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SATELLITE OCEANOGRAPHY: HARNESSING THE TECHNOLOGICAL REVOLUTION

Oceanografia por satélites: aproveitando a revolução tecnológica

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"We set sail on this new sea because there is new knowledge to be gained, and new rights to be won, and they must be won and used for the progress of all people. For space science, like nuclear science and all technology, has no conscience of its own. Whether it will become a force for good or ill depends on man ..." (John F. Kennedy, Rice University Stadium Houston, Texas, September 12th, 1962. Source: Swenson; Grimwood & Alexander, 1966)

ABSTRACT

In 43 years since the first civilian ocean satellite, the Seasat, observations of the world's oceans have progressed a lot. From color photographies taken by US astronauts during the first manned spaceflight programs back in the 60s to nano and picosatellites nowadays, Satellite Oceanography (SO) has allowed near real-time support capabilities for operational Oceanography and climate change studies. These outcomes can improve and contribute to the growth of the blue economy local, national and international by limiting the negative impact of climate change and the potential risks for aquaculture, fisheries, and environmental protection. Moreover, SO increases maritime situational awareness and surveillance for civilian purposes, accessing shipping routes, tracking illegal activities, and piracy. Therefore, the objective of this manuscript is to share some of the historical technical facts and needs that push SO observations and sensors forward to understanding our oceans and how they interact with our planet.

Keywords: Nasa, Seasat, NOAA TIROS-N, Swot, CubeSats.

RESUMO

Em 43 anos desde o primeiro satélite oceânico civil, o Seasat, as observações globais dos oceanos progrediram muito. De fotografias coloridas tiradas por astronautas dos EUA durante os primeiros programas de voo espacial tripulado na década de 1960 até os nano e –picossatélites de hoje em dia, *a Oceanografia por Satélites (OS) permitiu recursos de suporte quase em tempo real para estudos de Oceanografia operacional e mudanças climáticas. Esses resultados podem melhorar e contribuir para o crescimento da economia azul local, nacional e internacional, limitando o impacto negativo das mudanças climáticas e os riscos potenciais para a aquicultura, pesca e proteção ambiental. Além disso, a OS aumenta a consciência da situação marítima e a vigilância para fins civis, acessando rotas de navegação e rastreando atividades ilegais e de pirataria. Portanto, o objetivo deste manuscrito é compartilhar alguns dos fatos e as necessidades técnicas históricas que impulsionam as observações e os sensores da OS para a compreensão de nossos oceanos e como eles interagem com nosso planeta.*

***Palavras-chave**: Nasa, Seasat, NOAA TIROS-N, Swot, CubeSats.*

INTRODUCTION

Prior to satellite-derived data, most of our knowledge about the ocean and its close relation to climate variability came from sparse measurements, both in time and space, collected from ships, eulerian and lagrangian observations. However, ship-based data are limited to sampling the ocean in relatively small areas with often a great deal of difficulty (Martin, 2014). Moreover, data from ships, buoys, and drifters are insufficient to characterize the spatially diverse ocean's conditions (Mills, 1993). Indeed, the advent of ocean-observing satellites has foreseen a new era on marine discovery (Swenson; Grimwood & Alexander, 1966). This is where Satellite Oceanography (SO) fits in, with the synoptic view that improves our understanding of how the Earth system and its intrinsic compartments work. We can evaluate the planet's health from intra-seasonal to decadal time scales from the past four decades. Indeed, global maps of sea surface topography, ocean color, internal and surface waves, sea-ice extent, rainfall, and sea surface temperature are some of the products that help forecast and mitigate the newcome catastrophic effects of Earth's climate change.

The idea of this manuscript is to share some of the historical technical facts and needs that push SO observations and sensors forward to understanding our oceans and how they interact with our planet. We hope you enjoy it.

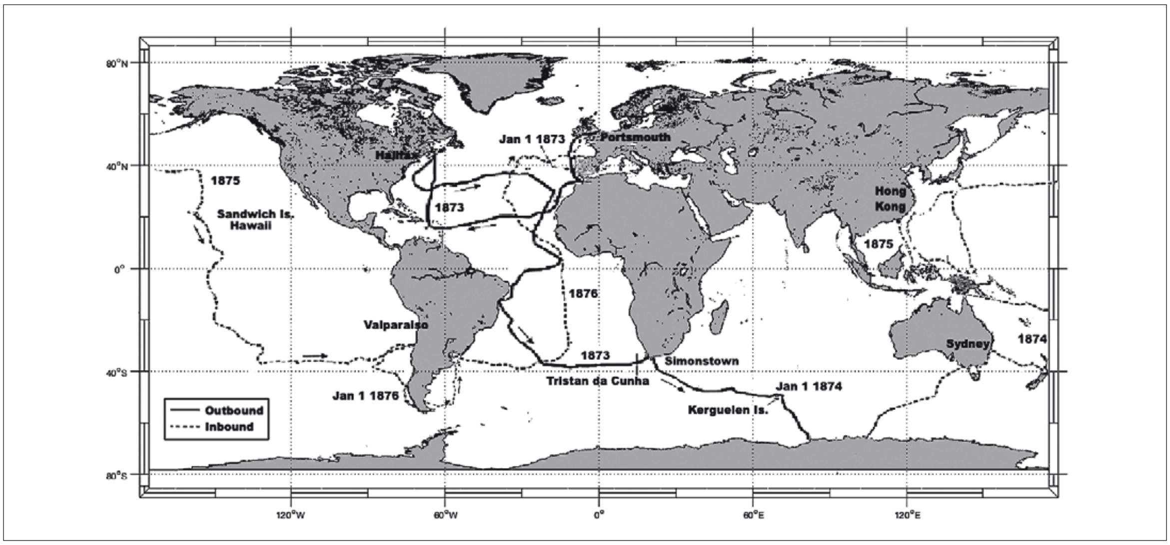
From the Victorian Era to nowadays: a brief history

For over less than two centuries, Oceanography began as a science field when seafaring explorers, navigators, and scientists began to venture from their coastlines to the open ocean, driven by their curiosity and ambition to conquer the unknown (Wüst, 1964).

This goes back to the late 19^{th} century, approximately 150 years ago, when people from the "*Old World*" began to pay attention to the ocean and decided to launch a few sea-going expeditions to explore the ocean currents, marine life, and the seafloor beneath it.

Indeed, the first scientific expedition to explore the world's oceans and the seafloor was the Challenger Expedition (1872 to 1876 – Figure 1) onboard the British three-masted warship H.M.S. Challenger (Aitken & Foulc, 2019). For 710 days, the H.M.S. Challenger circumnavigates the globe covering almost 70,000 nautical miles, sampling and collecting data (Corfield, 2003). The outcome of these 41 cruise months is a dataset of 370 ocean bottom soundings, 255 vertical temperature profiles, and 240 stations of hauls of trawl nets and dredges to collect bio and geological material beneath the ocean's surface (Burstyn, 2001).

Figure 1 – The route of H.M.S. Challenger Expedition (1872 to 1876)



Source: adapted from Corfield (2003)

Since then, sea-going research cruises have become almost a normal lifestyle of an oceanographer's life. However, the effective costs and laboring hours to be spent at sea today go off the charts and are always the Achille's heel of any funding agency. This goes hand in hand with the area covered by the vessel, the number of hydrographic casts, and days at sea, for example.

So, if one wants to sample an ocean region regularly, let us say every other week during a couple of years to capture seasonal and interannual signals, the final costs start to be a burden to any office manager. Once again, this is a direct relationship: longer cruises, higher budgets. Now, imagine sampling an entire ocean basin two times per week at a submesoscale level (i.e., 1 to 10 km), for example?

So how can we sample different ocean basins regularly for a decade or so? This is where SO becomes a desired key partner and player. According to Ewing (1965), these two words – *Satellite Oceanography* – sound incongruous. The idea may sound absurd to a generation of seafaring scientists accustomed to Nansen bottles, winches, and reversing thermometers. However, history proved him to be wrong. Back in the 70s, traditional oceanographers were provided with new tools to collect synoptic observations of geophysical parameters or near the surface of the world's oceans. For Thorpe (2009), the history of SO is the result of a fruitful marriage: satellite remote sensing with traditional oceanography.

According to several remote sensing books (e.g., Maul, 1985; Robinson, 2010), SO roots can be traced back to World War II. The term "*Satellite Oceanography*" was coined in the early 1960s, when a group of scientists foresaw the possibility of deriving useful oceanic information from pre-existing aerial sensors and polar-orbiting meteorological satellite collected images. These included color photographies taken by US astronauts in the

Mercury, Gemini, and Apollo manned spaceflight programs[1], and measurements of sea surface temperature using far-infrared sensors such as the Visible and Infrared Scanning Radiometer (VISR), which operates in the 10–12-mm thermal infrared band (Swenson; Grimwood & Alexander, 1966; Menzel, 2006).

Since the launching of Skylab (1973) and GEOS-3[2] (1975) in the early 1970s, these two ocean-viewing satellites had a series of sensors that included a radar-altimeter/wind-scatterometer (the S-193 so-called Rad/Scatt), a long-wavelength microwave, and a dual pulse radar altimeter, respectively. Although the GEOS-3 satellite-derived data was not available for the public at that time (it was classified as a US military program by the US Department of Defense), its dataset was good enough to demonstrate the possibility to map the polar ice-cap topography and to describe marine geoid anomalies related to plate tectonics (Thorpe, 2009).

The results seemed so promising that on June 26th, 1978, the first civilian dedicated oceanographic satellite, Seasat[3], was launched, followed by the NOAA TIROS-N Polar-satellite series on October 13th, and then the Nimbus-7 on October 24th (Thorpe, 2009). These satellites carried sensitive payloads whose capabilities covered virtually all known procedures of remotely observing the oceans from space back to the 70s. They provided good information on such diverse ocean phenomena as sea surface temperature, surface currents and waves, winds, rainfall, and ocean color.

Despite its very short lifetime (~ 100 days), Seasat's altimetry measured the marine geoid with a resolution of few meters, illustrating the variability of large scale ocean surface currents and wave heights. These characteristics allowed the first global marine geoid to be derived, granting the study of global mesoscale variability, oceanic Rossby wave dynamics, and global wave height statistics (e.g., Cheney & Marsh, 1981; Marsh & Martin, 1982).

Although we had some advances and improvements in the meanwhile (e.g., Landsat, SPOT, and GOES-3), making a long history short, it was only in the 90s that SO had a breakthrough: the launching of the TOPEX/Poseidon. The US-French TOPEX/Poseidon (T/P) program, launched in August 1992 and initially planned for three years[4], was a joint venture between CNES[5] and NASA[6] that measured ocean surface topography to an accuracy of 4.2 cm. This enabled scientists to forecast the 1997-1998 El Niño and improved the understanding of ocean circulation and its effect on climate variability (https://sealevel.jpl.nasa.gov/missions/topex-poseidon/summary/).

Since then, SO has made significant advancements lately with new sensors and platforms (Figure 2, Table I). The rapid advancement and dissemination of remote sensing technology have led to widespread recognition of its potential to improve efficiency,

1 Examples of this data can be seen from the National Aeronautics and Space Administration (NASA) flight archives collected in the 1960s.

2 GEOS-3, or Geodynamics Experimental Ocean Satellite 3, or GEOS-C, was the third and final satellite as part of NASA's Geodetic Earth Orbiting Satellite/Geodynamics Experimental Ocean Satellite program (NGSP).

2 Shortly after its launch, Seasat was "decommissioned" due to a catastrophic failure on October 10th, 1978. Its dataset showed such mind-blasting results for US military purposes during the Cold War, bringing up a “conspiracy theory” about its whereabouts. However, this is another history.

4 Initially planned for three years, with a possible extension for two additional years, the TOPEX/Poseidon operated for over thirteen years.

5 CNES: Centre National d'Études Spatiales (France), which is a French government space agency (administratively, a "public administration with industrial and commercial purpose"), and it is under the supervision of the French Ministries of Defence and Research.

6 NASA: National Aeronautics and Space Administration (USA), an independent agency of the U.S. federal government responsible for the civilian space program, aeronautics, and space research.

reliability, and monitoring. The progress of space agencies and research institutes, the improvements in electronic components (e.g., size and weight), computer sciences (e.g., digital image and signal processing), and the increasing number of satellites and sensors' diversity produced an exponential growth of remote sensing data acquired nowadays. In addition, sensors integration (e.g., data fusion, multi and hyperspectral data, and combination of large, small, and micro-satellites), cloud computing (e.g., data integration, organization, and management), artificial intelligence, and machine learning perspectives of geospatial information started to produce an increasing amount of data. For example, sensor fusion algorithms can improve accuracy and thus retrieve better images of a target area. In contrast, machine learning algorithms can significantly improve the data processing speed and the quality of the ocean's surface mapping and monitoring of coastal and open ocean areas.

The ever-increasing global archives of Earth's observational data enable environmental and societal problems to be assessed and monitored globally and over long time scales. Furthermore, remote sensing techniques and applications must perform over large areas promptly and at meaningful scales for time-series analysis. However, traditional remote sensing workflows, including downloading, processing, and analyzing data locally, become challenging for individual scientists and institutions. This is because they require massive storage space (i.e., terabytes to petabytes) and expertise in server or cloud-based storage and parallel processing systems. Soon the jargon "Big Data" became a reality.

In fact, the term "Big Data" has become an essential topic in many research areas recently. As one of the sources for big data, remote sensing of the oceans generates daily earth-observational data and analysis results from different remote sensing platforms and ground-based structures. These different types of remote-sensing data include Synthetic Aperture Radar (SAR), multispectral, and hyperspectral optical measurements. These data sets comprise different spectral bandwidths, spatio-temporal and radiometric resolutions. The increasing growth of remote sensing data in Geoscience research has firmly pushed earth scientists, setting up new challenges, including collection, storage, management, analysis, and interpretation. For instance, sensors capable of acquiring images with hundreds of spectral bands (known as imaging spectrometers[7]) can gather large amounts of information for the same area by recording hundreds of measurements in the spectral domain at different wavelengths. These hyperspectral images (HSI), with colossal dimensionality, permit an excellent characterization of the Earth's surface. For example, NASA's Airborne Visible Infra-Red Imaging Spectrometer (AVIRIS) sensor can capture HSI scenes with 224 spectral bands between 0.4 and 2.5 micrometers, with a spatial resolution of about 20 meters per pixel. Such richness of spatial and spectral information (despite imposing heavy computational requirements) has opened new possibilities in many applications, including monitoring and preventing natural disasters such as oil spills (e.g., Conceição *et al.*, 2021).

The need for analyzing and mapping satellite-derived big data gave birth to a new concept: cloud and parallel computing. Currently, some network infrastructure services allow the user to process large datasets remotely and relatively quickly. This is because the satellite original data does

7 According to the NASA website (https://aviris.jpl.nasa.gov/data/index.html), they are working on using the terms "imaging spectroscopy" and "imaging spectrometer data" rather than "hyperspectral" to communicate better with physics, chemistry, and biology science colleagues.

not need to be downloaded to the local computer hard drive. The possibility of using these virtual resources for intensive data analysis uses several levels of parallel execution to implement such applications (Ekanayake & Fox, 2009). API (Application Programming Interface) and MPI (Message Passing Interface) are some of the most widespread data processing models within standstill architectures, with a low-latency communication engine and a broad set of runtime communication.

In this big data processing concept in a cloud environment, Google sets a milestone: the Google Earth Engine (GEE). The GEE[8] (https://earthengine.google.com/) is a geospatial data processing service powered by the Google Cloud Platform (https://cloud.google.com/). It combines a multi-petabyte catalog of satellite imagery[9] and geospatial datasets with planetary-scale analysis capabilities enabling high-impact, data-driven investigations. GEE allows scientists, researchers, and developers to detect changes, map trends, and quantify differences on the Earth's surface (e.g., Vasconcelos *et al.*, 2020). Furthermore, as only a browser and internet access are required, this platform enables access to earth observation data employing a new generation of cost-free analysts without expensive infrastructure and software. Thus, GEE enables new tools for the SO scientific community and introduces data scientists to earth observation data analysis using familiar tools and platforms.

FUTURE PERSPECTIVES

Looking for advanced technologies and state-of-the-art remote sensors for wide application in the SO, the *Surface Water and Ocean Topography* (SWOT) mission is a future satellite altimeter jointly developed by NASA and CNES in partnership with the Canadian and UK Space Agencies. Its launching was initially planned to happen in mid-September 2020, but the mission had to be postponed due to the COVID-19 global plague. According to the SWOT Science Team, NASA has selected Space Exploration Technologies (SpaceX) to provide launch services for SWOT. Launch is targeted for November 2022 on a SpaceX Falcon 9 rocket from Space Launch Complex 4E at Vandenberg Air Force Base in California (USA).

SWOT is equipped with a Ka-band radar interferometer (KaRIn), which is a new class of altimeter, considering all the experience of previous altimetry and SAR missions[10]. According to the AVISO website[11], KaRIn is a near-nadir (1-4° look angles) swath-based instrument measuring the highly reflective water surface. The look angles at the altitude of the satellite entail swath coverage of about 120 km (from 10 to 70 km in the cross-track distance on both sides of the nadir track). It will make measurements at Ka-band (35.75 GHz) with two Ka-band synthetic aperture radar (SAR) antennae at opposite ends of a 10-m boom. The interferometry SAR processing of the returned pulses yields a 5 m azimuth

8 Google provides free training and example codes online to access the primary data and algorithms exposed through GEE quickly. Moreover, the GEE user community posts thousands of pieces of codes and workflow examples online, allowing users to adapt them to a wide variety of different processing and analysis techniques.

9 Free access to MODIS, Landsat 1-5,7, and 8, and Sentinel-1, 2, 3, and 5 archives with continual updates, as well as other imagery and ancillary datasets (e.g., land-use data, climate, and soil data), through either a Javascript or Python API.

10 The KaRIn interferometric altimeter has its heritage based on previous highly successful ocean observing radar altimeters (e.g., TOPEX/Poseidon and Jason family), the Shuttle Radar Topography Mission (SRTM), and the development efforts of the Wide Swath Ocean Altimeter (WSOA).

11 https://www.aviso.altimetry.fr/en/missions/future-missions/swot/instruments/karin-wide-swath-altimeter-in-ka-band.html.

and 10 m to 70 m range resolution, with instantaneous elevation precision of 50 cm. Spatial averaging over areas of 1 km^2 will improve this elevation precision to less than 2 cm.

Although the SWOT main objectives are two-fold – measure the variability of terrestrial surface water bodies and the ocean's fine detailed surface topography – from the ocean's perspective, SWOT will revolutionize Oceanography by detecting ocean surface features[12] at unprecedented scales of 15-25 km, approximately an order of magnitude higher than present technologies. According to recent studies (e.g., Lévy; Franks & Smith, 2018; Su *et al*., 2018), oceanic motions associated with horizontal scales smaller than 50 km, which are defined as submesoscales, contribute to the understanding of global climate change by absorbing and storing heat and carbon from the upper ocean to deeper layers away from the atmosphere. Moreover, SWOT's detailed information on coastal ocean dynamics and ocean circulation will improve ocean circulation forecasts, benefiting ship and offshore commercial operations, along with coastal planning activities such as flood prediction and sea-level rise.

Another promising advance in SO is the use of "*small satellites*", known as nano and picosatellites. Although small satellites have existed since the early days of spaceflight, such as *Sputnik*[13], it was only with the launch of the CubeSat standard in 1999[14] that the growth of applications in small satellites has become exponential (Janson, 2020). According to the NASA website[15], CubeSats are a class of nanosatellites that use a standard size and form factor. The standard CubeSat size uses a "one unit" or "1U" measuring 10x10x10 cms and is extendable to larger sizes; 1.5, 2, 3, 6, and even 12U. Even before the success of CubeSats, the term "nanosatellites" was coined in 1992 and popularized. This term defines any satellite with a mass between 1 and 10 kg, including most CubeSats. Nanosatellites' lower costs (~US$1 million) contrast with regular investments of traditional satellites, such as Landsat and Sentinel, which reach up to US$855 and US$300 million, respectively (Landsat Advisory Group, 2018). Furthermore, nanosatellites are put into space as a secondary payload, taking advantage of the traditional satellite launches, which reduces mission costs even further (Swartwout, 2013).

Since the beginning of the last decade, NASA is the principal agency supporting the development of nanosatellites. The agency started in 2010 an educational program called "*ELaNa - Educational Launch of Nanosatellites*", whose main objective is to attract students to space engineering and technological careers (Crusan & Galica, 2016). Last year the Hyper-Angular Rainbow Polarimeter (HARP) CubeSat, which will be used for the detailed measurements of aerosol and cloud properties, made history by becoming the 100th CubeSat Launch Initiative (CSLI) selected mission deployed into space. This mission marks nearly 12 years of the CSLI providing CubeSat developers rideshare opportunities to space via *ELaNa*[16].

12 SWOT is projected to characterize the ocean mesoscale and sub-mesoscale circulation (15 – 200 km) at spatial resolutions of 15 km (~9 mi) and greater.

13 Sputnik-1 or Prosteyshiy Sputnik-1(PS-1) was the first artificial Earth satellite, weighting 83.6 kg with a diameter of 58.5 cm. It was launched into an elliptical low Earth orbit by the USSR on October 4th, 1957, as part of the Soviet Space Program. It orbited for three weeks before its batteries died and then orbited silently for two months before it fell back into the atmosphere on January 4th, 1958.

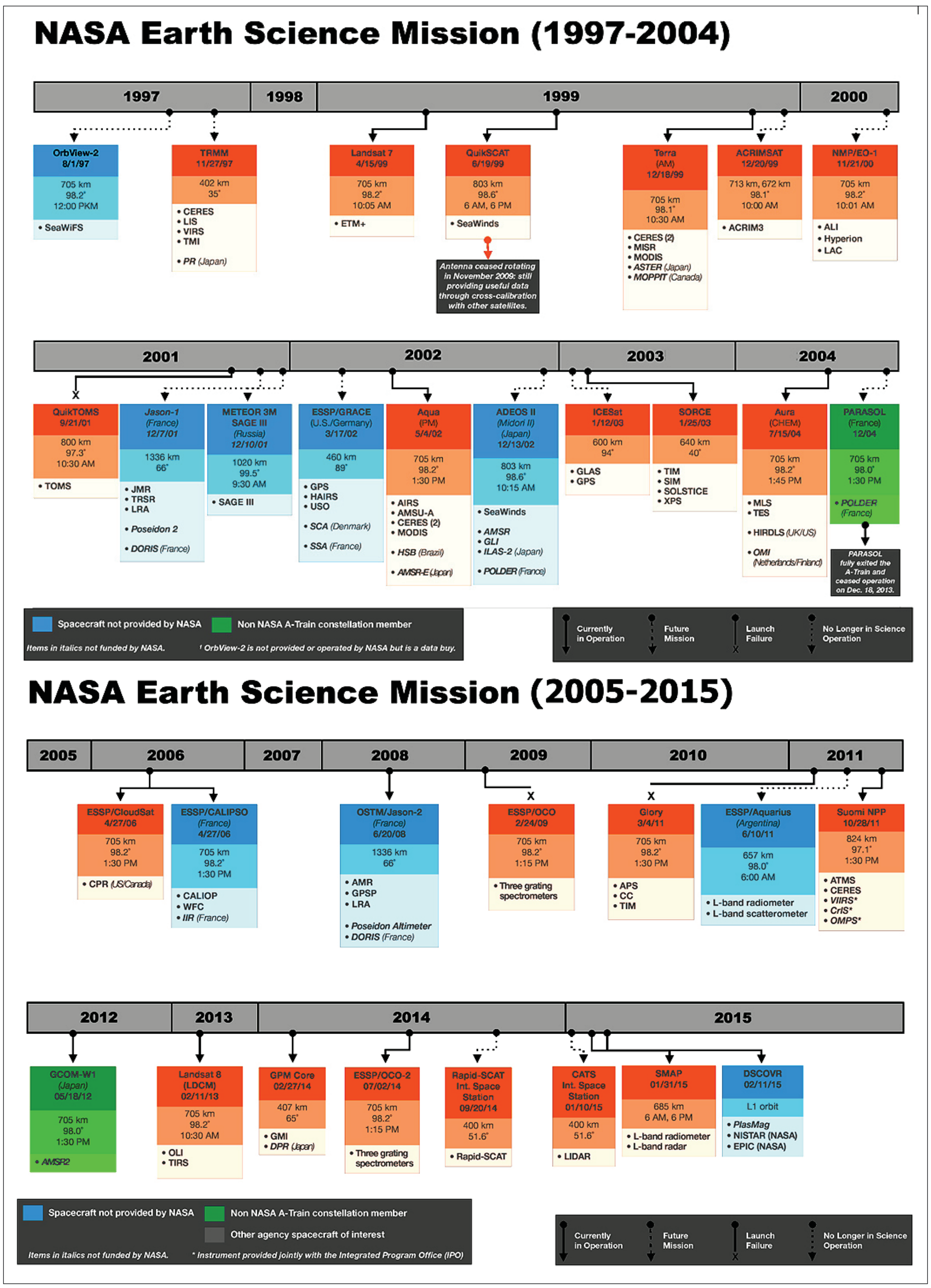
14 CubeSat was initially developed in 1999 by California Polytechnic State University at San Luis Obispo (Cal Poly) and Stanford University to provide a platform for education and space exploration.

15 https://www.nasa.gov/content/what-are-smallsats-and-cubesats

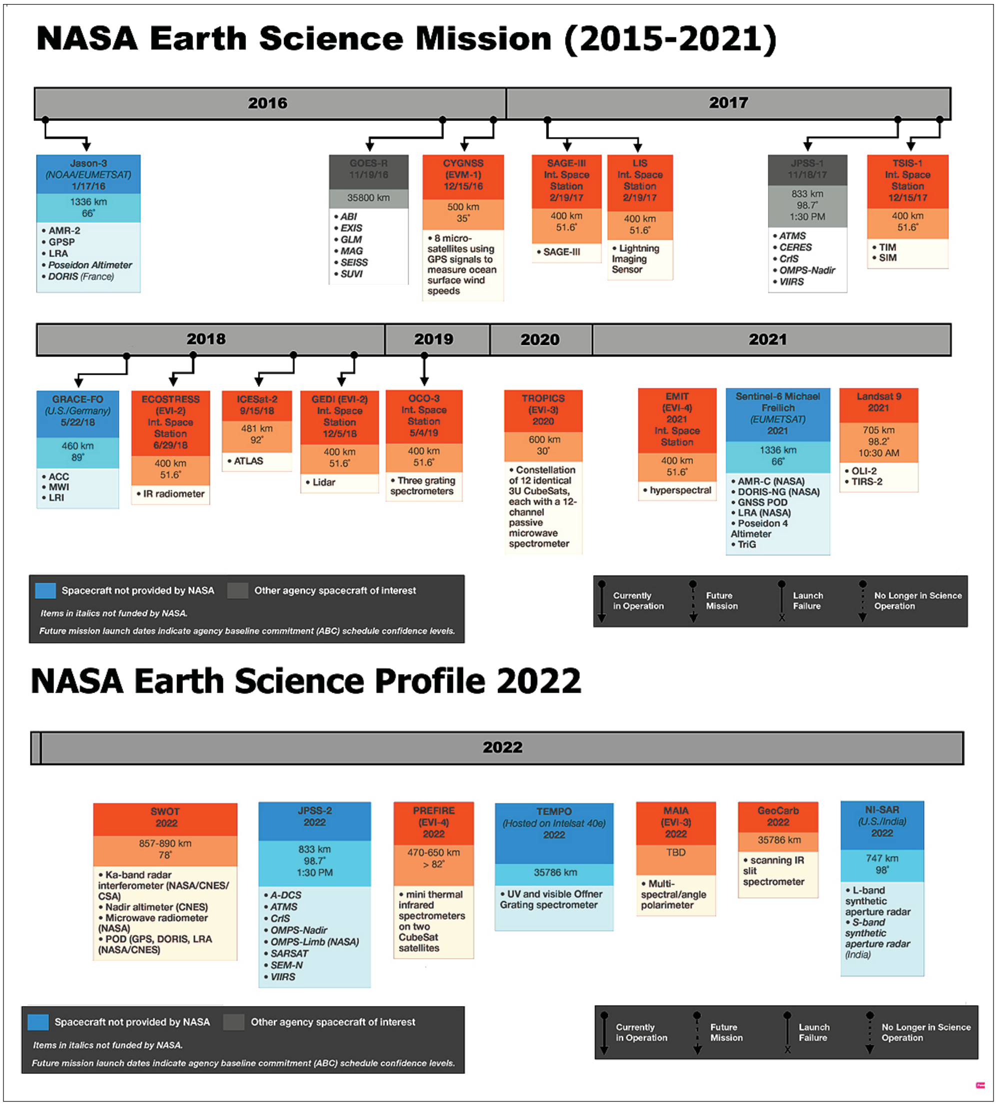
16 https://www.nasa.gov/feature/the-cubesat-launch-initiative-celebrates-its-100th-cubesat-mission-deployment

To our knowledge, the first use of nanosatellites in SO was predicted to be launched in 2020 in the so-called TROPICS mission (https://tropics.ll.mit.edu/CMS/tropics/). "TROPICS", which stands for "*Time-Resolved Observations of Precipitation structure and Storm Intensity with a Constellation of Smallsats*[17]", is a constellation of 12 identical 3U CubeSats, each with a 12-channel passive microwave spectrometer. However, it had to be postponed due to the COVID-19 pandemic (See Figure 2, Table I).

Figure 2 – The original Earth Observing System (EOS) missions from 1997 to 2022, together with all of NASA's Earth-observing satellite missions (many of them joint with other nations and/or agencies), along with other elements of NASA's Earth Science program



[17] https://eospso.nasa.gov/missions/time-resolved-observations-precipitation-structure-and-storm-intensity-constellation



Source: adapted from the Earth Science Division of NASA's Science Mission Directorate EOSPSO (https://eospso.nasa.gov/).

Table I – Mission profile and acronym list of all satellites displayed on Figure 2 for the same period (1997 to 2022)

Mission Profile and Acronym List	
Period 1997-2004	
OrbView-2 (8/1/1997) • SeaWiFS - Sea-viewing Wide Field-of-view Sensor	**METEOR 3M/SAGE III (12/10/2001)** • SAGE III - Stratospheric Aerosol and Gas Experiment III
TRMM (11/27/1997) ***Tropical Rainfall Measuring Mission*** • CERES - Clouds and the Earth's Radiant Energy System • LIS - Lightning Imaging Sensor • VIRS - Visible and Infrared Scanner • TMI - TRMM Microwave Imager • PR - Precipitation Radar	**ESSP/GRACE (3/17/2002)** ***Earth System Science Pathfinder/Gravity Recovery and Climate Experiment*** • GPS - Black-Jack Global Positioning System Receiver • HAIRS - High-Accuracy Inter-satellite Ranging System • SCA - Star Camera Assembly • SSA - SuperStar Accelerometer • USO - Ultra Stable Oscillator
Landsat 7 (4/15/1999) • ETM+ - Enhanced Thematic Mapper Plus **QuikScat (6/19/1999)** Quick Scatterometer • SeaWinds	**Aqua (5/4/2002)** • AIRS - Atmospheric Infrared Sounder • AMSU-A - Advanced Microwave Sounding Unit-A • CERES - Clouds and the Earth's Radiant Energy System • MODIS - Moderate Resolution Imaging Spectroradiometer • HSB - Humidity Sounder for Brazil • AMSR-E - Advanced Microwave Scanning Radiometer for EOS
Terra (12/18/1999) • ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer • CERES - Clouds and the Earth's Radiant Energy System • MISR - Multi-angle Imaging Spectroradiometer • MODIS - Moderate Resolution Imaging Spectroradiometer • MOPITT - Measurements of Pollution in the Troposphere	**ADEOS II (Midori II) (12/13/2002)** • AMSR - Advanced Microwave Scanning Radiometer • GLI - Global Imager • ILAS-2 - Improved Limb Atmospheric Spectrometer 2 • POLDER - Polarization and Directionality of the Earth's Reflectances
ACRIMSAT (12/20/1999) • ACRIM3 - Active Cavity Radiometer Irradiance Monitor	**ICESat (1/12/2003)** • GLAS - Geoscience Laser Altimeter System • GPS - Global Positioning System
NMP/EO-1 ***New Millennium Program/Earth Observing-1*** • ALI - Advanced Land Imager • Hyperion - Hyperspectral Instrument • LAC - Linear Etalon Imaging Spectral Array (LEISA) Atmospheric Corrector	**SORCE (1/25/2003)** ***Solar Radiation and Climate Experiment*** • TIM - Total Irradiance Monitor • SIM - Spectral Irradiance Monitor • SOLSTICE - Solar Stellar Irradiance Comparison Experiment • XPS - XUV Photometer System
QuikTOMS (9/21/2001) • TOMS - Total Ozone Mapping Spectrometer	**Aura (7/2015/4)** • HIRDLS - High Resolution Dynamics Limb Sounder • MLS - Microwave Limb Sounder • OMI - Ozone Monitoring Instrument • TES - Tropospheric Emission Spectrometer
Jason-1 (12/7/2001) • JMR - Jason Microwave Radiometer • TRSR - Turbo Rogue Space Receiver • LRA - Laser Retroreflector Array • DORIS - Doppler Orbitography and Radiopositioning Integrated by Satellite • Poseidon-2 Altimeter	**PARASOL (12/2004)** ***Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations for a Lidar*** • POLDER - Polarization and Directionality of the Earth's Reflectance

(*Continuation*)	
Period 2005-2015	
<u>ESSP/CloudSat</u> (4/27/2006) • CPR - Cloud Profiling Radar	**<u>LDCM Landsat Data Continuity Mission (Landsat 8)</u> (2/11/2013)** • OLI - Operational Land Imager • TIRS - Thermal Infrared Sensor
<u>ESSP/CALIPSO</u> (4/27/2006) ***Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations*** • CALIOP - Cloud Aerosol Lidar with Orthogonal Polarization • IIR - Imaging Infrared Radiometer • WFC - Wide Field Camera	**<u>GPM Core Observatory</u> (2/27/2014)** ***Global Precipitation Measurement*** • DPR - Dual Frequency Precipitation Radar • GMI - GPM Microwave Imager
<u>OSTM/Jason-2</u> (6/20/2008) ***Ocean Surface Topography Mission/Jason-2*** • DORIS - Doppler Orbitography and Radio-positioning Integrated by Satellite • TRSR - Turbo Rogue Space Receiver • LRA - Laser Retroreflector Array • Poseidon-3 Altimeter • AMR - Advanced Microwave Radiometer • GPSP - Global Positioning System Payload	**<u>ESSP/OCO-2</u> (7/2/2014)** ***Orbiting Carbon Observatory*** • Three high-resolution grating spectrometers
<u>ESSP/OCO</u> (2/24/2009) ***Orbiting Carbon Observatory*** • Three high-resolution grating spectrometers	**<u>Rapid-SCAT - International Space Station</u> (9/20/2014)** • Rapid Scatterometer
<u>Glory</u> (3/4/2011) • APS - Aerosol Polarimetry Sensor • CC - Cloud Camera • TIM - Total Irradiance Monitor	**<u>CATS</u> (1/10/2015)** ***Cloud-Aerosol Transport System*** • LIDAR
<u>ESSP/Aquarius</u> (6/10/2011) • LBR - L-Band Radiometer • LBS - L-Band Scatterometer	**<u>SMAP</u> (1/31/2015)** ***Soil Moisture Active Passive*** • L-Band Radiometer • L-Band Radar
<u>Suomi NPP</u> (10/28/2011) ***Suomi National Polar-orbiting Partnership*** • ATMS - Advanced Technology Microwave Sounder • CERES - Clouds and the Earth's Radiant Energy System • CrIS - Cross-Track Infrared Sounder • OMPS-Nadir - Ozone Mapping and Profiler Suite • VIIRS - Visible/Infrared Imager/Radiometer Suite	**<u>DSCOVR</u> (2/11/2015)** ***Deep Space Climate Observatory*** • PlasMag - Plasma-Magnetometer • NISTAR - National Institute of Standards and Technology Advanced Radiometer • EPIC - Earth Polychromatic Imaging Camera
<u>GCOM-W1</u> (5/18/2012) ***The Global Change Observation Mission-Water*** • AMSR2 - Advanced Microwave Scanning Radiometer	

(*Continuation*)

Period 2016-2022

Jason-3 (1/17/2016)
- DORIS - Doppler Orbitography and Radio-positioning Integrated by Satellite
- TRSR - Turbo Rogue Space Receiver
- LRA - Laser Retroreflector Array
- Poseidon-3 Altimeter
- AMR-2 - Advanced Microwave Radiometer
- GPSP - Global Positioning System Payload

GOES-R (11/19/2016)
Geostationary Operational Environmental Satellite-R Series
- ABI - Advanced Baseline Imager
- EXIS - Extreme Ultraviolet and X-Ray Irradiance Sensor
- GLM - Geostationary Lightning Mapper
- MAG - Magnetometer
- SEISS - Space Environment In Situ Suite
- SUVI - Solar Ultraviolet Imager

CYGNSS (EVM-1) (12/15/2016)
Cyclone Global Navigation Satellite System (Earth Venture-2)
- 8 micro-satellites using GPS signals to measure ocean surface wind speeds

SAGE-III) - International Space Station (2/19/2017)
- Stratospheric Aerosol and Gas Experiment - III

LIS - International Space Station (2/19/2017)
- LIS - Lightning Imaging Sensor

JPSS-1 (11/18/2017)
Joint Polar Satellite System
- ATMS - Advanced Technology Microwave Sounder
- CERES - Clouds and the Earth's Radiant Energy System
- CrIS - Cross-Track Infrared Sounder
- OMPS-Nadir - Ozone Mapping and Profiler Suite
- VIIRS - Visible/Infrared Imager/Radiometer Suite

TSIS-1 - International Space Station (12/15/2017)
Total and Spectral Solar Irradiance Sensor
- Total Irradiance Monitor
- Spectral Irradiance Monitor

GRACE-FO (5/22/2018)
Gravity Recovery and Climate Experiment-Follow-on
- ACC - Accelerometer
- MWI - Microwave Instrument
- LRI - Laser Ranging Interferometer

ECOSTRESS (EVI-2) - International Space Station (6/29/2018)
ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
- Infrared radiometer

ICESat-2 (9/15/2018)
- ATLAS - Advanced Topographic Laser Altimeter System

GEDI (EVI-2) - International Space Station (12/5/2018)
Global Ecosystem Dynamics Investigation
- Lidar

OCO-3- International Space Station (5/4/2019)
Orbiting Carbon Observatory
- Three high-resolution grating spectrometers

TROPICS (EVI-3) (2020)[18]
Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats
- 12 identical 3U CubeSats, each with a 12-channel passive microwave spectrometer

Sentinel 6 Michael Freilich (11/21/2020)
- AMR-C - Climate Quality Microwave Radiometer
- DORIS-NG - Doppler Orbitography and Radio-positioning Integrated by Satellite-NG
- GNSS POD Receiver
- LRA - Laser Retroreflector Array
- Poseidon-4 Altimeter - Poseidon-4 SAR Radar Altimeter
- TriG - TriG Receiver for Radio Occultation

EMIT (EVI-4) - International Space Station (2022)
Earth Surface Mineral Dust Source Investigation
Earth Venture Instrument
- Hyperspectral instrument

[18] TROPICS mission is targeted for launch between Jan. 8 and July 31, 2022, under a Federal Aviation Administration (FAA) launch license (https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/tropics).

(*Continuation*)	
Period 2022 (predicted launch)	
SWOT (2022) ***Surface Water Ocean Topography*** • KaRIn - Ka-band radar interferometer • Nadir Altimeter • Microwave Radiometer • POD (GPS, DORIS, LRA)	**TEMPO (hosted on Intelsat 40e) (2022)** ***Tropospheric Emissions: Monitoring of Pollution*** • UV and Visible Offner Grating Spectrometer **MAIA (EVI-3) (2022)** ***Multi-Angle Imager for Aerosols*** • Multi-spectral/angle polarimeter
JPSS-2 (2022) ***Joint Polar Satellite System*** • ATMS - Advanced Technology Microwave Sounder • CERES - Clouds and the Earth's Radiant Energy System • CrIS - Cross-Track Infrared Sounder • OMPS Nadir/Limb - Ozone Mapping and Profiler Suite • VIIRS - Visible/Infrared Imager/Radiometer Suite	**GeoCarb (2022)[19]** ***Geostationary Carbon Cycle Observatory*** • scanning IR slit spectrometer
PREFIRE (EVI-4) (2022) ***Polar Radiant Energy in the Far Infrared Experiment*** • Miniaturized thermal infrared spectrometers on two CubeSat satellites	**NI-SAR (2022)[20]** • InSAR - Interferometric Synthetic Aperture RADAR (Radio Detection and Ranging)

This mission will provide microwave measurements over the tropics that can be used to observe the thermodynamics of the troposphere and precipitation structure for storm systems at the mesoscale and synoptic-scale over the entire storm lifecycle. Each CubeSat will host a high-performance radiometer scanning across the satellite track at 30 RPM to provide temperature profiles using seven channels near the 118.75 GHz oxygen absorption line, water vapor profiles using three channels near the 183 GHz water vapor absorption line, imagery in a single channel near 90 GHz for precipitation measurements, and a single channel at 206 GHz for cloud ice measurements (https://tropics.ll.mit.edu/CMS/tropics/).

This class of relatively small satellites (1 kg $\leq$ nanosatellites $\leq$ 10 kg) is not designed to operate in a radiation environment like outer space. Therefore, it is relegated to short-term ($\leq$ 1 yr) low-Earth-orbit missions where radiation levels remain low (Lu, 2010; Janson, 2020). On the other hand, the cost of launching, associated with reduced budgets, and the current flood of commercial, small, low-power devices with exceeding capability, makes these nanosatellites an excellent alternative to do both science and military experiments previously not thought possible. For example, according to the NASA website, the National Science Foundation is actively funding CubeSats for space weather science. In addition, the U.S. Army recently announced experiments with CubeSats.

CONCLUDING REMARKS

In 43 years since the first civilian ocean satellite, the SEASAT, observations of the world's oceans have progressed a lot. They allow near real-time support capabilities for operational Oceanography, climate change studies, and mapping basin-wide year-to-year

[19] GeoCarb launching has been postponed to 2024 (https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2).
[20] Ni-SAr launching has been postponed to January 2023 (https://nisar.jpl.nasa.gov/).

current variations, as well as providing global data to validate ocean-atmosphere coupled models. These outcomes can improve and contribute to the growth of the blue economy local, national and international by limiting the negative impact of climate change and the potential risks for aquaculture, fisheries, and environmental protection. Moreover, Satellite Oceanography increases maritime situational awareness and surveillance for civilian purposes, accessing shipping routes, tracking illegal activities, and piracy.

Thus, what does the Satellite Oceanography future hold ahead of us? It is not the space engineering complexity behind a "traditional satellite" neither the size of this new class of nano and picosatellites that will bring the greatest return to humankind. Instead, the myriad of upcoming ocean satellites and new technologies are opening the doors to earth scientists and students with a real opportunity to dream, innovate, and improve our present knowledge of the Earth's environment as a response to technology's giant leaps.

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