4.5 NPOESS AND GOES-R—BUILDING A “SYSTEM OF SYSTEMS”

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1. INTRODUCTION

Late this decade, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) will initiate a new generation of passive electro-optical multispectral imagers and hyperspectral sounders to operate in three complementary orbit planes. NPOESS will replace the now-venerable civil Polar-orbiting Operational Environmental Satellite (POES) and Defense Meteorological Satellite Program (DMSP) systems operated by the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite and Data Information Service (NESDIS) and the Department of Defense (DoD), respectively. NPOESS will also provide data continuity for global environmental research initiated in 1999 by the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Terra, Aqua, and Aura polar-orbiting research satellites. NOAA NESDIS also plans to launch a next-generation Geosynchronous Operational Environmental Satellite (GOES-R) imager/sounder capability in 2012 to complement NPOESS, with a continuing focus on continental United States civilian severe weather monitoring and prediction to improve substantially on the current GOES contributions to national economic well-being and safety.

This paper reviews the most relevant lessons learned from EOS and NOAA’s currently operating Polar-orbiting Operational Environmental Satellite (POES) and GOES systems, and suggests that NPOESS and GOES-R together will represent a pragmatic and significant step towards the NOAA Administrator’s vision of integrated global environmental observation and data management system [Lautenbacher, 2003; http://www.osp.noaa.gov/strplan.htm], leading to an Integrated Earth Observation System (IEOS), an optimized, user-friendly four-dimensional (“4D:” spatial and temporal) global data assimilation resource. Specifically, this article identifies key requirements and an approach to realize the IEOS, predicated on data and information from international space- and land-based platforms operating in conjunction with US systems, and identifies specific aspects of NPOESS and GOES-R that will help make the IEOS vision a reality.

Key IEOS success requirements include: (1) encourage a dynamic and open international architecture, blurring development, sustaining engineering, and political boundaries; (2) spectroradiometric calibration coherence across sensors and platforms; (3) multiple sensing techniques and radiative transfer models with maximum synergy; (4) leverage today’s investments, specifically with respect to NPOESS and GOES-R and obtain maximum benefit from prototype systems; (5) employ data storage with transparent formatting, categorizing, sub-setting, and data distribution (both near-real time and reprocessing); (6) ensure effective NASA technology and research to DoD/NOAA operational deployment; and (7) pursue effective user feedback along the way.

1.1 “Let There be Light…”

Every day, the sun floods the Earth with light. Absorbed and re-emitted in the long-wave infrared (LWIR) from 8-20 µm, and anisotropically scattered off

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the atmosphere, clouds, ocean, and land in the visible to middle infrared from 0.3 to 8 µm, "environmentally processed" sunlight carries to space crucial spectroradiometric information describing the earth's natural and anthropogenic dynamics. Prior to 1960, most of this information was indeed "lost in space," but since then, GOES has provided hourly continental United States (CONUS) data, and POES has collected global data every few hours, both at a spatial resolution no better than a kilometer. With this very limited spatiotemporal coverage, they indeed capture only a small fraction of the available electromagnetically-coded information, yet 99.9% of all data assimilated into numerical weather prediction (NWP) models are satellite data (Uccellini, 2003, private communication). Therefore, any increase in satellite capability represents an equivalent increase in total global environmental prediction capability.

In his address to 2003 Earth Observation Summit, Greg Withee [www.earthobservationsummit.gov] described the five elements of the Earth observation system as: "research and operational observation instruments and platforms, *in situ* and remote sensing observation networks, communication links and computing capacity, application development centers, and the methodology to combine multiple-source data." This paper addresses these elements with respect to the maximum exploitation of a national treasure: our operational environmental satellite data and information.

2. DEPLOYING AN EVOLVABLE ARCHITECTURE

Neither science nor system architecture nor ingenuity stands still. Even "old," seemingly stable product systems must, and do, continually evolve to meet the needs and desires of the user community. This evolution is sometimes the result of improved science understanding and application. Other times, it is the result of scientist or even programmer ingenuity and innovation. And at still other times, the product evolution is the result of improved system architecture. Without a fully evolvable open architecture, one runs the risk of being obsolete by launch, and certainly by end of mission. As an example, the EOSDIS user interface was originally designed around the use of X-windows—this leading-edge-approach (at that time) was obsolete before launch due to the advent of the internet

Current operational GOES product systems have benefited, and continue to benefit, from all three of these evolutionary aspects. These types of evolutionary improvements have been most significant in the GOES Winds and GOES Soundings products. Using the GOES Soundings to exemplify these evolutionary changes, we can look at each of the aspects and how the GOES Soundings system has evolved from its original form.

In terms of scientific-understanding-based improvements, there have been several evolutions over the past decade. One such improvement was the comprehensive understanding of retrieval algorithm dependence on first-guess data. Forecast model data from the Environmental Modeling Center (EMC) is used as the first guess. Due to its high resolution, the ETA model was presumed to provide the best results. GOES soundings are predominantly used for their ability to analyze moisture, and not temperature. The ETA model was compared to the AVN (now GFS) model and was found to have superior moisture information. Thus, the ETA was used as the first guess. However, this did not represent a true understanding of the retrieval algorithm's dependence on the first guess. Because the GOES-derived moisture structure is the valuable data, the first-guess moisture is modified far more significantly than the first-guess temperature. Temperature and moisture are linked in the retrieval algorithm. Since the retrieval moisture is allowed more freedom to vary from the first guess, it is the first-guess temperature that is more critical. Upon further analysis, it was found that the low-level temperatures on the AVN model were superior to those on the ETA model (in the summer of 2003, a problem was discovered by EMC with the ETA low level temperatures). Given that, parallel tests were run to examine GOES soundings quality using the AVN as the first guess model. The results were rather dramatic, and the GOES soundings were notably superior using the AVN first guess.

As for evolutions due to ingenuity, a significant improvement in the GOES sounding system is scheduled for operational implementation in 2004. Because of relatively high noise in the current GOES sounder instrument, it was surmised during the initial design of the retrieval algorithm that several fields of view needed to be averaged to reduce noise and provide a scientifically reliable product. In a later evolution of the product system, an attempt was made to improve coverage as some apparently clear areas were flagged as cloudy (meaning that no retrieval could be generated at that location). In order to accommodate this apparent error, software was added to the cloud detection algorithm that would increase the noise allowance when insufficient clear fields of view were obtained. This resulted in an ingenious evolution. The retrievals with the increased noise allowance showed no quality degradation. As such, it was conjectured that the relatively poor signal-to-noise ratio was not as corruptive to the retrievals as originally expected. This led to testing of a parallel system performing retrievals on a single-field-of-view basis. After months of parallel testing, results actually showed the single-field-of-view technique to be of slightly higher quality than the original algorithm. So, not only was resolution improved dramatically, but the GOES Soundings quality actually improved slightly as well.

Finally, system architectures have also allowed for continuing evolution. Perhaps the most significant example also relates to the single-field-of-view retrieval production. From current operations (running five-by-five pixel retrievals) the single field of view production will result in about a 25-fold increase in the number of GOES soundings. Significant software enhancements were performed to improve the production efficiency, but when the time for BUFR encoding and product distribution is added in, there was still just enough slow-down that the GOES soundings would likely not meet latency requirements. The purchase of a higher-performance system architecture has resolved this issue. In fact, once single-field-of-view production begins operationally in 2004, the GOES soundings should actually get distributed earlier than their 5x5 production predecessors.

This is only the tip of the iceberg in terms of evolutionary changes. These are a few cursory examples of the types of upgrades and enhancements taking place in the current GOES product systems. The GOES Soundings have seen several other similar advancements. The GOES Winds have also gone through dozens of evolutionary improvements. Product evolution has been a bit less steep on the other product systems (Derived Product Imagery, ASOS Supplemental Cloud Product, GEWEX GOES Surface Insolation Product, etc.), but has still been noteworthy. The current suite of GOES products will likely continue evolving and improving until they are replaced by the new instrumentation in GOES-R and beyond.

The lesson learned in these examples is the need for a flexible environment and an adaptive culture. Demands, requests, and capabilities are constantly changing, even in the most apparently static of systems. Meeting evolving customer needs is more than mere maintenance and engineering of a steady system; it frequently requires an evolution of science and ideas. As a result, significant on-going development efforts are critical. Therefore, development and sustainability (research and operation) are not two separate areas of effort. Rather, active research and development is required to achieve operational sustainability. The examples given here have proven the development-sustainability synergy for over a decade on the present GOES satellite suites. Under current plans, this codependence and synergy will continue for the foreseeable future. It is difficult to imagine that NPOESS or GOES-R will alter this general idea.

3. CONSISTENT SPECTRORADIOMETRIC SCALES

3.1 Obtaining Desired Accuracies

4D data assimilation for NWP, as well as less-esoteric remote sensing data applications such as nowcasting, rural and urban environmental development monitoring, and research, all depend on satellite data in the form of estimated top-of-the-atmosphere (TOA) radiances. Clearly, the more accurate these estimates are, the more effective the applications. So, key ingredients in any effective remote sensing system are excellent satellite radiometers and well-characterized and validated radiative transfer models. While radiometer performance must be characterized by spatial and spectral coverage and resolution, “radiometry” is fundamental. Radiometry is characterized, in turn, in terms of both coverage and resolution, as well. In the case of radiometry, radiance “dynamic range” defines the sensor’s ability to measure radiance from the smallest to the largest magnitude to be encountered in a given application. Radiance “sensitivity” defines the sensor’s ability to distinguish the smallest variations in radiance to be encountered.

While spatial coverage and resolution must be accurate in terms of geolocation, this accuracy can be obtained across platforms and sensors via a common “global” reference frame, the Earth itself. Radiometric accuracy, however, defined as the error between a measurement of TOA radiance and the “true value” of that radiance, is difficult to measure consistently because every sensor must carry its own calibration reference, or refer to a common reference provided by another sensor that happens to be making precisely the same environmental measurement at the same time. Common radiance sources do exist that are known to a high degree of accuracy, and these can be used to develop accurate transfer reference radiance sources that can be carried aboard each sensor.

In the reflective spectral range from ultraviolet to short-wave infrared (SWIR) from 0.3 to 2.5 μm, the sun itself provides a direct reference source. This source has been estimated to a high degree of accuracy via continuing experimental and now more routine measurements by the National Institute of Standards and Technology (NIST) based on pioneering research conducted in the twentieth century by Neckel and Labs [1984]. The result is an excellent spectro-radiometric solar characterization at fine spectral resolution. This reference provides the basis for a solid standard which all radiometers can use. The difficulty is in transferring the solar reference to the sensor, as most sensors are not capable of looking directly at the sun.

Transfer references can be active or passive. Active references such as lamps that have been themselves calibrated against solar transfer standards provided by NIST are commonly used as a relatively “low radiance” substitute for the sun. Typically, the lamps are not directly viewed by the radiometer under test, but instead they illuminate a reflective surface whose reflectance is well-known. An example of this type of reference standard is the “integrating sphere.” The sphere provides a well-characterized white light source spectrally similar to the sun in terms of relative radiance across the spectrum from 0.4-2.5 um. A passive reference is a means of transferring the sun itself into the radiometer as a calibration standard. Typically, a diffuse reflecting surface is used to provide a reduced intensity solar illumination into the radiometer under test. The reflecting surface may not reflect precisely uniformly across the solar spectrum, so that it must typically be spectrally characterized prior to use. Moreover, these reflecting surfaces typically also vary in spectral response over time, particularly as they are repeatedly illuminated by the sun, mostly the ultraviolet portion of the spectrum. One way around this might be to place a UV blocking filter between the sun and the reflecting reference, but this filter also may change characteristics over time, therefore obviating its benefit.

The MODerate-resolution Imaging Spectroradiometer (MODIS) uses a Spectralon solar diffuser reflectance reference, reducing the reflectance with a partial screen so that the reflected light is within the MODIS dynamic range. To compensate for solar diffuser reflectance variation over time, MODIS carries its own lamp-illuminated integrating sphere calibration reference standard. This solar diffuser stability monitor (SDSM) comprises a radiometer that views the lamp-illuminated integrating sphere and the sun-illuminated solar diffuser, comparing the ratio of the two measurements over time to detect and estimate solar diffuser reflectance variations. These results are used to update the reflectance spectral calibration coefficients used in the MODIS ground calibration processing. These coefficients were initialized before launch based on MODIS measurements of the output of the NIST-calibrated laboratory integrating sphere radiance. The NPOESS Visible Infrared Imaging Radiometer Suite (VIIRS) will copy the MODIS reflectance calibration process, and therefore provide the best calibrated reflectance band TOA radiances ever obtained by an operational space sensor.

In the emissive portion of the spectrum, it is necessary to create an approximation of the ultimate reference, the classical Planck "blackbody." The blackbody is an ideal (not perfectly attainable) device that can remain at constant temperature in thermal isolation while absorbing radiative power at visible to SWIR wavelengths. It does this by emitting the same power at longer wavelengths, because otherwise its temperature would rise. The Kirchoff expression "power emitted = power incident" defines a blackbody. A greybody, on the other hand, reflects some incident light, and the Kirchoff expression includes the reflectance and a multiplicative factor in front of the emission term called the "emissivity" which is less than unity indicating that the device is not emitting the same power incident on the device. Were it possible to create a perfect blackbody, then a superb emissive spectral band calibration reference could be built, because the emission from a blackbody at any temperature is perfectly defined by the Planck radiation law. The approach would be to measure the emission of the blackbody at a series of temperatures covering the range of anticipated Earth scene temperatures. The known blackbody emission provides a "universal" reference frame, and the only problem left is to ensure that the temperature is well known.

Unfortunately, however, a perfect blackbody is unattainable. Instead, every attempt to create a blackbody results in a greybody, for which some incident light is reflected, rather than absorbed. "Emitted = reflected + emissivity x incident," where emissivity is less than unity, characterizes a greybody. While it is possible to create a device with an emissivity close to unity (e.g., 0.998 is obtained with the MODIS "blackbody" device), a greybody emissive calibration reference creates an inherent error because the emission is not precisely described by the ideal Planck radiation law, and a correction factor is necessary to compensate for the greybody emissivity. Therefore, not only the temperature, but the "blackbody" emissivity must be very well controlled and known to obtain the desired accuracy. And herein lies the challenge for inter-sensor and inter-platform comparisons in the IEOS era: how to obtain not only desired accuracies, but also inter-comparable data sets?

3.2 Obtaining Inter-Comparable Data Sets

One approach is to develop a consistent calibration reference process, and design architecture standard for all sensors. An example is the dual-instrument MODIS approach. Each MODIS instrument, one on the 2230 ascending-node Terra satellite, and the other on the 1330 ascending-node Aqua satellite, carries the same suite of calibration references discussed above. The solar diffuser and solar diffuser stability monitor (SDSM), and the emissive "blackbody" reference. The same pre-launch calibration procedures were applied to both instruments, as well. These design features and identical calibration procedures were intended to allow the two instruments to produce data sets that could be intercompared with radiometric consistency.

This desired result has been realized, as shown by K. Thome at SPIE in August 2003. There, results of comparisons of Terra and Aqua MODIS measurements of the University of Arizona White Sands desert test sites show close radiometric agreement. Interestingly, however, the two MODIS results are self consistent, but do not show such close agreement with other instruments. This may be a consequence of different calibration approaches used, as well as the different design features. Dr. Thome noted that the close agreement between the MODIS instruments could only be obtained if both instruments used matching calibration features and references tied to common standards, and matched with precision based on painstaking attention to a common calibration protocol. This lent confidence to the absolute radiometric quality of the MODIS results.

NPOESS VIIRS is designed from a calibration standpoint to match the MODIS approach, so that the NPOESS Preparatory Project (NPP) satellite to be launched in 2007 can be expected to offer radiometric consistency with Terra and Aqua MODIS instruments. Furthermore, successive NPOESS VIIRS instruments will offer inter-sensor calibration consistency. GOES-R is expected to offer a similar level of radiometric calibration accuracy, with reflective calibration accuracy of 3% (compared to NPOESS VIIRS 2%) and emissive calibration accuracy matching NPOESS VIIRS. GOES-R must provide improved imaging through the solar eclipse period around local midnight, as well as offer better global and mesoscale simultaneity and faster revisit at finer spatial resolution. All these improvements over the current GOES drive the GOES-R imagers towards better radiometric accuracy because faster repeat imaging of the environment means repetitive imaging of features which have less time to change. Therefore, better radiometric accuracy is required to ensure that differences in a scene feature from one image to the next are not just artifacts of instrument radiometric inconsistency between one measurement and the next.

Moreover, as NPOESS provides global three-hour repeat coverage and GOES-R provides partial global repeat coverage every 15 minutes or less, comparisons between the data sets from both systems are planned to facilitate utilization in global NWP models, and to use these to update inputs to CONUS and near-CONUS severe storm forecasts. The intent is to dramatically improve our ability to accurately extend severe storm forecasting so that the increasing coastal populations can receive longer-term warnings, reducing the economic and safety impacts of future hurricanes, tornadoes, and other damaging weather events. The success probability of this “mini-IEOS” (combining US GOES-R and NPOESS) strategy has already been improved substantially by the proven calibration approach demonstrated on MODIS and now being transferred to NPOESS.

IEOS carries this strategy further by seeking to integrate all space systems. It will be difficult, however, to effectively combine data sets from disparate international satellite systems if inconsistent radiometry is the basis of the integration. Intercomparisons of data sets measuring the same scene features will disagree if their calibrations are inconsistent. Therefore, a challenge of the IEOS development process will be to develop consistent calibration design features and protocols among international satellite remote sensing systems, as EOS MODIS and NPOESS VIIRS are demonstrating.

Polar and geostationary satellite data already constitute over 99% of the data ingested in NWP models. As these systems are improved, our ability to extend severe storm forecasts for the United States depends on consistent radiometry between NPOESS and GOES-R. Further success in extending severe storm warnings across the globe to benefit all nations will depend on extending the benefits of NPOESS and GOES-R calibration consistency to other international satellite systems.

4. EXPLOITING THE DIVERSITY OF MULTIPLE SENSING TECHNIQUES

The diversity of remote sensing measurements available from the NPOESS and GOES-R system of systems will provide an unprecedented opportunity to sample Earth's physical processes across a broad range of spatial and temporal scales in an accurate and repeatable manner. Exploiting the resulting synergies requires a ground system that can deliver data from this combined system to users in real time and in the same format to make it straightforward to use all NPOESS and GOES R+ data sources for weather forecasting, climate studies and other Earth science studies.

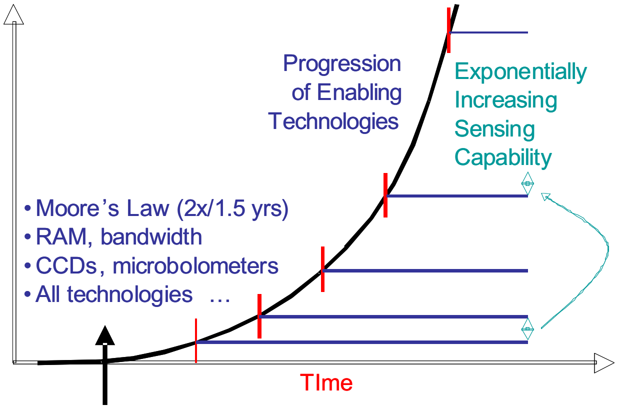
The obvious synergism provided by the diversity of observations made by NPOESS and GOES-R+ is to provide the full spatial and temporal coverage required to measure relatively long-term global changes in the Earth and its climate, such as global radiative energy fluxes, while simultaneously measuring the Earth's most transient physical parameters at high temporal resolution, such as the diurnal variations in aerosol, cloud, water vapor, and even air quality distributions.

In past and current systems, data from the POES and DMSP satellites in low-Earth orbit (LEO) have been used mostly for climate and longer-range weather prediction, while GOES data collected in geosynchronous Earth orbit (GEO) has been used primarily for daily forecasting, nowcasting and to issue severe weather warnings. In addition, data from the LEO satellites, which have been more repeatable and better calibrated than data from GOES, have provided quantitative input to numerical weather prediction models, while data from GOES has been used almost exclusively in a qualitative mode by weather forecasters.

In the NPOESS and GOES-R+ system of systems, due to significant advances in measurement repeatability and accuracy (especially for GOES) along with dramatic improvements in numerical weather prediction systems, both NPOESS and GOES data will provide quantitative input to numerical weather prediction (NWP) systems—through 3D and 4D variational data assimilation—and will provide measurements needed to derive and predict critical quantitative weather products such as total precipitable water and stability indices. Likewise, use of NPOESS data will extend beyond national NWP centers to regional and local weather forecast offices for providing specialized products such as soil moisture. NPOESS and GOES R+ data sets will be used together as a set of complementary integrated observations to address both weather analyses and forecasts produced throughout the western hemisphere, including the national centers and the local forecast offices.

5. LEVERAGING TODAY’S INVESTMENTS

As shown in the illustration below, progress in the upcoming decade may be equivalent to that of the last two or three decades. By 2009-12, many of today’s technologies will be obsolete. Yet progress is iterative. It is critical that we obtain maximum benefit from today’s prototype systems. Research and operations, properly managed, planned, and coordinated as a partnership with the user community, provide an integrated basis for future operational system, sensor, and algorithm stewardship. Let’s consider several examples.



First, consider the instruments and scientific algorithms that enable the sensing and conversion of sensed data into useful environmental information. It is critical that lessons learned in sensing the Earth be not only publicized, but also quantitatively stated, and then efficiently incorporated into next-generation systems. Every NPOESS and GOES-R planned sensor has a counterpart either in orbit today or will within the next year. Ongoing intensive validation of environmental products created from these new sensors is exposing, for the first time, specific areas of algorithm theoretical basis shortfall. These can be addressed through the collection of refined spectroradiometric data (a new or revised spectral band, for example), or improvement of the retrieval algorithm to more robustly account for the local phenomenology. The challenge is in achieving this so the lessons learned are rapidly exposed, socialized, and assimilated—thereby affecting next-generation systems. This requires quantitative, not qualitative findings so that cost-benefit assessments can be performed, understood, and communicated. Business "as in the past" may mean that the lessons learned are available just in time—for a third generation—skipping a near-future system that could otherwise have benefited.

Command, communications and control (C^3) and ground processing systems have been historically designed as sensor- or platform-specific implementations. We advocate systems built upon the collective experiences and best practices of NOAA, NASA, and DOD that apply transparently. A joint C^3 system for both POES and GOES platforms could potentially save money and provide for greater interoperability. Similar benefits can be realized in joint data processing and dissemination systems.

6. DATA STORAGE AND DISTRIBUTION

NPOESS and GOES-R increase the data volume delivered to NOAA by orders of magnitude. This increase must be accommodated by all the systems that support the operational and research environmental communities, particularly by the components that support data production, storage, and distribution. For example, today the NOAA Satellite Active Archive/CLASS ingests approximately 0.2 TB/day. The launch of NPP in 2006/2007 will raise that to 2.6 TB/day. The launch of the first NPOESS satellite in 2009 raises the daily archive rate to in excess of 5.3 TB/day. Subsequent NPOESS launches raise the rate by approximately 1 TB/day per spacecraft until the predicted archive rate is in excess of 10 TB/day [NOAA/NESDIS, CEMSCS Overview, July 22, 2003]. In addition, each satellite in the GOES-R series (first launch planned for 2012 is expected to produce >>1 TB/day of data).

Therefore, adaptable data storage and distribution strategies, which can be tailored to the specific needs of users, are needed to achieve a cost-effective set of capabilities that are part of the Integrated Earth Observation System. NOAAPORT, an important mechanism for broadcast distribution of operational weather products, provides data at 1.5 Mbps (or ~0.2 MBps). While incremental, or even step-function, increases in distribution bandwidth are possible via a NOAAPORT-like direct broadcast system technologies, these systems do not scale well unless the majority of the products being broadcast are required by most of the user base. When this is not the case, the issue becomes how to get *the right data, to the right user, at the right time* – not get *all of the data, to all of the users, all of the time*. There will always be high-volume users able and desirous of receiving all of the data (e.g., NCEP). However, there are many other operational and scientific users who would find this data tsunami overwhelming and not useful.

We believe the operations concept for data distribution should be built around tailoring products to the system's and users' processing, storage, distribution, communications resources, and information requirements. The following strategies are candidates for meeting the need of the broad spectrum of operational and scientific users of NOAA's data:

- **Direct broadcast**. The current direct broadcast capabilities of POES, GOES and NOAAPORT are critical elements of NOAA's overarching strategy to serve society's needs for weather and water information. Although it is probable that internet services for data distribution will satisfy a large fraction of the user community, it remains likely that availability and quality of service concerns with commercial internet providers, as well as cost of maintenance of private networks will mean that direct broadcast is still a valid option to many users either as the primary transport method, or as a backup. The concerns of this class of user (e.g., resolution, timeliness, bandwidth requirements, systems/technology/media, user upgrade cost, and transition approach) all need to be addressed.
- **Sub-setting**. Sub-setting of tailored products for distribution can be performed as a routine function and/or in response to a specific request (known as on-demand). Routine sub-setting is based on standing requirements (e.g., regional or data characteristic) that can be defined a priori. On-demand sub-setting is based on current and forecast conditions. For example, routine sub-setting can be used to cover tropical storm formation areas and can be defined well in advance whereas coverage of an existing tropical storm's path must be defined and updated as frequently as several times a day. Sub-setting to cover thunderstorm and tornado conditions need to be defined and refined on a timescale of hours, or even minutes. Sub-setting can be done in a temporal context also. A standing requirement for general surveillance might only require delivery of information several times a day, rather than every time an area is observed.
- **Sub-sampling**. Sub-sampling is done in either the context of reduced spatial (e.g., 10km resolution instead of a standard 1km resolution product), or, perhaps, spectral (e.g., reduced number of channels) resolution. Sub-setting and sub-sampling are combined to provide a continuum of data products from broad area, low/moderate resolution products to regional (or smaller) high-resolution products.
- **Subscriptions**. Subscriptions can form the basis for much of the data processing. Product subscriptions can range from *all data, all the time* to *some of the data, some of the time*. For example, the operational weather

modelers may want all of the data, all of the time while regional users may have requirements for the full or moderate resolution data, but only for limited geographic areas and/or times. Based on validated subscriptions, NOAA develops data products (e.g., upper Midwestt, tropical regions using sub-setting and sub-sampling capabilities). Similarly, event-driven subscriptions (e.g., lifted index or cloud cover) are used to tailor the delivery of data based on standing or *ad hoc* needs.

- **Search and order**. It will be difficult, if not impossible, to completely define a set of subscriptions that fully cover the range of conditions for which a user might need data. For example, an AWIPS user might be monitoring an area and decide that additional information not already covered by a static or dynamic subscription would be useful. An *ad hoc* query, either from the AWIPS terminal or a user client, allows the user to "drill-down" into the data for more resolution, more bands, more recent data, etc., or obtain data from other areas, time periods, or sensors that are helpful in understanding the current situation or forecasting.
- **Peer-to-peer access interfaces**. As data volumes increase, the traditional "person in the loop" search and order interfaces will be increasing supplemented by peer-system interfaces that automatically harvest NOAA data repositories for the products they need to generate their own domain specific information products.
- **Tailored delivery**. End-user capabilities and needs vary considerably. Their ability to both handle and make use of NOAA products varies from highly capable data-center-like operations to school-room desktop systems. Therefore, it is important that users have a range of data delivery requirements that can be documented in the subscription as either data push or data pull. In a push scenario, produced products are broadcast, transferred via FTP or otherwise sent to users. In a pull scenario, users are notified of the availability of products but products are not delivered until the user initiates the download.
- **Data Assurance**. Data assurance, the guaranteed delivery of scientifically valid data, is a key requirement for the system. Data assurance as a system requirement will result in meeting users' data needs via the architecture, design, implementation, and operations. Data assurance also means that the product, when delivered to the user, is scientifically valid. Sub-setting and sub-sampling create new products that must meet NOAA's quality standards. In addition, the user must be able to tell if data has become corrupted during transmission so the data must have a defined, controlled format that ensures data integrity regardless of the delivery media. Similarly, compression techniques to reduce communications and storage requirements must provide either lossless or lossy compression in a manner that maintains scientific and operational validity from the perspective of the system and the user.

While each of these approaches has the potential to reduce communications requirements and enabling the increased use of data throughout the operational and scientific community, these concepts impose additional requirements on data production, distribution, storage and management.

Level 0 or Level 1 products need to be stored and standard products produced based on operational and scientific needs. Dynamic requests create a need for *ad hoc*, produce on demand, processing to generate tailored products as described above. In addition, subscriptions based on data content (e.g., a parameter exceeding a pre-defined threshold value), are a source of additional produce on demand products and distribution. Simultaneous demands from many users or denial of service attacks could flood the system and degrade overall performance.

A long-term archive is needed to protect and preserve the permanent record, thereby enabling improvements in science through reanalysis, reprocessing and development of new, time-series products. As such the access patterns tend to be driven by long-term analysis campaigns and data volume rather than timeliness. The archive must contain, at a minimum, the Level 0 or Level 1 products, the production software and the control/initialization parameters used in operations. Selected higher-level products may also be archived to support distribution of historic data sets, provide a record for trend and long term studies, and support reanalysis and reprocessing. Reprocessing can then be performed on the data to improve algorithm performance or validate the impact of system changes via comparison with the operational products. Distribution of the archived data, reprocessed data, or new products is performed using the subscription and search and order capabilities described previously.

A short-term storage is needed to meet the immediate needs of the systems' users. As such, access requirements are very time sensitive. Short-term storage is needed to provide the community with a complete look at the recent and current environment. It also supports *ad hoc* subscriptions and search and order. It holds data between production and distribution for both push and pull scenarios.

System management is required to resolve resource issues when demand exceeds production, provide archive/storage, and distribution to ensure that needs are met in a prioritized manner and ensure system security and integrity are maintained. System management can mitigate these challenges by using allocating additional resources (e.g., GRID computing for processing), offloading service requests to back-up sites, or suspending service requests until higher-priority needs are met.

In summary, the higher resolution, improved temporal coverage, nature of the NPOESS and GOES-R systems requires innovative approaches to production, archive and storage, and distribution to achieve the NOAA goals of:

- Maintenance of a continuous and reliable operations environmental, and storm warning system to protect life and property.
- Monitor the earth's surface and space environmental and climate conditions

- Introduce improved atmospheric and oceanic observations and data dissemination
- Develop and provide new and improved applications and products (Miller, 2002).

7. RESEARCH-TO-OPERATIONS CONCEPT OF OPERATIONS

Research and Operations are inseparably linked. ***Operations*** is focused in achieving data product specifications at low risk and guaranteed certainty of timely delivery. These products are designed to satisfy documented, negotiated user requirements in a cost-effective, affordable manner. ***Research*** is interested in pushing the state of the art, striving to develop bleeding-edge solutions that answer emerging questions and issues. Many research efforts contain both fundamental science and applications with potential societal benefit. Together, research to operations should be considered a continuum—today's research anticipates, and underpins satisfaction of, tomorrow's operational requirements.

In a recent report, the Committee on NASA-NOAA Research to Operational Transition (CONNTRO, 2003) found that "a robust and flexible mechanism for transitioning research and technological advances quickly into operations is necessary." This has both strategic and tactical implications, and recognizes both "pull" (user demand) and "push" (research, development, and deployment) branches.

8. USERS' FEEDBACK

Obtaining users' feedback (the "pull") to provide general guidance and aid in the interpretation and implementation of the requirements towards designing optimal polar and geostationary environmental satellite systems is essential. The NPOESS and GOES-R systems are requirements-based missions (Withee, 2003). GOES-R Program Requirements Documents and NPOESS Integrated Operational Requirements Document are good examples of satellite agencies actively engaging in gathering users feedback. According to Mr. Withee, Assistant Administrator for Satellite and Information Services of NOAA: "*all sensors are traceable to specific requirements for one or all of the partner agencies. In many cases, a single sensor is required to meet different but equally important requirements of all three agencies and their customers and users*." So far two GOES user's conferences were held and the third one is scheduled. Unfortunately, while responsible agencies are putting users' requirements at the top priority for their satellite programs, no program can fully satisfy all interdisciplinary users with their intricate needs.

One of the good examples of users' feedback that has been taking place for more than 20 years is the International TOVS Working Group (ITWG) (http://cimss.ssec.wisc.edu/itwg/). ITWG is convened as a sub-group of the International Commission (IRC) of International Association of Meteorology and Atmospheric Physics (IAMAP). ITWG holds International TOVS Study Conferences (ITSC) every 18-24 months. While emphasis is focused mainly on operational polar orbiting atmospheric sounding data processing and utilization, it also serves as an excellent forum for participants to provide constructive users' feedback in the whole spectrum of the end-to-end process (Le Marshall, *et al*, 2002).

Another opportunity for users to voice their opinion about the end-to-end perspective of atmospheric and environmental remote sensing data utilization is the upcoming SPIE annual meeting to be held at Denver, Colorado on August 2-6, 2004. The Third GOES-R User Conference will be held on May 10-13, 2004, in Boulder, Colorado (http://www.osd.noaa.gov/announcement/).

To fully optimize users' feedback all involved parties such as satellite/sensor system providers, researchers, education/outreach institutes, data processing and algorithm developers, and commercial and general users must share the responsibilities of this end-to-end process. To achieve this goal we believe the following questions must be foremost on our minds:

- **Who** are the users?
- **What** do the users want and need?
- **How** do users use environmental remote sensing data and products?

While it is hard to get any degree of unanimous concurrence among the research community—this is a credit to their diversity—satellite agencies have relatively good knowledge and answers to these fundamental questions. To continue to gain additional insight into these areas and achieve total customer satisfaction, satellite agencies must continue to:

- **Promote** ongoing and future system capabilities
- **Hold** users conferences, workshops, and forums
- **Sponsor** expert team studies
- **Conduct** general surveys to pose the above questions and other relevant issues concerning information needed for implementing end-to-end programs, and, most of all
- **Provide** an efficient, transparent and open-minded interface to collect, understand, and embrace users' feedback

9. CONCLUSIONS, AND A LOOK TO THE FUTURE

How do we know that we are progressing towards a truly Integrated Earth Observation System? Many metrics apply and, like the various satellite architectures and issues discussed in this paper, the metrics themselves evolve over time. For example, one metric should be the interoperability, or degree of consolidation and interdependence, between polar and geosynchronous satellites. If this distinction blurs to the point that very few users realize that they are different, it will foster new creative methods for knowledge engineering: asset tasking, data collection, processing, fusion, and interactive dissemination. Another metric of success may be the degree of integration, of and interdependence across, different observing "systems." IEOS/NOSA will hopefully appear as another integrated, national infrastructure, like our highway system, phone system, and national power grid (but hopefully with higher reliability) where one "system" supports others to provide a transparent, continuous service. The analogy can be extended to include space, land, ocean, active, and passive sensing techniques. As with our current telecommunications system, callers do not necessarily know (and certainly don't care) if their call is supported over copper, fiber, satellite, or microwave. Similarly, environmental data users demand high quality, when they want it, for the lowest cost without regard to the source.

9.1 Vision Beyond 2020

It is unlikely our current approach of mixed polar and geosynchronous orbit platforms will cease to exist, given their unique benefits, but other options to augment this architecture may arise driven by economic factors, technology advancement, and geopolitical forces. These drivers certainly do not develop or exert their influence in isolation. In fact, they interact in a non-linear manner perhaps as complex as the global circulation itself.

Economic factors affect the future of environmental remote sensing systems in an unpredictable fashion. A booming economy often allows for more research and development thereby providing rapid advances. Moreover, major new or upgrades to existing sensing systems (e.g., NPOESS) often are started during economic upturns. Similarly, economic constraints (e.g., "… build GOES-R based on the GOES N-Q funding…") can stimulate innovation to achieve enhanced requirements with less money. It is often this paradigm that stimulates us to discover new and better methods. Economic factors will continue to encourage advances in the integration of observing platforms.

Forecasting the weather and economy may be easier than accurately predicting the future of technology. Fortunately a few aspects appear semi-predictable. Moore's law is likely to continue, along with analogs for other key technologies for the foreseeable future. Demand for computer resources will always exceed availability—this should be another recognized law. NWP, algorithm, distribution, and archive requirements always exceed the financial ability to provide the desired FLOPS, Gbps and Petabytes of on-line storage. A ray of hope is a recent advance in grid computing and other innovative approaches to better utilize existing resources. Sensing technologies continue to improve with better spatiotemporal and spectral resolutions, more reliable instruments, and better techniques to synthesize and extract meaningful information. For example, very large CCDs and compound optics will enable entire regions to be sensed simultaneously (without scanning mirrors) at high resolution thereby permitting regional NWP models to run nearly continuous 4D ensembles. High temporal and specialized "boutique" sensing may allow migration away from a generalized NWP model to more regionalized and "tailored" class of models that address specific user concerns (e.g., agriculture, power generation and distribution, climate variability, mesoscale, medical, economic.) The use of intelligent agents shows promise for customized processing. It is likely that advances in sensing technology will continue to outpace our ability to effectively utilize the knowledge. Perhaps the real challenge in 2020 will still be 4D data assimilation. However, revolutionary technology advances will increasingly occur in unpredictable step functions—e.g., last decade's internet explosion.

Advances in solar sails and optical communications may well permit "polesitters" with total Earth satellite coverage (for communications) from only two satellites instead of the large constellations currently required. Lightweight and low-power imager/sounders on polesitters may provide near continuous high-latitude data. These platforms (and other approaches) may help with existing global data latency issues. Active sensing may triumph as essential techniques from space, air, ocean, and land platforms.

Our current limitations of utilizing either sun-synchronous polar or geosynchronous orbits may be overcome by including other non-traditional space-based and air-based solutions. These might include pole-sitters, HEO, MEO platforms or other highly irregular orbit planes. Requirements that are currently only satisfied with space technology may come back down to Earth with new, inexpensive developments in land-based boundary layer profilers, over the horizon radars, or unmanned, high-altitude aircraft.

9.2 Only a Link in the Chain

NPOESS and GOES-R are just the beginning elements of IEOS/NOSA. It is important to remember that even IEOS/NOSA is only one critical link in the chain of systems required to provide important information to users throughout the world. Developing an advanced flight architecture and implementation for NPOESS or GOES or IEOS is necessary but not sufficient if the required elements to process, distribute, archive, distribute, and utilize the resultant data/information are not in place. To avoid this, the international community and NOAA, in partnership with academia and industry must consider, and comprehensively model, the complete end-to-end system from the end consumers of environmental information BACKWARD through each step in the chain terminating in the various sensing platforms.

9.3 Innovation—In the Eye of the Beholder

It is clear from the above sections that the every one of the core technologies required to make NPOESS, GOES-R, and the IEOS stunningly successful—meeting the needs of an ecstatic user community—are either already in place today or will be in place when they are needed. For example, thanks to Moore's Law, computing capacities in 2012 at the launch of the first GOES-R will be 64x (2^6) greater than today. Paradoxically, it is exactly this set of exponential changes in technology that creates our biggest challenge: seamlessly fusing research and operations to: (1) balance and merge freedom and order (Wheatley, 1993) and (2) achieve agile, consistent, repeatable, continuous adaptation. We must depend on a process that includes the routine utilization of emerging disruptive technologies at its very core.

As stated by Raytheon's CIO (Rhoads, 2003): "It is through the customer's value stream that we will deliver innovative solutions. A laser sharp customer focus is key to innovative solutions. Listening to [our] customers, [our] users, will yield the insight to develop innovative solutions. Listening to the customer makes it possible to respond to and deliver the unarticulated needs of the customer – true innovation." As the CONNTRO final report indicated, these opportunities exist at the system level, and include both advanced satellite sensor systems and enhanced data exploitation. By merging research and operations, in partnership with the end users, we can help to "create a culture that supports risk taking and a common sense of urgency."

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