Reduction of the Response Time of Earth Observation Satellite Constellations using Inter-satellite Links

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Data quality of Earth observation satellites is often evaluated in terms of short system response time and information age. Acceptable response time and information age can be achieved only by satellite constellations in LEO as they allow observations with high repetition rates. System response time can also be reduced by means of small or micro satellites exclusively dedicated to the commands delivery from a ground station to an imaging satellite or bridging two imaging satellites via inter-satellite links. In this paper a concept based on the use of inter-satellite links for commands delivery is presented. As a first feasibility study numerical simulations have been performed for one or more Earth observation satellites serviced by a small satellite constellation in different configurations.

Nomenclature

LEO	Low Earth Orbit
C/S	Courier satellite
ISL	Inter-satellite link
GSOC	German Space Center
SAR	Synthetic Aperture Radar
D/T	Data-take
D/D	Data-download
H/K	Housekeeping data
S/C	Spacecraft
SOC	State of charge
TC	Telecommand
TTTC	Time tagged telecommand

I. Introduction

Earth observation satellites provide valuable inputs for disasters detection and management (Ref. 1, Ref. 2 and Ref. 3). A main indicator of the data quality is a short system response time that is the time span between the delivery of the image requested by the users and the availability of the ordered data. Another important indicator is the information age that is the time span between the data collection by the satellites and their availability. Acceptable response time and information age can be achieved only by satellite constellations in LEO as they allow observations with high repetition rates. System response time can be reduced either by increasing the number of satellites in the constellation or by use of inter-satellite links for commands delivery combined with planning and scheduling technology to generate optimal operation schedules. If only one ground station is available for satellites commanding and increasing the number of satellites is not possible because of budget constraints, the use of inter-satellite links is necessary to reduce response time. In this paper a concept based on the use of inter-satellite links for commands delivery and data collection is presented. The proposal is to use one or more small or micro satellites exclusively dedicated to the commands delivery from a ground station to an imaging satellite or data collection from an imaging satellite to a ground station. The altitude of these *Courier* satellites will be different from that of the

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imaging satellites in order to increase the number of possible inter-satellite links. Planning and scheduling technology can be used for the optimal management of the system. The main advantages of this solution are that very low budget satellites can be used as C/S, no further dedicated ground station or imaging satellites are necessary to reduce the response time and the C/S can be used as a service system for different remote sensing missions.

A. Observation Satellite Operations

An Earth observation satellite in LEO has to store image data on-board until a data download to a ground station is possible. For a satellite in LEO with a ground station not positioned in the polar regions, ground station contacts are limited in number and duration (typically three or four contacts per day with a duration of less than 10 minutes). System response time, a critical parameter especially in mission dedicated to disaster management or military reconnaissance, can be reduced by one of the following methods:

1. Increasing the number of available ground stations for download and/or commanding.
2. Using one or more ground stations located in the polar regions (as observation satellites have typically a high inclination orbit).
3. Using planning and scheduling technology to generate optimal operation schedules.
4. Increasing the number of observation satellites: small-satellite constellations in LEO allow observations with high repetition rates and medium to high image resolutions.
5. TDRSS (Tracking and Data Relay Satellite).
6. A combination of these elements.

The aforementioned improvements may not be practicable either for an unsustainable increase of mission costs (1,4,5), or technological risk (3), or political reasons (2,5).

II. System Configuration

The satellites system here considered is composed by one or more ground stations and one or more remote sensing satellites serviced by a C/S constellation.

A. Observation Satellites

The main tasks of each satellite are: payload data-take on a certain target, on-board data-storage, payload and housekeeping data-download on a certain ground station, bus maintenance, monitoring and commanding. The following system features primarily determine the value of the response time:

1. The satellites have a limited number of opportunities of revisiting a target as they are in fixed orbits that pass over a particular location on Earth at definite times and in order to perform a data-take, a target has to be in the field of view of the imaging sensor. As a certain time is required to acquire an image, imaging windows duration is also an important factor.
2. Data stored on a satellite are available only after a download performed during a contact between the satellite and a ground station. The number of available ground station contacts and their duration are limited for each satellite. The duration of a ground station pass limits the quantity of payload data that can be down-loaded (depending on the download data-rate). A ground station contact is also the only possibility to command a D/T to a satellite in absence of ISL capabilities.
3. The limited on-board data storage capability is also cause of delay because once the on-board memory is full no new images can be taken without overwriting those already on-board before the next download possibility.

If there is only one available not polar ground station, the satellite-ground station visibility gap can be up to about 12 hours. It follows that in the worst case, if an image request comes from a user to the ground station during this gap and only one satellite is available, the response time for the request can be up to about 24 hours. The problem can be partially solved increasing the number of satellites forming a constellation with an optimal geometrical configuration until the desired system response time is achieved, but this solution can be in conflict with mission budget constraints. The availability of more than one ground station can also be precluded by budget constraints, political or strategic reasons.

B. Servicing Satellites

Main task of the C/S is data-take TTTCs commands delivery and data collection by means of inter-satellite links with the remote sensing satellites. The idea is to use one or more small or micro satellites exclusively dedicated to commands delivery from a ground station to an imaging satellite or bridging two imaging satellites, and/or data delivery from a satellite to a ground station. In fact ISL can be used either to bridge a command from the ground station to the remote sensing satellite that has the earliest access to a requested image but cannot be commanded in time directly from ground or to deliver image data from a satellite to another satellite with an earlier ground station access. The C/S are indeed used as small mobile ground stations. The main advantages of this solution are that very low budget satellites can be used as C/S (solution to items 1,4,5 of Sec. I.A), no further dedicated ground station or imaging satellites are necessary to reduce the system response time (solution to items 1,2 and 4 of Sec. I.A) and the C/S can be used as servicing satellites for the improvements of the performances of several remote sensing missions. A C/S can have one of the following capabilities:

1. Command delivery from a ground station to an observing satellite.
2. Command delivery from another C/S to an observing satellite.
3. Data collection and storage from an observing satellite and download to a ground station.
4. Data collection and storage from another C/S and download to a ground station.
5. All capabilities 1,2,3 and 4 or a feasible combination of them.

The technological risk is minimized for C/S dedicated to command delivery as omni-directional S-Band antennas mounted on very simple satellites can accomplish this task. The geometry of the C/S constellations has to be devised in order to have the largest number of passes over the commanding ground station. Data collection capability implies more technological complexity.

III. Numerical Simulations

The potential performance improvement of a remote sensing satellite or satellite constellation serviced by a C/S constellation has been tested by means of numerical simulations based on the scenario described in the following sections.

A. System Model

Tables 5 and 6 in the Appendix collate the user requests and the system elements that have been modeled in performing the numerical simulations. For a clear evaluation of the possible performance enhancements brought by the C/S servicing constellation, the remote sensing system has been configured as homogeneous as possible (1 type of satellite, 1 type of target, etc.) and the user requests have the minimal level of complexity (1 type of priority, 1 image request per target, etc.).

B. Simulation Scenario

1. User Requests

Figure 1 shows the user requests scenario: the targets are 525 (75 per day), identical in dimension and shape (Table 6) and randomly distributed on the mainland. The simulations represent one week of operations assuming that the user sent every day 75 image-requests to the operations center. As shown in Table 5 each request expires after one day.

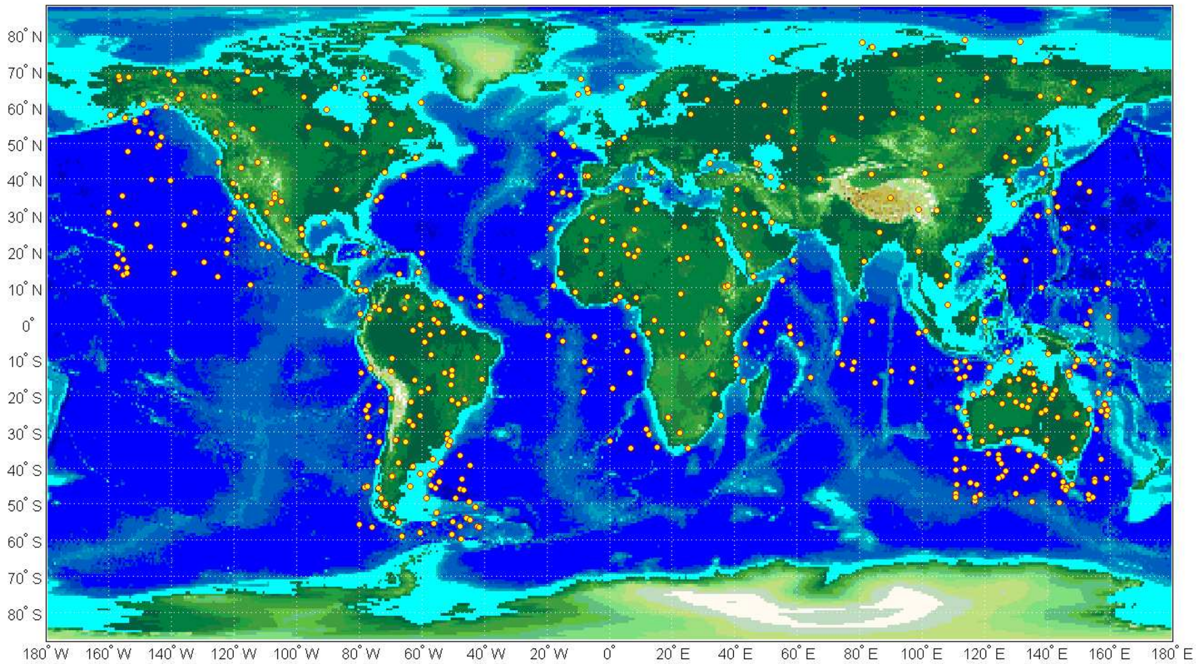

Figure 1. Targets scenario

2. Observation Satellites Constellation

Table 1 collates the nominal mean Keplerian elements (a = semi-major axis, i = inclination, e = eccentricity, $RAAN$ = Right Ascension of the Ascending Node, ω = argument of perigee, TA = True Anomaly) of the orbits of the satellites composing a representative remote sensing constellation in LEO that has been used in the numerical simulations.

Table 1. Nominal mean Keplerian elements

Satellite	a [km]	i [deg]	e [-]	$RAAN$ [deg]	ω [deg]	TA [deg]
SAT1	7000	98	0	0	0	0
SAT2	7000	98	0	0	0	67.5
SAT3	7000	98	0	64	0	35.5
SAT4	7000	98	0	130	0	0
SAT5	7000	98	0	130	0	67.5

The satellites are 5 identical agile-satellites, distributed on 3 orbital planes and each one equipped with a SAR sensor. The operations of each satellite are constrained by the limitations collated in Table 6. D/T and D/D operations require dedicated attitude maneuvers. It has been assumed that the observing satellites have no ISL capabilities, i.e. they can only receive TCs from the C/S but not send them.

3. C/S Constellation

Table 2 resumes the general features of the C/S constellations used in the numerical simulations. The C/S constellations used have the general feature to be Walker constellations (Ref. 4) with evenly distributed orbital planes and even in-plane distribution of satellites. If N is the number of satellites and P the number of orbital planes, N/P is the number of satellites per orbital plane. All the orbits are circular with an inclination of 45°. Two semi-major axis values have been considered for each constellation geometry. In order to relax, in the simulations, power and data storage constraints of the C/S satellites, they have been assumed to be the same of the observation satellites (Table 6). The C/S have only the capability of TC delivery from a ground station to an observing satellite (item 1 of Sec. B) but no data collection capability via ISL. Only one level of ISL routing has been considered, i.e. a TC can be bridged only by one C/S from a ground station to an observing satellite (for ISL networks routing Ref. 5 and Ref. 6). For C/S constellations with semi-major axis of 7500 km it has been assumed that an ISL is possible if the C/S is within a sphere centered on a SAR satellite and with radius of 5000 km. For C/S constellations with semi-major axis of 21000 km the radius of the sphere is 21000 km.

Table 2. C/S constellations features

N	P	a [km]	i [deg]	e [-]	RAAN spread [deg]	TA spread [deg]
4	1	7500 or 21000	45	0	-	90
4	2	7500 or 21000	45	0	90	180
4	4	7500 or 21000	45	0	45	-
6	2	7500 or 21000	45	0	90	120
6	3	7500 or 21000	45	0	60	180
6	6	7500 or 21000	45	0	30	-
10	2	7500 or 21000	45	0	90	36
10	5	7500 or 21000	45	0	36	180
10	10	7500 or 21000	45	0	18	-

4. Ground Station

A single operation center, the GSOC, using antennas located in a single location has been selected for the numerical simulations. The operations center is considered capable of managing more than one satellite pass at the same time.

C. Operations Scheduling Algorithm

The scheduling logic implemented in the software that has been used to perform the numerical simulation, is based on the distinction between different types of operations, temporal and physical reasoning constraints, and priority assignment. In order to evaluate only the potentialities of the physical system, no scheduling optimization method but a First In First OUT (FIFO) approach has been used for the building of the operations schedule. An extensive description of the scheduling logic can be found in Ref. 7.

IV. Results

In the evaluation of the numerical simulation results, the following has to be considered:

1. As this is a first evaluation study, main goal was not to find an optimal configuration of the C/S constellation, but to explore the potential performance enhancement brought by this servicing system.
2. As the simulation results are on a certain extent dependent on the target scenario, the user requests and on the specific scheduling algorithm used, they cannot be considered conclusive.

Table 3 collects the SAR satellite constellation performance when not serviced by a C/S constellation (first row) and when serviced by C/S constellations with different geometries. The main figure of merit regarded in the evaluation of the SAR satellite constellation performance is the response time as defined in Sec. I. Other significative figures of merit are the information age (Sec. I) and the total number of satisfied user requests. The values of response time and information age represent the peaks of the normal distributions computed over all the response times and information ages corresponding to each successfull D/T. Figure 2 shows the best values of the SAR satellite constellation performance. The best value of the performance figure of merit is represented for each number of satellites composing the servicing C/S constellation and each C/S constellation altitude. The results are compared with the performance of the remote sensing constellation not serviced by a C/S constellation. It can be noticed that in all the cases considered, the performance improve when the remote sensing constellation is serviced by a C/S constellation. The best values are found for C/S constellations composed by 6 satellites. A larger altitude brings an enhancement only on the number of satisfied user requests and in case of a 6 C/S constellation.

Table 3. SAR satellites constellation performance

N	P	a [km]	Response time [h]	Information Age [h]	D/T	D/D
-	-	-	18.3	6.0	336	326
4	1	7500	16.4	5.7	350	338
		21000	17.6	5.9	360	350
4	2	7500	16.7	5.7	364	348
		21000	17.2	5.9	336	326
4	4	7500	17.9	5.9	352	337
		21000	17.2	5.8	355	344
6	2	7500	17.2	5.8	375	363
		21000	17.4	5.8	366	356
6	3	7500	16.3	5.6	345	330
		21000	16.4	5.6	387	377
6	6	7500	17.6	5.9	368	352
		21000	16.7	5.7	349	337
10	2	7500	17.1	5.8	369	353
		21000	17.2	5.8	364	354
10	5	7500	16.7	5.7	358	345
		21000	16.8	5.7	346	336
10	10	7500	17.5	5.9	347	326
		21000	17.0	5.7	371	361

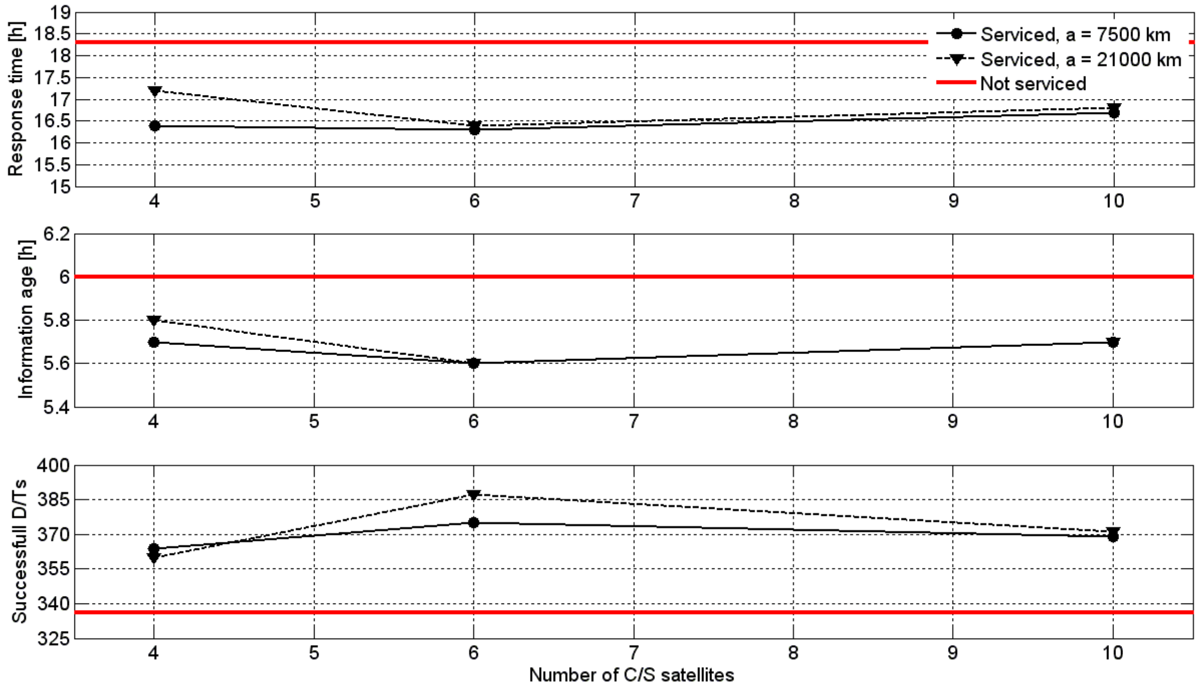

Figure 2. Best values of SAR satellites constellation performance

Figure 3 shows the response time and information age corresponding to each image request satisfied by the SAR satellites constellation serviced by the C/S constellation composed by 6 satellites distributed on 3 planes and with a semi-major axis of 7500 km. As shown in Table 3, this is indeed the C/S constellation whose servicing allows the attainment of the best observing satellites constellation performance in terms of response time and information age.

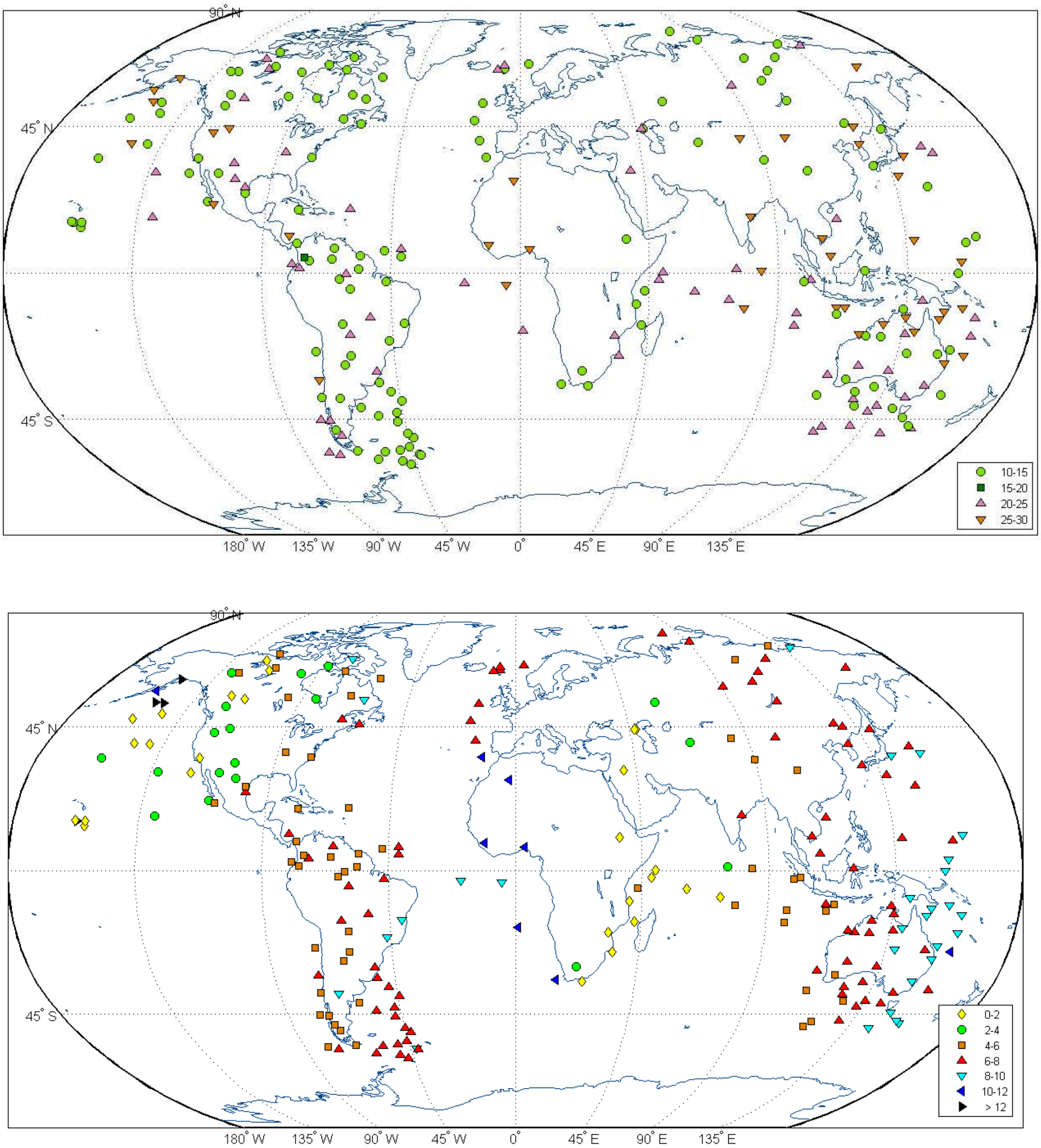

Figure 3. Response times [h] (top), information ages [h] (bottom)

Figure 4 shows the comparison of the normal distributions computed over all the response times and information ages corresponding to each successfull D/T in the cases that the observing constellation is either serviced or not serviced by the C/S. The improvement of 2 hours in terms of response time can be considered a promising result if the following fundamental observations are regarded:

1. For this first feasibility study a large number of image requests with the same priority level has been considered (Table 6).

2. As the image request priorities are the same for all the targets, only the normal distributions of the response times and not the value for each single image request could be compared.
3. The C/S capabilities described in Sec. II.B have not been fully exploited.
4. The possibility of the use of ground station antennas in different locations has not been considered.
5. Positive results with this user requests scenario bring to the conclusion that better results can be obtained with a scenario built on small groups of image requests with different priorities.

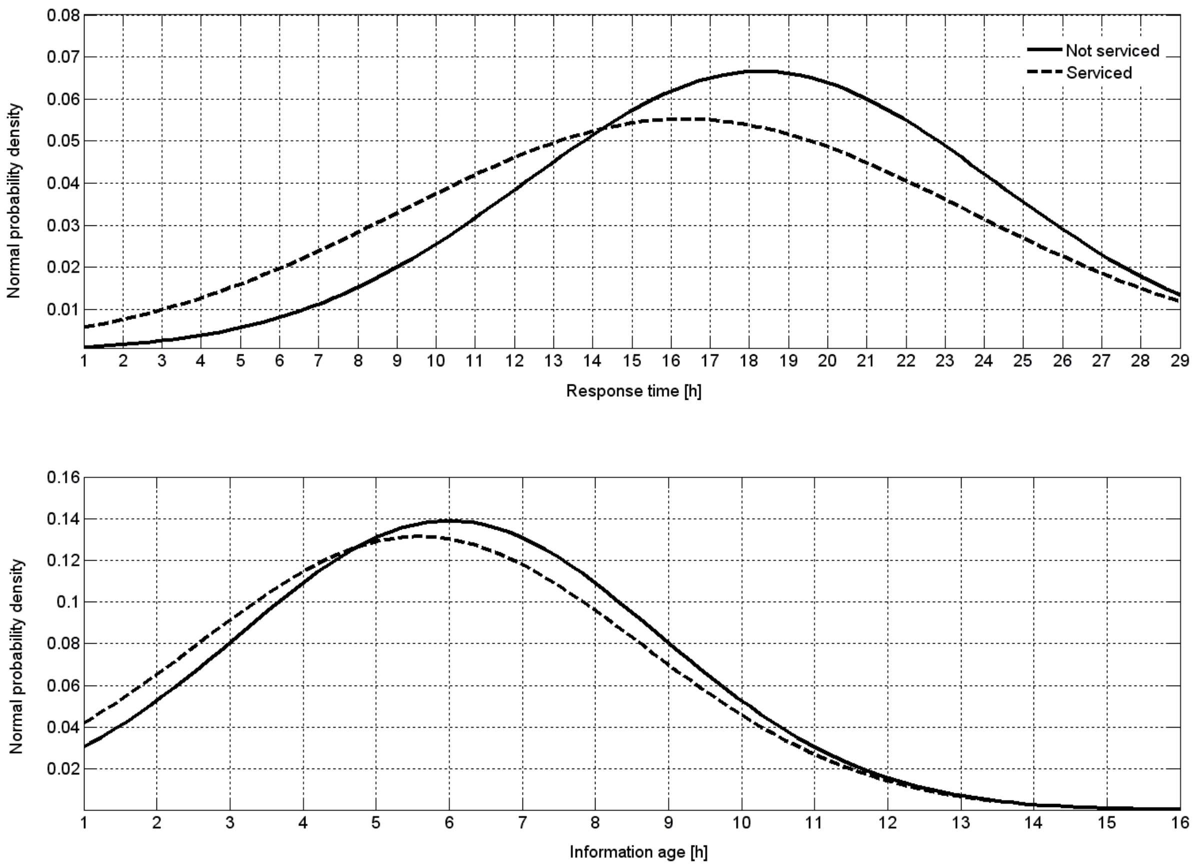

Figure 4. Normal distributions of response times (top), normal distributions of information ages (bottom)

As a representative example of the constrained exploitation of the on-board observing satellites resources, Figure 5 shows the sequence of events of SAT5 (Table 1) operating in the best results scenario just described. Every bar represents a satellite operation and its width is proportional to the duration of the event represented. Each bar in the four plots represents an event: ground station contacts in the D/D plot, images acquisition in the D/T plot, inter-satellite links in the ISL plot and light and shadow times. The markers represent instead the values of the on-board data and power storage devices. It can be noticed that the on-board data storage device is exploited to almost its full capability during the entire duration of the simulation.

Finally the results of the numerical simulation performed assuming that SAT1 (Table 1) is the only operating SAR satellite are collected in Table 4 (identical in its structure to Table 3). Once again the best servicing C/S constellation is composed by 6 satellites distributed on 3 planes but this time with semi-major axis of 21000 km. The improvement in terms of response time is 2.7 hours.

The results of this first study and collected in Tables 3 and 4 bring to the conclusion that a C/S servicing constellation could be convenient from an economical point of view if an optimal design can be realized to maximize the performance enhancement of the served missions and if it can be used as a service for a number of different missions.

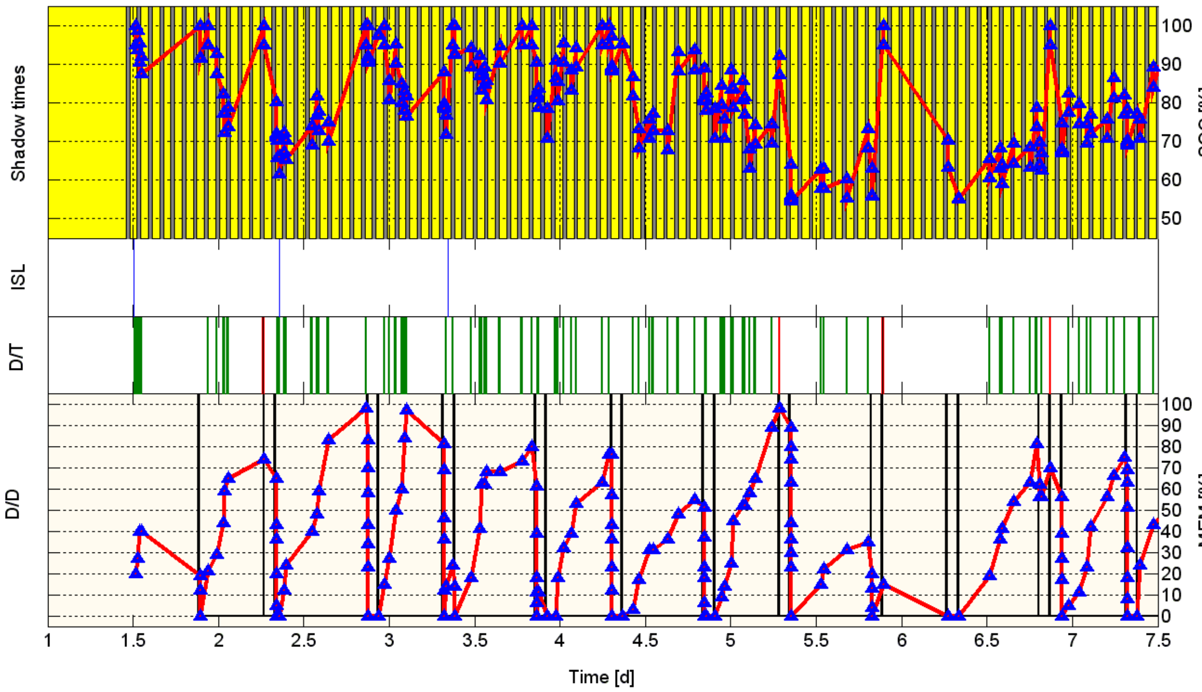

Figure 5. Sequence of events for SAT5 (7 days simulation).

Table 4. SAT1 performance

N	P	a [km]	Response time [h]	Information Age [h]	D/T	D/D
-	-	-	19.8	7.4	91	90
4	1	7500	18.4	7.5	98	90
		21000	18.9	7.1	94	86
4	2	7500	18.6	7.2	94	85
		21000	19.5	7.3	88	83
4	4	7500	19.8	7.4	95	90
		21000	18.6	7.2	93	88
6	2	7500	18.1	7.0	97	88
		21000	18.8	7.2	95	87
6	3	7500	18.1	6.9	92	83
		21000	17.1	6.6	105	97
6	6	7500	19.1	7.3	98	91
		21000	17.6	6.9	111	102
10	2	7500	18.3	7.0	96	87
		21000	19.5	7.3	88	83
10	5	7500	19.0	7.2	100	92
		21000	18.1	7.0	99	91
10	10	7500	18.4	7.0	92	85
		21000	18.9	7.4	98	93

V. Conclusion

A first study has been conducted for the evaluation of the performance enhancement of a remote satellites constellation served by a small or micro satellite constellation for commands delivery and data collection. Main performance figure of merit considered is the response time. Other significative figures of merit are the information age and the total number of satisfied user requests. Numerical simulations have been performed for a SAR satellite constellation in LEO serviced by a small-satellite constellation in different geometrical configurations and altitudes. The simulation scenario has been kept at a lowest possible level of complexity in order to evaluate only the potentialities of the physical system and no scheduling optimization method but a FIFO approach has been used for the building of the operations schedule. The simulation results are promising, though they cannot be considered conclusive. As only telecommands bridging capability has been exploited in the simulations, a future analysis should aim to evaluate the advantages afforded by the servicing satellites when exploited in their full capabilities. A simulation scenario should also be built for a more effective evaluation of the results. A large number of simulations has to be conducted considering different Earth observation systems and servicing satellite constellation configurations in order to have some statistical results. Though a cost analysis has not been performed, it shows up that a C/S constellation can be convenient if the complexity of the satellites can be kept at a minimum level and if the system can be used as a service for several Earth observation missions.

Appendix

Tables 5 and 6 collate the user requests and the system modeled elements that have been used in the numerical simulation scenario. Typical values of agile SAR satellites on-board resources limitations and constraints have been chosen.

Table 5. User requests

User request	**Value**
User	GSOC
Targets location on Earth	Localized random distributions
Targets acquisition time	Random (day or night)
Image resolution	None specified
Type of imaging sensor	SAR
Imaging sensor mode	Slip mode
Number of D/T on a specific target	1
S/C azimuth	Random (East or West)
S/C min. elevation angle on a target	20 [deg]
S/C max. elevation angle on a target	60 [deg]
Start time of the validity of a request	8.00 A.M.day n
End time validity of a request	8.00 A.M.day n+1
Time deadline for finite product delivery	None specified
Type of priority of image request	Max. priority for each image

Table 6. System model

Observation satellites	
Element	**Value**
Satellites orbit	Sec. III.B
Power storage	4950000 [Ws]
Power consumption attitude keeping	15000 [Ws]
Power consumption attitude maneuver	18000 [Ws]
Power consumption S-Band Communications	22000 [Ws]
Power consumption D/T	500 [Ws]
Power consumption payload D/D	200 [Ws]
Battery charging power	200 VA
Payload data storage	20000 [MB]
D/D TTTC storage size	4000 Bytes
D/T TTTC storage size	1500 bits
Sensor field of view	30 [deg]
H/K data download rate	32 [Mb/s]
Payload data download rate	256 [Mb/s]
C/S satellites	
Element	**Value**
Satellites orbit	Sec. III.B
Power storage	4950000 [Ws]
Power consumption attitude keeping	15000 [Ws]
Power consumption attitude maneuver	18000 [Ws]
Power consumption S-Band Communications	22000 [Ws]
Power consumption ISL Communications	20000 [Ws]
Battery charging power	200 VA
D/D TTTC storage size	4000 Bytes
D/T TTTC storage size	1500 bits
H/K data download rate	32 [Mb/s]
ISL data rate	150 [b/s]
Ground stations	
Element	**Value**
Name	GSOC
Location	48° N 11° E
Type of visibility horizon	Conical 5 [deg]
Handshake time	0 [s]
Targets	
Element	**Value**
Shape	Square
Dimension	7x7 [km]
Time constraints	
Element	**Value**
Spacecraft revisit limitations on targets	Sec. III.B
Ground station contacts	Sec. III.B
D/T acquisition maneuver	240 [s]
D/D acquisition maneuver	240 [s]
ISL acquisition maneuver	0 [s]
Nominal attitude re-acquisition maneuver	240 [s]
Ground station handshake	0 [s]

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