Performances Optimization of Remote Sensing Satellite Constellations: a Heuristic Method

Sergio De Florio
Microwaves and Radar Institute, DLR Oberpfaffenhofen
Münchner Str. 20, 82234 Wessling, Germany
Sergio.DeFlorio@dlr.de

Abstract

The realization of distributed sensor networks for the monitoring of the Earth, by means of a constellation of small satellites, poses the need of an extensive and effective application of planning and scheduling technology to space systems. The possibility to generate an optimal schedule, for a satellite constellation, based on user requests and some figure of merit to be optimized (e.g. system response time, number of data-takes) can drastically improve the performances of the system and enhance its automatization. Especially the minimization of the constellation response time to the user requests can be very useful to reconnaissance and disasters management purposes. A simple but effective heuristic algorithm enriched with look-ahead capability is presented. The algorithm has been tested on different constellation configurations in order to define the limits of its applicability. The performances of the different constellation configurations have been compared with respect to the figure of merit to be optimized.

System Description

The system considered is constituted of 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 onboard resources, target and ground station contacts, etc.). The main scheduling constraints are derived from the requests of the constellation users. The main input are a list of targets to be observed and requests of the constellation users, the main output are an operations schedule and a performance analysis based on the schedule generated.

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

- 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.
- Target location on Earth.
- Target dimension and shape: these target parameters can be chosen consistently with the imaging sensor capabilities.
- Target acquisition time: it can be requested to perform a data-take during the day or the night.
- 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.
- Type of imaging sensor to be used (if more than one can be used).
- Type of data: it is possible that a certain imaging sensor can be operated in different modes (e.g. different imaging modes for a SAR payload).
- Number of data take 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.
- 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).
- Spacecraft minimal and maximal elevation angle on a target: this parameter can determine the type of image that can be produced with a certain payload.
- Start and end time of the validity of a request.
- Time deadline for a finite product delivery.
- Type of priority: different type of priorities 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).

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, solar array type and power production capability are modelized. Eclipse/daylight start and end times are calculated for each spacecraft in order to have an always updated monitoring of the DOD (Depth Of Discharge).
- Power consumption: attitude manoeuvres required to sensors aiming and antennas pointing, payload operations, telemetry and telecommand subsystems, spacecraft bus maintenance on-board operations are modelized.
- 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 considered here. 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 or to receive image data to be downloaded 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.

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: as the spacecraft fly in fixed orbits which pass over a particular location on Earth at definite times, for a given target there is only a limited number of data-takes windows with a definite time duration.
- 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 Tele-Commands) 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, afterwards, to recover the nominal attitude. A certain amount of time can also be required to manoeuvre the satellite before the AOS (Acquisition Of Signal) with a ground station and after the LOS (Loss of Signal) or to send telecommands to another satellite during an intersatellite-link.
- 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. 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 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 able to receive and store payload data.
- 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 angles on the target is often an important remote sensing payload parameter to be considered.
- Data-download rate: the data-rate determines the amount of payload raw data which can be downloaded during a pass over a ground station.

Scheduling Algorithm

From the list containing all the possible operations that each satellite can perform, a practically unlimited number of different operations schedules for the constellation can be obtained taking into account all the constrains and conflicts. Indeed every single request of an image of a certain target can be fulfilled by different satellites at different times and only one of these possibilities will be selected while the others will be discarded (or a number in case more images of the same target are requested). It is then evident that every different choice, based on a definite selection logic, can lead to a different operations schedule.

Type of Operations

The following basic types of operations are defined:

- Monitoring pass (MP): a ground station contact during which the satellite downloads the housekeeping real and historical telemetry and receives real-time and time-tagged commands.
- Download pass (DL): a ground station contact during which the satellite downloads the payload data in adjoint of performing the operations performed during a monitoring pass. This operation can require an attitude manoeuvre.
- Data-take (DT): a contact with a target during which a payload of the satellite records data. Usually this operation requires an attitude manoeuvre and the preparation of the payload (e.g. warm up).
- On-line data-take (DTON): this is a data take operation overlapping a ground station contact. In this case a data-download contemporary to the data-take may be possible or not depending on the system capabilities.
- Inter-satellite link (ISL): this is a contact between two satellites (possible if the reciprocal distance is shorter than a certain minimal required distance). During an ISL a satellite can send/receive time-tagged commands and payload data to/from the other depending on the satellite capabilities. This operation can require an attitude manoeuvre.
- System maintenance: a satellite can be spared for some time from the routine operations of the constellation in order to perform maintenance operations like orbit maintenance, spacecraft routine subsystem tests and calibration, payload calibration, etc.

Temporal Reasoning Constraints

The following definitions, derived from temporal reasoning constraints, are relevant for the selection of the satellite operations to be scheduled:

- An operation is commandable by a ground station contact (GS-commandable) if and only if its execution time is later than its start time of validity, previous than its end time of validity and after the ground station contact end time. Here as start and end times are intended operation times including attitude manoeuvre times, payload preparation times, etc..
- Data-takes overlapping a ground station contact are collected together and classified as on-line data-take possibilities i.e. data-takes that can be performed during a ground station contact.
- An operation is classified as commandable by an inter-satellite link (ISL-commandable) if the following preconditions subsist: it is not GS-commandable, its execution time is after a possible inter-satellite link with another satellite and if the ISL operation (transmission of the time-tagged commands from the other satellite) is GS-commandable.
- At each possible ISL-commandable data-take, an ISL contact by which it can be commanded is associated. The association rules can be different. In a FIFO (First in First Out) selection approach, for example, at each possible ISL link sorted chronologically, all the successive data-takes that can be commanded by this contact can be associated(taking into account that the number of the data-takes which can be commanded during an ISL contact is limited by the contact duration).

Priorities Assignment

Operations of the same type (DT, DO, etc) and priorities are grouped in same lists. The order by which the different lists will be put into the scheduler module, depends of course on the priority value: higher is the priority, sooner the list will be processed. The value of the priority assigned to an operation to be scheduled depends on the priority assigned by the user of the constellation, on the type of operation and the type of optimization in use.

User The priority values assigned by the users have the major weight for any kind of operation. Three types of priority have been considered: high (urgent), medium and low.

Operation For operations that have the same level of priority assigned by the user, the order of priority from the highest to the lowest is the following:

- Highest priority value is assigned to ground station contacts as it is assumed that a ground station contact cannot be discarded without an explicit request of the user.
- As the scheduling of an online data-take (see GS-commandable paragraph) prevents a number of ground station contacts to be used for payload data download stored on-board the satellites (for the system considered in the simulations here performed), the lists containing this kind of operations have to be placed as first in the chain of data-takes scheduling. The main scheduling logic (immediate search downstream in the operations plan and schedule of a data download) precludes the possibility to engage every available ground station with an online data-take in case the number of possible online data-takes at different times exceeds the number of available ground station contacts.
- Inter-satellite links: as ISL operations enhance the minimisation of system response time, a priority value higher than that of a normal data-take is assigned to them.
- Ordinary data-take.

Optimization The value of priority assigned to an operation depends also on the figure of merit to be optimized and the type of optimization.

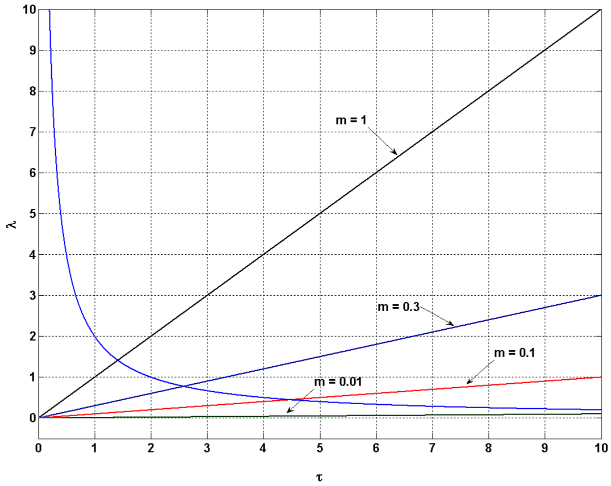

Figure 1: Space τ - λ.

Main Scheduling Selection Logic: the Sandwich Inserter

An operation schedule containing only all the satellite ground station passes is first created. This first operations plan will of course contain only satellite monitoring passes. In the most general case a list containing all possible target contacts of every satellite of the constellation and sorted chronologically, is scanned sequentially. At every scan-step an attempt is made to insert the target contact considered in the operations schedule. Considering operations that have the same value of user priority, the order of the lists considered is: on-line data-takes, ISL contacts, data-takes. In the most general case an operation of a specific satellite has to be inserted between two operations already scheduled for that satellite; in this case the following substeps, based on a look-ahead logic, are executed:

1. Time conflicts check.
2. The new spacecraft state (battery state of charge, storage capability, etc.) is calculated based on the states in the preceding already scheduled operations and eventual conflicts are checked.
3. Look-ahead: all the states of the spacecraft in the operations already scheduled and following in time that under examination, are temporarily updated and checked with respect to the constraints.
4. 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.
5. A data download possibility of the new stored payload data is searched and, if possible, scheduled immediately: the operations schedule is scanned by increasing time to find the next ground station contact scheduled for the spacecraft whose data-take has just been scheduled.
6. Once a download possibility has been found, the feasibility of this download operation is evaluated with the same logic of point 3.
7. 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.

Optimization: a Heuristic Method

The fundamental logic is to subdivide all the possible operations by priority in order to obtain a number of lists containing operations with the same priority and ordered chronologically. The lists are then processed by the scheduler in order of priority from the highest to the lowest. The assignment rule of the priorities depends on the figure of merit to be optimized (see Lemaitre & Verfaillie (2002)). Two figures of merit are here considered:

1. System response time: the outage between the time an image is requested by the user and the time the image is ready to the use.
2. Total number of satisfied image requests.

If the number of images taken over a certain period of time has to be optimized, a fair heuristic priority-assignment rule is that larger is the number of possibilities to take an image of a certain target, smaller will be the priority assigned to that data-take possibility. If the system response time has to be minimized, the most straightforward priority-assignment rule is that earlier operation execution times give higher priorities. Considering operations with a same priority assigned by the user, the following basic priority assignment rule has been tested:

$$P = \lambda \cdot OP + \tau \cdot TS \tag{1}$$

where

P is the priority value
OP is the number of opportunities to make a data-take
TS is a time slot
λ,$\tau \in \mathbb{R}^+$ are respectively the weights of OP and TS

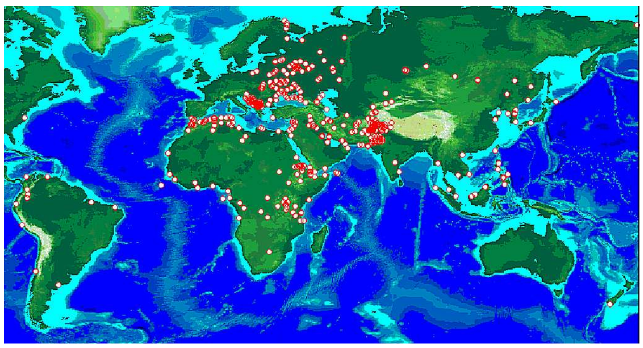

Figure 2: Distribution of Targets (white circles).

The numerical value of the highest priority is 1. The problem here is to find the values to assign simultaneously to τ and λ to maximize the number of satisfied requests or to minimize the time of response of the system. Hence the two-dimensional space τ - λ has to be explored (Figure 1). To this end two curve types representing simple relations between τ and λ have been considered:

$$\lambda = m \cdot \tau \tag{2}$$

$$\lambda \cdot \tau = cost \tag{3}$$

The order by which the different operations lists are processed depends on the value of the priorities. Hence from the simple form of Eq. 1 we can infer that moving along a line with a certain m, as the ratio λ/τ remains constant, the precedence order given by of the priorities assigned with Eq. 1 does not change.

Experimental Results

As a testbed, a constellation of 4 agile small satellites in LEO (Low Earth Orbit) equipped with a SAR (Synthetic Aperture Radar) sensor has been considered.

1 ORBITAL PLANE CONFIGURATION				
Satellite	SAT1	SAT2	SAT3	SAT4
a (km)	6893.14	6893.14	6893.14	6893.14
e	0	0	0	0
i (deg)	97.4	97.4	97.4	97.4
RAAN (deg)	0	0	0	0
ω (deg)	0	0	0	0
TA (deg)	0	90	180	270
2 ORBITAL PLANES CONFIGURATION				
Satellite	SAT1	SAT2	SAT3	SAT4
a (km)	6893.14	6893.14	6893.14	6893.14
e	0	0	0	0
i (deg)	97.4	97.4	97.4	97.4
RAAN (deg)	0	0	120	120
ω (deg)	0	0	0	0
TA (deg)	0	60	300	360
a = semi-major axis, e = eccentricity, i = inclination TA = true anomaly, ω = argument of perigee RAAN = right ascension of ascending node				

Table 1: Satellite Constellation Configurations.

Only one user and one ground station have been considered. The images requested are 620 distributed over 1 week (every day a number of new requests is added). The targets are 7km x 7km square surfaces and their distribution on the Earth surface is representative of a typical scenario (Figure 2). In order to relax the constraints, the data-takes are all requested to be performed in only one mode (spotlight mode), the priorities assigned by the user are the same for all the image requests and no deadline is assigned to every request.

The requests on other parameters of the images (during the day or night, satellite azimuth during data-take, etc.) are distributed randomly. It is assumed that the satellites have to perform an attitude manoeuvre before and after a payload data-take or a payload data download. The minimal allowed state of charge of the batteries on-board the satellite is 50 %. The satellites cannot perform a payload data download while

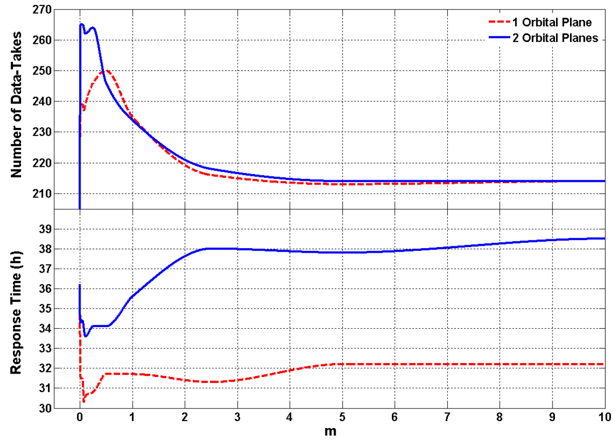

Figure 3: Variation of number of satisfied requests and system response time with m.

taking an image. In order to show the great potentiality that planning technology can have also in the design phase of a satellite constellation, two different constellation configurations have been considered and compared: one with 1 orbital plane and the other with 2 orbital planes. Table 1 shows the satellites orbital elements for the two configurations (all the orbits are circular and sun synchronous). The analysis of the simulation results have been focused on two type of comparisons: the variation of the figures of merit to be optimized with the weights τ and λ for each constellation configuration and the comparison of the optimal system performances in the two different configurations. Figure 3 shows the variation of the number of successfull data-takes (images obtained) and of the system response time with m for the two constellation configurations considered and for a simulation of 7 days. The τ - coordinate axis represents the case of the utilization of only TS (in this case time slots of 12 hours) for the assignment of the priorities.

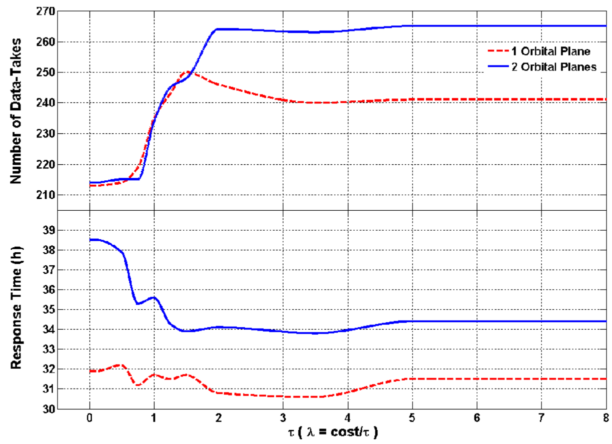

Figure 4: Variation of number of satisfied requests and system response time with τ along the hyperbolas $\lambda \cdot \tau = cost$.

In this case the planning approach is a simple FIFO approach as, without the assignment rule given by Eq. 1, the data-take possibilities are simply put into the scheduler in a chronologically order. The τ - coordinate axis represents the case in which only OP is accounted for the assignment of the priorities.

Some main general things can be immediately noticed:

1. For each configuration there are two values of m corresponding to optimal values of both the figures of merit.
2. For each figure of merit the variation with m is similar for the two different configurations.
3. The values of m that respectively maximize the number of satisfied requests and minimize the response time, are akin.

Similar consideration can be done considering the variation of the figures of merit moving along the hyperbolas of Eq. 3.

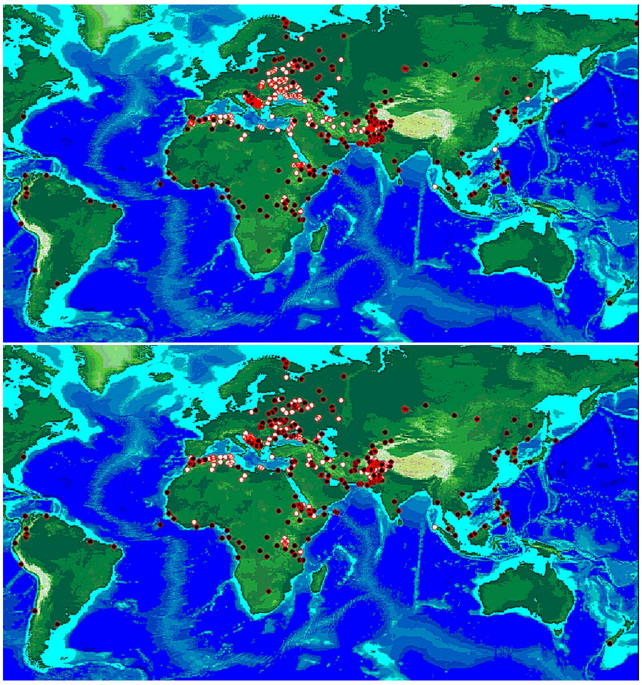

Figure 5: Two orbital planes configuration. Above: Satisfied requests (black circles) in 7 days with a FIFO approach. Below: Satisfied requests in 7 days with an optimal value of $m = 0.1$.

Figure 5 gives a visual demonstration of the results achieved with this simply optimization method: the number of successfull images achieved with a FIFO approach and the optimization are compared for the 2 orbital planes configuration. In the first case (FIFO) 200 images can be obtained in 7 days, while in the second case 265 images. Among these, 31 are on-line data-takes. The successfull downloads (corresponding of course to the satisfied requests) are respectively 192 and 256. As the FIFO approach in this case can be considered the simplest planning strategy, the results obtained with it can be considered as a reference

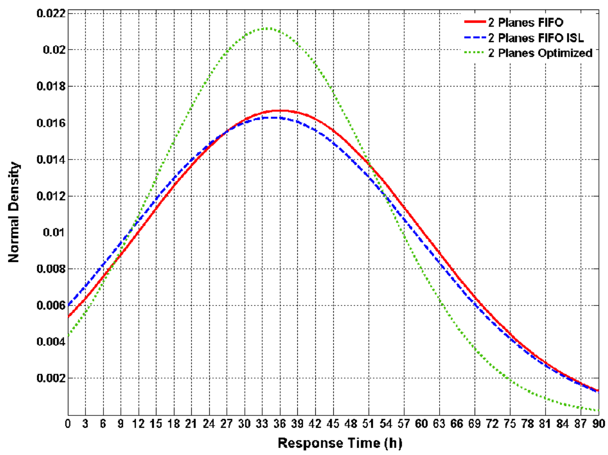

Figure 6: Normal distributions of system response time.

by which the quality of the results obtained with other methods can be evaluated. Figure 6 shows instead the normal distributions of the response time of all the satisfied requests in three different cases: FIFO approach, a FIFO approach with the satellite using the inter-satellite links and the optimization. The average value of system response time achieved with a FIFO approach is 36.1 hours, while with the use of ISL it sinks to 33.7 and with the optimization (but without ISL) to 33.6 hours. The comparison of the behaviour of the performances of the satellite constellation in the two configurations, gives a general trend: the maximum achievable number of satisfied requests is larger using the 2 orbital planes configuration, but the minimal system response time is smaller using the 1 orbital plane configuration.

The best values of maximum number of satisfied requests, minimal response time and information age (in this case not a figure of merit), are shown for the two configurations in Table 2. For the 1 orbital plane configuration, the ISL has not been considered because the constant relative displacement of the satellites exceed the minimum displacement required by an inter-satellite link. From these results it can be achieved that for this type of scenario an operation optimization can give system response time even better than using an ISL with a FIFO scheduling approach. Regarding

1 ORBITAL PLANE CONFIGURATION			
Parameter	**FIFO**	**Optimizaton**	**ISL**
Max satisfied requests	195	232	
Response Time (h)	35.6	31.7	
Information Age (h)	4.4	4.3	
2 ORBITAL PLANES CONFIGURATION			
Parameter	**FIFO**	**Optimizaton**	**ISL**
Max satisfied requests	192	256	213
Response Time (h)	36.1	33.6	34.7
Information Age (h)	4.6	4.3	4.6

Table 2: Comparison of different configurations.

the two figures of merit considered, from the values in Table 2 it can be concluded that the 1 orbital plane configuration has on average better performances, though the coverage has not been accounted.

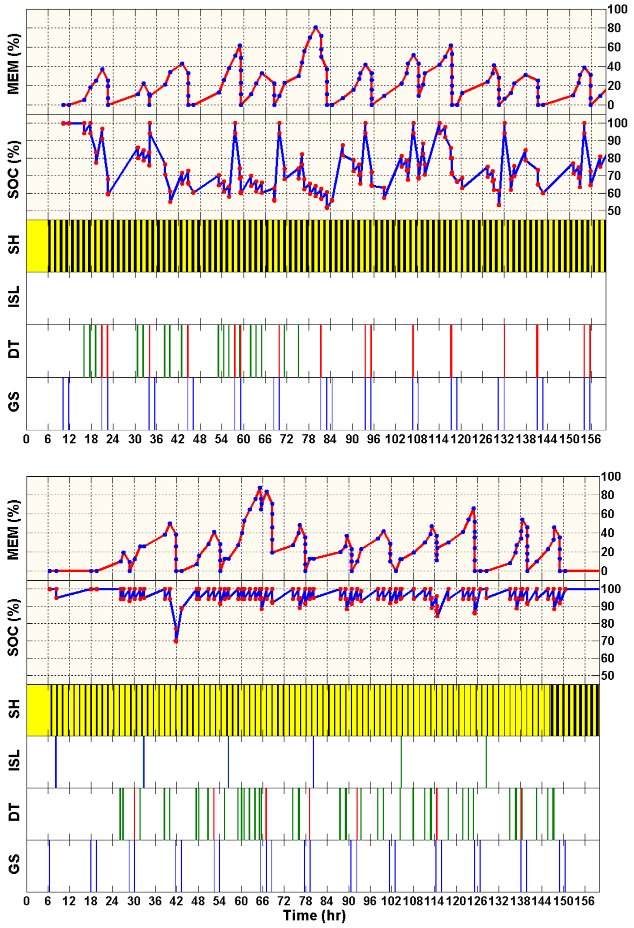

Figure 7: Sequence of events for SAT4 operating in two constellation configurations (7 days simulation). GS = ground station contacts, DT = data-takes, ISL = intersatellite links, SH = Earth shadow times, SOC = battery state of charge, MEM = on-board memory state. Above: 1 plane configuration. Below: 2 planes configuration with ISL.

Finally it is worthful to stress that scheduling can also be very useful to evaluate the exploitation of the on-board resources of each satellite in different constellation configurations. Figure 7 shows the sequence of events of SAT4 operating in two different constellation configurations during 7 days. Every bar represents a satellite operation and its width is proportional to the duration of the event represented.

It can be noticed that though the satellite has more operation scheduled when operating in the 2 planes configuration, its on-board battery has smoother charging cycles. In fact, due to the more favorable position of its orbital plane with respect to the Sun, the Earth shadow times are shorter with consequently longer charging times.

Conclusions and Future Investigations

The problem of the performance optimization of a remote sensing satellite constellation has been investigated. The figures of merit of interest are the maximum number of satisfied requests and the system response time. The constellation considered is composed of 4 agile satellites in LEO equipped with a SAR sensor. Only 1 user and 1 ground station and two different constellation configurations have been considered (1 and 2 orbital planes). A simple heuristic method, based on a weighted assignment of the priorities to the possible operations to be scheduled, has been proposed for the optimization. For the simulations the software SCOOP (Satellite Constellations Optimal Operations Planner) developed at the Microwaves and Radar Institute of DLR has been used. The optimization method has been proved to be effective. As regards the two figures of merit considered, the 1 orbital plane configuration looks better, though it does not allow the use of inter-satellite links and the requirements on the constellation coverage have not been regarded. The heuristic method adopted has to be refined in order to include a larger number of criteria in the assignment of the priorities. The inter-satellite link can be inserted in the optimization to further improve the system response time. More different constellation configurations have to be tested in order to verify if these results can be generalized.

References

De Florio S., Zehetbauer T., Neff T., 2006, SCOOP: Satellite Constellations Optimal Operations Planner, ICAPS 2006 Workshop on Constraint Satisfaction Techniques for Planning and Scheduling Problems, Cumbria, UK

Lemaître M., Verfaillie G., Fargier H., Lang J., Bataille N., Lachiver J., 2002, Sharing the use of Earth Observation Satellites, 3^{rd} NASA Workshop on Planning and Scheduling

Tsang E., 1993, Foundations of Constraint Satisfaction, Academic Press Limited, London, UK