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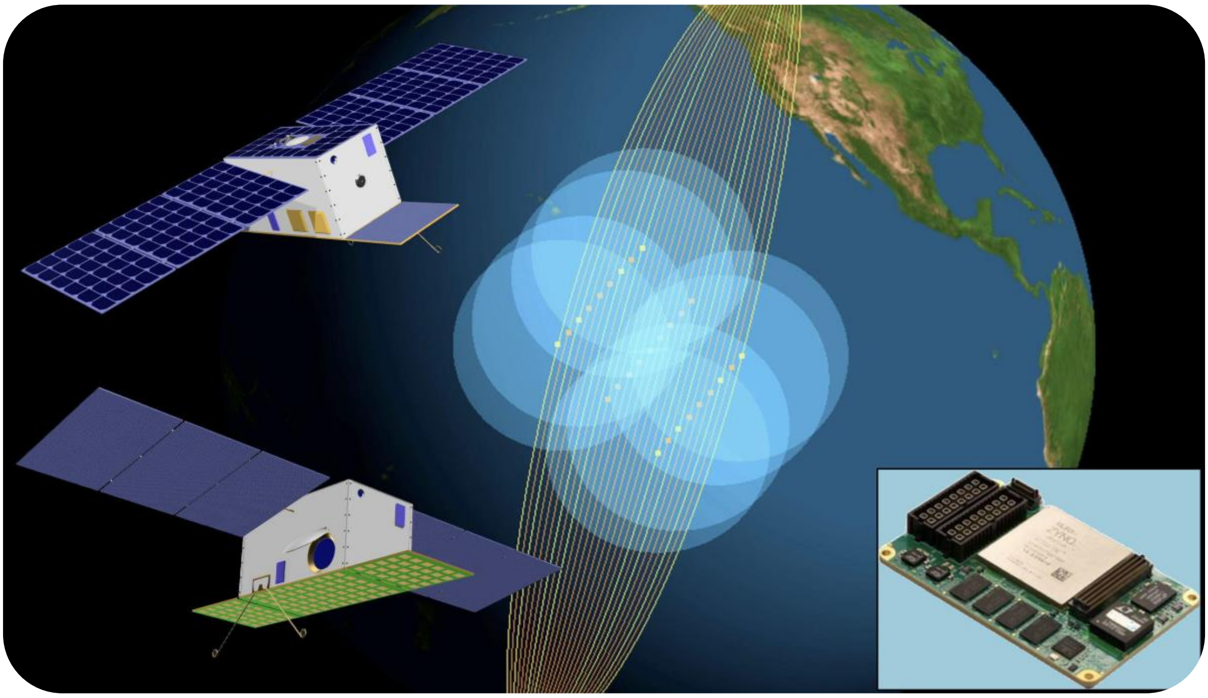

RADAR CLUSTER FOR EARTH REMOTE SENSING

Executive summary

Mission concept study

OSIP: Innovative Mission Concepts Enabled by Swarms of CubeSats

GeoOptics Switzerland SA (Prime), Tyvak International S.r.l., The University of Birmingham, National Interuniversity Consortium for Telecommunications

Activity summary:

RaCERS is a swarm of eight small satellites that will fly in close formation to exploit the enormous power of cooperating radars to boost the quantity and resolution of environmental observations from space. This will transform the science of Earth environmental monitoring and forecasting applied to such vital concerns as severe weather, natural hazards, snow/ice cover, soil moisture, vegetation canopy, surface winds, ocean circulation and much more.

➔ THE EUROPEAN SPACE AGENCY

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RaCERS Mission Overview

Spaceborne radar is central to Earth environmental monitoring and forecasting for such things as natural hazards, severe weather, snow/ice cover, soil moisture, vegetation canopy, surface deformation, ocean circulation, and more. Space radars today – SAR imagers, altimeters and scatterometers – are designed with mission-unique elements at high cost. No current systems combine SAR/Alt/Scat and no radar signal generator/processors offer multiple radar types.

GeoOptics Switzerland (GOS) is pursuing space radar innovations on two fronts: advanced instrumentation combining all radar signal generation and processing functions in a small, low-cost module, and observing system architectures comprising swarms of cooperating smallsats to achieve new observation types and performance levels. Formerly large platforms are "atomized" into swarms of simpler vehicles operating in concert, exploiting cubesat technology and the power of linked networks to yield new science – what we call cellular remote sensing.

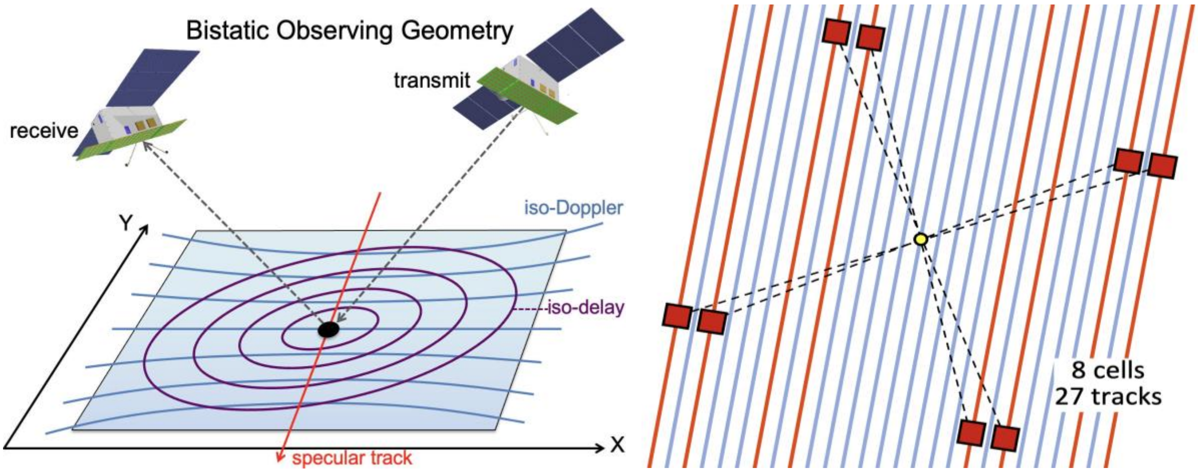


Fig. 1. *RaCERS bistatic geometry (left) and sample eight-cell formation for SAR and Alt/Scat.*

The proposed Radar Cluster for Earth Remote Sensing (RaCERS) is a multipurpose space radar system offering efficient SAR, altimetry and scatterometry in one cubesat swarm. The concept envisages a constellation of eight small satellites performing a combination of monostatic and bistatic radar functions, built around a small Radar-On-Module for Earth Observation engine (ROMEO). The initial operational RaCERS constellation will offer:

- Eight 16U cubesats in a swarm performing mono- and bistatic altimetry and scatterometry (Fig. 1, left), alternating with SAR imaging. Nominal design life: 2 years; goal 5+ years.
- Circular orbits at a nominal release altitude of 450 km, raised to 475 km.
- Vehicle separations of 2-400 km, achieved and maintained with onboard electric propulsion.
- Two radar frequencies similar to those used by Jason-2: ~13.5 GHz and ~5.4 GHz.
- A microwave radiometer on each vehicle to calibrate atmospheric moisture.
- Pseudonoise (PN-code) modulation of the radar signals at up to 300-Mbit/sec.
- Instantaneous electronic beam steering for alternating target points.
- An enhanced ROMEO instrument for signal generation and processing; real time position, navigation and timing; and precise GNSS orbit determination.
- Four radar operating modes:
    - <u>Mode 1</u>: Pulsed monostatic nadir altimetry by each vehicle independently
    - <u>Mode 2</u>: Pulsed bistatic altimetry/scatterometry (both directions at once)
    - <u>Mode 3</u>: Continuous bistatic altimetry/scatterometry (one direction at a time)
    - <u>Mode 4</u>: Side-looking SAR imaging

- Jason-class altimetry accuracy of ~3 cm with 1-sec integration.
- Average derived wind speed accuracy of 2 m/s over a 5-sec integration.

The Network Effect

A core idea behind GeoOptics' system architectures is to harness the "network effect" in which the utility and robustness of a linked system grows far faster than the number of nodes, typically as N^2, while costs, owing to mass-replication, miniaturization, and system-level redundancy, plummet. This principle is well exemplified in swarms of multi-function radars.

Our team is developing a custom radar system architecture, originally called Cellular Orbiting Altimetry/Scatterometry Technology (COAST). RaCERS will grow the COAST bus size, enhance its Alt/Scat functions, and add a powerful bistatic SAR capability. Fig. 1 (right) shows an eight-cell RaCERS configuration. By combining monostatic and bistatic observations, eight cells can yield 27 equally spaced Alt/Scat tracks. At 450 km altitude RaCERS yields a potential 30-fold increase in surface resolution over a single Jason, which flies at 1336 km.

Comparison to Current Art

The RaCERS mission concept advances the current art for space radar systems in several ways:

- A more versatile, compact, low-cost radar signal generator and processor (ROMEO)
- A substantially smaller (16U), low-cost multi-function spacecraft bus
- Use of the network effect with swarms to amplify observing power
- Use of PN-coded signals for versatile operation and to enable use of small antennas
- Combining monostatic and bistatic/multistatic radar observation in one system
- Combining SAR, altimetry and scatterometry observations in one system
- Dramatic reduction in system cost

Quantitative examples of advances offered by the RaCERS swarm concept include:

- Altimetry surface resolution improvement by 30x over Jason-class missions
- Scatterometry surface resolution improvement by 50x over single scatterometers
- Wind direction improvement by >10x owing to concurrent viewing from multiple angles (many single-platform scatterometers provide little or no wind direction information)
- Cost reduction per spacecraft of >30x compared with current flagship radar missions

At the heart of RaCERS is GeoOptics' new Radar-On-Module for Earth Observation (ROMEO) signal generation and processing system, which offers broad functionality in a small volume. ROMEO is derived from the Cion GNSS radio occultation receiver flying on our CICERO satellites. ROMEO expands the Cion to realize the full range of RaCERS radar functions.

Radar Signal Structure

Since the RaCERS signal is generated in software, we can choose any waveform we like and change it at will. A potent (and novel) choice is a spread spectrum signal formed by modulating a carrier with a pseudonoise (PN) square-wave code.

The PN-coded signal offers a number of attractions. We can chop a pulse echo into segments for detection and reassemble them without loss. We can transmit signals from multiple platforms on the same frequency and separate them by their different codes to enable powerful multistatic observations. And PN coding eliminates pulse-range ambiguity, enabling for the first time the use of short (sub-meter) antennas for SAR with a small platform. This structure allows us to extract all the information needed for any radar application, without compromise: precise delay for altimetry, precise amplitude and Doppler for scatterometry, and continuous phase for coherent formation of SAR images.

Radar Swarms

Regional swarms of small radar satellites operating in concert are uniquely suited to exploiting the network effect to greatly increase their observing power. The ROMEO engine allows us to extend that power to multiple radar applications at once – Alt/Scat/SAR – with a single swarm.

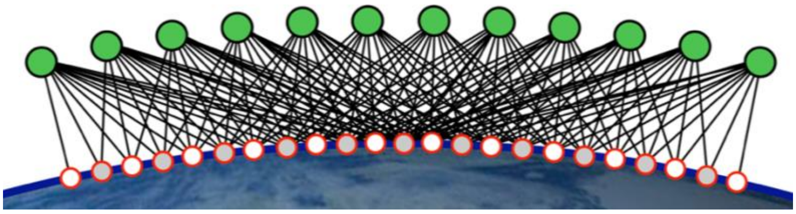


Fig. 2. *A maximally overlapping broad-beam chain can deliver N^2 independent observations.*

Fig. 2 depicts a 12-cell broad beam radar array with full mutual visibility, yielding N^2 (144) independent measurements, greatly expanding the recovered information. This geometry does not merely provide conventional data in greater quantity, it introduces new types of information from forward scattered signals. Backscattered returns tend to be weak as most of the energy scatters forward or in other directions. Multiple cells can collect stronger forward scattered (bistatic) signals, which contain complementary surface information. A swarm can observe surface points from multiple angles, providing far greater information about surface properties, particularly for determining ocean wind direction.

Formation Flying

To maximize surface resolution for Alt/Scat we adopt non-uniform spacing. Fig. 3 (left) shows a symmetric array of eight cells yielding 27 evenly spaced tracks.

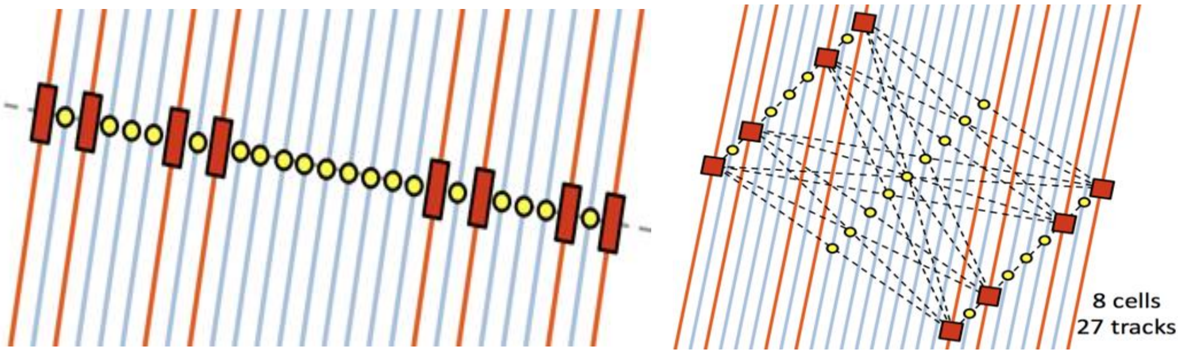


Fig. 3. *Two arrays of eight cells yielding 27 tracks. Yellow dots are bistatic reflection points.*

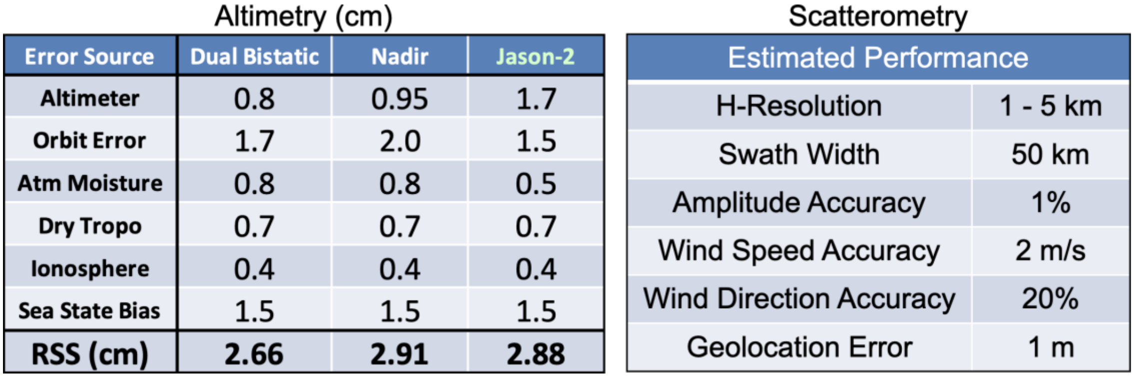
Wind direction recovery with scatterometry gains from observations taken from multiple directions with expanded 2D geometry. We can adjust the position of each cell along its velocity track without altering the spacing of the resulting ground tracks. Fig. 3 (right) illustrates this with eight cells in a dual echelon formation.

Every bistatic reflection point is observed from at least two directions, which is itself a big gain over monostatic scatterometry. The central point is observed from eight well-distributed angles, offering unprecedented accuracy for surface wind determination. Altimetry can be performed along all 27 tracks, with 64 distinct reflections. There are many other attractive array options.

Altimetry/Scatterometry Performance

The RaCERS team has performed extensive error studies for all operating modes. Table 1 (left) shows total altimetry error budgets for nadir monostatic and dual bistatic altimetry along with the best quoted error budget for Jason-2. The numbers are virtually the same for all and we can expect to achieve Jason-class altimetry with the baseline RaCERS configuration. Table 1 (right) shows projected RaCERS scatterometry performance. The 20% wind direction accuracy surpasses conventional scatterometers owing to viewing from several directions at once. Conventional nadir altimetry offers a surface resolution of 1-6 km (cross track and along track) and a swath width of ~1 km. While this is fine for ocean circulation studies it falls short of needs for monitoring coastal waters, which requires the power of SAR/InSAR.

Table 1. RaCERS altimetry error budgets compared with that for Jason-2



Altimetry (cm)

Error Source	Dual Bistatic	Nadir	Jason-2
Altimeter	0.8	0.95	1.7
Orbit Error	1.7	2.0	1.5
Atm Moisture	0.8	0.8	0.5
Dry Tropo	0.7	0.7	0.7
Ionosphere	0.4	0.4	0.4
Sea State Bias	1.5	1.5	1.5
RSS (cm)	**2.66**	**2.91**	**2.88**

Scatterometry

Estimated Performance	
H-Resolution	1 - 5 km
Swath Width	50 km
Amplitude Accuracy	1%
Wind Speed Accuracy	2 m/s
Wind Direction Accuracy	20%
Geolocation Error	1 m

Add SAR

For SAR imaging we observe to the side, 2°-40° off nadir, and sample a lateral swath by "range-gating" the returns with multiple delay windows (lags). We then coherently combine returns from many pulses to synthesize a wide aperture traced by the vehicle's motion. Interferometric SAR with multiple images can be performed in several modes – single-platform and dual-platform, single-pass and dual-pass – with different processing techniques, depending on objectives. RaCERS will extend monostatic techniques to swarm-based bi- and multistatic geometries to enable powerful new observation types exploiting the cooperating network.

Fig. 4 illustrates classical SAR/InSAR producing surface deformation maps. This can be done with two platforms in similar orbits or with one platform repeating its orbit. Fig. 5 shows a pair of RaCERS satellites in bistatic geometry observing two swaths at once. Each vehicle can send and receive pulses concurrently, or alternate continuous transmissions. RaCERS will offer both modes. Fig. 6 shows a similar arrangement with four satellites collecting dual one-way data to form four SAR images for cross track InSAR. We can enhance this further by having all four transmitting and receiving, something easily achieved since all use different codes.

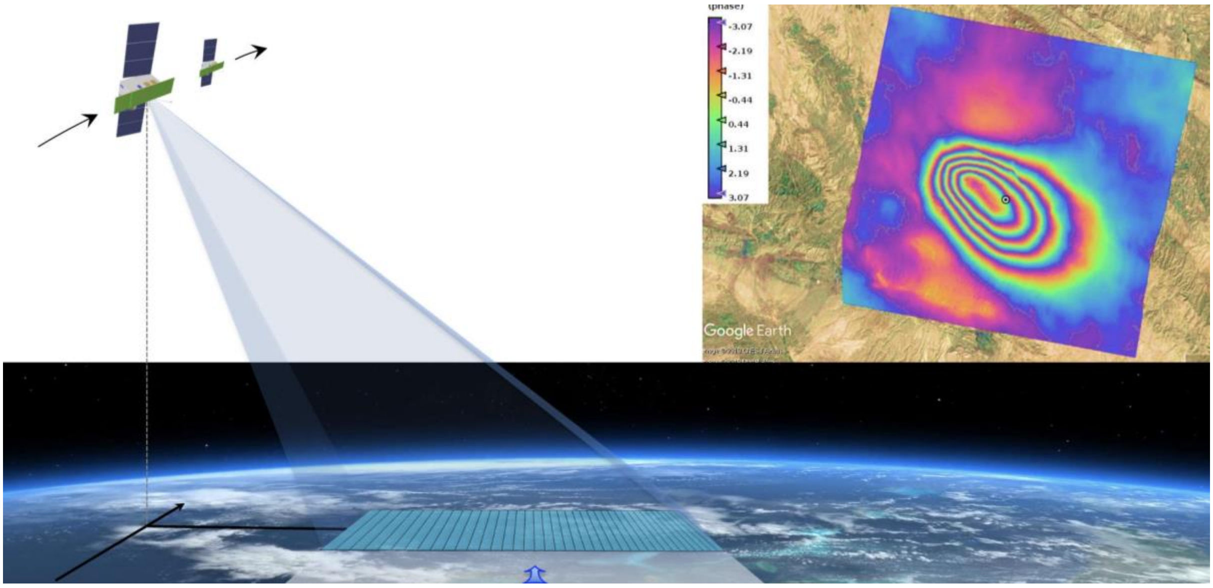


Fig. 4. Depiction of a conventional two-platform along track SAR/InSAR observing system.

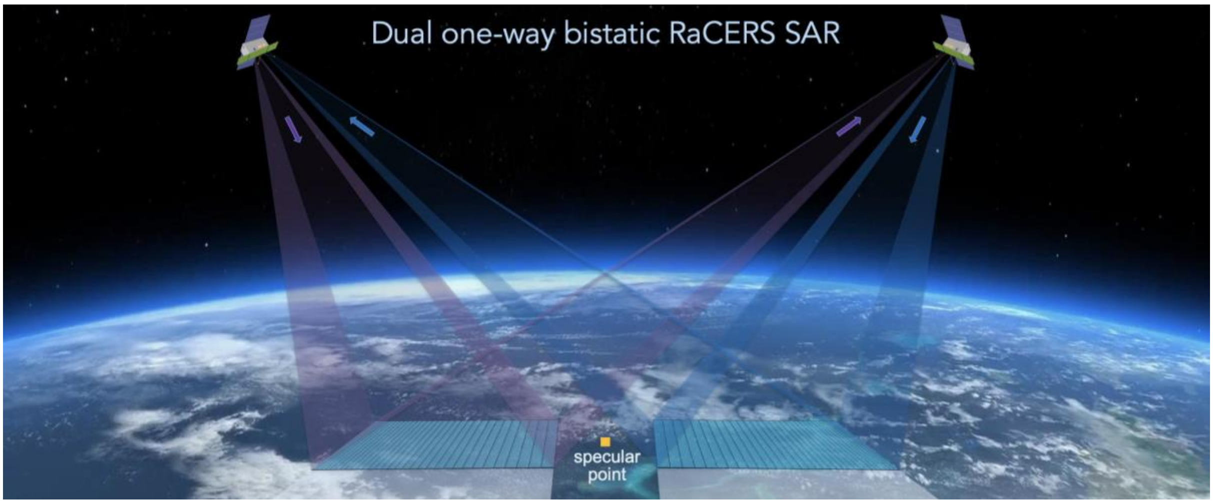


Fig. 5. *Geometry for two-swath dual one-way RaCERS bistatic SAR.*

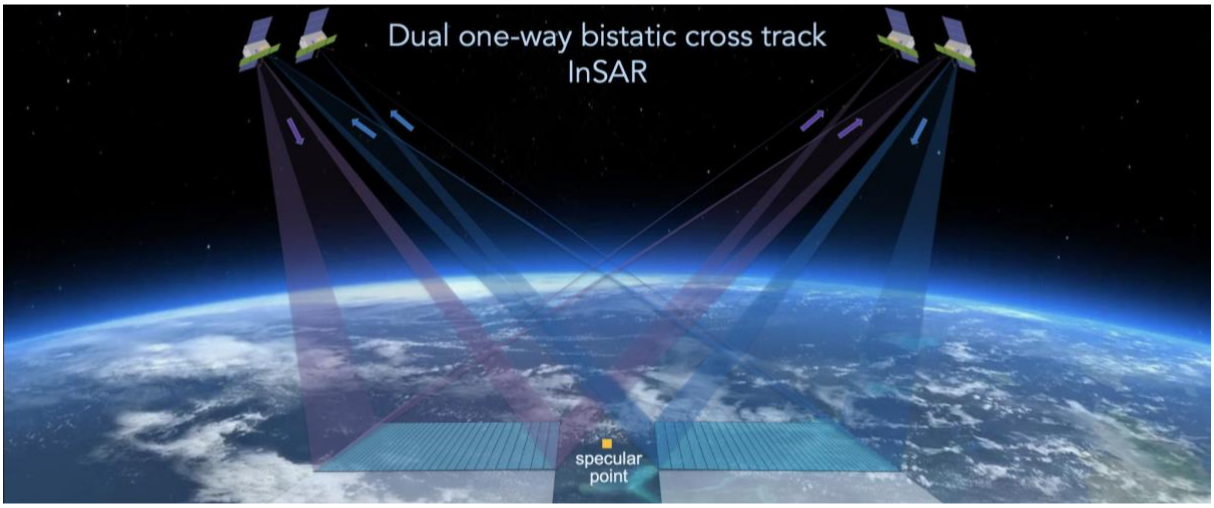


Fig. 6. *Geometry for two-swath dual one-way RaCERS bistatic cross track InSAR.*

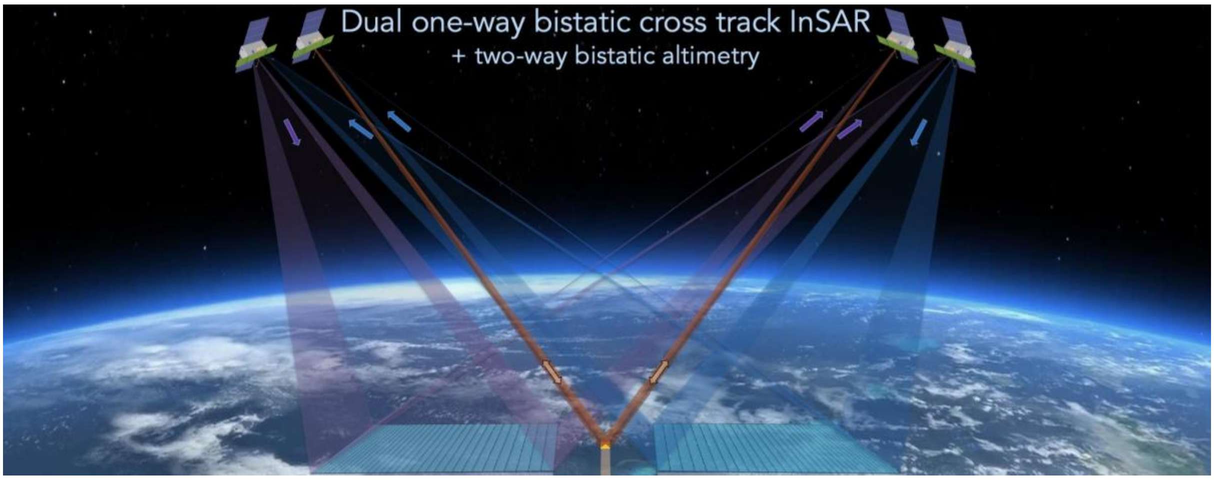


Fig. 7. *Two-swath dual one-way RaCERS bistatic cross track InSAR with two-way bistatic altimetry.*

In Fig. 7, we combine dual cross track InSAR with concurrent bistatic Alt/Scat to mimic the operation of the ~$1.5 billion NASA/CNES SWOT mission. In fact, we can do better by adding nadir altimetry from each platform (Fig. 8). In these cross track InSAR examples, the satellites fly side-by-side in quasi-parallel orbits. Another basic SAR technique – in fact the one shown in Fig. 4 – employs along track pairs in nearly identical orbits. The bistatic RaCERS variation is shown in Fig. 9. Two successive SAR images can be used interferometrically to measure velocities of objects on the surface or surface deformation from, among other things, volcanic inflation, earthquakes, resource extraction, and the changing volume of the vegetation canopy, a critical method for assessing carbon sequestration.

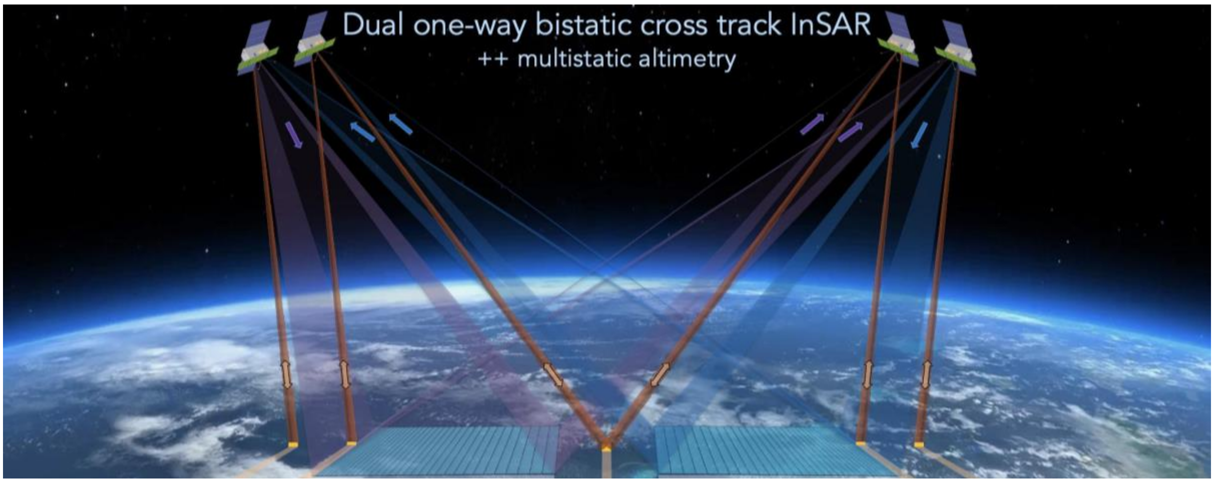


Fig. 8. *Two-swath dual one-way RaCERS bistatic cross track InSAR with multistatic altimetry.*

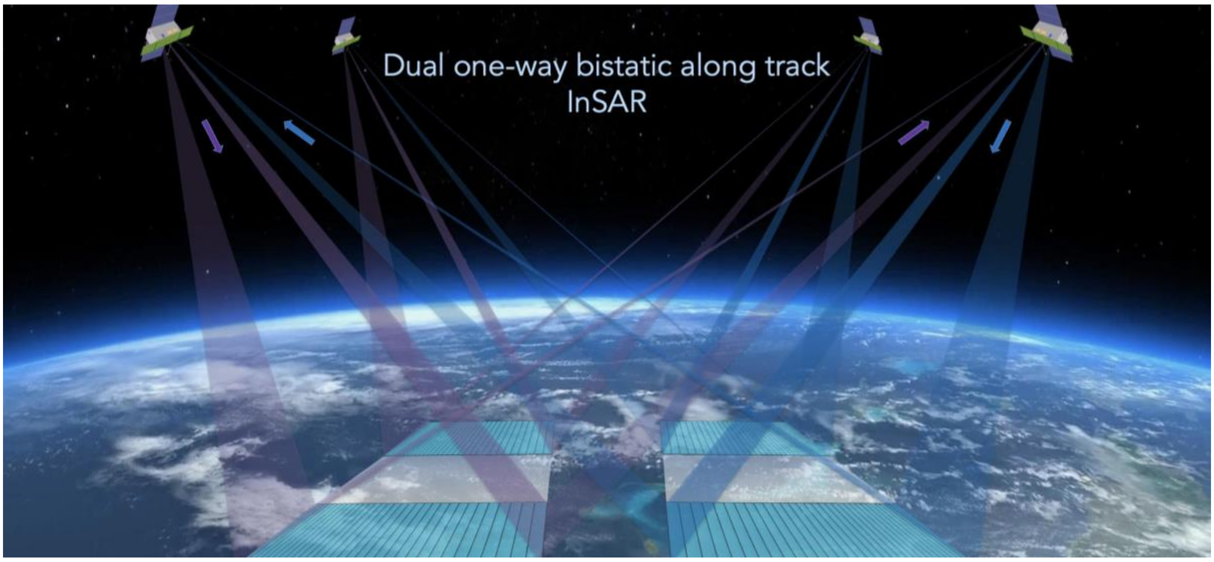
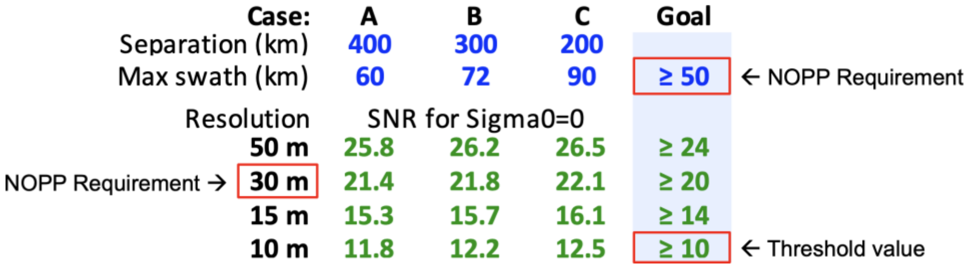


Fig. 9. *Geometry for two-pair RaCERS two-swath dual one-way bistatic along track InSAR.*

SAR Performance

A key SAR goal is to meet or exceed US National Oceanographic Partnership Program targets for coastal observations: **30 m** resolution, **50 km** swath width, **200 km** swath length, and a duty cycle of ≥ 6%. A key feasibility test is to achieve a nominal power SNR of ≥10 dB per pixel. Table 2 summarizes RaCERS analyses for three bistatic separations and for ground resolutions of 50, 30, 15 and 10 km. At 30 m resolution the SNRs are all above 21 dB and they are at or near 12 dB even down to 10 m resolution. Maximum swath widths range from 60 to 90 m.

Table 2. RaCERS SAR analysis for 3 S/C separations and 4 ground resolutions



	Case:	A	B	C	Goal	
	Separation (km)	400	300	200		
	Max swath (km)	60	72	90	≥ 50	← NOPP Requirement
	Resolution	SNR for Sigma0=0				
	50 m	25.8	26.2	26.5	≥ 24	
NOPP Requirement →	30 m	21.4	21.8	22.1	≥ 20	
	15 m	15.3	15.7	16.1	≥ 14	
	10 m	11.8	12.2	12.5	≥ 10	← Threshold value

Deploying The Cluster

The eight RaCERS spacecraft will fly in a close formation, separated by 2-400 km, at an initial altitude of ~450 km. All eight will be launched together and released a few minutes apart. Following initial checkout, the vehicles will be maneuvered into formation with onboard electric propulsion (EP). There are two main uses for propulsion: orbit plane drifting to achieve the formation, and station-keeping. One may also want to alter the formation during the mission. RaCERS will carry propellant sufficient to maintain its orbits for at least 5 years.

The plane drift is done by the technique employed, for example, by COSMIC and COSMIC-2 in which first one vehicle is boosted in altitude. That causes its orbit plane to drift in longitude more slowly than at the lower altitude. It will take a few weeks for the first plane to drift by one degree. Then, the next satellite is boosted and the higher vehicles drift together. This is repeated until all eight have been boosted to the same altitude and again drift in unison.

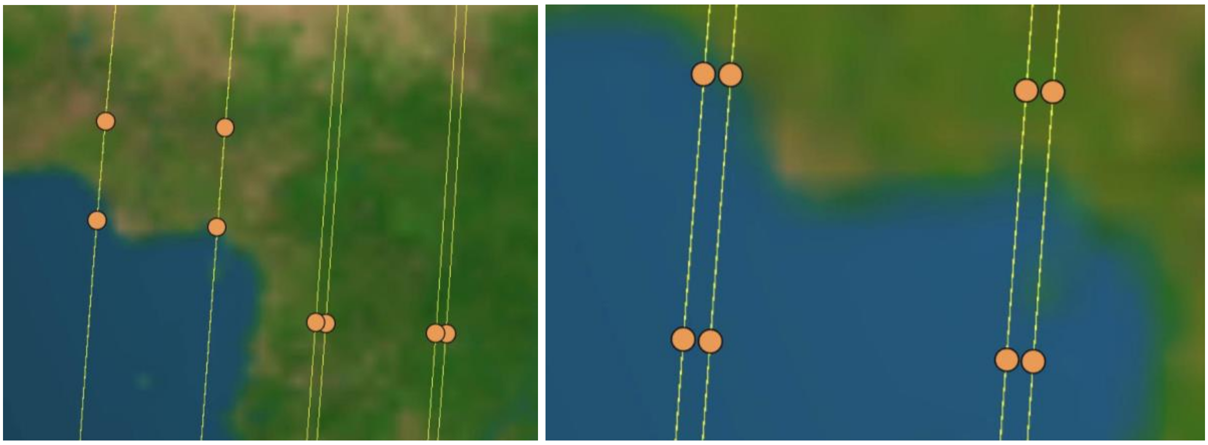


Fig. 10. *Eight-satellite configuration with interacting 4-satellite along track and cross track groups.*

Figs. 6 and 9 show two basic 4-satellite configurations for bistatic SAR/InSAR: cross track and along track. This suggests some useful distributions for RaCERS: Fig. 10. (left) shows two groups of four vehicles, one group of each type, close enough that all can interact, the along track group forming a square and the cross track group in a line, side-by-side. On the right we show a more compact array offering multiple along track and cross track combinations.

The RaCERS concept of operations draws upon many standard actions from launch to deployment to initial operations, at which point a more tailored process is needed. An overview of RaCERS conops from launch to end-of-life is shown in Fig. 11.

Benefits of Swarms & PN Codes

Through the network effect, local swarms of smallsat radars multiply observing power and strategies far beyond a simple increase in data volume. Benefits include combined forward and backscatter sensing, multiple concurrent observing directions, an N^2 compounding of observing combinations, creative new approaches to InSAR, and more. They present an economical new production paradigm that will slash costs compared with one-of-a-kind missions. Individual vehicles can be built for under €10 million. With many new and emerging low-cost launch options, a full eight-element operational array can be deployed for under €100 million.

The use of PN-coded pulses rather than the traditional radar chirps adds to the advantages. All vehicles can transmit on the same frequency in the same region and be readily distinguished without interference, a core concept of swarm radars. They eliminate the challenge of delay ambiguity, enabling SAR with small antennas and their required rapid pulsing rates. They offer versatility of processing methods, and are compatible with mature receiver designs. This, we believe, will be the smallsat radar paradigm of the future.

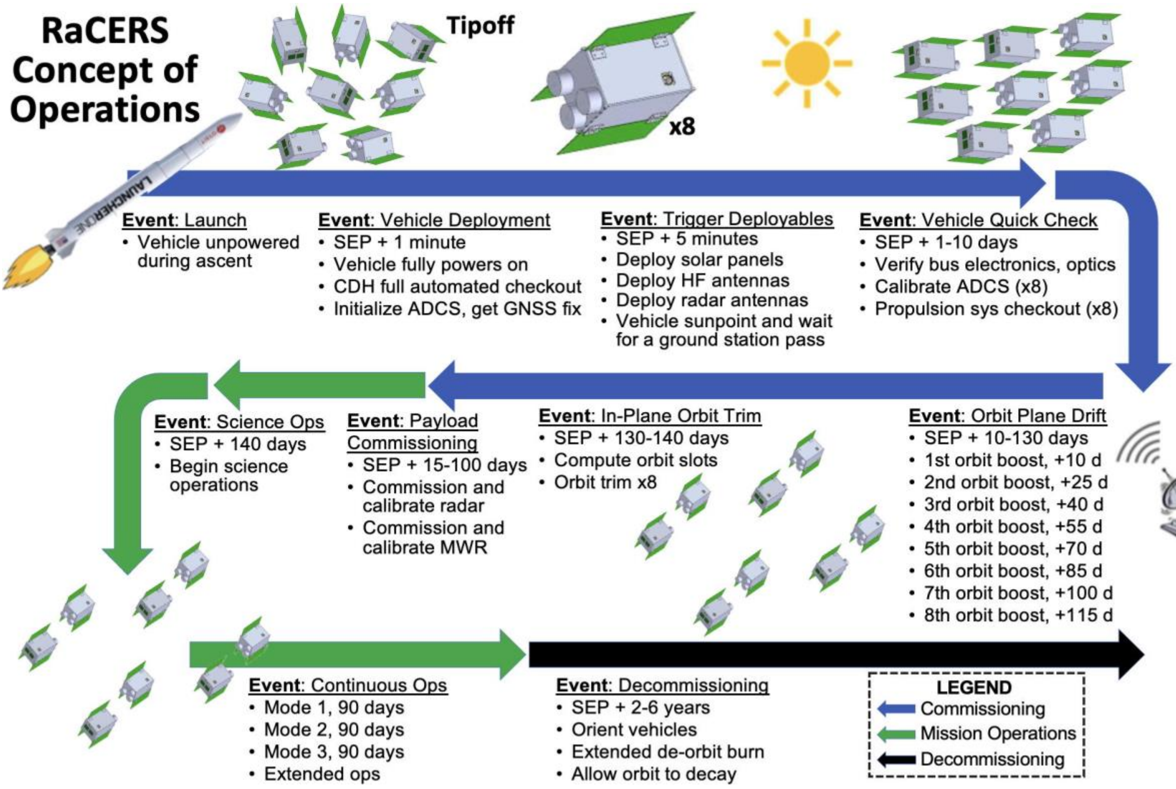


Fig. 11. *Overview of RaCERS concept of operations from launch to end-of-life.*

The ROMEO Hardware

The ROMEO engine is derived from the Trig GNSS instrument developed by JPL for few-centimeter orbit determination (Sentinal-6), gravity field mapping (GRACE-FO), and radio occultation (COSMIC-2, and others). While the TriG draws over 60W, the same performance is available in the 7W Cion, developed by GeoOptics and JPL. The Cion extracts all needed radar observables from dozens of signals at once with state-of-the-art precision, while acquiring GNSS radio occultation data and producing sub-decimeter real time orbits.

For ROMEO we've chosen for our core technology the Xilinx UltraScale+ RFSoC, which can receive up to 16 RF signals for processing and generate up to 16 signals for transmission. Critically, it offers extensive field programmable gate array (FPGA) logic for hosting ultra-high speed special purpose processing algorithms.

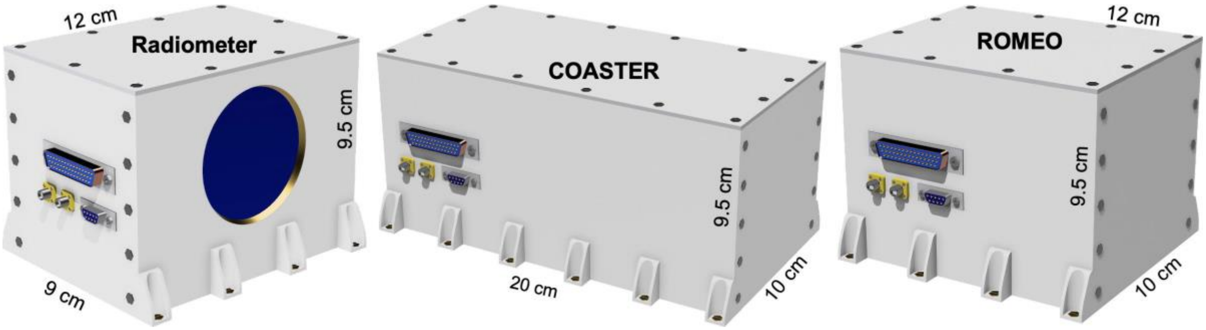


Fig. 12. *Renderings of the three principal RaCERS science subsystems.*

The Radar Electronics

Although it will be newly implemented for RaCERS with modern, high-density components, the radar electronics package is of conventional design consisting of precision C-band and Ku-band upconverters derived from a reference oscillator. The signals will be phase modulated in quadrature with PN codes having chipping rates selectable from 1-300 Mbps, fed into flight proven power amplifiers for transmission. GeoOptics recently developed similar upconverters for signals at 27 GHz and 60 GHz for gravity mapping. In comparison, the generation of radar signals at C and Ku bands is undemanding and offers countless successful examples. The three RaCERS science modules are illustrated in Fig. 12.

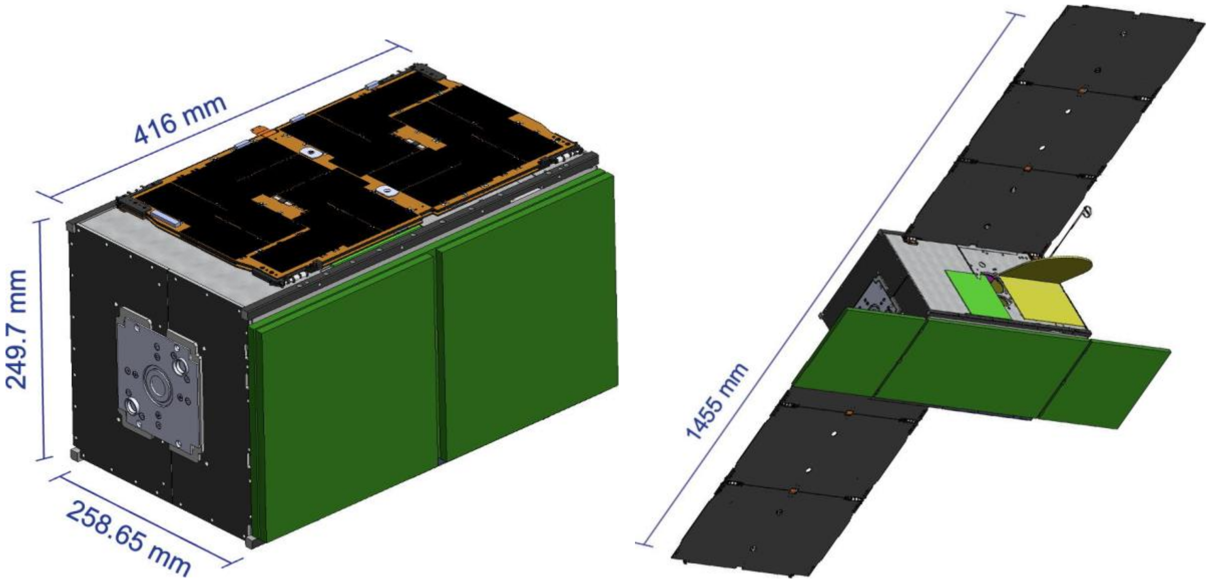


Fig. 13. Renderings of the 16U RaCERS bus, stowed and deployed

The RaCERS Bus

A low-cost 16U radar bus represents an advance over the current space radar state of the art, where operational platforms range from 100 kg to 500 kg and up and are not designed to exploit the power of cooperating swarms. Fig. 13 shows the RaCERS bus developed jointly by Tyvak International and GeoOptics, with its three-piece deployed radar antenna facing down. Fig. 14 shows the arrangement of the three science modules within the bus chassis. This is a proven spacecraft with multiple examples now flying. At present the RaCERS bus mass estimate is 30 kg including a 20% margin, well below the allowable 36 kg.

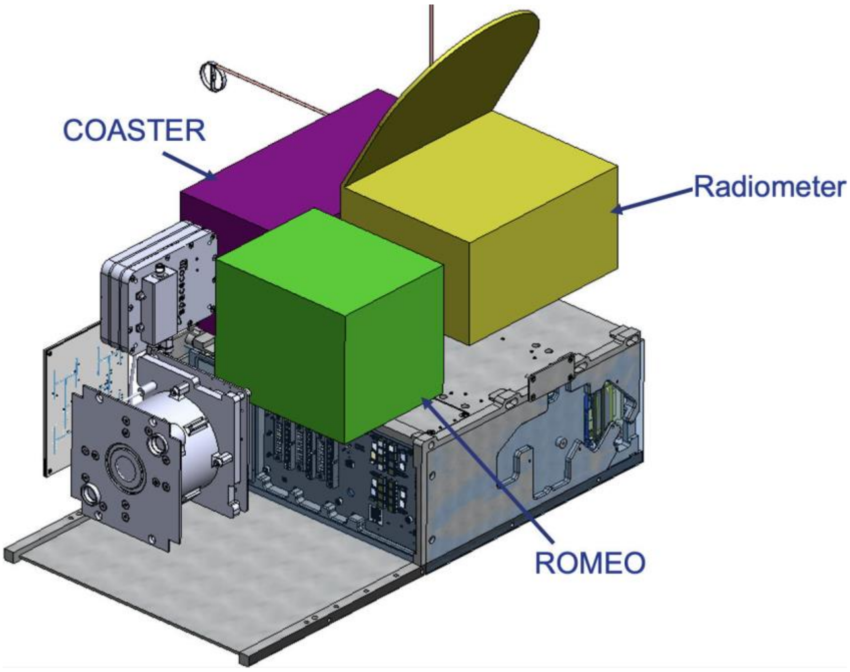


Fig. 14. Arrangement of the three science modules within the RaCERS bus

Operational Availability

With limited power we don't expect a cubesat radar to operate full time. For bistatic Alt/Scat we set a goal to provide nearly equivalent service to the Jason ocean altimetry missions. That implies nearly continuous operation over the major oceans, or a duty cycle of a little over 60%. The spacecraft will deliver about 60 W continuously after two years of operation. The radar will be off during sun pointing for charging, data downlinking and station-keeping maneuvers. Under these constraints, Alt/Scat can operate about **60%** of each orbit, just meeting our target. Surprisingly, power-hungry SAR can operate about **23%** of the time, far better than expected. This offers the real possibility, considering the swarm as a whole, of near-continuous SAR and InSAR operations. Advanced future designs that may include articulated solar panels, larger batteries, supercapacitors to store charge and increase pulse power, and both charging and data taking during downlink will extend duty cycles and further improve radar performance.

Implementation Schedule

The nominal implementation plan spans 31 months to the start of a 2-month launch window with a 3-month margin at the end. A high-level implementation schedule is shown in Fig. 15.

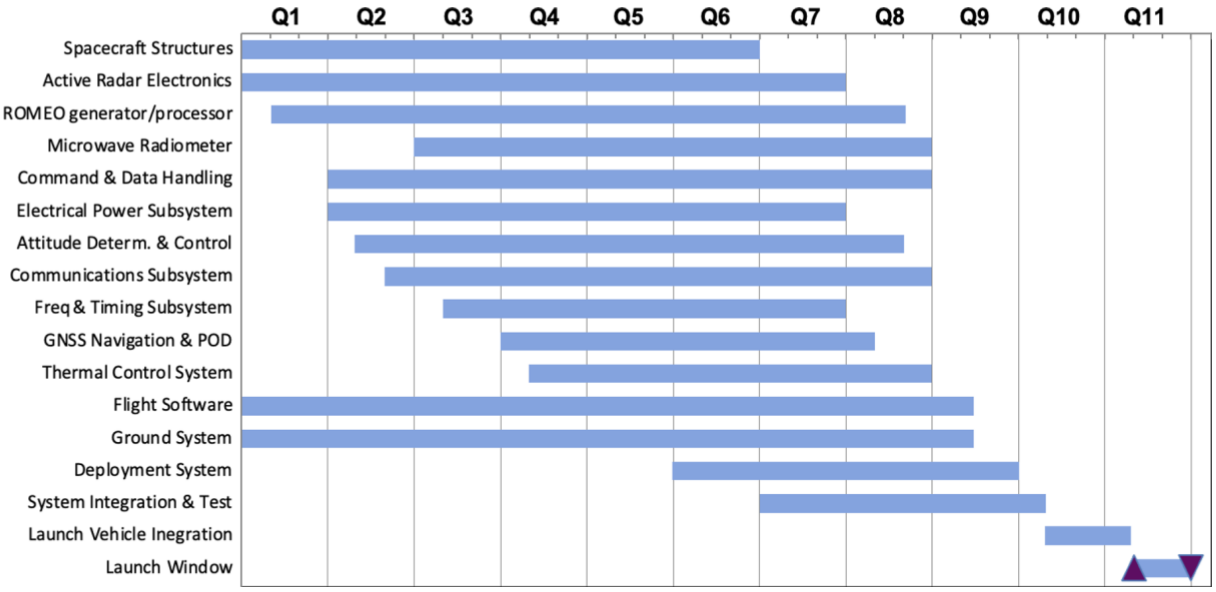


Fig. 15. *High-level 36-month implementation timeline for the eight-satellite RaCERS mission.*