Sigma Σ

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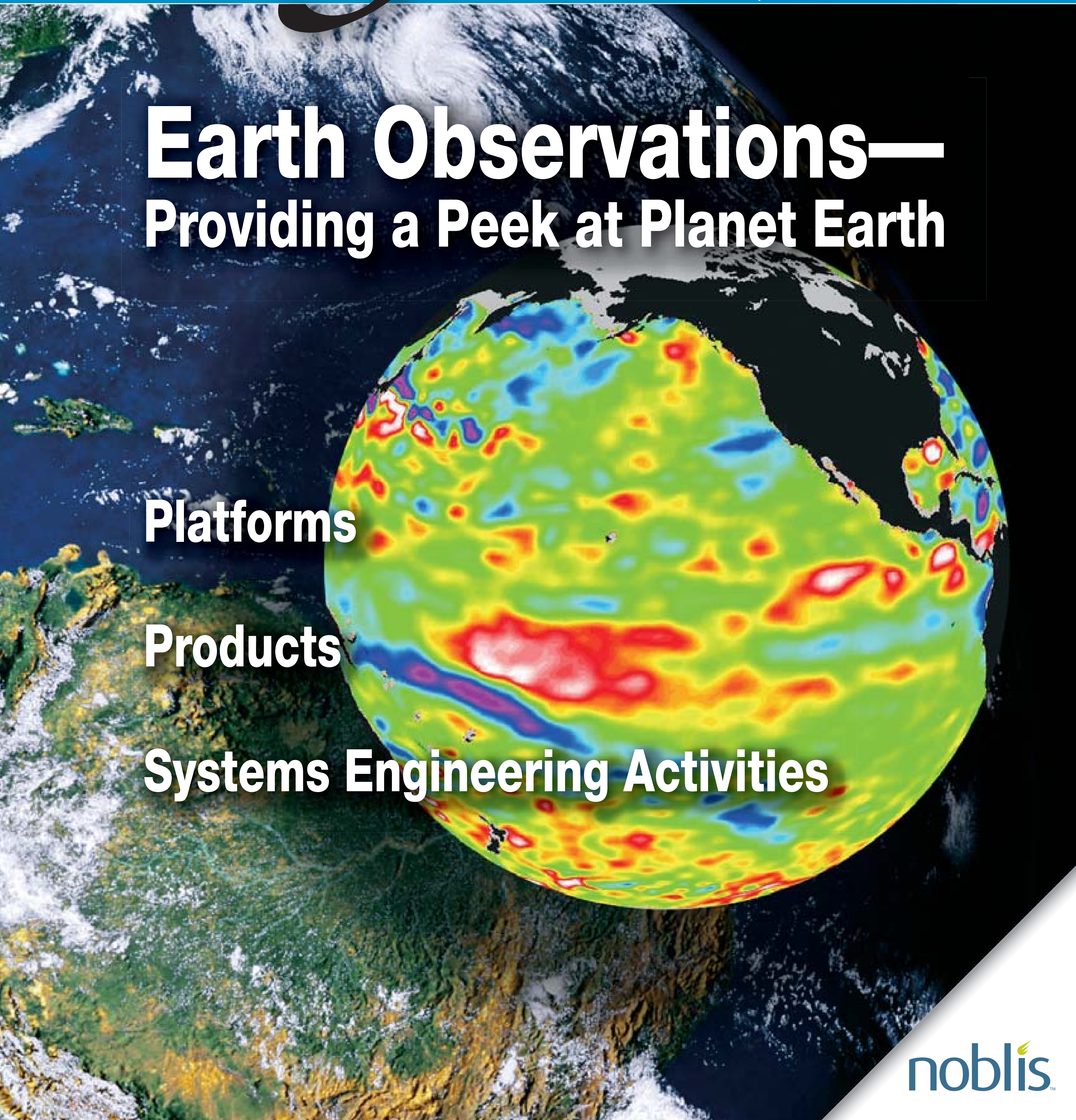
Earth Observations—Providing a Peek at Planet Earth



Platforms

Products

Systems Engineering Activities

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Exploring 'One Ocean'

Later this month, scientists, engineers, and other specialists will gather from around the world to consider the future of the earth's oceans at the OCEANS 2005 Conference. The experts gathering under the theme of 'One Ocean' will again confirm that we have only begun to understand, appreciate, and explore the oceans as complex and dynamic ecosystems. The OCEANS 2005 Conference will provide a venue for these experts to consider not only the current state of the oceans, and the significant stress factors currently placed on these ecosystems, but also to contemplate possible immediate and future actions required to ensure the continued health of our oceans.

As these ocean experts convene, a major international initiative is currently seeking to significantly improve our ability to observe and understand conditions on Planet Earth—the Global Earth Observation System of Systems (GEOSS). Working together, 54 countries are developing this system incorporating a wide variety of sensor, processing, and networking technologies with the express purpose of significantly improving our abilities to observe current and predict future environmental and climatic conditions. The scope of GEOSS-based observations includes not only the oceans, but also the Earth's land masses and atmosphere.

The release of this edition of *Sigma* intentionally coincides with the beginning of the OCEANS 2005 Conference. Guest Editor Steve Holt and the *Sigma* authors address advancements in the field of earth observation, highlighting the oceanic environment. The articles address topics and experiences from Mitretek's considerable work program related to meteorological, earth, and ocean sciences, as well as related technologies.

I hope the presented articles and the resultant discussions are informative and stimulating to our normal *Sigma* readers, but also to the experts gathered at OCEANS 2005. By working together, cooperatively developing observing systems and sharing knowledge, perhaps we can better understand our 'One Ocean.'❖

H. Gilbert Miller
Corporate Vice President
and Chief Technology Officer

In Addition: Earth Observations

More from Mitretek authors:

- "Using Autonomy Flight Software to Improve Science Return on Earth Observing One," S.W. Frye et al., *Journal of Aerospace Computing, Information, and Communication*, Vol. 2, 2005.
- "Deep Frontiers: Technology Development for Ocean Exploration," J.E. Manley et al., *Sea Technology Magazine*, 2005.
- "Initial Joint Polar-Orbiting Operational Satellite System: Verification and Validation Program," S.M. Holt et al., Presented at the 85th Annual Meeting of the American Meteorological Society (AMS), 2005.
- "Development of the Terminal Doppler Weather Radar Supplemental Product Generator for NWS Operations," A.D. Stern, Presented at the 85th Annual Meeting of the American Meteorological Society (AMS), 2005.
- "The FHWA Clarus Initiative: The Nationwide Surface Transportation Weather Observing and Forecasting System," L. Goodwin et al., Presented at the Intelligent Transportation Systems World Congress, 2005.
- "NOAA's NPOESS Data Exploitation Project," S.L. Bunin et al., Presented at the 85th Annual Meeting of the American Meteorological Society (AMS), 2005.
- "Ocean Science in NOAA in the age of Autonomous Underwater Vehicles," J.E. Manley, Presented at the 14th International Symposium on Unmanned Untethered Submersible Technology (UUST), 2005.
- "An Examination of U.S. Plans for Meeting Operational Ocean Observation Needs with Radar Altimetry," G.M. Mineart et al., Presented at the Marine Technology Society (MTS) / Institute for Electronics and Electrical Engineers (IEEE) OCEANS 2004 Conference, 2004.
- "NOAA/NESDIS Preparation for the NPOESS Era," S.L. Bunin et al., Presented at the 84th Annual Meeting of the American Meteorological Society (AMS), 2004.

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Mitretek Systems publishes *Sigma* to further its work in the public interest. *Sigma* seeks to inform public interest decision makers of recent advancements and experiences in a wide variety of scientific and technological areas, including information technology, networking, and life and chemical sciences. The Mitretek authors base the *Sigma* articles on experiences and knowledge gained from our public interest client work program and our internal Mitretek Sponsored Research program.

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Contents

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Earth Observations—Providing a Peek

Stephen M. Holt

The Global Earth Observation System of Systems is currently seeking to significantly improve our ability to observe and predict the impact of a wide range of natural phenomenon and human activities.

Imagine a future in which we know the state of our planet Earth—the oceans, the atmosphere, and the land masses. Imagine a future in which we predict future events on our planet. Imagine a future in which we develop effective remedies to mitigate the impacts of such events. Are we there yet? No, but governments and organizations around the world share this vision of the future and are working to make it a reality.

Global effort

A major international initiative—the Global Earth Observation System of Systems (GEOSS)—is currently seeking to significantly improve our ability to observe and understand our planet's natural conditions. When completed, we will not only better monitor the current conditions, but also better predict severe weather, volcanic activity, flooding, forest fires, and the impacts of human activities such as urban sprawl, over-farming and grazing, deforestation, and environmental pollution. The United States, 53 other countries, and 34 international organizations support the development of GEOSS, which will help all nations produce and manage the considerable information needed to understand the environment and climate of planet Earth.

The wide range of earth observations necessary to measure current conditions and prepare predictions and analyses requires the use of many different technologies. Satellites can provide space-based measurements of the atmosphere, as well as land and ocean surfaces. Ground-based radars, lidars, radiosondes, and weather instruments can measure various meteorological conditions of the earth's

at Planet Earth

atmosphere. A wide variety of ocean instruments can monitor chemical and environmental conditions in our oceans, both on and below the surface. The employed earth observing technologies can be as simple as a single sensor gathering basic environmental information over a small geographic area or as complex as a network of diverse instruments and sensors deployed over vast areas.

Platforms, products and systems engineering activities

This edition of *Sigma* addresses advancements in the field of earth observations and highlights the oceanic environment. We present three series of papers detailing efforts to advance earth observation platforms, products, and systems engineering activities, respectively. In our first series, we consider various platforms used to make earth observations. The ever-changing and expanding set of useful sensor technologies allows for improvement of platform performance and expansion of the breadth of observations. Gary Mineart introduces three emerging satellite radar altimeter technologies with the potential to significantly improve our ability to observe the oceans and help satisfy the global observation requirements of GEOSS. Stuart Frye and Daniel Mandl summarize advancements in platform autonomy allowing systems, with increasing independence, to identify, locate, and image phenomena such as wildfires, volcanoes, floods and ice breakup. Justin Manley explores the use of unmanned and autonomous robotic technologies for the purpose of observations on, below, and above the ocean.

In a world of rapidly changing sensor technology, a layered approach allowing products to be developed and produced independently of observation platforms is critical. Such an approach enables new products, based on the integration of observation data from multiple, heterogeneous platform sources, to be developed. In the end, the developed products are integral to the mission of predicting weather and assessing climate change. In our second series of papers, we consider the products produced by different earth observation instruments to support various scientific and commercial applications. Stacy Bunin summarizes the atmospheric, land surface, and oceanic products produced from geostationary and polar-orbiting environmental satellites. These products support domestic and international short-term warnings, long-term forecasting, and climate and hydrological applications. Kenneth Carey, John Marshall, and James Yoe describe how satellite data is used by analysis and prediction models to produce more robust weather and climate forecasts and increased warning time for severe events. Andy Stern and Lynette Goodwin describe an initiative that will collect and manage the nation's growing repository of surface transportation-related atmospheric and pavement observations. The thousands of existing observations and data from innovative uses of deployed and new technologies will ultimately lead to the development of weather products tailored to specific local conditions which will improve operations and safety on our highways.

The increasingly large, complex, and inter-connected earth observation systems require the use of appropriate systems engineering processes, discipline, and tools. So in our third series of papers, we consider the systems engineering activities underlying several earth observation programs. Fred Klein, Thomas Passin, and Robert Vorthman demonstrate the Integrated Ocean Observing System (IOOS) as a federated system of systems; that is, a system with many subsystem components which must cooperatively work together to enable the system to function effectively, but where there is no real central authority to control them all. The authors show the challenge of developing the enterprise architecture and systems engineering plan in such a complex environment of different technologies, multiple sensing sources, and cooperative stakeholders. Lauraleen O'Connor and Kenneth Carey, in the *Sigma* Spotlight highlight the observational requirements collection process that led to the first-ever comprehensive identification and documentation of all NOAA atmospheric, land, oceanic, and space-based environmental requirements.❖

Stephen M. Holt is a lead systems engineer at Mitretek. His experience includes systems engineering work in federal government programs related to the atmospheric, oceanic, and space environments. He received his master's degree in engineering from The Catholic University of America. Contact him at sholt@mitretek.org.

Emerging Space-Based Radar Altimeter Technologies

Gary M. Mineart

New radar altimeter technologies promise to revolutionize observations of the world's oceans. Three emerging altimeter concepts are ready for demonstration and validation.

A satellite radar altimeter transmits a radar pulse towards the ocean surface and measures the time needed to receive the reflected energy back at the satellite. The time difference between the transmitted and received pulse yields the distance between the satellite and the sea surface. The shape of the return waveform is proportional to the height of the ocean waves, and the magnitude of the returned power is linked to the sea surface roughness due to wind forcing, allowing measurements of surface wind speed. Over three decades ago, the National Aeronautics and Space Administration (NASA) designed and launched the first earth-orbiting, ocean observation satellite (Seasat) to definitively validate the potential ocean applications of a space-based radar altimeter.

With an accurate sea surface height measurement from space, a variety of oceanographic parameters can be derived for the global ocean including ocean tides, regional and global mean sea level, currents, and variability of mesoscale features. It is also possible to approximate the thermal structure of the upper portion of the ocean by assimilating sea surface height and sea surface temperature observations, a technique that has become vitally important to achieving accuracy and resolution in modern ocean circulation models.[1,2] Current altimeter instrument technologies combined with modern precision orbit determination using the Global Positioning System (GPS) allow for the observation of changes in sea surface height due to oceanographic phenomena to an accuracy approaching 2 cm.

Significant wave height and wind speed observations are independent of sea surface height precision since they are derived from the characteristics of the return signal and not on the time of its detection. There are also applications of radar altimetry related to the science of studying the size and shape of the earth, known as geodesy, which

Inside Track

- A space-based radar altimeter precisely measures sea surface height with accuracy sufficient to resolve the time-varying ocean surface topography, in addition to measuring surface wind speed and significant wave height.
- Radar altimeter observations can be used to derive global ocean tides, regional and global mean sea level, ocean currents, mesoscale ocean variability, near-surface thermal structure, and even global maps of the seafloor.
- Delay-Doppler, interferometric, and Ka-Band altimeter concepts represent altimeter technologies with potential to deliver important new ocean observing capabilities.
- Inadequate funding and program attention are currently limiting opportunities for demonstrating and validating emerging altimeter technologies.

take advantage of the altimeter's ability to map the shape of the ocean surface. The topography of the ocean surface generally approximates the reference surface of constant geopotential energy known as the geoid. Geoid undulations, the local differences between the height of the geoid and an established reference ellipsoid, are quite large compared to the height of the oceanographic contributions to sea surface height. These undulations range worldwide from -107 m to + 85 m using the World Geodetic System 1984 (WGS 84) uniform reference system.[3] Due to the magnitude of the influence of the shape of the ocean floor on the shape of the sea surface, geodetic altimeter missions have led to vastly improved maps of global ocean bathymetry.[4]

A primary measurement goal of an altimeter is to measure sea surface height with accuracy sufficient to resolve the time-varying portion of the ocean surface topography. At first order, this is achieved by taking the difference of the height of the satellite above a chosen reference ellipsoid and the height of the satellite above the instantaneous measurement of the sea surface. While this seems relatively simple, Figure 1 illustrates the complexity of the observation and the multiple factors that must be considered when calculating height measurements. These factors contribute to the measurement error budgets of altimeter missions. For high-resolution altimeters currently in orbit, the joint NASA-Centre National d'Etudes Spatiales (CNES) TOPEX-Poseidon (T/P) and Jason-1 altimeters, the single pass root mean square total range error is approximately 3.2 cm for T/P and 2.3 cm for Jason-1.[5] Using precision orbit determination systems such as Doppler tracking beacons and GPS, the height of the altimeter relative to earth geocenter can be determined to accuracies better than 2 cm.

Three promising radar altimeter technologies with the potential to revolutionize future operational ocean observations are discussed after a review of conventional, pulse-limited altimetry. The delay-Doppler altimeter concept uses the Doppler shift of the return signal to improve along-track resolution and signal-to-noise ratio. The instrument's signal processing is more efficient because of the noise suppression achieved and has a height precision of 0.5 cm, half the error of a conventional altimeter. The interferometric altimeter concept includes two antennae extending on either side of the spacecraft orthogonal to the ground track that allow real aperture imaging of a swath of area on either side of the spacecraft. This instrument has the potential to satisfy mesoscale ocean coverage requirements from a single spacecraft, compared to today's need for multiple spacecraft to adequately resolve these features. Ka-Band altimetry offers advantages over existing technologies due to the benefits of the higher frequency signal. Opportunities for demonstrating and validating emerging

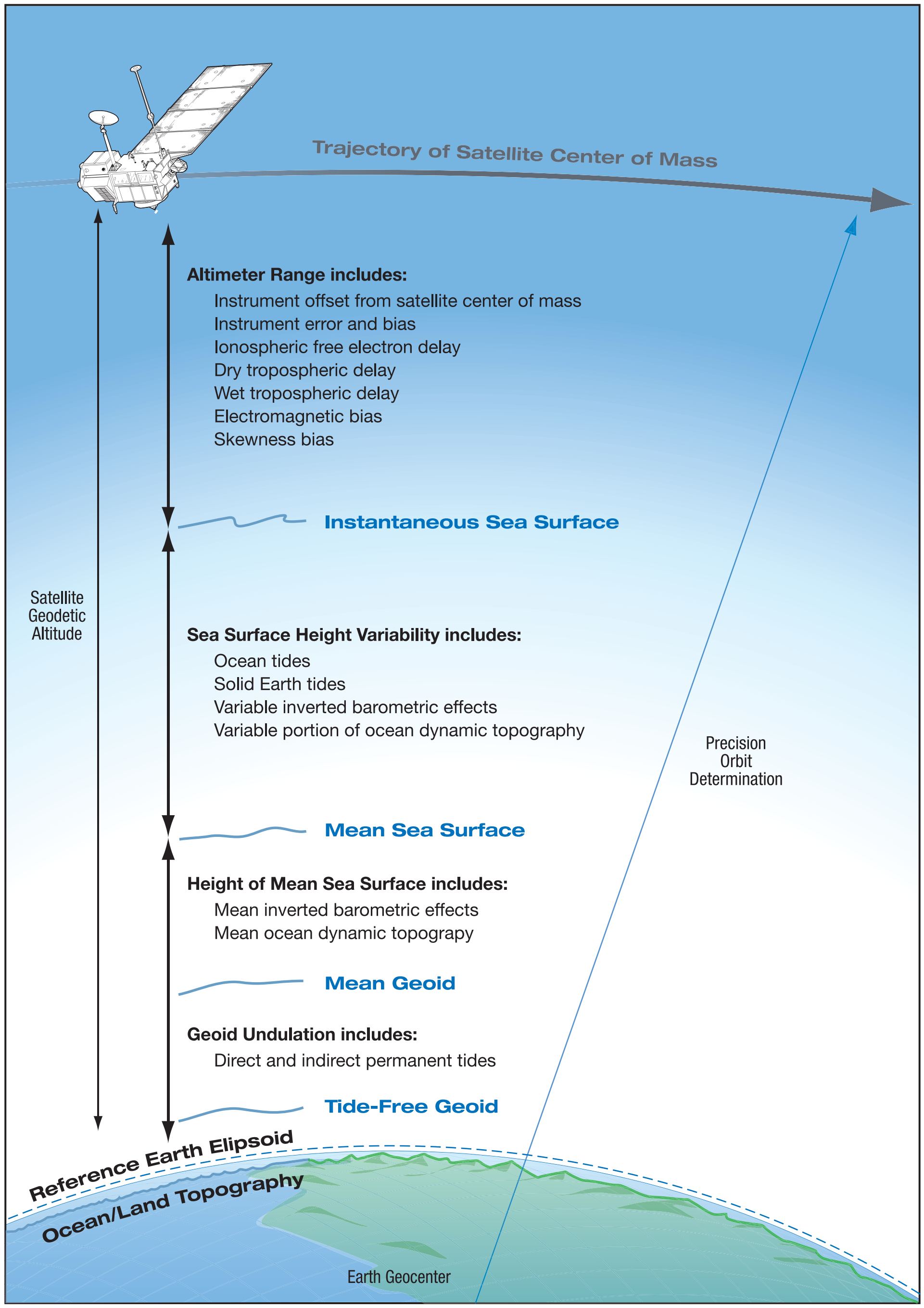

Figure 1. A diagram of the corrections applicable to the altimeter range measurement and the contributions to the height of the instantaneous sea surface above a reference earth ellipsoid. Depending on the field of study, the contributions to the instantaneous sea surface represent either parameters of interest or sources of error. The satellite orbit is determined relative to earth geocenter, necessitating a correct earth reference system to achieve accurate measurements.

altimeter technologies are limited due to a recent decrease in government investments in all space-based earth science initiatives.

Conventional pulse-limited altimetry

The radar pulse of a conventional altimeter is limited in its duration and illuminates an area of the sea surface at nadir that is smaller than the area that would otherwise be encompassed by the full extent of the radar beam. The spherical wavefront of the altimeter pulse always has a component propagating in the nadir direction even if the transmitting antenna is slightly tilted (i.e., less than the half-power beam width). This immunity of pulse-limited altimeters to small errors in nadir look angles contributes greatly to the quality of their measurements. As shown in Figure 2a, once the leading edge of the radar pulse reaches the sea surface, the illuminated area becomes a disk that increases linearly with time until the trailing edge of the pulse reaches the surface. As the wavefront continues to propagate, the disk becomes an annulus of increasing radius but constant area per unit time. When the leading edge of the pulse reaches and extends beyond the half-power beam width, the return power falls off to zero.

Once the altimeter instrument starts to detect the energy from the leading edge of the reflected pulse, the power of the received signal increases with time above the original background noise level. As the illuminated area becomes an annulus, the return power reaches a plateau, and then falls off once the half-power beam width is reached. Since the sea surface is rough from wind and waves, the altimeter return for any single pulse is quite noisy. In processing the altimeter signal, many returns are averaged over a period of time sufficient to ensure that the mean signal is revealed. For oceanographic applications, altimeter data are frequently averaged over 1 s; relative to TOPEX this would represent an average of 4,000 individual pulses over a resultant theoretical footprint—in the absence of ocean waves—that is about 3 km in the cross-track dimension and about 9 km along-track. The presence of wind-induced sea surface roughness reduces the magnitude of the returned power plateau.

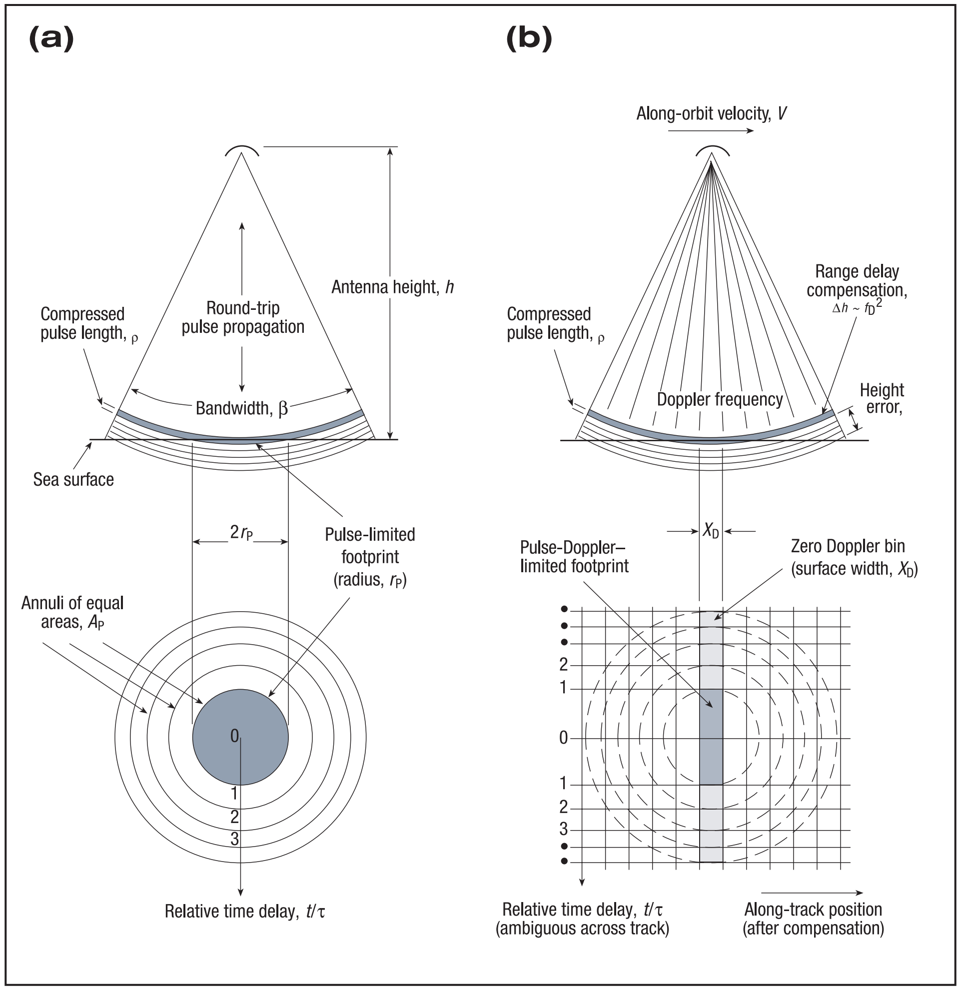

Figure 2. Comparison of (a) a conventional pulse-limited radar altimeter illumination geometry (side view) and footprint (top view); and with (b) a delay-Doppler altimeter illumination geometry and footprint.[6]

Similarly, there is an inverse dependence of the significant wave height on the slope of the return power and on the length of the rise time from noise level to plateau. These altimeter waveform concepts are illustrated in Figure 3. In the presence of sea and swell, there is a defocusing of the radar pulse that increases with increasing wave height. For a significant wave height of 15 m, the dimensions of the 1 s average footprint bloom to 13 km cross-track and 19 km along-track, limiting the spatial resolution.

Delay-Doppler altimetry

Description

The concept of the delay-Doppler Altimeter (DDA) is one of the most mature among the new technologies with potential to dramatically increase the value of observations from satellite radar altimetry.[6] The DDA takes advantage of the Doppler shift of the pulse frequency in the along-track direction to allow for an increase in pulse repetition frequency and a subdivision of the illuminated area along-track into discrete Doppler bins to provide a dramatic improvement in efficiency and precision.

A conventional pulse-limited altimeter independently averages many radar pulses as the spacecraft moves along its track during the averaging time window and its illuminated area becomes defocused with increasing significant wave height. The relatively slow repetition of pulses and the impact of the waves limit the available resolution of the instrument. The DDA concept shown in Figure 2b retains the

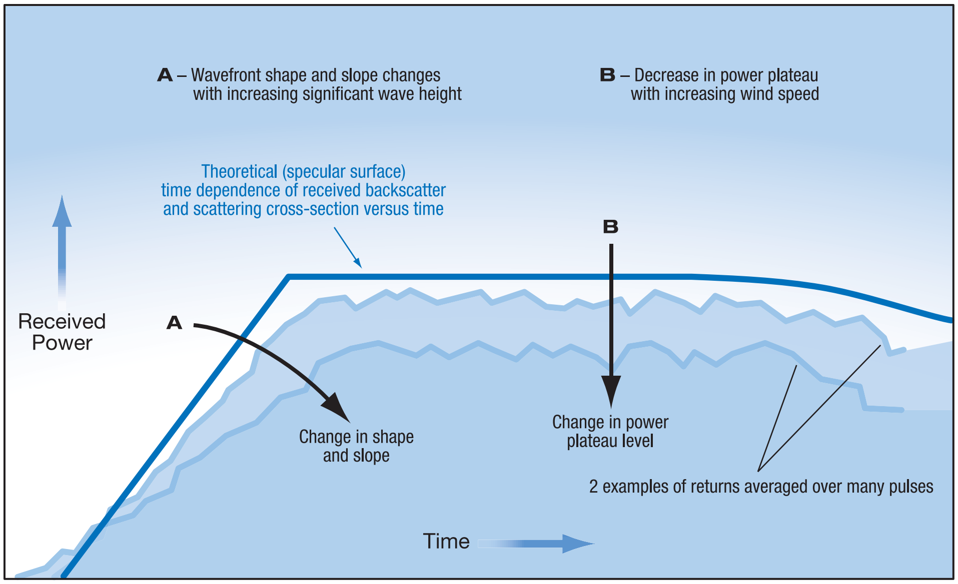

Figure 3. The waveform of the received altimeter signal.

inherent advantages of a pulse-limited altimeter with its spherical wavefront always providing a nadir component, thus avoiding instrument nadir-pointing errors. In addition, the DDA exploits the faster pulse repetition frequency by binning the Doppler frequency shifts in the along-track direction. These bins appear as narrow strips orthogonal to the satellite ground track. As the DDA moves along its path, the leading edge Doppler bin illuminated during the first pulse becomes the second Doppler bin during the next pulse and receives a second "look" by the instrument. This process repeats as long as the bin remains within the DDA footprint. Each pulse defines a new leading edge Doppler bin, re-samples each bin within the footprint, and integrates the retrievals as the satellite moves along its track. Since each bin is sampled many times, the samples can be coherently processed and the higher pulse repetition frequency provides for a higher resolution footprint along-track that is independent of the significant wave height. For example, a 30 Hz altimeter pulse provides a signal integration length that results in widths of the Doppler bins as narrow as 250 m.

This DDA technology provides several advantages over conventional altimetry. The sea surface height precision available from this type of instrument is approximately twice that of existing sensors. Simulations of the associated signal processing concepts have produced 0.5 cm precision in a calm sea, with precision remaining better than 1.0 cm even in significant wave heights as great as 4 m. The DDA is much less sensitive to errors induced by ocean waves. For a calm sea, DDA and conventional altimetry experience comparable levels of random noise; however, as the waves grow, a conventional altimeter experiences a dramatic noise level increase. With the coherent processing of the DDA, only a slight increase in random noise with wave height is experienced. This makes the DDA particularly well suited for geodetic applications where the random error due to ocean waves is the dominant error source. Wind speed and wave height retrievals from the DDA have twice the precision of current sensors. Another advantage of DDA is the ability to sample the coastal ocean where today's altimeters experience signal contamination from land. As the spacecraft approaches or departs a coastline where the angle of intersection with the satellite ground track is nearly orthogonal, on board processing can identify individual Doppler bins close to the coast and continue to sample it as the satellite passes over the boundary. From a system architecture perspective, the efficiency of the DDA provides for less transmitted power by the instrument and the potential for smaller and lighter spacecraft components—and thus a less costly mission—when compared to conventional altimeters with a similar design life.

Application

The DDA concept was originally envisioned for its potential application in terrestrial ice studies.[7] The supporting technologies were successfully demonstrated over southern Greenland in June of 2000 using an aircraft-based delay-Doppler instrument called Delay Doppler Processing (D2P) built and tested by the Johns Hopkins University Applied Physics Laboratory (JHU APL) and operated from a Navy research aircraft under the sponsorship of the NASA Instrument Incubator Program (IIP).

DDA technology is gaining interest due to its ability to precisely measure gravity anomalies that can be used to produce higher-resolution maps of the ocean floor. Given the fact that a geodetic altimeter mission does not require ionospheric and water vapor corrections—since measuring the shape of the ocean surface is independent of the exact sea surface height at any single sampled location—it would not need additional instrumentation, such as the water vapor radiometer, common to high-resolution oceanographic missions. Combined with the already economically-scaled DDA components, a geodetic mission could be designed to be small and light enough to take advantage of several low cost launch vehicle alternatives. An initial concept called Altimetric Bathymetry from Surface Slopes (ABYSS)[8] was proposed under the NASA Earth System Science Pathfinder (ESSP) Project. ABYSS was designed to map the global ocean floor with unprecedented accuracy using a DDA deployed on the International Space Station (ISS).

ABYSS was supported by a large group of collaborators and was proceeding to a demonstration; however, the loss of the Space Shuttle *Columbia* in early 2003 effectively placed into dormancy all ongoing ISS-based ESSP projects. The National Oceanic and Atmospheric Administration (NOAA) sponsored a system definition study for a free-flying DDA with similar ocean floor mapping goals called Abyss-Lite.[9] This mission would employ a non-repeating geodetic orbit that would provide ground track spacing on the order of 5 km after 18 months of operation, but would be designed for a mission life of six years to provide four-fold redundancy. The study concluded that the mission could be undertaken with a total investment of less than $100 million, including launch costs. Abyss-Lite has yet to acquire a critical mass of sponsors, although the diverse and important benefits that would be achieved with a bathymetric DDA have been widely recognized.[10]

The CryoSat mission, the inaugural satellite of the European Space Agency (ESA) Living Planet Programme scheduled to be launched in 2005, is the only ongoing or planned implementation of the DDA technology in space.[11] CryoSat is a three-year mission designed to accurately map terrestrial and sea ice with a science goal of studying possible climate variability and trends by determining the variations in thickness of the earth's continental ice sheets and sea ice cover. Its Synthetic Aperture Radar Interferometric Radar Altimeter (SIRAL) instrument will use a single Ku-Band (13.575 GHz) frequency in three operating modes. A conventional pulse-limited mode will be employed over the sea surface and interior pack ice where surface roughness is not a prohibitive factor. The DDA mode will be used over rougher ice in the marginal ice zone to achieve the desired resolution along-track. Finally, a third mode exploiting dual receive antennas will measure the height of ice over areas of sloping ice sheet topography.

Interferometric altimetry

Description

Interferometry refers to the science of observing a single location or area from two different viewing angles or at different times and using the combination of observations to measure surface displacement or velocity. It has a history of land applications for mapping and earth deformation studies, the most well-known being the Shuttle Radar Topography Mission (SRTM) that flew on the Space Shuttle *Endeavour* during an 11-day mission in February of 2000. The SRTM instrument consisted of two radar antennas, one located in the shuttle's payload bay and the other on the end of a 60 m mast. Using interferometric radar imaging, SRTM was able to provide global topographic maps with unprecedented spatial resolution.

Figure 4 illustrates the concept of cross-track interferometry for potential altimeter applications. Two radar antennas are separated in the cross-track direction by an exact baseline of distance B. The radars alternate transmitting and receiving, so that for each pulse and illuminated pixel the instrument provides the phase difference between the two signals. The difference between the two observation paths Δr is obtained from this phase difference between the two radar channels, with system timing accuracy determining the range for one side. The height of the sea surface relative to the altitude of the spacecraft can then be computed through simple geometry. For height measurements over a swath of ocean surface, additional information on the incidence angle of the radar pulses is required in order to properly geolocate each pixel within the swath.

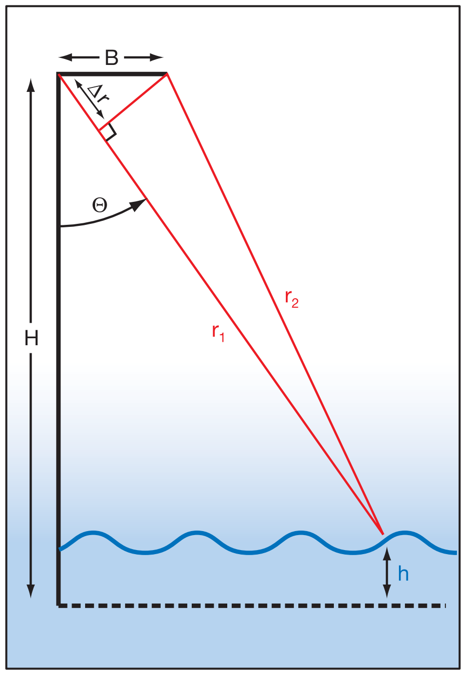

Figure 4. The geometry of the interferometric sea surface height measurement.

Application

The Wide Swath Ocean Altimeter (WSOA)[12,13] is an example of an interferometric radar altimeter. The WSOA was proposed by NASA as an experimental, companion payload with Jason-2—the planned climate-quality ocean observation mission to follow Jason-1—but was subsequently withdrawn due to funding constraints. The project proposed to deploy two antennas extending 3.5 m to either side of the conventional pulse-limited altimeter at the center of the spacecraft's nadir deck in the cross-track direction. Figure 5 illustrates the WSOA configuration concept. Using the Jason-2 conventional altimeter as a reference measurement, the WSOA would be able to interferometrically image a swath of ocean as wide as 100 km on either side of the satellite ground track, providing data on a 15 x 15 km grid within the imaged swath. While the expected sea height error budget of approximately 5 cm is slightly worse than conventional oceanographic altimeters, the revolutionary capability provided by the WSOA would be its ability to observe the spatial and temporal variability of mesoscale ocean fronts and eddies with a single satellite.[13] The WSOA instrument with Jason-2, together labeled the Ocean Surface Topography Mission (OSTM), could image almost every point on the ocean surface at least twice during the 9.916-day exact repeat cycle, often more frequently, and provide a level of mesoscale space-time coverage that would require four or five conventional altimeters. Also, the two-dimensional sea surface topography provided by the WSOA could produce direct measurements of oceanographic parameters previously unavailable from altimetry, such as surface current velocities and vorticity.

Ka-Band altimetry

Description

The Ka-Band altimeter operates in a pulse-limited mode, but its operation in a higher frequency range (35.5–37 GHz) offers several advantages. At these frequencies, the ionosphere effects are much lower than at Ku-Band and may be considered negligible except for extreme solar events, allowing for a single-frequency instrument. The decorrelation time of radar pulses at Ka-Band is shorter, providing for a significant increase in the pulse repetition frequency. The antenna beam width is smaller, giving a sharper return, lower power requirement, and ability to make measurements closer to the coast without land contamination. Also, the 480 MHz

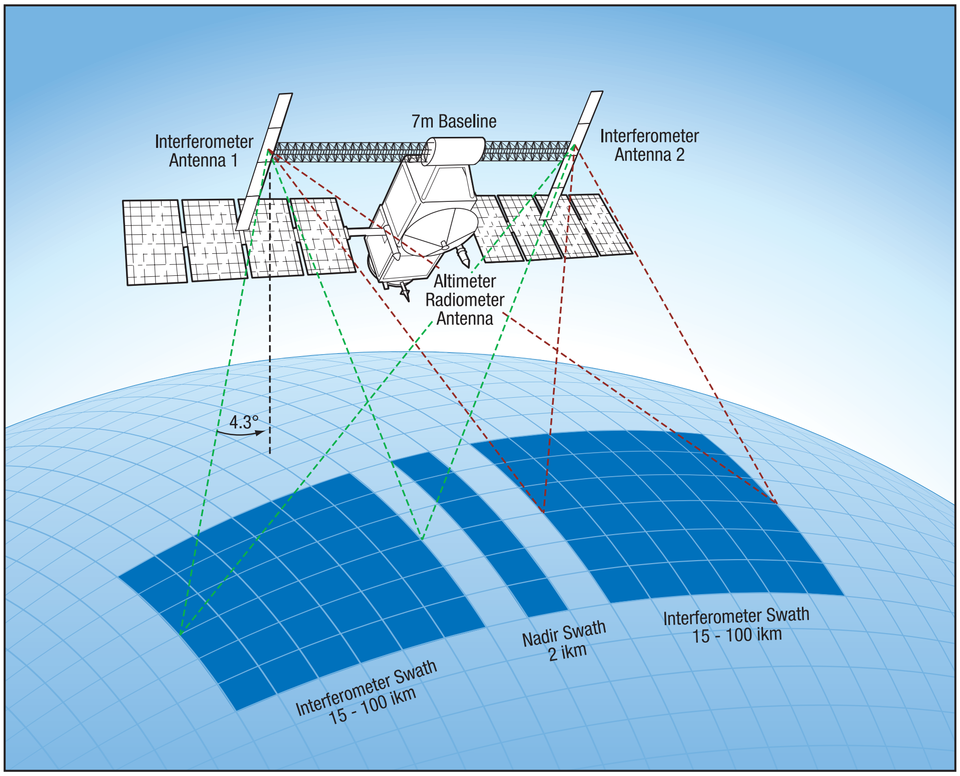

Figure 5. The proposed WSOA concept.

bandwidth available at Ka-Band can provide measurements with higher vertical resolution. One notable disadvantage is the fact that signals in the Ka-Band are much more prone to signal attenuation due to cloud droplets and rain.

Application

CNES has been examining a proposed demonstration of a micro-satellite Ka-Band (35.75 GHz) altimeter known as AltiKa.[14] Studies have examined the integration of the AltiKa instrument on as many as three micro-satellite buses that would be launched in a single faring and placed into synergistic orbits to provide optimal space-time coverage for mesoscale oceanography.

Demonstration and validation challenges

Global earth observations are fundamental components of the US Integrated Earth Observation System (IEOS) and Global Earth Observation System of Systems (GEOSS). With the ocean covering about 70% of the earth's surface, it has a fundamental impact on regional and global climate, water resources, marine ecosystems, human health, and global socioeconomic stability; areas emphasized by the IEOS Strategic Plan. To satisfy the established framework with reference to the world's oceans, technologies for observing ocean constituents that have global capabilities and applications are most likely to shoulder the burden of being the primary data providers to GEOSS. Satellite sensors—including altimeters incorporating new technologies—will serve a central role in addressing the global ocean observation needs of GEOSS. For example, the altimeter is one of only two space-based earth observation technologies (the other being earth radiation budget sensors) that can directly and ubiquitously measure changes occurring in the global earth environment that have potential links to human-induced climate change.

The European CryoSat mission remains the only known advanced altimeter technology with sufficient programmatic support for a space-based demonstration, with its launch expected in 2005. CryoSat is designed for ice measurements with an operations concept that is only marginally applicable to oceanographic observations. There are no fully funded programs known to exist that would demonstrate and validate advanced altimeter technologies specifically for ocean-related applications. Among the three major US government sponsors of earth observation satellites—NASA, NOAA, and the Navy—NASA and the Navy expend federal funds for space demonstration and validation activities. The likelihood of NASA or the Navy providing corporate support and budgeting for a space-based altimeter technology demonstration has been dramatically reduced due to recent programmatic pressures, changing strategic visions, and world events.

A new vision for NASA,[15] generated in response to presidential direction, emphasizes deep space exploration and a return to manned space flight with a reduced institutional emphasis on earth science. A subsequent reorganization led to the disestablishment of the NASA Earth Science Enterprise (ESE) and a division of its resources among other entities within the agency. In early 2005 NASA project managers withdrew WSOA as part of OSTM due to insufficient funding.

The end of the Cold War in the early 1990s reduced the Navy's emphasis on open ocean operations and submarine-based strategic deterrence. The Navy shifted its main focus to littoral operations and the projection of power from the sea into regions where the oceanographic environment is complex and traditional acoustic models do not perform as well. The critical value of altimeter data to global ocean circulation models still holds and the exploitation of the ocean acoustical environment continues as a critical Navy undersea warfare capability enabler, yet it has become more difficult to quantify the impact of altimeter data on platforms and sensors within the revised littoral operations paradigm.

In the aftermath of the January 2005 grounding of the submarine USS San Francisco about 350 miles south of Guam, the Navy began limited feasibility studies of a low-cost DDA in a geodetic orbit—analogous to the Abyss-Lite mission design—to provide navigation-quality global bathymetric knowledge and identify uncharted seamounts. This geodetic altimeter also has potential to contribute global observations of mesoscale ocean variability in addition to its gravity mapping mission.[16] An acquisition program in support of this altimeter mission has not been established.

Delay-Doppler, interferometric, and Ka-Band altimetry are technologies that have great potential for fulfilling the global ocean observation needs sought by GEOSS and identified in the IEOS Strategic Plan. These technologies are also likely to revolutionize the Navy's capability to exploit knowledge of the ocean structure and bathymetry in support of global naval operations. Within the constraints of current NASA and Navy corporate priorities and available funding, the near future holds few credible opportunities for US-sponsored demonstrations of these technologies in space. A recent report by the National Research Council[17] and associated testimony before the US House of Representatives Science Committee provide recommendations for earth observation satellite priorities and for developing a technology base for exploratory earth observations systems, within which advanced altimeter technologies would likely reside. Navy investment opportunities in support of these emerging altimeter technologies are expected to remain limited within the current geopolitical and budgetary climate.❖

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Gary M. Mineart is a principal scientist and systems engineer at Mitretek. His experience as an operational oceanographer and meteorologist includes specializing in the science of remote sensing and technologies for making observations of the earth from space, as well as addressing the planning, integration, and deployment of emerging remote and in-situ ocean sensor technologies. He received his master's degrees in meteorology and physical oceanography from the US Naval Postgraduate School. Contact him at gary.mineart@mitretek.org.

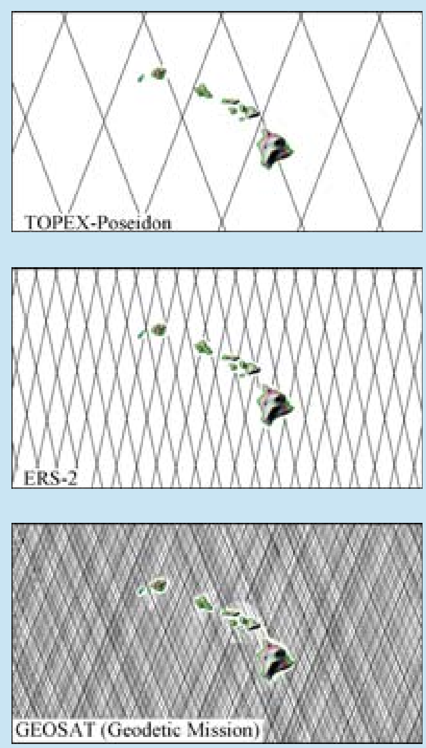
Satellite Radar Altimetry—What's in an Orbit?

Altimeter mission designers often employ an *exact repeat orbit* for observing oceanographic parameters. In this orbit, the sensor traces a path on the earth's surface within a tight tolerance that repeats itself for each spacecraft cycle. Over many cycles, the instrument completes many measurements along the same ground track. The greatest value of the exact repeat orbit is that exact knowledge of the geoid is not required. One can average measurements from each cycle to create a mean sea surface along the ground track, simplifying the extraction of sea surface height observations. The main disadvantage is that observations are only available along the specified ground track.

Exact repeat orbits vary widely in their oceanographic applicability because there is a trade off between spatial resolution and revisit frequency. TOPEX-Poseidon facilitates precise measurements of sea surface height over the globe and minimizes aliasing in tidal signals during its cycle of 9.97 days; however, the large spacing between ground tracks—315 km at the equator—results in large errors in sampling mesoscale ocean features that exist on smaller spatial scales. Conversely, the European Remote Sensing (ERS-2) satellite has altimeter ground tracks that are spaced no more than 90 km apart at the equator but is only able to observe the same point on the surface every 35 days. Also, since ERS-2 is in a sun-synchronous orbit it cannot avoid aliasing signals from diurnal tides.

Altimeters designed for geodetic measurements may use a *non-repeating orbit*. In this case, mission planners choose an orbit so that the ground tracks rarely, if ever, repeat. Over the life of the mission, one can achieve a dense spatial sampling of the earth's surface. The United States Navy's Geodetic Satellite (GEOSAT), during its 18-month geodetic mission, mapped the world's oceans with ground track spacing at the equator of about 5 km or less. Although revolutionary for geodetic applications, the resulting data were limited in their oceanographic utility due to the lack of repeating orbits.

Dedicated gravity missions are continually improving our knowledge of the geoid. Scientists envision the ability to independently characterize the geoid and deduce the mean sea surface without reliance on exact repeating orbits. The payoff could be dual-purpose altimeter missions that are able to serve the needs of both oceanographers and geodesists.



Altimeter ground track pattern for two exact repeat orbit missions (TOPEX-Poseidon and ERS-2) and the geodetic portion of the GEOSAT mission. Hawaii is illustrated for scale.

Graphic concept from W.H.F. Smith, NOAA Laboratory for Satellite Altimetry

Autonomous Mission Operations Systems

Stuart W. Frye and Daniel J. Mandl

The Earth Observing One satellite is being used along with a variety of ground and flight software, other satellites, and ground sensors to prototype a sensor web.

Several ongoing related activities at the National Aeronautics and Space Administration (NASA)/ Goddard Space Flight Center (GSFC) are acting together as pathfinders for future self-managing sensor constellations. Similar to commuters autonomously optimizing their route, future constellation components, whether they are orbital satellites, unmanned systems, or ground components, will autonomously optimize their operations activities. These systems will act independently while accomplishing coordinated observations that satisfy complex scientific objectives. Taken together, these smart components will enable more cost-effective management of future satellite constellations and other sensor platforms.

These pathfinder activities implement an operations approach integrating groups of autonomous sensor nodes to collaborate for observations. Autonomous event detections made by a source node are broadcast through the sensor web communications fabric in real time to trigger follow-up observation requests by other sensors and/or modeling elements. Middleware to enable interoperability between ground and space-based components provides a plug and play environment for new software and algorithms.

The sensor web technology activities use the Earth Observing 1 (EO-1) satellite[1] as an on-orbit testbed. EO-1 was launched November 21, 2000, as part of the New Millennium Program at NASA and was originally designed as a one-year mission to validate revolutionary space technologies. It hosts three land remote sensing instruments—the Advanced Land Imager, the Hyperion hyperspectral imager, and the Atmospheric Corrector—in addition to a dozen new, groundbreaking spacecraft

NASA's EO-1 satellite is used as an on-orbit testbed for exploring sensor web capabilities

Inside Track

- A series of ongoing experiments are being conducted at the NASA Goddard Space Flight Center to explore integrated ground and space-based software architectures that enable sensor webs.
- A sensor web is a coherent set of distributed nodes interconnected by a communications fabric that collectively behave as a single, dynamically adaptive, observing system.
- The nodes can be comprised of satellites, ground instruments, computing nodes, etc. Sensor web capability requires autonomous management of constellation resources.
- Autonomous management becomes progressively more important as more and more satellites share resources, such as communication channels and ground stations, while automatically coordinating their activities.

technologies. After its prime mission, it evolved into an orbital demonstration platform and, in particular, is used to validate a number of sensor web concepts.

Figure 1 depicts a high level overview of key automation and autonomy capabilities integrated into the EO-1 mission. The highlights are as follows:

- Tasking of the EO-1 satellite with high level goals instead of specific commands.
- On-board science processing, classification and autonomous decision-making.
- Autonomous triggers to task EO-1 from both the ground and other space-based assets.
- User interface to automatically sort and prioritize tasking requests. This includes building sensor web goal files and automatically uploading them to EO-1.

These capabilities continue to evolve and become more robust as the sensor web vision and architecture evolves.

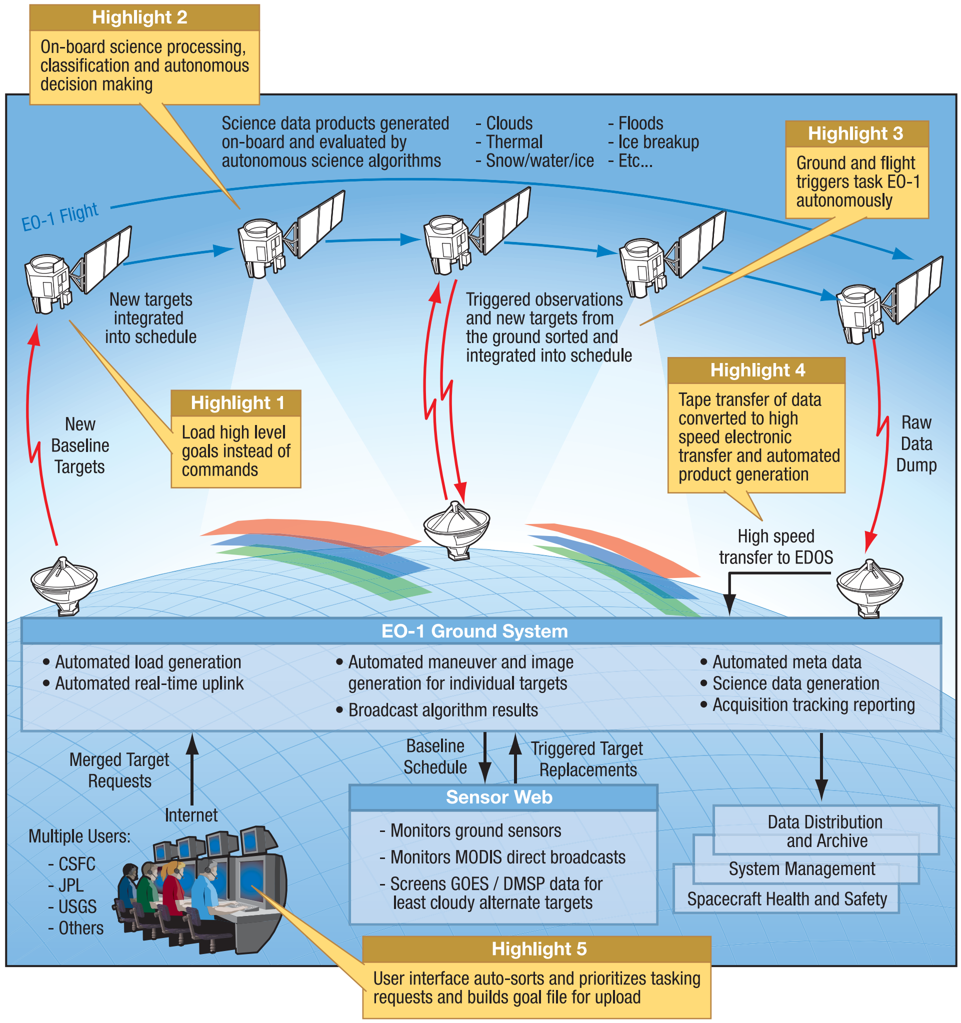


Figure 1. Overview of autonomy and automation software installed on the EO-1 mission.

Tasking EO-1 using high level goals

One of the key upgrades to the operations concept for EO-1 was to work with high-level goals instead of a series of individual low level commands and command loads.[2,3] A goal file consists of an objective statement with parameters that are uplinked to the spacecraft and expanded on-board into a prioritized sequence of individually commanded activities. This level of abstraction enables the user to be isolated from much of the underlying detail required to task the EO-1 satellite. When the original process of tasking EO-1 was defined, approximately 60 steps were required to task EO-1 for one image. When the autonomy and automation software was created, all of these steps were encapsulated in a few high-level goals by processing software that handles the underlying detail.

Ground system goal generation was done using both the Automated Scheduling and Planning Environment (ASPEN),[4] a NASA Jet Propulsion Laboratory (JPL) application, and the Science Goal Monitor (SGM),[2] a GSFC application. The EO-1 spacecraft also creates high level goals on-board in addition to ingesting them from the ground via Continuous Activity Scheduling Planning Execution and Replanning (CASPER) software.[3] The CASPER software is an eight megabyte executable that is uploaded into memory on-board one of EO-1's flight processors and, once invoked, interprets the high-level goals on-board, manages the on-board details of acquiring an image and processing the data, and manages on-board replanning of the short-term integrated schedule of activities. Initially, the SGM was used as a pathfinder to encapsulate the high-level goals. Later, the ASPEN/CASPER combination was used.

Autonomous decision making

The Autonomous Sciencecraft Experiment (ASE), the centerpiece of the improved operations, provided the autonomy on-board EO-1.[4] ASE is comprised of CASPER and additional algorithms that can perform:

- Science data processing on-board.
- Classification of images to screen for clouds,[5] thermal anomalies, floods, change detection, generalized feature detection.[6]
- Selection of alternate targets without prior notice by replacing high-level goals in the on-board goal file. The replacements can either be triggered on-board by one of the classifiers or can be loaded from the ground as a result of an autonomous trigger from another node in the sensor web.

In the beginning of the mission, all tasking of EO-1 to perform imaging with its three instruments was meticulously planned by a team of scientists, engineers, and operations personnel on a daily basis. Over the last two years, the operations concept has evolved to the point that autonomous triggers can task EO-1 without continuous human intervention. In the sensor web experiments, transient events such as volcano eruptions trigger EO-1 images via ASPEN or SGM. These triggers are folded into the normal tasking plan via a priority scheme which enables higher priority tasking requests to automatically replace lower priority tasking requests in the on-board schedule. The planning process is now greatly simplified since we are dealing with a higher level of abstraction than in the beginning of the mission.

Figure 2 depicts various sensor web experiments that have been conducted. Note the variety of software tools used and the variety of applications. Autonomous triggers included other satellites, such as Terra, Aqua, the Defense Meteorological Satellite Program (DMSP) satellites, and the Geostationary Operational Environmental Satellites (GOES), as well as ground instruments, such as the tilt meter installations to detect volcanic activity at Kilauea, Hawaii.

User interfaces and communications fabric

A Web interface has been prototyped that provides a mechanism to input tasking requests. Up to now, the customer interface for tasking requests originated at the US Geological Survey (USGS) Center for Earth Resource Observations and Science (EROS) and required weekly meetings with the EROS representatives, the GSFC flight operations team, EO-1 mission engineers, and the EO-1 project science team to integrate the various customer requests. However, on the new system, all of the priority schemes have been encoded in software, so the weekly meetings will become the exception. The translation of tasking requests to uplinkable goal files as well as the uplink and ingest on-board are all automated.

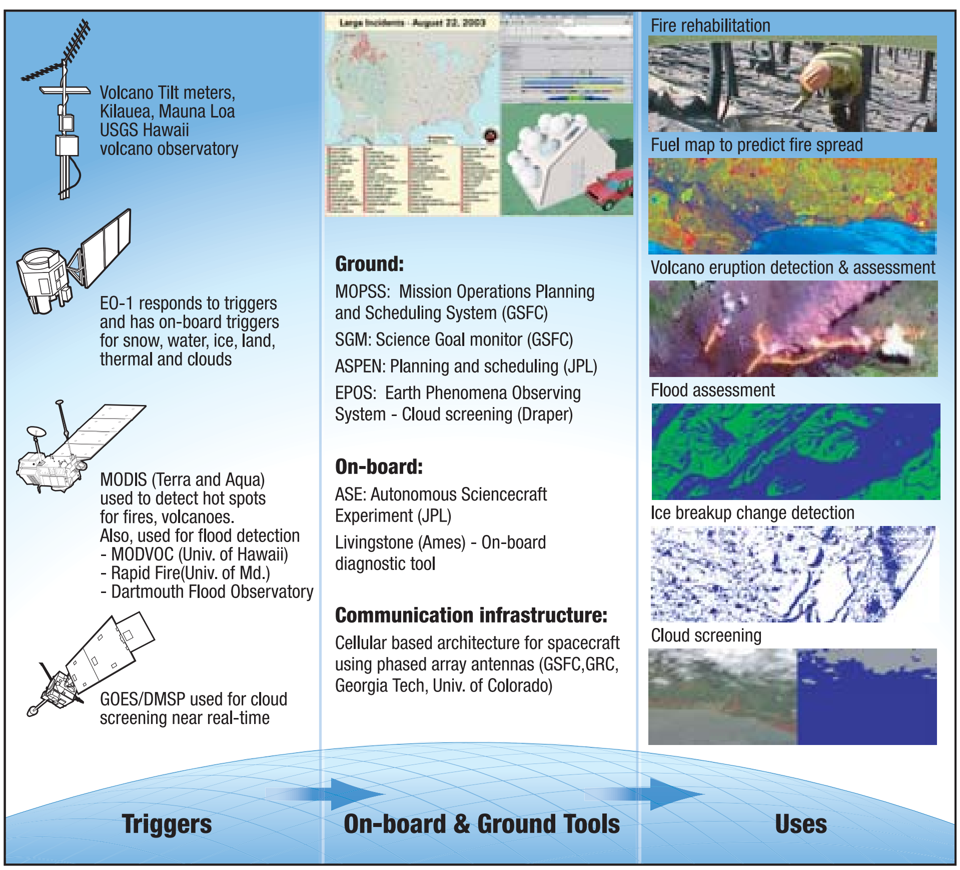


Figure 2. Overview of the various triggering combinations along with some of the applications that were used with EO-1.

The key to making sensor webs work is the communications fabric that exists between the various software applications. Inter-process communications is readily available for ground-to-ground based software processes. However, sensor webs require communications between software applications that are resident on-board satellites and the ground. Therefore, for the experiments we devised a software bus on-board EO-1 in which any application can address any other application and easily send a message as a means to coordinate activities. This concept was extended by using Internet technology interfaces to create a virtual connection between satellites, such as using the Terra satellite as a triggering source for locating hot pixels from volcano eruptions and tasking the EO-1 satellite with follow-up observation requests. An Internet site was used to create a virtual connection between ground instruments, such as tilt meters installed on the Kilauea volcano, EO-1's planning software, and the EO-1 satellite. System responsiveness is improved by using Internet protocol.

Lessons learned and future implications

By treating every component in a constellation as a network-based software component, we can create a collaborative environment that enables sensor webs. The key to the successes on EO-1 resided in the fact that EO-1 was built with two on-board computer processors with additional memory which is modifiable on-orbit. Future missions should be built with additional computing resources to enable new software applications to be installed on-orbit as mission experience and innovative new thinking extends beyond initial mission plans.

Experimental results in mission autonomy allowed us to explore the constraints related to conflict resolution for competing triggering requests. In addition, the implementation of fully automated systems uncovered error conditions that were a result of interaction with pre-existing operations procedures. As these problems were identified, additional intelligence was added to queuing scripts and ingest routines to eliminate these glitches. Many of these lessons were learned during on-orbit debugging of new code installations, since many of the functions could not be fully checked on the ground due to limitations in flight software simulators.

Figure 3 represents a future vision in which software can be loaded onto satellites in a “plug and play” manner so as not to require extensive integration and testing. Efforts such as these and other related activities are going to enable increased flexibility and thus cost-effective sensor webs.

Figure 3. Sensor web vision with seamless communications between space and ground software elements.

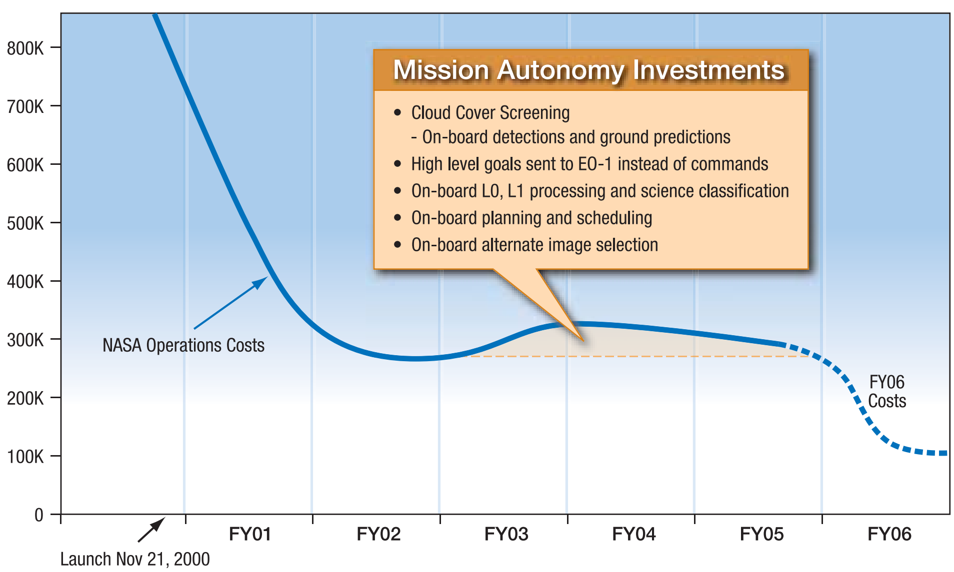


Figure 4. Cost profile of EO-1 with key software components identified on the inset box.

As an indirect result of the experiments conducted on EO-1, which added various autonomy and automation software components on both the ground and on-board the satellite, operations costs have dropped dramatically. It is expected that the actual cost of operations will drop further in the totally automated mode planned to begin fiscal year 2006. Figure 4 depicts the monthly cost of operating the EO-1 mission, where the solid line depicts the actual costs and the dashed line depicts the projected monthly cost as new software components are installed into operations.

Clearly, connecting software components to create sensor webs and increasing autonomy validated future operations concepts and created the immediate benefits of reducing cost and enabling additional science.❖

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Stuart W. Frye is a senior principal engineer at Mitretek, where for the past 25 years he has provided engineering and technical management expertise to various NASA flight projects, focusing on improving on-board instrument operations, data capture, and science data processing delivery capabilities within satellites and their ground systems. Contact him at Stuart.W.Frye.1@gsfc.nasa.gov.

Daniel J. Mandl is the EO-1 mission manager at NASA Goddard Space Flight Center, where he is responsible for integration, test, and on-orbit technology demonstrations for flight and ground components that enable mission autonomy and sensor webs. Contact him at daniel.j.mandl@nasa.gov.

Mobile Unmanned Systems On, Over, and Under the Sea

Justin E. Manley

As unmanned vehicles become ever more capable they offer new capabilities for ocean science and observation.

The marine environment is seeing a steady influx of robotic technology spurred by new developments. The past decade has seen a rapid advance in "robotic" technology. In some cases true leaps in artificial intelligence have yielded more capable "robots." In most cases, however, there is still a need for an operator "in the loop." Such platforms are unmanned but not fully autonomous. Less demanding applications have seen dramatic results from fully autonomous robots. In the consumer culture, the Roomba® by iRobot® created interest and sold hundreds of thousands of units. This device has reliably cleaned floors in many homes after the push of a button. Such pure autonomy is rare even with the most advanced robots.

In most cases the advances have come in the form of better platforms and communications and/or telemetry systems providing increased capabilities. In the military campaigns in Afghanistan and Iraq, new unmanned vehicles have made dramatic mission contributions on land, sea, and air. Undersea robots, the most autonomous of current military systems, have scoured harbor floors for mines, thereby reducing the risks to divers and maritime operations. Land robots have led the way into dark caves and probed suspicious roadside devices thereby saving the lives of soldiers. Unmanned aircraft have observed, and even launched missiles at, suspected terrorists—all while their pilots sit behind control stations thousands of miles away. Unmanned vehicles have dramatically changed the face of military operations.

This dramatic advance in unmanned vehicle capability is also impacting the scientific observation of our planet. In particular, marine observations and research have benefited from a growing field of unmanned systems. Underwater vehicles have made headway in commercial ap-

Inside Track

- During the past decade, unmanned vehicles have become a potent tool for defense and science.
- Unmanned systems have demonstrated success in flight, on land, and at sea.
- Navigation, telemetry and artificial intelligence present varying levels of difficulty in different operating environments.
- Earth, and particularly ocean, observations can benefit from the use of unmanned vehicles collecting scientific data.

plication[1] and science.[2] Their peers that sail upon or soar above the waves are also making a mark.

Current unmanned systems

In the marine environment there are three categories of unmanned systems—submarines, ships or boats, and aircraft. Many terms and names have been applied to describe these systems. The most commonly used are: autonomous underwater vehicle (AUV) or unmanned undersea vehicle (UUV) for submarines; autonomous surface craft (ASC) or unmanned surface vehicle (USV) for boats; and unmanned aerial vehicle (UAV) for aircraft. It is important to note that the science community often uses AUV rather than UUV when describing robotic submersibles. This has the potential for confusion among submersibles—AUVs—and aircraft—UAVs. For clarity this article will use the terms most often used in military circles, UUV (submersible), USV (boat) and UAV (aircraft). The characteristics of each system are described below and summarized in Table 1.

Table 1. A summary of unmanned vehicles.

Name/Acronym	Operating Domain	Strengths	Weaknesses
Unmanned Undersea Vehicle (UUV)	Undersea (salt or fresh) in any body of water from shallow to 6,000 meters deep	Stealth, ease of locomotion, very limited conflicting "traffic," few obstacles to detect/avoid, stable instrument platforms	Requires air-independent power systems, no radio-based technologies, limited telemetry bandwidth and range, challenging navigation
Unmanned Surface Vessel (USV)	Sea surface, moderate sea states, and wind conditions	Navigation (GPS), high bandwidth telemetry, full suite of sensors, including radar, internal combustion power for high performance	High dynamic environment, operational challenges posed by other vessels, can only sense/influence the air/sea interface
Unmanned Aerial Vehicle (UAV)	Atmosphere from very low altitude to 7,000+ meters	Altitude provides excellent sensing position, potentially long endurance and wide area coverage, navigation (GPS) and high bandwidth telemetry	Highest cost (for large UAVs), frequency and airspace interference for multi-vehicle operations, payload limitations force endurance (fuel) versus sensors tradeoffs

Unmanned undersea vehicles

UUVs are the most autonomous of the current unmanned vehicles. Usually UUVs bear a strong resemblance to torpedoes, which might claim the title of the first unmanned vehicle developed. UUV devices can range from the very small, easily deployed with one hand, to the very large, requiring dedicated ships and handling systems. Equipped with batteries, or other air independent power sources, and a wide variety of sensors, these vehicles are well suited to execution of routine surveys. Most familiar of the survey methods is the "lawn mower" pattern, designed to completely cover a region of interest.

An example UUV, an Odyssey III class AUV from the Massachusetts Institute of Technology (MIT), is shown in Figure 1. This UUV presents many of the common characteristics of UUVs. It is long and cylindrical, in this case 0.54 meters (21 inches) in diameter and nearly 2 (6.5 feet) meters long. It has a single propeller at the end of the vehicle. In this case the entire propeller is actuated to maneuver the vehicle but fins and diving planes are common. The hulls frequently provide some degree of mechanical modularity so that additional payloads or sub-sections can be installed. This vehicle requires a light crane for deployment as it weighs several hundred pounds. The hull is free flooding so the initial recovery weight can be over 1,000 pounds as the water drains out of the vehicle. Sub-systems within the hull are protected by their own pressure vessels. This is common in UUVs designed for deep ocean operations, usually beyond 300 meters deep. Other UUVs use a sealed hull, which avoids this issue but adds to the weight and cost of the main vehicle body.

The driving technical challenge in UUV development is the limitations on communication and navigation imposed by the medium of operation—sea water. Due to attenuation, electro-magnetic waves do not propagate effectively through the ocean. Fresh water is somewhat more benign but still poses problems to radio frequency (RF) transmissions. Thus, RF communications, radar for obstacle avoidance, and use of Global Positioning System (GPS) signals for navigation are not possible underwater. This has pushed UUV developers to design their vehicles with a relatively high degree of autonomy. A seafloor survey, for example, can be pre-programmed and then executed with no further user intervention. A UUV can use its own sensing and "intelligence" to avoid hitting the seafloor and to follow a programmed path. The relative lack of obstacles and ease of locomotion through the water column is an advantage

Figure 1. A typical UUV being deployed (photo courtesy of J. Manley/MIT AUV Lab).

that offsets the limited communication and navigation capabilities of UUVs.

Unmanned surface vehicles

A robotic boat can be based on any conventional boat, or even ship, design. Even smaller recreational vessels are now equipped with autopilot and navigation systems that allow a helmsman to push a few buttons and then ride along as the vessel executes maneuvers. These commercially available technologies enable "unmanned" operation and translate into low barriers to USV development. The wide variety of enabling technology is complemented by the fact that, in contrast to underwater vehicles, USVs can use a full array of RF devices. High bandwidth telemetry and GPS navigation are nearly standard in USVs. Another advantage on the surface is the availability of internal combustion engines. Gasoline or diesel engines can provide USVs with significantly more power for propulsion and energy for "hotel loads" (computers, sensors, and other non-propulsion systems) than batteries alone. Many USVs make good use of this advantage and are modeled on small surface vessels such as rigid hull inflatable boats (RHIBs). Such USVs can usually achieve speeds well over 10 knots and in some cases exceed 20 knots or more. The availability of precise navigation and high data rate telemetry allows operators to maintain control over the vehicle for real-time maneuvering.[3]

The tradeoff faced by USVs is the challenging dynamics of the sea surface. Rough seas make the mechanical design of USVs difficult. Antennas, sensors, and other sensitive devices must be protected from shock and vibration as well as salt spray. Propulsion systems and actuators must be prepared to endure pounding at speed and significant accelerations and momentum changes during maneuvers. Small vessels have been braving rough seas for thousands of years, but usually under the care of experienced sailors. A remote operator will never be able to "read the waves" like a shipboard helmsman. Hence USVs demand exceptionally robust mechanical design.[4]

USVs are of high value in coastal waters due to the variety of military and scientific missions there. Unfortunately, they must share this space with commercial and recreational traffic. While an operator is likely to remain in control of an USV, it may be in only a supervisory way. One operator may even be responsible for multiple vehicles. In such a situation it may be challenging to observe other vessel traffic and react appropriately and in accordance with regulations. Fully autonomous behaviors allowing USVs to interact with other traffic are under development but have not yet seen field trials.[5] Technology can and will improve the situation but it presents a unique consideration for USVs given the large volume of vehicles sharing the sea surface and especially coastal regions.

Unmanned aerial vehicles

The airborne family of unmanned vehicles—UAVs—are perhaps most familiar. Drone aircraft have been flying for decades, usually in support of aeronautical research. In recent years UAVs have grown from curiosity to staple of air warfare. Reconnaissance and observation are natural applications for this technology. Small hand deployed UAVs that resemble toys are used by troops on the front lines[6] and very large systems loiter at altitude for hours.[7] UAVs use a wide variety of power and propulsion systems. Aircraft geometry varies widely as well. Payloads carried by UAVs range from simple cameras to sophisticated electronic monitoring devices. Lethal payloads including guided missiles have also been deployed on UAVs. In short, UAVs are nearly as diverse as their occupied cousins, fixed and rotary wing aircraft. Readers desiring a detailed review of UAV specifications are encouraged to turn to works by organizations such as Jane's.[8]

While UAVs offer significant potential and have logged thousands of flight hours in action over Iraq and Afghanistan, they too face challenges. Weather can impact UAV operations, particularly smaller systems such as the hand-deployed units. Interaction with other aircraft is also a concern, especially in dynamic settings like military conflicts. Generally UAV collisions are less of a concern than USV incidents since there are fewer systems in the airspace, and they have the advantage of varying altitudes to further dilute the space. Frequency interference is a significant issue as these systems use powerful broadband data links and there is a limited amount of spectrum to work with. Again, this problem is largely confined to military operations where large numbers of UAVs are operating in the same area.[6]

Applications of unmanned technology to ocean science and observation

While unmanned vehicle developments and early operations have been driven by military applications, they are not exclusively a defense technology. Pioneering work in UUVs[9] and USVs[10] took place at academic institutions such as the MIT AUV Lab and the Woods Hole Oceanographic Institution (WHOI). The scientific community recognized the efficiency of unmanned platforms. UUVs and USVs offered opportunities for scientists to collect important oceanographic data sets without using expensive research vessels. A vision of networked AUVs called the Autonomous Ocean Sampling Network (AOSN)[11] was offered nearly 10 years ago to describe the potential power of unmanned vehicles in ocean science and observation. Early academic users paved the way for more regular use of unmanned vehicles in operational ocean science and observation.

UUVs

UUVs have been eagerly adopted in scientific circles, perhaps more so than UAVs or USVs. The National Oceanic and Atmospheric Administration (NOAA) was an early supporter of UUV research through its National Undersea Research Program (NURP) and Sea Grant College Programs. This investment has yielded strong returns as UUVs become operational in a variety of pilot programs in NOAA. A short list of tasks envisioned for NOAA UUVs includes: coastal survey, fisheries stock assessment, ecosystem, and habitat characterization and marine archaeology. Nearly every element of NOAA ocean observations can be improved by the use of UUVs and the agency is actively working to bring them into service.[2] In oceanographic research WHOI has used vehicles such as the Autonomous Benthic Explorer (ABE), and the Monterey Bay Aquarium Research Institute (MBARI) has used the Dorado vehicles to collect valuable new scientific data.

ABE also offers an example of cooperation between unmanned and manned vehicles. In many cases ABE and Alvin, a traditional submersible, are deployed from the same vessel. While the Alvin crew sleeps and the vehicle's batteries charge, ABE is deployed to reconnoiter the dive site for the next day. By the time the pilot assumes the control of Alvin he can be handed a high resolution bathymetric map of the day's operating area. This enhances the scientific time on the bottom significantly. Alone or in cooperation with other assets, UUVs are improving ocean science and observation.

Figure 2. A USV designed for USGS (photo courtesy of Sea Robotics Corporation).

USVs

Surface platforms lagged UUVs in their adoption for scientific tasks. The advantages of surface operation, particularly in more protected coastal environments, have recently been recognized, and USVs are starting to become more common in research efforts. Early demonstrations of USVs showed the potential of USVs to economically collect bathymetric data.[9] USVs also served as valuable test platforms supporting the engineering research and development of UUVs.[10] Easy communication and navigation make USVs an ideal platform for development of autonomous vehicle control strategies. Low production costs make them particularly useful for research into "swarms" of unmanned vehicles.[11] Scientific demonstrations and engineering research are not the only roles USVs fill outside the defense sector. They have become an ever more common tool for marine science.

A growing number of USVs are available for sale by commercial vendors. The low cost of such platforms has led to their adoption by a variety of ocean science and observation agencies. Some examples include the US Army Corp of Engineers, US Geological Survey, and US Naval Oceanographic Office. These agencies have all made use of small USVs for applications such as oceanographic sampling, river flow monitoring, and hydrographic survey. A good example is the USV-1000 offered by Sea Robotics Corporation, shown in Figure 2. This is a small vessel (3.0 meters by 1.2 meters) weighing only 40 kg and designed for easy deployment and even transport by helicopter. Despite this small package the USV can carry a variety of sensors for water column monitoring and can operate for up to 12 hours. Direct user-control or fully autonomous operation are possible. Current operations focus on the use of individual USVs in hard-to-access areas and shallow or remote rivers and lakes, where conventional surveys are impossible or impractical. As the technologies mature and become available in larger quantities and as costs decrease, USVs will continue to make contributions to ocean science.

UAVs

Due to their high cost, UAVs, particularly the larger more capable systems, have been slow to make inroads in the ocean science community. A recent joint project between NOAA and National Aeronautics and Space Administration (NASA) is moving UAVs into this arena. This project is called the Altair Integrated System Flight Demonstration Project and utilizes a UAV developed commercially by General Atomics Aeronautical Systems Inc. As the name implies, the demonstration will be based on the Altair vehicle, which is a medium-altitude long-endurance UAV. A key project goal is to evaluate UAVs for future ocean and earth observing missions. Some example missions include: climate research, marine sanctuary mapping and enforcement, nautical charting, and fisheries assessment and enforcement. The Altair payload includes instruments for measuring ocean color and atmospheric composition and temperature. A surface imaging system is also included. The vertical distribution of water vapor will be remotely measured with passive microwave sensors.[12]

Test flights of the Altair UAV, shown in Figure 3, took place in April and May of 2005. A final report is not yet available but the mission plan calls for six flights totaling 53 hours of flight time. Altitudes of up to 15,000 meters and individual flights approaching 20 hours duration were anticipated. Flight objectives included observing atmospheric conditions that bring moisture from the Pacific Ocean to the continental US from transport of polar air. Observations were to include examination of shorelines in the Channel Islands National Marine Sanctuary and evaluation of the potential for UAV enforcement of marine regulations in the sanctuary. While the rich data set collected by this pilot program has not been fully analyzed, it is reasonable to assume that interest in UAVs for ocean science and observation is likely to grow.

The next steps

To see the promise of unmanned systems fulfilled for ocean observation there are operational and technical challenges. The current pace of progress is rapid, so it is reasonable to expect some of these developments to come in the next few years. In UUVs, important development areas are power systems and telemetry bandwidth. Improving the endurance of UUVs will come as higher energy density batteries and other technologies such as fuel cells reach maturity. Acoustic communications are improving but the use of a network approach is likely to be the primary evolution of undersea telemetry. When many

Figure 3. The Altair UAV developed for science missions (photo courtesy of NOAA).

individual systems can seamlessly relay communications amongst themselves, and the entire network, UUVs will take another dramatic step forward.

USVs and UAVs face different challenges, largely operational issues. Both surface and aerial vehicles, benefiting from GPS capabilities, have little need for new navigation technologies. While additional bandwidth will always be welcomed, there is not a pressing demand for improvements in this sub-system. Improvements in UAV and USV endurance will be an evolutionary development, not a dramatic new requirement. The serious challenge to wider use of UAVs and USVs in ocean science is a lack of experienced users and potential policy concerns. Policy issues such as frequency compatibility and rules for interaction with other users of the air/sea space will require concerted efforts but will evolve as the technology takes hold. As more science programs experiment with these types of vehicles the user base will grow rapidly and researchers will gain valuable experience.

The ultimate implementation of unmanned systems in oceans science and observation may be in the context of an integrated ocean observing system (IOOS). As its name implies, such a "system" will entail a combination of many other systems. Fixed moorings, mobile platforms (manned and unmanned) in the air and on and beneath the ocean surface, power and data connections to docking stations, and other network nodes and complex computing systems will all be part of IOOS. The mobility of unmanned vehicles will be key to covering large areas. The economical operations offered by unmanned systems will be critical to maintaining IOOS over long time domains. While the technical challenges are substantial and the costs will be high, the value of IOOS is substantial. The US Commission on Ocean Policy has identified benefits such as:

- Improving the health of our coasts and oceans.
- Protecting human lives and livelihoods from marine hazards.
- Supporting national defense and homeland security efforts.
- Understanding human-induced and natural environmental changes and the interactions between them.
- Measuring, explaining, and predicting environmental changes.
- Providing for the sustainable use, protection, and enjoyment of ocean resources.
- Providing a scientific basis for the implementation and refinement of ecosystem based management.
- Educating the public about the role and importance of the oceans in daily life.
- Tracking and understanding climate change and the ocean's role in it.
- Supplying important information to ocean-related businesses such as marine transportation, aquaculture, fisheries, and offshore energy production.

Evolving unmanned vehicles will surely support IOOS and the wider global earth observing enterprise envisioned by many scientists. As robotic vacuums have made their way into millions of homes, so too will a multitude of robotic tools find their way under, on, and above our world's oceans.❖

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Justin E. Manley is a lead ocean engineer at Mitretek. He is an experienced and noted expert in advanced undersea technologies, including the operation of ROVs and AUVs, and participates in underwater expeditions across the globe, most recently to the wreckage of the RMS Titanic. *He received his master's degree in ocean engineering from MIT. Contact him at justin.manley@mitretek.org.*

Environmental Products from NOAA Satellites

Stacy L. Bunin

People are accustomed to seeing weather satellite imagery on the news. Learn about the wide variety of other environmental products generated from satellites.

The National Oceanic and Atmospheric Administration (NOAA) operational environmental satellite system consists of two types of satellites. The Geostationary Operational Environmental Satellites (GOES) orbit at an altitude of 35,800 km over fixed locations relative to Earth's surface, allowing for continuous monitoring of environmental phenomena. The Polar-orbiting Operational Environmental Satellites (POES) orbit Earth 14 times per day at an altitude of 830 to 870 km, giving environmental information for the entire globe. Together, data from the GOES and POES satellites provide for a global environmental monitoring system. Oceanic, atmospheric, and land surface products are derived on a variety of temporal and geographic scales. These products are used for short-term warnings, long-term forecasting, and climate and hydrological applications, both domestically and internationally. Satellite-derived products are critical to the user community. Each product provides a data point for understanding, explaining, and predicting weather and environmental phenomenon.

Ocean products

Sea surface temperature

The oceans play a major role in the global climate. Satellite measurements give important information about conditions over ocean areas lacking in widely available surface observations. Sea surface temperature observations are used as input to weather forecasting and climate models. Specific features can be used for understanding the impact of hurricanes, the prime locations for tracking marine life, and for identifying temperature gradients in the ocean, such as El Niño and La Niña events and the Atlantic Gulf Stream.[1]

Inside Track

- Environmental data from NOAA's satellites include ocean, atmosphere, and land surface products.
- Meteorological, hydrological, marine, agricultural, and transportation user communities all use NOAA's environmental satellite products.
- Environmental products provide information for understanding, explaining, and predicting weather and environmental phenomenon.
- Improved future technologies will enhance the products for the benefit of all users.

Sea surface temperature observations are generated from each POES orbit and are used to produce a daily global product, bi-weekly regional products that cover the coastal US with fields such as the East Coast, bi-weekly local products with fields including the Great Lakes and Gulf of Mexico, and a global monthly mean product. Coastal sea surface temperature products are generated from higher resolution data, which provide more detailed sea surface temperature information for environmental uses along the US coastlines. POES data are used to generate sea surface temperature anomalies. The anomalies are calculated by determining the difference between the sea surface temperature and the climatic norms, which are based on the monthly mean observations from 1984–1993. (Data from 1991 and 1992 are excluded from these calculations because the significant amount of aerosols in the atmosphere following the eruption of Mt. Pinatubo affected the accuracy of sea surface temperature retrievals.) These anomalies are used to gauge the development of El Niño, to monitor ocean temperature cooling conditions following the passage of a hurricane, and determine the extent of coral reef bleaching.[2]

GOES sea surface temperature images for the full Earth disk are provided every three hours, while regional analyses are provided hourly. The frequent imaging allows for a higher chance to obtain cloud-free images to give a complete understanding of current sea surface temperature.[2]

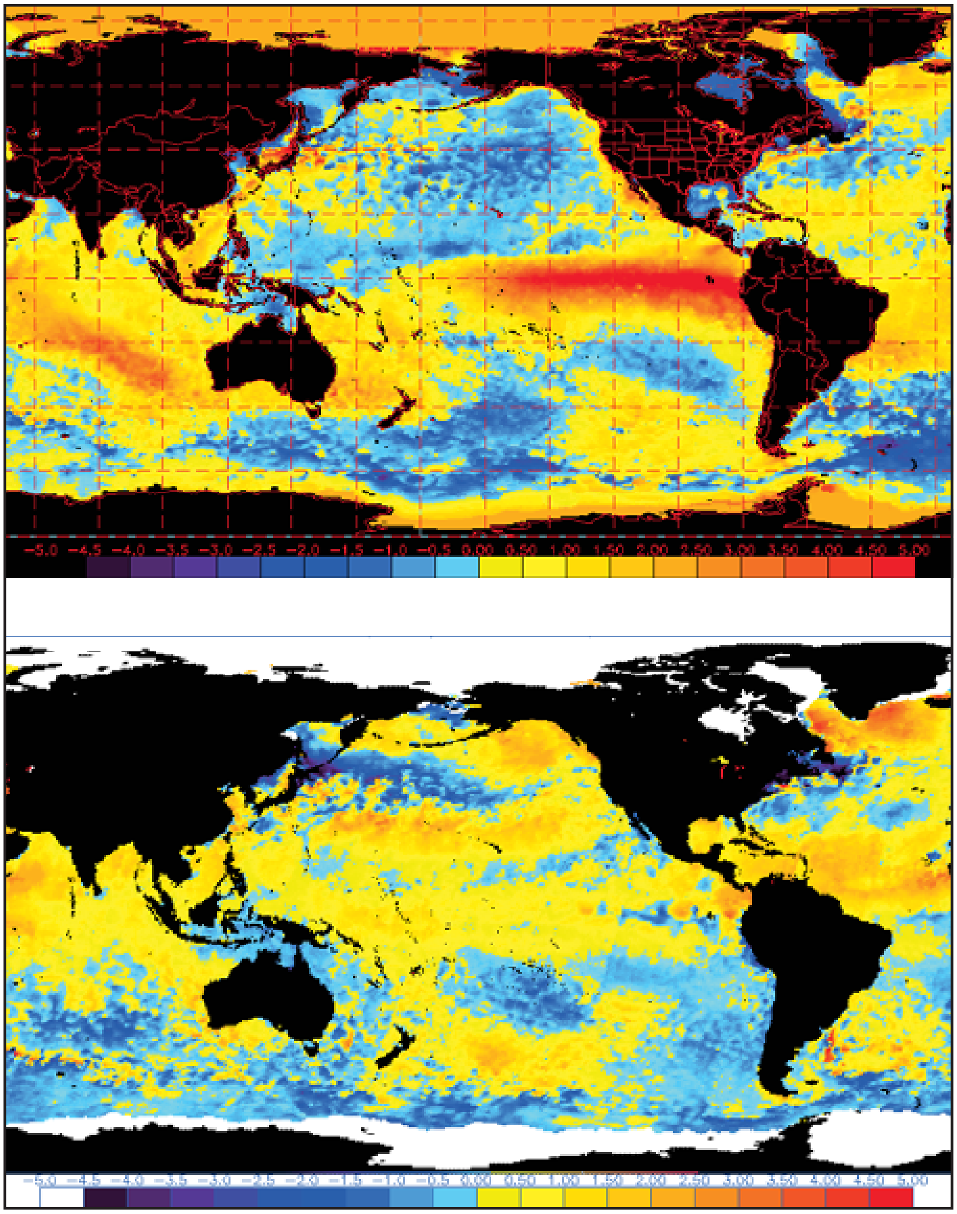

Figure 1. The higher than normal temperatures associated with El Niño off the western coast of South America are evident in this sea surface temperature anomaly image (top) from January 5, 1998. The image on the bottom shows the anomalies from May 31, 2005 when no El Niño is present. Credit: NOAA.

Coral reef bleaching

Coral reefs are sensitive ecosystems that support a vast array of animal and plant species. Coral reef bleaching can occur with the thermal stress associated with above average sea surface temperatures. Corals that might become damaged or die as a result of severe bleaching events can be located by tracking and analyzing sea surface temperature data.

Coral bleaching early warning products such as coral reef bleaching hotspots and tropical ocean coral bleaching indices are generated using the sea surface temperature anomalies. Degree heating weeks are also generated from the anomalies and indicate the amount of thermal stress that a coral reef has experienced over the last 12 weeks.

Ice cover

Sea ice forms in the higher latitudes of the oceans in the Arctic and Antarctic and fresh water ice forms over lakes and rivers in the continental US, notably in the Great Lakes, Chesapeake and Delaware Bay systems, and over important ports and transportation arteries along the East Coast. Studying sea and lake ice and its changes is important for scientists, as it is a factor in global change. As ocean and surface temperatures increase or decrease, the coverage of sea ice can change drastically over a short period of time.[3] This makes frequent observations important to many industries, including those that rely on shipping and maritime services, since the lack of information on the changes in sea ice or fresh water ice boundaries or the locations of icebergs on the open seas could lead to disastrous accidents.[1]

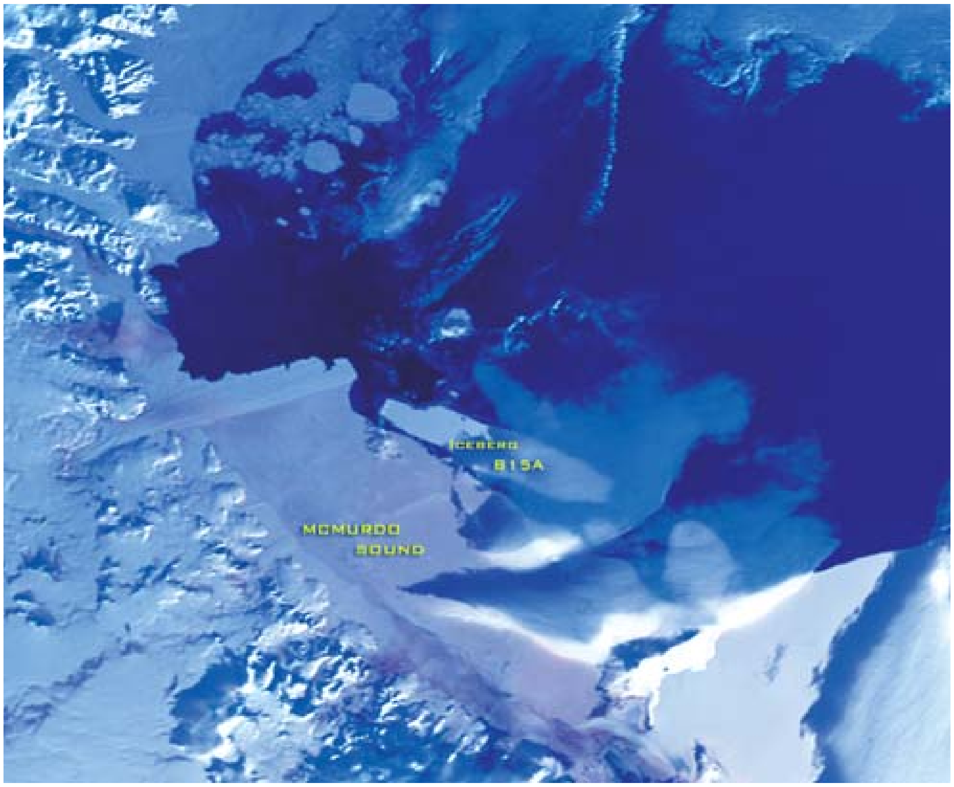

Figure 2. On December 12, 2004, a POES satellite observed Iceberg B15A in McMurdo Sound, Antarctica, which was reportedly blocking access to penguin colony feeding grounds and potentially blocking shipping access to scientific stations in the sound. Credit: NOAA.

Atmosphere products

Aerosol

Aerosols are particles in the atmosphere including dust, ash, and smoke. They are created by dust storms, volcanic eruptions, and smoke from fires and have an effect on aircraft, air quality, and health. The tracking of aerosols is useful for climate studies, the aviation sector, and atmospheric circulation research. Total column aerosol optical thickness products are generated from the POES satellites over the global oceans. The orbital observations are used to generate weekly and monthly products.

Atmospheric moisture and temperature soundings

When forecasting weather, meteorologists use numerical weather prediction models as a guide. These models often make use of atmospheric temperature and moisture profiles. Satellite observations provide meteorologists with a source of global information on the atmosphere. POES satellites provide approximately 300,000 retrievals of atmospheric temperature and 1,400,000 moisture retrievals on a daily basis.[4] Atmospheric temperature and moisture soundings from GOES and POES are provided for specific pressure levels throughout the atmosphere between 1,000 and 0.1 millibars.

Atmospheric imagery

Cloud imagery is used to detect weather systems and forecast their movement. Imagery is utilized to support the hazards missions of severe weather, heavy precipitation, smoke, and tropical cyclone and volcanic ash analyses. Atmospheric imagery includes visible, infrared, and water vapor images. Visible images are only available during daylight hours and represent the amount of sunlight being scattered back into space by the clouds, aerosols, atmospheric gases, and the Earth's surface. Thicker clouds have a higher reflectivity and appear brighter than thinner clouds on a visible image. Infrared satellite measurements are related to the brightness temperature, where warmer objects appear darker than colder objects. Clouds appear as white, while the warmer ground or ocean surface appears darker. Water vapor images help to determine the amount of moisture in the atmosphere. Darker colors indicate drier air, while brighter shades of white indicate progressively moister air.[5]

Visible and infrared images are generated daily from POES satellite data for the entire globe. Imagery from POES is particularly important to the northern latitudes, which are beyond the range of GOES coverage. The GOES satellites provide infrared, visible, and water vapor imagery in full disk coverages and for selected sectors. In addition, fog and low cloud imagery are available for the aviation community to help identify ceilings below 1,000 feet.

Earth radiation budget

Radiation budget products describe the distribution of the incoming and outgoing radiation at the top of the atmosphere and are used to study global climate change. Radiation is emitted by the Earth into space, and the outgoing long wave radiation (OLR) products provide this information for the climate community. Short wave absorbed solar radiation (SWAR) is a measure of how much solar radiation is absorbed and is calculated as the difference between the incoming and outgoing solar radiation at the top of the atmosphere. OLR and SWAR products are generated from POES data. Orbital radiation budget observations are used to create products on a variety of time scales, including daily analyses and monthly, seasonal, and annual means.

Ozone

A layer of ozone occurs naturally in the upper atmosphere and helps to keep damaging ultraviolet radiation from reaching the Earth's surface. Scientists use satellite measurements to identify changes in stratospheric ozone levels, particularly over the southern hemisphere's ozone hole. Using these satellite measurements, scientists study the long-term changes in the ozone levels to measure the extent of climate change.[2]

Precipitation

Rain rate products are generated in order for scientists and forecasters to determine the location and intensity of rainfall across

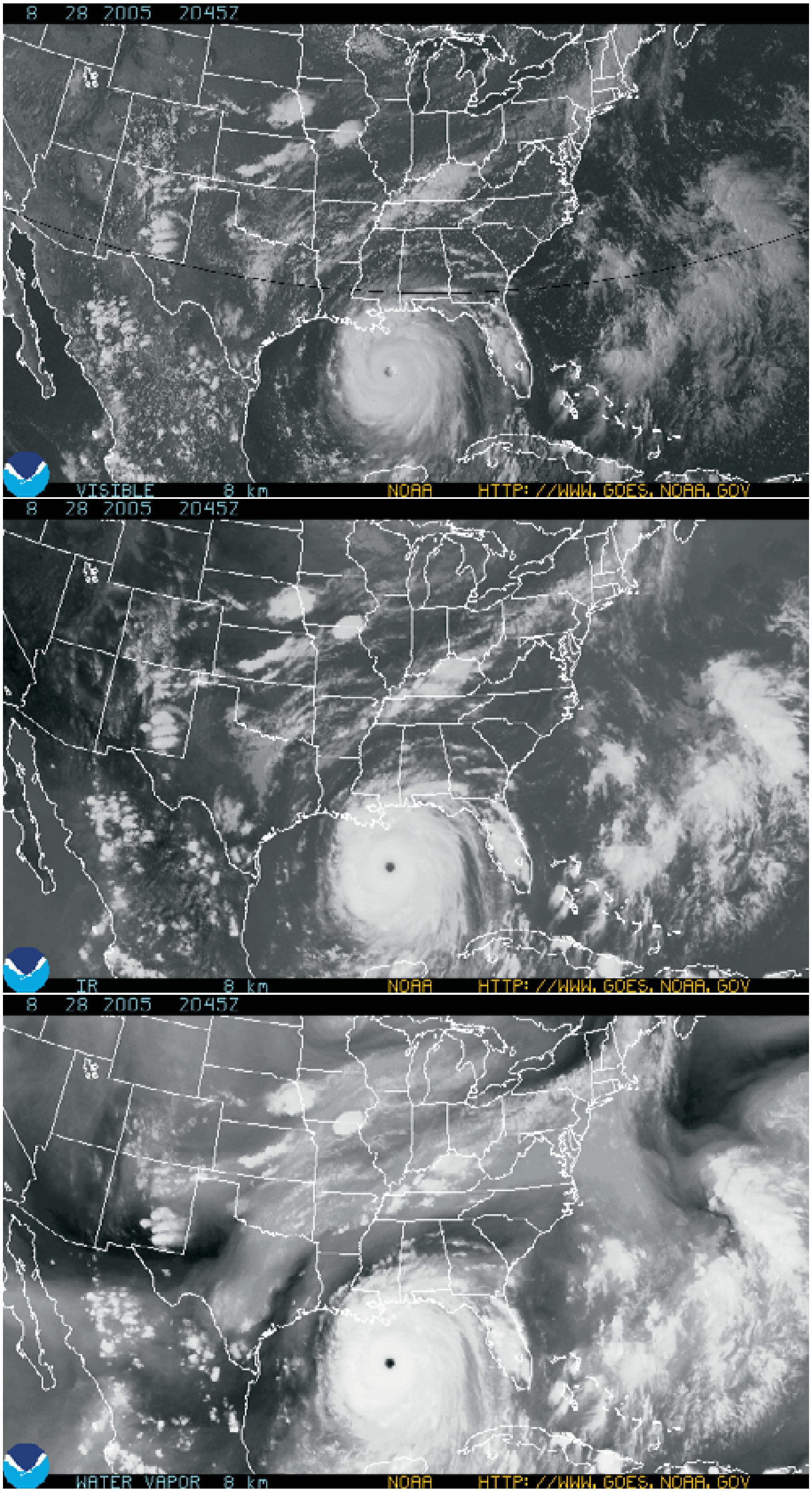

Figure 3. Visible (top), infrared (center), and water vapor (bottom) imagery shows Hurricane Katrina from the GOES East satellite. Credit: NOAA.

the globe. The products are also used to estimate rainfall potential for tropical systems. Rain rate estimates are used by forecasters as guidance for weather systems, such as tropical cyclones, having the potential for flooding prior to making landfall. Rain rates from each POES orbit are used to estimate short-term rainfall, while the GOES satellite data provide estimates of heavy precipitation amounts during convective storms, winter storms, and lake effect snow events.

Stability

Stability products provide information about the state of the atmosphere and are indicators of where convection may occur. They include products such as lifted index, convective available potential energy, maximum expected hail size, and the freezing level. Tracking stability parameters gives a user the opportunity to see dynamic changes within weather events. Stability products are generated from GOES satellites on an hourly basis. Their coverage includes the Continental US and adjacent ocean areas.

Volcanic ash

Volcanic ash poses a risk to people in the vicinity of an eruption as well as to aircraft thousands of miles away during major eruptions. The detection and tracking of volcanic ash plumes are particularly useful to the air traffic industry since volcanic ash can cause damage to jet engines which could result in engine shutdowns.[6] Volcanic ash plumes are monitored from both POES and GOES satellites. While the data from polar-orbiting satellites is important for detecting ash in the higher latitudes, their less frequent capture rate means a volcanic eruption might not be detected immediately, making them more useful for ongoing volcanic events.[7]

Atmospheric winds

Atmospheric wind products are used by numerical weather prediction modeling centers across the globe. Wind data are useful for forecasters in understanding the motion of weather systems and tropical storms. Infrared and water vapor imagery from GOES data are used to derive wind velocity estimates at multiple levels throughout the atmosphere, as well as indications of the vertical wind shear.

Land surface products

Fire analyses

Large fire events, such as forest fires, can be detected from environmental satellites. Analyses are used by forestry services and emergency managers. Some fire events attract the attention of the media, which occasionally uses satellite images to relay additional information on the fires to the public. Fire potential areas show where weather conditions exist that are conducive to wild fires.

Scientists use infrared POES data to detect the high temperatures of large fires and to track fire and smoke events. A trained analyst manually integrates data from various automated fire detection algorithms to create a quality-controlled display of fire locations and their smoke plumes. GOES data is used to detect significant fire and smoke events. In addition, it is used to detect and monitor fires and smoke, prescribed burns, deforestation, and other agricultural applications throughout the Western Hemisphere related to biomass burning.

Snow cover

By detecting changes in snow cover, it is possible to better understand cloud and storm patterns, the hydrologic cycle, surrounding surface and air temperatures, and areas that have the potential of having disastrous flooding.[8] Snow cover data and snow maps are critical inputs for numerical weather prediction models and can be used for climate studies. Snow water equivalent is beneficial for hydrological applications by providing information related to the melting of snow pack. Visible imagery from both GOES and POES are analyzed to detect the snow and ice fields and to create a daily snow and ice chart.

Vegetation

By measuring vegetation using satellite data, seasonal and climatic variations can be determined. Areas with the potential for drought conditions or wildfires can be detected by measuring the health and moisture content of the vegetation. Daily vegetation products are generated from POES and are used to create a weekly product. Because vegetation does not change significantly over a seven day period, this method helps to accumulate more vegetation data than can be obtained on a daily basis because areas obscured by clouds on one day will likely not be cloudy for the whole week.[2]

Looking ahead

The data from POES and GOES has become a significant tool for weather forecasting, climate studies, and understanding the Earth's environment. Plans are in place for future polar-orbiting and geostationary environmental satellite systems that will continue to provide data on the oceans, atmosphere, and land surface. Future instruments will provide more data as well as new types of data. New product areas will include ocean surface wind vectors for better understanding of tropical cyclones and for providing the maritime industry with additional data to supplement surface-based buoys; ocean color for monitoring red tides and other potentially dangerous biological events that can threaten human health; sea surface height and topography useful for estimating both hurricane intensity and small- to large-scale ocean circulations and for studying global change; and direct measurement of tropospheric winds for the improvement of weather forecasts. Higher resolution imagery and more accurate atmospheric moisture and temperature soundings from hyperspectral instruments will also be available. These new and improved products will ultimately have a positive impact on forecasting agencies, researchers, and the public. ❖

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Additional resources

- NESDIS Center for Satellite Applications and Research, http://www.orbit.nesdis.noaa.gov.
- NESDIS Office of Satellite Data Processing and Distribution, http://www.osdpd.noaa.gov.
- NESDIS Satellite Products Overview Display, http://satprod.osd.noaa.gov.

Stacy L. Bunin is a principal meteorologist at Mitretek, where she primarily supports the National Environmental Satellite, Data, and Information Service. She is currently determining requirements for operational product generation and distribution continuity during the next era of polar-orbiting weather satellites. She received her master's degree in space studies from the University of North Dakota. Contact her at sbunin@mitretek.org.

Joint Center for Satellite Data Assimilation

Kenneth F. Carey, John Le Marshall, and James G. Yoe

Assimilation of satellite data is a critical component to realizing the benefits of an improved weather, ocean, climate, and other environmental forecast system.

The data assimilation process combines data from several sources in order to provide the initial conditions that will produce the best possible model forecast. This process is a key element to exploiting ever-increasing volumes and varieties of satellite measurements to analyze and predict the state of the Earth's atmosphere and its land and sea surfaces using numerical models that incorporate increasingly realistic physical, chemical, and biological processes. Data assimilation is essential to realizing the benefits expected of an integrated global earth observation system and advanced modeling, such as increasing lead times for severe weather warnings and providing more accurate predictions and analyses to serve public and private sector decision makers. Accordingly, the Joint Center for Satellite Data Assimilation (JCSDA) was established by the National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) in 2001, with the Department of Defense (DoD) joining in 2002.

The goal of the JCSDA is to accelerate the use of observations from earth-orbiting satellites in operational environmental analysis and prediction models for the purpose of improving weather forecasts, improving seasonal to interannual climate forecasts, and increasing the accuracy of climate data sets. Advanced instruments of

Inside Track

- Satellite data assimilation is a necessary and critical component of a global earth observing system, and the Joint Center for Satellite Data Assimilation (JCSDA) is making strides towards integrating a five-fold increase in the volume of data available to the operational and research community.
- Three federal agencies—NASA, National Oceanic and Atmospheric Administration, and the Department of Defense—are engaged in and are jointly working data assimilation activities and are actively seeking to promote the work of the JCSDA.
- The JCSDA's mission is to accelerate the use of observations in operational numerical analyses and environmental analysis and prediction models—a high priority is to develop a community radiative transfer-model to improve data assimilation efficiency and forecast accuracy.
- Assimilation of clouds, precipitation and winds into environmental models are especially important given the fact that 70% of the earth is covered by water and satellite data is the only means of information.

the current and planned satellite missions increasingly provide large volumes of data related to atmospheric, oceanic, and land surface state. During this decade a five order of magnitude increase in the volume of data available for the operational and research weather, ocean and climate communities will be achieved (see Figure 1). These data will exhibit accuracies and spatial, spectral, and temporal resolutions never before attained. The JCSDA will ensure that the maximum benefit from the investment in space-based global observations is realized.

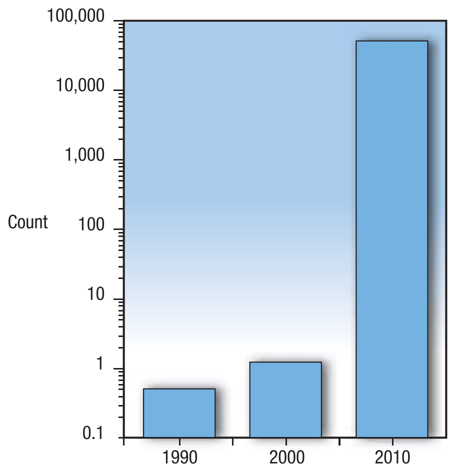

Figure 1a. Daily upper air observation count in millions as a function of time (1990–2010).

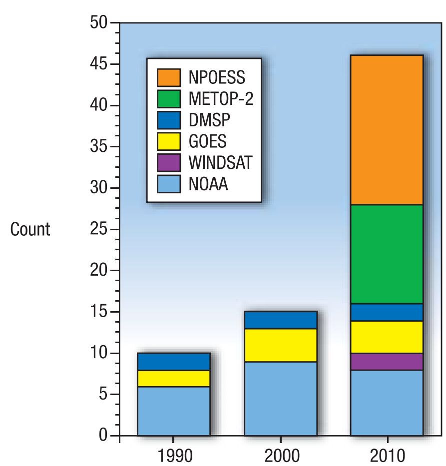

Figure 1b. Satellite instrument numbers by platform as a function of time (1990–2010).

Background

A useful metric of the impact of satellite data for improving operational numerical weather prediction (NWP) forecasts is the anomaly correlation (AC) between the observed and predicted deviations from the climatological average over an extended portion of the globe for a statistically significant duration. Neglecting seasonal variability, there has been a steady improvement in the AC coefficient, with a larger rate of improvement for the Southern Hemisphere. Improvements in the 1990s are due in large measure to the implementation of direct radiance assimilation and the availability of improved instruments such as the Advanced Microwave Sounding Unit (AMSU).

There remains room for improvement, in particular toward decreasing the frequency of larger than normal forecast errors, or "busts." Assimilation of satellite observations will make key contributions to that improvement. Furthermore, the improved global analyses based on the accelerated use of high spectral resolution observations will continue to allow models to expand useful prediction well into the 7 to 10 day range. As a result, there is a need for increasing the use of satellites, both in terms of introducing new and additional satellite data, and refining the assimilation methodologies. In coming years, new operational instruments with data at spatial, spectral, and temporal resolutions vastly exceeding those of earlier instruments will be launched. New challenges will emerge because of the sheer volumes of data they will provide and because of many scientific questions that need to be answered in order to make optimal use of these remotely sensed observations.

JCSDA mission, goals, and science priorities

The JCSDA's mission is to accelerate the use of observations, from both operational and research earth-orbiting satellites, in operational numerical analyses and weather, climate, and environmental analysis and prediction models.

Three specific goals support this mission. The first is to reduce from two years to one year the average time for operational implementation of new satellite technology. The second is to increase the use of current satellite data in NWP models, and the third is to assess the impacts of data from advanced satellite sensors on weather and climate predictions. The first goal will result in an increase of ~20% in the useful life of a typical satellite sensor. The third goal emphasizes greater uses of current satellite data because fundamental information from satellites associated with clouds and precipitation has not yet been optimally assimilated and the benefits of the current sensors to weather and climate predictions have not been maximized.

To achieve these goals, the JCSDA has *initially* set the *five scientific priorities* discussed below:

Science Priority I—Improve radiative transfer models

Atmospheric radiative transfer modeling and the community radiative transfer model. Satellite radiances are not components of atmospheric state vectors predicted by NWP models. For radiances to be assimilated by NWP models, a relationship between the model state vectors and the observed radiances is required. This is provided by forward radiative transfer models with the state vectors as input (see Figure 2). In addition, the Jacobian vectors (or the derivative of radiance relative to the state vectors) are also needed for satellite data assimilation systems. Radiative transfer modeling uses atmospheric transmittance as the key input. The transmittance varies with the atmospheric conditions and is often computed through the line-by-line (LBL) models. Although LBL models are accurate, they take considerable time to calculate transmittances for just a few atmospheres. To provide accurate transmittances in a timely fashion, the JCSDA uses fast approximations commonly known as fast forward models for specific channels. Current fast models are discussed in Kleespies et al., 2004.[1]

To utilize satellite measurements under all weather conditions for NWP, forward modeling capability needs to be enhanced to include both scattering and polarization processes. Cloud-affected satellite radiances have not generally been assimilated into operational forecasting models although the measurements contain considerable information pertinent to the atmospheric

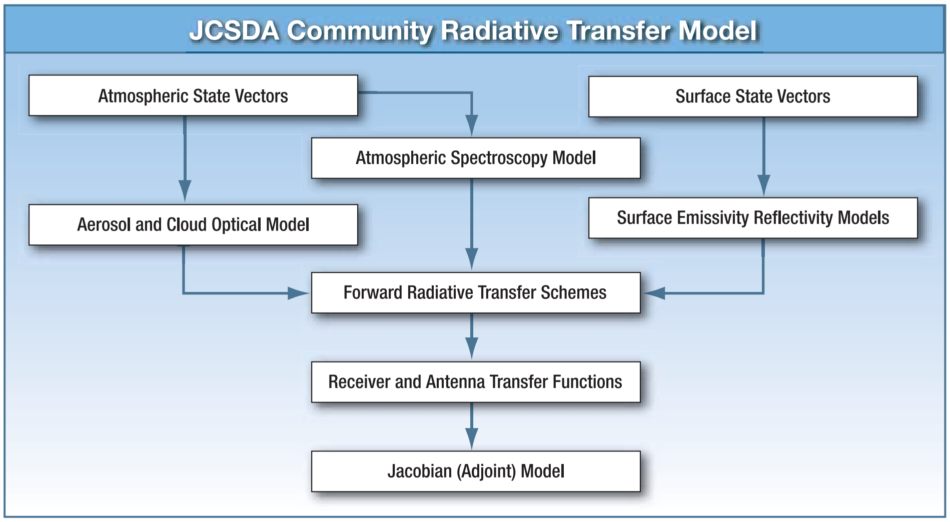

Figure 2. Components of the JCSDA community radiative transfer model.

hydrological cycle. In the next decade, many advanced infrared and microwave sensors will be deployed in space and their sensitivity to various atmospheric and surface parameters is significant. The usage of cloudy radiances in NWP models will ultimately enhance the impacts that have been demonstrated to date through clear radiance assimilation and will add to our knowledge of clouds, the surface, and the hydrological cycle.

Surface emissivity modeling. Satellite observations in and around window regions of absorption spectra are affected by surface emissivity. Without a suitable surface emissivity model, measurements from advanced sounders, for example, may not be effectively assimilated into NWP models. As a critical part of a radiative transfer model, surface emissivity modeling should incorporate the variability of both emissivity and reflectivity. The JCSDA is supporting theoretical and technology advances in quantifying the emissivity spectrum for various sensors covering the global environment.

Science Priority II—Prepare for advanced operational instruments

A key activity of the JCSDA is the development of the methodologies for assimilating data from the next generation of advanced satellite instruments. These instruments will be flying on NOAA, NASA, DoD, and international satellites. Numerous advanced sensors will provide environmental data at spatial, temporal, and spectral resolutions never before achieved. A key performance measure for the JCSDA will be a decrease in the time required to develop and transfer assimilation systems to NOAA, NASA, and the DoD for operational use, for each new instrument. The development process will have pre-launch and post-launch phases.

Science Priority III—Assimilating of observations of clouds and precipitation

Assimilation of precipitation. Satellite precipitation estimates have two key characteristics that render them desirable for assimilation. They have a wide area of coverage, especially over the data sparse oceans. They also provide a means for adjusting the vertical profile of latent heating in the atmosphere, a quantity that typically cannot be obtained using current in situ coverage. This adjustment is usually accomplished by inverting the convective parameterization scheme of the model and adjusting the vertical profiles of latent heating and, consequently, of temperature and moisture.[2,3] This can increase the consistency between the modeled and observed precipitation during a dynamic assimilation period. Adjustments can be made to vertical profiles of moisture for grid-scale precipitation.

Direct assimilation of radiances in cloudy and precipitation conditions. Radiance assimilation under cloudy and precipitating conditions may be improved by detailed information on the profiles of cloud microphysical variables that can be explicitly simulated by the NWP models. Cloud schemes based on Zhao and Carr, 1997,[4] and Ferrier et al., 2002,[5] have been implemented into NCEP global and regional (Eta) forecast models. These schemes run different physical models but predict water mixing ratios associated with various condensates within the model grids. In principle, these cloud schemes can resolve all cloud condensates only when the model resolution is increased to less than a few kilometers. At larger resolutions, forecast models must use the cumulus parameterization scheme to determine the clouds and precipitation associated with convective motion.

To estimate the quality of the model predicted cloud condensates, observational data sets must characterize the errors of the forecast model cloud water/ice content. Retrievals from satellite passive sensors may be used for assessments of model errors in the column-integrated water.[6] However, it remains difficult to characterize the errors in the profiles of cloud condensates predicted by forecasting models before the data from satellite active sensors such as Cloudsat[7] become available.

Science Priority IV—Assimilation of land surface observations from satellites

NWP models can use satellite-based observations to provide model lower boundary conditions, specification of surface characteristics and forcing in uncoupled model surface physics schemes. Lower boundary conditions for NWP models over land surfaces include properties of vegetation, soil, and snow/ice cover. Quantities such as green vegetation fraction, leaf area index, vegetation class, soil albedo, surface emissivity, and snow cover and snowpack parameters (snow water content, snow depth) can be estimated from satellite measurements. Because some of these characteristics change on time scales of hours to days, real-time estimates from satellite observations are required. Satellite estimates of components of the surface radiative fluxes and precipitation may be used to force uncoupled land data assimilation systems. Near real-time estimates of insulation, downward longwave and surface temperatures (the latter for surface physics validation, and later for assimilation into the surface model) are required.

Land surface states are also critical to the initialization of seasonal climate forecasts. Global retrievals of snow mass, snow cover, and soil moisture are available from various research satellite sensors. NASA's Global Modeling and Assimilation Office (GMAO) has developed a system to assimilate these data into the GMAO catchment land surface model using an Ensemble Kalman Filter and is in the early stages of incorporating the system into the GMAO coupled seasonal forecast system. An issue to be addressed is the observational error characterization and biases between different data sources and models.[8,9]

Science Priority V—Assimilation of satellite oceanic observations

Satellite-derived ocean observations/products are increasingly being used in environmental models. Wind vectors over oceans are retrieved directly from high resolution satellite sensors such as QuikSCAT and the DoD polar orbiting satellite constellation, and data is operationally assimilated into the global modeling systems. For QuikSCAT, NCEP has completed a study using the data at near half-degree resolution and has shown that forecasting skills are improved at this increased resolution. Further efforts will focus on utilizing the data in higher resolution models.

The JCSDA partnership

In April 2000, a small team of senior NASA and NOAA managers released a white paper[10] outlining plans to improve and increase the use of satellite data for NWP and climate applications. They recommended establishment of a JCSDA, since a partnership was thought to be best suited to address the growing needs for more accurate and improved weather and climate analyses and forecasts based on improved models and data assimilation techniques. The cooperative agreement allows the center partners to take advantage of the combined science and technology resources of NOAA, NASA, and Department of Defense (DoD) for data assimilation. The JCSDA provides a focal point for the development of common models and infrastructure among the partners. This shared approach to research and development activities reduces the chance of duplicated efforts within the government. NOAA has provided a centralized location for JCSDA administrative and information technology (IT) resources. Other JCSDA components will be located at various partner facilities.

Planning has been a collaborative effort by NASA, NOAA, and DoD, defining a process that ensures that teamwork is a basic attribute of the JCSDA. Initial efforts have focused on defining a life-cycle approach to data assimilation projects. Several critical elements have been defined: instrument definition, in-flight performance characterization, algorithms development, testing of radiative forward transfer models for data assimilation, testing the impact of synthetic data, operational integration, and finally assessment of the data's impact on analyses and forecasts.

Initial efforts have focused on defining a life-cycle approach to data assimilation projects.

A scientific review process by the JCSDA executives and the Science Steering Committee provides feedback on each scientific project and determines whether new systems are ready for implementation in operations. Then a transition-to-operations plan is created to ensure that new systems developed at the JCSDA are transitioned as efficiently as possible. JCSDA scientists are available to participate in the implementation process as needed.

The JCSDA activities may be divided into internal directed research, development, and infrastructure activities and external proposal-driven science. Internal activity focuses on the development and maintenance of science for the previously described community radiative transfer model, and infrastructure for performing assimilation experiments with real and simulated observations from new and future instruments. External scientific projects provide an important mechanism used to accelerate the transition of research and technological advances in satellite data assimilation by planned incorporation of new code into the NASA/NOAA/DoD operational data assimilation systems and by performance of preliminary testing with these systems. JCSDA projects in the past few years have solidified NOAA, NASA, and DoD collaborations on several missions. To facilitate and enhance further collaborations in areas deemed potentially important for improving climate and weather prediction, Mitretek has been working with the JCSDA partners to identify and document projects being undertaken by each of the JCSDA partners which, if integrated together, will contribute to the JCSDA "enterprise." Each project has been validated by the JCSDA staff, and budget and personnel projections have been linked to each of the projects to ensure that the maximum value is being gained from each project. In addition, each project will be validated against the aforementioned JCSDA science priorities to ensure they are meeting an agreed-upon goal or priority of the JCSDA.

The future

A primary goal of the JCSDA in the next few years will be to establish a common data assimilation infrastructure for assessing new satellite data and optimizing the utilization of these data in operational models. An important step is to make parallel versions of the NOAA, NASA, and DoD global/regional data assimilation systems accessible to the community on JCSDA computer systems. This will include real-time communications to JCSDA computers and real-time databases and observation handling algorithms for continued assessment of new instruments.

A most important activity for the center is planning, related to the form of the next generation assimilation system to be used by the partners. Strategic planning activity is already underway detailing the optimal form of the infrastructure needed by the next generation of modeling and assimilation system. Planning involves the use of the four-dimensional variational analysis and ensemble Kalman filter approaches.❖

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Kenneth F. Carey is a lead technical engineer at Mitretek. He has over 22 years experience in operational research/analysis, meteorology, network engineering, and training, working with DoD and NOAA clients. He received his master's degree in meteorology with a minor in oceanography from North Carolina State University. Contact him at kcarey@mitretek.org.

John Le Marshall is director of the Joint Center for Satellite Data Assimilation. He is noted for his investigation into new physically based sounding systems developed for use in vertical sounding instruments in operational numerical weather prediction, and high spatial and temporal resolution cloud and water vapor drift winds used in operational tropical cyclone track and intensity forecasting. He serves as an adjunct professor in mathematics at the University of New South Wales and in physics at La Trobe University. John earned his doctorate in physics from Monash University in Australia.

James Yoe is the deputy director of the Joint Center for Satellite Data Assimilation. His experience includes post-doctoral research at the Max-Planck-Institute for Aeronomy and serving as a NOAA/NESDIS physical scientist for active remote sensors research, specializing in Doppler wind lidar and meteorological sounding using GPS. He received his doctorate in physics from Clemson University.

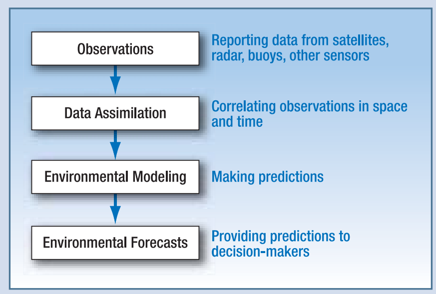
Assimilating Observations to Improve Global Weather Forecasts

Observations. An accurate weather forecast requires precise knowledge of current atmospheric conditions provided by thousands of global observations by a wide range of sensors (e.g., geostationary and polar-orbiting satellites, aircraft, ships, buoys, radiosondes and land stations) reporting a disparate set of atmospheric, oceanic, and land-based parameters (e.g., temperature, wind speed and direction, and humidity). The data assimilation process seeks to produce better environmental forecasts by integrating and time-correlating the different data types.

Assimilation. Data assimilation typically proceeds sequentially in time using a computer-based, numerical model that uses new observations to modify the model state to be as consistent as possible with previous observations. Observations are correlated with model parameters in space and time using a process known as variational analysis. Operational experience with weather prediction shows that typically there is more information in the model state from previous observations than from the most recently received observations. The assimilation must preserve previous information. To accomplish the assimilation, the model must be of sufficiently high resolution, with physically realistic detail, to represent all of the observations. Currently, researchers are investigating non-sequential data assimilation methods, especially four-dimensional (horizontal, vertical, azimuth, and time) assimilation.

Models and Forecasts. Global weather forecast models, at major centers such as the European Centre for Medium Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction, use the resultant assimilated observations to initialize their current states of the environment. Global, regional, and local observational data is also used to "ground-truth" the short-range forecasts to ensure consistency with statistical and climatological factors.

Benefits. NASA scientists demonstrated potential benefits by assimilating experimental data from the Atmospheric Infrared Sounder (AIRS) instrument on NASA's Aqua satellite, which monitors the world's oceans around the clock, to improve forecasts. The scientists improved the accuracy range of experimental six-day Northern Hemisphere weather forecasts by up to six hours, a four percent increase, by incorporating AIRS three-dimensional data of atmospheric temperatures, water vapor, and trace gases into numerical weather prediction models. The ECMWF began incorporating data from AIRS into their operational forecasts in October 2003, and reported an improvement in forecast accuracy of eight hours in Southern Hemisphere five-day forecasts.



Improved Observing for Surface Transportation

Andrew D. Stern and Lynette C. Goodwin

Improved weather information products for road travel are on the horizon through the integration of existing weather assets and the novel application of other technologies.

Beginning in the 1970s, state Departments of Transportation (DOTs) independently began installing roadside Environmental Sensor Stations (ESS)—mainly to support winter maintenance operations such as plowing and deicing of roads. While the sensors provided valuable weather and road information for local maintenance managers, there was no concerted effort to create uniformity in many aspects of ESS deployment and operations. Each vendor would provide different suites of sensors, with different access software and in many cases proprietary data formats that could not be integrated with other data sets. In general, there were no sophisticated quality control, archiving or metadata activities, and no standards to govern the placement and meteorological relevance of the platforms. By the late twentieth century, the nation's ESS assets had become a patchwork of non-communicating, non-integrated networks, whose value was only realized by some of the staff at given state DOTs. This lack of networking was one reason why surface transportation weather had received little attention from the greater meteorological community.

The Federal Highway Administration (FHWA), through its Road Weather Management Program, recognized this less than optimal use of resources and the lack of communication and understanding between the surface transportation and weather communities. To address this deficiency, the FHWA began the Surface Transportation Weather Decision Support Requirements (STWDSR) project in 1999.[1] The STWDSR project looked to state DOT maintenance personnel to develop a uniform set of requirements that would satisfy the needs of the winter maintenance community for environmental and road observations. By 2001, with the success of STWDSR and the visibility brought by the National Oceanic and Atmospheric Administration's (NOAAs) Office of the

Inside Track

- The nation's publicly funded road weather observing stations are not integrated, conform to no standards and have a limited benefit to the greater community.
- The Clarus Initiative will collect, quality control and make available the nation's assets of surface transportation weather and road condition information.
- Currently deployed technologies such as traffic cameras may be used to estimate driver level visibility on the nation's roads.
- New and envisioned technologies such as passenger vehicle-based weather observations and new types of radars may help improve road weather forecasting.

Federal Coordinator for Meteorology's (OFCMs) Weather Information for Surface Transportation (WIST) symposia and "National Needs Assessment Report,"[2] the FHWA was ready to implement a project to show that state ESS could be used by the weather community to create better products and services for maintenance operations. The Maintenance Decision Support System (MDSS) prototype[3] utilized ESS data as input into advanced numerical weather prediction models. Weather forecast information was then integrated with computer-coded winter maintenance rules of practice, chemical concentration algorithms and road temperature models to generate optimized treatment recommendations for specific routes. The objectives of the MDSS project were to create a more efficient (both in terms of equipment and labor), environmentally friendly and safer road system during times when winter precipitation was a threat. The MDSS had successful operational field tests in central Iowa during the winters of 2002–2003 and 2003–2004.[4] Additional field tests and targeted research are ongoing in central Colorado.

In addition to OFCM's efforts during the early 2000s to capture surface transportation weather requirements, there were several other initiatives that would eventually reshape FHWA's approach to road weather management. In 2002, a group of states, in a pooled-fund effort called Aurora, studied ESS data integration and best practices as to how these observations could be best utilized by other transportation agencies and the weather community. The Aurora report, "RWIS Data Integration and Sharing Guidelines,"[5] provided a conceptual design for information exchange among various states and different types of Road Weather Information Systems (RWIS). ESS are field components of RWIS.

In late 2003, the American Meteorological Society (AMS) held a forum to define a policy for surface transportation weather in the United States. The AMS Policy Forum report was released during the fall of 2004.[6] Finally, the National Academy of Sciences, Board on Atmospheric Sciences and Climate (BASC) provided a bridge between meteorology and surface transportation with their report "Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services."[7] A key recommendation of the BASC report highlighted the need for a nationwide resource to better utilize surface transportation weather observations to provide both a more concise picture of current conditions on the surface transportation system and to energize efforts to improve forecasting for the roadway environment. All of these efforts culminated in the creation of the Clarus Initiative.

The Clarus Initiative

Soon after the BASC report was released, FHWA's Office of Transportation Operations and Intelligent Transportation Systems (ITS) Joint Program Office (JPO) created the concept for a nationwide surface transportation weather observing and forecasting system. Rather than imposing another difficult project acronym on the community, the term "Clarus" (which means "Clear" in Latin) was selected as the official name for the initiative.

Clarus can be used to create enhanced decision making tools for DOTs and travelers.

In its purest form, Clarus is envisioned to be a 'system of systems;' the regional or nationwide collection of all state funded surface transportation-related observations (atmospheric, road surface and hydrologic) into a single or distributed database. It is an exercise in requirements gathering, systems engineering, communications, and database design across a spectrum ranging from federal and state agencies to academia and the private sector weather service providers. The transportation-related services supported by Clarus are captured in seven different scenarios in the Concept of Operations.[8] All Clarus-related documents can be accessed at the Clarus Initiative Web site (www.clarusinitiative.org).

The Clarus Concept of Operations includes a representative set of functional scenarios to help define the needs for the Clarus system design. Each scenario consists of a detailed description, use case diagrams and sequence diagrams. The seven scenarios are:

- Roadway maintenance and construction operations
- Traffic operations
- Traveler information
- Transit management
- Emergency management and public safety
- Rail operations management
- Commercial vehicle operations

To the information user, Clarus will provide a "one stop" Internet location (portal) where all surface transportation-related weather observations can be accessed in a timely manner, with or without quality control flags and metadata.[8] The availability of these data through the Clarus portal has the potential to significantly improve traveler information available through 511, add detail to Highway Advisory Radio broadcasts and Variable Message Signs alerts and provide new clarity to transportation agency Web sites. Information from Clarus can be used to create enhanced decision making tools for DOTs and travelers, as well as spawn new technologies that can provide road conditions and forecasts remotely via devices such as in-vehicle displays and handheld personal digital assistants (PDAs) (Figure 1). However, the Clarus concept does not stop with the collection of data from the nation's 2,500+ ESS operated by state and local transportation agencies. The database will also store a variety of derived (from current technologies) and new observation-related data sets from all modes of surface transportation (Figure 2). The result is envisioned to be new data sets and products for transportation agencies, weather service providers and researchers.

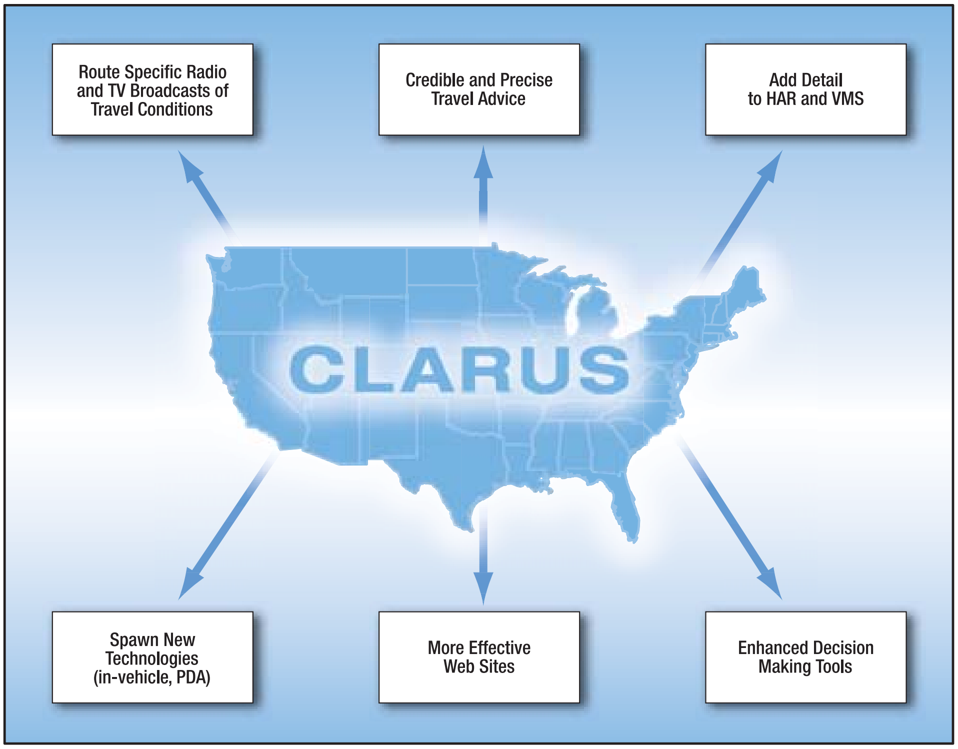


Figure 1. It is envisioned that the Clarus Initiative will benefit a broad spectrum of surface transportation information users. Data from the Clarus database could be used to create more detailed route forecasts and add more specific condition information to dissemination.

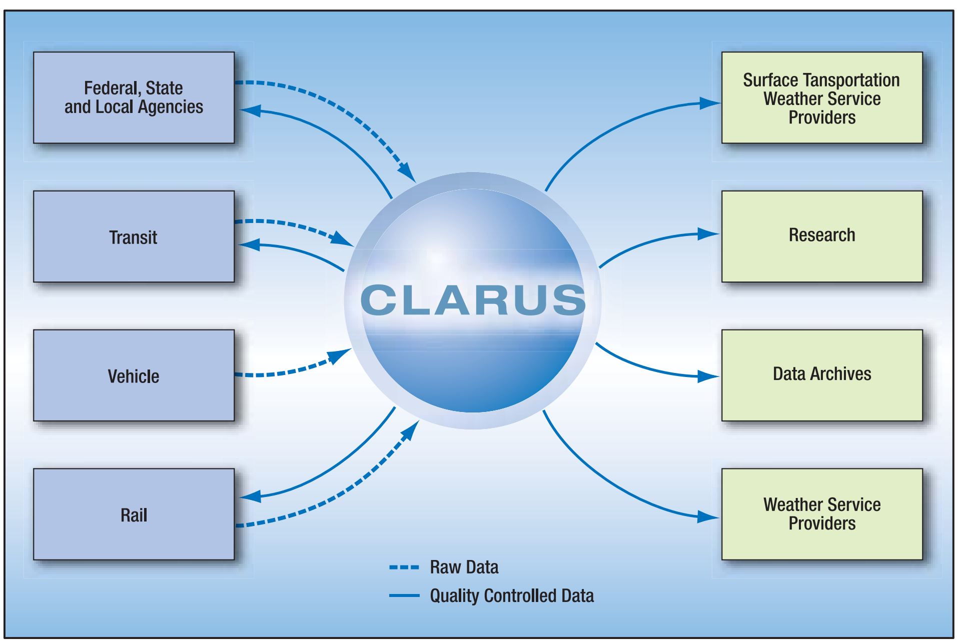


Figure 2. Conceptual data flow for Clarus.[8] Raw observations will enter the Clarus system from the multi-modal entities shown in the blue boxes. Solid arrows leaving the Clarus system back to the blue boxes denote transportation operations agencies that receive quality controlled data. The green boxes indicate non-transportation agency users of Clarus data. The Clarus database will be designed so that new observations and technologies from the multi-modal entities will be easily integrated into the system.

The Clarus Initiative has an aggressive timetable (Figure 3) for system design, demonstration and deployment. The Concept of Operations was completed in May 2005. The high level and detailed system requirements will be completed during the fall of 2005. The system design and proof-of-concept demonstration will be completed by the end of 2006. Following the proof-of-concept demonstration, a formal multi-state regional demonstration and evaluation will occur. This will lead to refinement of the system design and a second regional demonstration.

At the completion of the Clarus Initiative in 2009, the FHWA will have a comprehensive and tested design. The final step is to identify hosts for Clarus as a sustainable nationwide deployment. Success will be measured by the level of "buy-in" by those organizations that see value in the potential solutions that the Clarus Initiative could bring. These users include:

State and local agencies. The state and local road and transit agencies must see the value in participating in the Clarus Initiative by making their ESS data available to collection servers, by providing metadata and maintenance information, and in some cases increasing data polling frequencies.

Private sector service providers. The private sector weather industry and service providers must see the value in having a one-stop location to obtain quality controlled surface transportation-related observations. Clarus data sets can be used as input to weather or road condition models, real-time collectives or as input into new value-added forecast and decision support products. Additionally, streamlined accessibility enables greater flexibility in value-added products since a common framework for interface design will be specified.

A deployment benefactor. Some entity such as a collective of organizations or another federal agency (e.g., NOAA) must see the value in integrating and maintaining the Clarus system so that there is a viable path to sustainable operations. Depending on the origin of the benefactor, different business models can be used for providing data, tools and decision support capabilities.

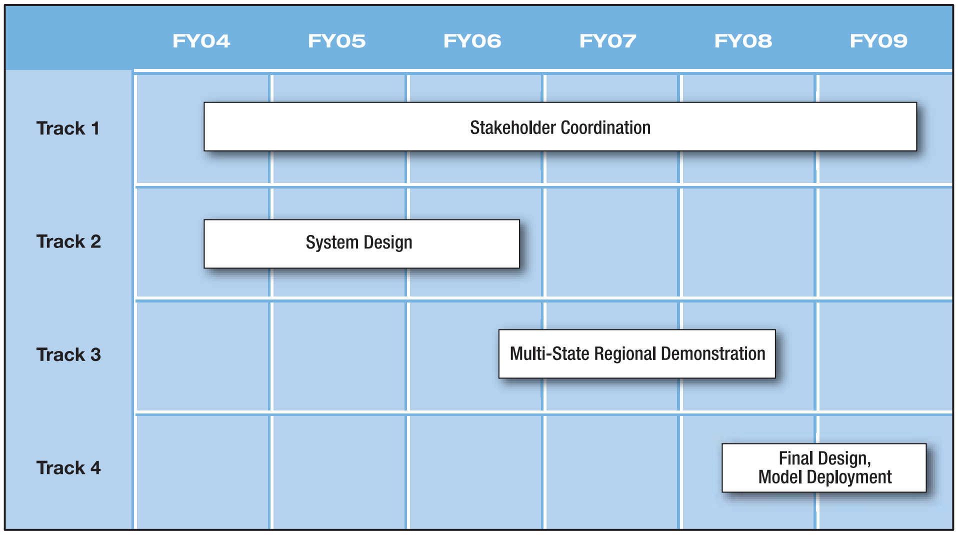


Figure 3. The Clarus Initiative roadmap consists of stakeholder coordination and participation through the Initiative Coordinating Committee (ICC) in Track 1.[8] The remaining tracks provide a high level view of a rigorous systems engineering process to create the Clarus system. Track 2 includes the creation of a Concept of Operations, preliminary system design and a proof-of-concept demonstration. Track 3 includes a regional demonstration, evaluation and update to the system design. Track 4 provides for a model deployment and final series of evaluations followed by updates to the system design. Upon completion of Track 4, there will be a fully tested design ready for nationwide deployment.

Clarus research

Clarus will be a dynamic initiative, growing and changing with the needs of its customers and with evolving technologies during its six year project time span. Tied with the development of the Clarus system design are three specific research activities to explore new and existing technologies that could provide better insight into the environment of the road and the lower atmosphere. These activities include:

- Inclusion of data from environmental sensors on vehicles,
- Examining the use of Closed Circuit Television (CCTV) cameras for driver level visibility estimation, and
- Testing the feasibility of using low cost, low power radar to enhance observing in the lower atmosphere.

Vehicle infrastructure integration initiative research

Vehicle Infrastructure Integration (VII)[9] is an independent initiative funded and directed by the ITS JPO, and directly linked to Clarus through its planned database and quality control capabilities. The VII Initiative, whose participants include the US DOT, state DOTs, local government agencies, and a consortium of automobile manufacturers, has the potential to change the way that drivers receive information from their vehicles and how their vehicles interact with other vehicles in nearby proximity.

The VII Initiative will examine the feasibility of creating an "enabling communications infrastructure" to support vehicle-to-vehicle and vehicle-to-infrastructure communications across the nation.[10] The primary goal of VII is to provide a safer driving environment (e.g., reducing the number of crashes, injuries and fatalities). However, the dozens of onboard sensors represent a significant opportunity to sense the weather and road conditions along the nation's surface transportation system.

The automobile manufacturers participating in the VII Initiative are working toward a common data formatting and communications standard. Early in the next decade, many new vehicles may be equipped with a short range radio transceiver. With a typical range of a half mile (0.8 kilometers), vehicles will be able to transmit data from dozens of onboard sensors to the roadside infrastructure. It is envisioned that in an initial implementation, there may be 100,000 roadside transceivers at signalized intersections and at strategic intervals along the nation's freeways, with a mature full implementation of over 400,000. This flow of information could literally "light up" the nation's transportation arteries with millions of data messages (including road weather information) and change the way meteorologists view weather observing and forecasting in the lower atmosphere and at the surface.

The draft VII Functional Architecture and Requirements document[11] describes some of the many data items that are envisioned to be available for transmission. Table 1 provides a subset of those items that either directly or indirectly measure environmental (atmosphere and road surface) conditions and their potential uses.

Some of the parameters listed in Table 1 include values that are directly measured (such as external air temperature or the rain sensor). For other elements, one might

Table 1. VII Environmentally-related data elements.

Onboard Vehicle Sensor	Derived Information
GPS vehicle location	Location, driving direction and traffic data
Wiper system state	Precipitation detection
Headlights	Lighting conditions
Exterior air temperature	Estimated ambient air temperature
Vehicle speed	Traffic data/implied road conditions
Rain sensor	Precipitation detection
Light sensor	Lighting conditions
Fog lamp usage	Fog or visibility information
Traction control state	Road traction state/mobility
Anti-lock brake system state	Road traction state/mobility

be able to infer certain conditions (such as road icing with the use of the traction control system or the anti-lock braking system). The National Center for Atmospheric Research (NCAR) will evaluate and validate the use of directly measured and derived elements and their potential value for road weather observing and forecasting.

CCTV research

Most state and local DOTs have deployed CCTV cameras at intersections and along freeways to aid in traffic management operations. These cameras provide images of not only traffic but also convey the condition of the roadway and even some weather information. The Massachusetts Institute of Technology (MIT) Lincoln Laboratory will study the feasibility of using these images to estimate driver level visibility and create a set of portable algorithms that could be customized for any location in the country. If successful, this research could use existing technologies and infrastructure to provide a new and valuable observational element which would eventually reside within the Clarus system database.

Radar research

A consortium of universities, public and private sector organizations known as the Collaborative Adaptive Sensing of the Atmosphere (CASA)[12] are performing research into deploying low cost, low power radars as "gap-fillers" for the network of weather surveillance radars operated by the National Weather Service (NWS) and the Federal Aviation Administration (FAA). A study performed by the University of Oklahoma indicated that 72% of the lower atmosphere (below 0.6 miles or 1 km) is not sampled by NWS/FAA radars due to their spacing (18.7 miles versus 62.2 miles or 30 km versus 100 km) and the effects of Earth curvature.[13]

The surface transportation weather community would benefit if this research indicated that these new surveillance radars would help atmospheric scientists better understand the complex weather and wind flow conditions close to the ground. Results from this research could be used directly in the routine analysis of the atmosphere, in the grid initialization of weather models or even spur the next generation of new boundary layer (land surface) models. It is hoped that this next generation of models will have more focus on creating improved forecasts for surface transportation.

The Clarus future

The FHWA Road Weather Management Program and ITS JPO are funding and directing the Clarus Initiative during a six year period from 2004 to 2009. It is envisioned that Clarus will leverage investments in ESS to collect, quality control, archive, and disseminate surface transportation weather observations. In addition, Clarus will fund three research threads that could add millions of new observed and derived weather elements through the use of existing and emerging technologies. Clarus will have the ability to change surface transportation weather observing and forecasting, foster the development of new decision support tools, and eventually create a more efficient and safe surface transportation system. ❖

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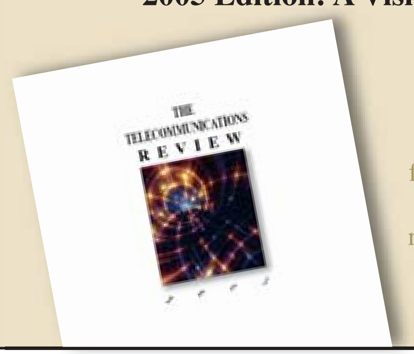
Andrew D. Stern is a senior principal meteorologist and software engineer at Mitretek. He has nearly 20 years experience as an operational weather forecaster. He is presently the consulting meteorologist for the Federal Highway Administration's Road Weather Management Program and works on the National Weather Service's Doppler Radar Product Improvement Program. He received his bachelor's degree in meteorology from the Florida State University and his master's degree in computer science from the George Washington University. Contact him at astern@mitretek.org.

Lynette C. Goodwin is a lead transportation engineer at Mitretek. She has 10 years experience working for consulting firms serving local, state and federal departments of transportation and currently supports the Federal Highway Administration Road Weather Management Program to promote tools and management strategies to mitigate the impact of weather on road safety, traffic flow and agency productivity. She received her bachelor's degree in civil engineering from Howard University and her master's degree in engineering management from George Washington University. Contact her at lynette.goodwin@mitretek.org.



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Systems Engineering for IOOS

Fred C. Klein, Thomas B. Passin, and Robert Vorthman Jr.

The Integrated Ocean Observing System will integrate US ocean observing systems. This loose federation of systems will present significant development challenges.

In the last several decades, the amount and variety of observations of marine environmental data has increased dramatically. From surface buoys and submarine networks to measurements made by many types of artificial satellites, a flood of data is gathered each day. Far more data will be generated by new systems now being planned and implemented. Some of these observation systems are operated by federal agencies, including the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and the Department of Defense (DoD). Others are operated by a variety of commercial and research endeavors. Figure 1 depicts some kinds of marine observations systems and communcations channels they may use.

Observations are the raw material for a large number of marine products, research programs, and other activities supporting global and coastal ocean initiatives. The product types include weather forecasts, climate models and prediction, tsunami warning, hurricane and typhoon forecasting, tracking, warning, and a host of ocean stewardship activities. These activities and programs are spread across a wide range of federal and non-federal agencies, associations, companies, and other kinds of groupings. Many activities, for example hurricane tracking and coastal zone management, are directly tied to important national goals, while others are linked more indirectly. Still others support various commercial interests.

One important characteristic of these activities is that most of them require data from many sources and many locations. Over time, researchers continually devise ways to compute marine parameters and behavior in new ways, which requires making use of new combinations of existing data, and often making new kinds of observations. A great amount of time and effort goes into the processes of locating suitable data (whether by type, source,

Inside Track

- Observations of marine environmental data are extremely important to the US and to the world.
- Current systems that observe ocean data are not integrated into a coordinated overall system.
- IOOS, the US Integrated Ocean Observing System, will coordinate these systems and their data, and allow them to interoperate as an integrated whole.
- There is a diverse range of federal, state, local, and non-government organizations to integrate. With no central authority over them all, IOOS will be a federated system of systems rather than a tightly-knit, centrally commanded system.

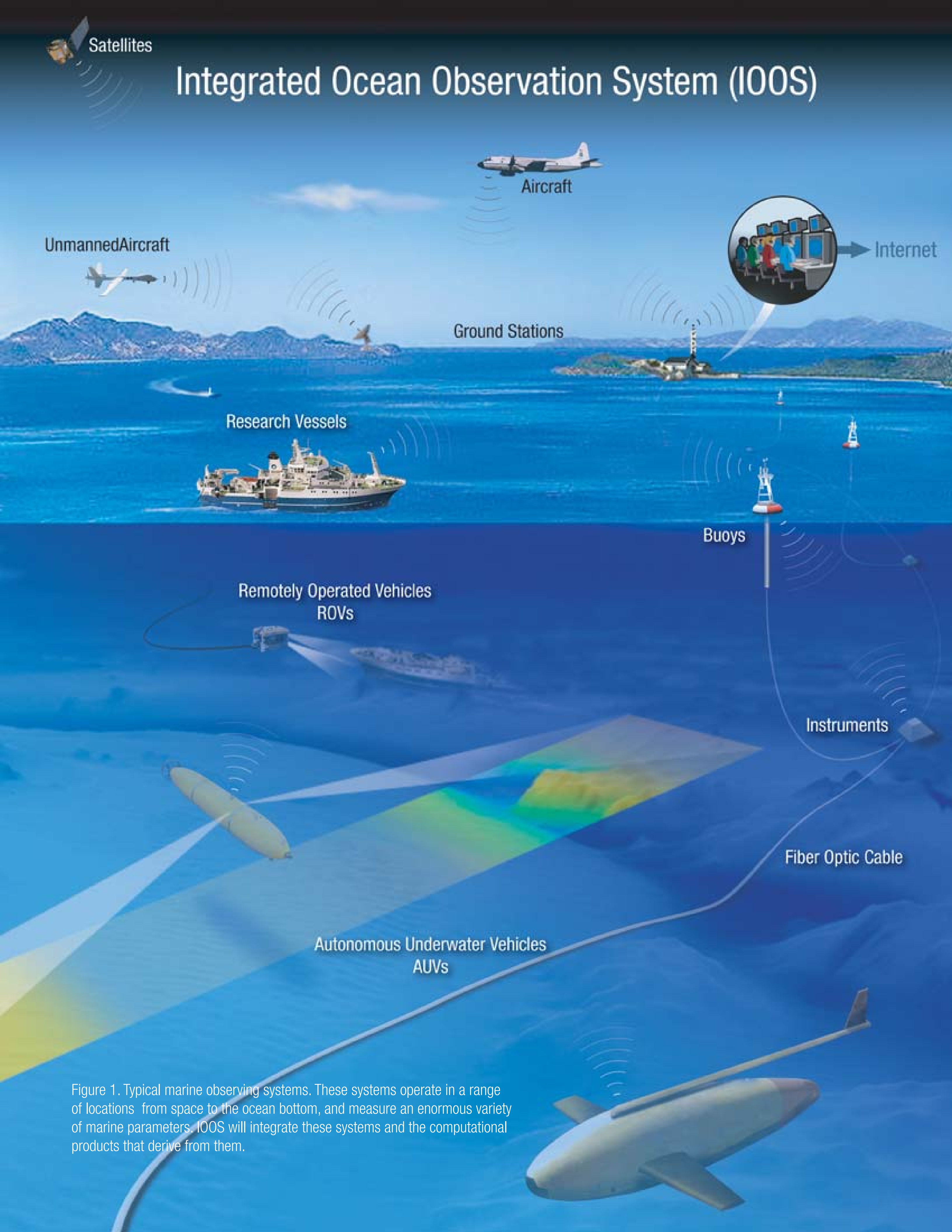

Figure 1. Typical marine observing systems. These systems operate in a range of locations from space to the ocean bottom, and measure an enormous variety of marine parameters. IOOS will integrate these systems and the computational products that derive from them.

geographic coverage, or time period), accessing it, and implementing software to receive and decode it correctly.

Some of these disparate observational, computational, and distribution activities are conducted with a degree of coordination; many are not. US activities are coordinated to a limited degree with international work. There is no central US office or activity that controls, or even tracks, all oceans-related observations, products, models, and the like. In brief, US and international ocean-related activity occurs in relatively autonomous groups that have some ability to communicate and work with each other in a pair wise fashion, on a case by case basis. Current planning is working towards changing this situation through integration and coordination.

National ocean policy

In the late 1990s, the US government, including the Congress, became aware that national goals would be better served, and national resources used more effectively, if the disparate marine observing systems were better coordinated. A joint federal/non-federal task team conducted an initial study documenting the way toward a US plan for an integrated, sustained ocean observing system for submission to Congress in February 1999. The Oceans Act of 2000 formally recognized the importance of the oceans, coasts and Great Lakes to the US and established the US Commission on Ocean Policy. The Commission completed its legislative mandate in September 2004 by publishing "An Ocean Blueprint for the 21st Century." This report called for an "Integrated Ocean Observing System"—an IOOS.

The Ocean Blueprint articulated seven societal goals, which the existence of an effective IOOS would support. The goals are to:

- Improve predictions of climate change and variability (weather) and their effects on coastal communities and the nation;
- Improve the safety and efficiency of marine operations;
- More effectively mitigate the effects of natural hazards;
- Improve national and homeland security;
- Reduce public health risks;
- More effectively protect and restore healthy coastal marine ecosystems; and
- Enable the sustained use of marine resources.

The President's US Ocean Action Plan in December 2004 responds to the Commission's Ocean Blueprint by establishing through an Executive Order a Cabinet-level "Committee on Ocean Policy." The Ocean Action Plan calls for action to integrate US Ocean Observing Efforts into the Global Earth Observing System of Systems (GEOSS) and directs the US Integrated Ocean Observing System to be a major US contribution to the international Global Ocean Observing System (GOOS), which is a substantial component of the intergovernmental GEOSS.

Federal partnerships and agreements

Currently, 10 federal agencies have signed a Memorandum of Agreement to establish an interagency organization called Ocean.US, the National Office for Integrated and Sustained Ocean Observations, under the authority of the National Oceanographic Partnership Program (NOPP). Ocean.US is charged with developing a national capability for integrating and sustaining ocean observations and predictions. At the time of writing, Ocean.US is neither chartered nor organized as a program office. It seems likely that Ocean.US will, in the future, become the IOOS program office.

In November 2004, the US Army Corps of Engineers and NOAA announced a partnership to advance the availability of the corps and NOAA geographic information systems, and associated technology and information, to the corps' districts and state coastal managers. This partnership will foster participation in IOOS, and use of its data, by all interested parties, as part of the president's US Ocean Action Plan. Additional ocean observation agreements with regional marine associations, commercial businesses, and others will integrate and sustain IOOS.

The IOOS system of systems

IOOS, one outgrowth of the national ocean policy, is conceived as a partnership between federal agencies, regional marine associations, universities and researchers, cooperating business interests, and other groups that wish to play a role. The intent is to have the various observation and processing systems, together with their operating organizations, work in an interoperable and integrated manner. The term *integration* includes both technical integration of marine information and the coordination of activities to cover all important national and regional needs.

Mission

The mission of IOOS is to provide integrated data, information, and products about the state of the oceans, to further major societal goals. The key elements of this mission are the term *integrated* and the phrase *to further major societal goals*. There is a large amount of marine information currently measured and made available, but much of it is not integrated or fully coordinated in order to provide a total characterization of the marine environment. IOOS will move to integrate and coordinate existing marine information systems and to align them with the societal goals where necessary. In turn, a more integrated and coordinated system is expected to evolve that will help fulfill the societal goals more effectively over time.

Goals

To fulfill its primary mission, the fundamental goal of IOOS is to provide **capabilities, coordination,** and **information** in support of the seven specific societal goals articulated in the Oceans Blueprint. Figure 2 is a graphical summary of IOOS in light of these goals.

High level enterprise activities

IOOS as a system will engage in a number of high level activities. These can be generally grouped under the headings of **create information, provide technical capabilities**, and **coordinate IOOS-related activities**. Figure 3 shows how IOOS missions link to high level enterprise activities and subsystems.

Development ground rules

According to current planning, IOOS will try to develop as little as possible in the way of new technology, adopting existing standards or profiling them whenever possible. Where existing standards will not serve, IOOS will consider developing new standards. Where the technology is not yet available, IOOS will consider developing it, at least on a demonstration basis. Standards and technology developed by IOOS are planned to be freely available, so as to best help promote integration, interoperability, and participation.

Relation to global integrated systems

The US has committed to participate in several international efforts to integrate observations of environmental parameters. Of these, IOOS is most closely related to, and is considered to be the US contribution to, GOOS and GEOSS. IOOS, whose planning and development is ahead of other international activities, will likely lead in the adoption of many of the standards and solutions.

Program management

There is a distinction to be made between IOOS as a *system* and IOOS as a *program*. The IOOS program is needed to arrive at IOOS the system. At the time of writing, IOOS the program exists mostly in the planning and promotion phases. It is administrated by Ocean.US, an interagency organization, is not chartered or organized as a program development office in the usual sense. It has been putting the foundations of IOOS in place through coordination meetings, active committee members from across the range of interested marine organizations, early IOOS educational activities, and other planning and outreach activities.

These early efforts have been successful, and the need for an actual program office is becoming acknowledged. A program office will be needed to manage the development and implementation of IOOS. It seems likely that Ocean.US will be charged with this responsibility in the near future.

The future IOOS program office will be the hub of federal multi-agency IOOS-related activities.

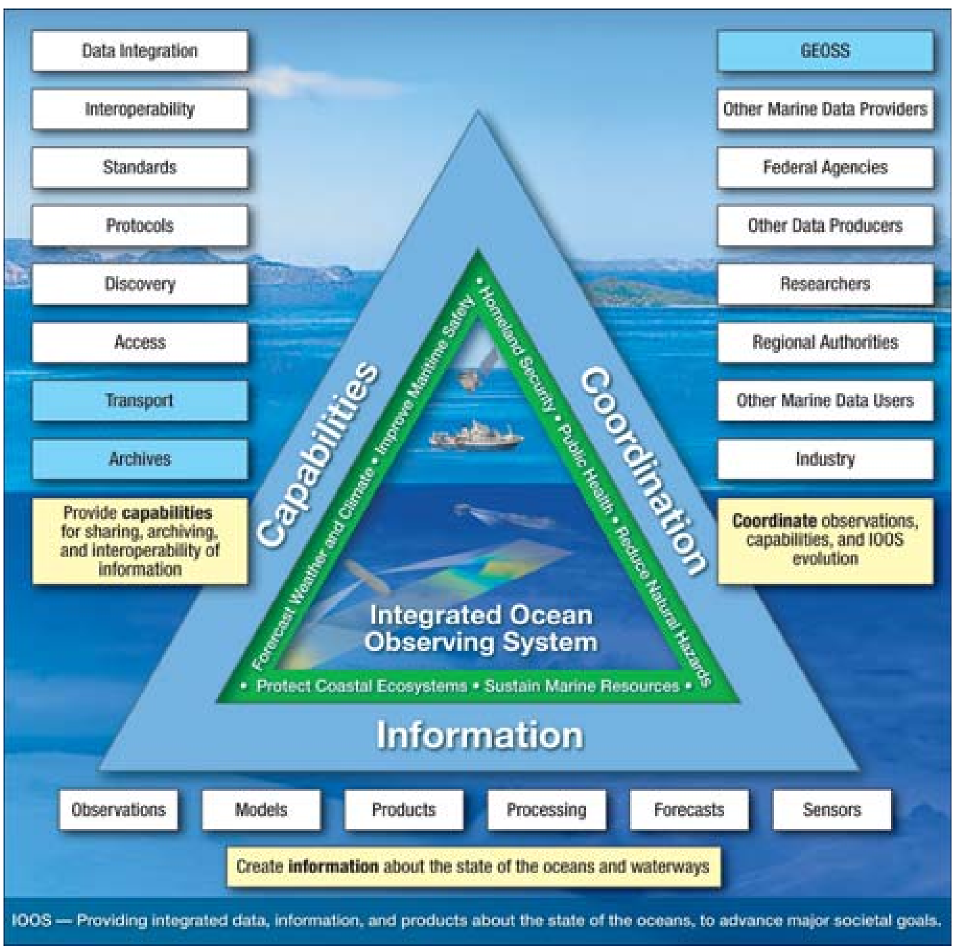

Figure 2. IOOS fundamental mission and goals.

Development challenges in the IOOS environment

Because the IOOS environment is so large and diverse, there will be many challenges as IOOS is developed and implemented. Systems that are more closely controlled by a central development authority do not face these challenges, at least not to the degree that the IOOS program will.

A federated system of systems

IOOS will be a system composed of other systems. For the most part, these systems already exist. Each of these systems has been built to satisfy its own missions and goals, which were not usually harmonized with each other or, in some cases, with national goals. Even when, in the IOOS era, these systems become more coordinated, they will still have missions that are not identical with each other. The challenge here is that IOOS will have to influence all these systems to align and coordinate more closely, without being able to dictate to them or control their budgets.

The federal portion of IOOS can be expected to bear the brunt of the costs of daily operations, and to be able to influence the other participants by means of federal contributions to their funding. Also, the IOOS program will act as a focal point to some degree. Because many entities are involved, because few of them have central authority in the area of marine observations, and because competing technologies are currently in use, IOOS will be a *federated system of systems*. The application of systems engineering to a federated system of systems has only recently been seen as an explicit discipline. Consequently, knowledge of typical systems engineering concerns, such as how to customize the systems engineering methodology, make tradeoffs, influence and coordinate the efforts of the participating organizations, and maintain schedules, is less well developed than it is for more conventional programs.

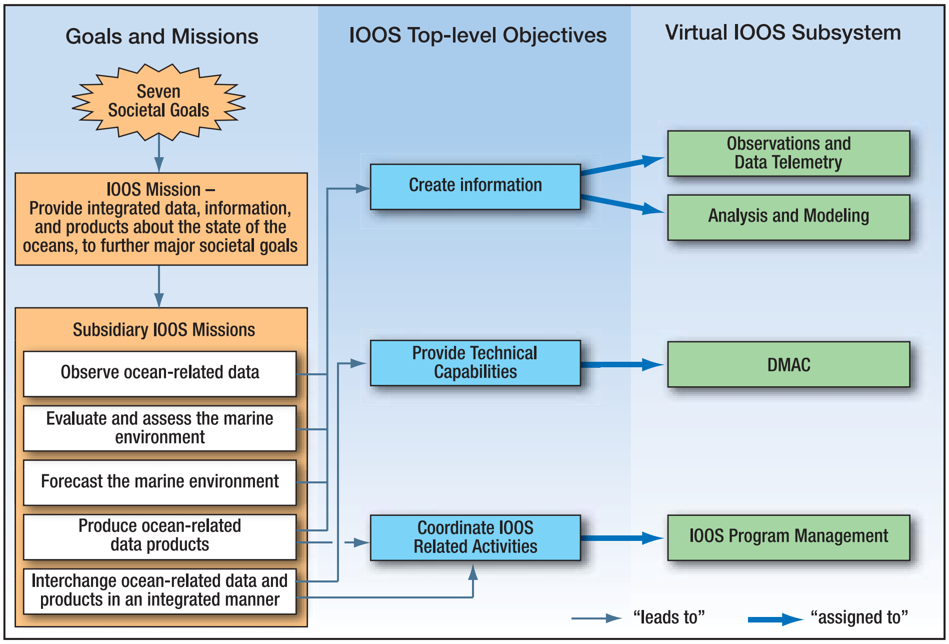

Figure 3. Linking IOOS missions and high level enterprise activities to subsystems. The acronym DMAC stands for "Data Management and Communications." The term virtual subsystem indicates that these entities will not be simple, tangible subsystems. DMAC, for instance, will likely include some technical subsystems, a portfolio of standards and recommended practices, and so on.

Many federal agencies

Currently, 10 federal agencies have signed the agreement establishing Ocean. US. Other federal agencies also have interests in the marine environment. All these agencies have their own interests, and these interests do not always coincide. In addition, each one has to be able to justify its funding requests for IOOS in terms of its own mission, goals, and architecture.

The IOOS program office will have to operate in the face of the diverse pressures generated by the conflicting needs of the participating agencies, and to demonstrate that its operations and continued existence supports their requirements. Even then, the program agency will be likely to suffer continually changing priorities of the participating agencies. The challenge for IOOS under these conditions is to maintain consistent direction and policy over time, as well as to maintain its funding levels.

Federal-private coordination

The bulk of the work required to develop, test, and implement IOOS standards and technologies will probably not be done directly by the IOOS program office. Instead, it will be done by a mix of the other federal and non-federal organizations that play leading roles in the marine data world. Some of the non-federal work will be federally funded, some not. Nevertheless, the program office will have to be effective in planning, scheduling, and coordinating these activities, in making sure that integration and interoperability occur as they are supposed to, and in managing change and change requests. Beyond this, the IOOS program office will have to promote coordination of the capabilities of the various systems making up IOOS, so as to uncover missing capabilities that are important for advancing the top level societal goals.

Open development

A certain amount of planning and early system design has already occurred. During this work, a commitment was expressed to a fully "open" IOOS development process. Given the wide range and nature of the participants, some of which are academic institutions, the only kind of feasible process may be one that is open and accessible to all of them. Unless the participants can clearly understand and influence the planning and design, they are likely to resist cooperating with efforts of the IOOS program to structure and schedule their contributions. In addition, some of the development may occur as joint projects with other participants, rather than being mediated by the IOOS program office, yet such work needs to be coordinated and merged with other development tasks. To add to the challenges, few government agencies are accustomed to working openly through all phases of system development.

In addition, there is no single process for, or even definition of, an open development process, let alone one for a federated system of systems. One will have to evolve over time. In the process, IOOS must avoid the tendency to "design by committee."

Distributed development

With such diverse and loosely controlled development activities spread out across the entire country, the future program office will not find it easy to keep them aligned and on schedule, nor to apply uniform quality control and change management practices. The commitment to open development may help in these instances, because existing open development projects have faced and solved these issues. They could be used as models or templates. Examples of successful, large scale, distributed, open source software projects are the Linux operating system, and the collection of projects developed under the Apache Foundation, which is best known for the Apache Web server.

Development process

The entire development process, in itself, will evolve and must work effectively. This evolution will probably have to be a cooperative affair. Not least is the process by which standards are developed and adopted, since these standards will be fundamental for the integration of IOOS data and products.

Progress to date

Mitretek developed a preliminary enterprise architecture for IOOS, along with a preliminary Systems Engineering Management Plan (SEMP). The latter provides a framework and roadmap for IOOS systems engineering.

Enterprise architecture

Architecture is the arrangement of parts or components into a whole, and the organization and relations of those components so as to achieve the goals of the enterprise or system. Enterprise architecture refers to the endeavor as a whole. Better known architectures, such as system architecture, technical architecture, and so on, can be considered subsets of enterprise architecture.

Creating a formal enterprise architecture can help a program avoid the fate of so many other programs, which when finally delivered do not satisfy the true needs of the business or agency, because a proper enterprise architecture considers the missions, activities, and organizational relationships of the entire enterprise. The architecture can also help to focus energy on productive tasks—by identifying high priority areas, for example.

A number of approaches to documenting an enterprise architecture have been developed both inside and outside the federal government. Among these are the Department of Defense Architecture Framework (DoDAF) and the Federal Enterprise Architecture (FEA). The IOOS architecture includes parts based on both the FEA and DoDAF approaches, as well as other architecture projects.

Systems engineering

"Systems Engineering is an interdisciplinary approach … [that] integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation…" [1]

IOOS will be a large, distributed, complex system linking together and integrating an enormous number of observations, calculations, forecasts, and other products relating to the marine environment. The technical task is to provide the means by which the different participating systems can be integrated in an interoperable manner. The programmatic task is to coordinate and influence the work of dozens or hundreds of participating organizations so that they develop, test, adopt, and implement the technical solutions, with the help of the eventual IOOS program office. Of these, the programmatic task is by far the most complex.❖

References

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Fred C. Klein is a managing oceanographer at Mitretek. His experience includes ocean and weather forecasting, meteorology and oceanography (METOC) project management, and underwater acoustics. He received master's degrees in national security and strategic studies from the Naval War College and in meteorology and oceanography from the US Naval Postgraduate School. Contact him at fred.klein@mitretek.org.

Thomas B. Passin is a principal systems engineer at Mitretek. His current research interests include XML-related technologies, data modeling, and enterprise architecture, and his experience ranges from designing nuclear radiation detectors to working with topic maps. He completed his master's degree level studies in physics at the University of Chicago. Contact him at tpassin@mitretek.org.

Robert Vorthman Jr. is a lead engineer at Mitretek. His experience includes Web-based data center procurement and consolidation, as well as multi-discipline systems engineering and acquisition leadership. He received the engineer degree in ocean engineering from the Massachusetts Institute of Technology. Contact him at vorthman@mitretek.org.

NOAA—Building a Solid Architecture Foundation

A quick look at a selected Mitretek project

Lauraleen O'Connor and Kenneth F. Carey

The Consolidated Observational Requirements List (CORL) documents atmospheric, land, oceanic, hydrologic, climatic, solar and space environmental observational requirements.

A 2002 program review recommended the National Oceanic and Atmospheric Administration (NOAA) establish the NOAA Observing Systems Architecture (NOSA) to support its mission as well as the global user community. A requirements-based observational requirements process provides the foundation for NOSA, transitioning away from a platform-oriented process while moving towards an integrated user needs driven end-to-end systems architecture. The result is the Consolidated Observational Requirements List (CORL) database. The CORL focuses research and technology initiatives on high-priority requirements, aids in the transition of research to operations, and is the basis for observing system investment analyses used for budget and program planning. As NOSA evolves and matures, it will more efficiently fulfill the total set of prioritized CORL-documented requirements, provide the best possible value, and avoid unnecessary duplication of observing systems.

Key to the process is the active participation of the stakeholders—the NOAA Goal Teams, Programs and NOAA Line Offices. Throughout the process, an online relational database management tool, CasaNOSA, allows stakeholders to view and download observation requirements lists, aiding in the annual requirements update. The database, updated weekly, is viewable from a variety of perspectives—NOAA mission, need timeline, spatial or temporal attribute—to optimize the observing system architecture and fulfill mission needs.

The initial step in this process is to consolidate each program's mission-specific requirements from program-related, platform-independent observing requirements documents as well as system-oriented specification documents. Each program's preliminary observation list is standardized, prioritized (mission critical, optimal, or enhancing). Program lists are linked to expected outcomes and performance measures, both internal and those contained within the Government Performance Results Act (GPRA) annual plans and reports. Work continues to develop a more comprehensive process to verify and validate each program's list. The validation process will associate all program observation requirements with both their specific science-based justifications and contribution levels to achieving NOAA's overall mission goals.

Currently, the CORL contains only NOAA observational requirements, but can be expanded to include other federal agency observational requirements and international partners and commercial entities in the future.

Mitretek continues to support NOAA in this critical systems engineering activity through design and implementation of the requirements collection process.❖

For the best of reasons

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