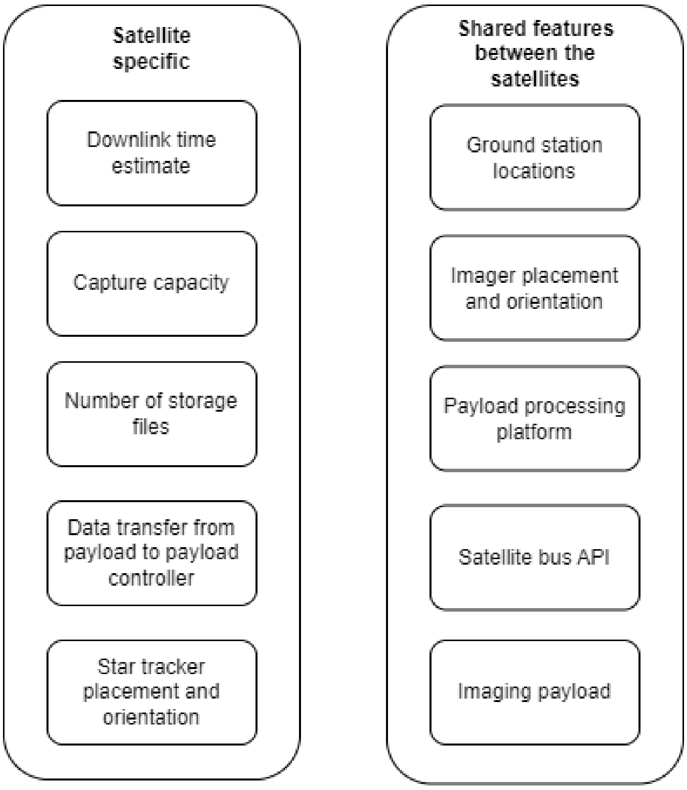

Figure 6. Overview showing the information that is shared between the HYPSO-1 and HYPSO-2 satellites, and what has to be satellite specific

Finally, it will try to schedule all image acquisitions first, and then schedule the data transfer when the satellite is not occupied with other tasks. If some captures are flagged as low-latency they will be transferred and downlinked in the first available slot. If it cannot find a way to downlink all the captures in time, it will delete the lowest priority acquisition in the collision, or the lowest priority capture overall if there is no specific collision, before trying again. When it succeeds, it generates the spacecraft scripts and updates a list with timestamps of when all the buffer files are available for new captures.

This system should run on a server such that the system can account for the status of the buffer files onboard the satellite when planning new payload operations. Then, this system allows for the satellite to acquire more images on days with less cloud cover and can focus on downlinking a backlog of images on days with more clouds. This system is designed specifically with the HYPSO-1 and HYPSO-2 satellites in mind but can be altered to work for other optical satellite missions as well. Additionally, other existing algorithms should be researched. When this is implemented, the planning software will take care of the satellite during nominal operations. If this system is set up to run at specific intervals on a server with access to the MCS computer it can also schedule the uplink of scripts, thus becoming a full planning and uplink pipeline. Operators would still be required to monitor the satellites' health and perform troubleshooting.

5. CONCLUSION

This paper describes the existing planning software developed for the HYPSO-1 satellite and shows which parts have to be initiated manually by operators. It was followed by a section describing the technical advances made in the development of the HYPSO-2 satellite, and how these changes will affect the capacity and functionality of the new satellite. This information was used to design a new ground system software that can accommodate the capacity of the HYPSO-2 satellite in terms of payload operation and taking care of the satellite during harsh space weather. The proposed design allows for a higher temporal resolution and higher spatial coverage for targets in geographically close vicinity of each other by separating the image acquisition from the associated

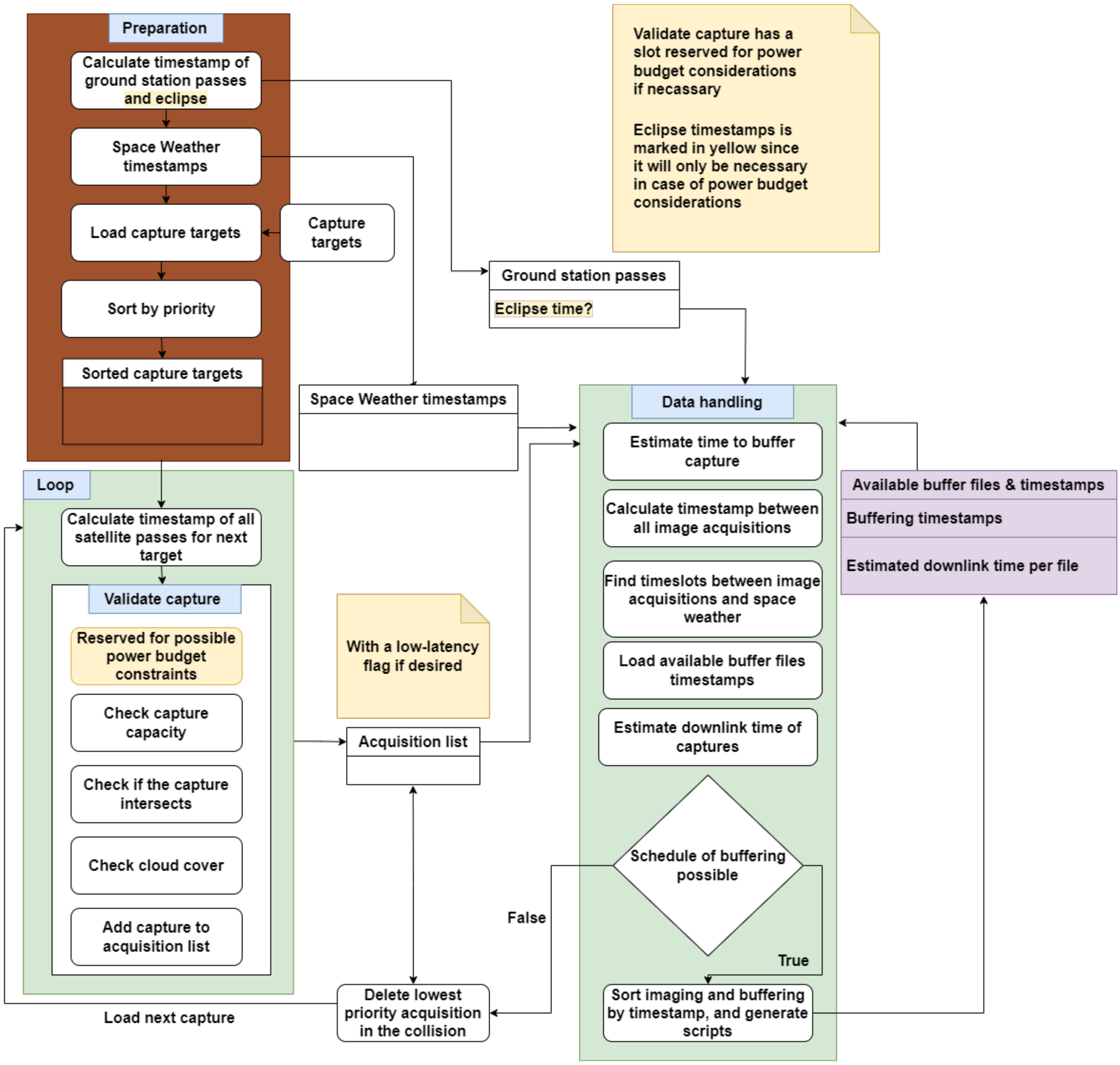

Figure 7. Overview of the proposed planning software. It is separated into three main blocks. The brown block is only run once whilst the green blocks are run until the system manages to schedule all image acquisitions and accompanied data handling. The Purple block is the input from previously planned captures currently running on the satellite.

data handling. Instead, the satellite can utilize its agility and directly start pointing towards the new target location and acquire another image. The data handling is given the logic to estimate the time at which all captures should be downlinked such that it can correctly schedule data transfers onboard the satellite. In terms of time-sensitive observations, a feature to mark such captures is added in order to downlink the data as soon as possible. Lastly, the system also checks the predicted space weather and schedules the power-off of non-essential subsystems to reduce the chance of damage. The process of implementation is ongoing. In the design, there are allocated processes to account for possible power budget constraints, but they are not presented here due to uncertainty in the power budget. However, there is ongoing work to perform energy-optimal attitude control of the spacecraft to mitigate the problem.

6. ACKNOWLEDGEMENT

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