Sounding the Atmosphere – from TIROS to Suomi NPP

A new era of remote sensing began with the successful launch of the Suomi National Polar-orbiting Partnership (NPP) on 28 October 2011. From the first radiometer to measure the Earth's heat balance from a satellite envisioned by Verner Suomi (1959) to the current suite of instruments on Suomi NPP, the Space Science and Engineering Center has pioneered advances in remote sensing research aimed at improving our understanding of the Earth and its atmosphere.

Satellite Meteorology - A History

The United States launched the first meteorological satellite, TIROS-1 (Television Infrared Observational Satellite) on 1 April 1960. From this vantage point, scientists could see, for the first time, complete pictures of the clouds associated with large weather systems. The operational meteorological satellite program evolved rapidly thereafter.

In 1964 researchers successfully created a global picture of the earth's surface and atmosphere. A new initiative then attempted to measure the atmosphere's vertical distribution of temperature and moisture to better initialize global numerical weather prediction models, otherwise known as atmospheric sounding. By the late 1950s, J. King and Lewis Kaplan, had advanced the theoretical underpinnings of soundings with research that showed it was possible to infer atmospheric temperature and the concentration of attenuating gas such as water vapor as a function of atmospheric pressure.

Temperature profile retrievals were first accomplished in 1969 with the Satellite Infrared Spectrometer (SIRS), a grating spectrometer aboard NIMBUS-3. This instrument demonstrated the capability of indirectly measuring these parameters from a satellite platform, rather than from direct measurements systems such as radiosondes. The advantage of satellite measurements is that they provide much improved spatial and temporal coverage than radiosondes.

Despite these early successes, clouds remained an issue for retrievals using measurements in the infrared portion of the spectrum. Researchers explored the best spectral bands for retrievals and various mathematical techniques to eliminate the influence of clouds. In 1972 a scheme was devised to reduce the influence of clouds by employing a higher spatial resolution (30 km) and by taking spatially continuous sounding observations, now possible with cross-track scanning on the seven-channel Infrared Temperature Profile Radiometer (ITPR) on board NIMBUS-5 (Smith et al, 1974).

From the available results and studies in the early 1970s, scientists recognized that optimum temperature profile results would be achieved by taking advantage of the unique characteristics offered by the 4.3 micron and 15 micron CO_2 absorption bands. The Nimbus-6 High resolution Infrared Radiation Sounder (HIRS) experiment was then designed to accommodate channels in both regions.

Current generation NOAA polar-orbiting satellites carry improved AVHRR imager (addition of a channel at 1.6 microns for cloud, ice and snow discrimination) and HIRS sounder instruments that continue to provide their basic measurements. Important improvements to microwave sounding instruments such as the Advanced Microwave Sounding Unit (AMSU), provide all-weather temperature sounding information at about 50 km horizontal resolution and moisture sounding information at about 15 km horizontal resolution. The all-weather sounding capability was established in 1998 with the advent of this enhanced microwave sounder (more channels, better spatial resolution) and continuation of the high spatial resolution infrared (good spatial resolution, evolving to higher spectral resolution). The data have become part of the operational practices of weather services internationally.

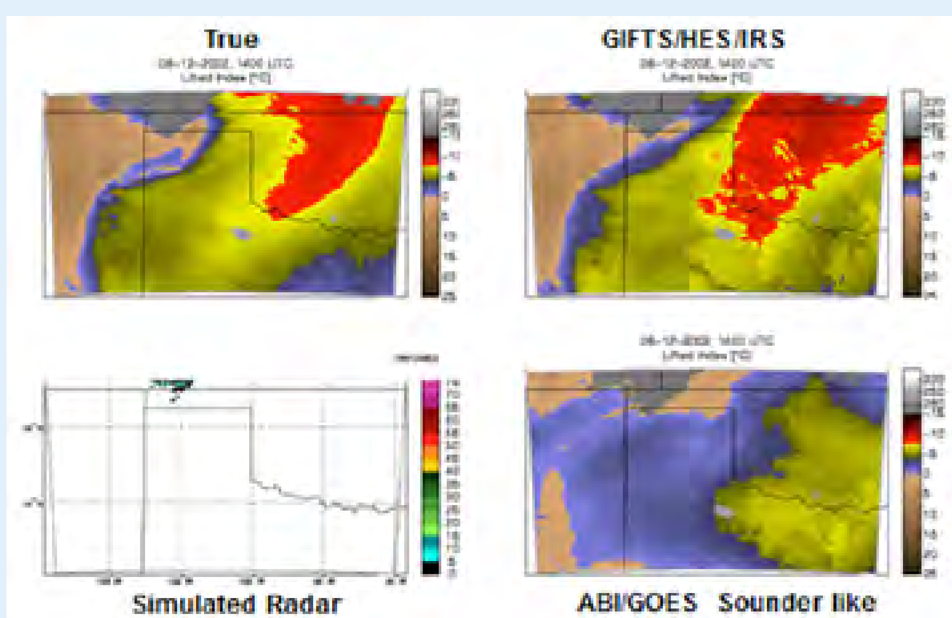

Figure 1. Observing System Simulation Experiment for 1400 UTC on 12 June 2002 during IHOP; a significant convective storm appeared at 2100 UTC in the unstable region of Oklahoma (upper left). Simulation of the true lifted index at 1400 UTC (upper right). Simulation of the LI from a geostationary high spectral resolution infrared sounder (lower left). Simulation of radar echoes (lower right). Simulation of Lifted Index from the current sounder or the planned Advanced Baseline Imager. Only the geostationary advanced IR sounder captures the atmospheric instability well in advance of the subsequent severe weather.

Geostationary Satellites Join the Effort

By 1980, the U.S. Geostationary Operational Environmental Satellite (GOES) system had evolved to include an atmospheric temperature and moisture sounding capability with the addition of more spectral bands to the spin scan radiometer known as the VISSR Atmospheric Sounder (VAS). The first GOES-VAS, GOES-4, was launched in September 1980. Recognizing the limitations of the VAS instrument, but realizing the importance of geostationary sounding, NOAA introduced a 16-channel broadband GOES sounder to its current generation of geostationary satellites (Menzel and Purdom, 1994) with the launch of GOES-8 on 13 April 1994.

The scientific community recognized the need for geostationary sounding with high-spectral resolution instruments (Schmit et al. 2009). By using an interferometer, focal plane detector arrays, and on board data processing to observe from 3.7 to 15.4 microns with 2000 plus channels, it was determined that contiguous coverage of 6,000 x 5,000 km could be accomplished in less than 60 minutes. The trend for more spectral channels at higher spatial resolution with faster coverage to capture the rapid weather changes and improve high impact weather warning and short-range forecasting will bring a crucial new capability to geostationary sounding.

Advanced IR Sounder

CIMSS scientists have demonstrated the importance of an advanced IR sounder from geostationary orbit to replace the current GOES Sounder. A convective initiation event from the International H_2O Project (IHOP) field experiment established the potential utility of a geostationary high spectral resolution IR sounder for severe storm nowcasting and regional NWP applications. Such a sounder would provide detailed stability information (e.g., lifted index and other parameters) with high temporal resolution critical for determining favorable locations for convective initiation. This important information about extreme destabilization is provided hours earlier than is possible from the current observing system.

In the IHOP example (Figure 1), an observing system simulation experiment showed that a geostationary high spectral resolution IR sounder provides accurate Lifted Index instability information about four hours earlier than the current sounder and about eight hours earlier than radar. This improvement suggests that nowcasting and short-term forecasts of 0–6 hours for severe weather would benefit significantly from the advanced geo sounders better and more frequent monitoring of low-level moisture and temperature conditions.

CIMSS scientists are also examining the use of water vapor and temperature observations from polar-orbiting advanced IR sounders (AIRS, IASI and CrIS). These high vertical resolution soundings provide excellent global coverage for severe weather detection and forecasting. One study conducted at CIMSS seeks to improve path and intensity forecast for tropical cyclones. A lack of good temperature and water vapor information appears to be a limiting factor for accurate forecasts from these systems. In a case study for Hurricane Irene conducted at CIMSS, the high vertical resolution atmospheric temperature and moisture profiles from AIRS were used to analyze the development of a hurricane.

The Weather Research and Forecast (WRF) model and Data Assimilation Research Testbed – DART (WRF/DART) developed by the National Center for Atmospheric Research (NCAR) were used to assimilate AIRS data and to generate forecasts. Assimilation of the sounding measurements resulted in better representation of model environmental conditions around the hurricane, thus improving the path and intensity forecasts. The hurricane path and intensity forecasts were examined with and without the satellite atmospheric temperature and moisture information.

From the initial GFS global analysis, both control and AIRS runs show the relatively large errors in sea level pressure at the beginning stages; these errors are gradually reduced as model progresses with time. However, the AIRS soundings consistently show the improvement of intensity forecasts during the process (Figure 2). Results of additional experiments with WRF/3DVAR were consistent with those from WRF/DART. Research has demonstrated the potential positive impact of available advanced

continued on page 16

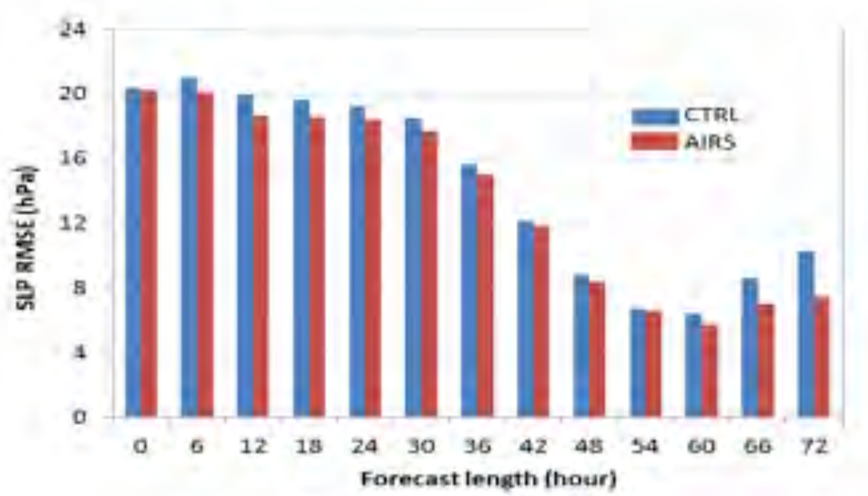

Figure 2. Tropical Cyclone Irene (2011) central sea level pressure (SLP) forecast RMSE for 0-h (analysis), 6-h, to 72-h forecasts. Every 6 hours between 06 UTC 23 and 00 UTC 25 August 2011 the data are assimilated with WRF/DART followed by a 72-hour forecast. The SLP RMSE is calculated from comparisons with the best track observations from National Hurricane Center.

IR sounder temperature and water vapor information from satellites for forecasting hurricane tracks and intensity.

AVHRR Transitions to VIIRS

With Suomi NPP's successful launch and the current NOAA satellite series transitioning to the new JPSS series, AVHRR is transitioning to a more capable visible and infrared imager called the Visible Infrared Imaging Radiometer Suite (VIIRS). VIIRS will be better calibrated than the AVHRR, with higher spatial resolution and 22-channel spectral capability.

HIRS is being replaced by the Cross Track Infrared Sounder (CrIS), a Michelson interferometer that is designed to enable retrievals of atmospheric temperature profiles at a much higher degree of accuracy. This accuracy is accomplished by the CrIS working together with the Advanced Technology Microwave Sounder (ATMS), the replacement for AMSU. A comparable sounding capability has been realized by the Infrared Atmospheric Sounding Interferometer (IASI) on the European Metop-A satellite in conjunction with the advanced microwave temperature sounding units (AMSU-A) and microwave humidity sounders (MHS). CrIS/ATMS is flying on the ascending afternoon orbit and IASI/AMSU is flying on the descending morning orbit.

SSEC's work in sounding and retrieval science covers both polar and geostationary platforms. CIMSS scientists are currently preparing Suomi NPP VIIRS, CrIS, and ATMS data for state of the art soundings aimed at advancing our capability to understand and predict severe weather. The CIMSS hyperspectral IR Sounder Retrieval (CHISR) algorithm has been developed to retrieve atmospheric temperature and moisture profiles from advanced IR sounder radiance measurements in clear skies and some cloudy sky conditions on a single field-of-view (SFOV) basis (Li and Huang 1999; Li et al. 2000; Weisz et al. 2007).

The algorithm is forecast independent and consists of three steps. The first step is the IR sounder sub-pixel cloud detection using a high spatial resolution imager cloud mask product (for example, the AIRS cloud detection can be derived from the MODIS cloud mask, and the CrIS cloud detection can be derived from the VIIRS cloud mask (Li et al. 2004)). The second step is to perform an eigenvector regression on the hyperspectral IR radiance measurements as the first guess of temperature and moisture profiles. The final step is to update/improve the first guess by performing a one-dimensional variational (1DVAR) retrieval algorithm with a Quasi-Newton iteration technique.

Radiance measurements from all IR channels are used in the sounding retrieval process. The CIMSS research product provides IR soundings with higher spatial resolution of approximately 12-14 km than the operational sounding product which is based on the AMSU or ATMS cloud-clearing algorithm (Susskind et al. 2003). The operational sounding product has a spatial resolution of approximately 45 km at nadir, which is much coarser than the resolution of most regional forecast models. CIMSS temperature and moisture soundings, retrieved from an advanced IR sounder at single FOV resolution, soundings in hurricane's environmental region can be assimilated in hurricane models for track and intensity forecasts. The single FOV soundings has also been used in the rapid refreshed model and has shown positive impact in forecast experiments (Li et al. 2012).

Building on decades-long research, CIMSS scientists continue to advance and refine the possibilities of advanced IR soundings from geostationary and polar orbit.

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Community Satellite Processing Package Transforms Data from Suomi NPP

The Suomi National Polar-orbiting Partnership (NPP) satellite is the first of a new generation of sentinels in low earth orbit for observing the atmosphere, land, and oceans. Suomi NPP carries sensors for detecting wildfires, measuring the temperature structure of the atmosphere, and mapping ocean productivity, among other applications. The data acquired by these sensors are transmitted to a ground station in Svalbard, Norway. From there, the data are sent to NOAA/NESDIS in Washington DC, where it is analyzed and processed on large computer systems. While these data cover the whole globe and span many different uses, users must wait two or more hours for them to be available. For anyone needing to make decisions in "real-time," this may take too long. Fortunately Suomi NPP has the capability to instantaneously transmit everything it observes to ground stations on Earth. With the appropriate receiving equipment, anyone can receive these data in real-time, process them on their own computer, and in less than 30 minutes, use the products to make decisions. This process is known as "direct broadcast" (DB), and it enables government agencies, research centers, and universities in the US and around the world to benefit from Suomi NPP observations of the Earth in real time.

U.S. weather satellites have had this capability since the 1970s, starting with the TIROS-N weather satellite and continuing with the POES and EOS Terra and Aqua satellites of today. SSEC has supported the worldwide DB community since 1985 with software packages for processing real-time data from these polar-orbiting satellites. These "Processing Packages" (ITPP, IAPP and IMAPP) were the forerunners in transforming the DB signal into data products and images, and a new set of software from SSEC named the Community Satellite Processing Package (CSPP) continues this tradition.

Figure 1. Image of Florida, Cuba, and the Bahamas on 21 November 2011, from the VIIRS imaging sensor onboard the Suomi NPP satellite.

To acquire direct broadcast (or DB) from Suomi NPP, a tracking antenna with a movable reflector is needed. The antenna tracks the satellite as it rises above the horizon and flies overhead. Typically the satellite will be visible from a mid-latitude location 2-3 times during daytime, and 2-3 times during nighttime. As the satellite flies overhead, specialized electronics and computer systems convert the radio waves received by the antenna into digital signals (or "raw data") that are stored on a computer hard drive.

Specialized computer software is then needed for decoding, geolocating, and calibrating the raw sensor observations. This software converts the raw data received by the antenna to physical quantities such as reflectance and temperature, and also assigns a geographic location to each observed data point. SSEC/CIMSS is playing an important role in providing this software to Suomi NPP DB users around the world.

The operational Suomi NPP software was originally developed to run on the large computer systems at NOAA/NESDIS in Washington DC. SSEC is funded by the JPSS Program to adapt the software to run on modest computer hardware in real-time. In April 2012, SSEC released the first version of the Community Satellite Processing Package (or CSPP) for Suomi NPP VIIRS, ATMS, and CrIS data to more than 40 different users representing government agencies and educational institutions around the world. The CSPP project provides the global DB community with a simple and reliable way to start using the data from Suomi NPP as soon as possible.

To introduce new users to Suomi NPP DB, SSEC/CIMSS scientists often travel far and wide. Recently scientists Kathy Strabala and Jordan Gerth traveled to Alaska and worked with members of the Geographic Information Network of Alaska (GINA) to install CSPP and trained National Weather Service (NWS) forecasters on how the VIIRS image products can be useful for weather applications. For the Alaska region, CSPP automates the processing and distribution of Suomi NPP VIIRS data for display in the Advanced Weather Interactive Processing System (AWIPS) at the National Weather Service (NWS) forecast office in Anchorage.

continued on page 18