From  to 

The Incredible Saga of Satellite Oceanography

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A quick introduction to COSPAR

- The Committee on Space Research (COSPAR) was established by the International Council for Science (ICSU) in 1958 to continue and deepen the cooperation begun during the International Geophysical Year (IGY)
- From its inception COSPAR's primary goal was to "provide the world scientific community with the means whereby it may exploit the possibilities of satellites and space probes of all kinds for scientific purposes, and exchange the resulting data on a cooperative basis."
- COSPAR has 46 members (countries), 8,000 Associates (scientists), organizes Scientific Assemblies, Symposia, Capacity Building workshops, and publishes a scientific Journals (*Advances in Space Research*)


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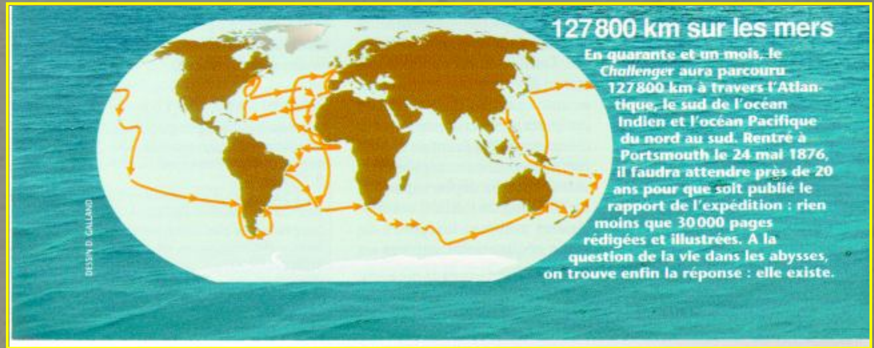
The Ocean, "*Terra incognita*"

First maps of ocean currents, 1780



First oceanography campaign, Challenger, 1873-76

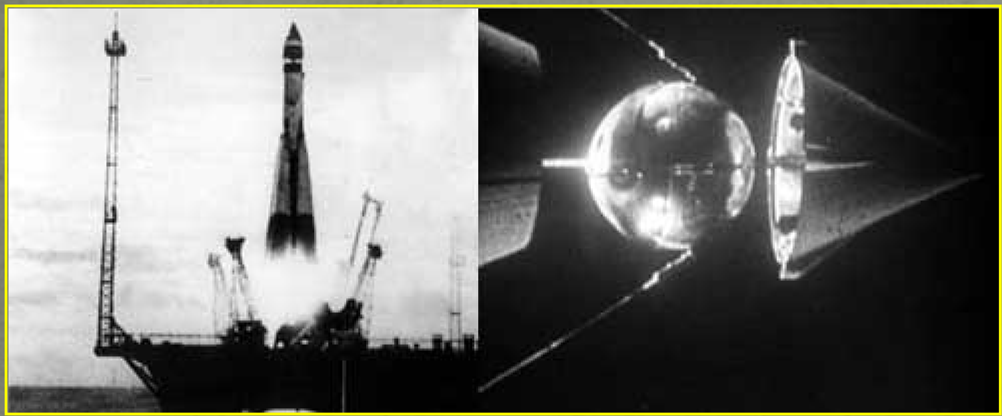
Ocean Observation Before the 1970's

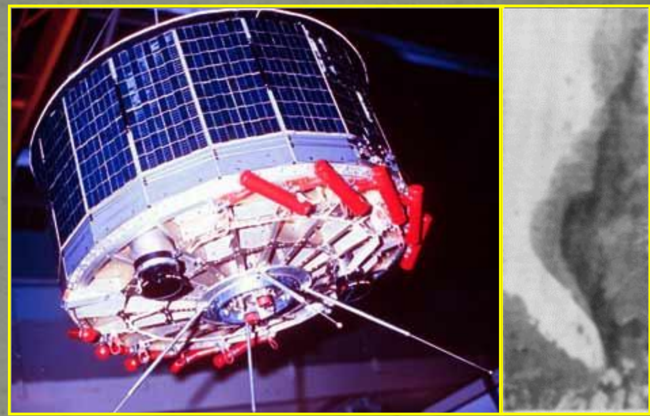
- A small number of costly ship cruises, sparse, evenly distributed
  - Mostly northern Hemisphere, along commercial ship routes
  - Little knowledge of energetic zones
  - Large campaigns every 20 years or so in Atlantic Ocean
- Low quality of measurements
  - Frequent erroneous geographical location (ships, buoys)
  - Inaccurate measurements of ocean currents by Lagrangian drifters
  - Small number of fixed moorings
- Data processed manually, off-line
  - No data quality control
  - Difficult access to disseminated data
- Lack of global ocean models

First remote sensing ocean observations

- Late 1940s, in the wake of World War II:
  - First microwave radar sensing of ocean surface waves from aircraft
    - British National Institute of Oceanography : radar altimeter experiments to measure SWH
    - U.S. Woods Hole Oceanographic Institution and Naval Research Laboratory: similar experiments with military purposes (correlation between *clutter* – background noise in a ship's radar display – and height of surrounding wave field)
- Late 1950s and early 1960s
  - Studies of microwave scattering by the sea surface in the USA and former USSR
  - These early experiments were the forerunners of modern SARs, altimeters and side-looking scatterometers

1957: The Satellite Saga Begins





- 4 October 1957: USSR launches the first artificial satellite of the Earth, a passive sphere of 80 kg
- 1st April 1960: the USA launches the first meteorological satellite TIROS-1, a B&W TV camera designed to track cloud motions, but also able to provide blurred SST images

1960s & 70s: More Images from Space

- Cameras were taken into orbit by cosmonauts in the Vostok, Voskhod, Soyuz and Salyut and astronauts in the Mercury, Gemini and Apollo vehicles
- Collected images showed the possibility to detect chlorophyll, sediments, internal waves and eddies from space, as shown here.

Color photo of the North Carolina barrier islands taken during the U.S./U.S.S.R. Apollo-Soyuz mission in July 1975 (Courtesy of NASA)

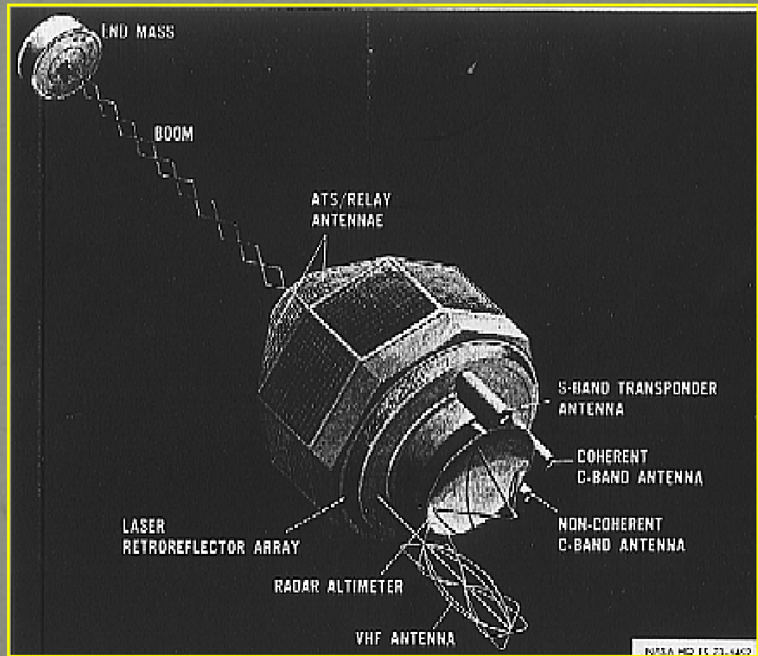
1960s & 70s: More Data and Concepts

- 1960s: Back in the U.S.S.R.
  - First passive microwave radiometers carried into space by the U.S.S.R. Kosmos-243 (1968) and Kosmos-384 (1970) satellites
  - Radiometers operating at 8.5, 3.4, 1.35 and 0.8 cm demonstrated the possibility of retrieving SST, near-surface winds, total atmospheric water vapour and cloud liquid water content, sea ice parameters, etc.
- USA
  - 1964
    - NASA-sponsored Conference at WHOI, where the concept of Oceanography from Space was developed by Gifford C. Ewing
  - August 1969
    - The Williamstown Conference made plans for a space-based geodesy mission using Doppler and laser satellite tracking and a nadir-looking radar altimeter
  - 1972
    - NOAA, NASA and U.S. Navy Conference in Miami on data requirements for sea surface topography

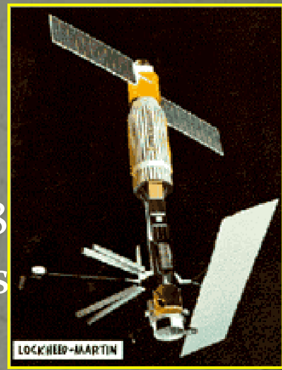
Two Early Ocean-Viewing Satellites

Skylab (1973): first active microwave sensors

GEOS-3 (1975): dual-pulse altimeter for marine geoid



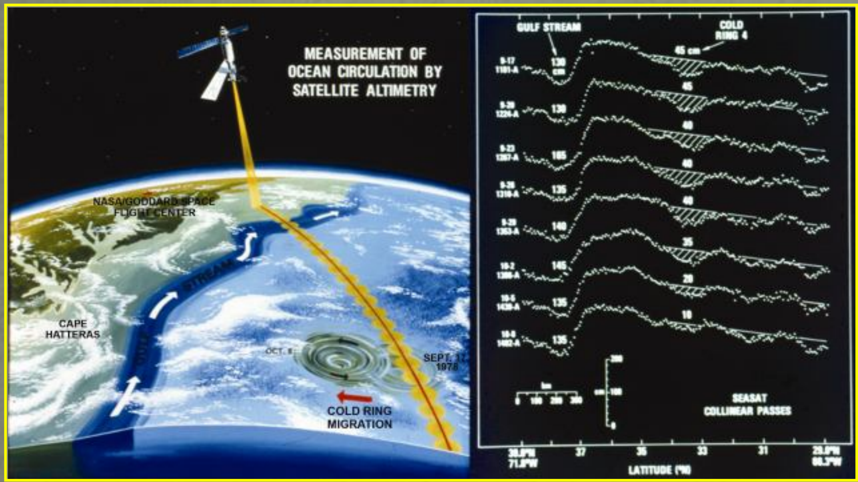
The Real Advent of Satellite Oceanography: the NASA Seasat (1978)



- Seasat was the first Earth-orbiting satellite designed for remote sensing of the Earth's oceans. SEASAT was launched on June 28 1978 into a nearly circular 800 km orbit with an inclination of 108 degrees
- Seasat carried five complementary innovative ocean sensors:
  - Radar altimeter to measure spacecraft height above the ocean surface
  - Microwave scatterometer to measure wind speed and direction
  - Scanning multichannel microwave radiometer to measure surface temperature
  - Visible and infrared radiometer to identify cloud, land and water features
  - Synthetic Aperture Radar (SAR) L-band, HH polarization, fixed look angle to monitor the global surface wave field and polar sea ice conditions
- The Seasat SAR operated for 105 days (only 42 hrs of data) until October 10, 1978, when a massive short circuit in the electrical system ended the mission.
- Seasat was designed by NASA/JPL using techniques experimented in planetary exploration
- A Seasat User Research Group in Europe (SURGE) was formed.

Seasat, a Precursor Mission

Seasat Altimeter Collinear Overpasses of the Gulf Stream

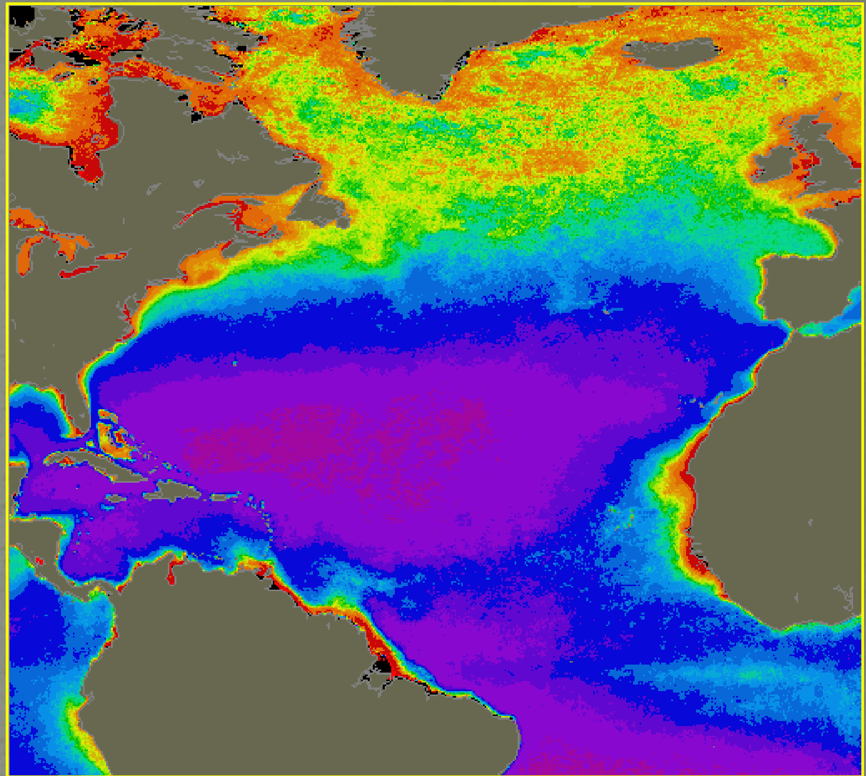


Seasat Scatterometer Observed an Intense Tropical Cyclone

QE II

Next Step: The NASA Nimbus-7 CZCS (1978-1986)

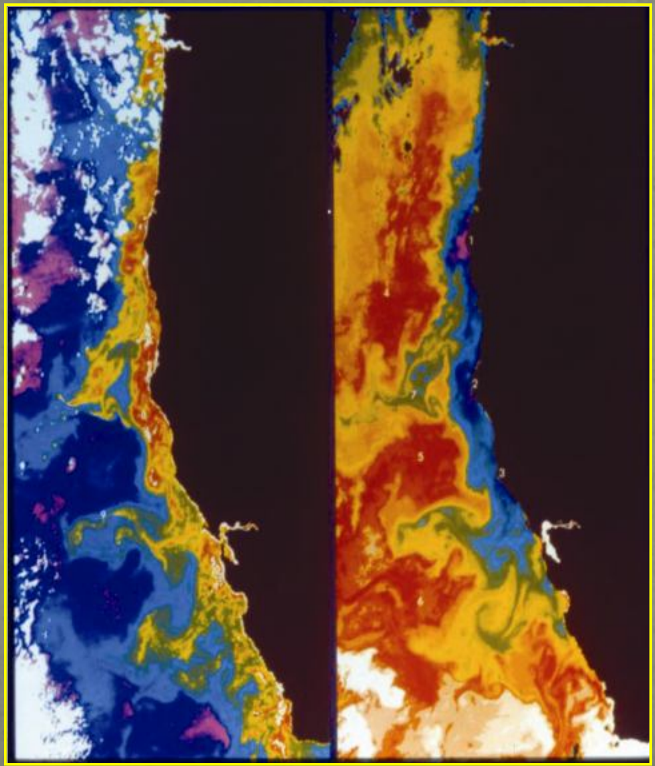
- Launched in 1978, Nimbus-7 carried the Coastal Zone Color Scanner (CZCS), the first sensor specifically intended for monitoring the Earth's oceans and water bodies. Nimbus-7 was placed in a sun-synchronous, near-polar orbit at an altitude of 955 km.
- CZCS observed ocean color and temperature, particularly in coastal zones, with sufficient spatial and spectral resolution to detect pollutants in the upper levels of the ocean and to determine the nature of materials suspended in the water column.
- Nimbus-7 was designed by NASA/GSFC, specialized in optical and IR passive remote sensing



Composite of all CZCS data acquired between November 1978 and June 1986. Nearly 66,000 individual scenes were processed to produce this image of phytoplankton concentration in the North Atlantic Ocean (Courtesy of NASA/GSFC).

Useful (and Costly) Comparisons

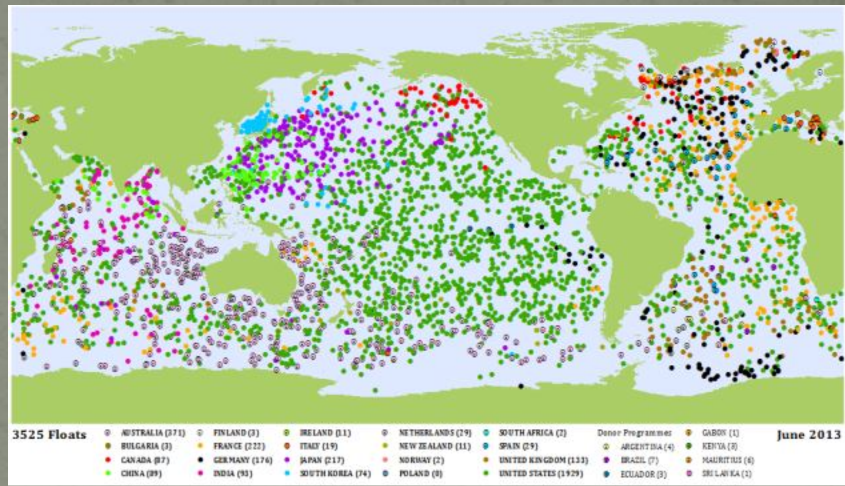
CZCS (Chl, left) vs. AVHRR (SST, right), 8 July 1981



Kosmos-1500 SAR (wind, left) vs. Visible (clouds, right), 20 Dec 1984

Data Collection and Positioning

- The ARGOS Data Collection and Positioning System has flown on the NOAA series of polar-orbiting operational satellites continuously since 1978
- Such systems have been seminal to develop the *in situ* ocean component, such as the ARGO profiling floats



- ARGO monthly map, June 2013:
  - 3525 active floats
  - 20 countries + 7 donor countries

(*Credit: JCOMMOPS*)

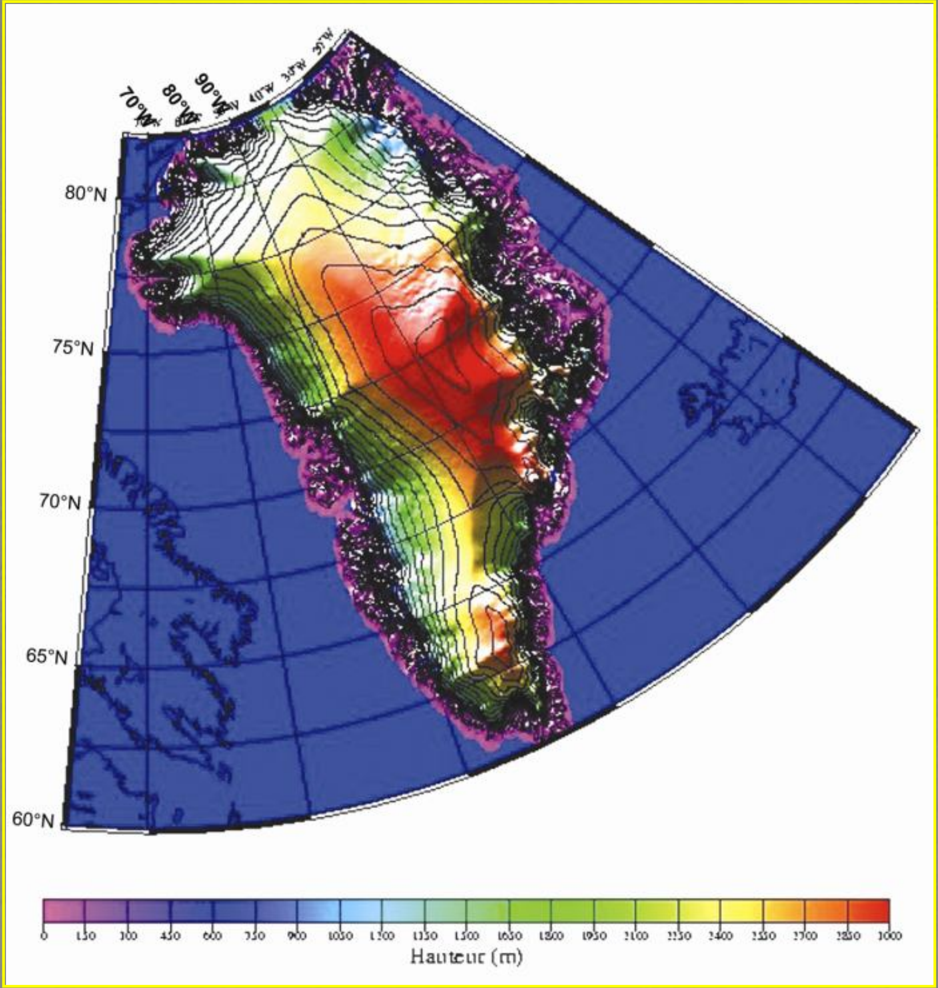
W. Munk and C. Wunsch, 1982: "*Observing the Oceans in the 1990's*"

- "Satellite altimetry and acoustic thermometry combined can give a very accurate measure of the heat storage in an ocean basin. The two methods are nicely complementary."
  - Satellite altimetry has good horizontal resolution, fair time resolution, and essentially no depth resolution.
  - Acoustic thermometry has poor horizontal resolution (limited number of receiver stations), good time resolution, and fair depth resolution.
- "The combined measurements give more than the sum of the two separate measurements."

The ESA ERS-1 (1991-2000) and ERS-2 (1995-2012)

- The first European Remote Sensing Satellite ERS-1 was launched on 17 July 1991, and operated in a sun-synchronous, near-polar orbit at an altitude of 785 km and an inclination of 98.5 degrees.
- ERS-1 used advanced microwave techniques to collect global measurements and images independent of time or weather conditions:
  - The Active Microwave Instrument (AMI), combining a Synthetic Aperture Radar (C-band) operating in image or wave mode and a Wind Scatterometer
  - The Radar Altimeter (RA), the Precise Range and Range-rate Equipment (PRARE) and Laser reflectors (LRR)
  - The Along-Track Scanning Radiometer and Microwave Sounder (ATSR/M)
- The primary objectives of the ERS-1 mission were the surveillance of the oceans and sea ice.
- The ERS-1 mission was terminated in March 2000.
- ERS-2 followed in 1995, and stopped operating in 2012.

ERS-1 Greenland Ice Sheet Mapping



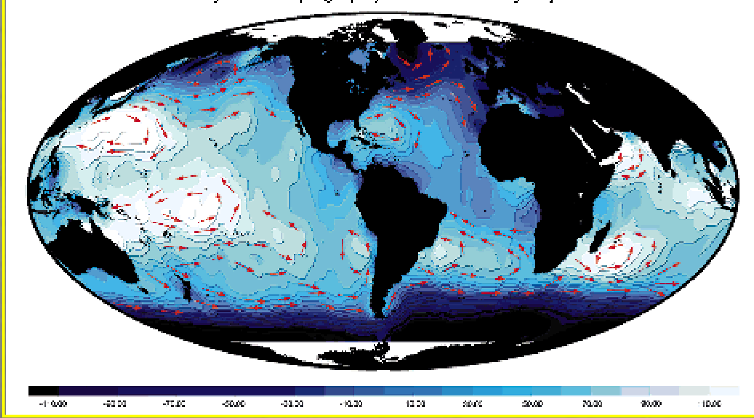
High-resolution map of the Greenland ice sheet topography from altimeter data collected during the ERS-1 geodetic mission (336 day-repeat orbit)

(Courtesy: Rémy et al., 1999)

High-precision altimetry, the breakthrough: the NASA-CNES Topex-Poseidon (1992-2005)

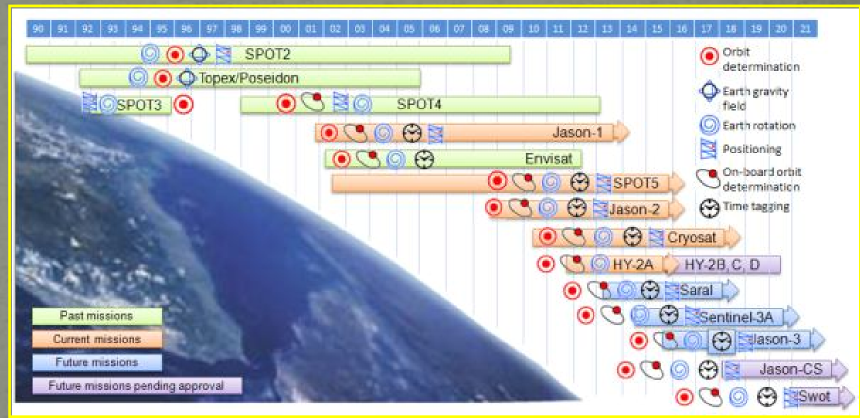
- Topex-Poseidon was launched on August 10, 1992.
- The satellite payload (two altimeters, microwave radiometer, several tracking systems for precise orbit determination), and its orbit parameters (1336 km, 66°) were optimized to achieve the highest possible accuracy in determining the ocean dynamic topography, and retrieving ocean large-scale currents and their variations.
- Topex-Poseidon precision goal was only 13.7 cm. It actually achieved an accuracy of 2 cm at basin scale!

Sea surface dynamic topography as observed by Topex/Poseidon

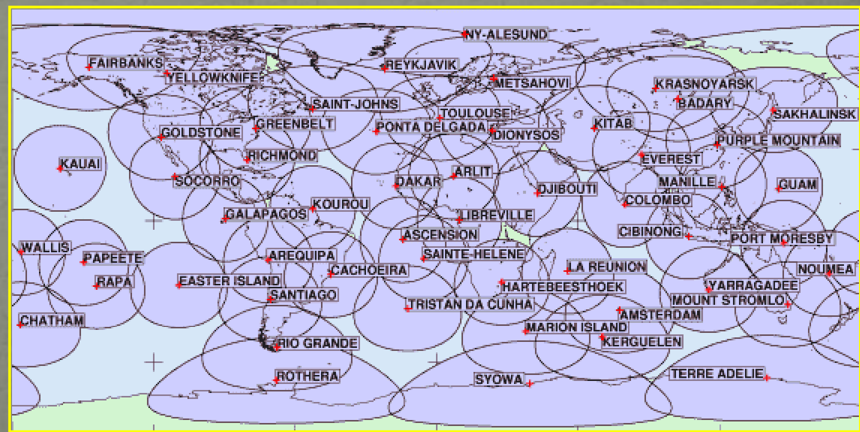


The DORIS Precise Positioning System

- The French positioning system DORIS has been used by the Topex/Poseidon, Jason, Envisat, Spot and other missions for the ultra-precise determination of their orbital parameters
- The DORIS ground network includes over fifty stations
- DORIS applications include the Earth's rotation, the positioning of beacons on the ground (plate tectonics, landslides), etc.

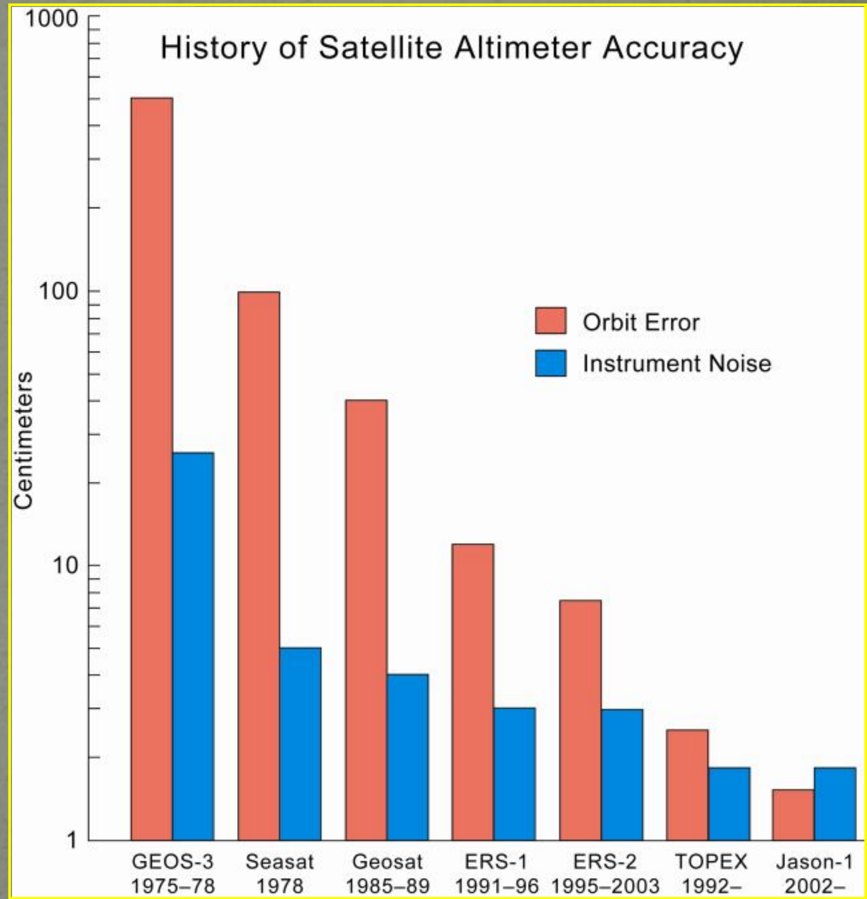


Credit: CNES/CLS

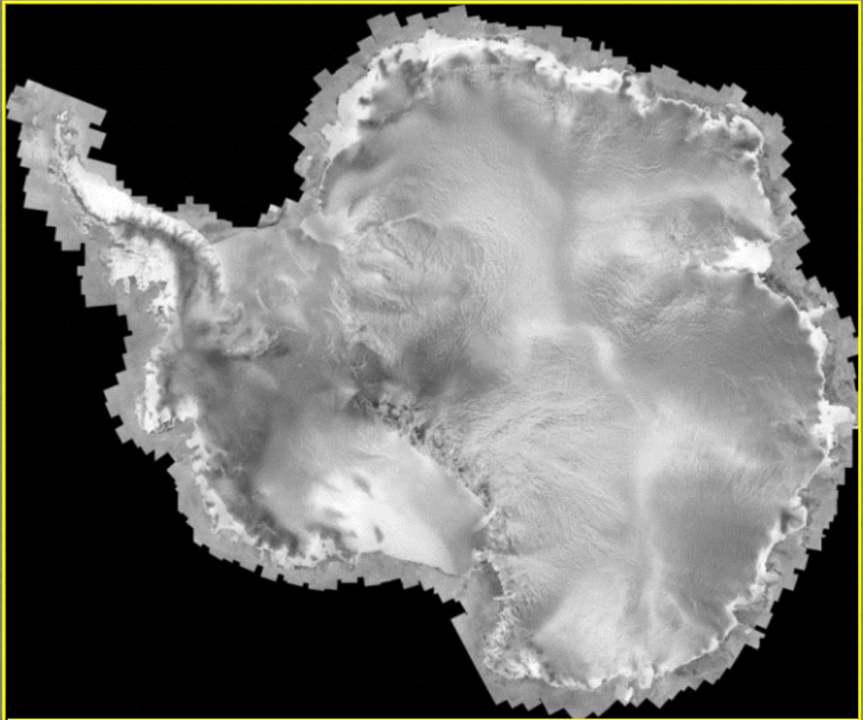


Improvement in Altimeter Accuracy

- The Topex-Poseidon 2-cm accuracy represented the culmination of more than a quarter of a century of steady incremental progress in the succession of altimetric satellites, thanks to its:
  - Dual-frequency altimeter,
  - High-altitude, low inclination orbit
  - Better orbit determination



Canada's RADARSAT-1 (1995-2013)

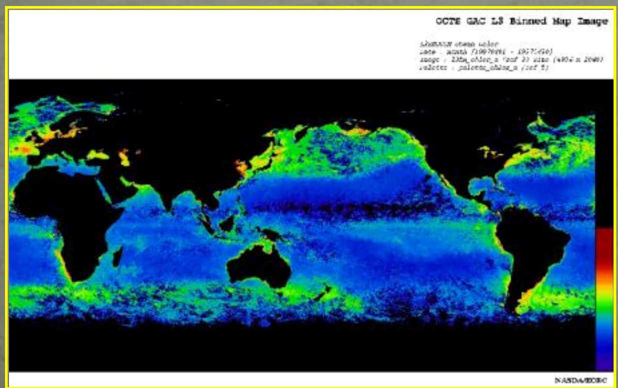


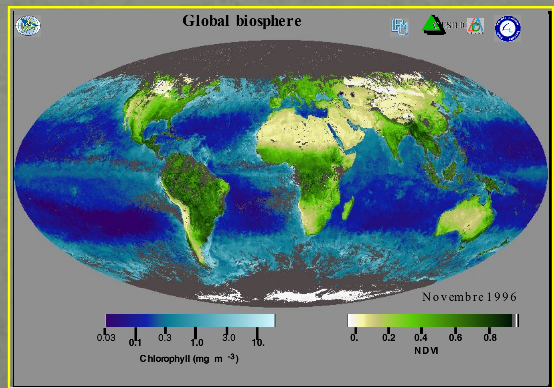
High-resolution (25m) map made up from a mosaic of over 4,500 individual scenes acquired in September 1997 (Courtesy of K. Jezek)

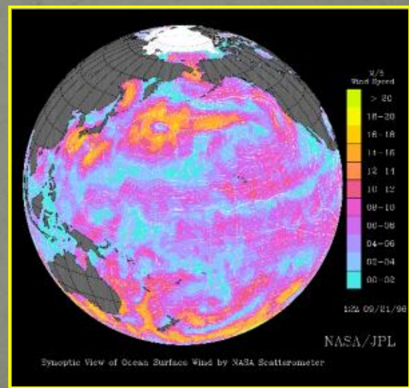
- With 17 years of continuous operation, Radarsat-1 has outperformed by 12 years its nominal lifetime.
- This first 'commercial' radar mission "provided 625,848 images to more than 600 clients and partners in Canada and 60 countries worldwide."

The Japanese ADEOS-1 (1996-1997) and 2 (2002-2003)

- On August 17, 1996, ADEOS-1 was launched into a sun-synchronous orbit at an altitude of 830 km. It carried:
  - Two core sensors developed by NASDA, among which:
    - the Ocean Color and Temperature Sensor (OCTS)
  - Six Announcement of Opportunity sensors, among which:
    - the POLDER radiometer provided by CNES
    - the NSCAT scatterometer provided by NASA
- Both ADEOS-1 and 2 failed after nine months!

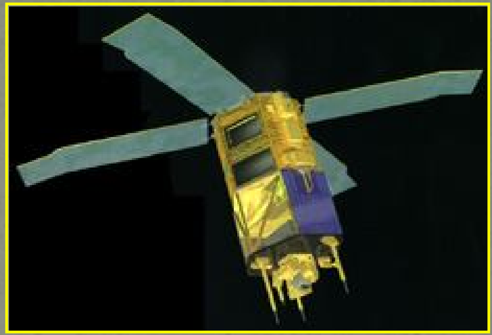


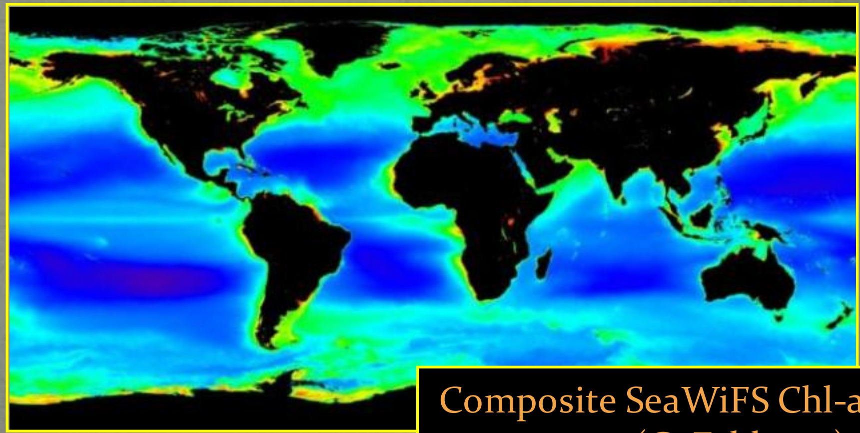




The U.S. SeaWiFS (1997-2010)

- The SeaStar spacecraft, developed by OSC, carrying SeaWiFS was launched on August 1, 1997.
- SeaWiFS is an 8-channel optical scanner designed to provide quantitative data on global ocean bio-optical properties.
- SeaWiFS data were used both for commercial and scientific purposes.
- SeaWiFS stopped collecting data on 11 December 2010

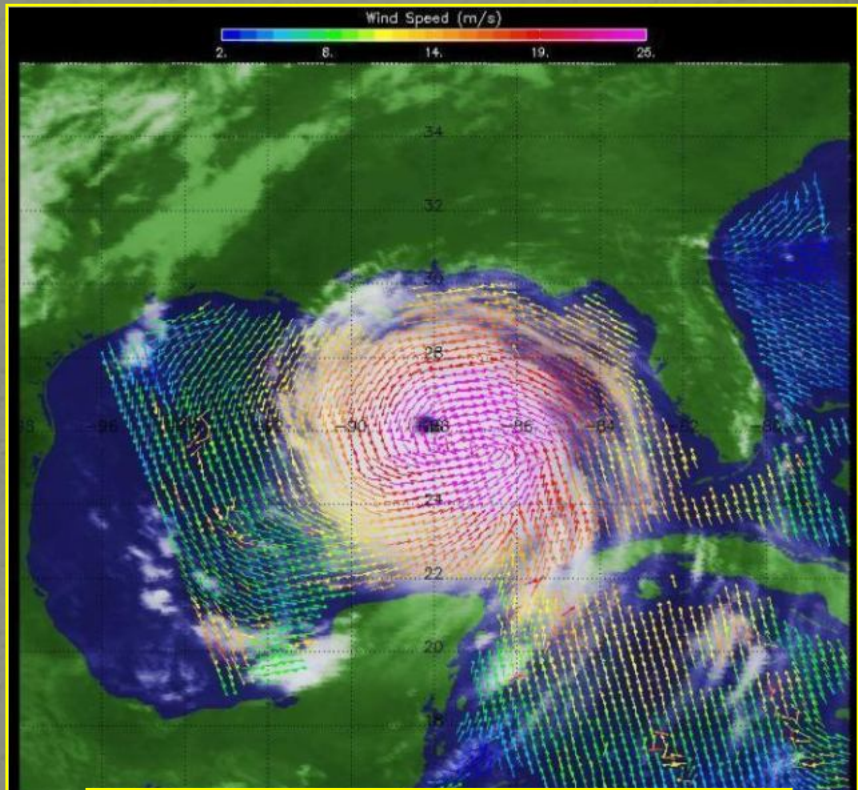




Composite SeaWiFS Chl-a 1997-2009 (G. Feldman)

The NASA QuikSCAT (1999-2009)

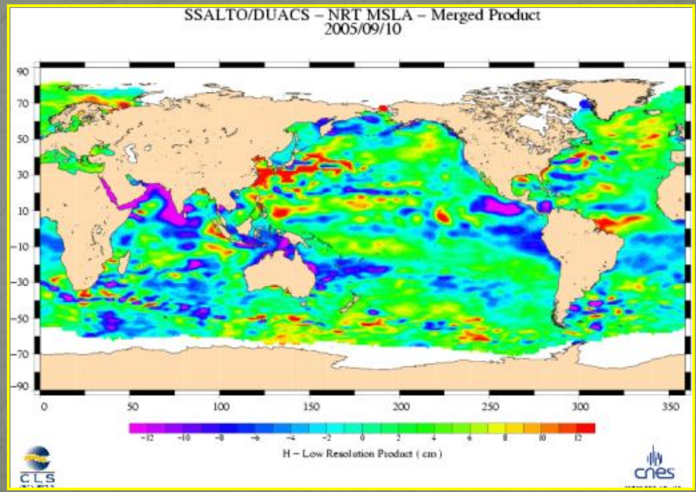
- Built in one year and launched on 19 June 1999, the NASA satellite QuikSCAT was placed on a sun-synchronous polar orbit at 800 km altitude. It acquired every day about 400,000 wind measurements over 93 % of the oceanic surface.
- With QuikSCAT weathermen might forecast 6 to 12 hours ahead harmful meteorological events over oceans. The United States and Europe had incorporated QuikSCAT data of surface wind speed and direction into their operational models for global weather analysis and prediction.



Katrina Hurricane
28 August, 2005

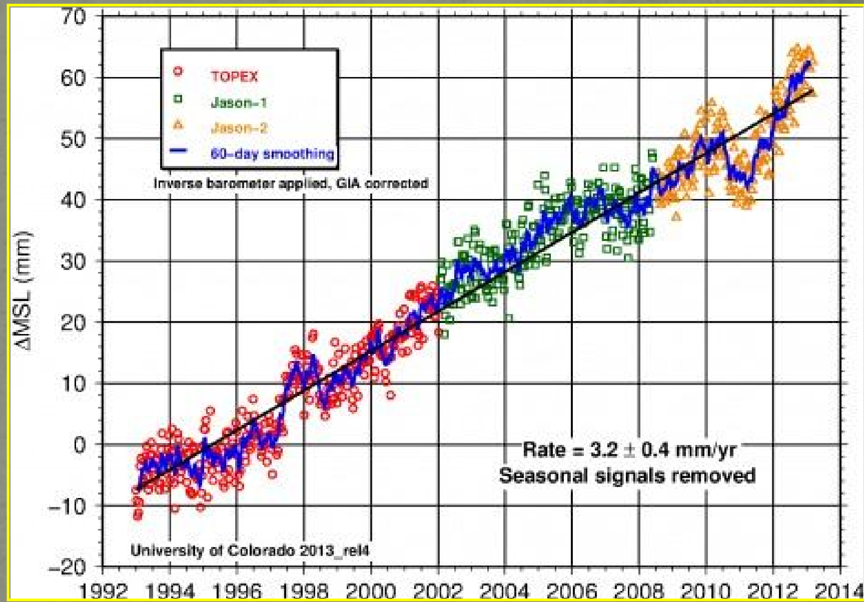
The CNES/NASA Jason-1 (2001-2013)

- JASON-1 was launched on December 7, 2001, from Vandenberg, on the same orbit as TOPEX/Poseidon. It carries an altimetry payload :
  - Dual-frequency altimeter (Poseidon-2)
  - DORIS tracking system receiver
  - Microwave radiometer
  - GPS receiver
  - Laser retro-reflectors
- The satellite weight is only 500 kg (TOPEX/Poseidon weighed over 2.5 tons)
- Jason Operational Sensor Data Records are delivered within 3 hours.



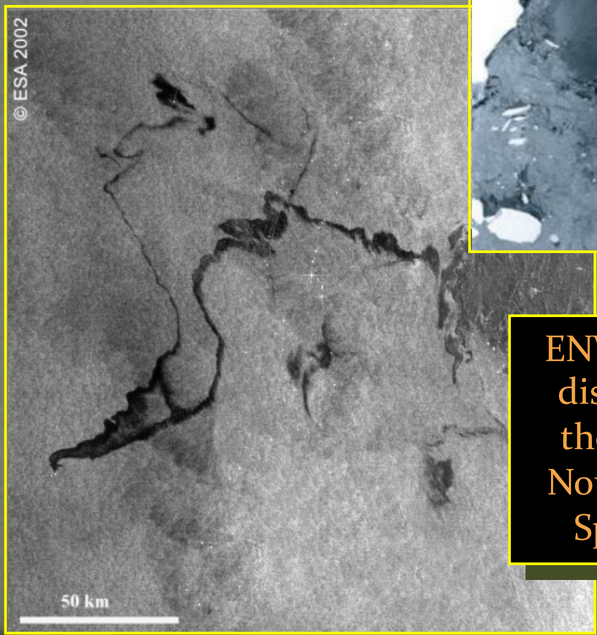
The Topex-Poseidon/Jason Ground Track

Jason-1 stopped collecting data on 21 June 2013



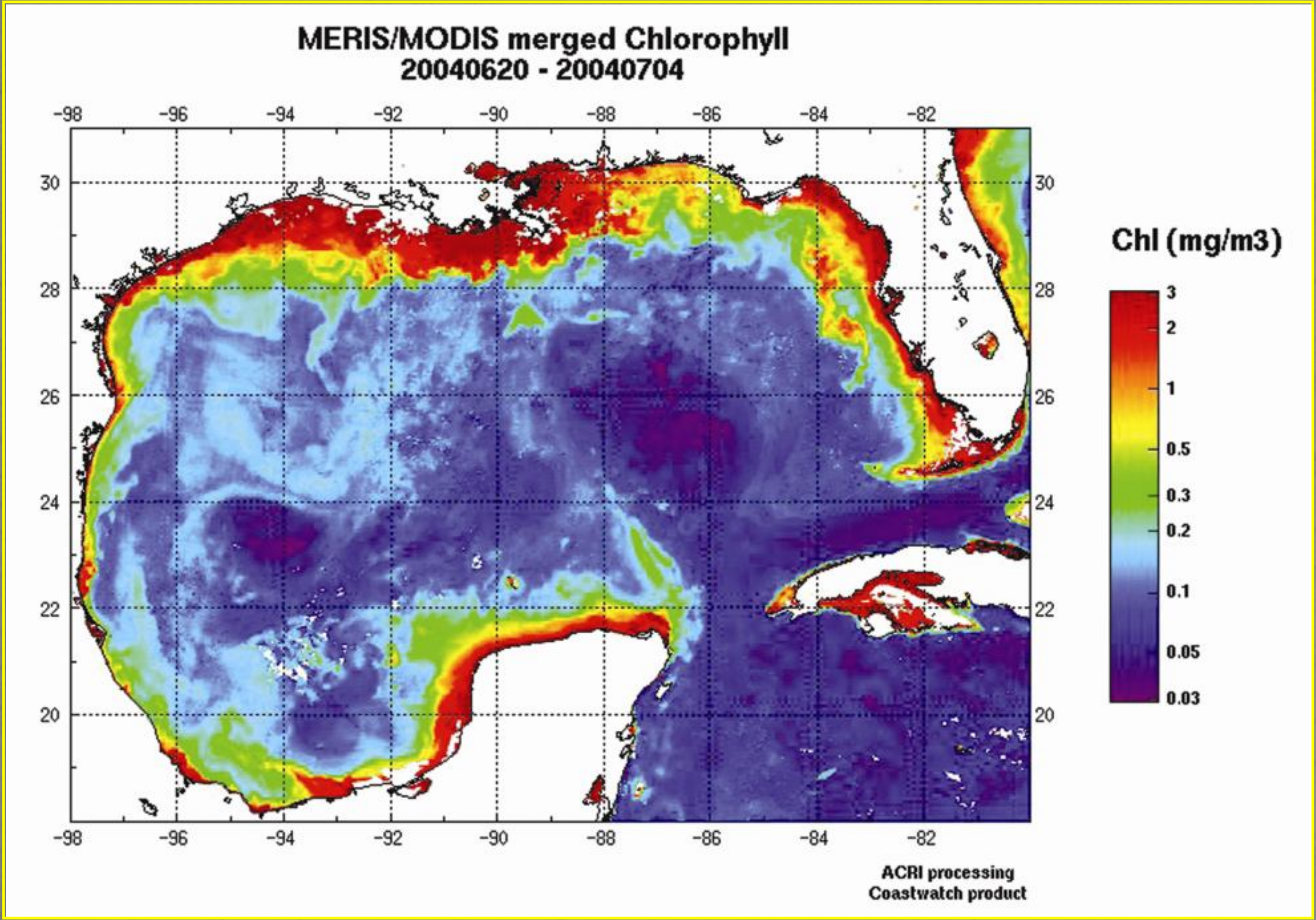
ENVISAT (2002-2012)

ENVISAT was launched just in time to observe the break-up of Larsen B in Antarctica



ENVISAT observed the dispersion of oil from the Prestige wreck in November 2002 off the Spanish West coast

- ENVISAT, the most powerful European Earth observation satellite, was launched from Kourou on February 28, 2002.
- ENVISAT carried 10 sensors, 7 of which were of ocean interest:
  - An Advanced Synthetic Aperture Radar (ASAR)
  - A Radar Altimeter (RA-2), a Microwave Radiometer (MWR), a DORIS tracking system receiver, and laser retro-reflectors (LRR)
  - The Advanced Along-Track Scanning Radiometer (AATSR)
  - A Medium Resolution Imaging Spectrometer (MERIS)

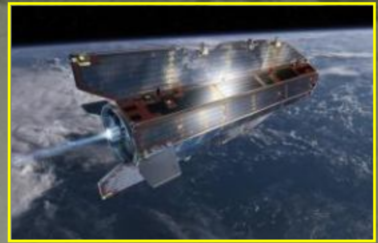


ESA's ENVISAT MERIS and NASA's Aqua MODIS

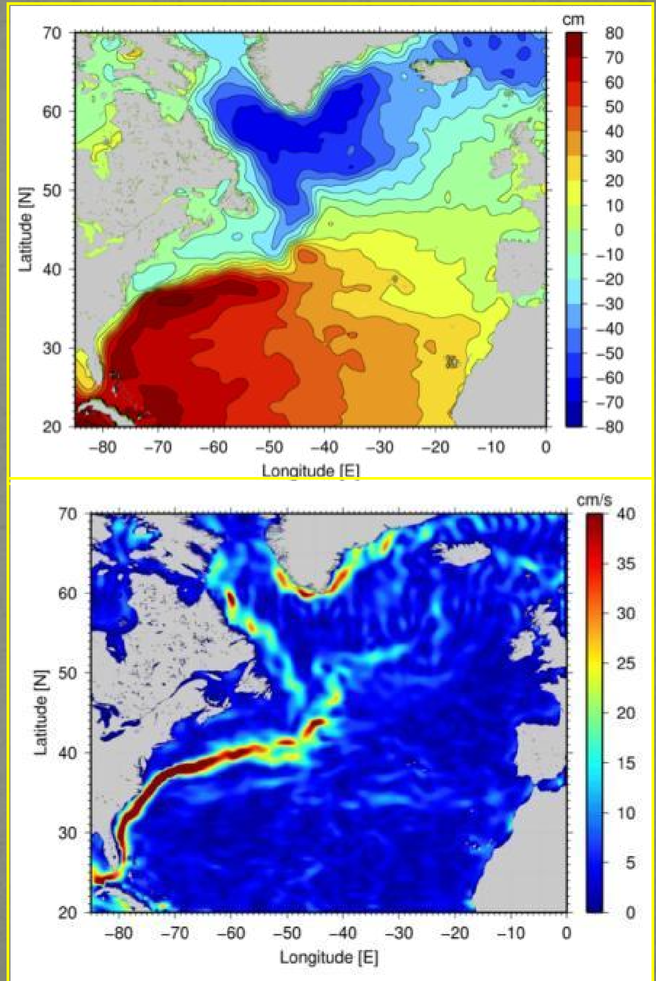
Merged Chlorophyll product derived from observations collected by MERIS (on-board ESA's ENVISAT) and MODIS (on-board NASA's Aqua from June 20 to July 4 2004 in the Gulf of Mexico.

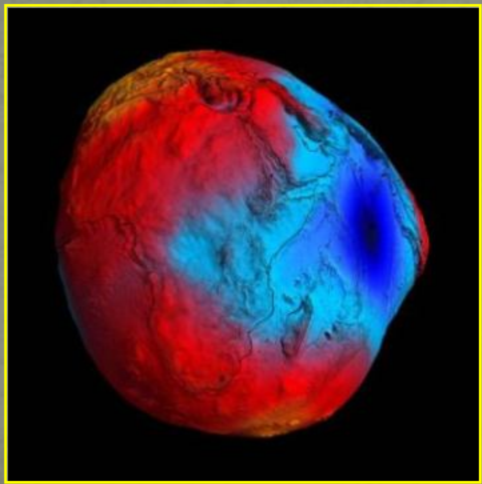
(Courtesy: O. Fanton d'Andon, ACRI)

GOCE – The ESA Gravity-field & Ocean steady-state Circulation Explorer



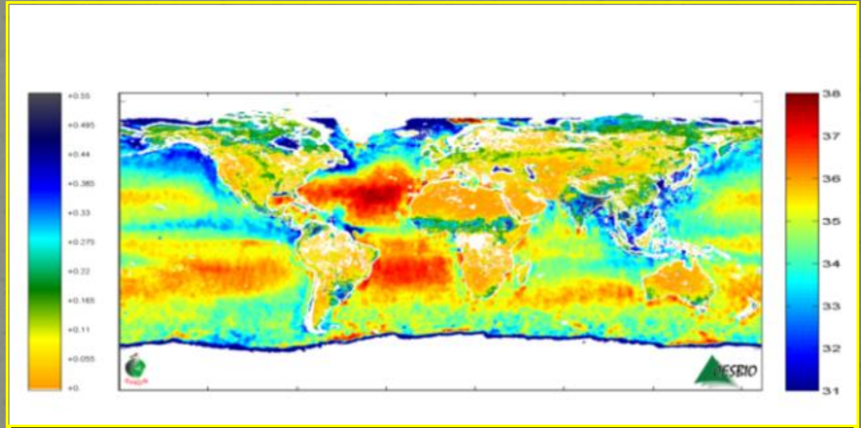
- Launched in 2009, the GOCE mission will end in November
- Using the GOCE independent geoid, global currents can be extracted, for the first time, directly from satellite altimetry data.



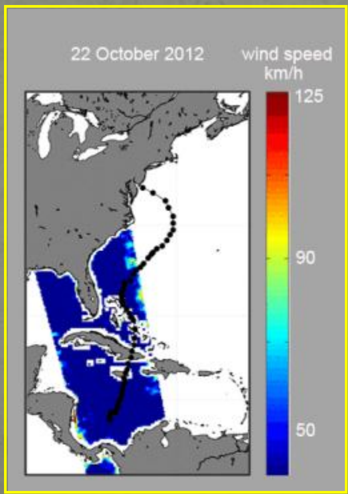


SMOS – The ESA Soil Moisture and Ocean Salinity Explorer

- Launched on November 2009, SMOS carries an L-band microwave interferometer aimed at measuring soil moisture and ocean surface salinity



First merged global maps of soil moisture (August 2011) and sea surface salinity (August 2010), morning orbits.
© CESBIO, IFREMER, CATDS

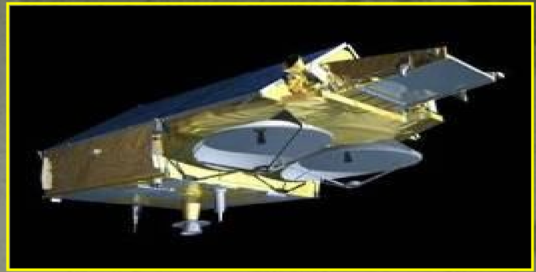


- Estimates of surface wind speeds (km/hr) from SMOS data along the track of Hurricane Sandy (October 2012)

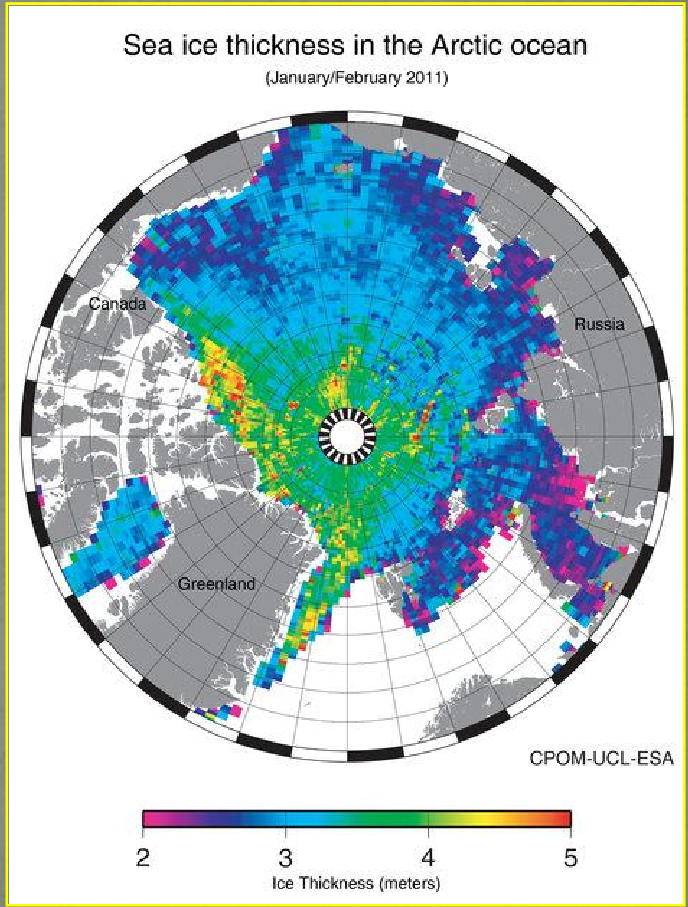
Combining SMOS and Jason observations

Mixed with altimetry data SMOS salinity observations allow to monitor the interaction between warm, salty water carried north by the Gulf Stream and the colder, less-salty waters transported southward by the Labrador Current

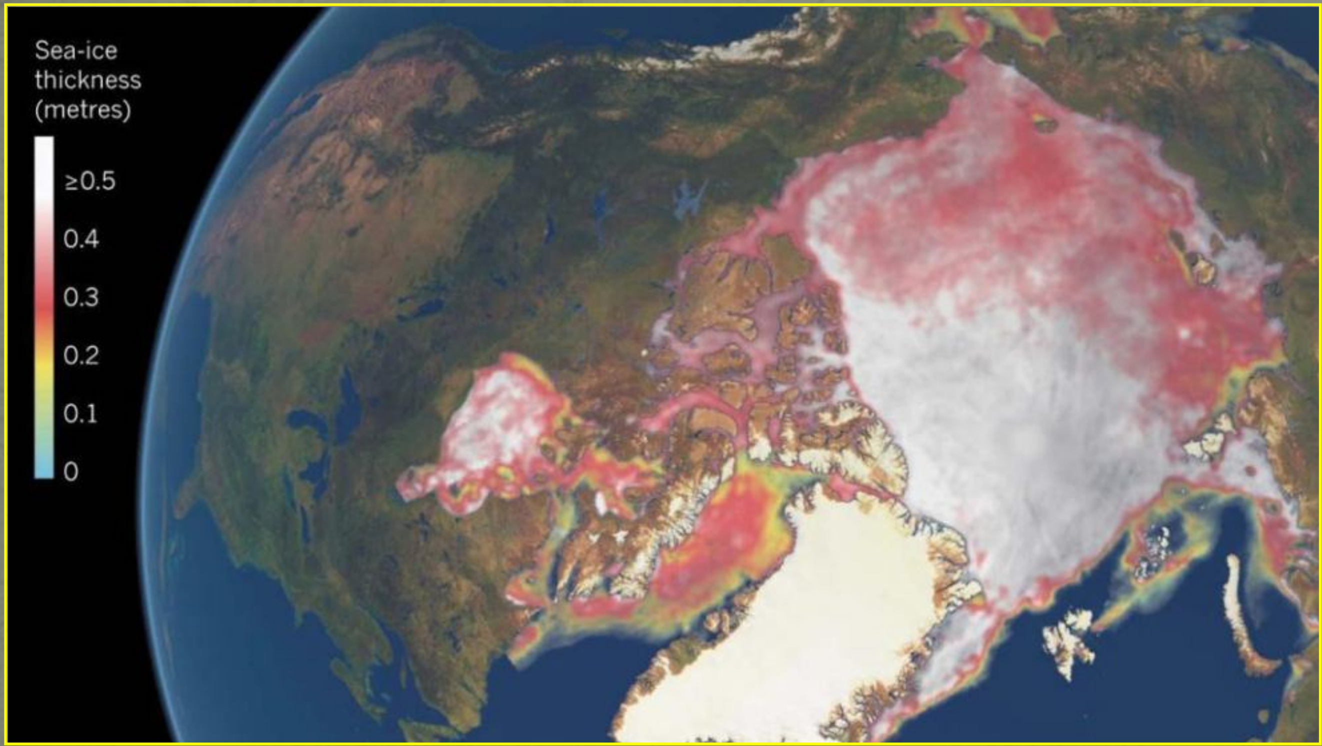
CryoSat-2 – The ESA Polar Ice Monitoring Explorer



- CryoSat-2 (launched 2009) primary mission goals:
  - Determination of regional and basin-scale trends in perennial Arctic sea ice thickness and mass
  - Determination of regional and total contributions to global sea-level of the Antarctic and Greenland ice sheets
- The first-ever map of Arctic sea ice thickness was released in June 2011



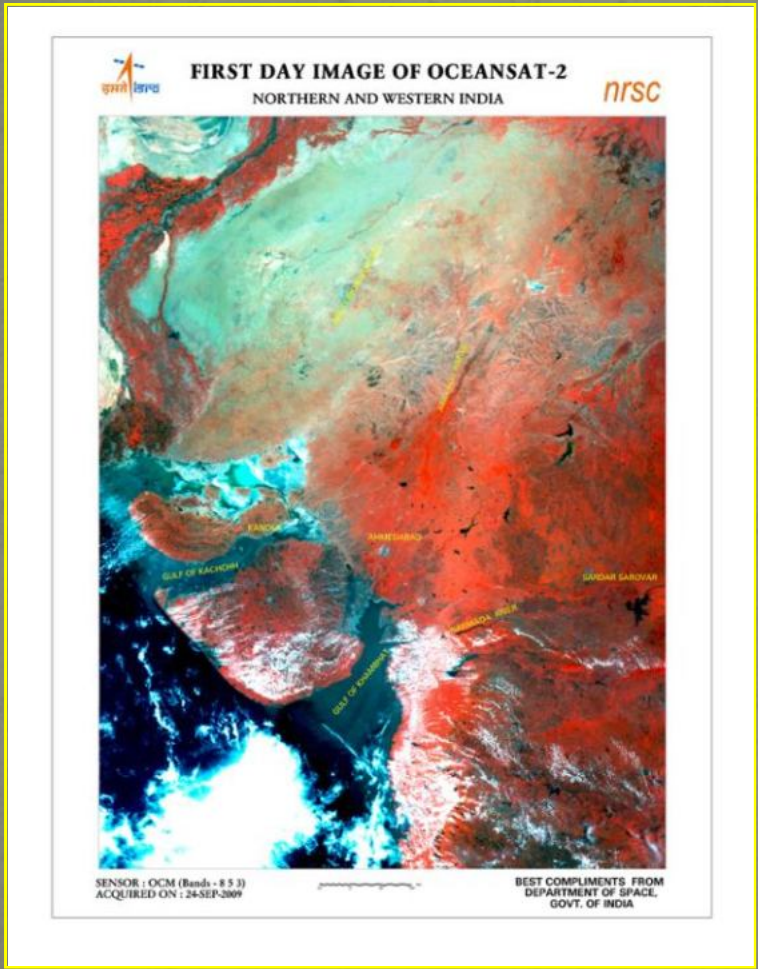
Sea Ice Thickness from… SMOS



SMOS data have also been used to monitor Arctic sea ice. The radiation emitted by the ice allows SMOS to penetrate the surface, yielding ice-thickness measurements down to 50 cm – mainly the thinner and younger ice at the edge of the Arctic Ocean.

(*Credit: L. Kaleschke, IFM, Hamburg*)

The Indian OCEANSAT-2

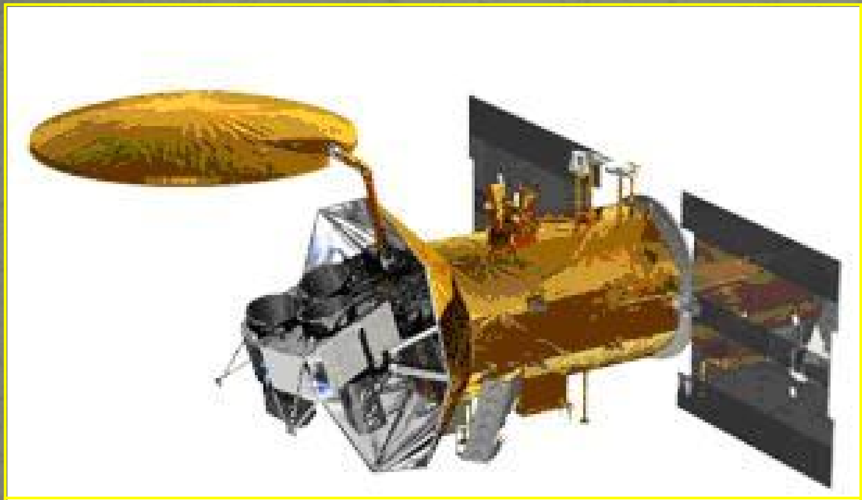


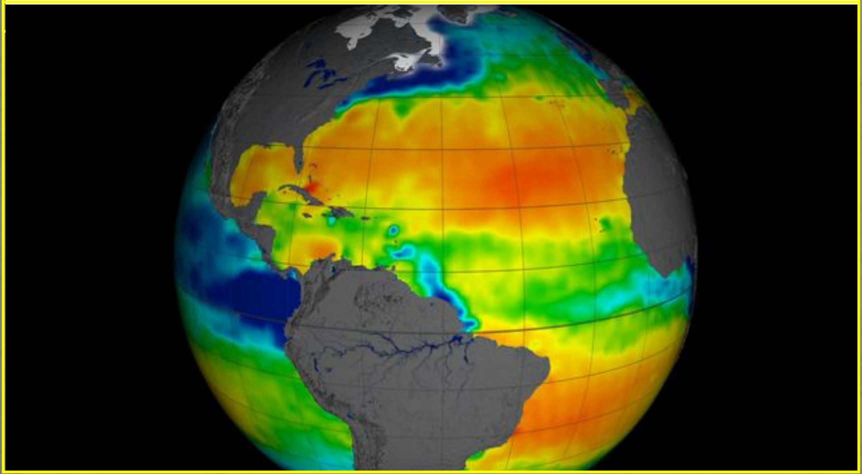
- The first day image of Oceansat-2 (Northwest India) was made available (in pdf format) within hours of its launch on 23 September 2009
- Oceansat-2 carries an Ocean Color Monitor, a wind Scatterometer and a radio-occultation sounder provided by the Italian Space Agency

The Indian-French SARAL-AltiKa

- ISRO and CNES have collaborated on this innovative mission using a Ka-band altimeter, a DORIS receiver, and an ARGOS-3 receiver
- SARAL was aimed at ensuring the continuity of altimetry observation from high-inclination orbit. It was launched on 25 February 2013 and its performance has just been successfully assessed.

The U.S.-Argentina Aquarius/SAC-D

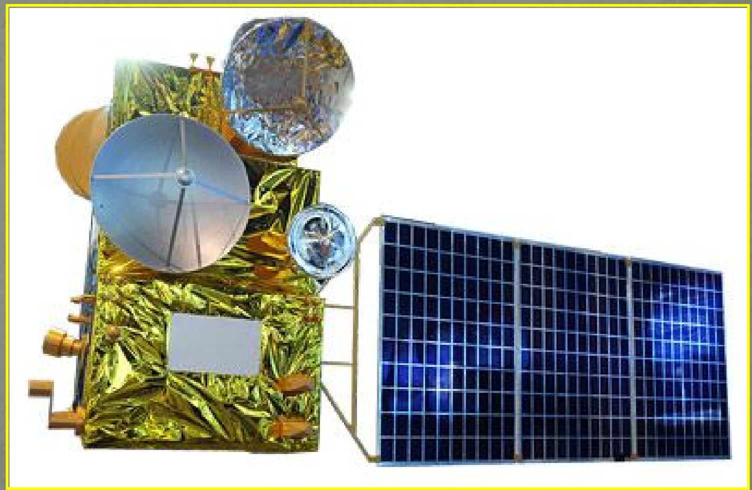




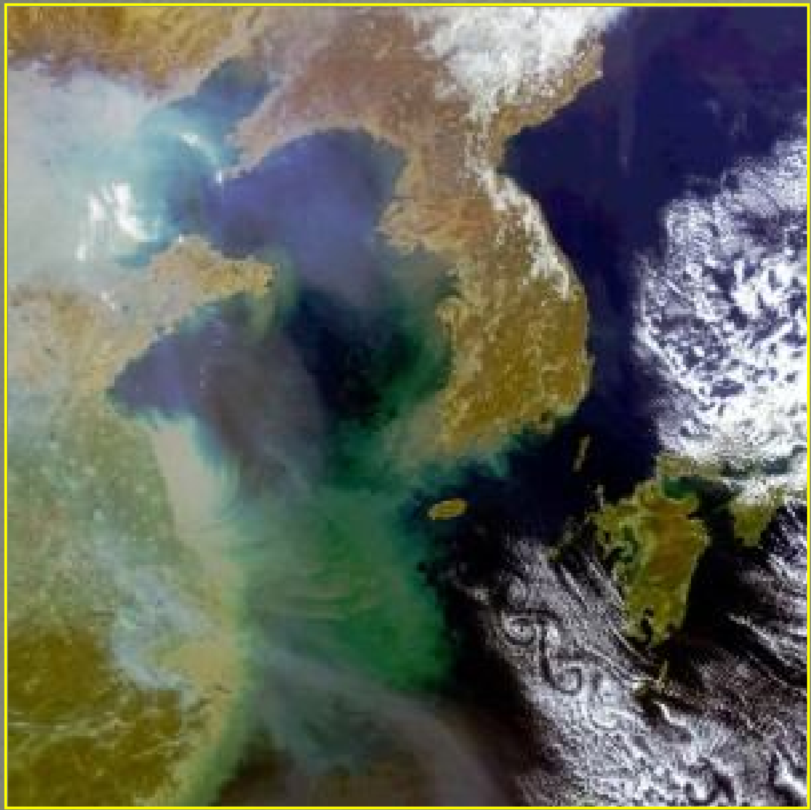
- Aquarius is a focused effort to measure Sea Surface Salinity and provide the global view of salinity variability needed for climate studies.
- The mission (launched 10 June 2011) is a collaboration between NASA and the Space Agency of Argentina (CONAE).

The Chinese HaiYang-2A & B satellites

- The objective of the HY-2 satellite series is to monitor the dynamic ocean environment with microwave sensors to detect sea surface wind field, sea surface height and sea surface temperature.
- The instrument suit consists of an altimeter (dual-frequency in Ku and C-bands), a scatterometer and a microwave imager, and a CNES-provided DORIS receiver for precise orbit determination
- HY-2A was launched on 15 August 2011 (SS orbit at 971 km altitude. Altimeter and scatterometer data are not yet distributed, but compare well with Jason-2 and buoy data.
- HY-2B is due for launch in 2013.

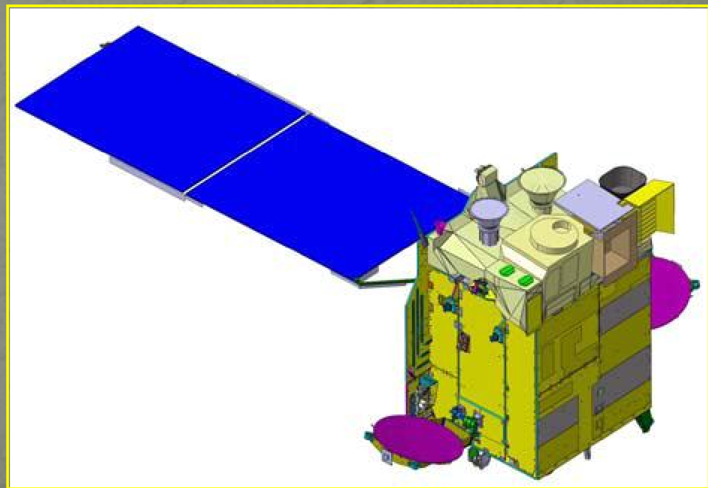


The Korean COMS (Chollian) satellite



Credit: KOSC/KARI

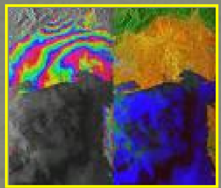
- COMS, the first Korea meteorological satellite carries an ocean color sensor GOCI on a geostationary orbit for the first time ever



Forthcoming Ocean Observing Satellites

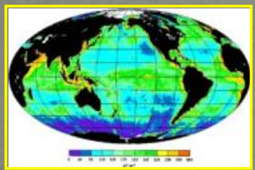
Coming Soon: Jason-3

Coming Soon: The ESA Sentinels (2014-2025)



- Sentinel 1 – Synthetic Aperture Radar (SAR)
  - All weather imagery, interferometry, polar regions

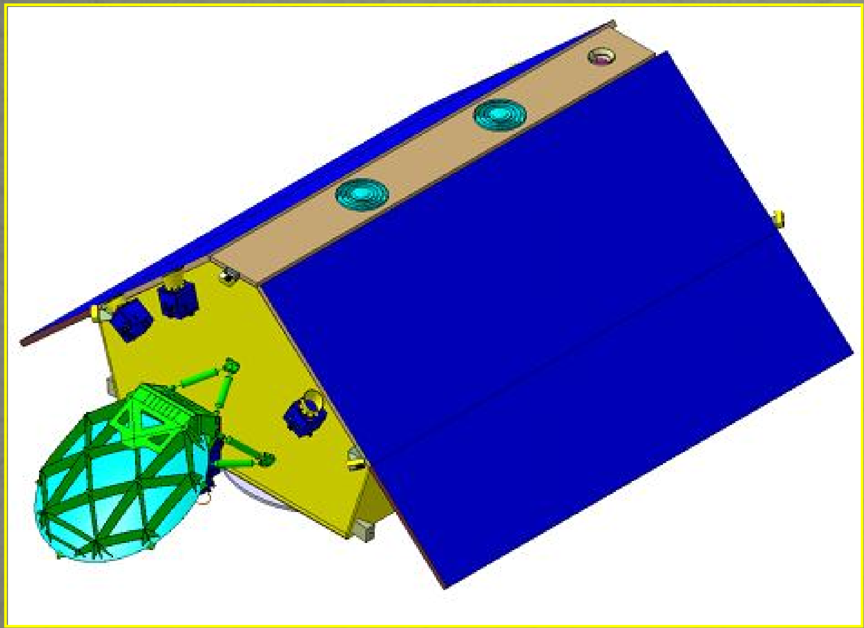
- Sentinel 2 – Super-spectral optical imagery
  - Continuity of Landsat, Spot & Vegetation data



- Sentinel 3 – Ocean monitoring
  - Ocean color, sea surface temperature and sea surface topography

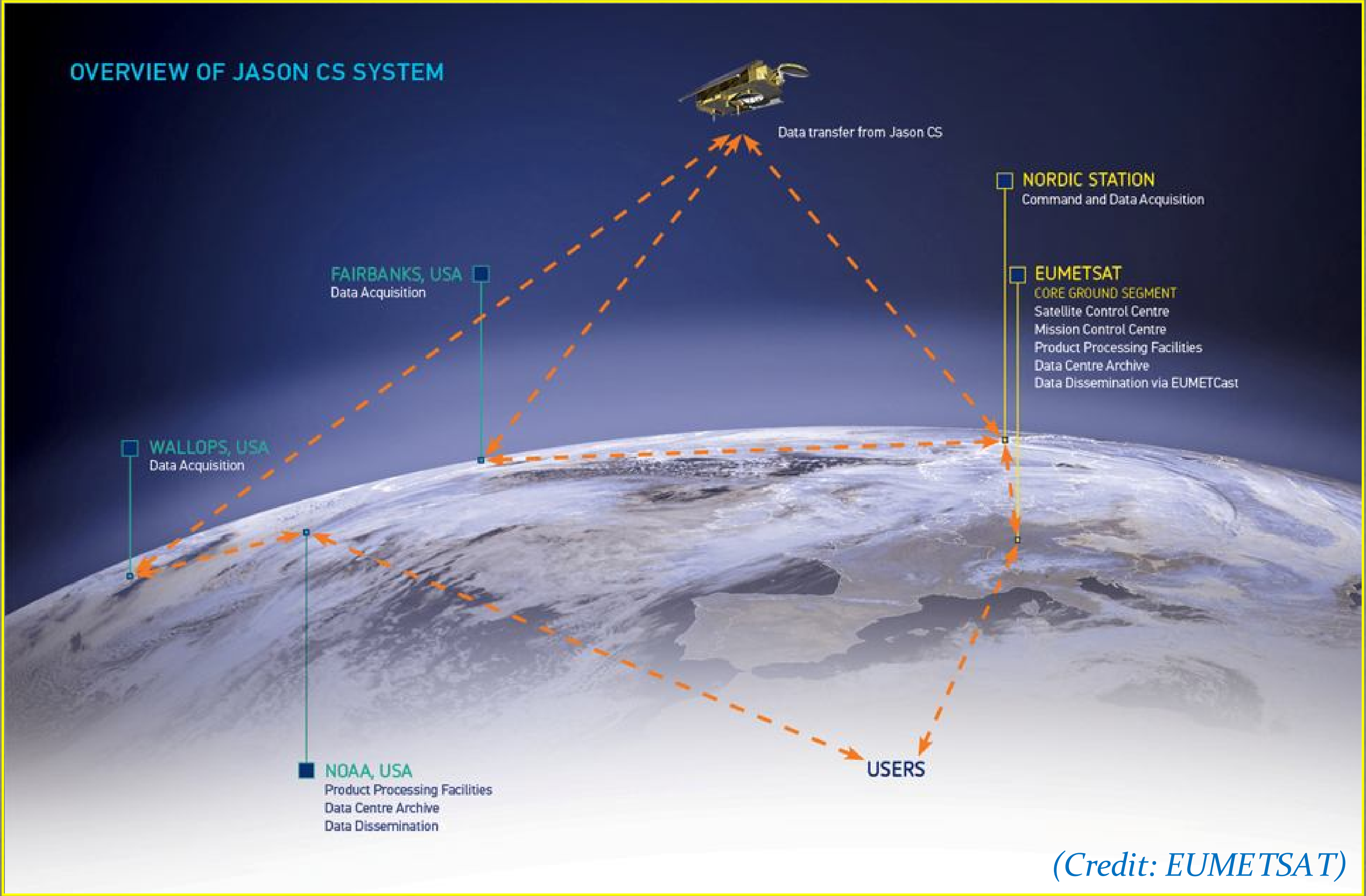
- Sentinel 4 – Atmospheric Monitoring from GEO
  - Atmospheric composition, transboundary pollution
- Sentinel 5 – Atmospheric Monitoring from LEO
  - Atmospheric composition

Coming Soon: Jason-CS (2017-2030)



- Jason-CS will ensure continuity with Jason-3 with a first launch early enough to guarantee adequate overlap with Jason-3. Two satellites with a 7 years lifetime each are planned.
- Jason-CS should ensure the same (or better) level of performance as earlier Jason series. It will extend the existing partnership between the U.S. and Europe (NOAA, NASA, EUMETSAT, ESA, CNES and industry).

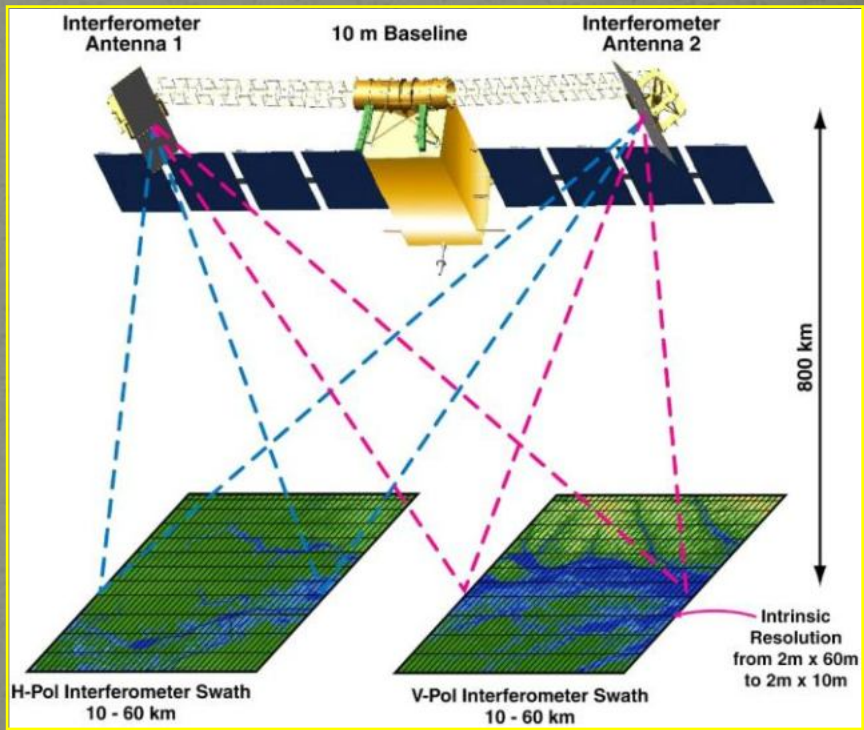
Extended International Cooperation



(Credit: EUMETSAT)

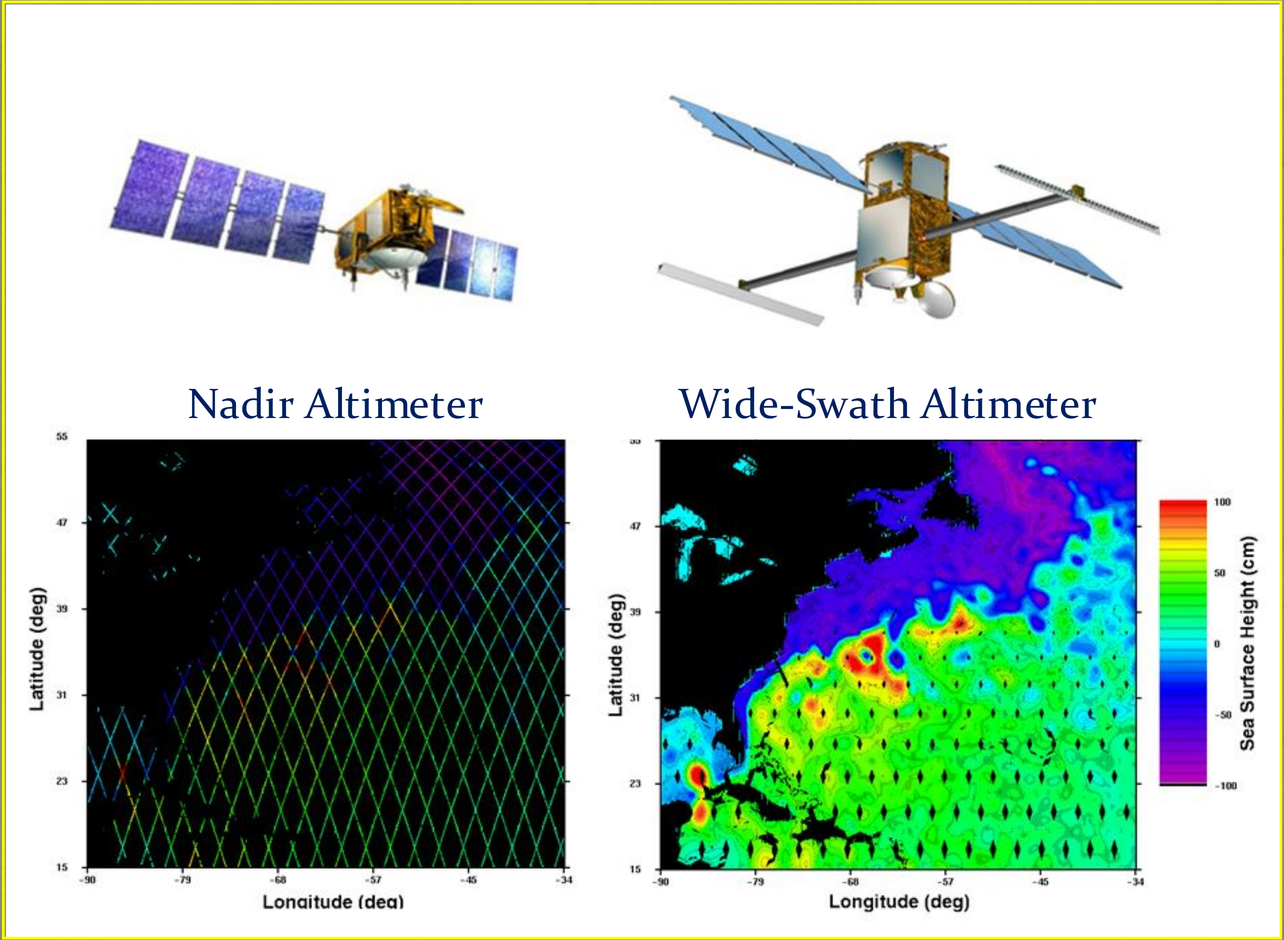
Coming Soon: the U.S.-France-Canada SWOT (2019-2022)

- The Surface Water Ocean Topography (SWOT) mission will make the first global survey of Earth's surface water, observe the fine details of the ocean's surface topography, and measure how water bodies change over time.
- With its wide-swath altimetry technology, it is a means of completely covering the world's oceans and freshwater bodies with repeated high-resolution elevation measurements.



Credit: K. Rodriguez/JPL)

Overcoming Global Coverage Limitation



The Reasons of a Success

An "incredible" success story

- In the 1980s, it was nearly impossible in the U.S. to justify a mission based on its contribution to ocean science
  - International cooperation and other non-science -related arguments made it possible to set up the joint NASA-CNES Topex-Poseidon

Top: four French engineers in July 1983 after a exhausting "collaborative" meeting at JPL
Bottom: over 200 scientists at the OSTST meeting in Lisbon, October 2010

An international effort: the high-precision satellite altimetry program

From back to front side:

D. WILLIAMS (EUMETSAT)

B. SMITH (NOAA)

J.L. FELLOUS (then with CNES)

From back to front side:

T. MOHR (EUMETSAT)

G. WITHEE (NOAA)

G. ASRAR and A. CONDES (NASA)

Signature of the letters exchanged by CNES and EUMETSAT with NASA and NOAA on the Ocean Surface Topography Mission, Kyoto, 7 November, 2001

ESA's Earth Observation program took a long time to mature

- ERS-1 was decided on the assumption that it would help develop a commercial sector. ERS-2 was decided on the basis on the need for continued SAR monitoring of land surface. ENVISAT was initiated as part of the ISS
- ESA's Living Planet Program (conceived by the former COSPAR President, Roger Bonnet, an astronomer!) was only initiated in 1999

The Role of International Coordinating Bodies: GCOS, CGMS, CEOS, GEO

- Global Climate Observing System (GCOS) requirements have nurtured the efforts of the Committee on Earth Observation Satellites (CEOS) and the Coordinating Group for Meteorological Satellites (CGMS), whose programs support the Group on Earth Observation (GEO) with a view to establish a Global Earth Observing System of Systems (GEOSS)

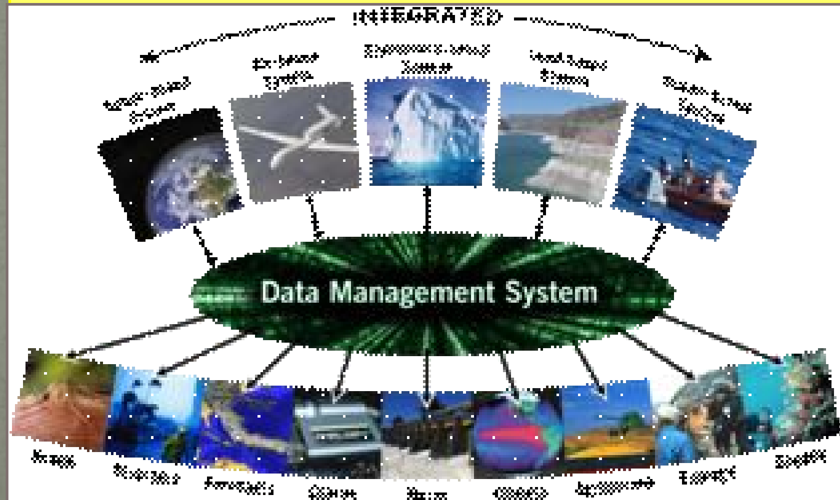
CEOS Response to the GCOS Implementation Plan – September 2006

Satellite Observation of the Climate System

The Committee on Earth Observation Satellites (CEOS) Response to the Global Climate Observing System (GCOS) Implementation Plan (IP)

Developed by CEOS and submitted to the United Nations Framework Convention on Climate Change (UNFCCC) Subsidiary Body on Scientific and Technical Advice (SBSTA) on behalf of CEOS by the United States of America (USA) delegation

Visit *http://www.ceos.org* for the full report

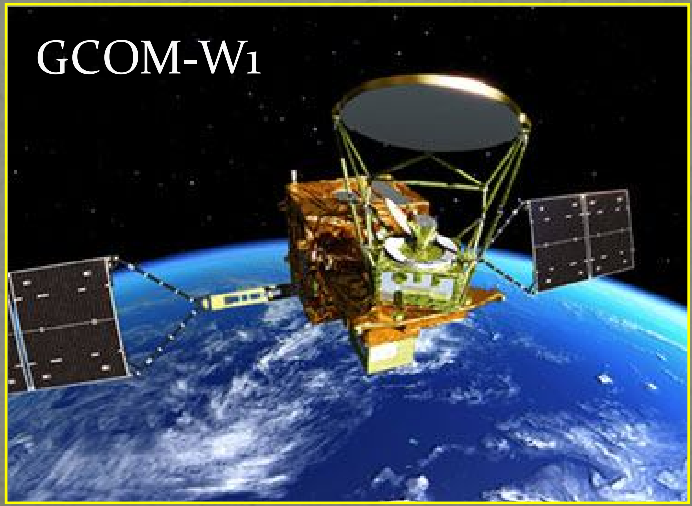


Ocean ECVs observed from space

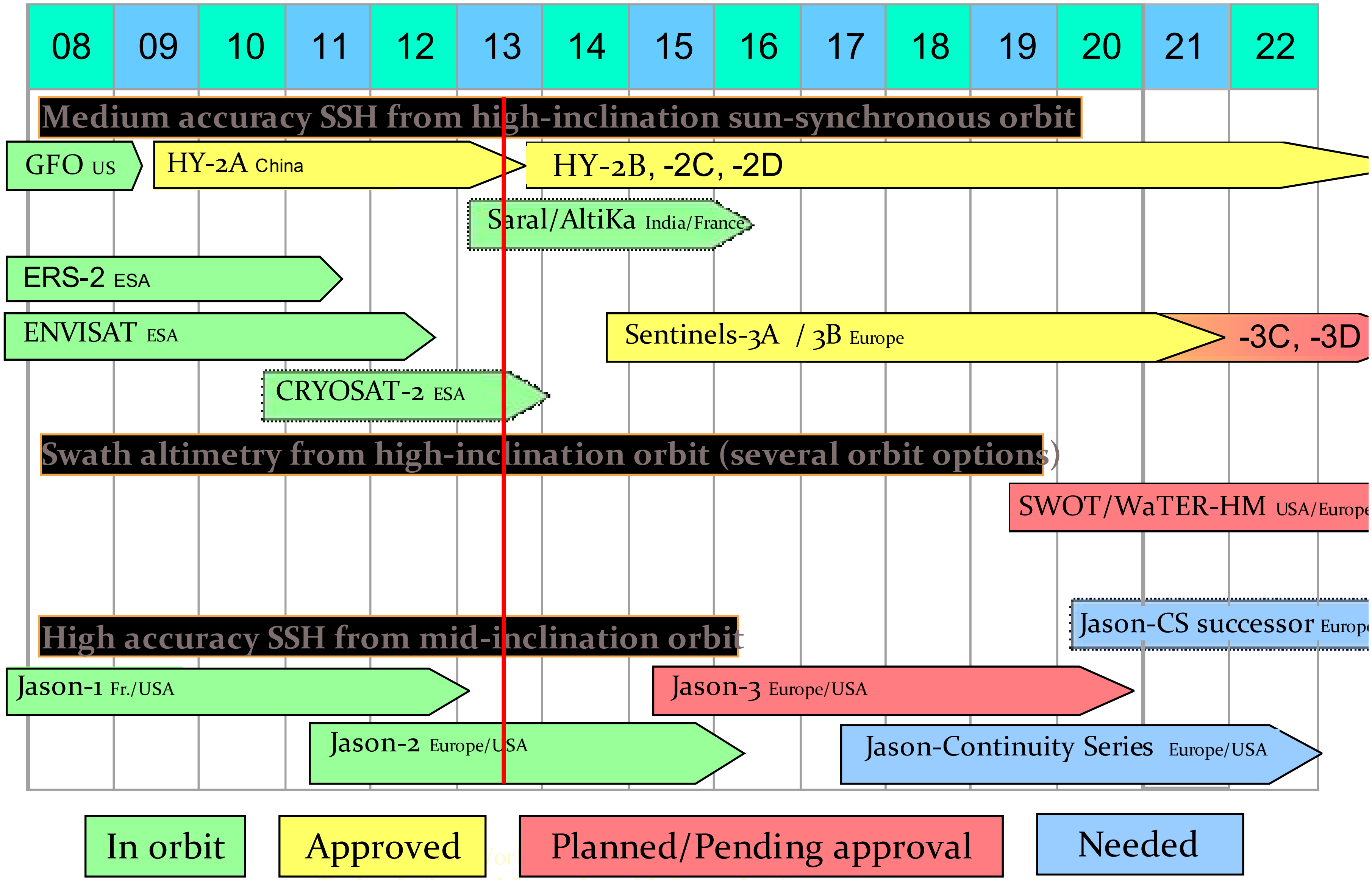
- Ocean Essential Climate Variables accessible to satellite measurement include:
  - Sea Surface Temperature
  - Sea Surface Height (ocean topography): currents, marine geoid
  - Sea State
    - Surface wind field (speed and direction)
    - Wave field (speed and direction)
  - Sea Surface Reflectance (ocean colour): surface concentration in chlorophyll pigments, sedimentary plumes, coastal currents, algae blooms
  - Sea ice concentration and thickness
  - Sea Surface Salinity

Operational Space-Based Ocean Measurements

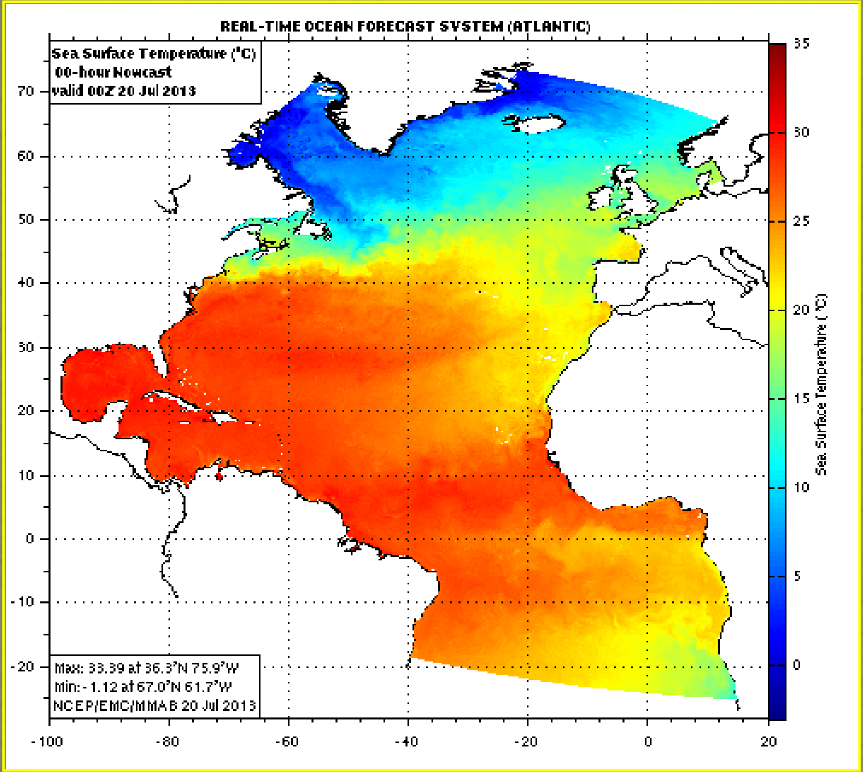
- Nowadays, several ocean surface parameters are measured operationally from space, with increased spatial and temporal resolution and accuracy
  - Sea Surface Temperature
  - Sea State (surface winds and waves – speed and direction)
  - Sea Surface Height
  - Ocean Color
- However there are still limitations (spectral bands, risk of data gaps)

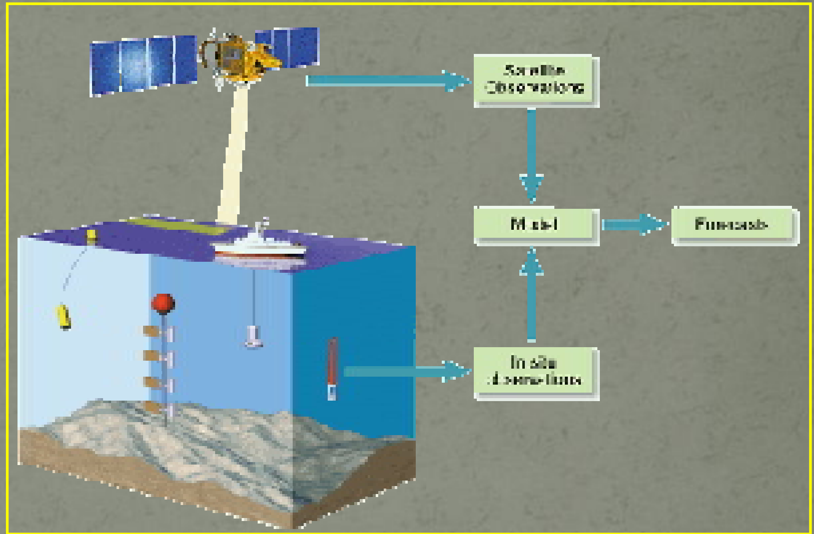


Ocean Surface Topography Constellation Roadmap



Operational Ocean Forecast Products





Credit: NOAA/NCEP

Full and Open Access Data Policies

- The missions discussed above showed a mix of data policies, evolving from the PI-type to full and open access to data without any period of exclusive use (Topex-Poseidon, Jason, QuikSCAT), along with a variety of intermediate cases (e.g. ERS, ALOS, ENVISAT) and involving in some cases commercial distribution (e.g. RADARSAT, real-time SeaWiFS for non-research purposes)
- Full and open access is the preferred route from a scientific perspective, and it has allowed to achieve the full potential of the missions and to lay the foundation for an ocean observing operational system

… and many other reasons

- Policy Relevance and Demonstrated Usefulness
  - Climate Change and IPCC
  - UNFCCC Conference of the Parties request for Continuous Space-Based Observations
- Availability of Integrated Products
  - Space-based and *in situ*
  - Data assimilation and improved ocean modeling
- A Good Balance of Continuity and Innovation
  - Continuity of data products
  - Improvement of observing techniques and accuracy
- The Involvement of Operational and R&D Agencies
  - Need for 24/7 operation
  - Need for quality assurance, calibration and validation

Some Actors – With Thanks!