Optimization of Imaging mission scheduling for Multiple Satellites and Ground Stations with MDP

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ABSTRACT

The goal of this paper is to optimize the scheduling of observation missions for Earth Observation Satellites (EOS) and ground stations. The objective function of this problem aims to capture the valuable targets as many as possible and assign them to the ground stations with the highest probability. The number of EOS is increasing along with user demand, and ground stations are being built around the world to communicate with them. The growing number of geostationary EOS, coupled with advances in attitude control technology, has led to more complex mission scheduling problems than ever before. In this paper, we divide this mission scheduling problem into two sub-problems: the target observation problem and the downlink problem. The target observation problem and the downlink problem. These problems are mathematically modeled using Mixed-Integer Linear Programming (MILP). The single observation problem is modeled as a binary variable that is determined by whether an observation is made or not, while the downlink problem takes into account the current memory of each satellite and tries to balance the memory capacity equally. Constraints include the limitations of the satellites themselves, such as the number of observations, power consumption, memory capacity, and the Visible Time Window (VTW) which indicates whether each target can be contacted. A modified dynamic programming algorithm with these considerations is used to solve the observation problem, while the ground station downlink problem is solved using branch-and-bound techniques. An enlistment scenario is constructed to demonstrate feasibility with a total number of 40 satellites and 500 targets. The location of each target is randomly selected within a certain range, and its urgency and importance are also randomly generated based on the user's priorities. For satellites, 8 to 40 satellites equipped with SAR sensor in Low Earth Orbit are configured with a walker delta constellation, allocating 1 to 5 satellites in 8 orbits. The planning period is 7 days from January 1 to January 8 2024. Through this calculation, we can analyze the number of satellites according to the target and their time for optimized image planning through a modified dynamic programming algorithm. It is also possible to resolve downlink conflicts between satellites per ground station and derive an optimized communication timetable.

Keywords: Optimization, Imaging mission scheduling, Earth Observation Satellite (EOS), Ground Station

1. INTRODUCTION

Earth observation satellites (EOS) play key roles in environmental monitoring, disaster management, defense, and many other areas [4]. These Earth observation satellites orbit around the Earth and transmit their observations to a ground station on command[2]. The communication between the satellite and the ground station is carried out when it passes through the communication area of ground station antennas. The antenna usually only support communication with one satellite. this process is mostly operated by manual commands due to this limitation and the unpredictability of the space environment[3] [6]. Traditionally, a few large satellites were adequate to meet the demands of these applications. However, recent advancements in technology have led to the proliferation of Agile Earth Observation Satellites (AEOS)[5] and small satellite constellations, increasing the complexity of mission planning and execution. The growing fleet of satellites has also led to an expanded ground station infrastructure, which was initially designed

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to support a limited number of missions. These changes have exacerbated the intricacies involved in satellite mission scheduling, particularly when considering the constraints of satellite resources, target observation priorities, and ground station availability.

In this paper, we propose to addresses the emerging complexities by using a modified dynamic programming algorithm for optimizing mission scheduling. The algorithm is designed to tackle two sub-problems: The first one is the observation scheduling problem, which deals with the allocation of satellites to various observation tasks, and the second one is the ground station communication problem, which addresses the efficient downloading of the collected data to the ground stations. The constraints considered in the algorithm include satellite resources, the urgency and significance of observation targets, and ground station priorities. The ultimate goal is to ensure a uniform distribution of data across the system.

The remainder of this paper is organized as follows: Section 2 elaborates on the constraints and variables incorporated into the model, as well as the mathematical formulations that express the objective functions. Section 3 contextualizes the proposed algorithm within the problem scenario and outlines its computational flow. Section 4 The mission scenario for simulation will be listed such as the list of targes, location of ground station. Section 5 validates the algorithm through an empirical study, demonstrating its effectiveness in optimizing mission schedules. Finally, Section 6 provides a conclusion and points towards future avenues of research.

2. PROBLEM FORMULATION

2.1 Problem Description

To avoid unnecessary repetition of overlapping sections, this chapter will be divided into energy collection, remote sensing missions, and data transmission. First of all, there are some common prerequisites for satellites that are not specific to each segment

- All satellites have the same maximum capacity of resources (memory and power), the same resource usage during observations, and the same resource fluctuations due to communication with ground stations.
- Satellites are spaced at regular intervals in different orbits, and each satellite uses solar panels to collect energy when it is not observing or communicating with the ground station.

2.2 Nomenclature

e_{ch} = Power that collected on energy collection task
e_{cu} = Power level of current satellite
e_m = Maximum power level of the satellite
e_{cr} = Charge rate of satellite per second
e_{rs} = Power consumption rate per second for remote sensing
e_{gs} = Power consumption rate per second for ground station communication
$t_{e_{\text{last}}}$ = Time that the satellite process remote sensing or communication task
t_s = Time when current mission starts
w_p = Weight of target based on priority
w_d = Weight of target based on deadline
w_t = Combined weight of target based on w_p and w_d
w_r = Ratio how to combine w_p and w_d for w_t
w_{gs} = Weight of ground station based on priority
tr = tr_{th} target, $tr \in \{1,\ldots,|T|\}$
sa = sa_{th} satellite, $sa \in \{1,\ldots,|S|\}$
m^{rs} = m^{rs}_{th} mission for remote sensing, $m^{rs} \in 1,\ldots,|M^{rs}|$
$m^{rs_{min}}$ = Minimun count of remote sensing
$m^{rs_{max}}$ = Maximum count of remote sensing
m^{gs} = m^{gs}_{th} mission for ground station, $m^{gs} \in 1,\ldots,|M^{gs}|$

me_{sa} = Memory of sa_{th} satellite
me_{sa}^{max} = Maximum value of memory for sa_{th} satellite
me_{ra}^{rs} = Rate of memory with remote sensing task
me_{ra}^{gs} = Rate of memory with ground station communication task

2.3 Energy Collection

Satellites collect energy using solar panels and store the collected energy in batteries. The collected energy is used for various activities utilizing the satellite, including remote observation missions and sending and receiving data through communication with ground stations. It is assumed for satellite that its energy collection is performed in all but two cases: remote sensing and communication with the ground station, and the energy collection is as follows.

$$e_{ch} = (t_s - t_{e_{\text{last}}}) \cdot e_{cr} \tag{1}$$

Power Consumption for Remote Sensing and Communication: The power consumed during remote sensing m^{rs} and ground station communication m^{gs} missions can be modeled as:

$$\Delta e_{rs}^{sa} = e_{rs} \cdot (t_s - t_{e_{\text{last}}}^{sa}) \tag{2}$$

$$\Delta e_{gs}^{sa} = e_{gs} \cdot (t_s - t_{e_{\text{last}}}^{sa}) \tag{3}$$

Each satellite updates its current power storage based on the value between these two times and the charge rate per second. If the amount of energy collected reaches the upper limit of each satellite's energy storage, no further energy collection is performed. Every satellites use the same nomenclature of energy.

2.4 Remote Sensing

Targets for remote sensing are assigned a weight value consisting of their priority and urgency as follow Eq (4).

$$w_t = (w_p \cdot w_{\text{r}}) + (w_d \cdot (1 - w_{\text{r}})) \tag{4}$$

Storage and Power Limits: The power level e_{cu} and storage me_{sa} for each satellite sa are constrained between a minimum 0 and an upper limit e_m and me_{max}, respectively.

$$0 \leq e_{cu}^{sa} \leq e_{m}^{sa}, 0 \leq me_{sa} \leq me_{sa}^{\text{max}} \tag{5}$$

The variables involved in the mission are specified as a binary problem with a value of 1 if the mission is carried out and 0 otherwise like Eq. (6)

$$x_{\text{trsam}}^{rs} = \begin{cases} 1, & \textit{The satellite complete observation} \\ 0, & \textit{The satellite passed the target} \end{cases} \tag{6}$$

2.5 Ground Station Communication

Ground stations are assigned a weight value based on their priority. Communicating with the ground station is also specified as a binary problem, with a value of 1 if communication is performed and 0 otherwise.

$$y_{\text{sam}}^{gs} = \begin{cases} 1, & \textit{The satellite communicated with ground station} \\ 0, & \textit{The satellite passed the ground station} \end{cases} \tag{7}$$

Storage Proportional to Number of Targets: The storage me_{sa} required for each observation mission m^{rs} is proportional to the number of targets x_{trsam}^{rs} in that mission.

$$\Delta me_{sa} = me_{ra}^{rs} \cdot x_{\text{trsam}}^{rs} \tag{8}$$

2.6 Objective Function

The objective function of remote sensing is to obtain remote sensing weights to be maximum value as a formula Eq. (9).

$$P^{rs} = max \sum_{tr=1}^{T} \sum_{sa=1}^{S} \sum_{m^{rs}=1}^{M^{rs}} x_{\text{trsam}}^{rs} \cdot w_{tr} \tag{9}$$

The goal of prioritizing communications with ground stations while minimizing the capacity of the satellite for continuous remote sensing. This can be expressed as a formula Eq. (10)

$$P^{gs} = max \sum_{sa=1}^{S} \sum_{m^{gs}=1}^{M^{rs}} y^{rs}_{\text{sam}} \cdot w_{gs} \tag{10}$$

2.7 Resources and Constraints

During the course of this mission, resources and constraints are initialized as follows:

- Initialization of Satellite's Storage and Power: At the beginning of each mission m_0^{rs}, each satellite sa is initialized with maximum power e_m and empty storage $me_{sa} = 0$.

$$e^{sa}_{cu}(t_s) = (t_s - t_0) \cdot e_{cr}, \quad me_{sa}(m_0^{rs}) = 0 \tag{11}$$

- Observation Mission Limit: A satellite sa can only observe a maximum $m^{rs_{max}}$ in an observation mission.

$$m^{rs_{min}} \leq \sum_{tr=1}^{T} \sum_{sa=1}^{S} \sum_{m^{rs}=1}^{M^{rs}} x^{rs}_{\text{trsam}} \leq m^{rs_{max}} \tag{12}$$

- Power Capacity for Missions: If the remaining power capacity e_{cu} is zero, no observation or communication missions can be performed.

$$e^{sa}_{cu} > 0 \Rightarrow \text{Missions are possible} \tag{13}$$

- Power Collection: The power collected during an energy collection task e_{ch} can be added to the current power level e_{cu} but should not exceed the maximum power level e_m.

$$e^{sa}_{cu} = \min(e^{sa}_{cu} + e^{sa}_{ch}, e^{sa}_{m}) \tag{14}$$

3. SOLUTION APPROACH

DP can be used when a small problem occurs repeatedly and the result of the same problem is the same[1]. By storing these small problems (memoization), we can reduce unnecessary computations.

Algorithm 1 MDP Algorithm

```
function MDP(total_target_list, contact_plan_target, contact_plan_gs)
    Input:
        total_target_list : List containing information of $|T|$
        contact_plan_target : Contact plans on targets for each of $|S|$
        contact_plan_gs : Contact plans on ground stations for each of $|S|$
    Output:
        dp_result : Summary of dp_result of all vtws
    vtws ← create_vtw(contact_plan_target, contact_plan_gs)
    satellites ← create_satellite()
    for vtw in vtws do
        DL_process_checker(vtw)
        weight, rs_count ← mdp_process(vtw)
        update_total_target_list(total_target_list, weight)
        update_satellites_memory(satellites, rs_count)
        dp_result ← record_mdp_result(weight, rs_count)
    end for
    return dp_result
end function
```

In MDP, we utilized this DP approach to solve the observation mission problem for satellites. First, we obtain the possible mission time M^{rs} for satellite S for observation target T from the STK, and divide it into units corresponding to the smallest problem in the DP based on the association between the specific time interval and the driving range of AEOS. This is called the VTW. In these VTWs, we have the initial start time of the observation, the satellite performing the observation, and a one-way connection between w_t for each observation tr and the tr in the next problem.

The Algorithm 1 is a description of the MDP procedure. The VTWs are created on create_vtw function with the connection condition above. Each satellite is initialized on create_satellite() function. The MDP traverses the VTWs to obtain the contact times with the ground stations, and then computes which targets were observed and the sum of w_t. Finally, the process of storing the observed targets is performed for the satellite that flew the mission. After this process is performed for all VTWs, the user is presented with a schedule of targets observed and ground station contact times calculated by the algorithm.

Algorithm 2 DL_process_checker Algorithm

```
function DL_PROCESS_CHECKER(vtw)
    Input:
        vtw
    $t_s \leftarrow$ vtw.start_time
    $sa \leftarrow$ vtw.satellite
    max_gs_weight = max($sa$.gs.weight)
    if $me_{sa}$ is 0 then
        Return
    else
        if $me_{sa} < me_{sa}^{max}/2$ then
            gs_weight_check ← True
        end if
    end if
    ground_station_list ← empty list
    for $m^{gs}$ in $sa$.gs do
        if gs.start_time + gs.duration < vtw_start_time then
            ground_station_list.add(gs)
        else
            Break For loop
        end if
    end for
    selected_gs ← max_weight_in_gs(ground_station_list)
    if (selected_gs.weight is not max_gs_weight) and (gs_weight_check is True) then
        Return
    end if
    if selected_gs.conflict is True then
        downlink_satellite ← selected_gs.satellite
        sat_1_ratio, sat_2_ratio ← get_downlink_ratio(selected_gs, downlink_satellite)
        downlink_task_process(downlink_satellite, sat_1_ratio, sat_2_ratio, selected_gs, conflict = True)
    else
        downlink_satellite ← selected_gs.satellite
        downlink_task_process(downlink_satellite, selected_gs, conflict = False)
    end if
    update_gs_list($t_s$, $sa$)
end function
```

The Algorithm 2 outlines the process for determining a communication schedule with the ground station based on a specific objective function. This process is skipped if the target satellite's memory is either non-zero or not fully filled and the ground station is not the highest priority. The communication schedule for the ground station is maintained within the Satellite object, which is the target of the observation mission, and it is sorted in chronological order. Because a ground station can only communicate with one satellite at a time, a 'conflict' is defined as an overlapping duration between the communication windows of two different satellites. In the event of a conflict, the remaining capacity of the involved satellites, as well as their future data acquisition and transmission capabilities, are considered to redistribute the antenna's travel time. Subsequently, any communication schedule entries that are earlier than the mission's start time are removed after data transmission.

4. MISSION SCENARIO

The mission area is the region between N 34° - 42° and E 124° - 130° in the vicinity of the Korean Peninsula. targets are generated by placing arbitrarily defined latitudes and longitudes and weights in the area. Table 4 shows an example of an target generated in the process. The satellites are equipped with SAR sensors and are spaced at specific intervals in low Earth orbit. There are 8 orbits in total, and the mission will last 7 days, from January 1, 2024 to January 8, 2024. The detailed parameters are shown in Table 2.

No	Name	Latitude°	Longitude°	W_T
1	e_target000	37.44	130.63	0.39
2	e_target001	35.71	129.45	0.60
3	e_target002	36.52	130.59	0.81
		...		
254	n_target199	42.25	130.56	0.48
255	n_target200	38.44	124.92	0.30
256	n_target201	39.30	126.54	0.30
		...		
498	w_target122	35.26	126.12	0.69
499	w_target123	32.89	125.91	0.48
500	w_target124	37.40	124.38	0.81

Table 1: Observation targets

Satellite Parameters	Value
Altitude (km)	500
Inclination (deg)	45
Worker Delta constellation	(40/8/1)
Number of target	500
Planning Horizon(day)	{1,2,3,4,5,6,7}
e_m	2,160,000
$e_r s$	100
$e_g s$	300
me_{sa}^{max}	1024
me_{ra}^{rs}	1
me_{ra}^{gs}	0.1
w_p, w_d	{0.9,0.6,0.3}
w_r	0.7
w_{gs}	{1.0,0.6,0.3}
$m^{rs_{min}}$	0
$m^{rs_{max}}$	5

Table 2: Satellite parameters

Fig.1 shows the locations of the 500 targets generated in this process and the satellites and their orbits that will be used in this scenario. Each mission increases the number of satellites per orbit from 1 to 5, for a total of 8 to 40 satellites.

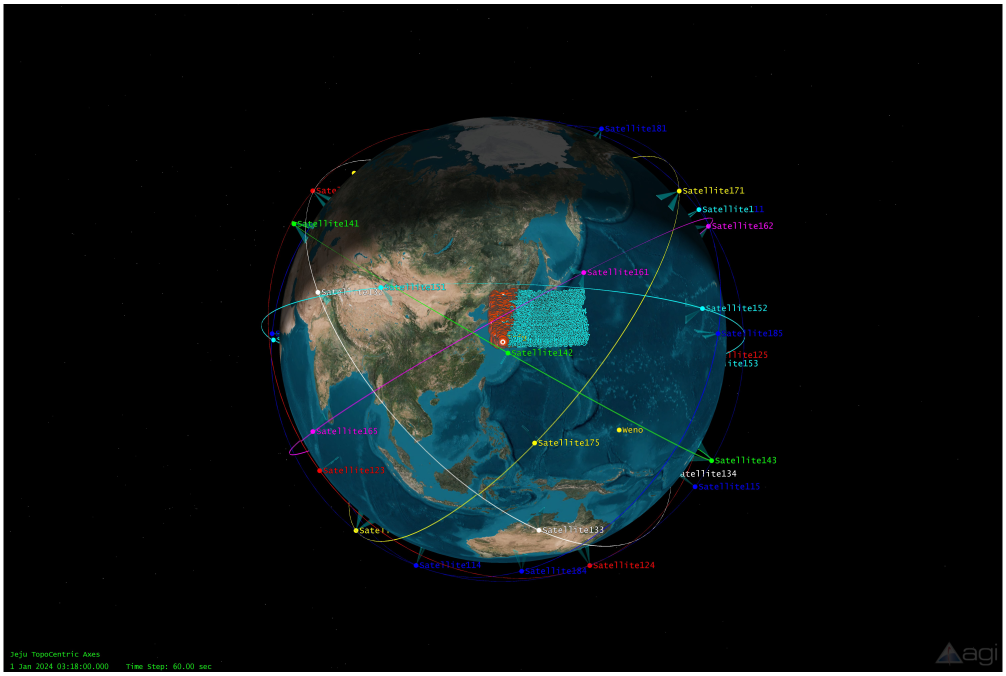

Fig. 1: Example of targets and satellites for simulation

Name	Latitude°	Longitude°	Weight	Cone Half Angle
GER	48.09	11.28	0.6	70
Jeju	33.41	126.56	1.0	70
Weno	7.44	151.86	0.3	70

Table 3: Locations and weights of ground station

Category	**Specification**
CPU	Intel(R) i7-11700
RAM	32GB
Implement tool	VS Code
Framework	Python 3.10

Table 4: Hardware and Development Environment

Table 3 lists the ground stations. All satellites have the same weight for each ground station. The cone half angle was originally 80 degrees, but it was reduced by 10 degrees due to the time required to perform up-link operations such as sending commands to the satellite.

5. RESULT

The proposed algorithm was performed using the 500 targets presented in Table 1 and the parameters presented in Table 2. and it is developed on the enviroment with Table 4. This section is based on a single result, as multiple iterations for the same target condition will yield the same value except for an error in process time.

In the case of Fig. 2, the achievement rate ranges from 1 to 5 satellites in orbit and from 8 to 40 satellites in total. The achievement rate is defined by the following equation:

$$\text{Achievement rate of } \mathrm{p}^{\mathrm{rs}}\ (\%) = \frac{\text{Value of obtained } \mathrm{p}^{\mathrm{rs}}}{\text{Total value of } \mathrm{p}^{\mathrm{rs}}} \times 100 \tag{15}$$

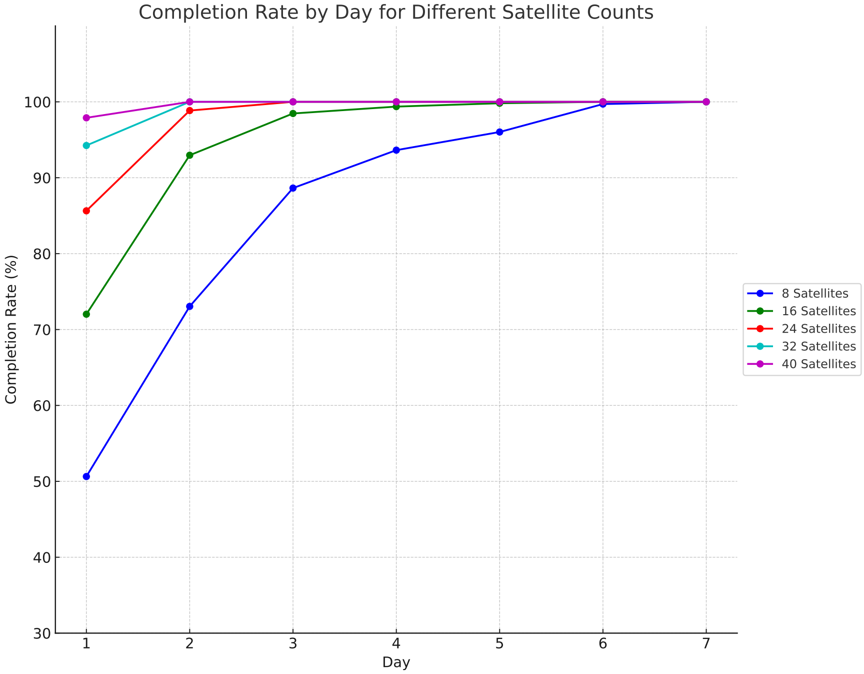

Fig. 2: Completion rate by day

Referring to the figure, we can see that almost all targets are observed by day 7, when the mission ends with the lowest number of satellites 8. As the number of satellites increases, the completion date gets earlier and earlier until, by the 40s, almost all targets are observed on the first day. The following results are based on the assumption that there is one satellite per orbit so that we can see the results by date. Fig.3 shows the communication frequency of each ground station by date. In the case of Jeju, which is located close to the mission area, even with the highest weight of 1.0, the frequency of communication was low because the observation mission was prioritized. On the other hand, GER, which is further away from the mission area, had a high communication rate during the mission. Similarly, for Weno, which has a low weight, we can see a low rate during the mission.

Fig. 44 shows a graph of individual and cumulative memory transfers by date for ground stations. The bar graph shows the individual memory transfers by date, and the line graph shows the cumulative transfers. Since there is no difference in the transmission rate for each ground station, the higher the communication frequency, the higher the transmission capacity, showing a similar trend to Fig.3.

Fig.5 and 6 show the variation of capacity and power of the satellite that performed the most observation/transmission missions among the eight satellites. From the above graphs, it can be seen that the constraints on the upper limit of the capacity and the simulation of the charging and use of power defined earlier work properly.

6. CONCLUSION

In this paper, we presented an optimization algorithm for target observation and ground station communication for a constellation of 40 satellites and three ground stations equipped with Active SAR. The algorithm can always obtain the same optimal value under the same conditions, which allows us to obtain a timetable for observation and communication in a given scenario. Future work could include the observation and communication with ground stations for EO satellites as well as SAR satellites.

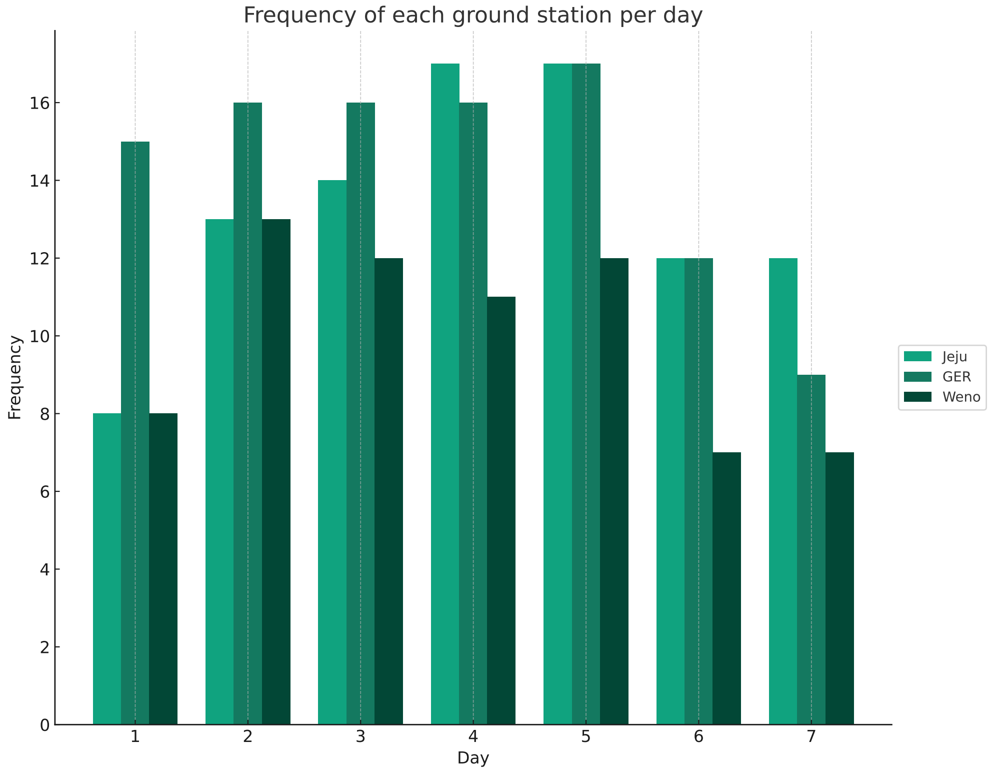

Fig. 3: Frequency of ground station by Day

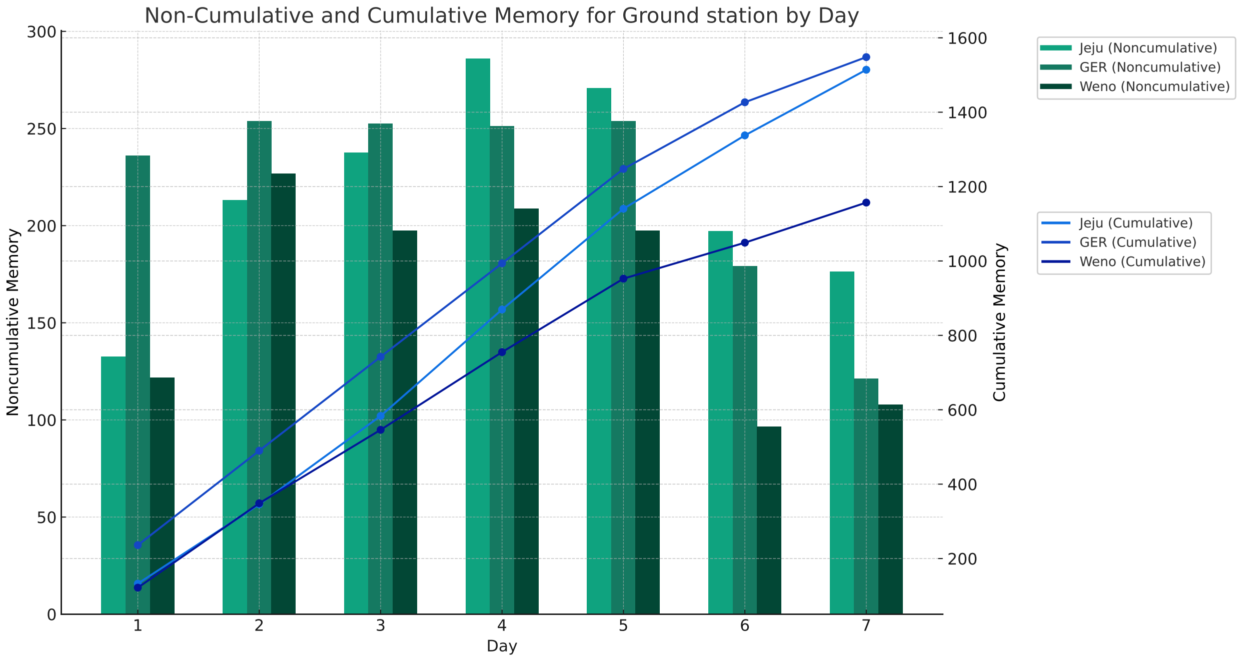

Fig. 4: Non/Cumulative memory by Day

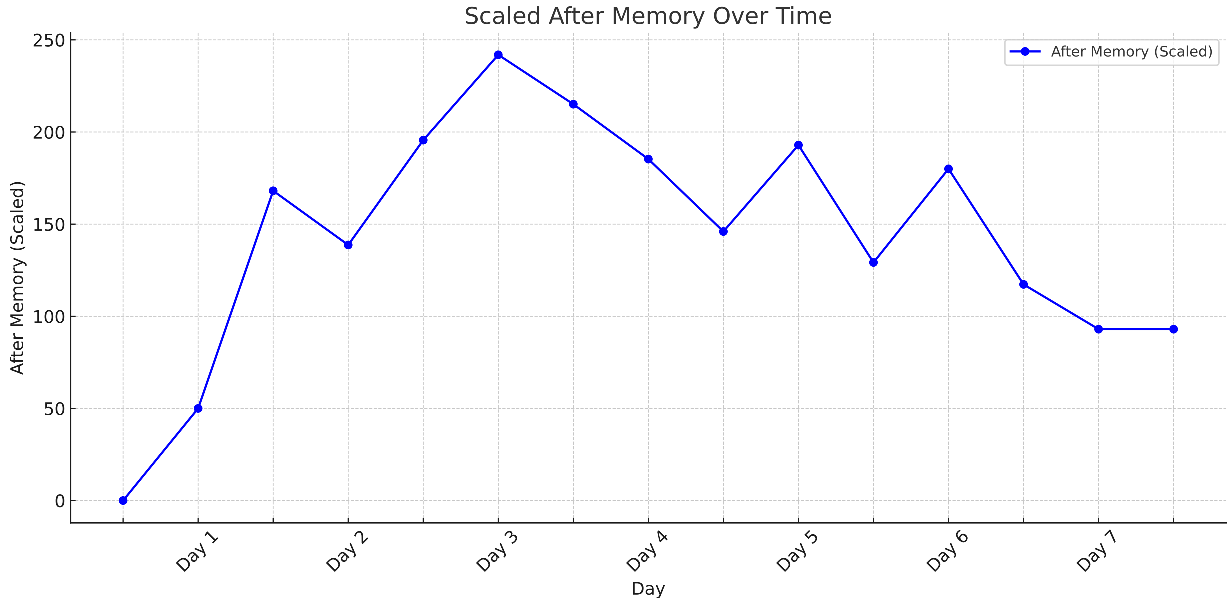

Fig. 5: Trends of memory by Day

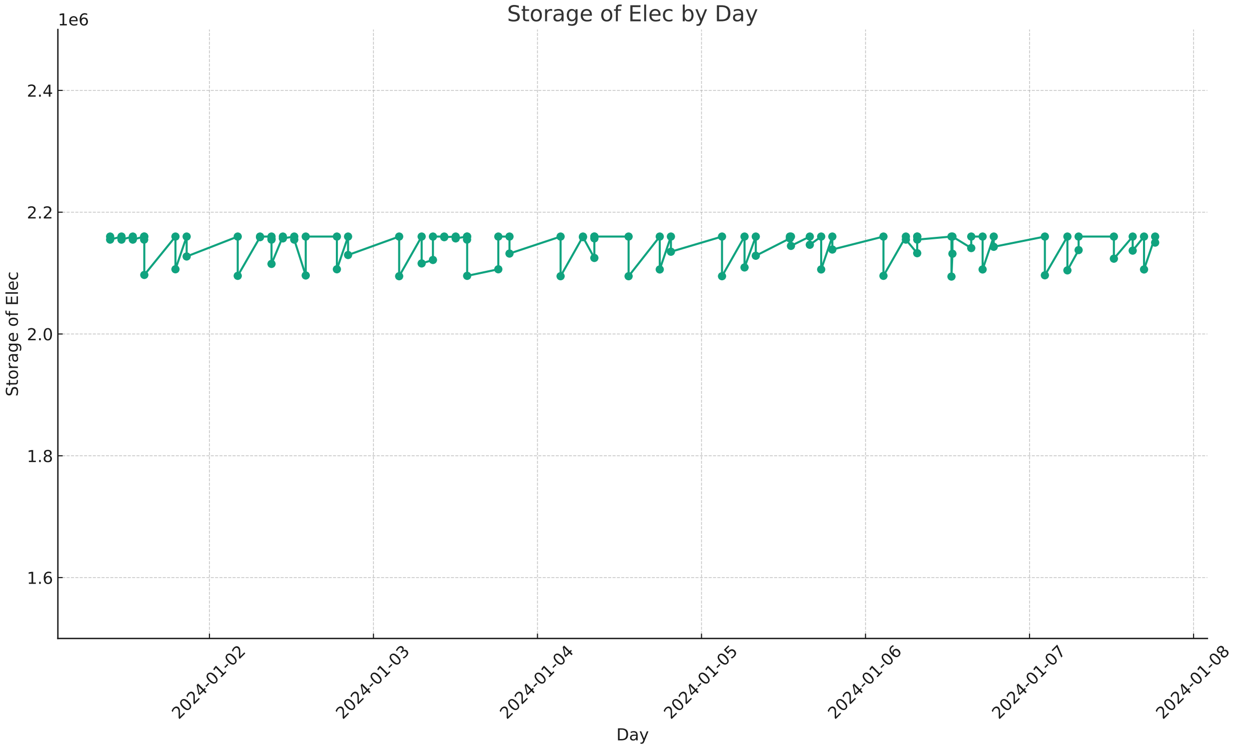

Fig. 6: Electric power of satellite by times

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