FUTURE FINE SCALE SATELLITE RADAR ALTIMETRY ARCHITECTURES USING A SMALL SATELLITES CONSTELLATION FOR LARGE SCALE AND MESOSCALE OCEANOGRAPHY

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Abstract

The launch of TOPEX/POSEIDON in 1992 marked the beginning of continuous radar altimetry ocean monitoring. Since then the community of ocean altimetry data users has grown significantly and today the data is used from fundamental ocean and climate (change) research to operational sea weather forecasts. TOPEX/POSEIDONSs successors are the Jason series satellites, with Jason-1 and Jason-2 currently in orbit and Jason-3 en-route for a launch in 2013, replacing the aging Jason-1 satellite. The measurements from the Jason satellites are complemented by the radar altimetry data from missions in polar (sun-synchronous) orbits. Polar radar altimetry measurements will be continued and improved by the satellites of the Sentinel-3 series, starting with Sentinel-3A, which is as well scheduled for launch in 2013.

Beyond the timeframe of the Sentinel-3 series satellites the future of satellite altimetry remains unclear. ESA has initiated a study that aims to look into the feasibility of accommodating an altimeter with associated instrumentation on a small satellite platform. The main idea is the deployment of small satellite constellations in low earth orbit (LEO) to fulfil the needs of oceanography in the future. The aim of these constellations is to provide additional support to the aforementioned satellites by further improving altimetry measurements. Different constellations using small, identical, altimetry-dedicated satellites providing improvements to the temporal and spatial quality of the measurements have been defined and analysed. The goal is to monitor mesoscale phenomena which typically require a measurement grid resolution better than 100km. Opportunities to provide long term very high spatial resolution measurements and very rapid but low spatial resolution measurements have been identified and are shown in the paper. The smallest constellation presented provides a measurement grid of 50km spatial resolution and gathers a complete data set every week. The key requirements driving the constellation design (temporal and spatial resolution of the measurements) and satellite design (large payload and multi-launch capabilities) are presented and their impacts discussed.

The altimetry instrumentation used in the study is mainly based on the Sentinel-3 radar altimetry payload suite, which represents state-of-the-art technology. It consists of a SRAL-like dual-frequency (Ku- and C-band) altimeter, a dual-frequency microwave radiometer, a next generation GNSS receiver and a Laser Retro-Reflector.

The starting point for the satellite design has been OHB System’s generic satellite platform for low Earth orbit missions the LEOBUS-1000. Several modifications, like a new structure design or a smaller payload data handling subsystem have been implemented to reduce the cost of the satellite and system. Different structure options that have been evaluated for the multi launch design.

1. INTRODUCTION

This paper presents a part of the preliminary results of the GMES-CARA study performed by OHB-System under contract to ESA. GMES-CARA is the abbreviation for *Global Monitoring for Environment and Security – Complementary Architecture for Radar Altimetry.* The study is about a radar altimetry satellite constellation utilizing small identical dedicated satellites in a constellation with different orbit planes to satisfy the needs of ocean altimetry users. The studied timeframe is post-Jason, with Sentinel-3 possibly operational at the same time. The earliest launch of the first satellites is estimated in 2020. The study examines the possibility of accommodating an altimeter with associated instrumentation on a small Low Earth Orbiting (LEO) satellite platform in view of future observation scenarios where a constellation of small satellites is deployed to serve the needs of oceanography, including mesoscale observations, coastal zones and reference altimetry (mean sea level rise). Both sun-synchronous orbits (SSO) and non-SSO are investigated for the constellation.

2. ALTIMETER WORKING PRINCIPLE

Radar Altimetry satellites determine the distance between the satellite and a target surface by means of permanently transmitting radar pulses to Earth and receiving the echoes from the surface. By measuring the signal round-trip time the satellite-to-surface distance is determined. For Oceanography, the main altimetry product is the *Sea Surface Height* (SSH), which is the distance between the sea surface and an arbitrary reference ellipsoid. As the satellite orbit and the reference ellipsoid are known, the SSH can be calculated easily. For precise measurements the uncertainty resulting from the satellite altitude knowledge needs to be minimized, therefore radar altimetry satellites are usually equipped with a set of precise orbit determination instruments.
However, the signal travelling-time is not the only measurement made in the process. A lot of other information can be gathered with satellite altimetry, e.g. the shape and magnitude of the echoes received contain information on the flatness of the surface which caused the reflection.

3. GMES-CARA STUDY AIMS

The radar altimetry accommodation and constellation design study is a part of the overall GMES-Complementary Architecture study that OHB-System has been performing under contract to ESA. It is a study using a state-of-the-art altimetry instrumentation based on the Sentinel-3 altimetry payload suite. The goals of the study are the evaluation of the feasibility of a satellite design using Sentinel-3 like instruments on a small common platform for a satellite constellation. Additionally, an estimate of the required number of satellites to satisfy identified oceanographic needs and an estimate on the costs of such a satellite and constellation are performed. The envisaged timeframe for the constellation assumes an earliest launch date of 2020.

4. NEEDS AND REQUIREMENTS

For the GMES-CARA study different radar altimetry services have been defined based on three types of identified mission requirements. The aim is to combine these three services providing synergistic data products to all participants.

1) *Reference Service*
This service comprises one or more satellites in a non-sun synchronous orbit providing very precise measurements. This type of service can be used to calibrate (by the use of cross over analysis) altimetry measurements from the other two altimetry services, improving their measurement accuracy and thereby of the overall altimetry satellites constellation.

2) *Core Service*
This type of service comprises satellites to extend the coverage to higher latitudes and provides denser geographical and temporal resolution measurements compared to the Reference service alone.

3) *Contributing Service*
Satellites carrying a radar altimetry payload that are not part of the reference or core service can provide additional support and complement the measurements. They contribute to the overall constellation as additional data source.

The demanded inclination and altitude ranges for the two services derived from observation and mission requirements are as follows:

- Altitude: 500 – 800 km (Reference and Core)
- Inclination: 66° - 78° (Reference)
- Inclination: 78° - SSO (Core)

The main limitations with respect to the altitude are due to the payload performance at the upper end and the atmospheric drag at the lower end.

Reference and *Core* service require different inclinations; this makes the combination of the two services difficult if a homogeneous spatial resolution is desired.
The requirements that pertain to the complete constellation (*Reference* plus *Core* service) are summarised in Table 1.

Table 1: Spatial and temporal resolution needs for oceanographic phenomena

Resolution Needs		
	Spatial Resolution	Temporal Resolution
Large Scale Measurements	500 – 100 km	5 – 10 days
Mesoscale Measurements	50 – 25 km	5 – 7 days
Sub-Mesoscale Measurements	10 – 5 km	1 – 2 days

The GMES-CARA study focused on the provision of the *core* service with a supporting investigation into providing the reference service too. The design impacts for using a common small satellite design for both services are addressed in the study.
The required temporal and spatial resolution is provided by the *Core* service solely. The *Reference* service is only taken into account to improve the accuracy of the *Core* service satellites measurements.

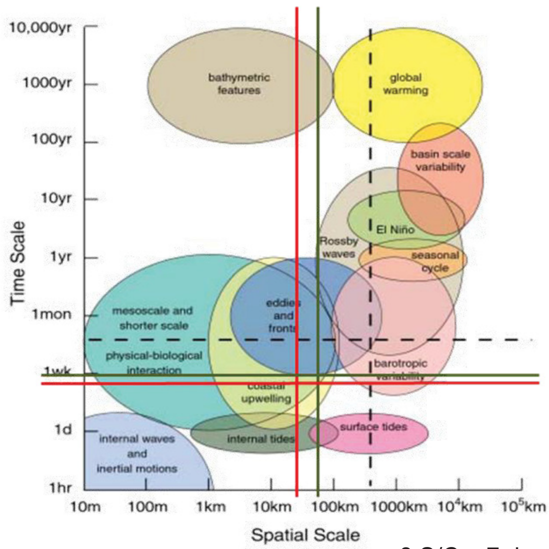
5. CONSTELLATION DESIGN AND MISSION ANALYSIS

The constellation design and mission analysis were initiated using the identified requirements shown in Table 1. In the evaluation of each constellation the achievable temporal and spatial resolutions were used as the primary identifiers of the constellation's performance. For clarity the temporal and spatial resolutions have been defined.

Temporal resolution is the time it takes for the constellation to complete one full observation pattern.
Spatial resolution describes the distance between the ground tracks of the repeat cycle pattern

Throughout the analyses, particular focus has been placed on these two resolution parameters.

Figure 1, illustrates the different phenomena that can be measured based on varying temporal and spatial resolutions. The upper and lower ends of the initially investigated constellation range are indicated in green and red. As a Reference, the performance of a single satellite (in this case Topex/Poseidon) is presented by the black, dashed line.



----- T/P – 10 day   —— 8 S/C – 7 day

—— 22 S/C – 5 day repeat

Figure 1: Oceanography phenomena and CARA constellation performance, taken from [1].

5.1. Initial Analysis

A first analysis was based on multiple parameters e.g. number of satellites, repeat pattern, contact times, delta-v, and spatial and temporal resolution to determine a preliminary constellation performance figure of merit together with the individual impact of each parameter. It was found that the number of satellites is the main driver for the constellation performance because it is directly related to the temporal and spatial resolution, which is achieved by the constellation. Another main driver for the constellation design is the repeat cycle. The repeat cycle determines the observation grid. This parameter also drives the design optimisation to avoid undesired overlaps which reduce the constellation performance in terms of spatial resolution. The repeat cycle was tuned to enable mesoscale phenomena to be characterised (Table 1).

Based on an initial assessment the number of satellites required for a particular spatial and temporal resolution was determined and can be seen in Table 2. A better understanding of the relationship between spatial and temporal resolution and the impact of these parameters on the constellation design can be obtained through the following table.

Table 2: Initial estimation of satellites required for particular spatial and temporal resolution

Number of satellites estimate				
		Temporal Resolution		
		10 days	7 days	5 days
Spatial Resolution	500 km	1	1	2
	100 km	3	4	6
	50 km	6	8	11
	25 km	11	16	22

Following this analysis the focus of the study became optimising a constellation for the Core Service. It is assumed that other missions such as Jason-3 follow-on will provide the Reference Service. Five constellation scenarios comprising 8, 10, 12, 14, and 16 satellites were proposed using the following orbital parameters:

- One orbit plane
- Inclination of 84°
- Altitude between 620 and 670 km
- Repeat cycle of 5, 7, or 10 days

The inclination of 84° was selected as a compromise between several observation and mission requirements.

The performance of each proposed constellation scenario has been then further assessed with a primary focus on spatial resolution. In addition, both the delta-v and ground station visibility needs were used to evaluate each constellation; however these were secondary criteria and will not be expanded upon in this paper.
The spatial resolution was evaluated at three latitudes, 0°, 30° and 60°, to provide a figure of merit. Latitudes higher than 60° were not evaluated due to orbital convergence. Table 3, shows a summary of

the achievable spatial resolutions for a repeat cycle of 7 days. These results show that the general trend is the greater the number of satellites in the constellation, the better the spatial resolution achieved.

Table 3: Feasible spatial resolutions for 7 day temporal resolution scenario

7 day repeat cycle			
No.S/C	Equator [km]	30° [km]	60° [km]
4	98	66	25
8	50	24	21
10	40	32	17
12	32	20	11.5
14	14.5	25	11.5
16	24	20	12.5

These results were discussed with oceanographers in order to refine future analyses and to determine priorities with respect to constellations capabilities. Upon the evaluation of the initial results, it was found that increased temporal resolution was a major priority compared to increased spatial resolution. It was indicated that most mesoscale oceanographic observations can be performed with a spatial resolution of around 50 km. A constellation improving only the spatial resolution further without improving the temporal resolution was seen to be less beneficial. Hence, the main focus of further analyses was placed on increasing the temporal resolution for a fixed spatial resolution.

5.2. Analysis Iteration

It was established in the first part of the study to focus on providing the *Core* service comprising satellites which would provide a fixed spatial resolution and a greatly improved temporal resolution. For the further analysis the spatial resolution was fixed to about 50 km, enabling mesoscale observations.

Taking into account the selected inclination and the preferred altitude range the shortest repeat cycle that could be utilised is 3 days (with all satellites placed in one orbital plane). Using one orbit plane linked the achievable temporal resolution to the repeat cycle duration. If more than one orbit plane is used, the variety of achievable temporal resolutions significantly increases. The constellation analysis included up to two additional orbit planes. Assuming equally populated orbit planes with equal satellite phasing, the second orbit plane leads to an increase in the temporal resolution by a factor of 2. Using a 5 day repeat cycle orbit, with 2 planes results in a temporal resolution of 2.5 days. The same number of satellites in one orbit plane would have a temporal resolution of 5 days but could provide a spatial resolution of about 25 km.

Launch strategies were also assessed which included the analysis of many launchers. The Soyuz launcher was identified as the baseline launcher due to its fairing size and cost considerations. Taking into account the preliminary satellite design, up to 6 satellites could be launched together. The number of satellites in the constellation should thereby ideally be a multiple of 6 including potential spare satellites. Constellations with fewer satellites per plane were also assessed presenting the achievable performance when some satellites are used as spares, filling gaps only. Figure 2, provides a visual representation of a constellation with 24 satellites in 2 planes. The constellation uses a 5 day repeat cycle and provides a spatial resolution of 50km with a temporal resolution of 2.5 days. Although 12 satellites per plane are used, only 11 satellites per plane are required to achieve this performance.

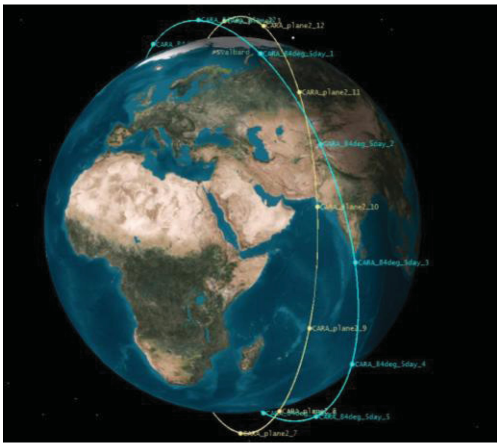


Figure 2: Orbital view of 24 satellites, 5 day repeat cycle, 2 planes

The ground track of the constellation is important to ensure the spatial resolution of 50 km is achieved. This can be seen in Figure 3, for the 24 satellite constellation with a 5 day repeat cycle with 2 orbit planes. The figure shows the ground tracks after 2.5 days. The first plane is shown in blue while the second plane is shown in yellow. The upper half of the figure shows the ground tracks of first orbit plane, the lower half the combined ground tracks of both orbit planes.

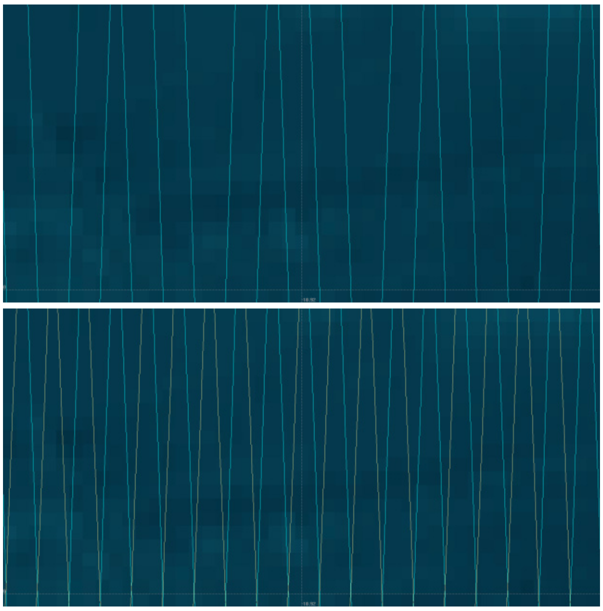


Figure 3: Ground tracks of 24 satellites, 5 day revisit, with 1 plane (top) and 2 planes (bottom) after 2.5 days

The first step in the selection of candidate orbits was identifying the orbit to represent each repeat cycle for the constellation analysis. The inclination and altitude limitations used for the 5 constellation scenarios in the initial analysis were also used in determining the appropriate orbits for the consequential analysis. The repeat cycles investigated in the constellation optimisation used temporal resolution requirements for large and mesoscale measurements as a guideline, Additional repeat cycles were considered yielding higher and lower values than the temporal resolutions used for the initial analysis. In Figure 4, the vertical red lines indicate the altitude limits proposed in the initial analysis, and the red circles indicate the selected orbits. The y-axis represents the repeat cycle of the orbit.

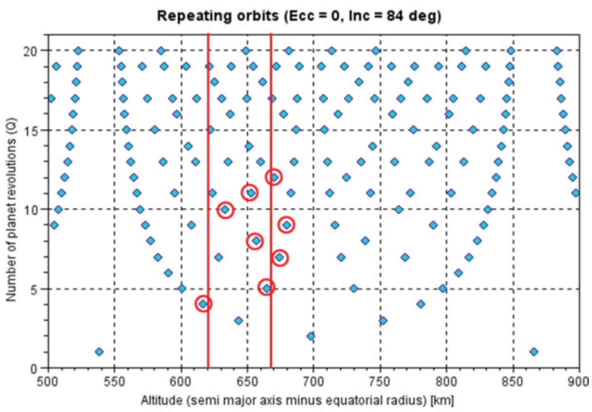


Figure 4: Orbits selected for consequent analysis

The analysis examined 17 different constellations consisting of 6 to 28 satellites with orbital repeat cycles ranging from 4 to 12 days providing temporal resolutions between 2 and 12 days for the baseline spatial resolution of 50km. Of the 17 constellations examined only 9 were deemed feasible, and 4 as potentially feasible requiring additional effort (e.g. different launch scenario). The primary factor making many of the options obsolete is the number of satellites per plane.

The **established baseline** is a constellation of 12 satellites in one orbit plane providing 50km spatial resolution with a temporal resolution of 5 days.

6. SATELLITE DESIGN

The starting point for the satellite design is the low earth orbit satellite platform designed by OHB-System called LEOBUS-1000. The LEOBUS-1000 is a development combining >19 years of accumulated in-orbit heritage gained with the 5 SAR-Lupe satellites with design improvements from the EnMAP and Galileo programmes.

The platform is designed for Earth observation missions in the 600 to 1300kg class and is exceptionally suited for deployment in constellations. Cost efficiency is achieved by the modular configuration design approach of the platform which easily allows the accommodation of the altimetry instrument suite comprising the altimeter, microwave radiometer and associated instrumentation. The platform is equipped with a high data rate payload processing chain including storage and downlink subsystems, which meet the system needs.

Although the satellite design is based on the LEOBUS-1000, additional design drivers must be considered for the detailed development of the platform. The main drivers of the payload accommodation and satellite design are:

- Dual/multi-launch capabilities
- Payload SAR mode (data volume)
- Electrical Power System (EPS) concept

6.1. Payload Description

The payload for GMES-CARA is a Sentinel-3 like altimetry payload suite. It consists of a SRAL like SAR radar altimeter, microwave radiometer (MWR) and a precise orbit determination (POD) package with a GNSS receiver and a laser retro-reflector (LRR). The accommodation of the payload on the satellite has all components excluding the GNSS on the bottom of the spacecraft facing the Nadir direction, which can be seen in Figure 5. A summary of the payload and its components is provided in Table 4.

Table 4: Payload summary

Payload Summary			
	Mass (kg)	Avg. Power (W)	Dimensions (mm)
Altimeter	65	110	Ø1258, 626 (antenna)
MWR	30	33	620, 670, 1460
GNSS	9	22	150, 110, 170 (antenna)
LRR	1	-	Ø 200, 100 (antenna)
TOTAL	**105**	**165**	

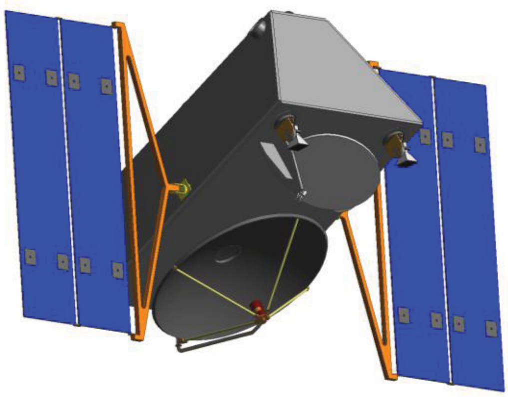


Figure 5: Payload accommodation

The dual frequency altimeter is operating in the C- and Ku-Band. The Ku-Band is used for the surface height measurements and the C-band is used for ionosphere corrections. The purpose of the Microwave Radiometer is to measure atmospheric humidity along the radar propagation path. It uses two NIR channels and enables the calculation of the tropospheric path correction of the altimeter signal. Very precise orbit altitude information is required for radar altimetry. To satisfy this demand the Precise Orbit Determination (POD) package assumed for the constellation consists of a geodetic grade quality (miniaturised) GNSS Receiver and a Laser-Retro-Reflector.

6.2. Platform Description

As noted previously the need for dual/multi-launch capabilities was a major design driver for the satellite structure design and accommodation. As such the structure of the LEOBUS-1000 platform was examined to determine which structural approach and accommodation would be optimal for the GMES-CARA mission. It was decided to use a completely customized structure.
Not only for structure, but for many subsystems various trade-offs were performed resulting in the following baseline design, detailed in Table 5.

Table 5: Satellite Baseline and key figures

Subsystem	Concept	Achieved Performance
Structure	New design, using shear webs as main structure	*Platform Mass:* 440 kg
DHS	COTS OBC *(LEOBUS-1000 standard)*	
TT&C	2 S-band transponders 2 S-band antennas (omni directional) Recorded HKTM will be multiplexed with payload data and downlinked in X-band (nominal conditions).	*Uplink/Downlink Data Rate:* 4/128 kbit/s
EPS	Solar array with SADM Li-Ion battery	*Avg. Power generated* 900 W
PDHT	Isoflux antenna with SSPA or TWTA X-band transmitter Payload Data handling unit (PDHU)	*Data Rate:* 80 to 260 Mbit/s (dependant on payload operation approach) Mass Memory >500Gbit
Propulsion	Monopropellant (Hydrazine) 2x 1N thrusters Sized for orbital corrections to maintain a ground track repeat within 1km.	*Propellant Mass:* 25 kg
AOCS	3-axis stabilised S/C *Sensors:* Star trackers Coarse gyros Sun sensors Magnetometers *Actuators:* Reaction Wheels Magnetic Torquers	Gyro free attitude determination Nadir pointing

6.3. Launch Considerations

The launch considerations for GMES-CARA are strongly influenced by the desire to have multi-launch capabilities to reduce the cost of the launch segment and reduce the lead time for the Core Service data provision.

A preliminary launcher analysis was performed with the baseline satellite design, and the initial 5 constellation scenarios that were determined in the initial analysis. The analysis was completed with the assumption that the satellite would have a mass of less than 600 kg and the shape indicated in Figure 5.

Initial analysis showed that using the Soyuz launcher provided the best results with respect to the cost/performance ratio, and therefore was selected as the baseline launcher. The selected back-up launcher to the Soyuz is the Falcon-9.

With the Soyuz selected as the baseline launcher, 6 satellites can be launched into orbit at a single launch. Two launch adapter options were evaluated. The first of the two options utilising a central hexagon adapter in a 3+3 configuration is depicted in Figure 6. A central cone/octagon adapter in a 4+2 configuration is the second option.

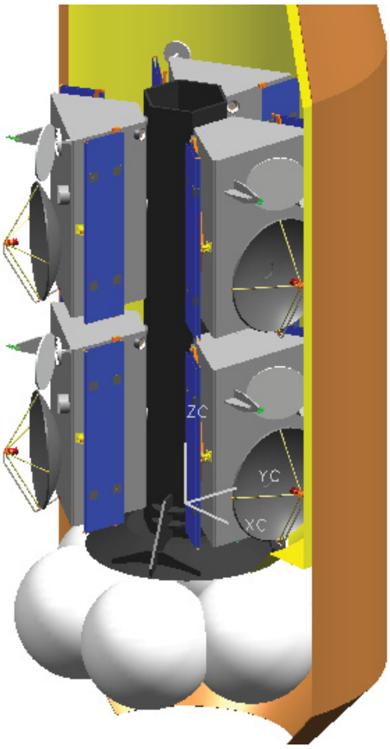


Figure 6: Soyuz fairing with 3+3 satellites launch configuration

7. CONCLUSION

Satellite Radar Altimetry for Oceanography is an important information source for ocean and climate modelling as well as for operational (sea) weather forecast services. Climate change requires an improved understanding of the climate and oceans. This study evaluates the feasibility of using a small generic satellite platform for a dedicated satellite constellation for radar altimetry. The study scenario timeframe is set for a launch date around 2020, after the currently under development Sentinel-3 satellites. OHB-System's baseline proposal is a multi-launch satellite to be launched with the Soyuz. This is well suited for this mission, as its offers a cost-effective means to launch the baseline constellation which will offer a spatial resolution of 50 km.
The baseline constellation will be 12 satellites on a 5 day repeat cycle. With this baseline constellation GMES-CARA is able to provide 50 km resolution in 5 days.

8. REFERENCES

[1] College of Oceanic and Atmospheric Sciences. (2001). *Report of the High Resolution Ocean Topography Science Working Group Meeting.* Retrieved from http://www-po.coas.oregonstate.edu/research/po/research/hotswg/HOTSWG_report.pdf