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AltiCube+

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#### AltiCube+: A Low-Cost Long Fixed-Baseline Radar Altimeter Solution Based On CubeSats On-Orbit Assembly

# Jian Guo<sup>a\*</sup>, Peter Hoogeboom<sup>b</sup>, Paco Lopez Dekker<sup>c</sup>, Jasper Bouwmeester<sup>d</sup>, Gabriele Meoni<sup>e</sup>, Jose Nieto<sup>f</sup>, Juan Fayos<sup>g</sup>, Eric Bertels<sup>h</sup>, Camille Pirat<sup>i</sup>

<sup>a</sup> Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, <u>j.guo@tudelft.nl</u>

<sup>b</sup> Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands, <u>P.Hoogeboom@tudelft.nl</u>

<sup>c</sup> Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands, <u>F.LopezDekker@tudelft.nl</u>

<sup>d</sup> Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, jasper.bouwmeester@tudelft.nl

<sup>e</sup> Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, <u>G.Meoni@tudelft.nl</u>

<sup>f</sup> COMET Ingeniería, Calle Convento Carmelitas, 2, 46010 Valencia, Spain, <u>inieto@comet-ingenieria.es</u>

<sup>g</sup> COMET Ingeniería, Calle Convento Carmelitas, 2, 46010 Valencia, Spain, <u>jfayos@comet-ingenieria.es</u>

<sup>h</sup> ISISpace, Motorenweg 23, 2623 CR Delft, The Netherlands, <u>e.bertels@isispace.nl</u>

<sup>i</sup> CubeSat Systems Unit, European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, <u>camille.pirat@esa.int</u>

\* Corresponding Author

#### Abstract

Radar interferometry can be used to obtain sub-kilometer resolution over a swath at the expense of additional transmit power and a sufficiently long baseline to accommodate at least two antennas. This paper reports an innovative concept called AltiCube+, a low-cost long fixed-baseline interferometric radar altimeter based on CubeSats on-orbit assembly. The AltiCube+ concept consists of multiple 16U CubeSats. After an early operation and commissioning phase, these CubeSats will perform autonomous rendezvous and docking with each other via deployable booms to establish a long fixed-baseline, and then deploy antennas for an interferometric altimeter configuration. The uniqueness of AltiCube+ is on the potential scientific opportunities brought by two left and right looking interferometric altimeters with around 6 meter baseline (total system length is more than 8 m) and the sustainability due to its significantly low cost and short development lifecycle. If budget allows, multiple AltiCube+ systems with same or different altimetry capabilities can form a constellation to dramatically reduce the revisit time and, therefore, provide much better spatiotemporal coverage.

Keywords: Radar interferometry, radar altimeter, CubeSat, on-orbit assembly

#### 1. Introduction

Radar interferometry can be used to obtain subkilometre resolution over a swath at the expense of additional transmit power and a sufficiently long baseline to accommodate at least two antennas. For each range bin in the interferometry mode, the phase difference between the two channels determines the direction where the received signal comes from. Then, the range of this signal is used to determine the actual height of the reflecting point. An error in the phase difference between the two channels will result in a location error. This can be considered as the cross-track resolution of the interferometer. A further development of the "conventional" interferometer is the SAR Interferometer (SARIn) [1], which performs synthetic aperture processing and uses a second antenna as an interferometer to determine the cross-track angle to the

earliest radar returns. The combination of SAR (Synthetic Aperture Radar) and interferometry makes it possible to accurately determine the arrival direction of the echoes both along and across the satellite track, by comparing the phase of one receive channel with respect to the other. SARIn technology was first demonstrated on NASA's Shuttle Radar Topography Mission (SRTM) by deploying two C/X-band SAR antennas on the two ends of a 60-meter mast, then used on the CryoSat-2 as a Ku-band SIRAL (SAR/Interferometric Radar ALtimeter) with 1-meter antenna baseline [2].

A remarkable mission using SARIn is the KaRIn (Ka-band Radar Interferometer) aboard the SWOT (Surface Water and Ocean Topography) satellite [2], which was launched in Dec 2022 and represents the state-of-the-art in radar altimetry. The SWOT satellite accommodates two 5-meter long radar antennas with a

10m baseline, resulting in a spatial resolution of 1km for the ocean and 100m for inland water, both at Ka-band. The development of such a satellite took 15 years and more than one billion dollars [3]. Lower frequency altimeters would need a baseline of tens of meters (for example around 60m for C band), which is extremely difficult for one monolithic satellite, if not impossible. These difficulties makes it unlikely that oceanographers will ever get a much wanted high spatiotemporal revisit rate. However if the cost of a single altimeter can be significantly reduced, then launching multiple systems to obtain a constellation with good spatiotemporal coverage could overcome the problem.

To this end, considering the successful RainCube satellite (a 6-unit CubeSat with Ka-band precipitation profiling radar) [4], a distributed CubeSat swarm forming a long baseline seems a low-cost alternative. However, a previous ESA study AltiCube already concluded that a distributed interferometric swarm for cross-track measurement would require extremely high accurate time/attitude synchronizations and centimetre level formation maintenance, which is not easier than building a large monolithic satellite [5].

To address aforementioned challenges, an innovative concept called AltiCube+, a low-cost fixed long baseline radar altimeter solution using an aggregated CubeSat swarm, is proposed to realise a baseline close to 10-meters with almost two orders of magnitude lower cost than the SWOT satellite. This fixed long baseline will open new opportunities for radar altimetry.

In addition, AltiCube+ provides a flexible system that can use different mode for different targets. Observations of inland and coastal water levels are often contaminated by bright targets. Using beam-forming the signals from surrounding targets can be suppressed, which would lead to an increase of valid measurements and a reduction of range errors. Over ocean surfaces beamforming helps to separate signals from left and right of the altimeter ground track, which would help to retrieve wave properties. Over land ice, AltiCube+ can be used as an interferometer to compensate for crosstrack slopes that would introduce height errors in nadir altimetry. Eventually, AltiCube+ opens the road to increased baselines, which improves the sensitivity to height.

AltiCube+ does not intend to compete with or even replace SWOT since the latter one is much more powerful from many perspectives. The uniqueness of AltiCube+ is on the potential scientific opportunities brought by the fixed long baseline (close to 10 m and above) and the sustainability due to its significantly low cost (~20 MEuros) and short development lifecycle (3 years for IOD, In Orbit Demonstration). If budget allows, multiple AltiCube+ systems with same or different altimetry capabilities can form a constellation to dramatically reduce the revisit time and, therefore, provide much better spatiotemporal coverage. In this way, AltiCube+ can be seen as a complement to big altimetry missions.

This concept has been selected by ESA through the Open Space Innovation Platform (OSIP) campaign 'Innovative Mission Concepts Enabled by Swarms of CubeSats' and it has been performed by an European consortium led by TU Delft, in cooperation with Isis Space and Comet Ingeniería. The feasibility study has just been completed, and this paper will report the study results.

This paper consists of 9 sections. After the introduction, Section 2 summarizes objectives and high level requirements. According to these requirements, two aggregated configurations based on the AltiCube+ solution are proposed in Section 3. The system performances and a trade-off of the two configurations are described in Section 4, followed by system specifications and Concept of Operations in Section 5. Use these as inputs, Sections 6, 7 and 8 provide designs on three key technologies, i.e. deployable structure, autonomous assembly, and highly capable CubeSat platform. Last but not the least, conclusions including future work are presented in Section 9.

# 2. Objectives and requirements

The high level requirements of the AltiCube+ concepts are driven by its objectives.

# 2.1 Objectives of AltiCube+

The AltiCube+ has main objectives on scientific and technological aspects:

• The scientific objective is to provide a low-cost fixed long baseline radar altimeter solution based on aggregated CubeSat swarm for water-level monitoring of coastal zones and inland water bodies. Observation of sea-surface height and wave heights in the nearshore is important to understand coastal dynamics, sediment transport and potential hazards in case of extreme events. Levels of inland water bodies provide information for run-off modelling, water resource monitoring, flood and drought prediction. Based on the AltiCube+, a promising low-cost observation capability of subkilometre cross-track resolution will be validated. Given the low-cost mission set-up, successful implementations could be expanded in the future to a global constellation for unprecedented spatiotemporal coverage.

• The technological objective is to demonstrate and promote the relevant technologies to enable future aggregated swarm satellite missions. The AltiCube+ mission poses great technological challenges on various aspects of aggregated swarm systems and, on the other side, also provides a unique opportunity of tackling these challenges. The state-of-the-art in deployable structure, autonomous assembly, highly capable CubeSat platform and others will be further developed, engineered and demonstrated through this mission. This will also open the door for broader applications in future swarm satellite missions.

## 2.2 High level requirements

The high level requirements consist of two major parts: the altimeter data product requirements and the system constraints.

## 2.2.1 Altimeter data product requirements

For the AltiCube+ study, two application areas are foreseen: oceans and hydrology (inland water). Since the SWOT mission also covers these two applications, it makes sense to use the Science Requirements Document of SWOT as one of the references to derive requirements on data products of AltiCube+ [6]. However, the AltiCube+ mission has to deal with limited energy, volume, data processing capability and cost level. Hence it is preferred to stay close to the minimum user requirements as threshold, but try to surpass them wherever possible.

According to above discussions, the most important requirements of AltiCube+ altimeter product are summarized in Table 1 and used as guideline in the remainder of this document.

## 2.2.2 System constraints

The following system constraints have been posed by ESA:

1) Number of CubeSats: a swarm should consist of at least 4 CubeSats (a lower number shall be fully justified) and maximum number needed to meet mission requirements & cost constraints

2) Spacecraft volume: CubeSat standard up to 16U (stowage volumes compatible with European deployers)

3) Total spacecraft wet mass: <32 kg

4) Deployer: European solutions accommodating CubeSats of up to 16U form factor including available stowage volumes(tuna cans, above CubeSat body etc), additional electrical/data interfaces may be considered

5) Space debris: compliance with ESA Space Debris Mitigation requirements

6) Overall ROM cost: less than  $\notin 100$  million for definition, implementation, launch, and operations (first 3 years in case of longer lifetime), including carrier vehicle/mothercraft (if any).

# 3. Aggregated configurations and their principles

Two aggregated configurations are developed based on the high level requirements. One is an off-nadir SARIn called MiniSWOT and the other one is a Multiple-Input and Multiple-Output (MIMO) called MIMOSARAL.

# 3.1 Configuration I: MiniSWOT

The MiniSWOT interferometer is a side-looking radar imaging instrument. The imager produces a twodimensional radar map of the ground with a swath width in the order of tens of kilometres. A second antenna separated by a suitably chosen and well defined baseline from the first antenna produces a similar image. The cross-track baseline between the antenna phase centres ensures phase differences occur that for each resolution cell that are a function of the relative position of the scattering surface and the platform. The range and phase differences are used to determine the height of a target.

The MiniSWOT consists of 5 nodes (satellites), two nodes operating an interferometer observing a swath on the left side, two other nodes observing the right side and a central unit for control, data processing and downlink, see Fig. 1. The antennas are pointed in crosstrack direction at small angle away from nadir, in the order of 2-4 degrees. The nodes can be fully identical if the cross-track pointing can be selected in the satellite, either by mechanical or electronic means. Electronic control (beam steering) seems the best solution as it allows fine tuning of the beams during the mission. Both interferometers can have a baseline of 6 meter, if each satellite carries a boom that can extend to 2 meter. The final dimensions have yet to be selected. Longer baseline improves the performance by a square law. However, the space for storing deployable booms on a 16U CubeSat is very limited, ruling out very long ones.

A central node in the middle of the configuration takes care of controlling the interferometers (e.g. transmit timing and parameter setting), measurement data collection, on-board data processing and data downlink. The exchange of data and control information between the central unit and the nodes should be done over a Wi-Fi network or with wired connections if possible. The MiniSWOT interferometers need real time ranging information and PRF (pulse repetition frequency) setting for their operation. This can indeed be provided by the central node if it is equipped with GPS (Global Positioning System) and has a DEM (digital elevation model) available. A very precise time and trigger signal needs to be distributed by the central node to the radar nodes to synchronise the master oscillators.

The MiniSWOT can operate in various modes, e.g. a burst mode and an interleaved mode, by switching software in orbit. In both modes there is a choice of pulse transmission plans, enabling monostatic and bistatic operation. Unlike the SWOT system, in MiniSWOT each node has a transmitter and a receiver, allowing monostatic operation (in this case the 2 radar nodes of the interferometer use their own transmitter to make a measurement almost simultaneously). The advantage of monostatic operation is a two times better height accuracy compared to bistatic operation with a single transmitter. So, where SWOT uses 10-meter baseline, MiniSWOT could obtain the same height sensitivity with 5-meter baseline.

A very first analysis reveals specific advantages of the MiniSWOT configuration:

1) Contrary to SWOT, MiniSWOT has two separate interferometer systems, which both can look left and right of nadir. Each system has two transmitters, one in each node. A failure in a transmitter leads only to graceful degradation, not to a complete malfunction.

2) The height error in MiniSWOT is efficiently reduced by using monostatic observations which perform a factor 2 better than the bistatic operation as used in SWOT. Moreover, the use of all transmit/receive combinations improves the height accuracy by a factor up to 2.5 compared to single transmitter bistatic operation.

3) MiniSWOT operates at Ku-band with a moderate transmit power (15 W peak per transmitter as compared to 1500 W for SWOT), which greatly reduces the cost of the system.

# 3.2 Configuration II: MIMOSARAL

The MIMOSARAL is a MIMO SAR altimeter, which combines two techniques to realize a swath altimeter with high resolution in along-track and crosstrack direction: SAR processing ensures a high alongtrack resolution, the MIMO enhances cross-track discrimination and removes the left/right ambiguity.

The MIMOSARAL consists of several altimeter satellites, e.g. four to nine, and a control satellite connected by booms. More altimeters lead to a better quality of the MIMO antenna pattern, but lead to an abundance of data, which can probably not be processed on-board to a reduced dataset without precise calibration. Fig. 2 shows a schematic drawing for a Kuband 4 node system (not to scale).

Each altimeter operates as a normal altimeter, the designs are very similar to the AltiCube in this case [RD8]. The control node takes care of synchronizing the measurements, gathering and processing the data from the altimeters and data downlink to the ground. The altimeters have SAR capability, therefore the resolution in the flight direction (perpendicular to the paper plane in Fig. 2) is high, but quite limited in cross-track direction.

The number of altimeters in the MIMO can vary. In this study between 3 and 9 nodes were analysed. The length of the complete system depends on frequency and on the number of nodes. For this study, sizes between 1 and 8.7 meter at Ka-band have been analysed, corresponding to lengths between 2.8 and 23 meter at Ku-band. The distances between the altimeters are not equal, and chosen such that the phase centres form an optimal distribution over the aperture. Like in other altimeters and in the MiniSWOT, two SAR operating modes are foreseen: Burst SAR mode and Interleaved SAR mode. In principle the altimeter could also work in the traditional LRM (Low Resolution Mode), but it will lose its MIMO capabilities. In both modes there is a choice of pulse transmission plans.

The MIMOSARAL configuration shows several specific advantages:

1) MIMOSARAL is a unique system that combines the advantages of several techniques to a high resolution and accuracy in three dimensions.

2) MIMOSARAL is scalable, it can start off with a small configuration and be extended with more nodes later on.

3) MIMOSARAL requires very modest peak transmit powers as it makes measurements in the incidence angle range with the highest backscatter.

## 4. Performance analysis and trade-off

A winning configuration shall be selected for further design. To this end, the system performances of the two configurations are analysed, followed by a trade-off. Details of the analysis and trade-off can be found in [7], and in this paper only a summary is provided.

# 4.1 Performances of MiniSWOT

An end-to-end implementation of the formulas that determine the performance of the MiniSWOT system in various conditions forms the basis for the design and the optimization thereof. In Section 3.1, burst mode operation and interleaved operation were introduced. Interleaved operation is preferred for situations that require high resolution. The continuous SAR observation in this mode allows very high SAR resolution. It is well suited for inland water observations. On the contrary burst mode has more limited SAR resolution but can deliver the height accuracy needed for ocean observation with a relatively low seizure on energy and data storage. Hence, burst mode is well suited to observe oceans.

For both modes a spreadsheet is used to calculate and optimize the performance. Selected results for three different systems with two modes of operation are shown in Table 2. For each system the burst-mode performance and the interleaved mode performance are calculated and optimized. For the two modes the same hardware is assumed, only operating parameters are changed. One system design operates at Ku-band, the other two at Ka-band.

Based on Table 2 the preference is for a Ku-band system, rather than a Ka-band one. The obtained specs of the instruments are comparable. The Ka-band technology performs less stable, e.g. phase noise and drift of oscillators will be higher, reducing integration gains. Losses are higher, both in the instrument and in the atmosphere. Moreover, backscatter values are slightly lower. Ka-band technology is much more expensive and puts more stringent requirements on the antenna surface accuracy, and on many other aspects of the system. Ku-band therefore seems to be the better choice. Ku-band may experience a little more ionospheric delay influence, but MiniSWOT is designed to observe height differences, not to obtain accurate absolute height values.

## 4.2 Performances of MIMOSARAL

For MIMOSARAL, the analysis has two aspects that can be separated: the design of the MIMO, and the design of the altimeter used in the nodes. Based on Section 3.2 MIMO could have 3 to 9 nodes working at Ku or Ka bands. This results in many options. The performances of the most interesting options are summarized in Table 3.

The obtained specs of the instruments are comparable with only small differences. The Ku-band system requires less transmit power and has the best orbit duty cycle for raw data downlink. The 8 node Ka band system has the best MIMO cross-track resolution.

In general Ka-band technology performs less stable, e.g. phase noise and drift of oscillators will be higher, reducing integration gains. Losses are higher, both in the instrument and in the atmosphere. Moreover, backscatter values are slightly lower. Ka-band technology is much more expensive and puts more stringent requirements on the antenna surface accuracy, and on many other aspects of the system. On the other hand the Ka-band systems have more potential for expansion, the 8- and 9-node systems are only feasible with Ka-band. Moreover Ka-band was also the choice for the AltiCube.

Ku-band may experience a little more ionospheric delay influence, but MIMOSARAL is designed to observe height differences, not to obtain accurate absolute height values. For that it would need additional instruments, like radiometers, more accurate orbit determination and possibly a multifrequency altimeter.

#### 4.3 Trade-off

A trade-off based on the criteria derived from high level requirements was implemented, and the results are shown in Table 4. Several options from Table 2 and Table 3 have been omitted since they have similar performance and complexity compare with others.

From Table 4, first of all, the MIMOSARAL concept working at Ka-band is excluded, because it does not have the capability to provide acceptable cross-track resolution over inland water. In addition, the limited swath and the high number of CubeSats indicate high costs for achieving good revisit time even when multiple systems are utilised. MIMOSARAL @ Ku-band is also not preferred as cross-track resolution, the most important performance, and the swath are not

acceptable for hydrology applications. Its complexity and costs cannot justify the performance. The two options of the MiniSWOT concept both have superior performance to the MIMOSARAL concept. The Kaband MiniSWOT has slightly better accuracy, but the very high power demanding and expensive Ka-band radar transmitter makes it less preferable than the Kuband MiniSWOT. Therefore, the MiniSWOT working at 13.6 GHz is selected as the baseline for further study.

## 5. Mission specifications

Like any other space system, the design of AltiCube+ is an iterative process. After the trade-off and the selection of MiniSWOT, further analysis and designs have been implemented in various work packages, which influence each other. As a consequence, it was evident that the MiniSWOT design needed a minor update to make sure it is optimally adapted to the mission and the science requirements. It has been carefully checked and confirmed that this update does not change the trade-off result. In this chapter, the updated MiniSWOT design will be described. Based on this updated design, the Concept of Operation (ConOps) will be discussed.

# 5.1 Updated design and specifications

The most important changes that are incorporated in the MiniSWOT updated design include:

• Increased measurement baseline length from 6 m to 6.6 m due to change in platform orientation.

• Beam-steering for each node in the range from -4 to -2 and +2 to +4 degrees. Beam-steering was already proposed in the original design but has afterwards been explored in more detail.

• Decreased orbit height from 600 km to 500 km due to new regulations.

• Antenna effective cross-track size decreased to 50 cm, to widen the antenna beam to relax the requirements on attitude and deformations.

• Increased height accuracy margin to fulfil the height accuracy requirement in case of antenna misalignment in along-track) up to 10% of the beamwidth (0.11 deg)

• Transmit power increased to 15 W to accommodate for the wider cross-track beam.

The updated key specifications of the AltiCube+ can be found in Table 5. The complete system sketch can be found in Fig. 3.

# 5.2 Concept of operations

The Concept of Operation (ConOps) is established from initial orbit deployment until post-mission disposal, divided into 4 stages:

# 5.2.1 Stage 1: LEOP

The five CubeSats will be launched into the same orbital plane by the same launcher. The baseline orbit is 500 km SSO. All the five CubeSats have 16U form factor, and are ejected into orbit from standard deployers (Quadpack 16U of ISISpace as baseline). According to the deployment sequence, the five CubeSats are numbered from Sat#5 to Sat#1. Among them, Sat#1 and Sat#4 are right-looking ones, Sat#2 and Sat#5 are left-looking ones, and Sat#3 is the central node for data processing and downloading. Therefore, the four side-looking CubeSats are almost identical, except for slightly different antenna/feed angles. Once deployed from the Quadpack, the five CubeSat will start commissioning with free drift of orbital phases. During the Launch and Early Operation (LEOP), the booms and altimeter antennas will remain stowed.

#### 5.2.2 Stage 2: In-orbit assembling

After commissioning and early operation (including necessary orbit maintenance), the five CubeSats will have kilometre level along-track distance one by one. Then Sat #1 deploys a boom with a docking mechanism installed at the tip, followed by Sat #2 performs autonomous RVD (Rendezvous and Docking) with Sat #1 from behind (Fig. 4(a)). Sequentially, Sats #3, #4 and #5 dock with assembled body, respectively (Fig. 4(b)). It should be noticed that the option to have docking before the boom deployment is not excluded and can be changed if needed.

After finishing all the docking operations, the assembled aggregated system will have a 90-degree yaw attitude manoeuvring from along-track to cross-track direction (Fig. 4(c)), followed by the deployment of radar antennas from the CubeSats (Fig. 4(d)).

# 5.2.3 Stage 3: Scientific operation

After assembling, the scientific payloads, i.e. the radar transmitter and antenna on each satellite will have tests, followed by scientific observation.

During scientific observation, raw data generated by each altimeter CubeSat (i.e. #1,2,4,5) and a first processing step at each node will applied to reduce the data rates without losses. This data is transmitted to the central node (#3), using an inter-satellite link, for centralised onboard data processing. Housekeeping data will also be exchanged between satellites. In this way, the Onboard Computer (OBC) of the central node will work as the central OBC of the whole system, and the AOCS (Attitude and Orbit Control System) unit of the central node will manage the attitude sensors and actuators distributed on the five CubeSats. The preprocessed data will be stored in the data storage unit of the central node, and then downloaded by the high datarate transmitter to the ground station when the latter is in the range. Since the altimeter requires extremely stable thermomechanical behaviour of the boom, it will

not work during the minutes following the transition period between sunlight and eclipse.

## 5.2.4 Stage 4: Decommissioning

At the end of the mission lifetime, to speed up the decay and re-entry, the assembled system will use the remaining propellant of the propulsion system to perform a manoeuvring to reduce its altitude. A 90 degree pitch attitude manoeuvring can also speed up the orbit decay by turning the antenna surface towards the opposite direction of orbital velocity to increase the assembled system's surface-drag ratio. At 500 km orbit, with the 90 degree pitch attitude manoeuvring only, the assembled system will have re-entry within 3 years, complies with the new regulations.

# 6. Deployable structures

Two kinds of deployable structures are used in this mission: deployable boom and deployable antenna reflector.

# 6.1 Deployable boom

The deployable boom is based on a repeated module composed of a platform and four folding legs. The length of the complete boom can be achieved varying the number of modules and/or the length of the legs. The latter also modifies the transversal section size, since the folded legs must not interfere each other.

The four legs of the module can be folded, collapsing its height. When all modules are folded, a large compaction ratio is achieved, which limits the volume needed to stow the boom.

A whole view of the main boom in deployed and folded configurations can be seen in Fig. 5.

# 6.2 Deployable antenna reflector

The deployable antenna reflector is composed of a deployable peripheral truss ring which, when deployed, tensions a cable net that, in turn, tensions a metallic mesh which conforms the reflecting surface. An adequate design of the cable net allows the mesh to take a faceted shape close to the ideal parabolic one. Fig. 6 shows the reflector in deployed and stowed configuration.

# 6.3 Deployable structure accommodation and deployment sequence

Fig. 7(a) shows the deployable structures stowed within each of the five CubeSats. Feed accommodation space is also shown.

The deployment sequence consists of the following steps:

- 1) Deployment of main boom and sliding of the reflector out of the reflector (Fig. 7(b)).
- 2) Deployment of the reflector and the boom holding the feed (Fig. 7(c)).

#### 7. Autonomous assembly

Autonomous assembly is the process of rendezvous and docking the five CubeSats together to construct the AltiCube+ assembled system for scientific operations later. Two aspects are considered in the study for autonomous assembly: the assembly operation, and the selection of RVD sensors/actuators.

#### 7.1 Assembly operation

The assembly operation consists of four RVD processes. A typical RVD process can be divided into four phases, i.e. phasing, close-range rendezvous, final approaching, and docking [8]. During the LEOP stage, the five CubeSats will maintain kilometres level along-track distance one by one. This indicates from GNC point of view, the assembling stage will start from close-range rendezvous directly, followed by final approaching and docking. However, the autonomous assembly is not only about GNC, but also about complex operations in sequence. Therefore, the assembly strategy shall consider the following aspects:

• Reduce the types of different platforms.

• Balance the propellant consumptions among platforms.

• Follow generic RVD operations (Fig. 8), but allow some differences.

• Performing final docking only along track.

• Speed up the assembly process for earlier scientific operation.

Based on the ConOps defined in Section 5.2 and these considerations, the assembly operation is defined in Fig. 9. Since the figure is self-explained, no further descriptions are needed.

#### 7.2 RVD sensors/actuators

The selected RVD sensors/actuators can be found in Fig. 10.

Two types of navigation sensors are required by AltiCube+: an advanced GNSS (Global Navigation Satellite System) receiver and a VBN (Vision-Based Navigation) system. The GNSS receiver not only works during RVD, but also works for science operation after docking. Therefore, its performance has to meet the strict scientific requirement of 5 cm. Considering the target is cooperative, a monocular camera with LED (Light-Emitting Diode) pattern system can provide enough navigation accuracy, which has been proved by simulations.

Two types of propulsion systems are used as actuators. One is with large thrust level for big maneuvers, and the other one is a Reaction Control System (RCS) to provide 6DOF small thrust for precise orbit control during final approaching and docking.

#### 8. Capable platform

The CubeSats of the AltiCube+ have very strong capability and, therefore, accommodating this capability into a 16U platform is challenging.

#### 8.1 Platform layout

Both external and internal views of the platform layout are shown in Fig. 11.

A few things should be noted:

• Adaptation of the standard 16U frame is necessary to accommodate both the payload deployable and main thruster.

• Plumbing towards the RCS thruster is not taken into account and should be considered in more detail.

• Following more detailed mission analysis, it may be possible to complete the mission using only RCS thrusters, meaning the main thruster may be dropped.

#### 8.2 Technical budgets

The mass budget is provided in Table 6. The mass of each node CubeSat is close to 18 kg, with enough additional margin available.

For the power consumption, four cases were analysed; safe mode, remote operations, proximity and docking operations, science operations. The four cases can be split into seven power modes. It was identified that the most power consumption-heavy day of a mission is during the science operation. Every orbit, this operation is assumed to consist of:

- 600 sec of downloading
- 720 sec of payload operations
- Remaining 4957 sec in nominal mode

The resulting per orbit average power consumption is 32.94W, as shown in Table 7. This is assuming a BCR and BDR efficiency of 90%. The power generated over the 5-year mission lifetime is also shown in the same table. Worst-case orbital average power generated is 35.94W. Compared to the 32.94W maximum orbital power consumption results in a 3.0W/9.6% power margin on the worst day.

#### 9. Conclusions

An innovative space system concept called AltiCube+, a low-cost fixed long baseline radar altimeter solution using an aggregated CubeSat swarm, has been proposed to ESA and reported in this paper. The uniqueness of AltiCube+ is on the potential scientific opportunities brought by the fixed long baseline (close to 10 m and above) and the sustainability due to its significantly low cost (~20 MEuros) and short development lifecycle (3 years for IOD, In Orbit Demonstration). If budget allows, multiple AltiCube+ systems with same or different altimetry capabilities can form a constellation to dramatically reduce the revisit time and, therefore, provide much better spatiotemporal coverage. In this way, AltiCube+ can be seen as a complement to big altimetry missions. The pre-Phase A study funded by ESA has proved the feasibility of this concept, and a follow-up Phase-A study is expected to kick-off at the end of this year. It is expected an IOD of AltiCube+ can be launched by 2027 and the full operational mission by 2029.

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Fig. 2. The MIMOSARAL configuration (an example for Ku-band with 4 altimeter nodes)





Fig. 5. Boom in deployed (left) and stowed (right) modes



Fig. 6. Reflector in deployed (left) and stowed (right) modes



(a) Deployable structures and feed accomendation within the CubeSat

(b) Main boom deployed, and reflector and feed's boom ready to deploy



Fig. 7. Deployable structure accommodation and deployment

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Fig. 8. Generic RVD process



Fig. 9. Autonomous assembly operations

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l'able	I AlfiCube+	altimeter	product	requirements	
I UUIU	1. I millouov	ununiterer	produce	requirements	

Application	SSH <sup>*</sup> accuracy	Resolution	Swath
Oceans	<2,5 cm (relative) @ 2x2 km	Final product resolution	20 km or better
	cells or better (1x1 km cells	2x2 km or better	
	preferred)		
Hydrology (inland	<10 cm @ 1x1 km	Al.track x cross-track	20 km or better
water)	<25 cm @ 0,25 x0,25 km	250x250 m or better	
		Cross track in the order of	
		500 m is OK if al.track is	
		better than 10 m	

\*SSH = Sea Surface Height

System type	Main applica- tion area	#satellites	System dimens. [m]	Boom length [cm]	Antenna aperture AI.Tr x Cr.Tr [m]	Peak transm power [W]	Swath width [km]	Height accuracy [cm] at product resolution AlTr x CrTr [m]	Best Ground resolution Al.Tr x Cr.Tr [m]	Range resol. [m]	Max. orbit duty cycle raw data	Max orbit duty cycle on board proc. data	Max. orbit duty cycle for energy 7,5 Wh	Remarks
MiniSWOT burst @ 13,6 GHz	Oceans surface slope	4 radars + 1 control	8	2	0,8 x 0,65	10	2*18 @ 15 km from nadir	2,3 cm NR, 1,3 cm MR 2,4 cm FR @ 2000 x 2000	220 x 500 NR, 220 x 313 MR, 220 x 228 FR	12,5	15,8%	>100%	16,5%	-Overlapping transmits -monostatic operation
MiniSWOT interl @ 13,6 GHz	Hydrology	4 radars + 1 control	8	2	0,8 x 0,65	10	2*20 @ 16 km from nadir	7,5 cm NR, 3,9 cm MR 9,6 cm FR @ 1000 x 1000	30 x 235 NR, 30 x 145 MR, 30 x 105 FR	6,25	1,9%	17,8%	9,0%	-bistatic operation with one transmitter
MiniSWOT burst @ 35GHz	Oceans surface slope	4 radars + 1 control	8	2	0,8 x 0,3	10	2*18 @ 15 km from nadir	2,1 cm NR, 0,9 cm MR 2,3 cm FR @ 2000 x 2000	84 x 500 NR, 84 x 313 MR, 84 x 228 FR	12,5	15,8%	>100%	16,5%	-Overlapping transmits -monostatic operation
MiniSWOT interl @ 35GHz	Hydrology	4 radars + 1 control	8	2	0,8 x 0,3	10	2*16 @ 20 km from nadir	5,9 cm NR, 3,0 cm MR, 5,6 cm FR @ 1000 x 1000	23 x 250 NR, 23 x 179 MR, 23 x 139 FR	8,3	2,9%	22,5%	8,7%	-bistatic operation with one transmitter
MiniSWOT burst @ 35GHz	Oceans surface slope	4 radars + 1 control	8	2	1 x 0,2	10	2*20 @ 15 km from nadir	2,1 cm NR, 1,3 cm MR 2,1 cm FR @ 2000 x 2000	84 x 500 NR, 84 x 301 MR, 84 x 215 FR	12,5	16,8%	>100%	16,5%	-Overlapping transmits -monostatic operation
MiniSWOT interl @ 35GHz	Hydrology	4 radars + 1 control	8	2	1 x 0,2	10	2*20 @ 16 km from nadir	6,0 cm NR, 3,7 cm MR, 5,6 cm FR @ 1000 x 1000	23 x 235 NR, 23 x 145 MR, 23 x 105 FR	6,25	2,3%	13,8%	8,9%	-bistatic operation with one transmitter

Table 2. Performances of selected MiniSWOT variants

Table 3. Performances of selected MIMOSARAL variants

System	Main	#satellites	System	Boom	Antenna	Peak	Swath	Height	Best Ground	Range	Max.	Max orbit	Max.	Remarks
type	application		dimens.	length	active or	transm	width	accuracy	resolution	resol.	orbit	duty cycle	orbit	
-71	area		[m]	[cm]	illuminated	power	[km]	[cm] at	AT x CT [m]	[m]	duty	on board	duty	
					aperture	[W]		product			cycle	proc. data	cycle for	
					AT x CT [m]			resolution			raw		energy	
								AT x CT [m]			data		7.5 Wh	
MIMO SAR	Oceans	6 altim. +1	10	105-	0.8 x 0.65	0.5	14	1.98 @	220 x 586	0.47	24.9%	>100%	19.8%	-3 overlapping pulses,
burst6 @	surface	control		234				2000 x 2000	(MIMO). 750					54*2*3 per burst
13.6GHz	slope								(pulse lim)					
MIMO SAR	Inland	6 altim. +1	10	105-	0.8 x 0.65	1	14	2.68 @	30 x 586	1.5	7.1%	>100%	19.3%	-3 times 2 overlapping
interl6 @	water	control		234				1000 x 1000	(MIMO). 1341					pulses per MIMO
13.6GHz									(pulse lim)					
MIMO SAR	Oceans	6 altim. +1	3.8	40-89	0.8 x 0.25	2	14	1.97 @	84 x 586	0.47	23.7%	>100%	19.4%	-3 overlapping pulses,
burst6 @	surface	control						2000 x 2000	(MIMO). 750					54*2*3 per burst
35GHz	slope								(pulse lim.)					
MIMO SAR	Inland	6 altim. +1	3.8	40-89	0.8 x 0.25	4	14	2.76 @	30 x 586	1.5	7.1%	>100%	17.1%	-3 times 2 overlapping
interl6 @	water	control						1000 x 1000	(MIMO). 1342					pulses per MIMO
35GHz									(pulse lim)					
MIMO SAR	Oceans	8 altim. +1	8	61-130	1 x 0.2	2.10	14	1.97 @	84 x 314	0.47	18.1%	>100%	19.3%	-4 overlapping pulses,
burst8 @	surface	control						2000 x 2000	(MIMO). 750					44*2*4 per burst
35GHz	slope								(pulse lim.)					
MIMO SAR	Inland	8 altim. +1	8	61-130	1 x 0.2	4.2	14	3.15 @	30 x 314	1.5	6.8%	>100%	17.6%	-4 times 2 overlapping
interl8 @	water	control						1000 x 1000	(MIMO). 1342					pulses per MIMO
35GHz									(pulse lim)					

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Criterion	MinoS	WOT	MiniSWOT		MIMO	DSARAL	MIMOSARAL	
	@13.6	6GHz	@35GHz		@13.6GHz		@35GHz	
	Ocean	Inland	Ocean	Inland	Ocean	Inland	Ocean	Inland
Accuracy	1.3	3.9	0.9	3.0	1.98	2.68	1.97	3.09
	cm@2x2	cm@1x1	cm@2x	cm@1x1	cm@2x2	cm@1x1	cm@2x2	cm@1x1
	km cell	km cell	2 km	km cell	km cell	km cell	km cell	km cell
	(MR)	(MR)	cell	(MR)				
			(MR)					
Resolution	220×313 m	30×145 m	84×313	23×179 m	220×586	30×586 m	84×314 m	30×314 m
(al.tr.×cr.tr.)	(MR)	(MR)	m (MR)	(MR)	m	(MIMO)	(MIMO)	(MIMO)
					(MIMO)			
Coverage	2×18 km	2×20 km	2×18	2×20 km	14 km	14 km	14 km	14 km
			km					
Complexity	Number of C	ubeSats: 5	Number o	f CubeSats: 5	Number of	CubeSats: 7	Number of Cu	ibeSats: 9
& Cost	(good)		(good)		(fair)		(unacceptable	)
(Payload &	Power: 10W	RF @Ku-	Power: 10	W RF @Ka-	Power: 0.5V	V RF @Ku-	Power: 2.2W	RF
platform	band =30W f	rom bus and	band $=>7$	0W from bus	band (excellent)		power@Ka-band = $\sim 20$ W	
requirement)	cheap device	(good)	and high c	ost	Boom: 1.05-2.34 meters		from bus with relatively	
	Boom: 2 met	ers each	(unaccepta	ıble)	each with moderate		high cost (goo	d)
	with very hig	h stability	Boom: 2 n	neters each	accuracy (good)		Boom: 0.61-1.30 meters	
	(fair)		with very high stability		Antenna: 0.8×0.65 m, a		each with mod	lerate
	Antenna: 0.8	×0.65 m, a	(fair)		bit large but	not complex	accuracy (goo	d)
	bit large but r	not complex	Antenna: 0.8×0.3 m, a		(good)		Antenna: 1×0	.2 m, large
	(good)		bit large b	ut not	Datarate: m	oderate (good)	and complex (	fair)
	Datarate: ver	y high for	complex (good)				Datarate: mod	erate (good)
	inland (fair)		Datarate:	very high for				
			inland (fai	r)				

Table 4. Trade-off	for the two	configurations	and their	variants
I dollo ll Ildae oll		• • • • • • • • • • • • • • • • • • •		

Green	Excellent performance
Blue	Good behaviour
Yellow	Fair: need some efforts to correct the drawbacks
Red	Unacceptable

Characteristi	C	Specification
System	Composition	5 nodes of 16U CubeSats, docked via booms
	Aggregated system length	880 cm width
	System mass	5 x 18 = 90 kg
	Payload antenna	Two interferometric radars with 660 cm bas
	Orbit	500 km SSO with an LTAN of 10:00h
Product	Height accuracy	1.7 cm (burst mode), 3.9 cm (interleaved mo
	(at product resolution)	
	Sample ground resolution	220 m along track x 577 m cross-track (burs

# Table 5. Mission specifications

	System mass	5 X 10 - 70 Kg
	Payload antenna	Two interferometric radars with 660 cm baseline
	Orbit	500 km SSO with an LTAN of 10:00h
Product	Height accuracy _(at product resolution)	1.7 cm (burst mode), 3.9 cm (interleaved mode)
	Sample ground resolution	220 m along track x 577 m cross-track (burst mode), 27 m along track x 241 m cross-track (interleaved mode)
	Swath width	18 km
	Duty cycle	13% (minimum, baseline) up to 20% (max. av. power)
	Radar frequency	13.6 GHz

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Subsystem	Margin	Mass [kg]
AOCS		1,98
Avionics		0,32
GNSS & Timing		0,25
ISL		0,24
Mechanical		3,47
MiniSWOT		2,11
Payload Data Handling		0,31
Power		2,21
Propulsion		1,19
Rendezvous & docking		5,07
Subtotal		16,35
System margin	10%	1,64
Total Satellite Mass		17,99

Table 6. Mass budget

Table 7. Typical science operations orbit average power consumption

Subsystem	Power (W)	Mission Generated Power
AOCS	5.93	Daily orbit average power generated and solar beta angle.
Avionics	1.30	46
GNSS & Timing	2.80	44
ISL	2.64	
MiniSWOT	4.31	
Payload Data Handling	5.14	
Power	0.83	
Propulsion	4.80	<b>8</b> 34
Rendezvous & docking	0.63	32 Power
Consumed Power	28.37	30 Generated
System Margin	10.00%	01/01/2026 01/01/2027 01/01/2028
Battery loss	1.73	Date [D/M/Y]
Total Used Power	32.94	