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Autonomous Mission Planning for OLFAR: A Satellite Swarm in Lunar Orbit for Radio Astronomy

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Abstract

Orbiting Low Frequency Array for Radio Astronomy (OLFAR) is a radio astronomy mission that has been studied since 2010 by several Dutch universities and research institutes. The mission aims at producing sky maps by collecting cosmic signals at ultra-low wavelengths regimes, below the 30 MHz frequency band. A satellite swarm comprising more than 10 satellites equipped with passive antennas will be deployed in space where the radio frequency interference can be minimized, e.g., on the far side of the moon. So far, several studies have been devoted to design the space segment, which consists of the payload and platform elements. However, the ground segment, particularly the mission planning system has not yet been designed in detail. In this paper, a systematical mission planning method for OLFAR is presented after a mission planning problem is formulated based on the current satellite design.

Keywords: Mission planning, radio astronomy, satellite swarm, lunar orbit, ground segment, autonomy

1. Introduction

The ground segment plays an important role for the mission success as well as the space segment and the launch segment [1]. The Mission Control Element (MCE) is one of the ground segment elements, and its main function is mission planning and scheduling. It aims at scheduling several tasks within limited resources and under constraints; eventually, generating a timeline for the specific planning horizon.

The mission planning algorithm (or shortly algorithm) can be generally divided into three categories: deterministic exact algorithm, deterministic approximate algorithm, and non-deterministic approximate algorithm [2]. Firstly, the deterministic exact algorithm provides an exact optimal solution but requires longest computational time among the three. For example, the brute-force search needs to enumerate all possible candidates before achieving a global optimal solution. Secondly, the deterministic approximate algorithm provides a sub-optimal solution with significantly lesser computational burden. It is often called as a heuristic algorithm [3]. There are for example greedy algorithms and local search algorithms. Thirdly, the non-deterministic approximate algorithm also provides a suboptimal solution, and it is often called as a metaheuristic algorithm or a population-based algorithm. Genetic algorithm and particle swarm optimization are two of the well-known non-deterministic approximate algorithms. However, it should be noted that definitions and classifications of algorithms often vary over the literature.

In spacecraft operations, the heuristic algorithm [4,5] that belongs to the second category in the previous classification, has been much more applied to real missions [2,6], compared to algorithms that seek optimal solutions. In Germany, the DLR/GSOC has been continuously developing priority-based greedy algorithms that have been applied to several earth observation missions, e.g., TerraSAR-X [7] and TET-1 [8]. In France, two heuristic algorithms, the greedy algorithm and the local search algorithm, were applied for acquisition planning of the Pleiades satellites, and their performances were compared with two classical algorithms: dynamic programming algorithm and constraint programming approach [9]. In the US, the JPL developed a heuristic conflict-based algorithm and applied it into on-ground mission planning for EO-1 [10]. For the on-board planner, the JPL has been developing local search-based algorithms that have been implemented on on-board mission planning for the EO-1 satellite [11] and for the IPEX CubeSat [12].

This paper proposes a mission planning algorithm for space-based radio astronomy. A project named OLFAR (Orbiting Low Frequency Array for Radio Astronomy) [13] is served as a mission example. There are two major operational differences between OLFAR and conventional earth observation missions that have been driving OLFAR to develop its own mission planning algorithm. Firstly, in OLFAR, more than 10 satellites will operate together (by forming a satellite swarm), and they need to frequently communicate with each other to exchange their observation and health data and to synchronize their reference times. Therefore, a

mission planning algorithm should explicitly assign intersatellite communication tasks into their timelines and consider relevant satellite resources changes, e.g., additional power consumed by intersatellite communication. Secondly, an OLFAR deployment location will be very far compared to the earth-based missions; the most promising one is lunar orbit. Due to the much longer downlink communication distance, the downlink data rate will be significantly lower, e.g., hundreds of kbps, compared to the earth-based missions, e.g., hundreds of Mbps. Therefore, a mission planning algorithm should carefully examine whether the observation data (i.e., science data) can be completely downlinked to the earth ground station within available resources and time.

The following sections are organized as follows. Firstly, OLFAR mission objectives and its roadmap are introduced. Then, system requirements and the current satellite design are introduced. Thirdly, a mission planning problem is formulated. In the fourth place, long-term and short-term mission planning schemes are proposed. Lastly, numerical results of 3-day mission planning are presented followed by future work for mission planning of swarm satellites.

2. OLFAR Mission Objectives and Roadmap

2.1 Radio Astronomy and OLFAR Overview

Radio astronomy at ultra-low wavelengths regimes (below 30 MHz frequency) is considered as the last piece of puzzle to produce sky maps in a broad frequency band [14]. The achieved science data will be beneficial to understand the very early universe, referred to as the dark ages. However, since cosmic signals below 30 MHz are blocked by the earth ionosphere, in-space observation is considered as the only viable option. In Europe, several space missions for ultra-low wavelengths radio astronomy have been proposed since 2009 [15].

OLFAR is a Dutch-funded project initiated in 2010. It has been jointly studied by several universities and research institutes. While it also aims at opening up the 0.3-30 MHz for radio astronomy like previous missions (e.g. DARIS), its operation concept is different from them by employing a distributed system framework, where multiple satellites individually receive the commands and transmit the data from/to the earth ground station. This framework can improve the system reliability by avoiding the single point of failure, existing in the centralized system framework in case of the failure of a mothership.

2.2 Previous Studies

In OLFAR, several deployment locations for a satellite swarm have been studied [16,17]. So far, the

lunar orbit is considered as the most promising orbit due to the existence of the radio quiet zone (on the far side of the moon) and the shorter distance compared to the other candidates such as heliocentric orbit. Two orbits around the moon at 200 and 3000 km altitudes were proposed for OLFAR by [18]. However, there was a limitation that one of the orbit design requirements which is the baseline rate requirement could not be satisfied. Recently, a new satellite swarm orbit that meets the baseline rate requirement was proposed by [19]. The orbit proposed in our previous study is applied to this research.

A preliminary design of the OLFAR space segment has been made by several researchers. [20] designed a payload system focusing on an antenna system and [21] designed a power system and [22-24] designed a communication system that conducts intersatellite and downlink communications. [25] designed not only the individual satellite but also the higher-level swarm system consisting of 25 satellites, focusing on the system reliability analysis.

2.3 Study on Mission Planning

OLFAR operation phases for one orbital period were designed by [26]. A sequence of several tasks starting from observation to downlink was presented. However, an explicit time-based plan (i.e., timeline) consisting of successive time intervals of tasks was not provided. In addition, (as far as the authors know) modeling of an OLFAR mission planning problem has not yet been done.

3. OLFAR System Design

3.1 Mission Operation Principle

In OLFAR, tens of (or even hundreds of) satellites will operate together in a distributed system framework. They will individually collect cosmic signals, transmit the observed data to each other by intersatellite link, and then correlate the observed data and downlink them to an earth ground station. To reduce the downlink data volume (considering the low downlink data rate), payload data handling consisting of preprocessing and correlating will be conducted by the on-board (payload) computer.

3.2 System Requirements and Design

Table 1 summarizes OLFAR system requirements [13]. Here, we further define that the number of satellites is 50 and the mission lifetime is 2 years, referring to our previous paper [19].

Table 1. Simulation conditions

Number of satellites	≥ 10
Observation frequency	0.3-30 MHz
Observation wavelength	1000-10 m
Instantaneous bandwidth	≥ 1 MHz
Maximum baseline length	100 km
Spatial resolution	1 arc-minute at 10 MHz
Snapshot integration time	1-1000 s

The current satellite design conforms to the conventional 3-Unit CubeSat form factor, 10 cm x 10 cm x 30 cm, and its total mass is approximately 5 kg [16]. Nominal power consumption is approximately 10 W whilst 28 W of solar power can be generated by deployed solar panels [25]. Two dipole antennas are integrated on the opposite ends of the satellite to collect the cosmic signals [16]. Six S-band patch antennas are placed on each facet of the satellite for intersatellite link [22]. There have been three antenna designs for swarm-to-earth downlink: X-band high gain antenna [16] like DARIS [27], S-band patch antenna attached to one facet of the satellite [24], and S-band phased array attached to the back side of the solar panels [23]. Here, we assume one of the first two designs in order to enable solar power generation during downlink.

3.3 Subsystem Design and Tasks

Figure 1 describes main tasks of the payload and platform subsystems. An overall sequence of tasks from observation to downlink can be described as follows:

- The EPS powers off non-essential hardware prior to observation to minimize the internal RFI [25].
- The payload collects cosmic signals.
- The EPS powers on (wakes up) powered-off hardware.
- The payload preprocesses the raw observation data [16].
- The TT&C transmits/receives the preprocessed data to/from the other satellites via intersatellite link.
- The payload correlates the preprocessed data.
- The TT&C transmits the correlated data as well as the House-Keeping (HK) data to the earth ground station via (swarm-to-earth) downlink.

Other tasks conducted either continuously or one time per orbit can be listed as follows:

- The EPS generates power from the solar panels and distribute it to the payload and platform subsystems.
- The EPS recharges batteries when there exists a surplus of power.
- The TT&C measures the intersatellite distance and transfers it to the CDHS.
- The CDHS synchronizes times and localizes the relative position [28].
- The CDHS handles the commands and data.
- The AOCS determines and controls the attitude.

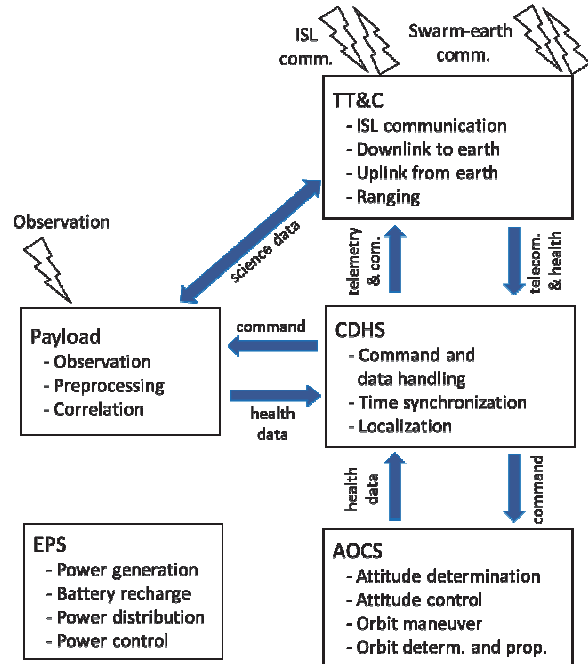


Fig. 1. Payload and platform subsystem tasks and signal flows between them. Note that while there is a minor change in number and functions of subsystems, the major tasks listed in [25] are all included here. Acronyms are defined as follows: TT&C (Telemetry, Tracking, and Commanding Subsystem), CDHS (Command & Data Handling Subsystem), FSW (Flight Software), AOCS (Attitude and Orbit Control Subsystem), PS (Propulsion Subsystem), and EPS (Electrical Power Subsystem).

- The AOCS determines the orbit using intersatellite distance measurements or only propagates it relying on dynamics when the measurements are not available.
- The payload and all subsystems report their health to the CDHS and receive the commands from the CDHS.

The other tasks conducted less often (e.g., one time per several days) can be listed as follows:

- The PS (jointly with AOCS) conducts the orbit maneuver for reconfiguration and formation-keeping.

4. Modeling of Mission Planning

4.1 Full Problem

In general, mission objectives are achieved by performing several tasks in serial. However, there are constraints between the tasks that should be obeyed. For example, there is a time dependency constraint in OLFAR that data preprocessing cannot be performed in advance of data collection. In addition, there are constraints on satellite resources as well, e.g., on a battery capacity. Therefore, tasks should be scheduled according to constraints imposed on the tasks, on the resources, and between the tasks and resources.

In this section, an OLFAR mission planning problem is formulated (i.e., modeled) by tasks, resources, and constraints. Since the tasks were already defined in Figure 1, we start here by defining resources which are:

- Science data volume
- HK data volume
- ISL communication data rate
- Downlink data rate
- Battery capacity (i.e., energy)
- Propellant mass
- Ground station availability
- Earth visibility (i.e., out of the earth eclipse period)
- Sun visibility (i.e., out of the solar eclipse period)

Here, we classify constraints into three types: time dependency constraint, resource bound constraint, and resource comparison constraint. This classification is based on the DLR/GSOC modeling language [1]. Firstly, the time dependency constraint specifies a minimum mandatory separation in time. Here, we define following time dependency constraints:

- Sequence of the nominal operation: power down → observation → power on → preprocessing * → ISL communication → correlation → downlink
- Do uplink before performing the tasks that are included in the telecommand packet.

Secondly, the resource bound constraint confines a resource within its minimum and maximum bounds in a global time scale. Here, we define following resource bounds that the resources should obey:

- Maximum ISL data rate
- Maximum downlink data rate
- Maximum battery capacity
- Maximum Depth-of-Discharge (DOD) level
- Science data mass storage (equipped in the payload)
- HK data storage (equipped in the CDHS)
- Maximum (i.e., initial) propellant mass

Thirdly, the resource comparison constraint specifies a local resource bound that should be obeyed. Here, we define following resource comparison constraints

- Power generation only while the sun is visible
- Observation only while the earth is eclipsed
- Downlink only while the ground station is available

4.2 Simplified Problem

The previous full problem comprises many different tasks, resources, and constraints. Moreover, in general, a mission planning problem is NP-hard, i.e., it is highly combinational [9]. Therefore, it is computationally

intensive to obtain a solution for the full-scale mission planning problem without simplifications. Here, four reasonable assumptions are applied to simplify the problem:

- Ignore sparse tasks (e.g., tasks of more than several days cycle): For example, the orbit maneuver task can be separately assigned to the timeline later.
- Ignore short-duration tasks (e.g., durations less than 1 minute): For example, time synchronization and localization can be quickly done thanks to the closed-form solution [28]. Hence, it can be scheduled between other tasks later.
- Ignore independent tasks: For example, attitude determination, and command and data handling can be performed in free of conflict to the other tasks, and their impacts on power consumption is not significant.
- Ignore resource constraints that either were already analyzed by worst-case analysis, such as science data volume and HK data volume, or are separately controlled by other subsystems, such as propellant mass controlled by the Flight Dynamic Subsystem in the MCE.

5. Mission Operations Concept

In this section, a long-term operation concept for OLFAR is introduced. A 1-month operation scenario proposed by the authors [19] lays the foundation for this research. In the previous study, time intervals for observation, consisting of start times and durations, were determined by earth eclipse time intervals and the baseline rate requirement. Here, for brevity, only the final result of the previous study focusing on the observation task, is introduced. The other tasks, listed in Figure 1, are left to be assigned later in short-term mission planning, which is to be presented in the next section.

Figure 2 depicts time intervals of the earth eclipse over 1 month. Orange trapezoids indicate timeslots in which swarm satellites can collect meaningful payload measurements (which satisfy the baseline rate requirement). For each month, we assign observation tasks within approximately a half month in total. The other half month is spent for performing other tasks, for example, that need to be periodically performed regardless of observation, and/or that were not be able to be assigned within the observation orbits due to the constraints (e.g., due to low battery power), and/or that are related to secondary payload missions (while it is not certain yet whether secondary missions will be carried out in OLFAR).

Figure 3 illustrates orbital motions of the moon and the satellite swarm projected onto the ecliptic plane. Again, the timeslots for observation are highlighted by orange color. The times (represented by Days) are analogous to the times labeled on the x-axis in Fig. 2.

* In [16], preprocessing consists of three subtasks: analog-to-digital conversion, coarse poly-phase filter bank, and RFI mitigation. Here, we assume that the first two subtasks are done by the observation task, and only RFI mitigation is performed in the preprocessing task.

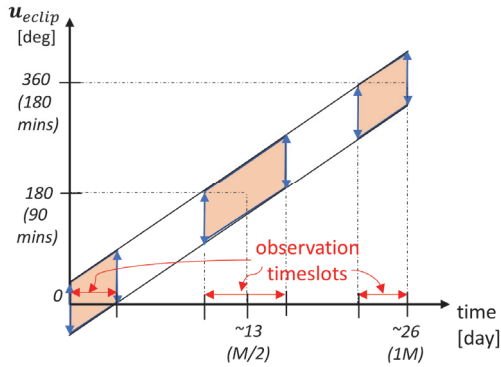


Fig. 2. Earth eclipse phase/time intervals and potential timeslots for observation (orange color) over 1 month. The earth eclipse intervals on the y-axis are expressed in terms of the argument of latitude of the reference swarm orbit. It is assumed that the reference orbit is an equatorial orbit at 680 km altitude. The orbital period is approximately 3 hours. Earth eclipse durations are approximately 45 minutes, which correspond to approximately 90 degrees of the orbit phase angle. Moreover, it can be noted that the final time on the x-axis (26 days) is less than the known sidereal month (27.3 days), and it is due to the lunar gravitational perturbation. The figure is adapted from [19].

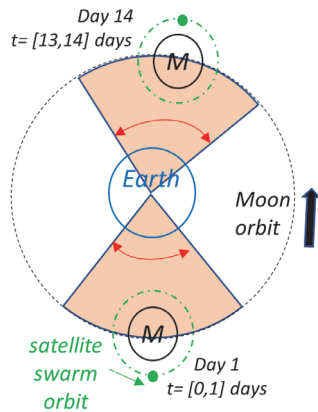


Fig. 3. Orbital motions of the moon and the satellite swarm projected onto the ecliptic plane.

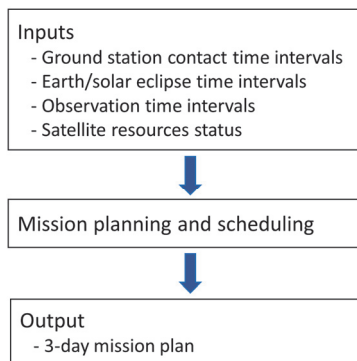


Fig. 4. A simplified mission planning and scheduling process.

6. Mission Planning and Scheduling

6.1 Introduction

In this section, a short-term mission planning algorithm for OLFAR is proposed. A 3-day is assumed as the planning horizon while it can be modified easily later. Considering 3 hours of orbital period at 680 km altitude, a satellite swarm will orbit around the moon 24 times over 3 days. It is assumed that there exists one ground station that communicates with OLFAR swarm satellites. Considering the fact that each of NASA's Deep Space Network (DSN) ground station has an 8- to 14-hour contact period for an interplanetary satellite, it is reasonable to assume here that swarm-to-earth downlink in OLFAR can be established in 2 successive orbits per day (which corresponds to 6 hours).

Figure 4 depicts a proposed mission planning and scheduling process. Inputs can be provided by two subsystems in the MCE; in detail, three kinds of time intervals by the Flight Dynamic Subsystem and initial satellite resources by the Satellite Operation Subsystem.

6.2 Algorithm

6.2.1 Scheduling Process

Figure 5 describes a proposed mission planning and scheduling algorithm. It is assumed that downlink orbits (2 orbits per day) in which downlink tasks can be assigned are identified beforehand according to the location of ground station. The proposed algorithm consists of 8 steps. They are briefly explained in the following.

Firstly, starting from orbit #1, an observation task is assigned into the timeline. Secondly, a set of tasks from power-off to data correlation is assigned. The power-off and -on tasks are assigned as close as possible to the observation task to minimize the period of solar power generation to be stopped. On the other hand, the preprocessing, ISL communication, and correlation tasks are assigned right after the power-on task to secure the science (payload) data storage as soon as possible. Thirdly, a downlink task is assigned (while details on how to assign it is presented in the next paragraph). In the fourth place, the satellite resources are updated to check whether other tasks (e.g., orbit maneuver) can be also assigned into the current orbit. Finally, go back to Step 1 if the current orbit is not the last orbit, i.e., orbit #24.

6.2.2 Downlink Task Assignment

Three steps to assign the downlink task into the timeline are explained as follows:

- 1) Firstly, predict a downlink data volume to be accumulated up to the final (second) orbit of the downlink orbits.
- 2) Calculate a time duration to fully downlink the data and then divide it into halves to assign each of them into the two downlink orbits.

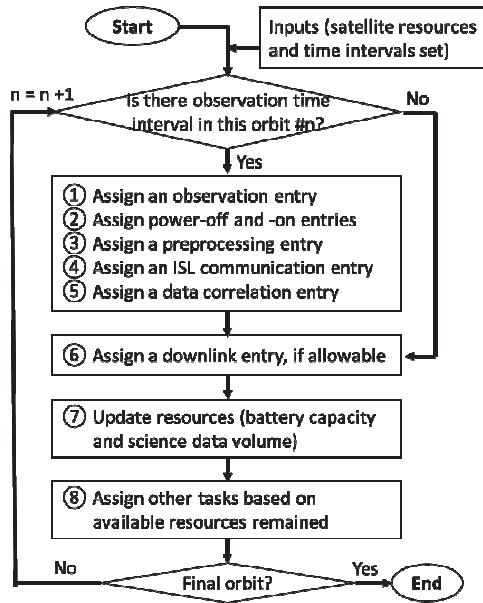


Fig. 5. Mission planning and scheduling algorithm. A time interval of task is denoted by an (timeline) entry in the figure.

3) Assign a downlink task into the timeline. Two guidelines can be followed. One is starting downlink as soon as possible after data correlation to secure the science data storage. The other is avoiding the solar eclipse period to avoid the use of battery power. If it is not possible to schedule downlink in a single time interval, then downlink can be performed at two separate time intervals: e.g., one before and the other after the solar eclipse.

6.3 One-Orbit Mission Plan Example

Figure 6 describes an example of the short-term mission plan obtained by the proposed scheduling algorithm. It can be seen that observation is performed during the earth eclipse, and then preprocessing, ISL communication, and data correlation are conducted sequentially. It can be also seen that solar power is generated continuously except the power-off, power-on and observation tasks and the solar eclipse period.

7. Numerical Example

7.1 Simulation Conditions

Numerical simulations are performed to verify the proposed mission planning and scheduling algorithm. Several simulation conditions applied here are summarized as follows:

- General: Number of swarm satellites is 50.
- Orbit: A reference orbit is an equatorial orbit at 680 km altitude [19]. Both of sun and earth eclipse durations will be approximately 45 minutes.

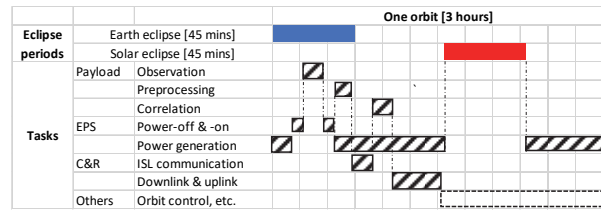


Fig. 6. An example of a single orbit plan.

- Payload: Observation durations are within a [0,10] minutes interval and determined by the earth eclipse time intervals (see Figure 2). Preprocessing and correlation durations are both 5 minutes. The science data volume is decreased by a factor of 14 after RFI mitigation and is further decreased by a factor of 60/9 after data correlation [16].
- TT&C: An ISL communication duration is 10 mins. An ISL data rate is 6 Mbps, and a downlink data rate is 900 kbps.
- EPS: Power-off and -on durations are both 2 mins. A full battery capacity is 40 Whr. A solar power generation rate is 28 W [25]. A desirable DOD level is less than 20 %. Nominal power consumption is 10 W. It increases by 3.8 W during preprocessing and correlation [25], by 20 W during ISL communication [16], and by 25 W during swarm-to-earth downlink.

7.2 Simulation Results and Discussions

Figure 7 depicts a 3-day mission plan consisting of 8 tasks for 24 orbits. A regular pattern over the orbit can be seen except orbits where downlink tasks (task #7) are assigned, occurring two successive orbits per day. Fig. 8 shows a particular one-orbit plan at orbit #4 where downlink is to be performed. The plan starts from nominal operations (task #0), followed by power-off (#2), observation (#1), power-on (#3), preprocessing (#4), ISL communication (#5), correlation (#6), and then downlink (#7). It can be confirmed in the figure that observation is assigned during the earth eclipse period and downlink is assigned out of the solar eclipse period as originally planned.

Figure 9 illustrates a battery capacity history for 24 orbits. It can be seen that the battery is fully recharged before the end of every orbit, and its capacity does not go to below 32 Whr, which corresponds to the 20% DOD level. It can be also seen that average battery capacities during the downlink orbits are lower than those during the other orbits because downlink consumes 35 W power whereas power generated by the S/A panels is 28 W. Figure 10 illustrates a history of the science data volume which store three different types of data, defined by their levels of process: 'D1' means the data before RFI mitigation; 'D2' means the data before correlation; and 'D3' means the data after correlation, therefore, ready to be downlinked. It can be confirmed that 'D1' and 'D2' are cleared every orbit, and only 'D3' are accumulating until they are downlinked (i.e., dumped) to the earth over the two downlink orbits.

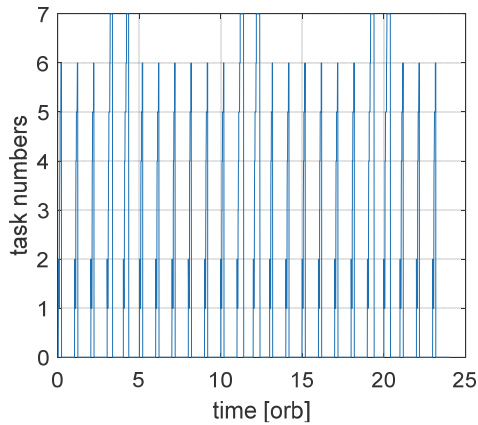


Fig. 7. A 3-day mission plan comprising 8 tasks where task #0 means nominal operations, task #1 is observation, tasks #2 and #3 are power-off and -on, task #4 is preprocessing, task #5 is ISL communication, task #6 is correlation, and task #7 is swarm-to-earth downlink.

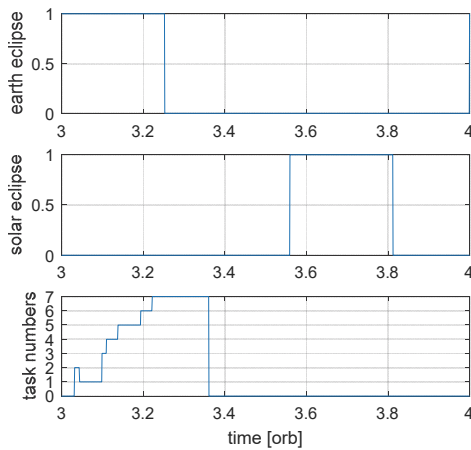


Fig. 8. A one-orbit mission plan at orbit #4.

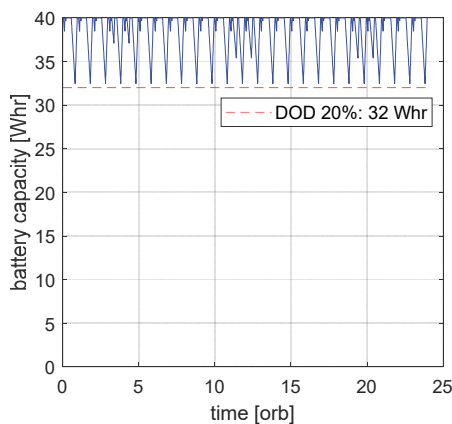


Fig. 9. A battery capacity history with a 20 % DOD level.

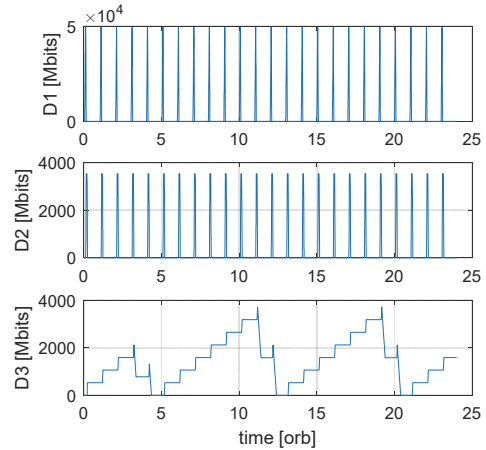


Fig. 10. A science data volume history.

8. Mission Planning for Swarm Satellites

So far, it is assumed that the swarm satellites have identical mission timelines, i.e., all their tasks have the same start times and durations. However, in reality, swarm mission planning is more complicated due to differences between their amounts of resources and observation time durations. In the following, four examples that can generalize swarm mission planning in OLFAR are introduced.

Energy balancing between the swarm satellites [23] can be beneficial for a case when some satellites have lower (battery) energies than the others (e.g., due to longer observation periods). In this case, while the data of the low-battery-energy satellites may not be able to be downlinked by direct swarm-to-earth link (due to excessive DOD), they can be still transmitted to the earth indirectly by using intersatellite link. Their (partial) data are first transmitted to nearest higher-battery-energy satellites and are downlinked on behalf of the original satellites. This strategy is possible because of lower power consumption and higher data rate in intersatellite link compared to those in downlink. However, a more complicated mission planning algorithm should then be necessary, which schedules tasks depending on battery capacities of swarm satellites.

Observation time durations are in fact dependent on swarm satellites' orbits [19]. In general, the larger distances between the swarm satellites and the reference orbit (to form a 100 km of radar array diameter) leads to the shorter observation durations due to the baseline rate requirement. Therefore, in this case, mission timelines of swarm satellites should be jointly built considering the different observation durations between the satellites.

The reliability of nanosatellite (which is a form factor of the current OLFAR satellite design) is generally lower than the traditional large satellite. However, its system-level reliability can be greatly

improved by employing a large number of satellites like a satellite swarm [14]. For example, in OLFAR, even if the downlink capability of one satellite is completely lost, its observation data can be still transmitted to the earth by using one of the other satellites as a repeater. However, for doing so, a new mission planning strategy that allows one satellite to take over some functionalities from the other satellites (and vice versa) should be developed.

In this paper, a full mesh network was assumed for intersatellite communication. It means that each satellite can communicate with all the other satellites. However, in reality, a communication range is restricted by (mostly) the maximum transmission power in the antenna system so that it is often not possible to establish link between every pair of two satellites. One possible solution is adopting a distributed network where the data are spread out across the nodes (i.e., satellites here) and can be eventually reached to all the satellites through a few number of intersatellite link. While the distributed network will increase the time until the swarm satellites' observation data are fully correlated, it might be more practical to be implemented compared to the full mesh network, considering the large intersatellite distance in OLFAR, which is 100 km at maximum. However, new mission planning should then be required that jointly schedules intersatellite communication tasks and downlink tasks between the swarm satellites.

9. Summary

An OLFAR mission planning problem was modeled by several tasks, resources, and constraints. The necessary tasks were defined by the current system design and are categorized into the tasks of payload and platform subsystems. Then, the full problem was simplified by four assumptions, which can greatly reduce the complexity of the original problem without meaningful loss of generality. A concept of long-term mission operations (for 1 month) and a scheduling algorithm for short-term mission planning (for 3 days) were proposed. Numerical results verified that the science data collected by the payload can be completely downlinked to the earth ground station in free of conflict. Four aspects where the proposed mission planning algorithm can be fully extended into swarm mission planning were also investigated.

Acknowledgements

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