feature articles

An Overview of Europe's Expanding Earth-Observation Capabilities

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Established in the mid-1990s, ESA's Living Planet Programme heralded a new approach to satellite observations for Earth science, with focused missions defined, developed, and operated in close cooperation with the scientific community, worldwide.

Introduction

The European Space Agency (ESA) has been managing an Earth Observation Programme since the launch of its first Meteosat meteorological satellite in 1977. Following the success of this first mission, a subsequent series of Meteosat satellites, two Earth Remote Sensing satellites (ERS-1, ERS-2), and the Envisat mission provided a wealth of valuable data about Earth, its climate, and its changing environment. For the last 30 years special emphasis has been given to calibrating instruments, validating data products, developing improved algorithms, and documenting these processes. This has been a joint effort of specialized laboratories, partner space agencies, and user communities to ensure that the missions are an innovative asset for research and public services. As a result, ESA has become a major provider of Earth-observation data to the Earth-science community.

Established in the mid-1990s, *ESA's Living Planet Programme* heralded a new approach to satellite observations for Earth science, with focused missions defined, developed, and operated in close cooperation with the scientific community, worldwide. Over time, three categories of Earth-observing missions have emerged: Earth Explorer (research), Earth Watch (meteorological), and Global Monitoring for Environment and Security (GMES[1]) Sentinel missions; these are described in more detail, below. **Figure 1** shows ESA's past, present, and planned Earth-observing satellites missions divided roughly into the three current mission categories.

[1] For more information on GMES, visit: *www.esa.int/Our_Activities/Observing_the_Earth/GMES/Overview3*.

Breakdown of ESA's Living Planet Programme

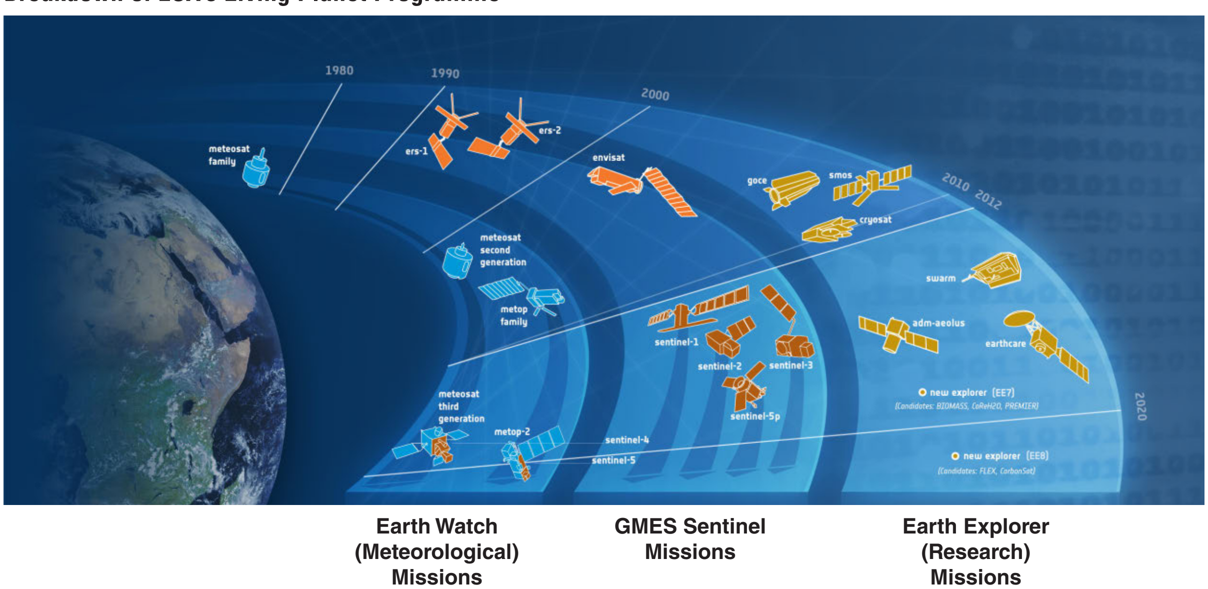

Figure 1. Since 1977, ESA has launched a series of satellites to explore the Earth's environment. *Earth Watch* (meteorological) missions are driven by weather forecasting and climate monitoring needs. *GMES Sentinel* missions are driven by users' needs to contribute to the GMES. *Earth Explorer* (research) missions are driven by scientific needs to advance our understanding of how the ocean, atmosphere, hydrosphere, cryosphere, and Earth's interior operate and interact as part of an interconnected planetary system. **Image credit**: ESA

ERS and Envisat—Europe's Earth Observing Research Pioneers

ERS and Envisat predate the formal establishment of the Earth Explorer and Sentinel missions described below. Hence, these missions straddle the space between the Sentinel and Earth Explorer streams in Figure 1. Both missions successfully demonstrated remote-sensing technology that provides new information on Earth science and applications that are being applied to future research missions and by operational service agencies.

European Remote Sensing Satellites

The first ERS satellite (ERS-1), launched in 1991, was ESA's first Sun-synchronous, polar-orbiting, remote-sensing mission. ERS-1 carried a comprehensive payload including an imaging Synthetic Aperture Radar (SAR), radar altimeter, and other instruments to measure ocean surface temperature and winds. In March 2000 a computer and gyroscope control failure led to the end of ERS-1 operations after it had far exceeded its planned lifetime. ERS-2, which overlapped with ERS-1, was launched in 1995 and, in addition to a duplicate of the ERS-1 payload, carried an additional sensor—the Global Ozone Monitoring Experiment (GOME). Both satellites collected a wealth of valuable data on Earth's land surfaces, oceans, and polar regions—data used to monitor natural disasters such as severe flooding and earthquakes in remote areas of the world. Shortly after the launch of ERS-2, ESA linked the two satellites in the first *tandem mission*[2], which lasted for nine months. During this time the increased frequency and level of data available to scientists offered a unique opportunity to observe changes over a very short time—as both satellites orbited Earth only 24 hours apart. GOME data were used for atmospheric ozone research and included in a European satellite-ozone dataset that complemented the established NASA/National Oceanic and Atmospheric Administration (NOAA) satellite-ozone dataset. In July 2011 ERS-2 was retired and the process of de-orbiting the satellite began.

The user demand for Envisat data remains very high: about 600 new user proposals were registered at ESA during 2012, requesting Envisat data. So far, there are about 4500 Envisat-user projects.

Envisat

The Environmental Satellite (Envisat[3]), the largest civilian Earth-observing satellite ever built by any space agency, was launched in 2002. It was an advanced polar-orbiting satellite that provided measurements of the atmosphere, oceans, land, and ice for over 10 years—twice as long as its planned lifetime. Envisat built on the successful ERS legacy; carried an ambitious and innovative payload that enabled acquisition of advanced Earth-observation science data and also ensured the continuity of data measurements from the two ERS satellites, described earlier.

Envisat data collectively provided a wealth of information to allow studies of atmospheric chemistry, ozone depletion, biological oceanography, ocean temperature and colour, wind-generated ocean waves, hydrology (i.e., humidity and floods), agriculture and arboriculture, natural hazards, digital elevation modelling (using interferometry), maritime traffic monitoring, atmospheric dispersion (i.e., pollution) modelling, cartography, snow, and ice. The archive of data received from the satellite supports long-term monitoring of environmental and climatic changes.

In April 2012 contact with Envisat was suddenly lost and the mission came to an abrupt end. However, 10 years of Envisat's archived data continue to be analyzed and applied to studies of our planet. The user demand for Envisat data remains very high: about 600 new user proposals were registered at ESA during 2012, requesting Envisat

[2] *Tandem mission* means that ERS-1 and ERS-2, carrying nearly an identical instrument manifest, flew in close orbital proximity for a time to intercompare their respective instruments and to calibrate the new ones on ERS-2.

[3] For more information about Envisat and its instruments, visit: *earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments*.

The Earth Explorers are research missions designed to address key scientific challenges identified by the science community, while demonstrating breakthrough technologies in observing techniques.

data. So far, there are about 4500 Envisat-user projects. **Figure 2** illustrates the growing number of Earth science projects for science and applications stemming from Envisat data.

Earth Explorer Missions – In Orbit and Upcoming Launches

The *Earth Explorers* are research missions designed to address key scientific challenges identified by the science community, while demonstrating breakthrough technologies in observing techniques. These missions involve the science community in defining new missions from the outset, through a peer-reviewed selection process that ensures efficient mission development and provides end-user-requested data. This approach provides Europe with an excellent opportunity for international cooperation, involves the global scientific community, and also aids in the technological development of new missions. Described below are three current Earth Explorer missions in orbit, three planned missions, and a recently selected mission.

GOCE: Gravity Mission

Launched on March 17, 2009, the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission was the first Earth Explorer. GOCE was designed to provide information for understanding critical Earth system variables driven by the Earth's gravitational field. The gravitational gradients are measured by a set of six, three-axis accelerometers. GOCE has provided data used to accurately develop global and regional models of Earth's gravity field and geoid, advance research in areas of ocean circulation and ocean dynamics, address the physics of Earth's interior, characterize geodesy and surveying, and monitor sea-level change. While the mission is ongoing, all mission requirements were fully met by the end of 2012. GOCE also mapped gravity signals significantly beyond the original goal of *spherical harmonic degree* 200 [equal to 100 km (~62 miles)]. Using data from GOCE,

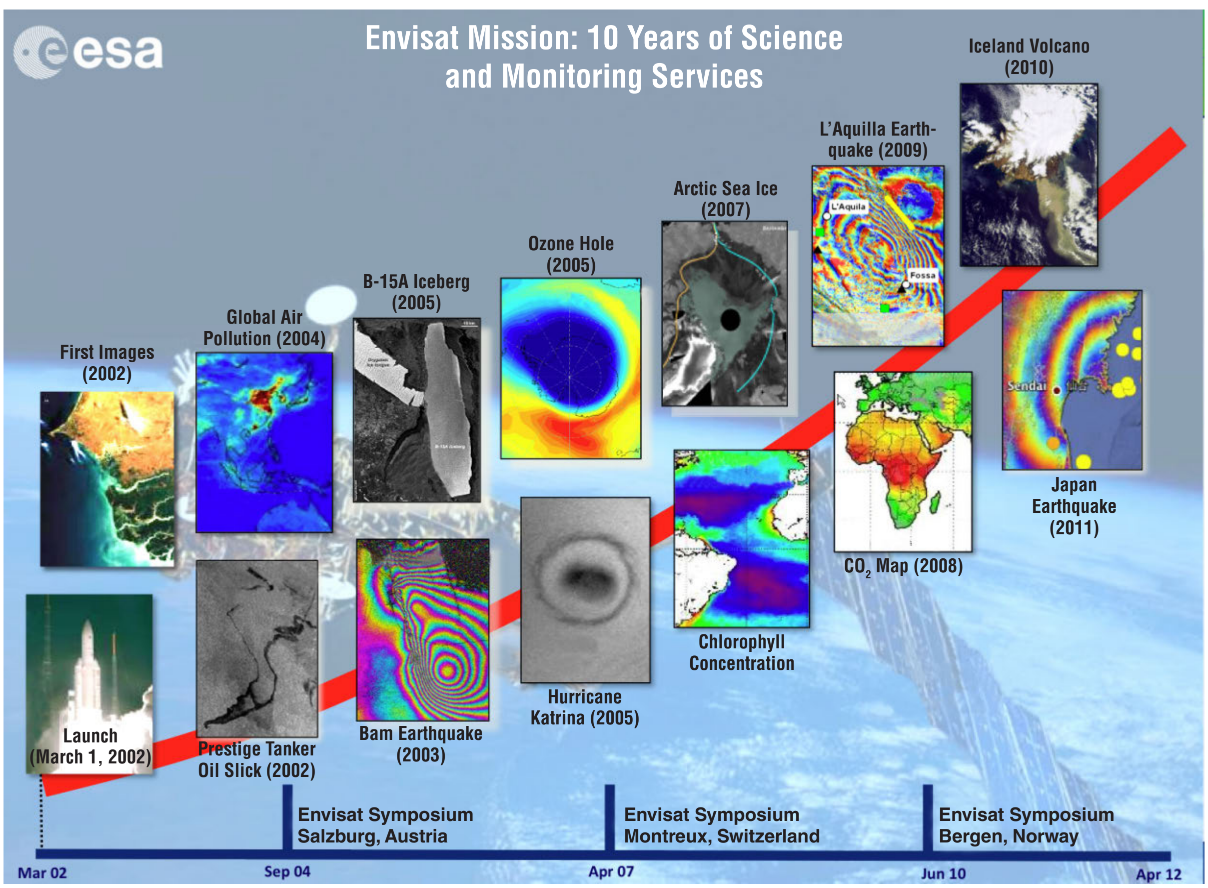

Figure 2. During its lifetime Envisat beamed back over 100 TBytes of data. To date, these data have been used in more than 4000 scientific projects and in numerous near real-time applications. A few of the mission's more noteworthy achievements are pictured above. **Image credit**: ESA

global ocean currents can be extracted directly from satellite altimetry data. The GOCE orbit was lowered to 235 km (~146 mi) at the end of January 2012, thereby increasing the accuracy and resolution of the measurements from 100 to 80 km (~62 to 50 mi)], and improving GOCE's view of smaller ocean dynamics. The satellite was further lowered to 225 km (~140 mi) at the end of May 2013. **Figure 3** illustrates GOCE's ability to derive ocean-current velocities.

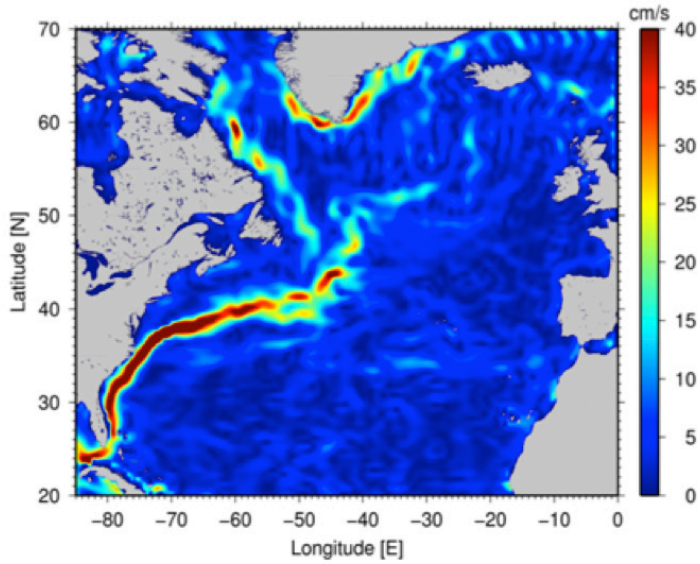

Figure 3. Geostrophic surface velocities for the North Atlantic as derived from GOCE and satellite altimetry. Velocities range from 0-50 cm/sec (red to blue). **Image credit:** ESA

SMOS: Water Mission

Launched on November 2, 2009, the Soil Moisture and Ocean Salinity (SMOS) mission collects global observations of soil moisture and ocean salinity using its unique L-Band Radiometer Microwave Imaging Radiometer with Aperture Synthesis (MIRAS). Soil moisture data are required for hydrological studies; ocean salinity data are vital to improve our understanding of ocean circulation patterns. SMOS completed its nominal three-year mission lifetime in November 2012, but continues to provide valuable results beyond its initial mission objectives, measuring ice thickness and wind speed. **Figure 4** illustrates the sea surface salinity (SSS) gradient off the northeast coast of the U.S. as measured by MIRAS.

SMOSS SSS (color) + currents (vector) from July 27–August 10, 2012

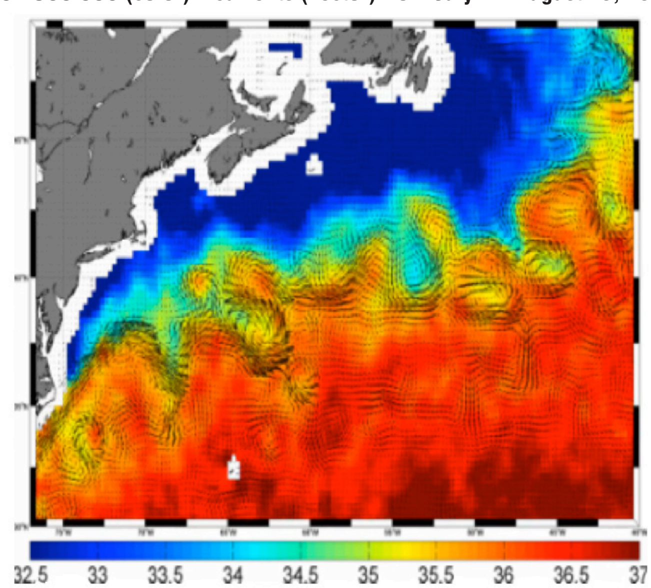

Figure 4. This figure illustrates the ocean circulation features off the U.S. northeast coastline. A SMOS 10-day-average sea surface salinity map is shown in the background with vectors representing surface currents derived from altimeter and surface wind products. Red shades represent the warm and salty central Atlantic waters, while blue shades indicate fresh and cold slope and shelf waters. **Image credit**: French Research Institute for Exploitation of the Sea

CryoSat: Ice Mission

Launched on April 8, 2010, the CryoSat-2 is Europe's first ice mission[4]. Its principal instrument is the Synthetic Aperture Radar/Interferometric Radar Altimeter, which is designed to measure centimeter-scale changes in the thickness of floating ice in oceans and the ice sheets that blanket Greenland and Antarctica. These CryoSat-based measurements provide accurate, synoptic, Arctic measurements of ice thickness and volume in unprecedented detail and, when combined with other satellite data, show how the volume of Earth's ice is changing. This information gives researchers a better understanding of the relationship between ice and the Earth's climate system. **Figure 5** illustrates CyroSat-2's ability to track seasonal changes in sea-ice thickness.

Swarm: Magnetic Field Mission

With a target launch date set for the end of 2013, Swarm is a constellation of three satellites that will provide high-precision and high-resolution measurements of the strength and direction of Earth's magnetic field using an advanced magnetometer, accelerometer, and electric field instruments. The geomagnetic field models resulting from the Swarm mission are expected to provide new insights into the Earth's interior, further our understanding

[4] CryoSat-2 replaces CryoSat, which was lost in October 2005 due to a launch failure.

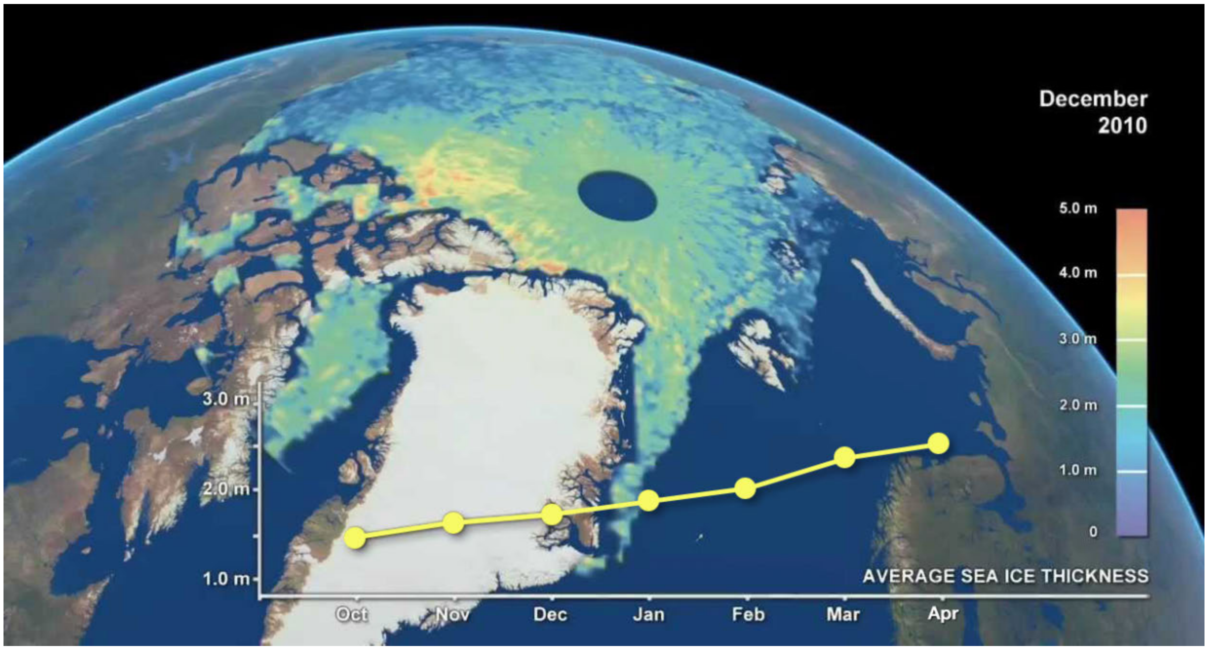

Figure 5. Arctic sea-ice thickness measured by CryoSat-2 from October 2010 to March 2011. **Image credit**: ESA-University College London-Planetary Vision 2012

of atmospheric processes related to climate and weather, and have practical applications in many different areas such as space weather and radiation hazards.

ADM-Aeolus: Wind Mission

With a 2015 target launch date, the Atmospheric Dynamics Mission *(*ADM)-Aeolus mission will advance global wind profile observations and provide much-needed information to improve weather forecasting. ADA-Aeolus will orbit in a Sun-synchronous, dusk/dawn orbit at 408 km (~253 mi) and employ a highly sophisticated Doppler wind lidar with a large telescope that collects light backscattered from gas, dust, and droplets of water in the atmosphere. Data from ADA-Aeolus are expected to pave the way for future operational meteorological satellites dedicated to measuring Earth's wind fields.

EarthCARE: Cloud and Aerosol Mission

With a target launch date in 2016, the Earth Clouds Aerosols and Radiation Explorer (EarthCARE[5]) mission is being implemented in cooperation with the Japan Aerospace Exploration Agency (JAXA) to improve the representation and understanding of Earth's radiative balance in climate and numerical weather forecast models. This will be achieved by global measurements of the vertical structure and horizontal distribution of cloud and aerosol fields together with outgoing radiation. The payload comprises two active instruments—a high-resolution atmospheric lidar and radar—and two passive instruments—a multispectral imager and a broadband radiometer. EarthCARE will orbit in an early-afternoon, Sun-synchronous orbit at 393 km (~244 mi).

Biomass

At ESA's User Consultation Meeting in March 2013 the scientific community made a recommendation to select the Biomass mission as the Earth Explorer 7; ESA member states subsequently approved that decision in May 2013. Biomass will employ a novel P-band synthetic aperture polarimetric radar operating at 435 MHz with a 6-MHz bandwidth; the satellite will fly at 637-666 km (~395-414 mi) in a near-polar, Sun-synchronous orbit. Data from Biomass will address one of the most fundamental questions necessary to our understanding of the land component in the Earth system—namely, the status and dynamics of forests—as represented by the distribution of

[5] To learn more about EarthCARE, see the March–April 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 2**, p. 45].

biomass and how it changes over time. Gaining accurate and frequent information about forest properties at observable scales will equip the scientific community with the information needed to address a range of critical issues with far-reaching benefits for science and society. Moreover, Biomass will greatly improve our knowledge of the size and distribution of the terrestrial carbon pool, and provide much-improved estimates of terrestrial carbon fluxes. In addition, the mission responds to the pressing need for biomass observations in support of global treaties such as the United Nations Framework Convention on Climate Change initiative for the Reduction of Emissions due to Deforestation and Forest Degradation.

Selecting the Next Earth Explorer

More Earth Explorer missions are planned for the future. As a result of the call for proposals for Earth Explorer 8, two missions were approved to move forward to Phase A/B1 as of November 2010. This phase includes a feasibility study and consolidation of the various components that make up a satellite mission. The two missions are:

- **Fluorescence Explorer (FLEX)**— a proposed three-year mission that would enable global monitoring of the steady-state chlorophyll fluorescence in terrestrial vegetation; and
- **CarbonSat**—a proposed three-to-five year mission that would measure global atmospheric amounts of carbon dioxide (CO_2) and methane (CH_4) with high spatial resolution and coverage, which can be used for inverse modelling. The CarbonSat instrument would take advantage of the technology and experience derived from the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) onboard EnviSat.

The ESA–EUMETSAT partnership was established in 1986 and implemented with a series of operational geostationary (Meteosat) and polar-orbiting (Metop) satellites; ESA builds the satellites that are then operated by EUMETSAT. This program represents a new flagship model for cooperation between ESA and EUMETSAT, providing enhanced capabilities for weather and climate science as well as economic and societal benefits.

Earth Watch Missions

The *Earth Watch* missions are designed to provide Earth observation data for operational services, including the operational meteorological missions of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT[6]). EUMETSAT's main purpose is to deliver operational weather- and climate-related satellite data, images, and products to the European National Meteorological Services, as well as to other users, worldwide.

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Geostationary Satellites

The Meteosat First Generation (MFG) series was a series of seven satellites—beginning with the first ESA launch in 1977—that provided Earth imagery and enabled continuous tracking of global weather patterns. Meteosat data formed the basis for weather forecasts in Europe for over two decades. The final launch took place in 1997.

[6] For more information about EUMETSAT, visit: *www.eumetsat.int*. This is also a good source for information on the MFG, MSG, and MTG series.
[7] This is similar to the arrangement that NASA and NOAA has had for the Geostationary Operational Environmental Satellite (GOES) System.

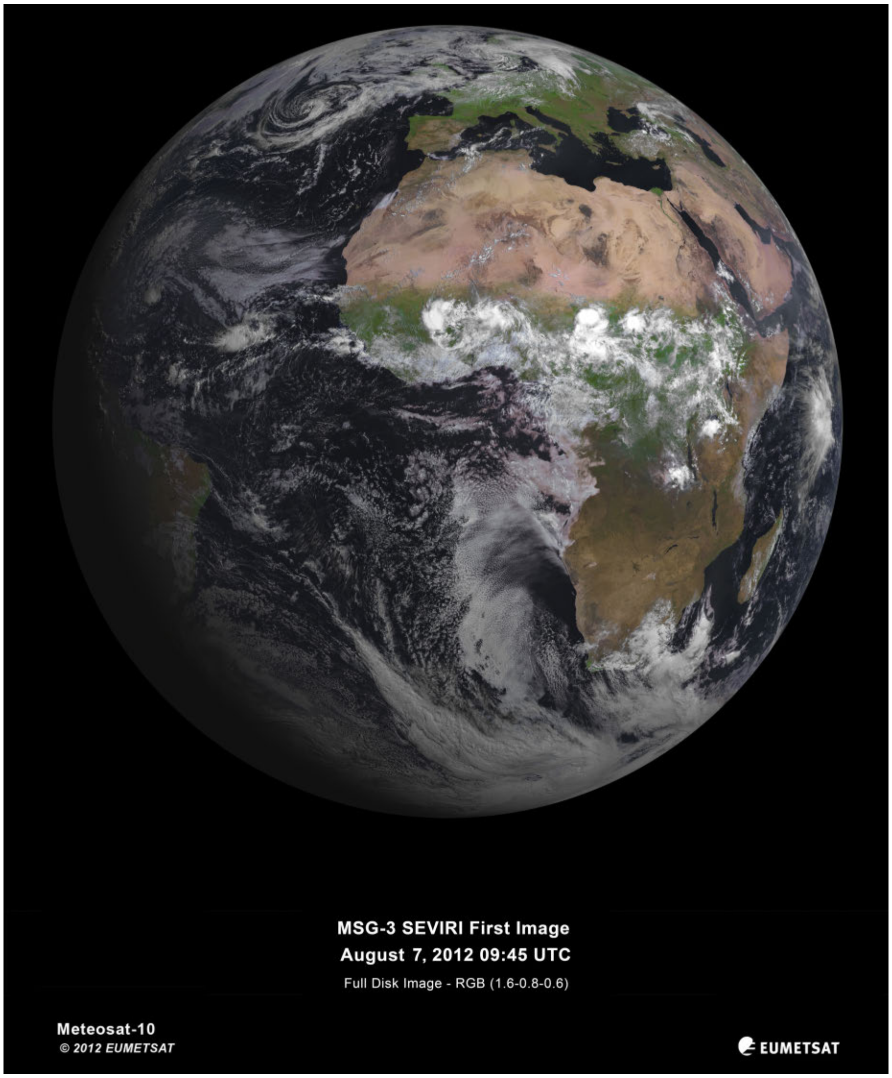

Figure 6. This image was taken from the Meteosat Second Generation-3 satellite (or Meteosat 10) that launched on May 7, 2012. The satellite is in a geostationary orbit located at 0° longitude. The image was generated by the SEVERI instrument using the red-green-blue channels and has a spatial resolution of 1 km (0.62 miles) at the satellite nadir. **Image credit:** EUMETSAT

Meteosat Second Generation (MSG) is a series of four launches, which began with Meteosat-8 (or MSG-1) in 2002. It is a significantly enhanced follow-on system to MFG, with a ground-based infrastructure, that will operate consecutively until 2020. The MSG satellites carry two instruments: the Spinning Enhanced Visible and InfraRed Imager (SEVIRI), which has the capacity to observe the Earth in 12 spectral channels and provide image data that are core to operational forecasting needs; and the Geostationary Earth Radiation Budget (GERB) instrument that supports climate studies by measuring the balance between the incoming radiation from the Sun and the outgoing reflected and scattered solar radiation plus the thermal infrared emission to space.

The Meteosat Third Generation (MTG) satellite program is envisioned as a series of six launches—beginning no earlier than 2020. Each MTG mission will consist of two parallel-positioned satellites: an imager platform (MTG-I) and a sounder platform (MTG-S). MTG-I will have the Flexible Combined Imager (FCI) and Lightning Imager (LI); MTG-S will have the Infrared Sounder (IRS), a hyperspectral thermal imager, and the InfraRed Sounder (IRS), an interferometer. In addition, MTG-I will also host the GMES/Sentinel-4 air quality observatory described below. These new observational capabilities should truly enable a "step change" in operational meteorology capabilities. The program should guarantee access to geostationary orbit meteorological data until at least the late 2030s. MTG will continue visible and infrared (IR) imagery and IR and ultraviolet (UV)/near-IR sounding observations from geostationary orbit, the data from which will result in three-dimensional information on humidity, temperature, and wind to support *nowcasting*—weather forecasting with a six-hour horizon.

Polar-orbiting Satellites

The EUMETSAT Polar System (EPS) is Europe's first polar-orbiting operational meteorological satellite system; it is the European contribution to the Initial Joint Polar-orbiting Operational Satellite System (IJPS)—a joint effort between EUMETSAT and NOAA. EUMETSAT polar-orbiting satellites (i.e., MetOp satellites) carry a suite of state-of-the-art sounding and imaging instruments that offer improved atmospheric sounding capabilities to both meteorologists and climatologists.

The EPS Space Segment includes three successive Metop satellites and is being developed and procured in a cooperative agreement between ESA and EUMETSAT. Metop-A was launched in October 2006, and Metop-B in September 2012. In April 2013, following the end of its commissioning period, Metop-B replaced Metop-A as EUMETSAT's prime operational polar-orbiting satellite, Metop satellites fly in a polar, low-Earth orbit corresponding to local "morning" while the U.S. and other partners are responsible for "afternoon" coverage[8, 9]. The series will provide data for both operational (meteorology) and research (climate) studies. The combined instruments on the Metop satellites have remote sensing capabilities to observe the Earth both day and night, as well as under cloudy conditions.

Each Metop satellite has a nominal lifetime in orbit of five years with a six-month overlap between consecutive satellites, thus providing more than 14 years of service. The European and U.S. meteorological satellites carry similar instruments for operational weather forecasting, however some instruments such as the AVHRR, provided by NASA and NOAA are identical on both NOAA and Metop satellites. In addition, the Metop satellites carry a set of European sensors aimed at improving atmospheric soundings, as well as measuring atmospheric ozone and near-surface wind vectors over the ocean. With this arrangement, NOAA and EUMETSAT satellites are highly complementary, providing the meteorological community with powerful tools with which to forecast weather.

The European and U.S. meteorological satellites carry a suite of identical sensors, for which NOAA provides most of the joint instruments on the satellites. In addition, the Metop satellites carry a set of European sensors aimed at improving atmospheric soundings, as well as measuring atmospheric ozone and near-surface wind vectors over the ocean. With this arrangement, NOAA and EUMETSAT satellites are highly complementary, providing the meteorological community with powerful tools with which to forecast weather.

Definition of the follow-on EUMETSAT Polar System is now under way, to replace the current satellite system in the 2020 timeframe and to contribute to the IJPS. Mission requirements have been defined to support operational meteorology and climate change research. Satellite platforms, instruments, and ground-support infrastructures are under study in coordination with NOAA, ESA, and other European space agencies. Similar to Metop, the satellites will fly in a Sun-synchronous, low-Earth orbit, with a descending node at 9:30 AM local time, providing global observations with revisit times of 12 to 24 hours, depending on the instrument. This program began in 2005 under the name of Post-EPS; when the design and development phase began in 2012, it was under a new program called EPS Second Generation (EPS-SG).

Sentinel Missions

Sentinel is part of the GMES/Copernicus Space Component, which will collect robust, long-term, climate-relevant datasets. Together with other satellites, their combined data archives will be used to produce Global Climate Observing System (GCOS[10]) Essential Climate Variables (ECV[11]) for climate monitoring, modeling, and prediction. The five Sentinel missions are based on a constellation of two satellites each to fulfill revisit and coverage requirements, providing robust datasets for operational services. The Sentinel missions will launch beginning in 2013; they are briefly summarized hereafter. For additional information on the Sentinel missions, visit: *www.esa.int/Our_Activities/Observing_the_Earth/GMES/Overview4*.

- **Sentinel-1:** Scheduled to launch anywhere from late 2013 to early 2014, this polar-orbiting, all-weather, day-and-night mission will enable a SAR in C-band that will support GMES/Copernicus operational services for land, marine, and risk-assessment applications. It builds on ESA's and Canada's heritage SAR systems on ERS-1, ERS-2, Envisat, and Radarsat.

[8] NASA and its international partners operate several Earth-observing satellites that closely follow one after another. This coordinated group of satellites (called the Afternoon Constellation, or the A-Train, for short) are in a polar orbit and cross the Equator at about 1:30 PM local time.
[9] The "morning" and "afternoon" orbits result in four overpasses per day rather than two for one satellite, and result in improved numerical weather predictions.
[10] GCOS is intended to be a long-term, user-driven operational system capable of providing comprehensive observations. For more information, visit: *www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS*.
[11] To view the chart of 50 ECVs defined by GCOS, visit: *www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables*.

- **Sentinel-2:** Planned for launch in 2014, this is a polar-orbiting, multispectral, high-resolution imaging mission for GMES land monitoring to provide imagery of vegetation, soil and water cover, inland waterways, and coastal areas. Sentinel-2 will also provide information for emergency services. It is a follow-on enhancement of the French Système Pour l'Observation de la Terre (SPOT).

- **Sentinel-3:** Planned for launch in 2014, this mission is composed of two operational satellites with a one-day (over land) and two-day (over ocean) revisit time. Each satellite will carry an Ocean and Land Colour Instrument (OLCI), Sea and Land Surface Temperature Radiometer (SLSTR), and a microwave payload that includes a SAR Radar Altimeter (SRAL), and a two-frequency Microwave Radiometer (MWR). This mission will address surface topography, sea and land surface temperature, ocean carbon, and land color.

- **Sentinel-4:** Planned for launch in 2019, this geostationary-orbit mission is devoted to atmospheric monitoring (see previous section on MTG). UV and NIR spectrometers will be used to continuously monitor air pollution and its precursors—from North Africa to Northern Europe—at 6 x 6-km^2 (~2.3 x 2.3-mi^2) spatial and one-hour temporal resolutions.

- **Sentinel-5 Precursor:** This mission is a polar-orbiting, Sun-synchronous mission scheduled to launch in 2015. It is designed to reduce data gaps between Envisat and Sentinel-5 for global atmospheric composition measurements including ozone, aerosols, and atmospheric pollution precursors. The instrument will be a follow-on to the Ozone Monitoring Instrument (OMI) flying on NASA's Aura satellite, with additional channels in the NIR.

- **Sentinel-5:** This mission will monitor the atmosphere from polar orbit aboard an EPS-SG satellite projected for launch in 2020. It will continue the atmospheric composition data collected from Envisat and employ UV and IR spectrometers that will measure profiles and column amounts of trace gases and aerosols important for atmospheric chemistry and climate studies.

Figure 7. This figure is an artist's rendition of the Sentinel-3 satellite. The SRAL antenna is the larger circular structure on the bottom of the spacecraft. Sentinel-3A will be launched into a Sun-synchronous orbit at 10:00 Local Sidereal Time. **Image credit:** ESA

European Space Data Policy and Distribution

ESA has leveraged the continuous technological progress made possible by the computer and Internet revolution, and implemented a free and open data policy that has enabled maximum exploitation of ESA data.

ESA also distributes satellite data from international partner agencies—called Third Party Missions (TPM). The data from these missions are distributed under specific agreements with the owners or operators of those missions, which can be either public or private entities outside or within Europe*.

ESA has defined a new Earth Observation Data Policy (EODP) that applies to all missions including those mentioned in this article. The revised ESA EO data policy defines two groups of datasets: *free* and *restrained*. Data from both types of datasets are provided free of charge; however, user registration is needed to access the data. Online Earth science datasets can be accessed through an easily navigated registration interface. To access, visit: *earth.esa.int/web/guest/home* and click *Register* at the top-right corner of the page.

For more information on the EODP, visit: *earth.esa.int/web/g]t/missions/content?p_r_p_564233524_assetIdentifier=revised-esa-earth-observation-data-policy-7098*.

* Detailed information about ESA Earth-observation missions, data access, user tools, events, proceedings, and highlights can be found at *earth.esa.int/web/guest/home*.

ESA–NASA Earth-observation Collaborations

Collaboration with worldwide research and operational space agencies and international environmental organizations is a high priority for ESA. The Agency has conducted joint field campaigns for data validation with mission partners and has worked closely with international science teams for algorithm development and data homogeneity and accessibility.

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ESA and NASA have the largest Earth-observing programs in the world and have developed strong collaboration for postlaunch activities over the last several years. These activities include algorithm refinements, calibration/validation, data homogenization, and data distribution. Collaborations are established as either bilateral agreements or facilitated through international organizations such as the GCOS, World Meteorological Organization (WMO), and Committee for Earth Observing Satellites (CEOS). CEOS is an assembly of all the world's space agencies, the existence of which allows even further international collaborations[12].

Bilateral scientific meetings are held by ESA and NASA at least once per year, backed by regular, top-level management meetings. Three ESA–NASA working groups were set up in 2010 to prepare for and organize cooperation in the field of missions and technology, calibration/validation activities and field campaigns, ground segments and data homogenization, and distribution policies. Subsequent working groups were organized to include further broadening of calibration/validation activities to advance science goals, generate agreement on free and open data distribution policies, and develop programmatic guidelines for further potential coordination, as discussed below. The material that follows gives a few examples of ongoing and planned collaborative activities for ESA and NASA. Beyond these, additional collaborative opportunities have been identified for calibration/validation and data sharing from the SMOS and Aquarius, Soil Moisture Active Passive (SMAP), ADM-Aeolus, and Biomass missions.

[12] For more information about CEOS, visit: *www.ceos.org*.

Greenland and Antarctic Ice Sheet Mass Loss

Excellent collaboration has been achieved with ESA's CryoSat Validation Experiment (CryoVEx) and NASA's Operation IceBridge field campaigns to validate data from ESA's CryoSat and NASA's ICESat[13] missions. The recently performed Ice-sheet Mass Balance Intercomparison Exercise (IMBIE) was a combined ESA–NASA effort to perform experiments to better understand discrepant results concerning the mass balance of ice sheets over Greenland and Antarctica. The different techniques were intercompared among different groups using the same satellite-derived data. The IMBIE 2012 reported that by combining datasets for a 19-year time series starting in 1992, Greenland and Antarctica lost ice-sheet mass equivalent to a global sea-level rise of 11.1 ± 3.8 mm (~0.44 ± 0.15 in). This collaboration involved approximately fifty institutions and was given great visibility in both the scientific and international media.

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Upwelling Signals in the Gulf of Panama

ESA and NASA are using data from SMOS and Aquarius to identify upwelling, which usually signals nutrient-rich waters from the ocean depths rising to the warmer, sunlit zone at the surface. A test area recently has been identified in the Gulf of Panama, where low spatial coverage is available with *in situ* measurements, but where strong seasonal signals exist. Consistency in measurement error has been demonstrated between SMOS and Aquarius instruments. More meetings are planned in 2013 to further develop synergy between these two missions in the areas of soil moisture, ocean surface salinity, and cryospheric applications.

Essential Climate Variables

The collaboration between both parties extends also to the GCOS ECV. Cross-calibration activities are planned over Antarctic calibration sites to ensure accuracy of long-term datasets, and to characterize climate-change issues using relevant data from missions such as ESA's Earth Explorers and NASA's upcoming SMAP mission.

Long-term Ozone Records

Under the auspices of CEOS and its Constellation projects, a joint effort has been undertaken to further improve the long-term ozone record collected by both NASA/NOAA and ESA/EUMETSAT instruments: There are over 30 years of ozone data from NASA, and about 20 years from ESA. Homogenizing or reconciling differences in these datasets is crucial to understanding anthropogenic ozone depletion and the impact of climate on ozone recovery. Ongoing collaborative studies include compiling spectroscopic databases, refining algorithms, and continuing calibration/validation activities; an active international chemical climate-modelling program supports this activity. Through ESA's TPM program Canada is also participating, with their Atmospheric Chemistry Experiment (ACE) and Optical Spectrograph and InfraRed Imaging System (OSIRIS) satellites. The result of this collaboration will impact how future ozone data will be collected, processed, and archived for the upcoming NASA/NOAA Joint Polar Satellite System (JPSS) and ESA GMES/Sentinel missions. Ozone data are also a GCOS ECV and therefore a high priority among the three agencies. ESA–NASA collaboration through CEOS also continues with the working groups and Constellation efforts such as the Atmospheric Composition Constellation (ACC) that is formulating an air-quality satellite constellation of three geostationary missions to be launched by Europe, the U.S., and Korea[14].

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[13] ICESat stands for Ice, Clouds, and Land Elevation Satellite. Operation IceBridge is a series of field experiments "bridging" the data-gap between ICESat (which ended in 2009) and ICESat-2 (with launch planned for 2016).

[14] To learn more about this combined effort, read "NASA Ups the TEMPO in Air Pollution" [**Volume 25, Issue 2**, pp. 10-15].

Landsat 8 and Sentinel-2

Recently, a cooperative effort between the U.S. Geological Survey, NASA, and ESA under the GMES/Copernicus Programme was established that will employ the U.S. Landsat 8 and Sentinel-2 land-imaging missions. The objective of the effort is the interoperability of data products from the Landsat 8 satellite and the two identical Sentinel-2 satellites—i.e., Sentinel-2A and -2B. The collaborative approach initially foresees ground crosscalibration of the instruments to generate consistent calibration data from the three satellite-based instruments. The goal is to guarantee space-based data from multiple instruments, with comparable radiometric performance over similar ground scenes, thus enabling synergistic use of data for end users.

Hosting Instruments

Although there are precedents for hosting each other's instruments for flight missions in the ESA and NASA planetary and astronomy programs, no such exchange has occurred for Earth science. However, there are examples of international exchanges, such as the Dutch OMI being flown on NASA's Aura spacecraft, Japan's Advanced Microwaving Scanning Radiometer–EOS (AMSR-E) on Aqua, and NOAA sounders on EUMETSAT satellites. Recent discussions between ESA and NASA's Earth-science programs have begun, including discussion about gravity measurements for NASA's Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) and GOCE missions. The science teams have already shown synergy between GOCE and GRACE in developing static global gravity field models, which are applicable to several Earth-science disciplines. Follow-on studies are assessing the possibility of having GRACE and GOCE fly as a constellation, as well as the feasibility of flying a new U.S. instrument on an ESA Earth Explorer mission.

Summary

NASA and ESA represent the two largest space agencies in the world and both have extensive Earth science missions that have provided vast amounts of Earth observation data for Earth science and for various services that benefit society. The ESA missions have resulted in high-quality and freely available datasets, which are being exploited by the worldwide science and applications communities. ESA will continue to launch research missions to explore Earth system science using advanced technologies. They will continue to provide to EUMETSAT space hardware and algorithms needed for the European meteorological services. ESA is also providing the space component for the European Global Monitoring for Environmental Security initiative. As NASA begins to deploy the Decadal Survey and smaller, focused missions, many collaborative opportunities with ESA are arising in all aspects of mission development and implementation. Synergy resulting from such collaboration will result in better use of Earth observations and likely afford opportunities for financial efficiency. ■

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