A New Satellite Constellation -- Leveraging NPOESS and GOES-R

Syn•er•gy [fr. Gk. *synergos* working together] : combined action or operation

Since the mid-1970's, the National Oceanic and Atmospheric Administration (NOAA) has operated a fleet of low-Earth orbit (LEO) and geostationary Earth orbit (GEO) meteorological satellites to monitor the weather and climate of the Earth and provide data to support short- to medium-range weather forecasts and severe weather warnings. Both LEO and GEO satellites are necessary for weather forecasting because they provide independent but highly synergistic and complementary capabilities and data. NOAA's Polar-orbiting Operational Environmental Satellites (POES) and their Department of Defense (DoD) counterparts, the Defense Meteorological Satellite Program (DMSP) spacecraft, fly in polar, sun-synchronous, LEO collecting repeatable, quantitative atmospheric, near-Earth space environment, terrestrial, and oceanic data (e.g., calibrated radiances) - primarily to initialize and update global and regional short- to medium-range (out to 7 days) numerical weather prediction (NWP) models. While polar LEO satellites provide global coverage daily, they cannot provide timely and continuous measurements over the continental United States (CONUS), the area of primary importance for U.S. forecasters. NOAA's Geostationary Operational Environmental Satellites (GOES) maintain position in GEO, taking nearly continuous "snapshots" of weather systems over CONUS and major portions of the central and western Atlantic Ocean and the eastern and central Pacific Ocean, including the Hawaiian Islands and the Gulf of Alaska, but not at higher latitudes (e.g., Alaska). GOES data are used for both qualitative and quantitative image analysis to support nowcasting, short-term forecasting (1-24 hrs), and severe weather warnings and are assimilated into global and regional NWP models. Although GOES imagery is well known to operational forecasters, broadcast meteorologists, and the public, data from GOES alone are not sufficient to support weather forecasting and numerical weather prediction across all spatial and temporal scales required to protect safety of life and property and support economic sectors in the U.S.

Continuity of current POES and GOES operations is important to maintain the flow of data into NWP models and into the hands of operational forecasters and climate researchers. There is also a compelling need to advance capabilities in operational satellite measurements to improve weather, hydrologic, and climate services to the nation. To meet these needs, NOAA and its partner agencies are embarked on a decadal effort to build and fly the next generation of LEO and GEO operational environmental satellites that will replace the heritage POES, DMSP, and GOES systems. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will replace POES and DMSP beginning in 2013 and the Geostationary Operational Environmental Satellite-R series (GOES-R) is planned for launch in ~2015 to replace the current series of GOES. NPOESS and GOES-R will carry similar, advanced-technology, high-resolution visible/infrared imagers to provide the weather forecasting community with highly complementary data.

NPOESS will carry a 22-band (29 counting seven dual-gain bands) Visible/Infrared Imager Radiometer Suite (VIIRS) that will be radiometrically calibrated and consistent on successive VIIRS instruments to provide complete daily global coverage over the visible, short/medium-infrared, and long-wave infrared spectrum at horizontal spatial resolutions of 370 m and 740 m at nadir. VIIRS will image at a near constant horizontal resolution across its ~3000 km swath. VIIRS will also have a day/night band to detect low levels of visible-near infrared radiance at night from sources on or near the Earth's surface, such as city lights, low clouds and fog illuminated by moonlight, snow cover, and lightning flashes. The visible and near infrared channels on VIIRS will be used to generate high resolution cloud imagery, ocean color, sea ice, aerosols, vegetation, and land surface type products. The short- to long-wave infrared channels will provide data to derive cloud properties (cloud type, cloud particle size, cloud top height, cloud top temperature), snow cover, sea surface temperature (SST), and fires. Multi-channel algorithms will combine visible and infrared data to generate measurements, such as albedo, that are important in measuring and understanding the Earth’s energy balance. These multi-spectral capabilities will allow users to accurately detect phenomena such as volcanic ash plumes and discriminate low clouds from fog that may significantly impact aircraft operations. VIIRS will deliver high resolution, radiometrically accurate data on surface albedo, land surface type, SST, snow cover, and ice extent for ingesting into global and regional NWP models.

The GOES-R Advanced Baseline Imager (ABI) will be a state-of-the-art, 16-channel imager covering 6 visible to near-Infrared (IR) bands (0.47 um to 2.25 um), and 10 IR bands (3.9 um to 13.3 um). Spatial resolutions are band dependent: 0.5 km at nadir for broadband visible; 1.0 km for near IR; and 2.0 km for IR. The channel selection for the ABI is a balance of heritage with existing GOES bands (on the imagers and sounders), consistency with imaging bands on other satellites (both in geostationary and polar-orbits), and consideration for products that could be produced jointly with advanced high-spectral resolution sounders, such as the Cross-track Infrared Sounder (CrIS) that will be flown on NPOESS. Imagery from ABI will be used to derive Atmospheric Motion Vectors (AMVs), Quantitative Precipitation Estimates (QPEs), cloud parameters, clear-sky radiances, and surface (skin) temperature. ABI imagery will enhance capabilities to detect and characterize fires, volcanic ash, fog and (experimentally) cloud-top information. ABI will also provide cloud-top phase/particle size information and much improved snow detection, aerosol and smoke detection for air quality monitoring and forecasts. Other new products and capabilities from ABI will include vegetation monitoring and upper-level SO_2 detection.

These next generation satellites will also carry other advanced-technology instruments unique to each system that will enhance the synergy between NPOESS and GOES-R, helping to build a “system of systems.” These sensors will be used to profile the atmosphere, observe and image atmospheric, terrestrial, and oceanic phenomena, monitor the Earth’s radiation budget and climate, and probe the near-Earth space environment.

NPOESS will carry CrIS and the Advanced Technology Microwave Sounder (ATMS) to provide vertical profiles of atmospheric temperature, humidity, and pressure from the surface to the top of the atmosphere. The CrIS is a cross-track scanning Fourier Transform Spectrometer that uses a Michelson interferometric sounder capable of sensing upwelling infrared radiances from 3 to 16 µm at very high spectral resolution (~1300 spectral channels) across a swath width of 2200 km. CrIS will succeed the Atmospheric Infrared Sounder (AIRS) which is on the National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) Aqua spacecraft and will fly in a complementary orbit with the Infrared Atmospheric Sounding Interferometer (IASI) on the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Meteorological Operational (MetOp) satellites. The ATMS is the next generation cross-track microwave sounder that will combine the capabilities of current generation microwave temperature sounders (Advanced Microwave Sounding Unit - AMSU-A) and microwave humidity sounders (AMSU-B) that are flying on NOAA's POES and NASA's EOS Aqua spacecraft. The ATMS draws its heritage directly from AMSU-A/B, but with reduced volume, mass, and power. ATMS has 22 microwave channels in the 23-183 GHz range to provide vertical temperature and moisture soundings. Data from CrIS and ATMS will be used to construct atmospheric temperature profiles at 1° K accuracy for 1 km layers and moisture profiles accurate to 15 percent for 2 km layers to approximate the accuracy of data obtained from radiosondes. The ABI on GOES-R, together with output from NWP models and data from advanced sounders such as CrIS and IASI will provide GOES legacy sounder products until a dedicated sounder instrument can be flown on a future GEO mission.

Higher (spatial, temporal, and spectral) resolution and more accurate sounding data from CrIS and ATMS will support continuing advances in data assimilation systems and NWP models to improve short- to medium-range weather forecasts. Assimilation of high-spectral resolution radiance data from AIRS into NWP models at NOAA's National Centers for Environmental Prediction (NCEP) has already resulted in a several hour increase in forecast skill/range at five to six days in both northern and southern hemispheres, a significant improvement that normally takes several years to accomplish. CrIS will produce operational sounding data comparable to AIRS.

NPOESS will also carry a Microwave Imager/Sounder (MIS) on the NPOESS C2 through C4 spacecraft to perform key, "all weather" measurements including soil moisture and sea surface winds, as well as other environmental parameters including atmospheric temperature and moisture profiles, and integrated atmospheric moisture and precipitation. The design for MIS is based on heritage conically-scanning microwave radiometers that are currently flown on DMSP spacecraft and on the Naval Research Laboratory's WindSat/Coriolis mission. MIS will use a 1.8 m rotating main reflector to cover a 1,700 km swath width while measuring over a range of 6 GHz to 183 GHz.

GOES-R will carry a new Geostationary Lightning Mapper (GLM) that will complement operational ground based lightning detection systems with information on total lightning flash rate (including both cloud to cloud and cloud to ground strikes) over both land and adjacent oceans. Detection of lightning flashes by the VIIRS day/night band on NPOESS will add to the GLM data that will have immediate applications to aviation weather services, and severe thunderstorm forecasts and warnings. These space-based lightning measurements will provide information to identify growing, active, and potentially destructive thunderstorms over land as well as ocean areas. The GLM will provide critical information to assist operational weather, aviation, disaster preparedness, and fire weather communities in a number of areas: improvement in tornado and severe thunderstorm lead times; more reliable warning of lightning ground strike hazards; improved routing of commercial , military, and private aircraft over oceanic regions where observations of thunderstorm intensity are scarce; better short-range forecasts of heavy rainfall and flash flooding; and improved capability to monitor the intensification of tropical cyclones, which is often accompanied by increased lightning activity in the eyewall.

In the next decade, GOES-R and NPOESS will be the principal U.S. operational, space-based observing systems for monitoring climate variability. GOES-R and NPOESS, flying in controlled, stable orbits, will both carry well-calibrated instruments suitable for long-term monitoring of essential climate variables including sea and land surface temperature, water vapor, cloud properties, ozone, aerosols, and winds. Two operational GOES-R satellites will provide ABI coverage over most of the western hemisphere at spatial resolutions of 2 km or better and full disk temporal resolution of 5 minutes that will allow monitoring of the diurnal cycle. A unique advantage of instruments in GEO is the high refresh rate at the same viewing geometry that allows for accurate assessment of diurnal and regional changes. In comparison, instruments on NPOESS and EUMETSAT/MetOp satellites in LEO will provide data that will only minimally resolve the diurnal cycles of variables such as ocean and land surface temperatures, a limitation that is further compounded in regions where cloudiness is diurnally dependent (e.g., west coast of U.S.). However, cross-calibration of similar instruments on GOES-R and NPOESS (i.e., ABI and VIIRS) will facilitate the production of consistent and reliable climate data records for these types of variables based on measurements from both systems. NPOESS will carry the Ozone Mapping and Profiler Suite (OMPS) to collect atmospheric total column and vertical profile ozone data; the Cloud and Earth Radiant Energy System (CERES) instrument to measure the space and time distribution of the Earth’s Radiation Budget (ERB) components; and the Total Solar Irradiance Sensor (TSIS) to measure variability in the sun's solar output, including total solar irradiance. The OMPS, CERES, and TSIS are important climate sensors that will help maintain continuity of the climate data records for space-based measurements that now span over three decades.

Both GOES-R and NPOESS will carry instruments to monitor the highly-variable solar and near-Earth space environment where space weather can disrupt satellite operations, impact the communications and navigational infrastructure, damage electric power distribution grids, and increase human risk to radiation exposure in high altitude aircraft and on manned spaceflight missions. GOES-R will carry the Space Environment *in-situ* Suite (SEISS), the Extreme Ultraviolet and X-Ray irradiance Sensor (EXIS), and the Solar Ultra-Violet Imager (SUVI) to provide multiple measurements to characterize the charged particle distribution, including measurements of the electron, proton, and heavy ion fluxes. A magnetometer (MAG) on GOES-R will measure the Earth’s magnetic field. The Space Environment Monitor-NPOESS (SEM-N) will be a multi-channel, charged particle spectrometer to measure the population of low-, medium-, and high-energy particles in the near-Earth space environment and the particle precipitation phenomena resulting from solar activity. The expanded services from GOES-R and NPOESS will improve support to forecasters at NOAA's Space Environment Center, customers in DoD and NASA, commercial users of space weather services, and to international space environment services. In addition, NPOESS and GOES-R will continue the POES and GOES legacy of user support services by carrying payloads to support the global Data Collection System (DCS) and the Search and Rescue Satellite Aided Tracking System (SARSAT).

The potential benefits of leveraging the capabilities of NPOESS and GOES-R are apparent even as the instruments for the new satellites are being developed. For example, imagery and radiance data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) Terra and Aqua satellites are being used to simulate the expected capabilities and performances of both ABI and VIIRS. Approximately half of the channels on VIIRS will be identical to or will be closely matched to similar channels on ABI. The horizontal resolution of imagery from VIIRS and ABI will be much more closely matched than can be achieved currently between imagery from POES and GOES. The radiometric calibration and accuracy of ABI will be significantly better than the heritage imager on GOES, permitting routine cross-calibration of visible/infrared imagery and radiance data between ABI and VIIRS. Consistency of radiometric measurements between NPOESS and GOES-R instruments will help improve present NWP weather forecasting capabilities and potentially allow forecasters to extend the range of severe storm forecasts for the United States. LEO and GEO meteorological satellites currently provide over 99% of the data that are assimilated into NWP models and increase the accuracy of the models as much or more than data from all other observing systems combined. GOES-R and NPOESS will continue this role and will provide timely measurements needed to derive and predict critical quantitative weather products. Use of NPOESS data will extend beyond NWP centers to regional and local weather forecast offices to support specialized forecast products.

Exploiting the synergies between NPOESS and GOES-R will require faster delivery of data and skillful combination of data from complementary instruments on the two systems. The ABI on GOES-R will be capable of scanning the Full Disk (FD) in approximately 5 minutes, a major improvement that will facilitate more rapid imaging of severe weather systems that often evolve quickly. The NPOESS SafetyNet™ ground system will deliver 77% of the global data within 15 minutes and 95% of the data within 28 minutes from the time of on-orbit collection, a data latency that approaches the current GOES system and a dramatic improvement in data latency compared to the heritage POES and DMSP systems. Faster delivery of data will facilitate greater use of NPOESS and GOES-R data at regional and local weather forecast offices. These more rapid updates from GOES-R and NPOESS will provide critical information leading to longer lead times on warnings and advisories, thus saving lives and property and reducing costs.

Data from complementary instruments on NPOESS and GOES-R will provide opportunities to improve existing products and to derive new products that cannot be generated from a single system. For example, combining cloud imagery from ABI and

VIIRS with sounding data from CrIS may result in better assignment of heights for GOES-R derived AMVs. Derivation of AMVs, based on heritage GOES and MODIS methods, will likely be transitioned to VIIRS for polar regions. The combination of IR data from VIIRS and ABI with microwave data from the MIS and ATMS that will be flown on NPOESS will result in improved global, regional, and local scale SST products.

Products from both GEO and LEO satellites can be invaluable for monitoring the intensity of tropical cyclones. Forecaster confidence can be enhanced by using both systems together and exploiting data from instruments on one system (e.g., microwave imagers and sounders on POES, DMSP, and NPOESS) that aren't on the counterpart (GOES and GOES-R). The potential benefits of the synergy between NPOESS and GOES-R are highlighted well in a recent example of data acquired from heritage GOES and POES systems during the recent landfall of Hurricane Ike on the Texas coast.

As Hurricane Ike approached Texas, it appeared that the storm was starting to strengthen after two days of near constant intensity, based on the redevelopment of a pronounced eye as shown in the GOES-12 IR image in Figure 1. But with the prospect of massive evacuation orders looming, forecasters needed to be confident of their assessment. The AMSU-A on NOAA-15 (note that ATMS on NPOESS will replace AMSU) has special temperature sensing channels that can be imaged to reveal warm anomalies aloft that are characteristic of tropical cyclones. In general, the higher the temperature aloft the more intense the hurricane will be. As shown in Figure 2, the AMSU-A image of Hurricane Ike acquired just prior to landfall in Texas reveals pronounced warming compared to AMSU-A data from an earlier pass. This information helped confirm the strengthening trend observed from the GOES-12 IR image. Imagery from NOAA-15 AMSU-B strengthens the case for intensification even further. This microwave channel shows cloud and precipitation features near the surface. The image in Figure 3a acquired at about 1100 UTC on September 12, 2008 shows an eyewall that is only partially wrapped around the center. Twelve hours later the wraparound is more complete (Figure 3b), increasing forecaster confidence in the intensification of Ike just before making landfall. Final analysis of Hurricane Ike indicates that the storm strengthened by about 10 knots in its final approach to landfall, confirming the effectiveness of the remotely-sensed data. Efforts are underway to combine the attributes of these images into an objective, automated algorithm that estimates hurricane intensity. The method, called SATCON (SATellite CONsensus), statistically blends information from IR, AMSU-A, and AMSU-B to derive a consensus estimate of hurricane maximum wind and minimum pressure. For more information see: http://cimss.ssec.wisc.edu/tropic2/real-time/satcon/. Even in the aftermath of Hurricane Ike, satellite imagery can be used to assess and help respond to the storm's damage. Nighttime composite images that were acquired from the DMSP Operational Linescan System (OLS) before (Figure 4a) and after (Figure 4b) Hurricane Ike passed through Texas show areas along the coast and inland where power was completely or partially lost. The NPOESS VIIRS day/night channel will produce similar imagery at a higher spatial resolution than OLS to enhance these types of post-storm damage assessment.

Together, NPOESS and GOES-R will serve as the basis of the United States contribution to build the Global Earth Observation System of Systems (GEOSS). A global network of observing systems will allow scientists to improve weather forecasts, predict energy needs months in advance, monitor forest fires and volcanic ash, issue timely warnings of air quality effects, and anticipate outbreaks of environment-related diseases. The potential economic benefits of an Earth observation system are enormous. The return on investments in NPOESS and GOES-R will benefit the general public in the U. S. and the international community for decades to come.

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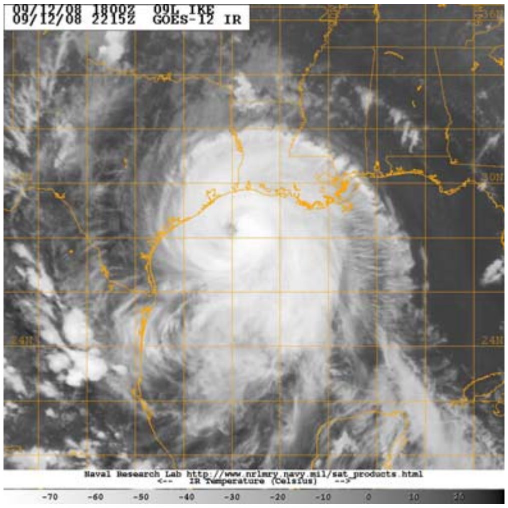


Figure 1. GOES-12 IR image of Hurricane Ike on 12 September 2008 just hours before making landfall at Galveston, TX. Image credit: NRL http://www.nrlmry.navy.mil/TC.html.

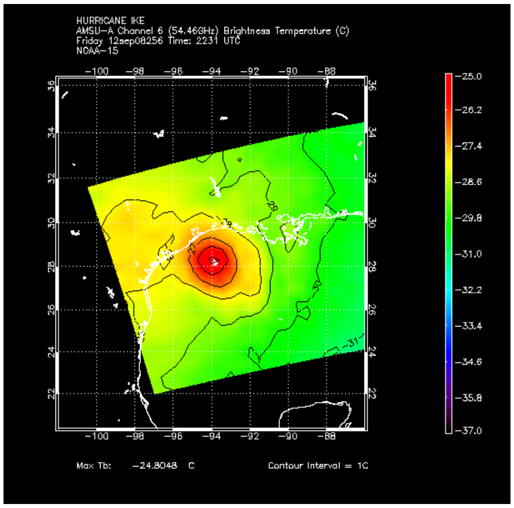
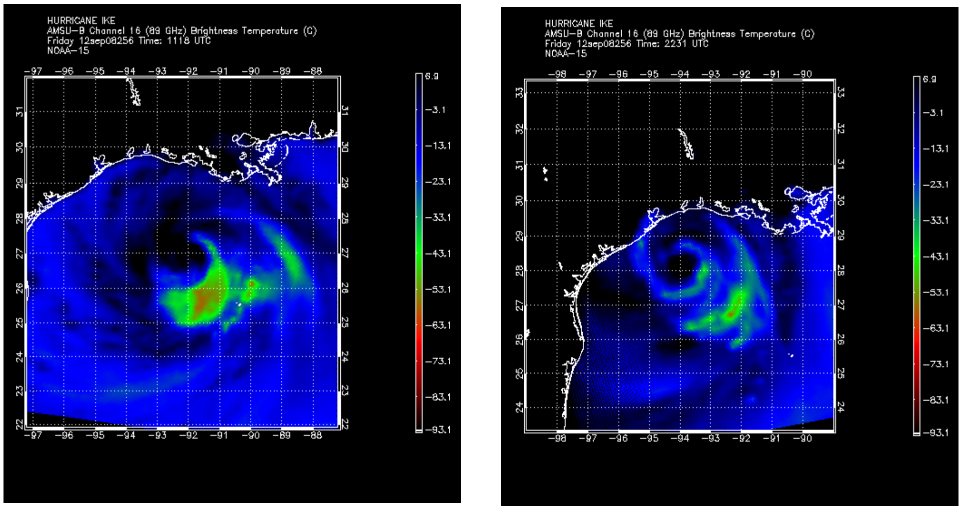
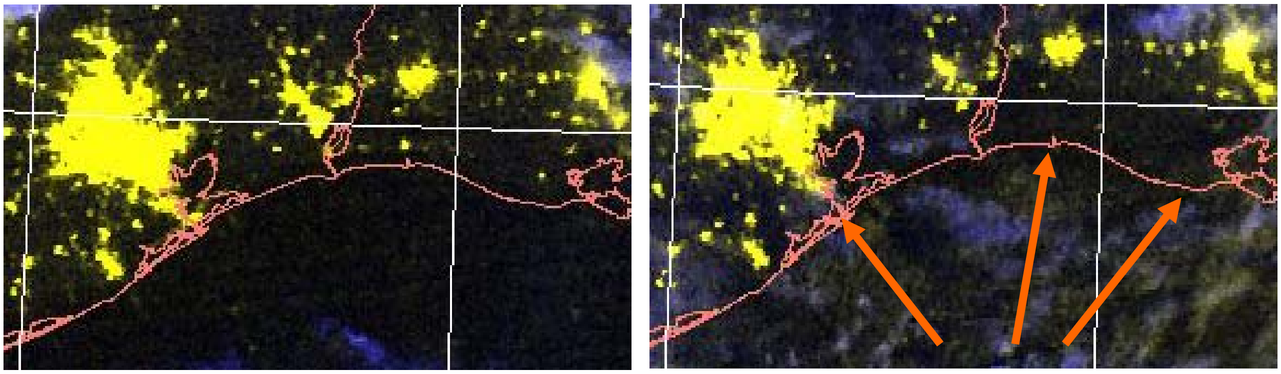


Figure 2. NOAA-15 AMSU-A Channel 6 (54.46 GHz, ~350 hPa), Brightness Temperature taken on 12 September 2008 reveals pronounced warming with a maximum value of -24.8 C or about 1.5 C of warming in 24 hours compared to an earlier pass. Image credit: University of Wisconsin CIMSS http://amsu.ssec.wisc.edu.



(a) (b)

Figure 3. NOAA-15 AMSU-B Channel 16 (89 GHz), Brightness Temperature taken on 12 September 2008 at 1118 UTC (a) and 2231 UTC (b). Image credit: University of Wisconsin CIMSS [*http://amsu.ssec.wisc.edu*](http://amsu.ssec.wisc.edu).



(a) (b)

Figure 4. DMSP F-16 OLS Nighttime Composite taken on (a) 9 September 2008 before Hurricane Ike and (b) 17 September 2008 after Hurricane Ike. Note the changes in city lights along the coast highlighted by arrows. Image credit: NRL