OPTIMAL OPERATIONS PLANNING FOR SAR SATELLITE CONSTELLATIONS IN LOW EARTH ORBIT

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ABSTRACT

Satellite constellations for Earth observation are remarkably useful, powerful and flexible tools, but their realisation and maintenance pose a big issue on costs. From a design engineering perspective building up a constellation with small and simple satellites is a key to contain or reduce costs, while from a mission operations engineering point of view, optimal constellation management is a key in cost reduction and an important performance driver. In this paper the problem of the optimisation of planning and scheduling the operations for a remote sensing satellite constellation is addressed.

Key words: satellite constellation; operations planning & scheduling; software.

1. INTRODUCTION

The system here considered is a satellite constellation including two or more spacecraft in LEO (Low Earth Orbit) or MEO (Medium Earth Orbit), one or more ground stations for spacecraft monitoring-control and data collection-handling, and a list of targets to be observed. The system has structural and operability limitations (limited on-board resources, limited target and ground station contacts, etc.). The main scheduling constraints derive from the requests of the constellation users. These elements make the operations scheduling a challenging combinatorial optimisation problem. As a first approach to solve it, two different FIFO (First In First Out) algorithms have been developed. A software capable to generate an operations plan from an input list of targets and requests of the constellation users, has been realized. The two different planning approaches have been tested in different scenarios.

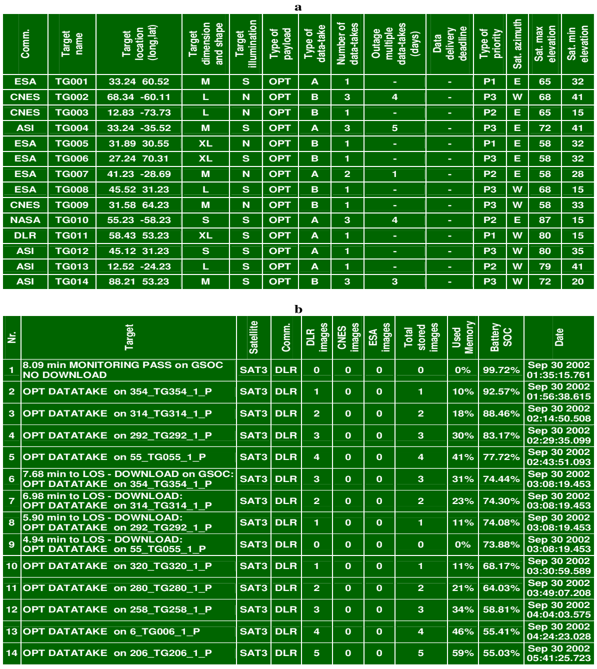
2. REDUCING THE OPERATION COSTS OF SATELLITE CONSTELLATIONS

Realizing and operating a multi-satellite constellation is complex and expensive and expensive resources need to be used efficiently. From the point of view of the operations engineering, constellation management and payload data management are key cost drivers (Wertz, 2001). Constellation management is also a key performance driver. In the following the attention will be focused here on constellation management. We will assume the following:

- Dealing with operations issues can dramatically lower down-stream costs.
- Personnel is a key cost driver. The automatization of planning and scheduling can reduce the required operations management personnel. Functions where personnel are key are: monitoring and exception handling, planning and scheduling.
- The number of spacecraft and their complexity are key cost drivers.
- Optimising the operations of a constellation, a requested performance can be achieved with a lower cost system or better performances can be achieved with a given system.
- Managing the operations of a satellite constellation with an optimal planning and scheduling software allow to increase the automatization level of the operations and consequently has the potential to increase performance and reduce cost dramatically.
- An optimal planning and scheduling software is necessary, already in the design phase of the constellation, to define the constellation geometrical configuration that can fulfill the system performance requirements in a reasonable way.

3. PROBLEM

The problem here considered can be outlined in this way: with a given remote sensing satellite constellation and a list of product requests of the constellation users (Figure 1.a), an optimal operations plan subject to one or more figures of merit (maximum number of images, system response time, etc.), has to be generated (Figure 1.b).



a

Comm.	Target name	Target location (long,lat)	Target dimension and shape	Target illumination	Type of payload	Type of data-take	Number of data-takes	Outage multiple data-takes (days)	Data delivery deadline	Type of priority	Sat. azimuth	Sat. max elevation	Sat. min elevation
ESA	TG001	33.24 60.52	M	S	OPT	A	1	-	-	P1	E	65	32
CNES	TG002	68.34 -60.11	L	N	OPT	B	3	4	-	P3	W	68	41
CNES	TG003	12.83 -73.73	L	N	OPT	B	1	-	-	P2	E	65	15
ASI	TG004	33.24 -35.52	M	S	OPT	A	3	5	-	P3	E	72	41
ESA	TG005	31.89 30.55	XL	N	OPT	B	1	-	-	P1	E	58	32
ESA	TG006	27.24 70.31	XL	S	OPT	B	1	-	-	P3	E	58	32
ESA	TG007	41.23 -28.69	M	N	OPT	A	2	1	-	P2	E	58	28
ESA	TG008	45.52 31.23	L	S	OPT	B	1	-	-	P3	W	68	15
CNES	TG009	31.58 64.23	M	N	OPT	B	1	-	-	P3	W	58	33
NASA	TG010	55.23 -58.23	S	S	OPT	A	3	4	-	P2	E	87	15
DLR	TG011	58.43 53.23	XL	S	OPT	A	1	-	-	P1	W	80	15
ASI	TG012	45.12 31.23	S	S	OPT	A	1	-	-	P3	W	80	35
ASI	TG013	12.52 -24.23	L	S	OPT	A	1	-	-	P2	W	79	41
ASI	TG014	88.21 53.23	M	S	OPT	B	3	3	-	P3	W	72	20

b

Nr.	Target	Satellite	Comm.	DLR images	CNES images	ESA images	Total stored images	Used Memory	Battery SOC	Date
1	8.09 min MONITORING PASS on GSOC NO DOWNLOAD	SAT3	DLR	0	0	0	0	0%	99.72%	Sep 30 2002 01:35:15.761
2	OPT DATATAKE on 354_TG354_1_P	SAT3	DLR	1	0	0	1	10%	92.57%	Sep 30 2002 01:56:38.615
3	OPT DATATAKE on 314_TG314_1_P	SAT3	DLR	2	0	0	2	18%	88.46%	Sep 30 2002 02:14:50.508
4	OPT DATATAKE on 292_TG292_1_P	SAT3	DLR	3	0	0	3	30%	83.17%	Sep 30 2002 02:29:35.099
5	OPT DATATAKE on 55_TG055_1_P	SAT3	DLR	4	0	0	4	41%	77.72%	Sep 30 2002 02:43:51.093
6	7.68 min to LOS - DOWNLOAD on GSOC: OPT DATATAKE on 354_TG354_1_P	SAT3	DLR	3	0	0	3	31%	74.44%	Sep 30 2002 03:08:19.453
7	6.98 min to LOS - DOWNLOAD: OPT DATATAKE on 314_TG314_1_P	SAT3	DLR	2	0	0	2	23%	74.30%	Sep 30 2002 03:08:19.453
8	5.90 min to LOS - DOWNLOAD: OPT DATATAKE on 292_TG292_1_P	SAT3	DLR	1	0	0	1	11%	74.08%	Sep 30 2002 03:08:19.453
9	4.94 min to LOS - DOWNLOAD: OPT DATATAKE on 55_TG055_1_P	SAT3	DLR	0	0	0	0	0%	73.88%	Sep 30 2002 03:08:19.453
10	OPT DATATAKE on 320_TG320_1_P	SAT3	DLR	1	0	0	1	11%	68.17%	Sep 30 2002 03:30:59.589
11	OPT DATATAKE on 280_TG280_1_P	SAT3	DLR	2	0	0	2	21%	64.03%	Sep 30 2002 03:49:07.208
12	OPT DATATAKE on 258_TG258_1_P	SAT3	DLR	3	0	0	3	34%	58.81%	Sep 30 2002 04:04:03.575
13	OPT DATATAKE on 6_TG006_1_P	SAT3	DLR	4	0	0	4	46%	55.41%	Sep 30 2002 04:24:23.028
14	OPT DATATAKE on 206_TG206_1_P	SAT3	DLR	5	0	0	5	59%	55.03%	Sep 30 2002 05:41:25.723

Figure 1. a. Constellation users requests. b. Example of an operations schedule.

3.1. User requests

Operations planning and scheduling constraints are typically determined by users requests (scientific, commercial, military, etc.) and mission operations system needs (orbit maintenance, spacecraft routine subsystems tests, etc.). Typical constraints are:

1. Final product commissioner: payload data may be either downloaded to a limited number of ground stations specified by the constellation management and then delivered to the commissioner, or can be directly downloaded to a ground station specified by the data commissioner.
2. Target location on Earth.
3. Target dimension and shape: these targets parameters can be chosen consistently with the imaging sensor capabilities.
4. Target illumination: it can be requested to perform a data-take during the day or the night.
5. Image resolution: requested image resolution (if it can be chosen), will also condition the data-take power and storage requirements and the image raw-data ground processing commitment and time.
6. Type of imaging sensor to be used (if more than one can be used).
7. Type of data: it is possible that a certain imaging sensor can be operated in different ways (e.g. different imaging modes for a SAR payload).
8. Number of data takes to be performed on a specific target: the same area can be required to be observed periodically, or a definite number of times, with a definite outage between consecutive data-takes.
9. Spacecraft azimuth: the spacecraft can be requested to have a certain azimuth with respect to the target during the data-take (spacecraft coming from East or West directions).
10. Spacecraft minimal and maximal elevation on a target: this parameter can determine the type of image that can be produced with a certain payload.
11. Start and end times of the validity of a request.
12. Time deadline for a finite product delivery.
13. Type of priority: different types of priority can be assigned to each image request. A priority can be correlated to scientific data utility in case of a scientific mission, environmental disasters or political contingencies in case of a government funded mission (see Lemaitre & Verfaillie (2002) for system sharing principles).

3.2. System Configuration

The following components of the system have to be modelized: constellation of two or more satellites (not necessarily homogeneous). The satellites may be in any LEO or MEO orbit and are equipped with a suite of remote sensing instruments. One or more ground stations are considered, at least one having both telemetry and telecommand capabilities. A certain number of targets to be observed complete the system configuration.

Satellites The following elements are taken into account and modelized:

- Satellite orbit: a precise orbit prediction is performed for each spacecraft in order to know the accurate times of the possible contacts with the ground stations and the targets.

- Power storage: on-board batteries storage characteristics and capabilities are modelized, as also solar arrays type and power production capability. Eclipse/daylight times and durations are calculated for each spacecraft in order to have an always updated monitoring of the DOD (Depth of discharge).
- Power consumption: ACS (Attitude Control System) power consumption to perform attitude manoeuvres required to sensors aiming for data-take and antenna pointing for data-download during ground station contacts. Payload data-take power consumption, telemetry and telecommand subsystems power consumption and spacecraft bus maintenance on-board operations.
- Data storage: on-board data storage devices and capabilities are modelized. Data storage requirements for different types of spacecraft payload products and different payloads are taken into account.
- Payload: only remote sensing payloads are here considered. Sensor field of view is defined whether by one ore more sight cones or by a polygon (regular or irregular).
- Data download: housekeeping and payload data download rates are accounted.
- Inter-satellite links: the possibility to send telecommands from one satellite to another is accounted.

Ground Stations Ground station type of visibility horizon is considered. Ground station handshake time is taken into account.

Targets Targets are modelized as closed contour regions with a certain location on the Earth's surface and defined by a series of points that are the vertices of it.

3.3. System Limitations and Constraints

Scheduling of satellite constellations for Earth observation is made complex by a number of system capabilities limitations and exploitation constraints. A proposed observation sequence must satisfy a certain number of system limitations as well as user defined constraints. In the following system limitations and constraints which have been accounted are listed and described.

Time Constraints A spacecraft has to be considered busy not only during an operation (data-take, data-download, etc.) but also for a certain period of time preceding and following an operation. It is here assumed that a spacecraft can only perform one operation at a time.

- Spacecraft revisit limitations on targets: the spacecraft fly in fixed orbits which pass over a particular location on Earth at definite times and a target has to be in the field of view of the imaging sensor in order to perform a data-take. For a given target there are therefore only a few and sometimes none imaging windows. As a certain time is required to take an image, imaging windows duration is also a limiting factor.
- Ground station contacts: the number of available ground station contacts is also limited. The duration of a ground station pass has to be adequately long to allow at least a TTTC (Time-tagged telecommands) uplink. The ground station traffic management (ground station can be busy to serve higher priority passes) is also a time constraining factor. In the case that a ground station has only one antenna a time conflict is even possible between contemporary passes of two satellites of the same constellation.
- Attitude manoeuvres: if the satellites are considered as agile satellites (they can change their attitude to point their imaging sensors in any direction), a certain amount of time is required prior a data-take in order to aim the imaging instrument to the target and, after it, to recover the nominal attitude. A certain amount of time can also be required to manoeuvre the satellite before the AOS (Aquisition of Signal) with a ground station and after the LOS (Loss of Signal).
- Payload management: a certain amount of time can be necessary to switch on/off payload dedicated energy units, processing units, heaters, etc. depending on the type of payload and operation.

On-board resources limitations Energy and data storage capabilities, sensor operability and data-download rates, typically determine the remote sensing system performances.

- On-board power availability to carry on spacecraft operations and on-board energy sources are limited. Here a typical configuration has been considered with solar arrays as the only power source and a secondary battery (Wertz, 2001) for on-board energy storage. The fact that the battery provides power during eclipse periods and it can recharge only in sunlight has been accounted. A maximum value of the battery DOD (Depth-of-discharge) i.e. the percent of total battery capacity removed during a discharge period, cannot be exceeded. As during a ground station contact a spacecraft is under direct control of the ground operators, the DOD limit can be set up higher for a download operation.

- Limited on-board data-storage: payload products are stored on-board the spacecraft, in a SSR (Solid State Recorder). The data stored in the SSR can be sent to the ground only when the spacecraft passes over a ground station and it has a communication contact with it.
- Sensor operability: it can happen that in particular circumstances an imaging sensor cannot be operated (e.g. cloud cover for optical sensors). Spacecraft minimal and maximal elevation on the target is often an important remote sensing payload parameter to be considered.
- Data-download rate: the amount of data-bits per unit of time, which can be downloaded determines the amount of payload raw data which can be downloaded during a pass over a ground station.

4. PLANNING AND SCHEDULING: THE FIFO APPROACH

The problem of planning and scheduling the operations of a satellite constellation for remote sensing is a highly combinatorial problem. If an optimal or sub-optimal operations schedule is required, the problem is a constrained combinatorial optimisation problem (see Foulds (1984) and Papadimitriou (1982)). The FIFO approach has been chosen at first to solve the problem described in the preceding sections. The basic idea is first to list in a time order all the possible target and ground station contacts for each spacecraft. Then, scanning this list, the first data-take on a target (TG) or ground station contact possibility consistent with all imposed constraints is selected. Once this selection is done, all possible data-takes on TG following in time are deleted from the list. Two types of FIFO approaches has been analysed implemented in a software and tested with different scenarios. In both types of selection, it is assumed that a ground station contact has always the priority on every other type of possible operation.

4.1. Sequential selector

A list containing, in time order, all the possible ground station and target contacts of every satellite of the constellation is the main input of the planning algorithm. At every contact possibility, are accompanied the information required to calculate the state of the satellites on-board resources and to check eventual conflicts with the imposed constraints. Time conflicts between ground station contacts and target contacts are solved in the set up of the list, i.e. every possible target contact included within a certain period of time before and after the ground station contact, is eliminated during the preparation of the list. During the sequential scan of the input list, at every step the following substeps are executed:

- Estimation of the time required to perform the new operation.
- Estimation of the energy stored and spent from the last scheduled operation: the solar arrays collected energy and the energy spent to accomplish the routine spacecraft bus maintenance on-board operations. Estimation of the energy required to perform the new operation.
- Estimation of the size of the new incoming payload data to be stored if a data-take is performed or size of the free on-board data storage space after a download.
- The estimated spacecraft state is checked with respect to all users and system constraints in order to decide to append the spacecraft operation currently examined to the operations schedule, or not.
- If any conflict is detected, the operation under examination is discarded and the following possible operation is examined. If no conflict has been detected, the new operation is appended to the plan and the spacecraft state is updated (time, on-board energy storage device state, data-storage device allocated space, etc.).
- If a data-take over a certain target has been appended to the schedule and only one data-take is requested on that target, all the following contact possibilities for this specific target are deleted. If more than one data-take is requested on a certain target, the parameter that specifies the number of data-takes to be executed on this target is decreased of one unit.

4.2. Sandwich inserter

An operations plan containing only all the satellite ground station passes is first created with the sequential selection approach described in Section 4.1. This first operations plan will of course contain only monitoring passes. A list containing, in time order, all the possible targets contacts of every satellite of the constellation is also created: this is the same input list described in Section 4.1 but with the exclusion of the ground station contacts. The targets-list is scanned sequentially and at every step the possibility to insert, in the operations schedule, the target contact considered, is examined. In the most general case, an operation of a specific satellite has to be inserted between two already operations scheduled for that satellite; in this case the following substeps are executed:

- Time conflicts check.
- The new spacecraft state is calculated based on the preceding already scheduled operations and eventual conflicts are checked.
- All the states of the spacecraft in its already scheduled operations and following in time that under examination, are temporarily updated and checked with respect to the constraints.
- If no conflict is detected, the operation under examination is inserted in the operations schedule and the states of the spacecraft for the inserted operation and for all the following ones are definitely updated.
- A download possibility of the new stored payload data is searched immediately: the operations schedule is scanned to find the next ground station contact scheduled for the spacecraft whose data-take has just been scheduled.
- Once a download possibility has been found, the feasibility of the operation is evaluated with a new estimation of the state of the spacecraft at the moment this new download operation is executed and in the operations following in the operations schedule.
- If no conflict is detected, the new download operation is inserted in the operations schedule and the spacecraft states are updated. Otherwise a new download possibility is searched down in the operations schedule.

4.3. Comparison of the two approaches

The two different FIFO approaches have been tested and compared in planning the operations of a 5 homogeneous satellites constellation with an optical payload. For comparison purposes, a scenario simple as possible has been used: a single user, a single ground station, an evenly distribution of targets of the same dimension and shape, a single data-take request for every target, an unique type of payload and payload data, no preferences on target illumination and on spacecraft azimuth, an unique type of priority for all the requests. The two algorithms give identical operation schedules when tested with scenarios in which the constellation has to work well below her performance limits. However a main difference can be appreciated when the constellation is requested to operate at the limit of her performances. While the sequential selector, at each step, checks exclusively the state of a spacecraft in the accomplishment of a new operation, the sandwich selector has a feedback, down in the operations schedule, from the changes of the states of a spacecraft, determined by the insertion of a new operation in the operations schedule.

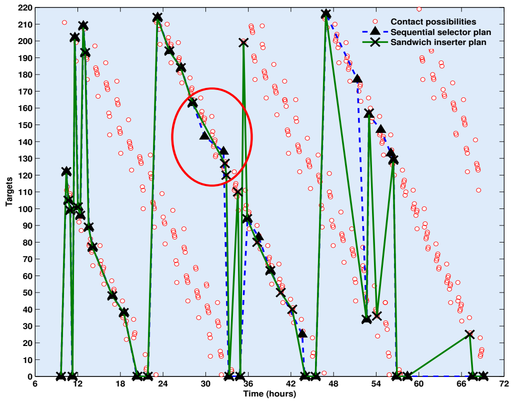


Figure 2. Space of the solutions: operations plan of one of the satellites of the constellation (a ground station contact correspond to the value 0).

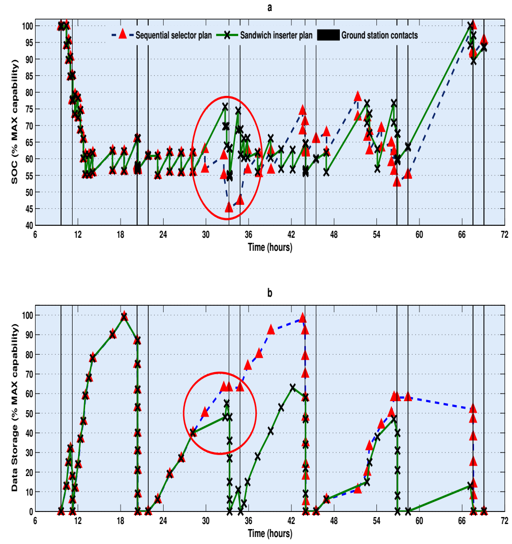


Figure 3. Estimated trend of on-board energy and data storage during for one satellite of the constellation performing the scheduled operations.

Figures 2 and 3 show, respectively, the operations plan and the estimated trends of the on-board energy and data storage of one satellite of the constellation, during the accomplishment of an operations schedule. In this case 220 targets evenly distributed on the Earth within a latitude band of -60° and 60° had to be observed and minimal allowed battery SOC (State of energy) was 55 % for data-takes and 50 % for ground station contacts. A point of divergence in the plans generated by the sequential and sandwich

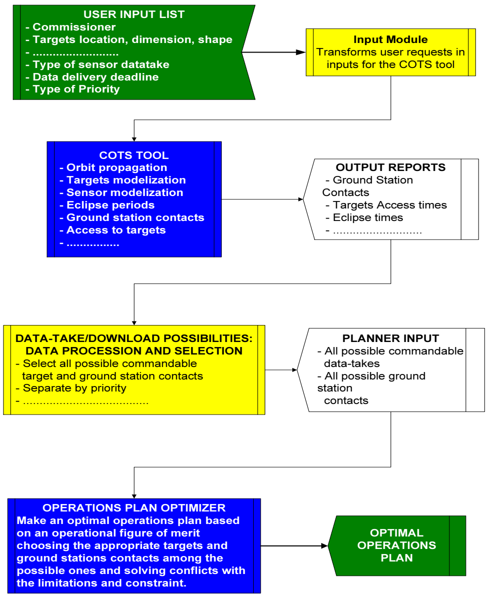


Figure 4. SCOOP software main structure.

approaches has been highlighted. It can been noticed that the sandwich inserter waits some time to schedule a new operation while the sequential selector go on in scheduling. As a result, in the following ground station contact, (which, as assumed in Section 4, cannot be deleted), according to the sequential approach schedule the spacecraft will not be able to perform any download (Figure 3.b) and the battery SOC will sink well under the allowed minimum limit (Figure 3.a). According to the sandwich inserter schedule the spacecraft will instead be able to perform some data download, keeping the battery SOC above the minimum allowed level. The overall performances of the constellation using the two schedules are essentially the same: the number of executed data-takes and downloads is the same. It can be then stated that, for this kind of scenario, the sandwich inserter schedule gives the same performance of the sequential selector schedule but with a better use of the spacecraft on-board resources. The sandwich selector has demonstrated also to be more flexible in the management of different level of request-priorities.

5. SCOOP (SATELLITE CONSTELLATIONS OPTIMAL OPERATIONS PLANNER)

The SCOOP operations planning and scheduling software has been developed at the Microwaves and Radar Institute of DLR. Figure 4 show an essential block diagram of the structure of the software. The software has two cores: a COTS (Commercial off the schelf) tool (the tool FreeFlyer has been adopted), for the spacecraft orbits propagation, sensor modelization, ground station and target contacts times and related information, eclipse periods; the planner which creates the final operations plan (Figure 1.b). A number of serving modules are necessary to process the requests information to input in the COTS, to gather the COTS outputs, process them and then input to the planner. Up to now, the software can manage a constellation of 5 satellites , 6 ground station, 6 users, any type of observation payloads. The file containing the user requests is the only input, the operations schedule with all the satellite associated information is the main output.

6. CONCLUSIONS AND FUTURE INVESTIGATIONS

The problem of operations planning and scheduling of a satellite constellation has been outlined and different types of approach to its solution have been explained. An operative planning software has been realized. Future directions of work may concern:

- Simulations in complex scenarios.
- The realization of an actual operations schedule optimization driven by specific performance figures of merit (fast system time response, maximum number of data-takes, etc.): heuristic approaches, branch and bound approaches, genetic algorithms.
- Enhancement of the use of the SCOOP software for the definition of the configuration of a satellite constellation in the design phase.
- Use of the optimizer to operate single independent flying satellite or constellation missions as a single constellation.

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