10.1 THE ORIGIN OF SENSORS: EVOLUTIONARY CONSIDERATIONS FOR NEXT-GENERATION SATELLITE PROGRAMS

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1. PERSPECTIVE

U.S.-operated weather satellites have come a long way in the past half century since the launch of the Television/Infrared Observation Satellites (TIROS) in the early 1960's. Without question, TIROS heralded a new paradigm in our ability to observe and predict the weather. The evolution of the national weather satellite program through the modern-day National Oceanic and Atmospheric Administration (NOAA) K-series of Polar-orbiting Operational Environmental Satellites (POES) has been characterized by incremental improvements in hardware sophistication and associated sensing capability. The national geostationary weather satellite program, represented by the Geostationary Operational Environmental Satellites (GOES), has followed a similar path.

In the coming decade both the U.S. polar-orbiting and geostationary programs will undergo significant changes. POES will merge with the Department of Defense's (DoD) program to form the National Polar-orbiting Operational Environmental Satellite System (NPOESS; e.g., IPO, 2002), and the next series of geostationary satellites (GOES-R; e.g., Schmit *et al*. 2005) may opt for the first time to distribute its suite of sensors over more than one satellite. Both programs call for revolutionary upgrades to sensor design and capabilities, with the specifications governed by requirements-driven processes.

With the NPOESS and GOES-R programs serving as a contextual backdrop, this paper seeks to address in a more general sense some of the modern issues decision makers must face when designing the operational satellite programs of the future. With billions of dollars at stake, and the future of an asset that we have grown to rely on hanging in the balance, it has never been more imperative to take careful stock of our existing science capabilities, observation shortfalls, and realistic transition-ready technologies.

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2. THE BALANCING ACT

In an ideal world, definition of instrument requirements for environmental satellites would be determined solely by the observation requirements, as defined by research and/or operational community needs. In the real world, program budgets and politics play a large and competing role. Attaining optimal sensor performance in the instrument design phase of a program requires big-picture vision and correct interpretation of user needs. The degree to which balance is attained early on among these attributes will define the ultimate success of the program far down the road. Maintaining a degree of agility as the program enters its mature phase enables any minor corrections to its course.

The nature of our science is that there will always be more observational needs than resources to provide them. Even in the most well thought-out programs, potentially important sensor capabilities can fall through the cracks of the requirements process. Given the reality of budget limitations, placing an uncompromising emphasis on one technical capability will lead unavoidably to concessions or outright omissions in another.

In many cases, however, shortcomings of the final observing system design arise not from careful trade-space considerations but from unforeseeable issues. For example, sometimes a new discovery, technique, or capability emerges. Other times a previously established physical linkage is simply unexplored due to the scope of mission requirements. In still other cases users may not understand how to articulate the full breadth of their needs.

Fortunately, both the NPOESS and GOES-R programs include mechanisms for gathering research and operational community input (e.g., via the NPOESS Joint Agency Requirements Group (JARG) and Senior User Advisory Group (SUAG), and the GOES-R Users Conferences, Algorithm Working Groups, and Application/Science-Review Teams). The NPOESS Pre-Planned Product Improvements (or "P^{3}I") initiative provides a vehicle for ad-hoc sensor refinements/additions during the active-phase of the program, based on guidance and recommendations compiled from various channels of communication. NPOESS also sponsors Internal Government Studies (IGS) which includes the topic of un-accommodated Environmental Data Records (EDRs).

3. 'WEIGHTING' IN THE WINGS

Balance between program objectives and program budget is seldom achieved without the painful compromise or omission of capabilities recognized as being of great potential value. The sub-sections to follow detail a select assortment of satellite applications, pertaining to the upcoming NPOESS and GOES-R programs, which tipped the scales of this balance and as a result currently fall under the category of "P^3I candidates". It should be clear that these topics are presented here as general food for thought on coordinated satellite programs. While reality will never allow for a perfect sensor or system, we strive to attain the most informed compromise between reality and the ideal.

3.1 *Upper Tropospheric Winds and Turbulence*

A common misconception concerning the differences between polar orbiting and geostationary platforms is that the former provide global coverage and higher spatial resolution at the expense of infrequent temporal refresh, while the latter provide only hemispheric coverage and coarser spatial resolution but at the advantage of high temporal refresh. These generalizations are based on a mid-latitude reference frame. At higher latitudes, polar orbiting satellite swaths converge and overlap such that revisit times decrease for a significant fraction of the day. In this way, a constellation of sun-synchronous satellites having orbits spaced evenly across the day can provide nearly continuous, high resolution coverage over the earth's poles at a temporal refresh sufficient for tracking atmospheric motion.

The technique of wind speed and direction (vector) estimation based on feature-tracking was developed originally for geostationary satellite observations (e.g., Velden *et al*., 1997). While motion can be inferred from tracking cloud features using infrared window channels (e.g., 11.0 μm), the 6.7 μm (water vapor absorption band) channel expands the application significantly by providing motion information in the clear sky regions as well. The water vapor channel is not available on the current operational POES constellation. Only recently has this capability at last been demonstrated from polar-orbiting satellites (Key *et al*., 2002) using the 6.7 μm channels included on the Moderate-resolution Imaging Spectroradiometers (MODIS) aboard the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites (e.g., King *et al*., 1997).

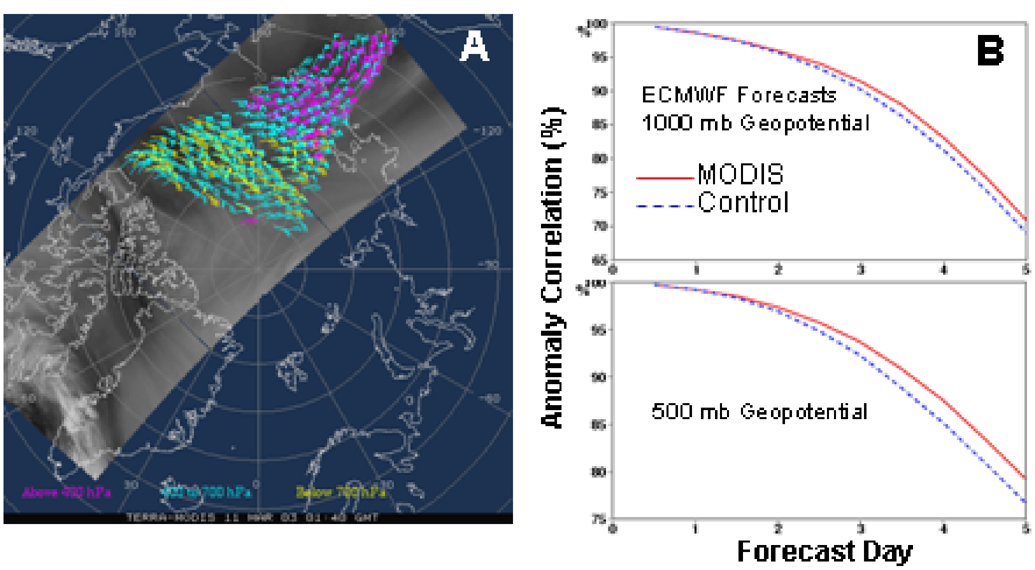


Figure 1. Example MODIS multi-level feature-tracked winds over the Arctic (A) and positive impacts of their assimilation into ECMWF forecasts of geopotential height fields (B).

Figure 1 shows an example of polar winds derived from Terra MODIS data, and the positive impact the assimilation of these winds has made in numerical weather prediction model forecasts (as applied to the European Centre for Medium-range Weather Forecasts). Panel A shows multi-layer wind vectors overlaid upon an Arctic-crossing Terra-MODIS swath based on water vapor feature tracking. Panel B demonstrates the improvements to 500 mb height anomaly correlations when introducing these polar winds into the multi-day European Centre forecasts.

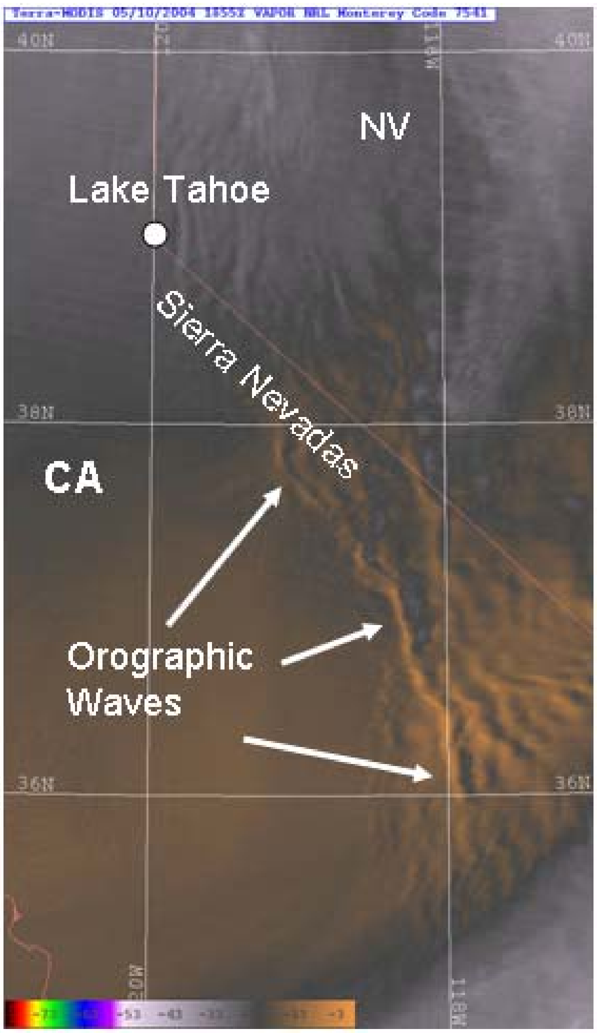


Figure 2. MODIS 1-km water vapor imagery reveals mountain wave structures in clear-sky regions.

In addition to polar wind vectors, the higher spatial resolution 6.7 μm water vapor imagery available upon Terra and Aqua MODIS has demonstrated additional utility in identifying clear-sky atmospheric wave structures (e.g., mountain-induced waves) which may prove useful in identifying regions of clear-air turbulence (e.g., Uhlenbrock *et al.*, 2006). Figure 2 demonstrates the clear-sky mountain wave structures revealed by Terra-MODIS 1-km vapor imagery over the Sierra Nevada mountain range of California. Other applications making use of this band include the diagnoses of deep convection (e.g., Schmetz *et al.*, 1997) and thin cirrus (e.g., Turk and Miller, 2005).

The 6.7 μm band was not among those included on the notional baseline for the Visible/Infrared Imager Radiometer Suite (VIIRS; Schueler *et al*., 2002). Given the strong case of its utility to improved numerical weather prediction and potential impact to NPOESS cloud mask environmental data records, considerations for inclusion of this band on follow-on VIIRS sensors (C3 and beyond) are now being made. However, given the NPOESS launch schedule, a full polar winds capability (2+ satellites with the requisite 6.7 μm band) similar to what is currently available from NASA research sensors will not be attained until the latter half of the next decade.

As the case may be, the omission of this capability on VIIRS is due to more likely the nature of the requirements-driven process (where polar winds in this case were not specified as a mission requirement), in addition to the relatively new demonstration of its utility on a polar orbiting constellation. Narrowing the scope of instrument capabilities optimizes the performance of selected EDRs but will come at the expense of overall sensor versatility. The multi-faceted topic of mission design philosophy and associated trade-offs will be revisited in sections to follow.

3.2 *Active Fires*

Satellite detection of active fires is a very important capability for understanding linkages between the biosphere and atmosphere, ultimately with implications to global climate. In an operational sense, wildfire managers and agencies interested in monitoring air quality (e.g., health or visibility impacts) use satellite-detected fire products extensively. Current users of MODIS-based fire products include the United States Department of Agriculture (USDA) Forest Service, the Nation Interagency Fire Center, the Bureau of Land Management, the National Park Service, NOAA, the United States Fish and Wildlife Service, and the Department of Homeland Defense. In addition, the Department of Defense has begun examining the utility of fire products as input to aerosol dispersion models (e.g., for atmospheric visibility models).

The physical detection of fires is predicated on the highly non-linear response of the Planck function (blackbody emission) to temperature as a function of wavelength. In the vicinity of the near infrared atmospheric window (~4 μm), the Planck function sensitivity to heat is very high, such that even sub-pixel heat features (e.g., narrow fire lines, whose temperatures can easily exceed 1000° F) dominate the total signal. This sub-pixel sensitivity to heat is markedly reduced in the ~11 μm thermal infrared window (i.e., in order to register the same temperature would require a much larger fraction of the pixel being ablaze).

In addition to knowledge about fuel type, moisture, and total biomass, knowledge of fire temperature itself is necessary for proper specification of smoke flux into the atmosphere. Dozier (1981) and Prins *et al*. (1998, 2001) detail a bi-spectral method for determination of the sub-pixel fire size and temperature given the brightness temperatures measured at 3.9 μm and 10.7 μm (two measurements and two unknowns). The technique requires that the measurements be unsaturated (primarily a concern for larger fires in the 3.9 μm measurements).

The current design specifications for NPOESS/VIIRS do not accommodate active fire characterization. The VIIRS moderate resolution (750 m nominal pixels, produced by a variable aggregation of sub-pixels across the VIIRS swath) bands useful for fire characterization include a 634 K saturation temperature for M13 (the ~3.9 μm band, attained via dual-gain operation) and a 343 K saturation temperature for M15 (the ~10.7 μm band, operated in single-gain mode). The lower limit for M15 will result in pixel saturation for large/hot fires. For comparison, the corresponding 10.7 μm band on MODIS saturates at ~400 K, which when combined with slightly coarser spatial resolution (1 km pixels) results in far fewer incidences of saturation.

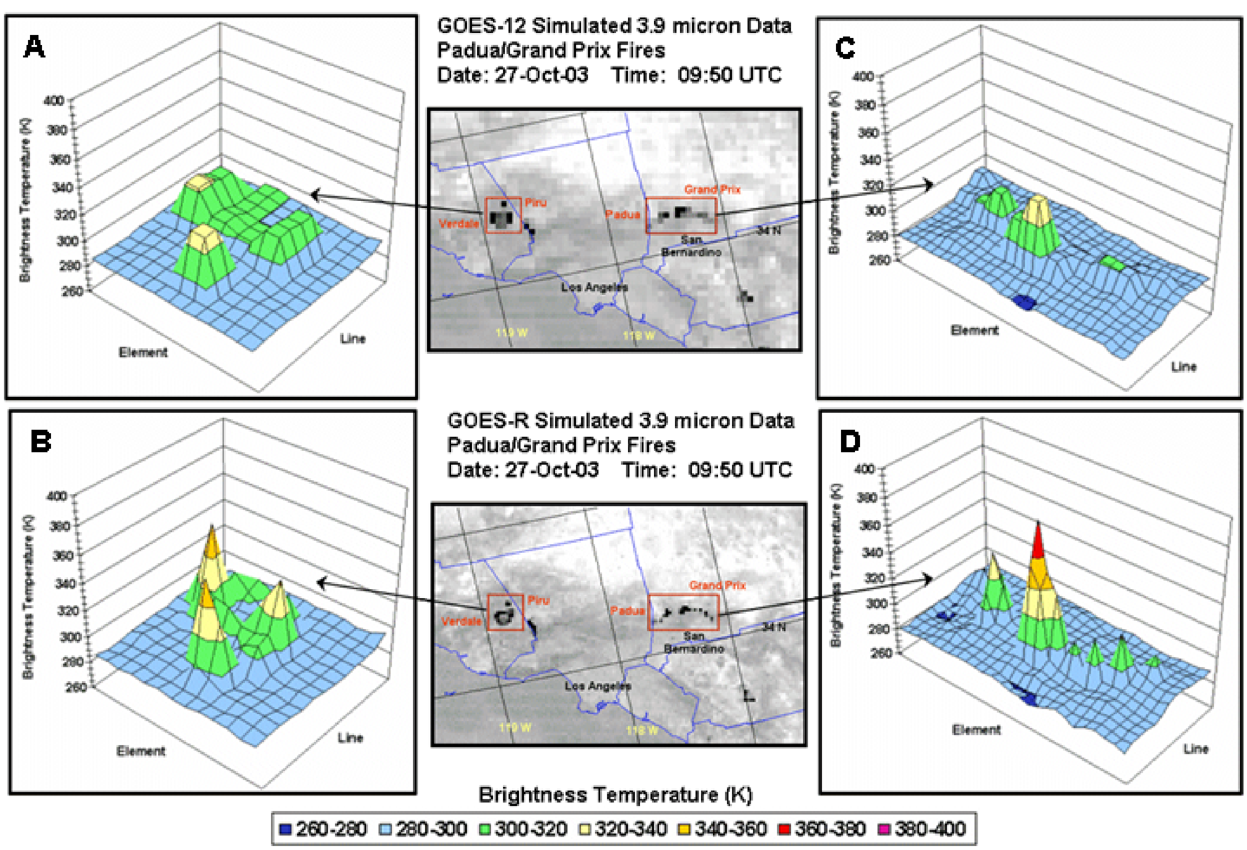


Figure 3. Example of the fire pixel saturation, based here on simulations of the GOES-R 3.9 μm channel for wild land fires over Southern California. Similar issues exist for the NPOESS M15 channel. Low/high saturation pairs (panels A&B, and B&C) show different structures and peak values bearing direct impact to aerosol dispersion model smoke flux characterizations. (From Prins *et al*., 2004).

Figure 3 demonstrates the general concept of detector saturation and its impact on the characterization of an active fire zone. In this case, fires observed by MODIS over southern California during the disastrous wild land firestorm of Fall 2003 have been rebinned and truncated to simulate the equivalent observations of the current (GOES-12) and future (GOES-R) geostationary operational satellites. Panels A and B correspond to the Verdale/Piru fires northwest of Los Angeles, and panels C and D correspond to the Padua/Grand Prix fires north of San Bernardino. In both sets of fires, the GOES-R simulations reveal significant additional structure and intensity detail. The hottest fire in panel D exceeds its counterpart in panel C by nearly 60° K.

Additionally, the on-board aggregation of samples to form the nominal pixel (3 samples aggregated for pixels 0-1060 km from instrument nadir, 2 samples from 1060-1700 km, and one sample from 1700-3000 km) currently does not include a quality flag indicating whether any of the individual samples was saturated (realizing that the aggregate of saturated and sub-saturated samples will yield a sub-saturated result). As such, all data within ±1700 km of nadir (two or more samples) cannot be used to characterize active fires via the methods mentioned above.

Kaufman *et al.* (1998) offer an alternative method for fire characterization, Fire Emitted Power, which is based solely on the 3.9 μm band measurement. Without *a priori* knowledge about fire area, there is of course no way to differentiate between smaller/hotter fires and larger/cooler ones via this single measurement method. However, the models used to parameterize smoke flux and the crude validation datasets available to researchers currently are not at a level of sophistication sufficient to reveal differences in skill between the variable area/temperature solutions. Furthermore, the bi-spectral method (e.g., Dozier 1981) method does not provide information on the sub-pixel distribution of the fire area computed, confounding the use of fire area for heterogeneous scenes.

The preferred situation from both a research and operational perspective naturally would be to field a sensor providing the ability to conduct all fire characterization methods—allowing for performance comparisons. For VIIRS, this would require either adjusting the dynamic range of M15 or implementing a dual-gain calibration. Dynamic range expansion would impact the radiometric resolution, with potentially adverse impacts to other EDRs employing M15. Dual-gain, as implemented on M13, could be triggered at a sufficiently high temperature threshold so as to avoid impacting other EDRs. In terms of achieving positive impacts to fire characterization at minimal hardware change to VIIRS, a lower-hanging fruit is the potential inclusion of a sub-pixel element saturation flag associated with the M15 band aggregate pixels between ±1700 km of nadir. Either change would require careful trade studies, and likely would not be realized on the first satellite of the NPOESS constellation (C1) but instead on follow-on members (similar to the previously discussed 6.7 μm water vapor band situation).

Given the importance of smoke source function characterization to all aspects of aerosol research, a group of affected agencies (representing defense, commerce, forestry, and academia) recently contacted the NPOESS JARG with the shared interest of defining a middle ground (in terms of exploring dual-gain on M15, or a report of M15 sub-element saturation). The SUAG accepted the JARG's recommendation to indicate for the record that an active fires product would be 'mission enhancing' for both civilian and military users. The NPOESS Integrated Program Office (IPO) will keep the SUAG and USFS informed regarding any ways that could provide a better active fires product without significantly impacting key performance parameters (KPPs) or program budget. Although no sensor design changes or additional quality flags were mandated as a result of this classification, it is a very positive sign in terms of opening an important dialogue toward initiating changes to follow-on members of the NPOESS series.

3.3 *Bioluminescence*

As our abilities to sense the earth increase in scope, sophistication, scale, and frequency, satellite remote sensing will continue to yield new insights on our planet's environment and its many unknowns. While common knowledge might suggest that the majority of these findings relate to clarifications on previously documented phenomena, occasionally we are reminded that there still exist many mysteries to our planet that remain to be revealed. Recently one such mystery was lifted out of the realm of folklore and science fiction and placed within the grasp of satellite remote sensing, with the NPOESS program suddenly representing a possible means for its future inquiry.

The ‘milky sea’ phenomenon (e.g., Herring and Watson, 1993), so called for the impression it has left upon many a sea-faring witness of these immense nocturnal displays over the centuries, is defined as an intense, uniform, and extensive body of glowing waters (often observed to extend to the horizon in all directions). Save for a single chance encounter with a milky sea by a research vessel in the mid 1980’s (Lapota *et al*., 1988), laymen accounts dominate the records. In a milky sea, the isotropic light emission from all parts of the water’s surface eliminates all contrast and depth perception, such that a ship passing through these waters perceives the motion of the ocean swell but cannot view it. The brightness of light has been likened to a snow or cloud covered plain, sufficient to read a book by, casting shadows on the ship decks and illuminating the bases of the clouds above.

While bioluminescent bacteria (which are known to produce a steady glow when a critical cell concentration is achieved) provide perhaps the most plausible explanation for these events, details surrounding the environmental conditions supporting the required bacterial populations remain a subject of scientific debate for lack of additional *in situ* observations. In any case, pursuit of additional knowledge pertaining to the circumstances under which such a profound ecological event could occur and the lessons they may hold for microbial ecology, the greater marine ecosystem, and perhaps the climate of the worlds oceans, certainly is a worthy research endeavor in its own right.

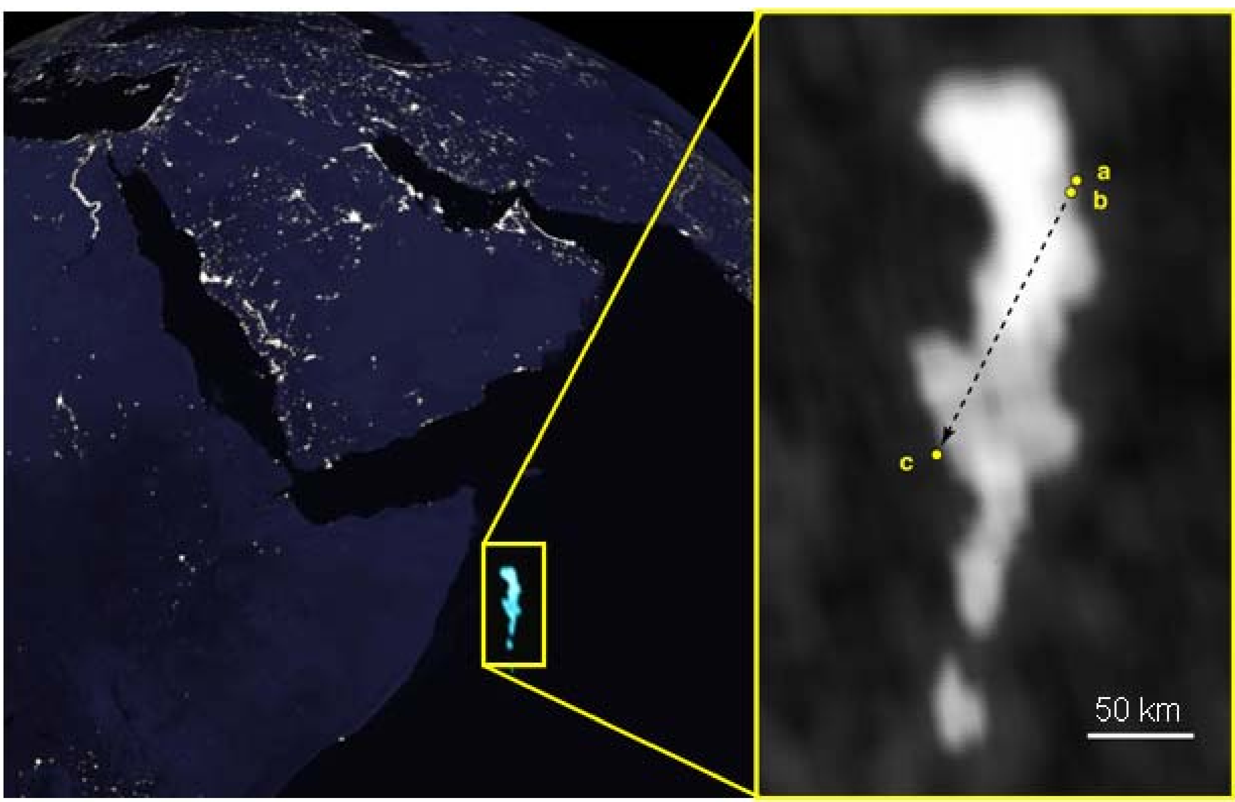


Figure 4. Left: satellite perspective in false color of a widespread region of glowing ocean, called ‘milky seas’, off the coastline of Somalia as observed by the DMSP OLS low light sensor. Right: ship observations confirming first-sight (a), first immersion (b), and exit (c) of glowing waters. Based on data collected 25 January 1995 (see Miller *et al.* 2005a).

Using low-light sensors available on the Defense Meteorological Satellite Program's Operational Linescan System (OLS; e.g., Elvidge *et al*. 1997, designed originally for the mapping of cloud cover at night by way of moonlight reflection), Miller *et al.* (2005a) demonstrate the first confirmed satellite observation of a milky sea. Figure 4 provides a satellite perspective on the never-before seen milky sea structure and scale (here, digitally filtered to remove low-level noise). The boundaries of the glowing waters feature, which spanned a surface area roughly equivalent to the size of Connecticut, were corroborated on the first night of observation by a transiting merchant vessel. Labeled points drawn on the zoom-in panel of Fig. 4 correspond to ship observations from the British merchant vessel *S.S. Lima* as it transected this event, denoting the ship positions when a glow on the horizon was first noted (point a), when it first entered the glowing waters (b), and when it finally sailed clear of the milky sea (c). The structural evolution of the glowing feature, as detected over the following two nights, was consistent with known sea surface currents in the area (tying it more definitively to the ocean surface).

The general significance of these findings is that scientists may now have a means of targeting these ephemeral phenomena with research craft, provided improved low-light satellite sensing capabilities are available in the future. The OLS sensor technology, which will be available on the DMSP constellation through ~2014, is very limited in terms of its ability to examine milky seas apart from confirming perhaps a small subset of surface observations. Barring the launch of a research satellite dedicated to the hunt for milky seas, the NPOESS/VIIRS Day/Night Band (DNB; Lee *et al*., 2005) represents the only viable sensor for their detection at reasonable confidence (i.e., sufficient to deploy research craft) over the next two decades. The DNB offers several technological advances over its legacy sensor, the OLS, which make it a far more capable sensor overall. Superior spatial resolution, improved radiometric resolution, reduced stray light and detector saturation issues, improved signal to noise ratios, and calibrated measurements will enable the quantitative exploitation of moonlight reflection and terrestrial light emissions. Used in synergy with its companion channels on VIIRS and other sensors on NPOESS, the DNB has the potential to augment many nighttime applications while opening possibilities for entirely new pursuits.

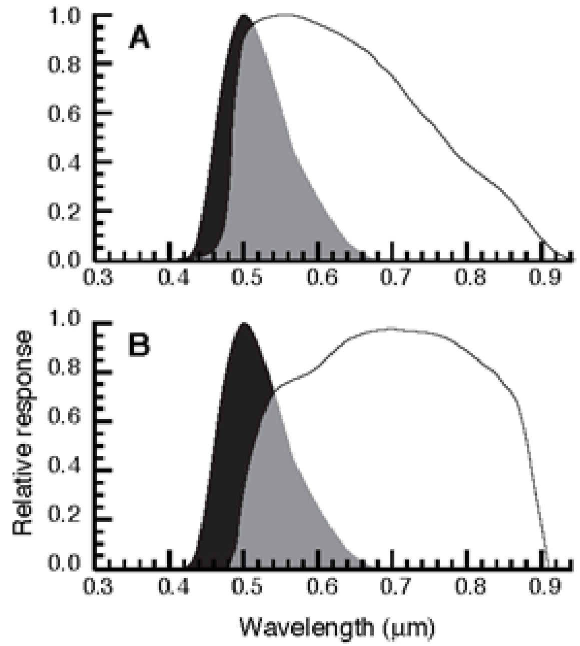


Figure 5. Spectral response functions for the DMSP OLS nighttime visible band (A) and NPOESS VIIRS day/night band (B) (gray lines), compared to bacterial emission spectra (solid black curve). Regions of spectral overlap are shaded in light gray. (From Miller *et al*., 2005a)

The lone shortcoming to the DNB design in the specific context of milky sea detection is its spectral sensitivity, which is shifted toward the longer (red) wavelengths of the visible spectrum in comparison to the OLS spectral response function (see Figure 5). Given that bacterial bioluminescence emission occurs over only a very narrow band in the blue/green light part of the spectrum (peaking near 500 nm), the resultant decrease in sensitivity to these emissions (a factor of two, as determined by Miller *et al*., 2005a) could offset the benefits of improved sensor fidelity. The current uncertainty of 'typical' milky sea emission power precludes a conclusive statement on this problem. However, shifting the DNB spectral response function to provide additional overlap with marine bioluminescence would certainly increase the likelihood of detection.

Changing the DNB spectral response would require careful trade studies to assess potential impacts to other NPOESS EDRs that may enlist this band. While development of a dedicated research sensor is a possibility, the DNB is so close to satisfying the detection requirements (as we currently understand them) for milky seas that it represents the first logical option. In light of the potentially significant positive impacts to the ocean sciences community, this would appear to be a worthwhile pursuit. Whether the scientific merit of such a discovery can influence a program already under tight budget constraints and having no explicit requirements for bioluminescence detection (‘bioluminescent potential’, listed as a DoD requirement in the NPOESS Technical Requirements Document, is an inference based on daytime shortwave ocean color observations and is not a direct detection of active bioluminescence) remains to be seen. The NPOESS P^{3}I allows for opportunistic revisions to a program as unanticipated applications arise, improved algorithms are developed, or preliminary design shortfalls are discovered. This is an important element of any next-generation satellite system, and will be the avenue pursued as a possible solution to the milky sea detection problem in coming years.

3.4 *Geostationary True Color*

Natural or “true” imagery is enabled by combining solar reflectance measurements from three narrow bands defining the blue, green, and red wavelength portions of visible-spectrum light and scaling the result to simulate the response of the human retina’s cone cells. While the representation to actual human vision is only approximate by way of current sensors (whose red/green/blue channel spectral response functions match those of cone cells only to first order), presenting satellite imagery in this way improves the ability of human analysts to interpret various components of a complex earth/atmosphere scene by providing an inherently familiar reference frame. Whenever available, true color imagery is the presentation option of choice for experts and non-experts alike.

Although radiometers aboard low earth orbiting satellites have long demonstrated the superb image quality benefits of true color along with quantitative information (e.g., aerosol and ocean color) derived from its component bands, not since 1967 (Multispectral Spin-Scan Camera aboard NASA’s ATS-3) has a radiometer offering the capability flown in geostationary orbit. Geostationary sensors provide high temporal refresh rates that are of fundamental value to operational users. Interactions between NRL satellite meteorologists and Navy and Air Force weather officers during Operation Enduring Freedom and Operation Iraqi Freedom (Miller *et al.* 2005b) regularly touched on the desires of these users to obtain more frequent updates to the polar-orbiting natural-color-capable sensors.

The 16-channel Advanced Baseline Imager (ABI; Schmit *et al.* 2005), developed as the featured imager for the next-generation Geostationary Operational Environmental Satellite (GOES)-R Series, included in its original design all three channels required for natural color imagery rendering. However, the 0.55-micron (green) band was subsequently removed from the ABI notional baseline due to budget constraints within the program. Given that imagery traditionally has represented a key performance parameter of optical imaging radiometers, the reasons behind the omission of what is arguably the most popular imagery application to end-users upon one of the most operationally relevant satellite orbits for so many decades are worth exploring.

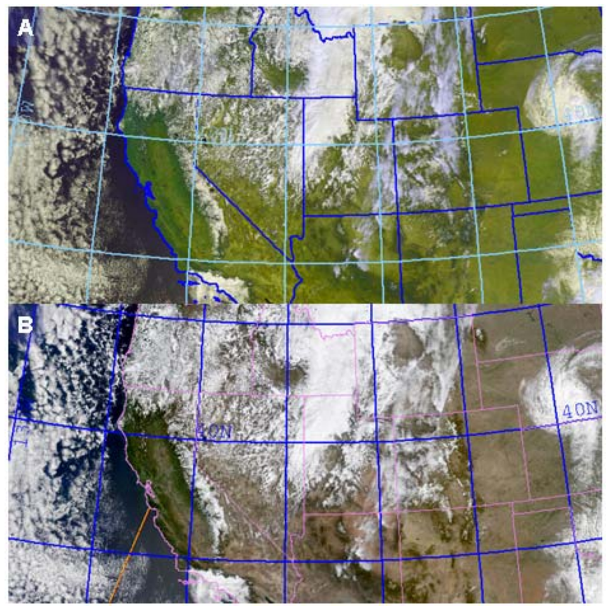


Figure 6. Comparison between an AVHRR pseudo color approach (A) and MODIS true color (B) for a close space/time matched scene over the western United States.

Surrogate techniques to natural color imagery do exist, and have been demonstrated to various levels of effectiveness. In lieu of red/green/blue spectral bands, “pseudo” natural color techniques based, for example, on combinations of broadband visible, reflective infrared (sensitive to vegetation) and thermal infrared (primarily for cold cloud distinction) bands have been attempted. The technique has been applied to Advanced Very High Resolution Radiometer (AVHRR) data with generally poor/unrealistic results (e.g., yellow/blue-tinted low/high clouds, exaggerated vegetation, and poor littoral characterization) compared to natural color. Figure 6 compares AVHRR (pseudo) and MODIS natural color techniques for a close time match over the western United States, and illustrates several of the artifacts mentioned above (cloud tonality, in particular).

For sensors lacking only one of the three required bands for natural color (e.g., the ABI and its missing green band), more sophisticated approaches are possible, involving look-up tables (LUTs) that take advantage of correlations between the missing information and that which is available. The LUTs are developed using polar orbiting sensors possessing all requisite spectral bands for natural color, and then are applied to sensors lacking the full suite of information.

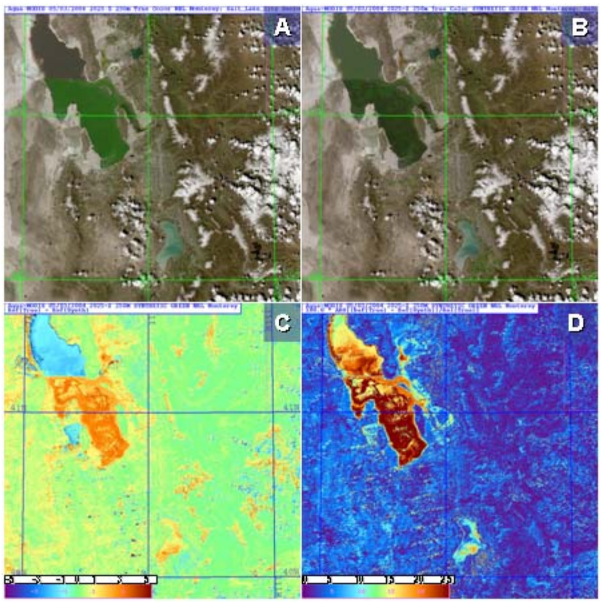


Figure 7. Analysis of errors in a synthetic true color technique (where the green channel is modeled as a function of red, blue, and reflective infrared information) applied to MODIS data. A: true color imagery, B: synthesized green channel, C: absolute error in green reflectance, D: relative error in green reflectance.

The LUT approach has been demonstrated and quality-checked using MODIS data, where the green (0.55 μm) band has been synthesized via a functional relationship between blue (0.47 μm), red (0.65 μm), and reflective infrared (RIR; 0.87 μm) channels. Figure 7 shows an example of this technique for a MODIS scene centered over Salt Lake City, Utah, illustrating the capabilities and limitations of the technique. Panel A depicts the natural color reference image, panel B shows the synthetic-green simulation, and panels C and D show respectively the absolute and relative differences between the true and synthesized green band reflectance. While most of the land areas are reproduced reasonably, the turbid waters of the Great Salt Lake suffer considerable artifacts arising from non-unique relationships between the red/blue/RIR and green bands.

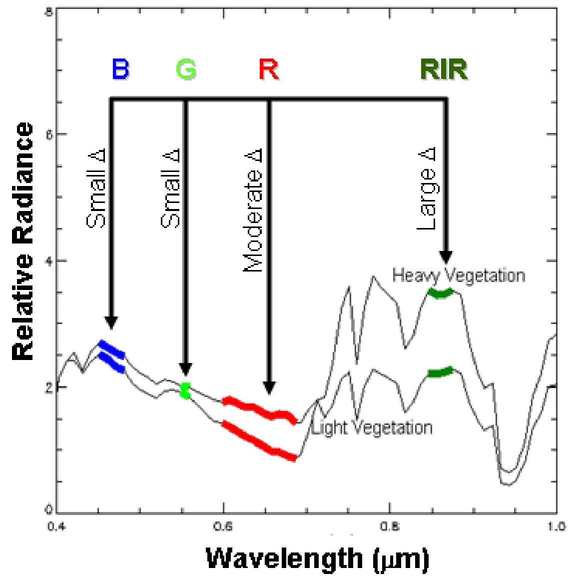


Figure 8. Example spectra based on AVIRS measurements over two green vegetation scenes, illustrating the concept of ill-posed relationships between B/G/R/RIR bands.

The nature of this non-uniqueness is illustrated in Figure 8, based on Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data shown for two different vegetation scenes. In the same way that non-unique solutions exist for RIR as a function of red/green/blue triplets in this example, the relationship between green and blue/red/RIR triplet is often non-unique. The problems are most notable in relatively dark, laminar scenes, such as lakes and shallow water coastal zones. Unfortunately, the littoral is precisely the region where natural color is most useful to many operational users. In addition, LUTs must be updated in different areas throughout the year in order to capture seasonal trends to retain any semblance of realism, and can under no circumstances capture transient phenomena (natural disasters—[tsunamis, forest fires, hurricanes, oil spills], drought patterns, ocean phytoplankton blooms and water turbidity).

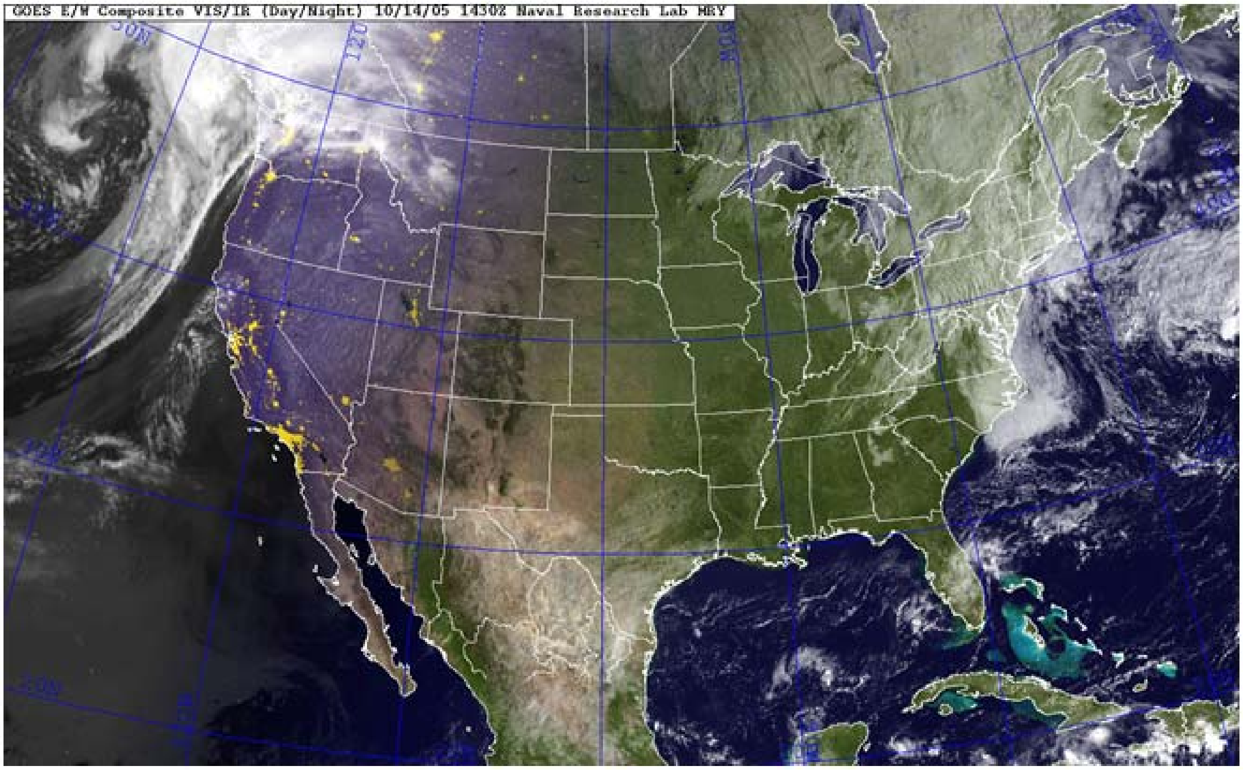


Figure 9. Example of a ‘dynamic transparency’ technique based on GOES satellite visible/infrared foregrounds and earth atlas data (e.g., MODIS Big Blue Marble and NGDC Nighttime Lights of the World shown here for day/night, respectively) backgrounds over the continental United States.

As a fallback option to simulation methods, one can enlist static backgrounds with a dynamic transparency strategy enabling the overlay of clouds from a panchromatic visible sensor. Figure 9 demonstrates such a technique applied to a morning time view of the continental United States, wherein GOES-E visible data provides cloud information atop the NASA MODIS “Big Blue Marble” dataset over the eastern portion of the country, and GOES-W infrared data provides similar cloud information atop a customized nighttime background that enlists the National Geophysical Data Center’s “Nighttime City Lights of the World” dataset. As with the LUT approach, these static backgrounds must be updated to capture seasonal changes.

An intriguing question of satellite meteorology is how such a highly sought after satellite imaging capability could be omitted entirely from geostationary sensors for half a century, particularly when considering that imagery quality has always been the principle user requirement. One possibility is that the naturally quantitative nature of the instrument requirements process has no means to identifying and reconciling the qualitative (but equally viable) needs of human analysts. The ability to “read between the spectral lines” in addressing all aspects, both quantitative and qualitative, of user needs and then translate that information into corresponding sensor requirements is regarded as a key element to the success of any integrated satellite program.

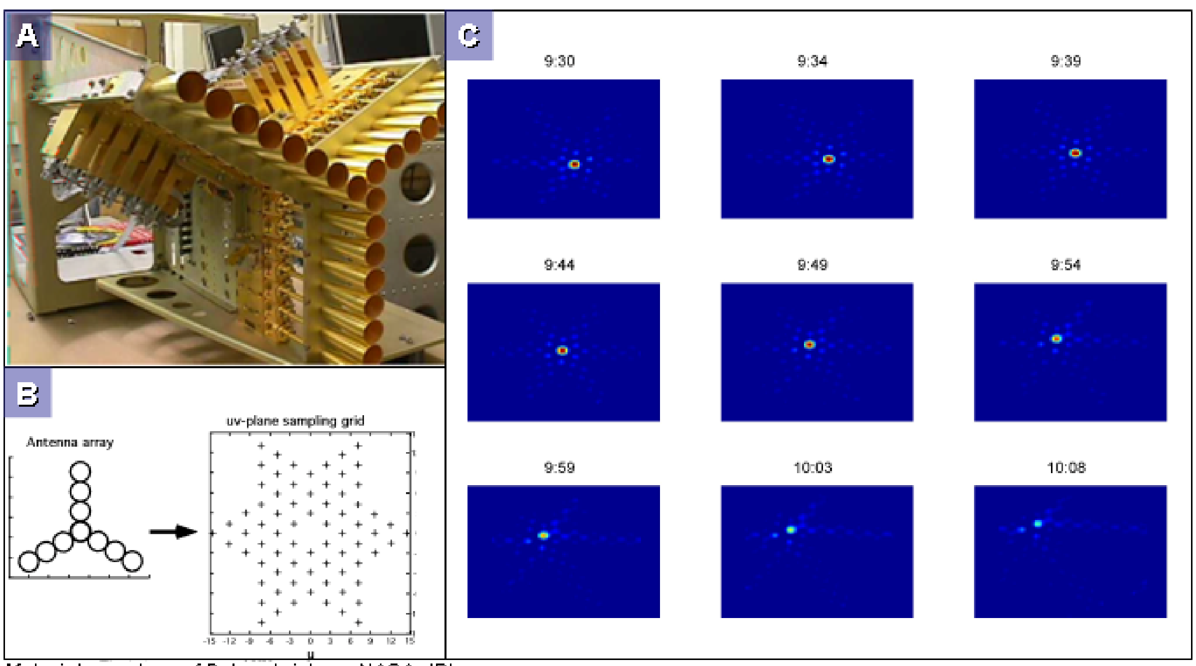
3.5 *Geostationary Passive Microwave*

In motivating the benefits of a passive microwave (PMW) atmospheric remote sensing capability in geostationary orbit, we need look no further than the elaborate methods currently employed to piece together the intermittent PMW from the low earth orbiting constellation for a myriad of applications (Turk and Bauer, 2005). In general, microwave remote sensing provides a viable means to obtaining intra-cloud and sub-cloud information (whereas passive optical sensors are limited to primarily to cloud-top characterization, e.g., Greenwald *et al.* 1999). PMW channels in the oxygen (e.g., 50 GHz) and water vapor (e.g., 183 GHz) absorption bands allow for ‘all-weather’ atmospheric temperature and moisture sounding. The PMW has also proven useful in quantitative precipitation estimation (e.g., Turk *et al*., 2000; Kummerow *et al*., 2001; Bauer and Mugnai, 2003) and tropical cyclone monitoring (Hawkins *et al.*, 2001). Identifying water vapor features and knowledge of temperature profile (e.g., from 183 GHz and 50 GHz PMW bands) would also allow for wind vector retrievals based on techniques mentioned previously (Velden et al., 1997).

While there has historically been a strong desire for PMW sensors on geostationary orbit (e.g., to characterize rapidly changing weather phenomena), significant technological challenges have stood in the way—foremost among them, the requirement of a prohibitively large real aperture (parabolic reflecting) dish in order to obtain sufficient signal from the ~36,000 km geostationary orbital range at the spatial resolutions necessary for useful environmental applications. For example, a 10 km nadir resolution would require dish diameter of 15 m, 35 m, and 70 m (!) for 90 GHz, 37 GHz, and 19 GHz frequencies, respectively.

As suggested by these numbers, improved spatial resolution requires either a larger aperture or operation at shorter radiation wavelengths. Recent proposals have been submitted to place a ~3 m diameter (real aperture) reflector dish (featuring a nodding sub-reflector to accomplish the physical scanning motion) in geostationary orbit under the U.S.-led Geostationary Microwave observatory (GEM; Staelin *et al* 1998) and the European-led Geostationary Observatory for Microwave Atmospheric Sounding (GOMAS; Bizzarri *et al.* 2002). These sensors would offer modest spatial resolution for a 54 GHz (87 km), 118 GHz (37 km), 183 GHz, and 380 GHz (12 km) over selected spatial domains.

The GOMAS and GEM systems emphasize improved precipitation retrievals and all-weather temperature (T) and moisture (Q) soundings based on high frequency (> 50 GHz) PMW measurements in geostationary orbit. While the relationship between these measurements and hydrometeors in the lower atmosphere is indirect, the rapid-update observations would represent a significant boon to other applications such as the visualization of storm structural evolution (e.g., tropical cyclone eyewall replacement cycles) through morphing techniques (e.g., Joyce et al.,2004).



Materials courtesy of B. Lambrigtsen, NASA-JPL

Figure 10. Panel A: Prototype for the 'GeoSTAR' geostationary microwave sensor. Panel B: demonstration of sparse array sampling grid correlation pairs. Panel C: example data collected by GeoSTAR as the solar disk crosses the sky.

As a work-around to the logistical challenges of deploying a large real aperture dish in space, engineers recently have developed technology for synthetic aperture PMW systems. Synthetic aperture antennas eliminate mechanical scanning by using a two-dimensional sparse array of receivers (spectrometers, to measure multiple frequencies) oriented linearly to form a symmetric "Y" configuration and synthesize a large aperture. Each receiver element corresponds to an image pixel, with the missing pixels in between the "Y" axes being reconstructed through interferometry (correlators between each receiver-pair).

Sponsored by the NASA Instrument Incubator program, the Geostationary Synthetically Thinned Aperture Radiometer (GeoSTAR; Lambrigtsen *et al.*, 2006) design provides in principle an unlimited aperture with no moving parts (platform disturbance is eliminated), the inherent ability to view the full disk (as opposed to limited coverage areas), and at lower power consumption. A laboratory prototype, constructed at the Jet Propulsion Laboratory in Pasadena, CA, is shown in Figure 10A, along with a schematic of the sampling grid (B) and test observations of the solar disk passing over the instruments field of regard (C). Spatial resolution, defined by properties of the receiver spacing as proposed for GeoSTAR provide 54 GHz at ~50 km and 183 GHz at ~25 km. A 90 GHz atmospheric window channel is also possible.

Similar to GOMAS/GEM, GeoSTAR emphasizes T/Q and precipitation retrieval capabilities, of benefit to cloudy-scene soundings and analysis of tropical cyclone warm core evolution (e.g., Brueske and Velden, 2003). Measurements of acceptable quality for data assimilation will require more channels with relatively narrow bandwidths (for sharper weighting functions) and longer sample times (for improved signal-to-noise ratios). A prototype system has been developed and tested at the NASA Jet Propulsion Laboratory, with an eye toward fielding a risk-reduction space sensor in the years prior to launch of GOES-R. Given the large number of correlators and associated electronics involved, cost and risk trade studies between systems like GeoSTAR and simpler systems like GEM will be required.

Regardless of the technology version settled on, geostationary microwave remote sensing is apparently a capability whose time has come. However, as with all new technology to be transitioned to operations, it is imperative to first shepherd it through a risk-reduction program that includes a space-system prototype. These activities traditionally have been conducted under the auspices of NASA. In light of recent visionary shifts toward robotic and human space exploration (e.g., Moon, Mars, and beyond) at NASA, competition for sponsorship for various earth science programs will stiffen. The next section points out challenges central to the development of future environmental satellite programs.

4. FACING THE CHALLENGES

The Committee on Environmental Satellite Data Utilization (CESDU; formed in 2003 under the auspices of the National Academy of Sciences at the request of NOAA and NASA), was convened to examine current practices, characterize process weaknesses, assess resources and needs, and identify factors impacting optimal management of data and strategic analysis for the purpose of maximizing the potential of environmental satellite data. The CESDU has identified a "Three-Pillar Partnership" in which government, academia, and industry work hand-in-hand in optimizing advances in end-to-end satellite remote sensing programs.

Recommendations stemming from the CESDU are likely to influence key elements of the U.S. Environmental Protection Agency-led Global Earth Observation System of Systems (GEOSS; www.epa.gov/geoss/; Goldberg 2006) policy. The GEOSS is an international effort to integrate/coordinate a diverse suite of observing systems to address natural disasters, predict future climate, and understand historical climate change on the global scale. Its 10-yr implementation plan is endorsed by over 60 countries and the European Commission.

An important emphasis of any integrated program (domestic or international) is on the development of generalized, physically based algorithms capable of leveraging multi-sensor observations and quantifying rigorously the uncertainty of their results. For multi-agency, internationally coordinated programs such as GEOSS, a calibration standard for all sensors participating sensors is also mandatory. Some additional (by no means comprehensive) considerations, quagmires, and conundrums pertaining to requirements definition, prioritization, and implementation are examined briefly here.

4.1 *Lost in Translation: The Full Scope of User Requirements*

The ability to address user needs defines the core success of any operational satellite observing system. The task of capturing these needs is not always as straightforward as it may seem. Operational applications must first be dissected to reveal the underlying environmental parameter dependencies, from which the measurement (or science) requirements can then be inferred. Only then can the transfer function that maps science requirements to instrument requirements be defined by the sensor fabricators (i.e., industry).

It may be helpful to consider this problem from the perspective of a moderated negotiation between the mission planners and end-users. The primary complication to attaining a constructive dialogue is the technical language barriers that often exist between science and operations. Is it necessarily reasonable to assume that the end-users always comprehend what their requirements are? If not, then who shall interpret the needs on their behalf? Does the scientific interpretation of the user's requirements capture the full scope of actual user requirements? In the most general sense, how do we avoid situations where 'implicit' user requirements are lost in translation?

For example, in re-visiting the geostationary true color topic, the overwhelming sentiment of satellite imagery users within the DoD, forecasters within the National Weather Service and broadcasting, the private sector, and the general public (based on both personal discussions and general observations of imagery usage) is to use true color satellite imagery whenever it is available. While to these users true color is the implied outcome of a "high quality imagery" requirement, to scientists the same requirement is interpreted in terms of spatial resolution and radiometric accuracy (quantifiable) parameters. While these latter attributes of course are important to imagery quality, in this case they do not fully capture the user's requirement. In fact, a qualitative capability such as true color, however important, holds little footing in the current requirements process since it does not map to quantitative threshold/objective terminology. Since humans are implicit end-users of satellite imagery, there will always be cases where qualitative needs must somehow factor into an inherently quantitative requirements process.

4.2 *Prioritizing Science Requirements: Where the Apples and Oranges Fall*

Operating under finite program budgets, satellite programs often are confronted with the very difficult task of having to eliminate initially planned capabilities due to unforeseen cost overruns. While a clear vision for the core mission requirements provides the first level of protection for a subset of capabilities, below this level the waters muddy and the fate of those capabilities remaining lies in the hands of an ad hoc judicial ranking system. To what extent such a system can effectively prioritize secondary capabilities in the context of mission requirements determines the degree of difficulty and contention associated with this selection process.

A central challenge, and one that we cannot fully address here, is how to fairly and objectively prioritize requirements belonging to different genres of science and having entirely different metrics. Understanding what defines a mission "critical", mission "optimal", and mission "enhancing" capability is a helpful first step, but even here an element of subjectivity is present. One obvious mechanism for salvaging (or adding/changing) a capability is when the head of an agency, acting on the guidance of an appointed panel of experts, declares it as mission-critical to the agency and puts money toward supporting it. Applications without such agency backing must attempt to stand on their own merit, championed most often by small consortiums of stakeholders.

Circumstances may also dictate the compromise of certain capabilities (e.g., backing off on threshold performance requirements) in order to enable/preserve additional ones that currently rest on the chopping block. Examples are exchanging radiometric resolution for increased dynamic range, or adding one channel at the expense of spatial resolution in another. Particularly in the context of inter-disciplinary research, having a more complete picture of the environment can often be superior to having more detailed information about only a component of it.

4.3 *Achieving Balance in the Three Pillars Paradigm*

The CESDU-defined "Three Pillars" (comprising government, academia, and industry) each serve distinct and important roles in the development of a satellite program. Generally speaking, the role of government is to provide an overarching vision, assemble and coordinate resources, and ensure the fundamental scientific/technical integrity of the mission. Academia provides a free realm for technically diverse conceptual development, innovation, prototyping, and proof of concept. Industry is responsible for fabricating through technical development and innovation a system capable of meeting all the science mission requirements specified. These are of course idealized roles, and actual programs may differ substantially. However, departures from this ideal can lead to an imbalance in the overall system, resulting in confusion at the programmatic level.

For example, in a system procurement approach, where industry is provided a set of mission requirements and is then handed the reigns to carry out the development of all science algorithms and requisite hardware, there exists the potential to jeopardize the research quality of a satellite program unless closely monitored. For example a contractor hired by industry may depart from heritage approaches in order to meet an environmental data record threshold by any means possible. This approach can also lead from a research perspective to over-constrained instrument design (i.e., marginal improvement to one capability coming at the expense of more general sensor utility) and may not provide observation record continuity (vital to climate data records) with regard to heritage algorithms.

As a result, algorithm development (prior to hand-off to industry for technology implementation) may be a task more appropriately conducted under the auspices of government and academia. In this way, innovation occurs upon a solid foundation, lines of interdisciplinary communication are kept open, and the natural checks and balances of the peer review process would be ensured at all stages of algorithmic development. Most importantly, the full attention of industry would be dedicated to its inherent strengths: the design of hardware and software solutions to sensor performance specifications as determined by the user community.

4.4 *Agility within a Large Program*

Managing a satellite program is in some ways like negotiating a large ship through a crowded harbor; decisions must be well informed, timely and acted on immediately. Once the ship is moving, there is no possibility for sharp corrections to its course, and poor decisions or indecisiveness at the helm can have disastrous consequences. Given the dynamic array of hazards confronted within the harbors navigated by modern day satellite programs (e.g., waters fraught with program budget cut barriers, technology development snags, and general inter-agency coordination logistical whirlpools) an accommodation for program agility has come to be acknowledged as an important part of satellite system design.

In terms of sensor capabilities, some of the examples presented in Section 3 emphasized how important it is that the window of opportunity for sensor modifications leading up to the physical “bending of metal” (instrument fabrication) be widened in the pre-award phase (primary contractor not yet identified) and left ajar in the post-award phase as much as possible. Advances in our understanding of sensor applicability, innovations, and discovery of new capabilities come at irregular intervals and cannot be assimilated readily into a system whose concept of operations and hardware are frozen over the duration of the program. The implicit challenge to program managers is finding ways to retain some level of control over sensor evolution throughout the program. A budget that includes contractor incentives (e.g., in the form of broad agency announcements) for future sensor modifications is one possibility. For example, NPOESS provides such a vehicle through its IGS programs.

4.5 *Physics-Centric vs. EDR-Centric Philosophies: A Tale of Cats and Dogs*

Anyone who has spent any amount of time in a university environment can attest to the healthy level of competition among researchers in developing innovative solutions to the problems of science. The old saying “there’s more than one way to skin a cat” has never more succinctly captured the essence of an institution as it does academia (save, perhaps, taxidermy). For a specific example we may consider the problem of cloud top heights, which can be estimated using infrared window channels (based on brightness temperature and cloud opacity), absorption channels (e.g., CO_2 slicing), parallax effects (e.g., multi-angle views), cloud shadow geometry, or if available, active sensors (e.g., radar or lidar). Each of these physically-based techniques has its own assortment of strengths and weaknesses from both a performance and practical implementation standpoint.

The design of an observing system for cloud top heights may then follow one of two paths. If a specific approach is settled on, the system can be specially tailored to optimize that algorithm at the expense of all others. Alternatively, the sensor can be designed to capture certain physics/viewing-geometries in a way such that many algorithms could potentially apply. These are forms of ‘EDR-centric’ and ‘physics-centric’ approaches to sensor design, respectively. While considerations for EDR and sensor performance of course cannot be conducted independent of one another, the ultimate utility of an operational satellite program to new algorithm development will be determined by the dominating philosophy.

As future satellite programs will more often be asked to serve the needs of both the operational and research communities, it is important to ensure their measurements are of sufficient fidelity and generality. If EDR requirements are the primary consideration (e.g., in a system-procurement arrangement), the algorithm developer may neglect legacy techniques in favor of a novel approach that appears to better satisfy the requirement. This may lead to corresponding sensor requirements that do not provide sufficient information to carry on other important environmental applications. Above EDRs, researchers require good measurements.

For example, in order to provide better cloud height retrievals on GOES-12 (currently positioned at 75° W), the traditional GOES-I series channel 5 (12 μm) on was changed to a 13.3 μm (CO_2 absorption) channel. Optimizing the cloud height application in one fell swoop compromised the ability to detect/retrieve a) sea surface temperature, b) thin cirrus, c) aircraft contrails, d) thin/thick cloud overlap regions, e) volcanic aerosols, and f) mineral dust. In some cases, the optimization of a single EDR at the expense of general utility can be described by another old expression: "the tail wagging the dog". All EDRs are based on algorithms that are imperfect, may require modification or replacement as the results of new research warrant, and ultimately are completely dependent on sensor fidelity. To provide the greatest opportunities for general advances in atmospheric and oceanic research, it is suggested that physics-centric requirements be considered as the common denominator, and at the very least, the heritage capabilities deemed important to the mission be maintained.

4.6 *Evolution vs. Revolution: The Penalties of Operational Sensor Novelties*

The ideal system for satellite program evolution entails a multi-level architecture, composed of both research and operational sub-systems. Here, implementation of the operational satellite system would in principle be a relatively low risk affair (associated with data I/O and sensor integration rather than sensor specifications). Sensor technology development would be relegated entirely to the research satellite sub-system, and those sensors demonstrating technology readiness and positive impact are transitioned seamlessly ("off the shelf") onto the operational platform. The proving grounds for potential EDR performance upgrades is also within the research program (and in particular, the Academic Pillar), such that the only possibilities when integrating various sensors onto a single operational platform are windfall applications based on instrument synergy.

Problems can arise when an operational program over-steps the capabilities of its research counterpart. Attempting to field superior sensors based on new technology is a venture inherently fraught with peril and ultimately is counterproductive to the operational process. Any departures from the state of the art effectively act to transfer unnecessarily high risk into the operational paradigm. As such, satellite programs should avoid taking giant leaps in technology at the operational transition stage, even if it comes at the cost of failing to meet ambitious EDR thresholds. The only appropriate technology modifications at this late stage in a satellite program would be to address any outstanding challenges to the research prototype system, and only then if the required corrections are not accompanied by considerable technical risk.

5. A MODEL FOR SENSOR EVOLUTION

The central goal of any satellite program is to attain a cost effective, sustained, and flexible observing system that satisfies the need for more accurate, reliable, and timely data by a diverse and increasingly sophisticated user base. Earlier, the case was made that the path followed from research to operations should ideally be a well trodden one, with risk minimized by way of a dedicated research and development program. This section illustrates a simplified model consistent with this thought process.

The NOAA Office of System Development (e.g., overseeing GOES-R program development) includes appropriate programmatic barriers to deploying new-technology payloads on operational systems, while NASA traditionally has filled the role of R&D development. Given the increasing demands on environmental sensors and the limited resources at hand, it is likely that future operational systems will likewise need to wear two hats in terms of catering to the needs of both operational and R&D requirements.

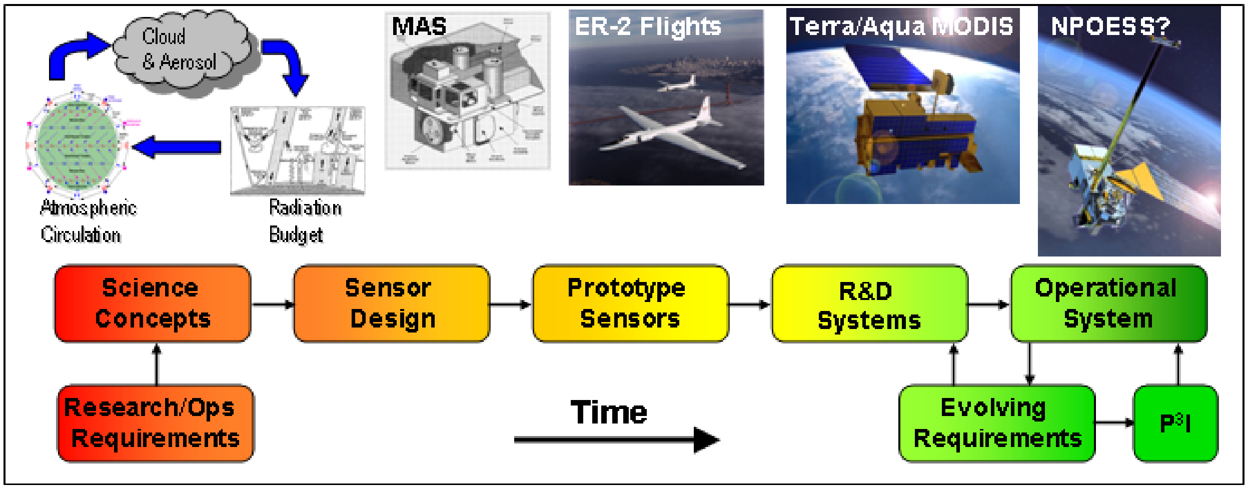


Figure 11. Conceptual schematic of sensor evolution from scientific principles through operational transition. The MODIS sensor's transition into the NPOESS/VIIRS era is shown as an example following this model. See text for details.

A idealized conceptual diagram of sensor evolution is shown in Figure 11. All stages of sensor development from a) initial concept, b) laboratory prototype, c) field-ready platform, d) R&D sensor, to e) operational space system, follow a logical path that includes feedback for evolving requirements. For a good model, based in this case on the NPOESS program, the MODIS Airborne Simulator (MAS; King *et al*., 1996), developed under the auspices of NASA and flown for several years aboard the NASA ER-2 aircraft, transitioned into the successful Terra space sensor in 1999 (and on Aqua in 2002). The NPOESS VIIRS sensor will inherit many MODIS techniques and capabilities. To integrate sensors optimally within a larger, multi-sensor program requires an understanding of teleconnections between EDRs and common sensing requirements. System flexibility, represented as "P^3I" concepts in Figure 11, provides the all-important element of program agility as discussed previously.

8. SUMMARY AND CONCLUSION

This paper has attempted to engage readers in a basic thought process surrounding the many issues confronted by planners of operational environmental satellite observing systems. Realizing that the challenges are indeed far more complex than this limited discussion can do justice, the rhetorical questions offered here must be regarded only as a starting point for more rigorous and insightful review and discussion.

The opinion expressed here is that operational systems to the greatest extent possible should be simple transitions having direct linkage to established R&D counterparts, with every attempt made to confine the primary sensor technology challenges to the R&D arena. In particular, the R&D program is developed in a pseudo-operational framework (e.g., the MODIS near real-time model) to allow for hands-on testing and feedback from operational users, and to facilitate technology transfer into the operational system.

It is evident that as we move from a paradigm of specialization to one of interdisciplinary applications, many algorithms will share core processing steps. Likewise, we should expect an adaptation from small pockets of expertise toward larger, goal-oriented teams (Powell, 2005). Functioning successfully in this new environment will require cognizance of the big picture, open lines of two-way communication between developers and users, mechanisms for discerning the full scope of user needs, and the agility to adjust the course to keep on track with evolving user requirements. It becomes clear that at the heart of fruitful sensor evolution is an implicit dependency on intelligent design.

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