Preliminary assessment of observing different regimes in the marine environment using SENTINEL-3 data

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Abstract

The Sentinel-3 constellation of Earth Observation satellites is designed to provide accurate and timely information to better manage the marine environment, and to understand and mitigate the effects of climate change by utilizing systematic measurements and products of sea-surface topography, sea-state and ecosystem characteristics over the open ocean and the regional and shelf seas. The aim of the paper is twofold: (a) to provide a brief overview of the types of data available to users from the current Sentinel-3 satellites, and (b) to outline the new features, compared to the conventional radar altimeters, and the new capabilities provided by the Sentinel-3 SRAL (SAR mode) altimeters. The presentation will show representative results based on comparative analyses using previous (conventional) and current Sentinel-3 altimetry data, in an effort to identify critical data handling aspects (i.e. data access) and associated constraints (such as primary outputs, ground coverage, etc.) vis-à-vis typical user requirements for various marine applications, especially closer to the coastal areas where the SAR altimetry method is shown to be superior to conventional systems in terms of accuracy, spatial resolution of the observations etc.

Preliminary assessment of observing different regimes in the marine environment using SAR mode altimetry data

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Abstract

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The aim of the paper is twofold: (a) to provide a brief overview of the types of new altimetry data available to users from the current Sentinel-3 satellites, and (b) to outline the new features, compared to the conventional radar altimeters, and the new capabilities provided by the Sentinel-3 SRAL (SAR mode) altimeters. The presentation will show representative results based on comparative analyses using previous (conventional) and current Sentinel-3 altimetry data, in an effort to identify critical data handling aspects (i.e. data access) and associated constraints (such as primary outputs, ground coverage, etc.) vis-à-vis typical user requirements for various marine applications, especially closer to the coastal areas where the SAR altimetry method is shown to be superior to conventional systems in terms of accuracy, spatial resolution of the observations etc.

Keywords Satellite altimetry, Sentinel-3 Mission, Marine observations, Sea Surface Topography.

1 SCOPE AND CAPABILITIES OF SATELLITE ALTIMETRY

In the 1970s, the satellite altimetry technique was initially designed to observe sea level by a combination of radar pulses used to measure the distance from the satellite to a reflecting (sea, lake or ice) surface, and positioning techniques allowing the precise location of the satellite on its orbit. These measurements yield a wealth of information about the state of the sea surface which, in turn, can be used for a wide range of marine applications – in particular, for mapping the global/regional ocean surface topography with sufficient accuracy to describe and study the marine environment, from the large-scale ocean circulation to the detailed observations of ocean mesoscale variability.

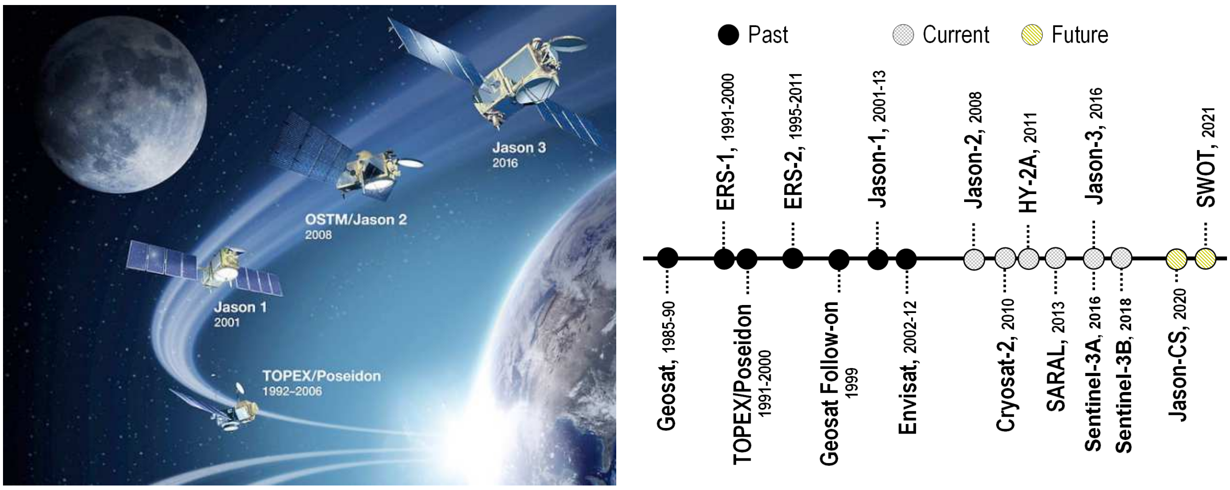


Figure 1: Past altimetry missions often used as reference (left)-Image credit NASA/JPL; Timeline of past, current, and planned missions (right)

Since 1992, a 20-year period of "continuous ocean surface measurements", with the operation of TOPEX/Poseidon, Jason-1, -2, GFO and ENVISAT as the follow-on to the ERS-1 and -2 satellites, led to an explosive growth in ocean and climate studies made possible by a longer and more accurate time series of sea surface measurements. In 2013, the launch of SARAL/AltiKa, marked the beginning of a series of new generation altimetry satellites with objectives geared towards the SWOT (Surface Water Ocean Topography) mission envisioned for 2021, and the Jason Continuity Service (Jason-CS/Sentinel 6) series of satellites planned for 2020 and 2025. The SWOT mission aims to make the first global survey of the Earth's surface water (of rivers, lakes and flooded zones) and to observe the fine details of the ocean surface topography (the ocean mesoscale and sub-mesoscale circulation), and to measure how terrestrial surface water bodies change over time (Morrow et al. 2018). It will all be done from a single satellite to be equipped with the latest altimetry concept technology: a Ku-band wide-swath interferometric altimeter (SIRAL), with multiple antennas, and capable of nadir, SAR, and InSAR mode measurements allowing better acquisition of measurements closer to the coastlines.

1.1 Saral/AltiKa and Sentinel-3 mission characteristics – New robust and stable altimetry technology advancements

Among the current altimetry satellites the SARAL and Sentinel-3 satellites provide the opportunity for systematic evaluation of the new capabilities of Ka- and Ku-band altimeters for fine resolution along-track applications, including for new coastal and inland water applications, which will also help further developments for the future Swot mission.

The SARAL (*Satellite with **AR**gos and **AL**tiKa*) mission is considered to be complementary to the Jason-2 mission and serving as a gap filler between the Envisat and the Sentinel-3 missions. SARAL's AltiKa altimeter is the first oceanographic altimeter working in the Ka-band (35.75 GHz) at a pulse repetition frequency of 4000 Hz, whereas conventional Ku-band altimeters operate at a pulse repetition frequency of 2000 Hz. Such a high radar signal frequency enables better observation of ice, rain, coastal zones, land masses (forests, etc.), and wave heights for coastal, inland waters and ice applications. Furthermore, the Ka-band (as compared to altimeters operating at Ku-band) is much less affected by the ionosphere, and has greater performance in terms of vertical resolution, time decorrelation of the radar echoes, spatial resolution and range noise. On the other hand, its main drawback is that Ka-band electromagnetic waves are sensitive to strong (>1.5 mm/h) rain rates which, nevertheless, only occur globally 10% of the time, and mostly in the Tropics.

The Sentinel-3 mission is dedicated to providing operational oceanographic services within the frame of the European Union's *Global Monitoring of Environment and Security* (GMES) programme. Using multiple state-of-the-art sensing instruments (such as the *Sea and Land Surface Temperature Radiometer/SLSTR*, the *Ocean and Land Colour Instrument/OLCI*, the *SAR Altimeter/SRAL*, and the *Microwave Radiometer/MWR*), two satellites are already in orbit (the Sentinel-3A and -3B available since 2016 and April 2018 respectively), and two more satellites are scheduled to be launched by 2021. Their sensors deliver high-quality measurements for determining the sea surface topography, significant wave height (SWH), sea-surface temperature and ocean-surface color parameters, all with dense global coverage.

The Sentinel-3 SRAL altimeter is a nadir-looking radar designed with many "dual-functionality" technical characteristics such as: dual frequency signals for sea surface measurements in the Ku-band (13.575 GHz, bandwidth = 350 MHz) and C-band (5.41 GHz, bandwidth = 320 MHz); dual radar modes, with the conventional altimeter pulse *Low Resolution Mode* (LRM), providing sea surface topography measurements approximately every 7 km, and the SAR mode for along-track *High Resolution Mode* (approximately every 300 m) composed of combined bursts of Ku- and C-band pulses (cf. Fig. 2); and dual, closed-loop (traditional) and open-loop tracking modes for better monitoring of the radar return pulses and the corresponding waveforms over rough surfaces. In addition, the SRAL altimeter is supported by a dual frequency (23.8/36.5 GHz) microwave radiometer measuring atmospheric humidity as supplementary information for added precision of the tropospheric path correction of the altimeter signal, as well as a DORIS (Doppler Orbitography and Radiopositioning) and a GNSS receiver, and a laser retroreflector for precise orbit positioning.

In order to address the differing user needs for various applications in both the online and offline domains, the Sentinel-3 altimetry data products are disseminated at various pre-processing levels (e.g. Product Level-1, -2, -3, -4); according to the surfaces covered by the data (e.g. WAT (water) or LAN (land)); and by geographical region (global or regional). There are also delivered with differing turnaround (availability) timelines, as: *Near Real-Time* (NRT), *Short-Time-Critical* (STC) and Non-

Time-Critical (NTC) products which are made available to the users within 3 and 48 hours and 1 month after acquisition, respectively. For many marine applications (e.g. ocean weather forecasts) the 48-hour turnaround of the STC products may still be considered as near real time.

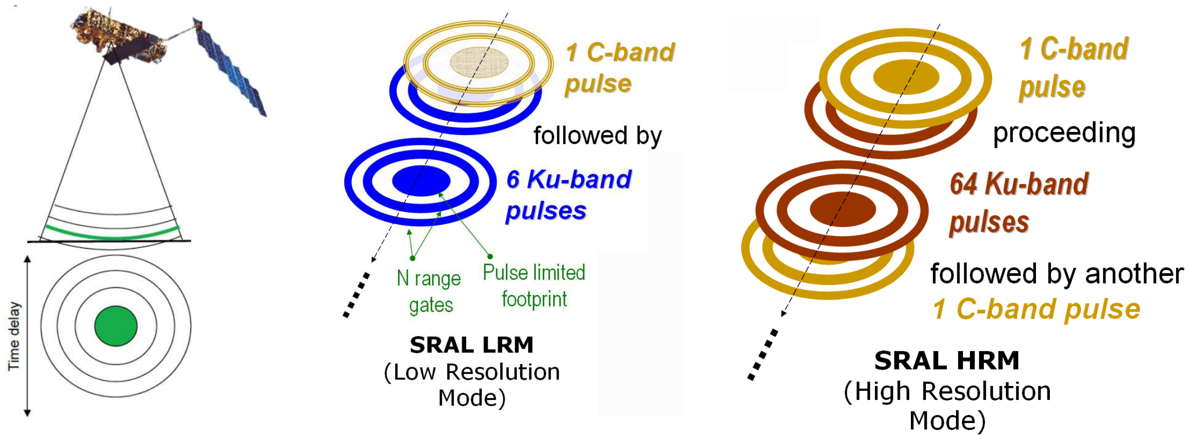
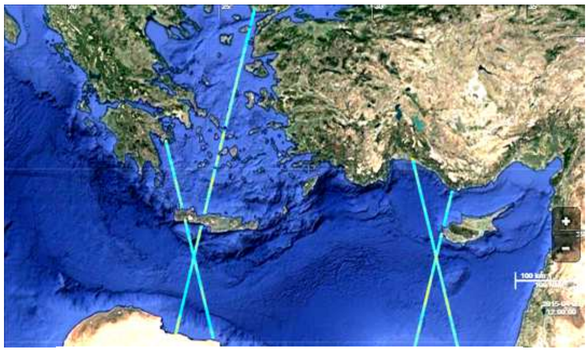


Figure 2: Schematics of conventional LRM altimetry (left), Patterns of radar pulses in SRAL's LRM and HRM radar cycles respectively(middle and right)

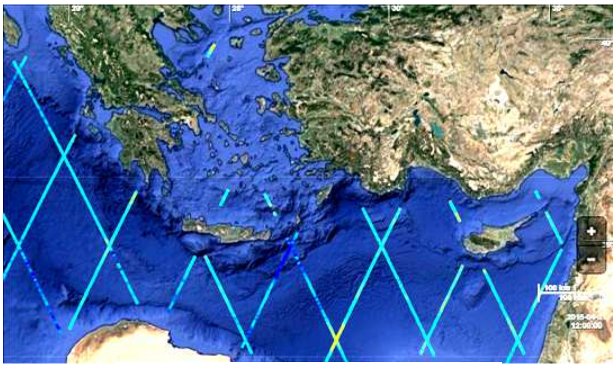
2 USAGE OF SATELLITE ALTIMETRY IN COASTAL AREAS

Conventional satellite altimetry has had large success over the open ocean, the domain for which it was originally designed. In this endeavor, the unique combination of day/night and all weather operation, global coverage of high resolution sea state-related measurements along tracks of the sea surface with the possibility of revisiting the some marine locations regularly makes it possible to provide a detailed global picture of sea level and monitor its spatial-temporal changes routinely.

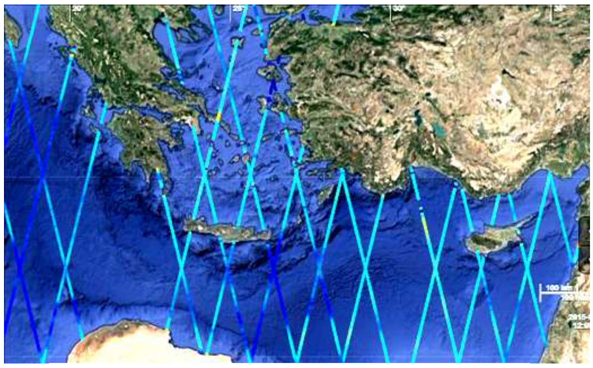
(a) 9-11 April 2015, Jason-2 tracks



(b) 8-10 April 2015, SARAL/AltiKa tracks



(c) 14-27 April 2015, Jason-2 tracks



(b) 14-27 April 2015, SARAL/AltiKa tracks

Figure 3 Altimetry data availability from the conventional vis-à-vis the new generation altimeters

On the other hand, the processing strategies used in analyzing altimetry data from the open ocean are not fully exploited to their full potential in getting sea level information in the coastal zones, i.e. in the domain that should be of interest to a broad range of marine data users that have an interest in using altimeter data from the coastal regions in their operational products or services.

From the viewpoint of altimetry data usage, coastal zones (usually within a few tens of kilometers from a coast) present a more complex environment where water conditions change all the time. In such areas, altimetry data from the conventional satellite missions are often discarded as exhibiting extreme noise levels making it difficult to interpret or model land contamination effects on the altimetric waveforms (Idris et al., 2014; Vignudelli, 2011). As a result, utilizing coastal altimetry data becomes a more complicated task mainly due to the intrinsic difficulties in performing a computationally intense 'retracking' of the observed waveforms and to correct the estimation of various critical geophysical parameters (i.e. sea level anomalies (SLA), significant wave height and wind speed). The practical implication is that for the purpose of retrieving SLAs near coastal zones, particular attention is also needed when applying the corrections of sea states (e.g. inverse barometer and sea state bias), oceanic signals and tides, and of the atmospheric effects on the radar signals (e.g. wet and dry tropospheric components, ionospheric delays, and high-frequency wind and pressure (barometric) response to atmospheric forcing which otherwise are less accurate due to high variability of the sea surface closer to the coasts.

Figure 3 illustrates the coverage and data availability constraining factors of the conventional LRM altimeters vis-à-vis the new capabilities made available with the newer generation SAR altimeters. In Fig. 3(a), the 3-day altimetry tracks of Jason-2 stop providing data when the satellite crosses over the Aegean islands. By contrast, as shown in Fig. 3(b), similar 3-day altimetry tracks of SARAL/AltiKa provide continuous data coverage over the same area. Respectively, Fig. 3(c) and 3(d) show analogous situations over a 2-week period, with the SARAL tracks providing good continuous spatial sampling over the Aegean region. Practically, this means that in order to provide homogeneous maps of sea level would require analysis and homogenization of the data from multiple altimeters typically on at least biweekly basis. Furthermore, together with the ground-tracks repeatability patterns and the dense spatial sampling achieved due to the orbital characteristics of the different satellites, it is now possible to acquire very accurate marine topography data over all types of surfaces (sea, coastal areas, sea ice, ice sheets, ice margins, and in-land waters). All these factors provide significant advantages in many marine applications gearing towards the management of the marine environment, e.g.: the support of coastal and offshore operations, the monitoring of wave propagation and the protection of the coastal zones against extreme environmental conditions, and the location of 'hot spot areas' suitable for deploying wind and wave systems for sustainable energy conversion and exploitation.

This improved performance of the SAR altimeters in coastal zones is largely due to the way both the time delay and the Doppler shift of the radar pulse echoes are recorded. Firstly, in a similar manner to the conventional pulse-limited LRM, the observed time delay indicates which annulus or ring of constant return signal strength (i.e., range gate) about the nadir point is contributing to the returned pulse energy. In addition, the measured Doppler shift gives the position fore or aft of the satellite flight direction, thus providing a much finer spatial resolution, nominally as narrow as 300 m in the along-track and 1.64 km in the across-track directions. A SAR altimeter thus provides multi-look viewing for each sub-satellite point; range correction then aligns these multiple records for a given point within a "waveform stack". An incoherent sum over all look directions gives a SAR waveform, which is sharper than an LRM waveform because of the finer footprint achieved through Doppler processing, and has a lower noise level due to the higher number of pulses averaged.

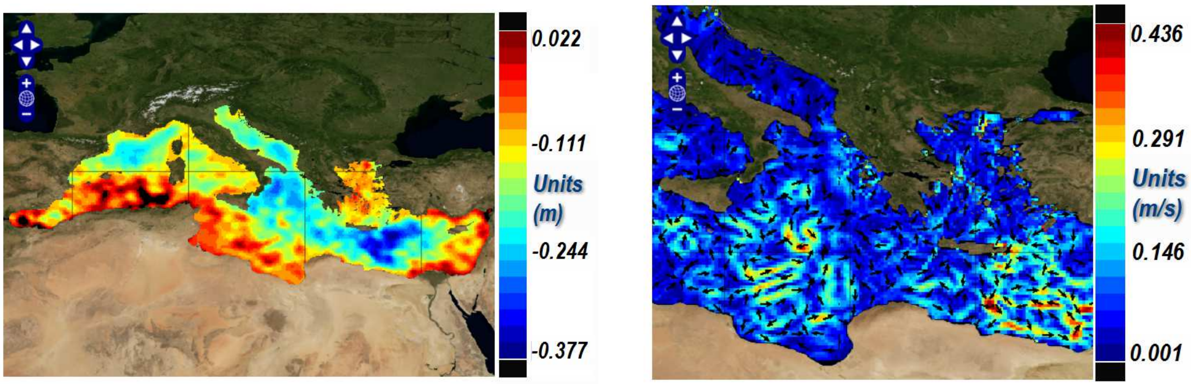


Figure 4: Regional patterns of observed sea level anomalies (left), and velocity field (right)

Overall, with the new SAR mode altimeters, combining data from several of the currently operational satellites gives a better space/time resolution (typically at scales of 50 km to 500 km and 10 days to 100 days respectively), and thus enable to observe nearly the full spectrum of the sea-level and ocean circulation variations. Typical examples are shown, in Fig. 4, where on the left is a map of regional patterns in sea level anomalies (in m), SLA_N=SSH – MSS_N, expressing the dynamic part of the SSH signal, for day 1/4/2019 from NRT data, as deduced from the combination of gridded, multi-mission altimetry sea surface heights with respect to a twenty-year mean sea surface ($MSS_{N=20}$) since 1993. Such maps enable local sea surface slopes to be estimated with high resolution (¼ degree), as shown on the map in Fig. 4 (right) which, for the same day, depicts the geostrophic velocity field of the sea surface. Such maps are useful because the sea surface slopes relative to the geoid basically carry the information on the ocean surface circulation, and can be used for many applications, from the assimilation of altimetric data into operational ocean forecasting systems, to the study of eddy-mean interactions, the computation of volume transport, and the monitoring of ocean currents. Similarly, Fig. 5 (left) and Fig. 5 (right) depict respectively, the along-track variations and a composite map of the Absolute Dynamic Topography of the sea surface, as deduced from the combination of gridded, multi-mission-derived SLAs using the Mean Dynamic Topography (MDT), $MDT_N = MSS_N - geoid$, which is the temporal mean of the SSHs above the geoid, over a period of N years (N=20 in this case). That is: $ADT = SLA_N + MDT_N = SSH - MSS_N + MDT_N$.

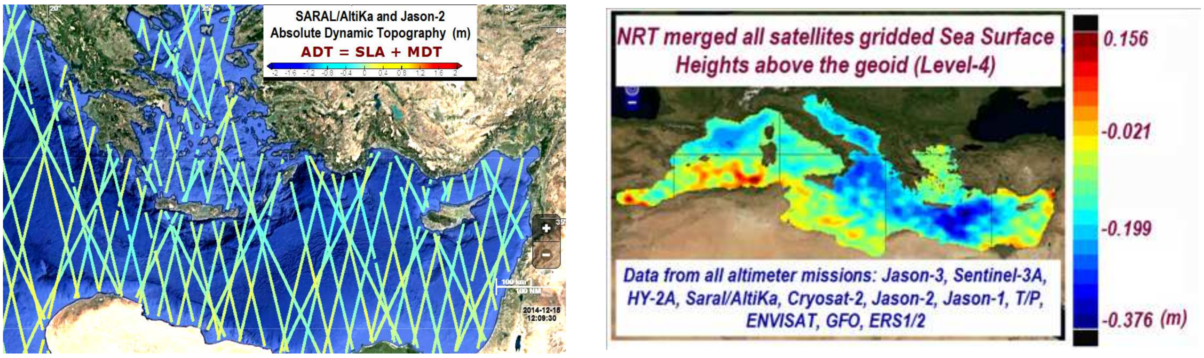


Figure 5 Multi-mission altimetry data availability enables to observe nearly the full spectrum of the sea-level and ocean circulation variations

3 SUMMARY

On the way to the future SWOT mission, the SARAL/AltiKa and Sentinel-3 satellites provide operational wide-swath high-quality altimetry measurements for open ocean, coastal and atmospheric applications requiring accurate information from sea and lake surface height, and significant wave height and surface wind speed, to sea ice height and thickness. Especially, near the coasts (and more so for inland waters) where the precision of conventional altimeters decreases, SAR altimetry measurements contain extremely useful information, allowing to get closer to the coasts or over continental water bodies with a better coverage and with good quality data.

References

Idris NH, Deng X and Andersen OB (2014) The importance of coastal altimetry retracking and detiding: a case study around the Great Barrier Reef, Australia Int. Journal of Remote Sensing 35(5): p 1729-1740

Morrow R, Blumstein D, and Dibarboure G (2018): Fine-scale altimetry and the future SWOT mission. In "New Frontiers in Operational Oceanography", E. Chassignet, A. Pascual, J. Tintoré, and J. Verron, Eds., GODAE OceanView, 191-226, doi:10.17125/gov2018.ch08

Seitz BC, Mavrocordatos C, Rebhan H, Nieke J, Klein U, Borde F and Berruti B (2018): The Sentinel-3 mission overview. In 2010 IEEE International Geosciences and Remote Sensing Symposium, 25-30 July; **DOI:** 10.1109/IGARSS.2010.5650772

Vignudelli S, Kostianoy AG, Cipollini P and Benveniste J (2011) Coastal altimetry (Berlin: Springer)

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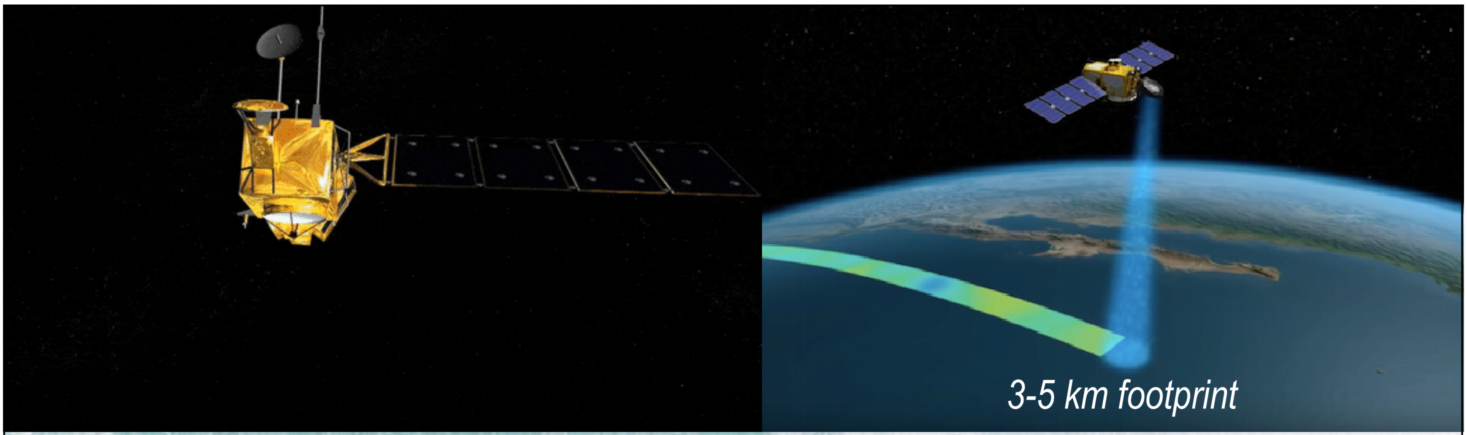
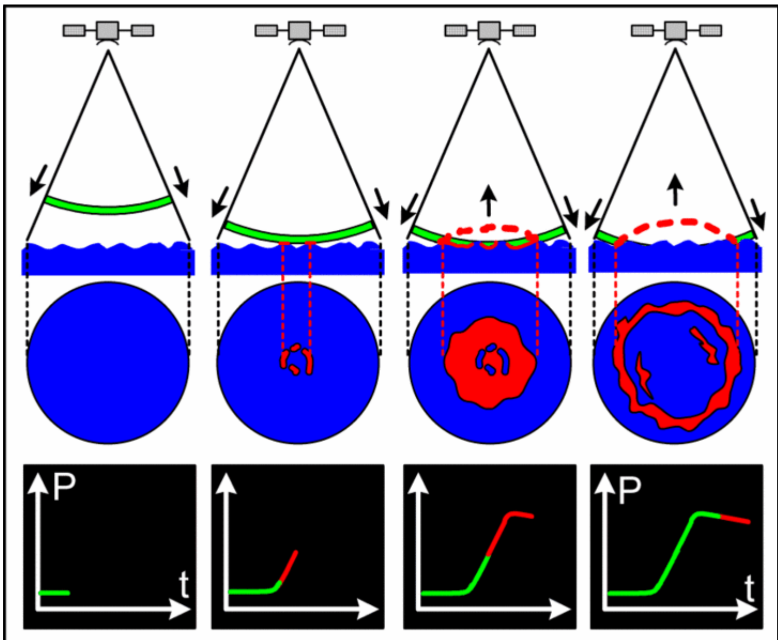
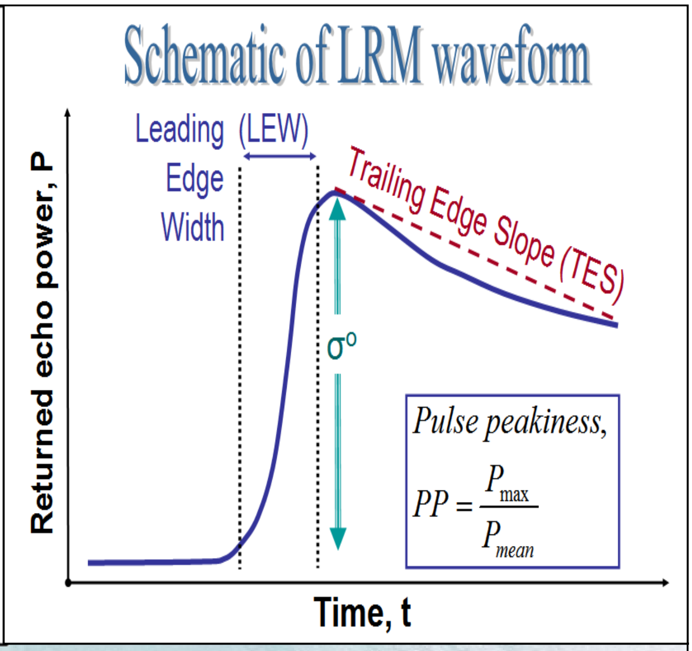
Satellite altimetry

- One of the mature and most important space techniques for marine studies.
- Over 30 years heritage *(17 satellites and counting)*:
  - Large scale of ocean information including
    - wind speed, ocean currents, sea surface and significant wave heights, tides, ocean depth, ...

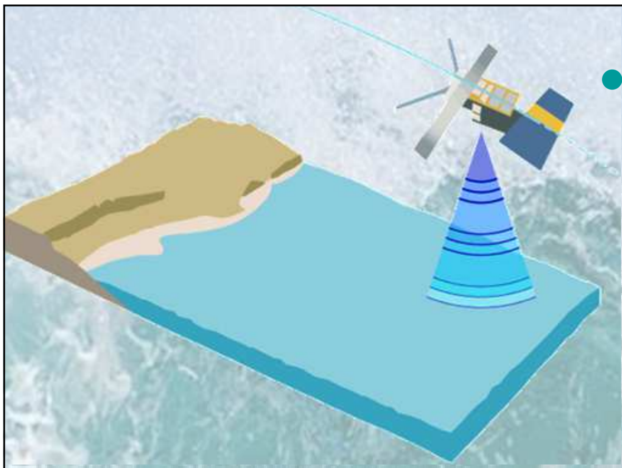


- Conventional space borne altimeters transmit modulated radar pulses towards the sea *at nadir* (but *with no swath coverage*), and then record the returned echoes which were reflected from the sea surface in an *altimeter footprint*
- The time series of the power of received echoes is usually known as *"waveform"*.

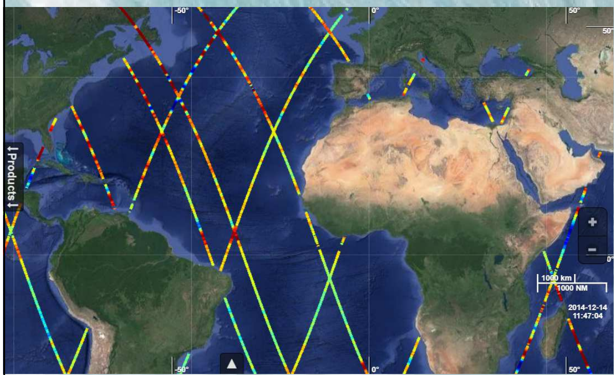


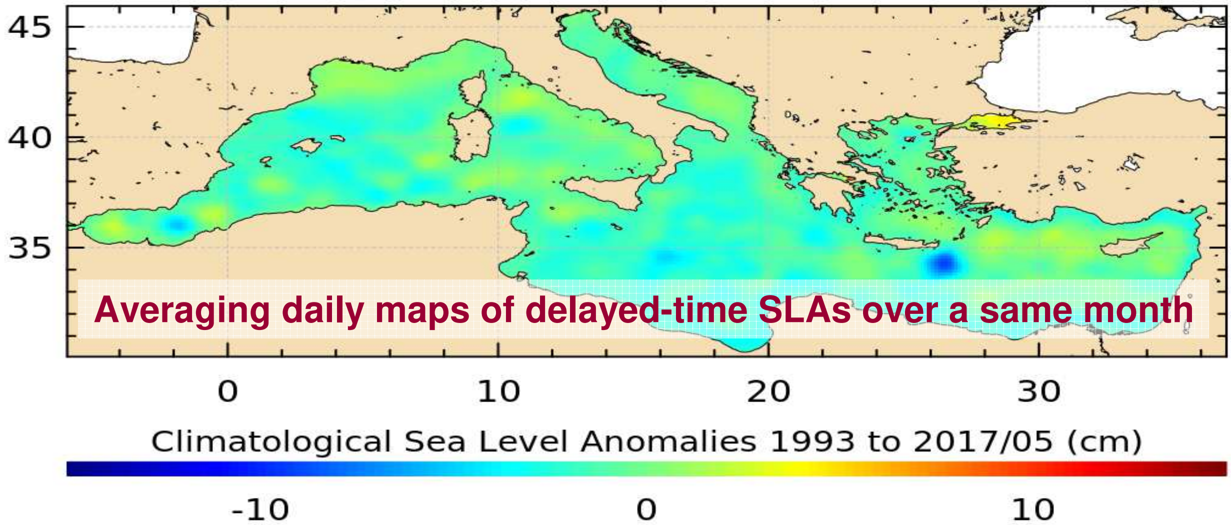


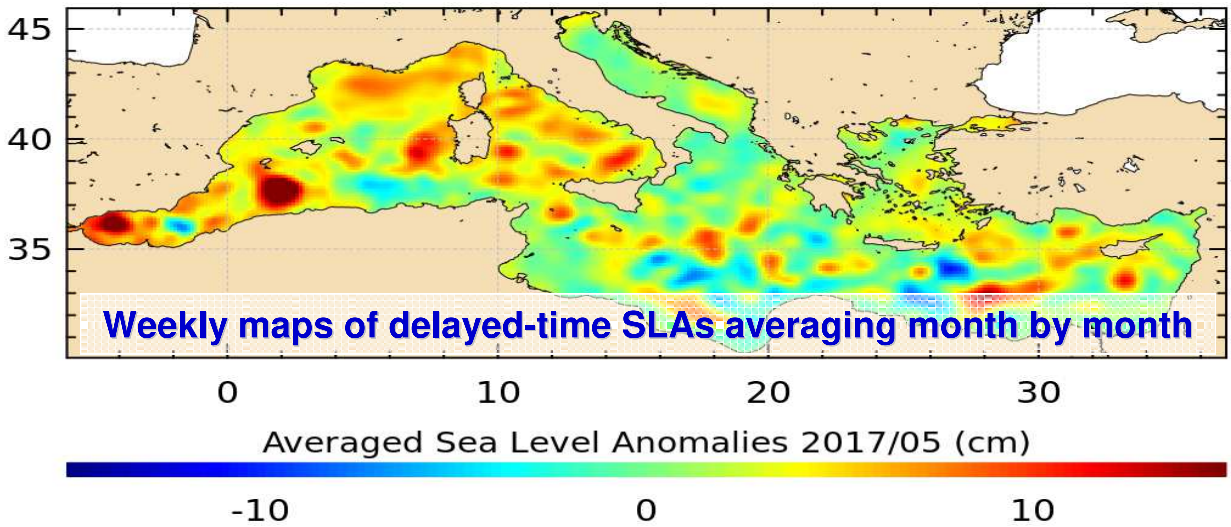
- Parameters of interest (derived from the waveforms):
  - Satellite Height above the sea surface (range),
  - the Significant Wave Height (SWH) and
  - a Backscatter Coefficient (σ^o) related to sea surface wind



- Over the open ocean satellite altimetry is rather well understood, and has been used extensively in measuring *the dynamic state of the sea surface →* *the "mesoscale variability" (eddies & currents)*
- The orbit of an altimetry satellite is a compromise between *spatial resolution (distace between two ground tracks)* and *temporal resolution (period between two revisits)*

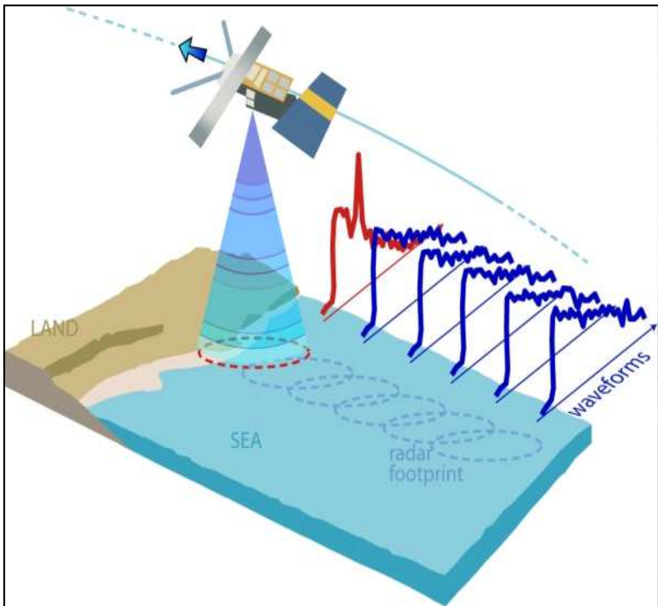






- Close to the coasts (<20 km), sea surface conditions are influenced by: currents, tides, wind speed direction and strength, …

→ All these parameters are highly variable over continental shelves, and have an impact on the shape of the altimetry waveforms

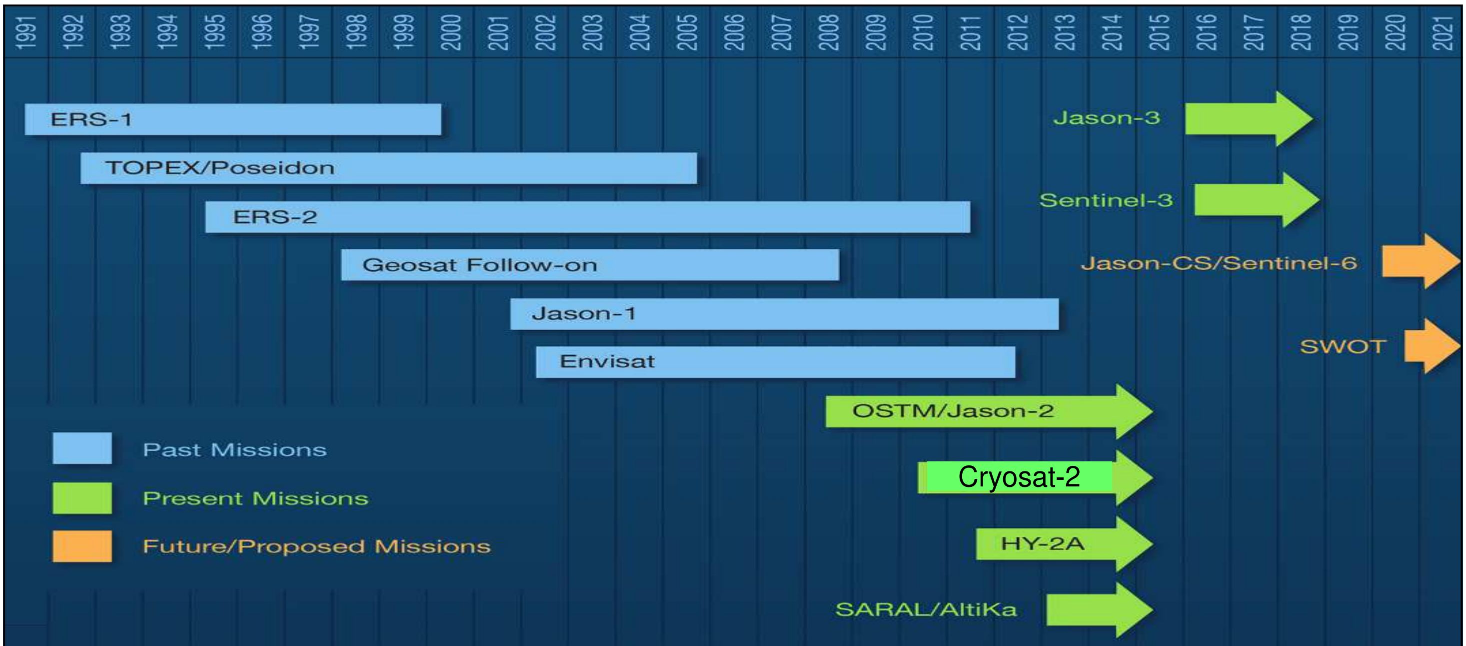


- Coastal data (from conventional altimeters) normally are “flagged” as “bad” (and are usually discarded), due to *land contamination in the altimeter footprint* and *intrinsic limitations in the corrections* applied to the signal → Stricter processing requirements:
  - Improved geophysical corrections (wet troposphere, tidal modeling, …)
  - New radar waveform processing strategies (retracking)

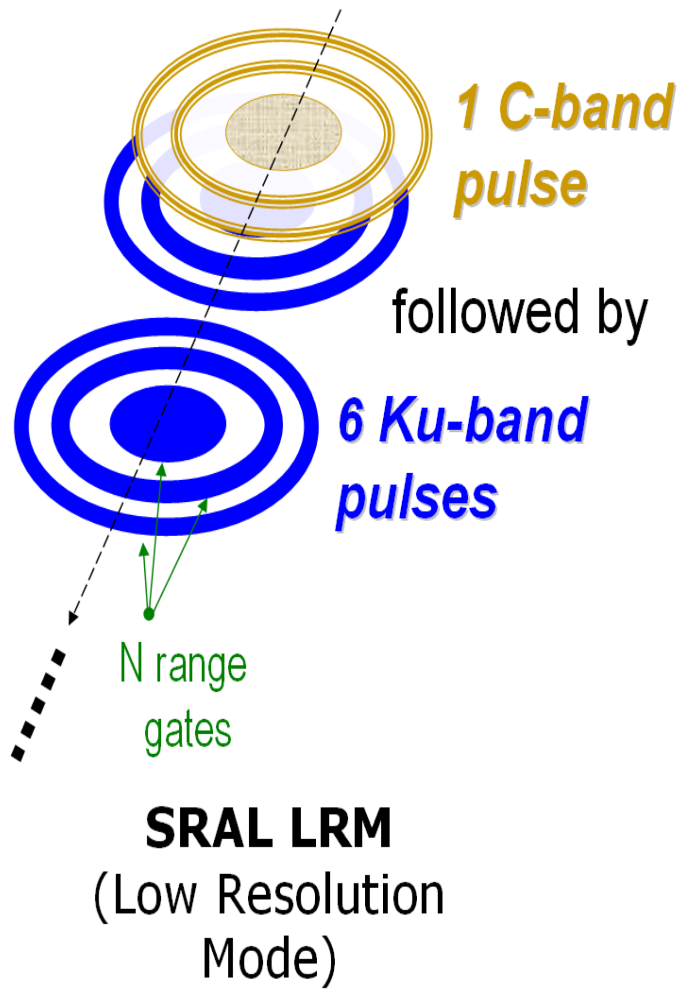
- The offshore/coastal zones, including many stretches where satellite altimetry may provide the only data coverage, are of utmost importance → Need to improve altimetry data products close to land including inland waters

What is done to improve on this ?

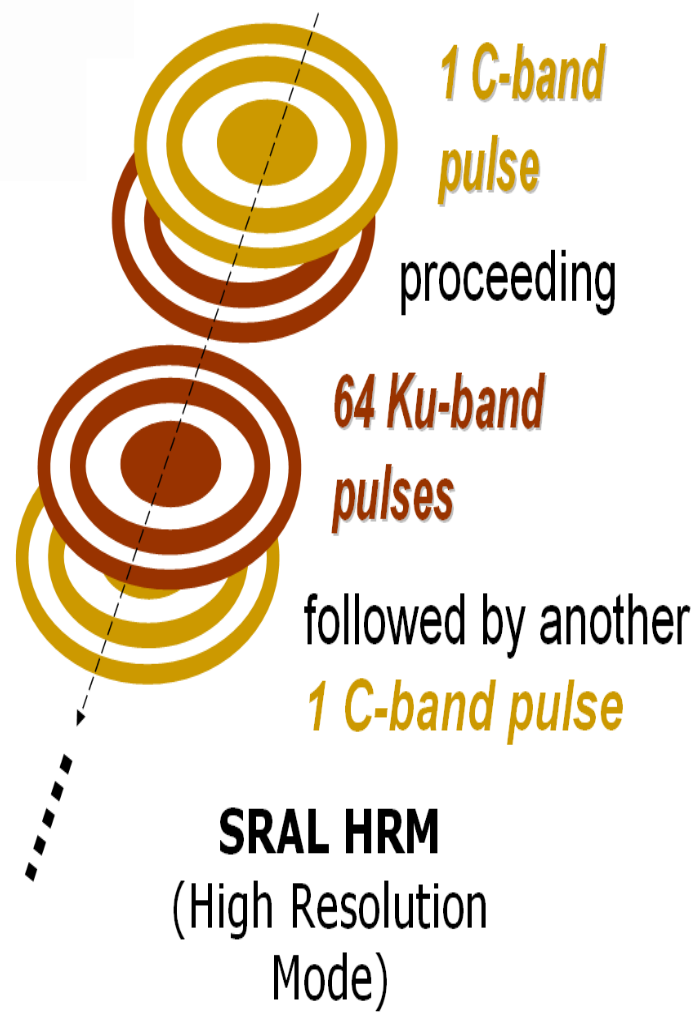
– More innovative processing (still quite essential)
– New generation altimeters (two radar antennas for interferometric measurements)



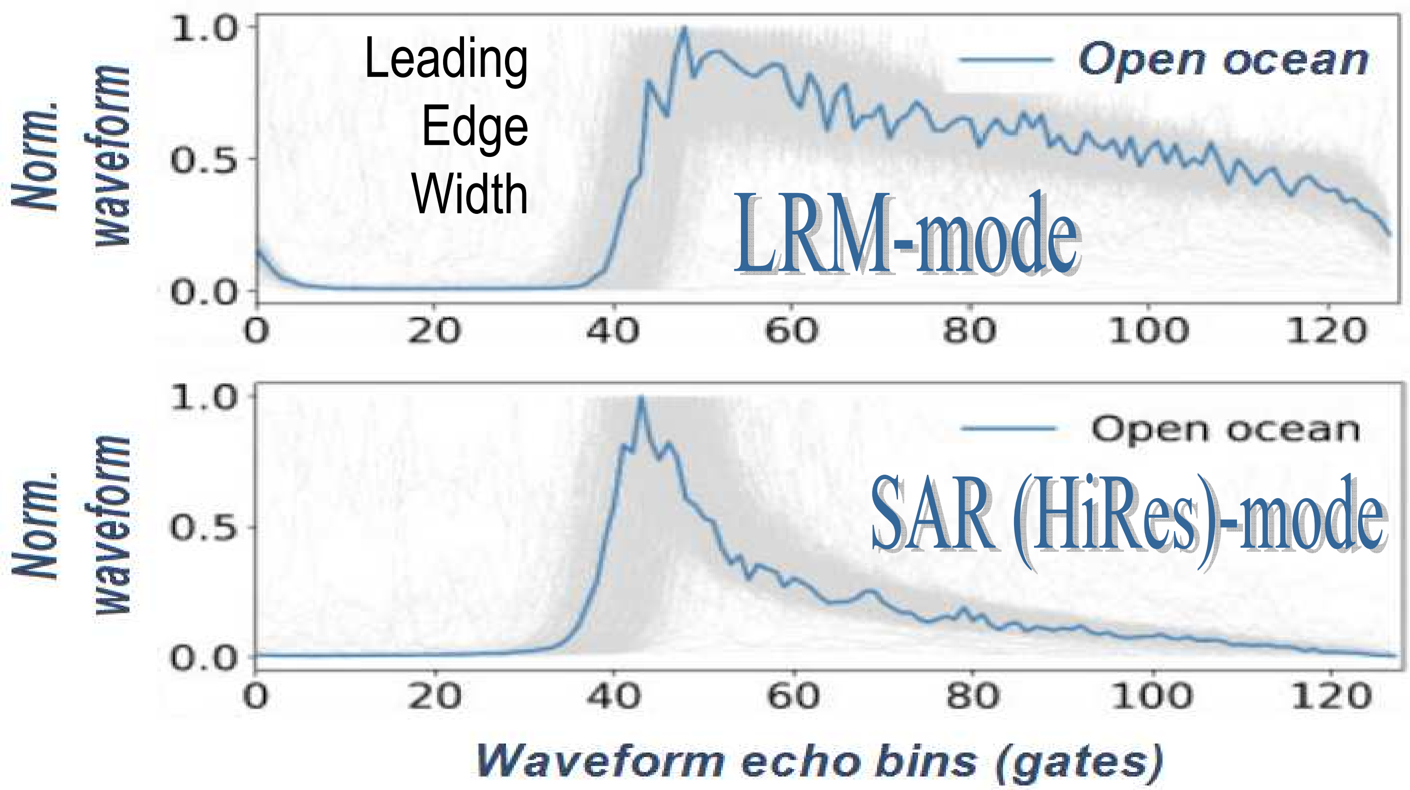
- Modern altimetry missions → new altimeters developed to exploit the quality of high-resolution data for enhancing the sea level mapping at coastal regions → *Delay-Doppler (or SAR) Altimetry*



- LRM is the conventional pulse-limited altimeter operation (back-up mode for the Sentinel-3 missions)
- Patterns of six Ku-band pulses surrounded by one C-band pulse → used for ionospheric bias correction.
  - 84 Ku-band and 14 C-band pulses accumulated over a 50 ms cycle



- SAR patterns of 64 coherent Ku-band pulses
  - Emitted in a burst surrounded by two C-band pulses.
- Duration of a burst cycle approximately 12.5 ms → *a four-burst cycle is equal to the LRM cycle of 50 ms.*
- Echo received from each pulse sampled on 128 gates.



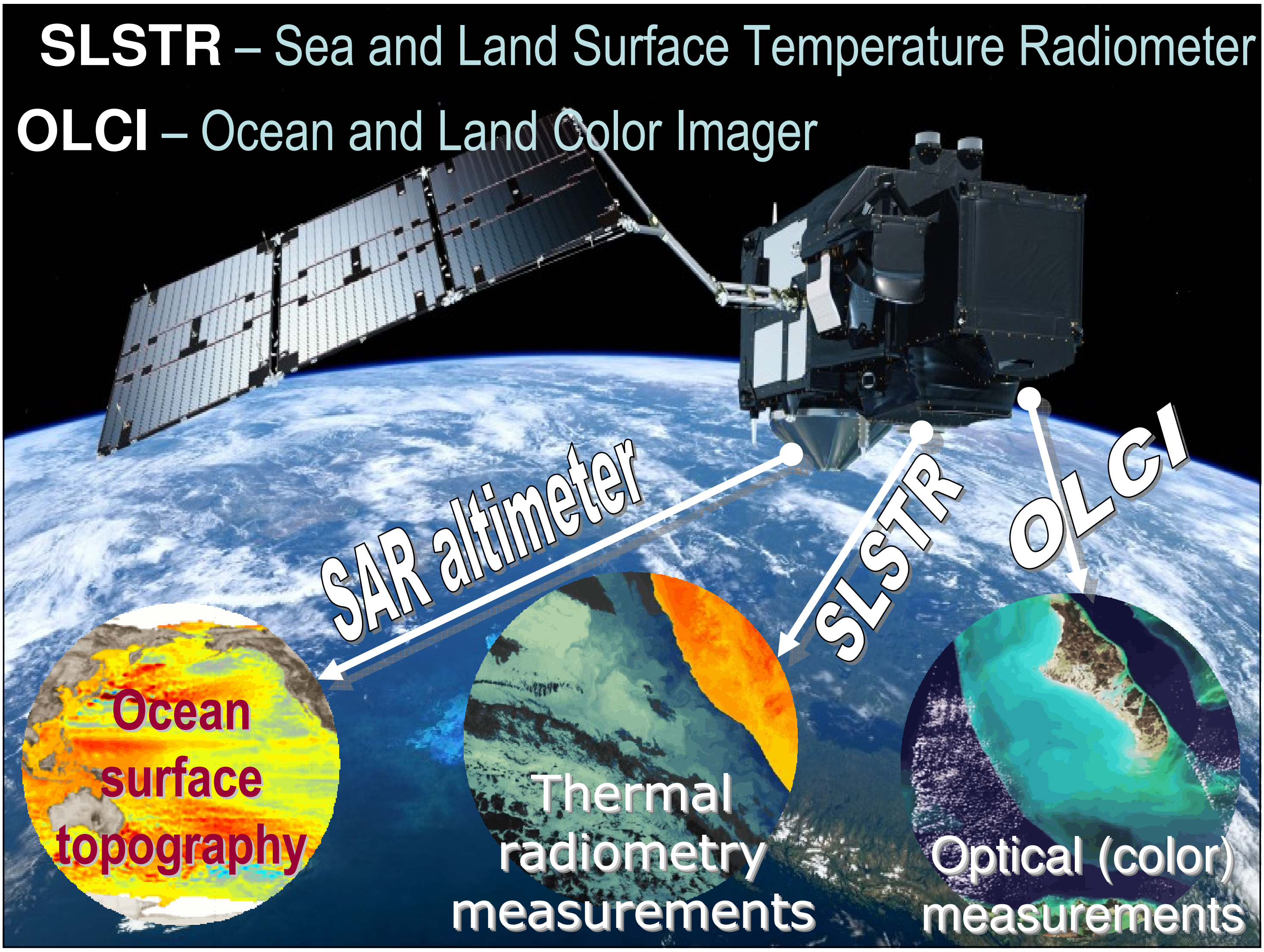
- Differences are mainly in the shape of the waveforms and the SNR for the echoes being modelled

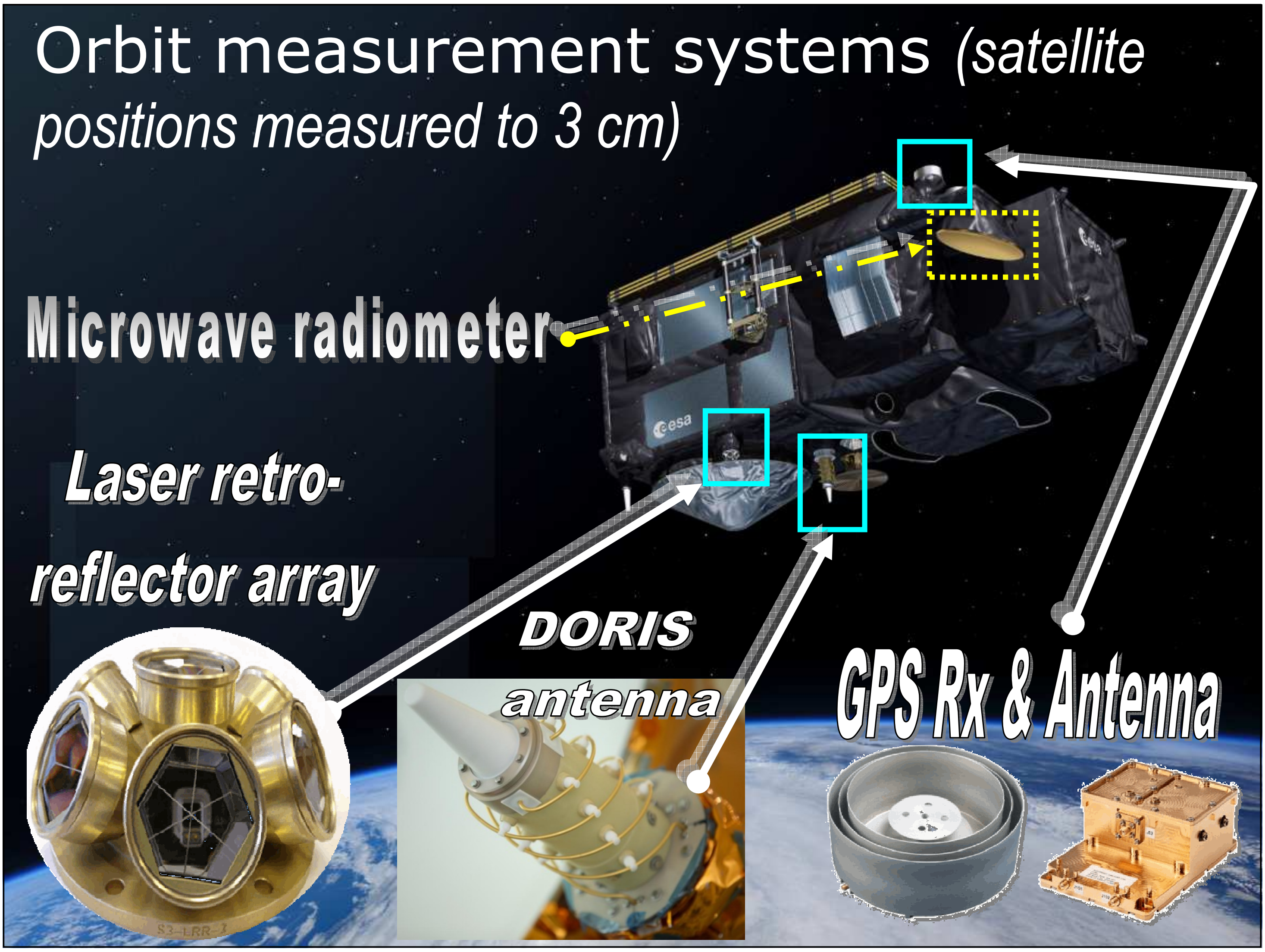
Copernicus' Sentinel Satellites

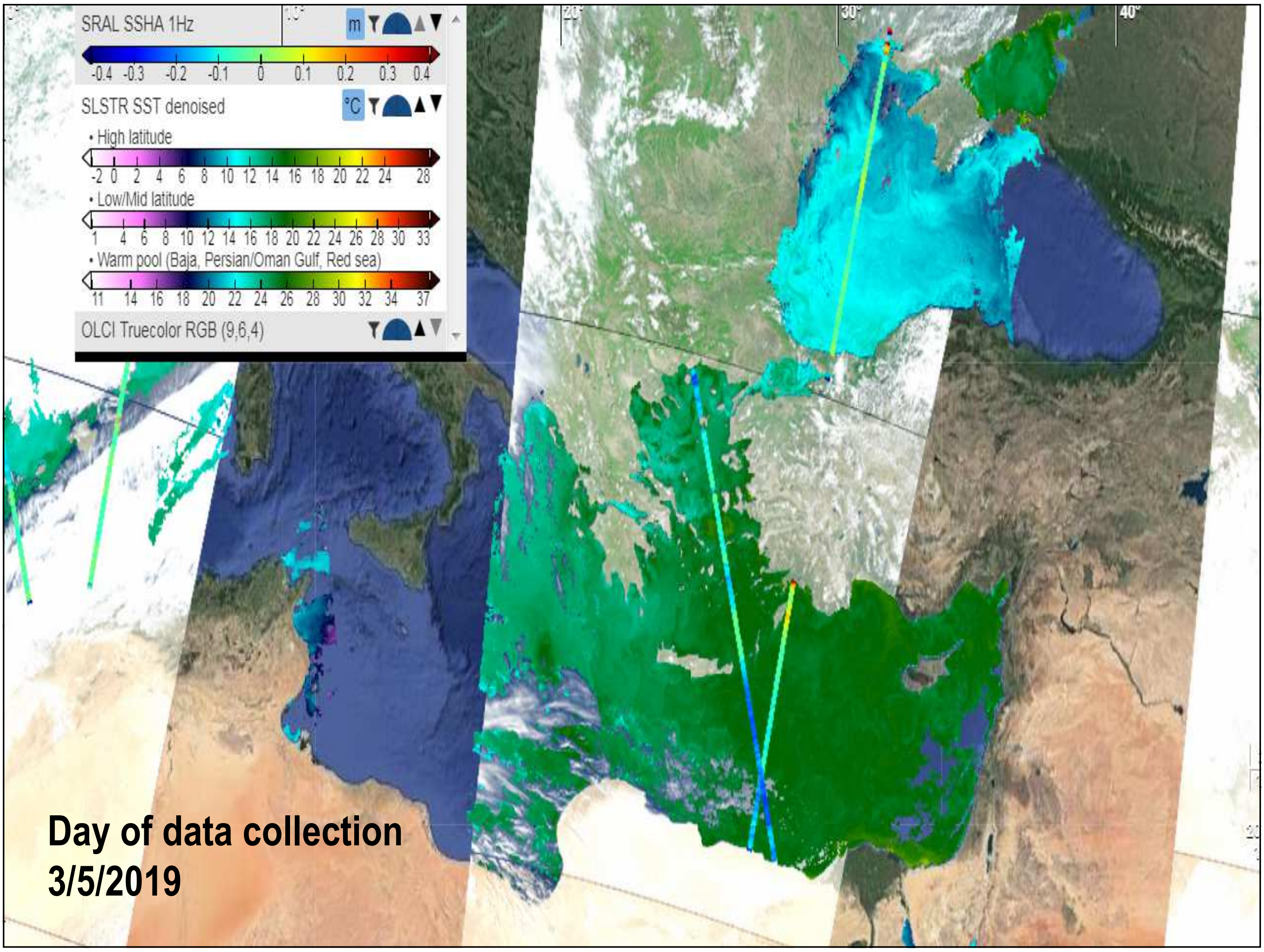
- ESA/EU led programme for operational monitoring the state of the oceans, land, ice and atmosphere

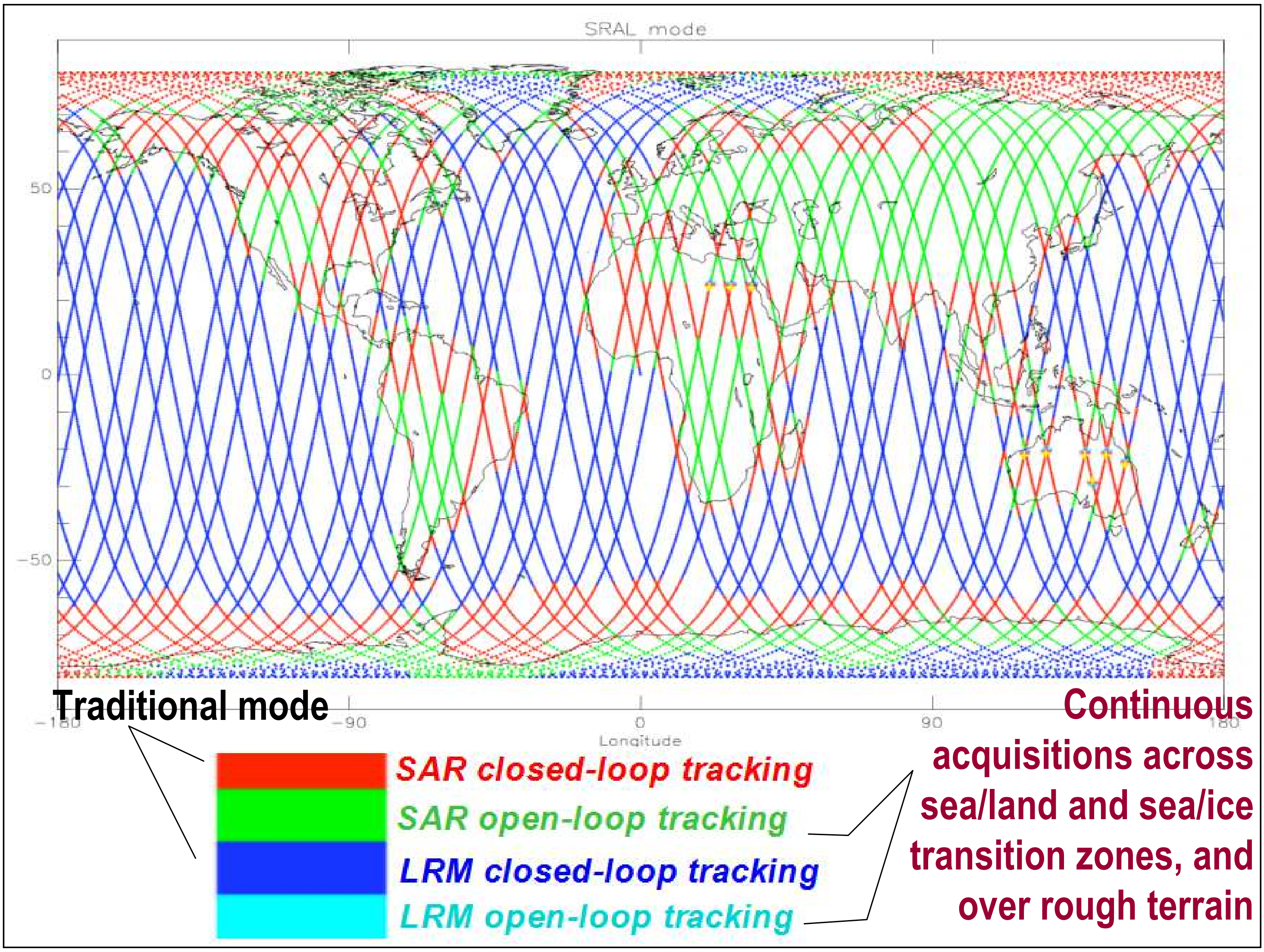
Copernicus

- "Sentinels": 6 EO missions, each with twin satellites designed to fulfill specific revisit and coverage requirements → robust datasets

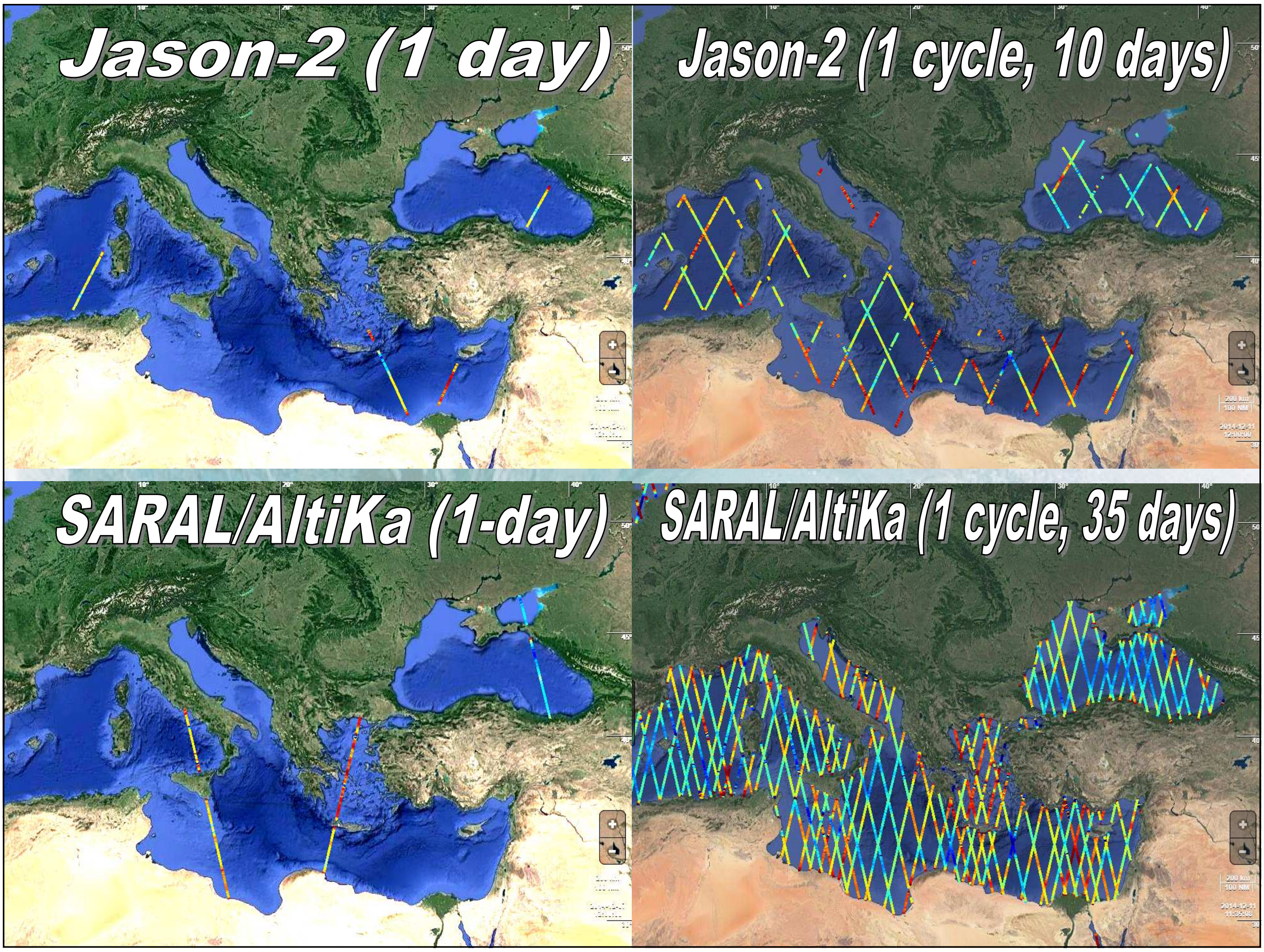

SLSTR – Sea and Land Surface Temperature Radiometer
OLCI – Ocean and Land Color Imager
SAR altimeter
SLSTR
OLCI
Ocean surface topography
Thermal radiometry measurements
Optical (color) measurements

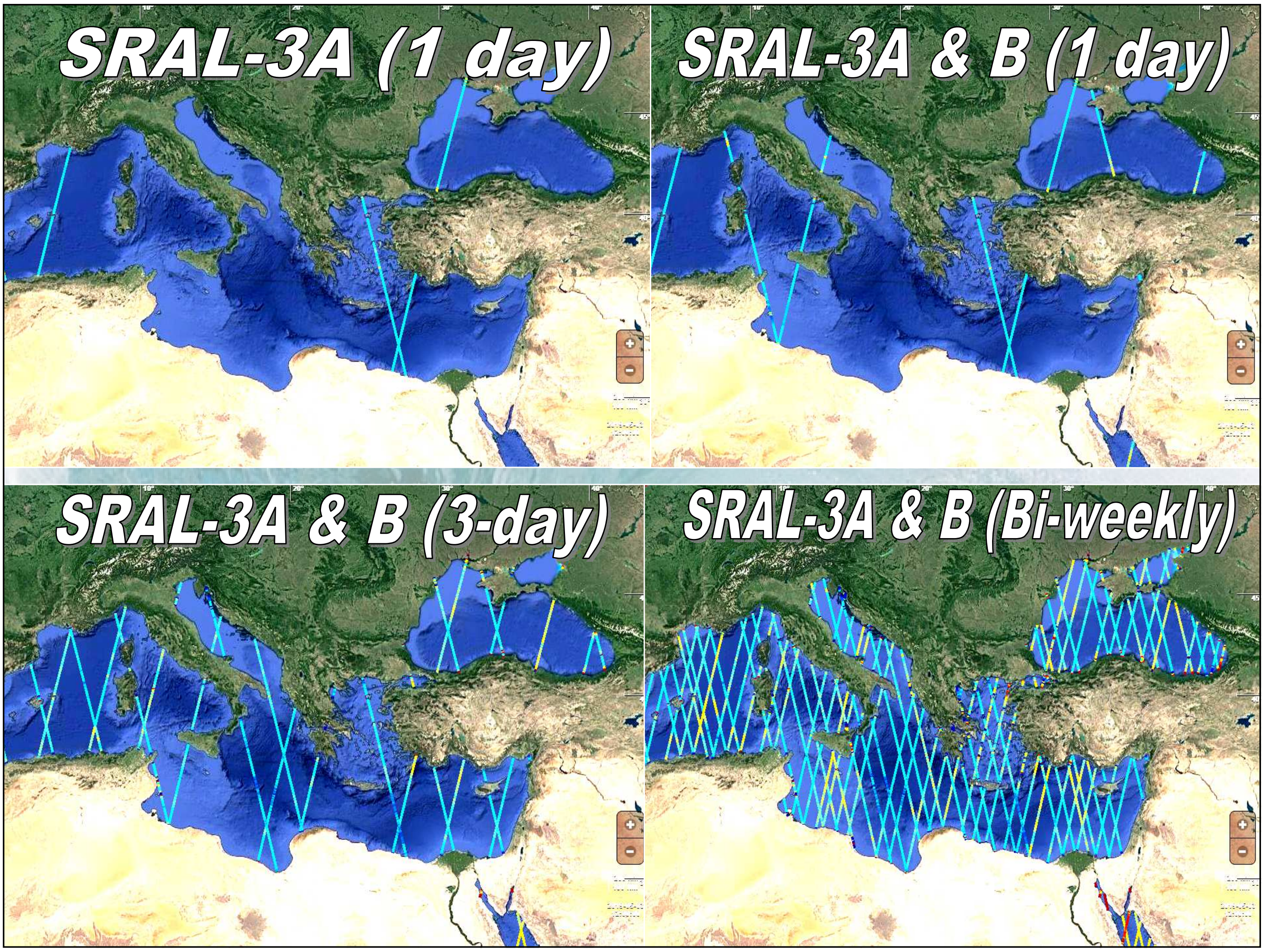

Orbit measurement systems (satellite positions measured to 3 cm)
Microwave radiometer
Laser retro-reflector array
DORIS antenna
GPS Rx & Antenna


SRAL SSHA 1Hz
m
-0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4
SLSTR SST denoised
°C
• High latitude
-2 0 2 4 6 8 10 12 14 16 18 20 22 24 28
• Low/Mid latitude
1 4 6 8 10 12 14 16 18 20 22 24 26 28 30 33
• Warm pool (Baja, Persian/Oman Gulf, Red sea)
11 14 16 18 20 22 24 26 28 30 32 34 37
OLCI Truecolor RGB (9,6,4)
20°
30°
40°
Day of data collection
3/5/2019


SRAL mode
50
0
−50
−180
−90
0
90
180
Longitude
Traditional mode
SAR closed-loop tracking
SAR open-loop tracking
LRM closed-loop tracking
LRM open-loop tracking
Continuous acquisitions across sea/land and sea/ice transition zones, and over rough terrain

- By using retrackers adapted to the specific characteristics of Delay Doppler/SAR altimeter echoes → Improvements offered by the SAR mode with respect to the conventional LRM:
  - Improved precision in range (and derived parameters, e.g. SSH, Sea Level Anomalies, SWH, etc.
  - Better accuracy and improved along track resolution → scales of coastal oceanic features less than 100 km (potentially down to <10 km) can be resolved





Where we go from here …

- The new coastal data from SAR mode altimeters that are becoming available, open new opportunities for building capacity in coastal altimetry.
- Over 20 years of coastal data from various past and present altimetry missions are waiting to be reprocessed → new challenges:
  - Comprehensive validation and intercalibration of both coastal altimetry and other observational data (e.g. from tide gauges, drifters, buoys, …) dedicated to coastal ocean studies.
  - New coastal data products suitable to be part of a crucial input for coastal observing/monitoring systems

Thank you!