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AltiCube+: A low-cost long fixed-baseline radar altimeter solution based on cubesats on-orbit assembly

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ABSTRACT

Radar interferometry can be used to obtain sub-kilometre 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 m 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.

1. Introduction

Radar interferometry can be used to obtain sub-kilometre 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-m mast, then used on the CryoSat −2 as a Ku-band SIRAL (SAR/Interferometric Radar ALtimeter) with 1-m 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-m long radar antennas with a 10 m baseline, resulting in a spatial resolution of 1 km for the ocean and 100 m 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 metres (for example around 60 m 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.

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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 realize a baseline close to 10-m 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 beamforming 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 cross-track 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 ISISpace 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, Section 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 sub-kilometre 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

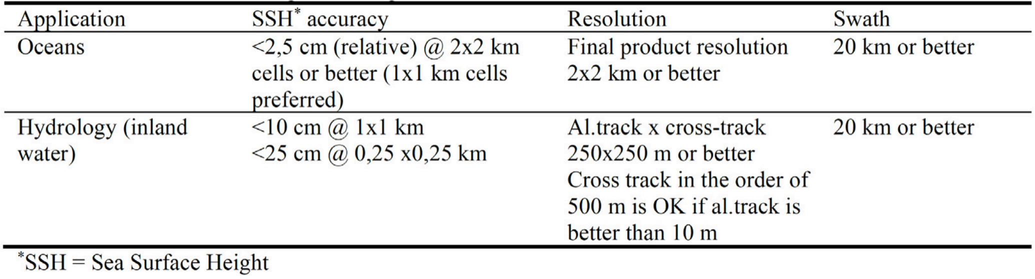
The following system constraints have been posed by ESA:

(i) 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
(ii) Spacecraft volume: CubeSat standard up to 16U (stowage volumes compatible with European deployers)
(iii) Total spacecraft wet mass: <32 kg
(iv) 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
(v) Space debris: compliance with ESA Space Debris Mitigation requirements
(vi) Overall ROM cost: less than €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.

Table 1
AltiCube+ altimeter product requirements.



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

*SSH = Sea Surface Height

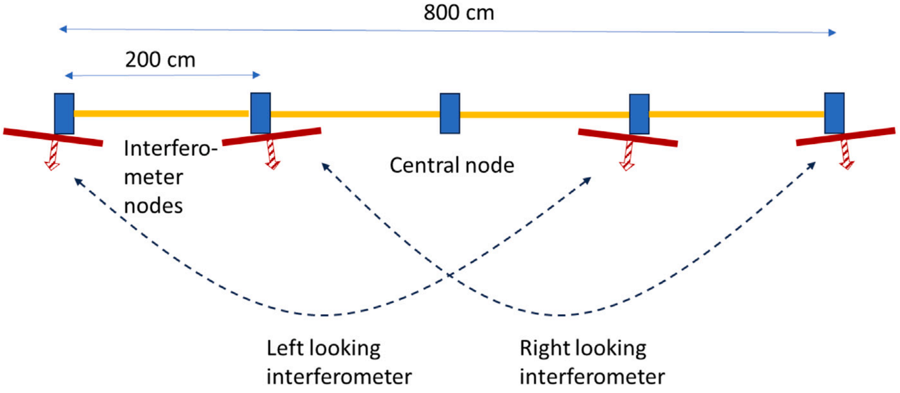


Fig. 1. The MiniSWOT configuration.

3.1. *Configuration I: MiniSWOT*

The MiniSWOT interferometer is a side-looking radar imaging instrument. The imager produces a two-dimensional 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 cross-track 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 m, if each satellite carries a boom that can extend to 2 m. 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 synchronize 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-m baseline, MiniSWOT could obtain the same height sensitivity with 5-m baseline.

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

(a) 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.
(b) 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.
(c) 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 cross-track direction: SAR processing ensures a high along-track resolution, the MIMO enhances cross-track discrimination and removes the left/right ambiguity.

Table 2
Performances of selected MiniSWOT variants.

System type	Main application area	#satellites	System dimens. [m]	Boom length [cm]	Antenna aperture Al.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

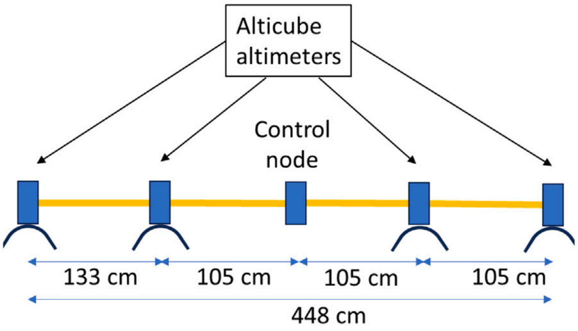


Fig. 2. The MIMOSARAL configuration (an example for Ku-band with 4 altimeter nodes).

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 Ku-band 4 node system (not to scale).

Each altimeter operates as a normal altimeter, the designs are very similar to the AltiCube in this case [5]. 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 m at Ka-band have been analysed, corresponding to lengths between 2.8 and 23 m 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:

(a) MIMOSARAL is a unique system that combines the advantages of several techniques to a high resolution and accuracy in three dimensions.
(b) MIMOSARAL is scalable, it can start off with a small configuration and be extended with more nodes later on.
(c) 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.

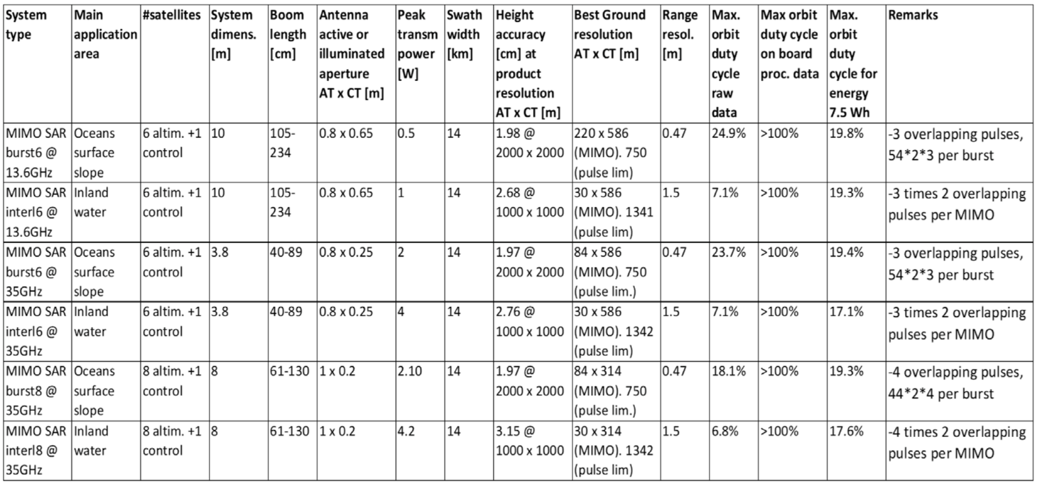
4.1. Performances of MiniSWOT

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

Table 3
Performances of selected MIMOSARAL variants.



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

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 utilized. 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 Ka-band MiniSWOT has slightly better accuracy, but the very high power demanding and expensive Ka-band radar transmitter makes it less preferable than the Ku-band 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:

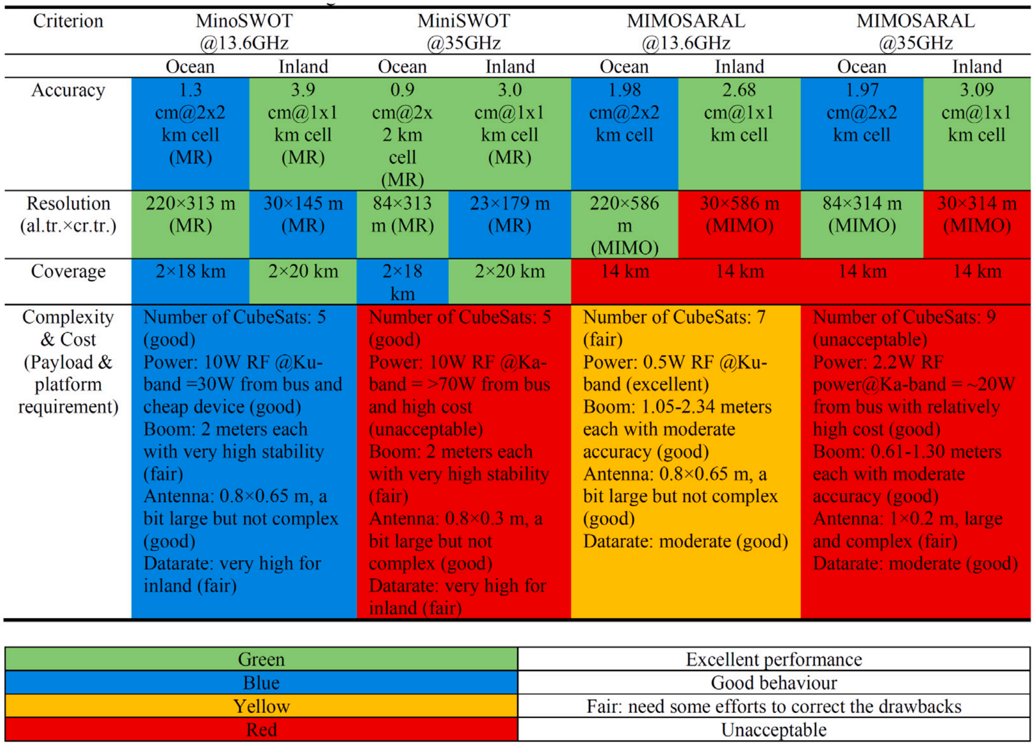
- Increased measurement baseline length from 6 m to 6.6 m due to change in platform orientation.
- Beam-steering for each node in the range from −4 to −2 and +2 to +4 degrees. Beam-steering was already proposed in the original design but has afterwards been explored in more detail.
- Decreased orbit 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:

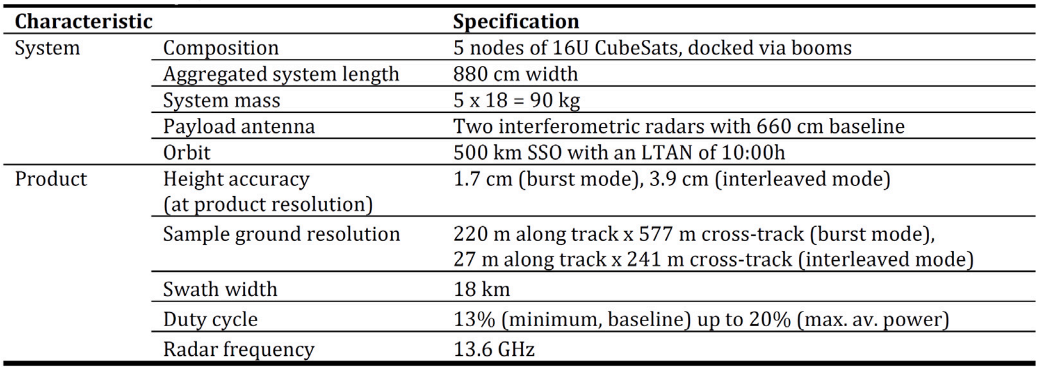
Table 4
Trade-off for the two configurations and their variants.



Criterion	MinoSWOT @13.6GHz		MiniSWOT @35GHz		MIMOSARAL @13.6GHz		MIMOSARAL @35GHz	
	Ocean	Inland	Ocean	Inland	Ocean	Inland	Ocean	Inland
Accuracy	🟦 1.3 cm@2x2 km cell (MR)	🟩 3.9 cm@1x1 km cell (MR)	🟩 0.9 cm@2x 2 km cell (MR)	🟩 3.0 cm@1x1 km cell (MR)	🟦 1.98 cm@2x2 km cell	🟩 2.68 cm@1x1 km cell	🟦 1.97 cm@2x2 km cell	🟩 3.09 cm@1x1 km cell
Resolution (al.tr.×cr.tr.)	🟩 220×313 m (MR)	🟦 30×145 m (MR)	🟩 84×313 m (MR)	🟦 23×179 m (MR)	🟩 220×586 m (MIMO)	🟥 30×586 m (MIMO)	🟩 84×314 m (MIMO)	🟥 30×314 m (MIMO)
Coverage	🟦 2×18 km	🟩 2×20 km	🟦 2×18 km	🟩 2×20 km	🟥 14 km	🟥 14 km	🟥 14 km	🟥 14 km
Complexity & Cost (Payload & platform requirement)	🟦 Number of CubeSats: 5 (good) Power: 10W RF @Ku-band =30W from bus and cheap device (good) Boom: 2 meters each with very high stability (fair) Antenna: 0.8×0.65 m, a bit large but not complex (good) Datarate: very high for inland (fair)		🟥 Number of CubeSats: 5 (good) Power: 10W RF @Ka-band = >70W from bus and high cost (unacceptable) Boom: 2 meters each with very high stability (fair) Antenna: 0.8×0.3 m, a bit large but not complex (good) Datarate: very high for inland (fair)		🟨 Number of CubeSats: 7 (fair) Power: 0.5W RF @Ku-band (excellent) Boom: 1.05-2.34 meters each with moderate accuracy (good) Antenna: 0.8×0.65 m, a bit large but not complex (good) Datarate: moderate (good)		🟥 Number of CubeSats: 9 (unacceptable) Power: 2.2W RF power@Ka-band = ~20W from bus with relatively high cost (good) Boom: 0.61-1.30 meters each with moderate accuracy (good) Antenna: 1×0.2 m, large and complex (fair) Datarate: moderate (good)	

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

Table 5
Mission specifications.



Characteristic		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 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

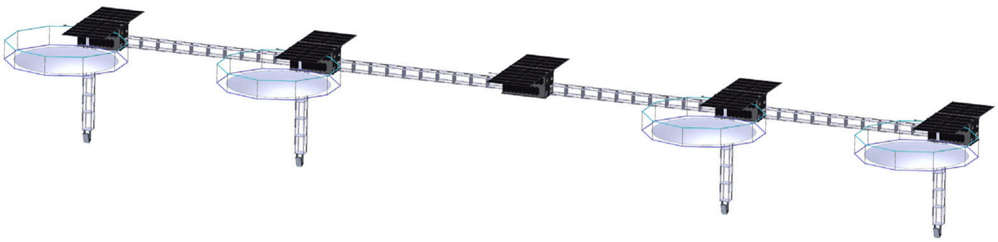


Fig. 3. Complete AltiCube+ system sketch.

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.

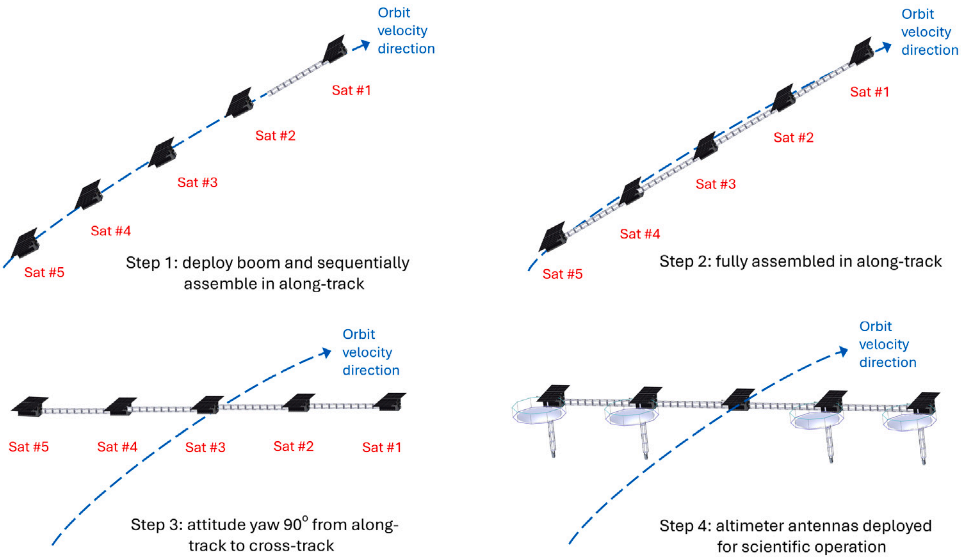


Fig. 4. In-orbit assembling procedure.

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 the in-orbit assembling stage starts. The first step is 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 (Step 1 in Fig. 4). Sequentially, Sats#3, #4 and #5 dock with assembled body, respectively (Step 2 in Fig. 4). 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 (Step 3 in Fig. 4), followed by the deployment of radar antennas from the CubeSats (Step 4 in Fig. 4).

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 centralized 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 pre-processed 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.

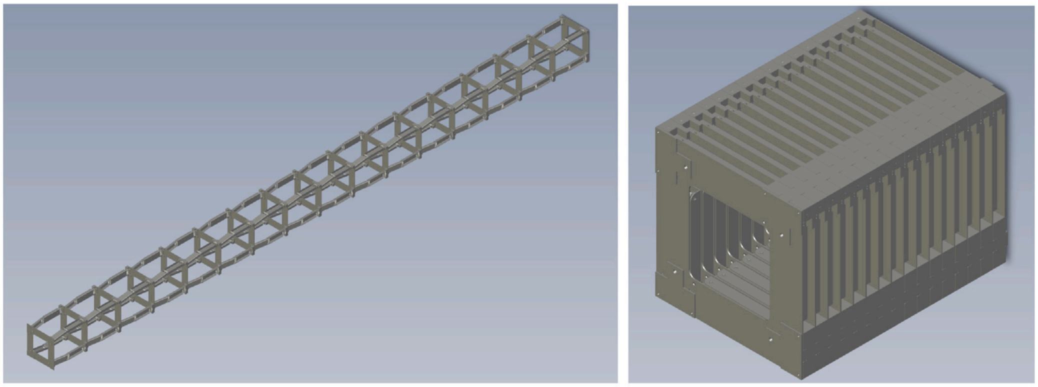
6.3. Deployable structure accommodation and deployment sequence

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)).

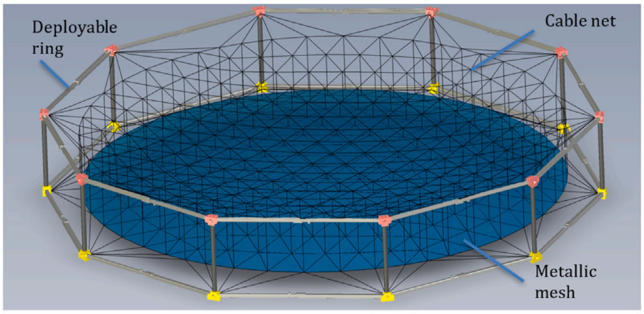
7. Autonomous assembly

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 covered in this paper for autonomous assembly: the assembly operation, and the docking methodology.



(a) Deployed mode (b) Stowed mode

Fig. 5. Main boom configurations.



(a) Deployed mode

(b) Stowed mode

Fig. 6. Antenna reflector configurations.

7.1. Assembly operation

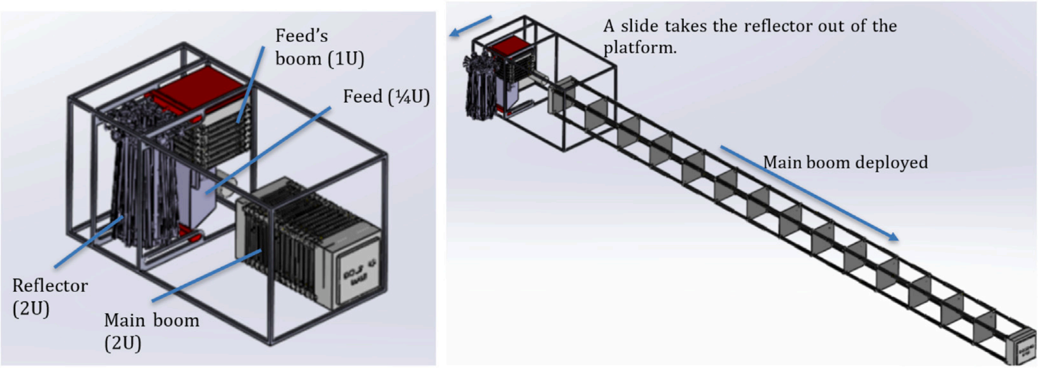
The assembly operation consists of four RVD processes, each one to a large extend follows the generic process as shown in Fig. 8. During the LEOP stage, the five CubeSats will maintain kilometres level along-track distance one by one. This indicates from GNC point of view, the RVD process will start from the homing phase, followed by closing, final approach and docking (not explicitly shown in Fig. 8) phases. Different navigation sensors, orbit actuators and control strategies are utilized in different phases. 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. Two types of propulsion systems are used as actuators. One is with large thrust level for big manoeuvres, and the other one is a Reaction Control System (RCS) to provide 6DOF small thrust for precise orbit control during 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:

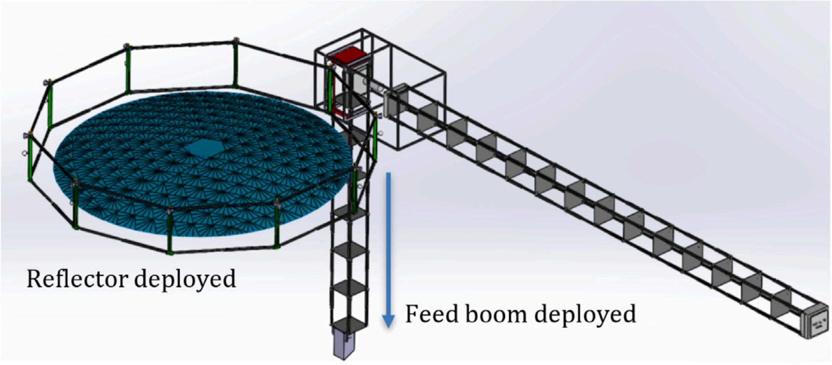
- Reduce the types of different platforms.
- Balance the propellant consumptions among platforms.
- Follow generic RVD operations (Fig. 8), but allow certain level of deviations.
- Performing final docking only along track.
- Speed up the assembly process for earlier scientific operation.

Based on the ConOps defined in Section 5.2 and these considerations, the complete assembly operation is defined as the following:

- Sat#2 docking Sat#1
  - Sat#2 implements homing to arrive at S1 w.r.t. Sat#1
  - Sat#2 from S1 implement closing manoeuvres until S5 using DGPS and RCS
  - Sat#1 deploys boom
  - Sat#2 final approach using straight-line translation with SK points at 5 m, 1 m and 0.2 m (VBN+RCS)
  - Sat#2 performs docking phase with Sat#1
- Sat#3 docking Sat#(1+2)
  - Sat#3 implements homing to arrive at new S1 w.r.t. Sat#(1+2)
  - Sat#3 from S1 implement closing manoeuvres until S5 using DGPS and RCS
  - Sat#2 deploys boom
  - Sat#3 final approach using straight-line translation with SK points at 5 m, 1 m and 0.2 m
  - Sat#3 performs docking phase with Sat#(1+2)
- Sat#4 docking Sat#(1+2+3)
  - Sat#4 implements homing to arrive at new S1 w.r.t. Sat#(1+2+3)
  - Sat#4 from S1 implement closing manoeuvres until S5 using DGPS and RCS
  - Sat#4 deploys boom
  - Sat#3 final approach using straight-line translation with SK points at 5 m, 1 m and 0.2 m

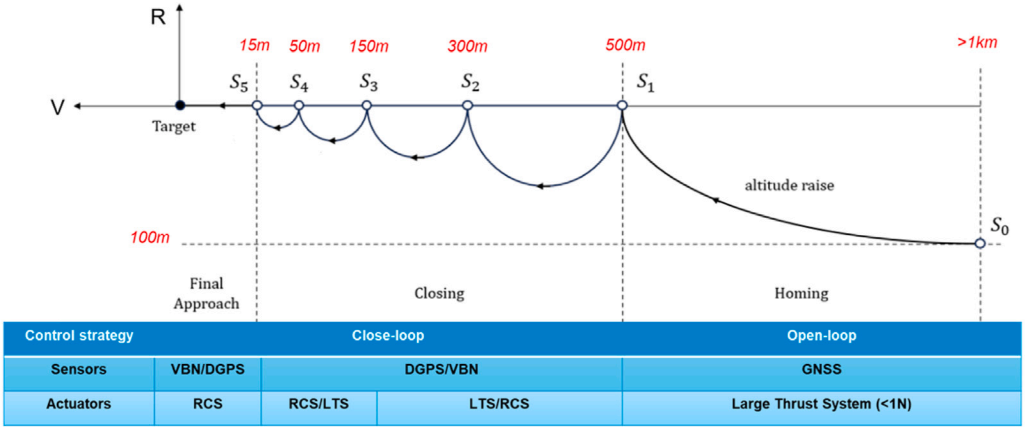


(a) Deployable structures and feed accommodation within the CubeSat (b) Main boom deployed, and reflector and feed's boom ready to deploy



(c) All structures deployed

Fig. 7. Deployable structure accommodation and deployment.



Control strategy	Close-loop			Open-loop
Sensors	VBN/DGPS	DGPS/VBN		GNSS
Actuators	RCS	RCS/LTS	LTS/RCS	Large Thrust System (<1N)

Fig. 8. Generic RVD process.

  - Sat#3 performs docking phase with Sat#4
- Sat#5 docking Sat#(1+2+3+4)
  - Similar with Sat#4 docking Sat#(1+2+3)
  - Final approach uses RCS of Sat#(1+2+3+4) instead of that of Sat#5

It is possible that during intermediate stages of this assembly operation, an ad-hoc attitude or orbit manoeuvring is needed due to, for example, the collision avoidance manoeuvring. If this happens, one of the docked CubeSats will act as the central (master) controller to perform master–slave control. Details of this coordinated control are still to be further defined in next stage of study.

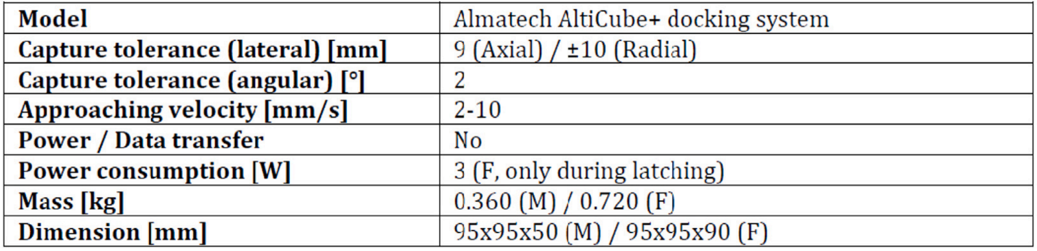
7.2. Docking methodology

The docking of the CubeSats within AltiCube+ is a challenge, not only because this has never been realized by CubeSats, but also due to the fact that the docking will be performed at the tip of the deployable boom. To address this challenge, the docking mechanism and the docking performance simulation results are introduced here.

7.2.1. Docking mechanism

The docking mechanism to be used on AltiCube+ is adapted from the RACE mission, as shown in Fig. 9. The RACE docking mechanism takes over the control from the moment when the auto alignment pillars

Table 6
Specification of the AltiCube+ docking mechanism.



Model	Almatech AltiCube+ docking system
Capture tolerance (lateral) [mm]	9 (Axial) / ±10 (Radial)
Capture tolerance (angular) [°]	2
Approaching velocity [mm/s]	2-10
Power / Data transfer	No
Power consumption [W]	3 (F, only during latching)
Mass [kg]	0.360 (M) / 0.720 (F)
Dimension [mm]	95x95x50 (M) / 95x95x90 (F)

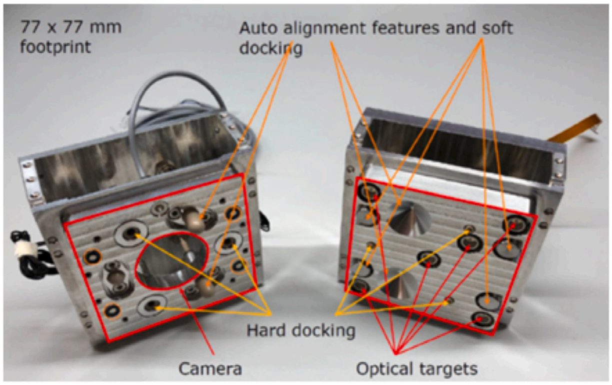
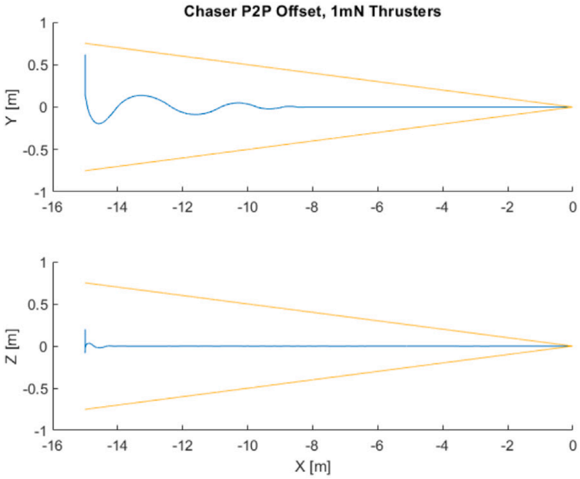
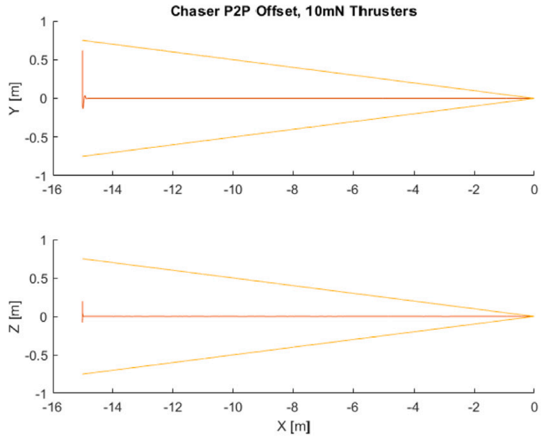


Fig. 9. The original RACE docking system (left) male part (right) female part.



(a) Offset with 1 mN thrusters



(b) Offset with 10 mN thrusters

Fig. 10. Relative positional offset during boom oscillations.

(half-round head short ones) on the male part get into the surface plane of the female part. Due to residual relative speed, the pillars will move further along the conical holes, which also align the male part with the female part until the two surfaces touch each other with a soft docking. After that, the hard docking mechanism will firmly connect the two parts by deploying latching from the female part into the male part.

To be used on AltiCube+, some adaptions have to be made on the RACE docking system, including:

- The through hole in the centre of the male side will be moved to female side, and the new diameter is 40 mm.
- All the six LEDs on the female side will be moved to male side, with the same locations.
- The motor on the female side will be miniaturized, so the total thickness of the female side is reduced from 110.15 mm to 90 mm.

After these modifications, the camera and the motor will be on the female part, which is installed in the CubeSat, while the male part can be compact and light without camera and, therefore, suitable for the tip of the deployable boom. The key specifications of the AltiCube+ docking interface are summarized in Table 6.

7.2.2. *Docking performance*

Extensive simulations have been performed to evaluate docking performance. Due to page limitation, here only two most important aspects are summarized: Misalignment when docking port takes over, and the effect of boom movement.

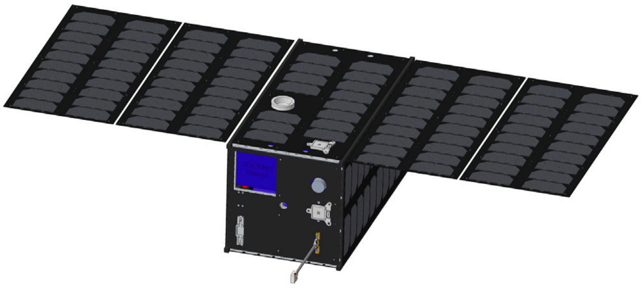
At the end of the final approaching phase, the docking port will take over the control. The misalignment at the moment of taking over will determine the success of docking. Table 7 shows the final docking misalignment represented by both the translational and angular offsets, in cases of using 1 mN or 10 mN thrusters of the RCS. It can be seen that the 1mN configuration performs slightly better, with lower dispersion and slightly smaller final offsets then the 10mN configuration for both the translational and angular offsets. The slight bias observed in both configurations are caused by the relative dynamics. Considering the docking mechanism's capture tolerance as shown in Table 6, the misalignment satisfy the requirement with enough margins.

The effect of the target boom movement during the final moments of docking and soft capture must also be considered. First, a simulation was run with an artificial rotational oscillation of no more than 1.03 deg/s added to the target to introduce large boom movements. The results, seen in Fig. 10, show that the performance of the chaser is minimally impacted even by large displacements of the boom tip.

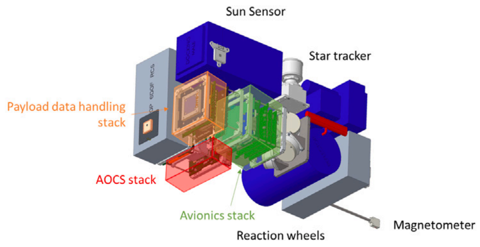
Thus, the movement of the boom only needs to be taken into account during the moments of contact between the chaser and target docking interfaces. From this, it can be seen that the rotational velocities are well within the bounds of control for modern CubeSats. With a controlled target, commanded to remain in a stable orientation, the

Table 7
Final docking misalignment.

	1mN Thruster			10mN Thruster		
	Mean	95% CI	1σ SD	Mean	95% CI	1σ SD
Y Offset (mm)	-0.3867	±0.8828	4.4491	0.0094	±0.0259	0.00013
Z Offset (mm)	-0.0507	±0.0112	0.0563	-0.1390	±0.0214	0.00011
α Offset (deg)	0.00863	±0.01294	0.06522	0.00848	±0.00034	0.00172
β Offset (deg)	0.00214	±0.00191	0.00963	0.00330	±0.00015	0.00077
γ Offset (deg)	0.00829	±0.00918	0.04626	0.00806	±0.00024	0.00122



(a) External view



(b) Internal view

Fig. 11. Platform layout.

Table 8
Mass budget.

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

experienced angular velocities will be well under the maximum values. Therefore, it can be concluded that any movement of the boom tip during contact will remain well within the misalignment envelope and have negligible impact on the docking procedure.

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 8. 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 s of downloading
- 720 s of payload operations
- Remaining 4957 s in nominal mode

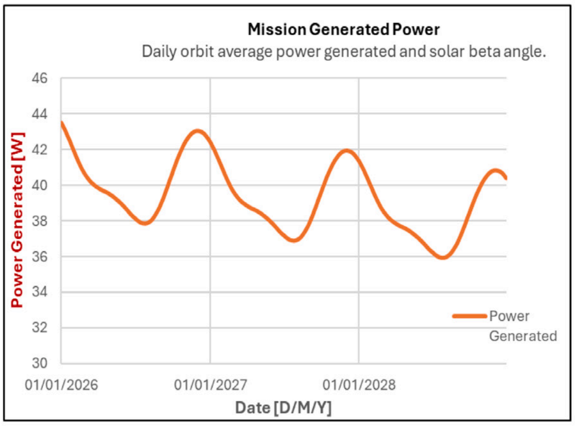
The resulting per orbit average power consumption is 32.94 W, as shown in Table 9. This is assuming a BCR and BDR efficiency of 90%. The power generated over the 5-year mission lifetime is also shown in the same table. Worst-case orbital average power generated is 35.94 W. Compared to the 32.94 W maximum 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

Table 9
Typical science operations orbit average power consumption.

Subsystem	Power (W)
AOCS	5.93
Avionics	1.30
GNSS & Timing	2.80
ISL	2.64
MiniSWOT	4.31
Payload Data Handling	5.14
Power	0.83
Propulsion	4.80
Rendezvous & docking	0.63
Consumed Power	28.37
System Margin	10.00%
Battery loss	1.73
Total Used Power	32.94



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 has started from Feb. 2025. It is expected an IOD of AltiCube+ can be launched by the end of 2027 and the full operational mission by 2029.

CRediT authorship contribution statement

Jian Guo: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Peter Hoogeboom:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paco Lopez Dekker:** Writing – review & editing, Investigation. **Jasper Bouwmeester:** Writing – review & editing, Validation, Investigation, Formal analysis. **Gabriele Meoni:** Writing – review & editing, Investigation, Formal analysis. **Jose Nieto:** Writing – review & editing, Investigation, Formal analysis. **Juan Fayos:** Writing – review & editing, Investigation, Formal analysis. **Eric Bertels:** Writing – review & editing, Investigation, Formal analysis. **Camille Pirat:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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