

# Milky Seas: A New Science Frontier for Nighttime Visible-Band Satellite Remote Sensing

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## Abstract

On a dark winter's night in 1995 a merchant vessel traveling off the coast of Somalia encountered massive expanse of brightly glowing waters similar to those reported for centuries by other mariners traversing the waters of the northwestern Arabian Sea. Archived low-light visible imagery from the Defense Meteorological Satellite Program's Operational Linescan system found a match between the ship's position and an anomalous light source that spanned a surface area of 15,400 square km and was observed to rotate counter-clockwise over the course of four consecutive nights in a way consistent with local sea surface currents. The findings represent the first remote-sensing corroboration of the legendary "Milky Sea," a rare and poorly understood phenomenon scientists believe is linked to population explosions of luminous bacteria. This paper details the unusual circumstances and implications surrounding this discovery, foremost among them being the potential for improved detection by the next-generation low-light sensors to be flown on the future National Polar-orbiting Operational Environmental Satellite System (NPOESS) constellation and potentially follow on members of MetOp.

## INTRODUCTION

On rare occasions over the centuries, mariners have returned from long excursions at sea with fascinating tales of glowing ocean waters. The 'milky seas' coined by these observers describes vast expanses of seemingly 'white' water which glow constantly and over great distances. Milky seas are nocturnal phenomena and occurring particularly under very dark, moon-free conditions. The light is not the reflection of a down-welling source of radiation (e.g., moonlight) but instead a true emission from something within (or perhaps floating atop) the water. All parts of the water appear to be emitting light, eliminating depth perception (such that one might feel the roll of the ocean swell but not see it, adding to the surreal nature of these experiences). Long before their scientific acknowledgement, milky seas were a well-established part of maritime folklore. Eventually they found their way into classic sea-adventure fiction novels of the mid-19th century such as Jules Verne's "Twenty Thousand Leagues Under the Seas" and Henry Melville's "Moby Dick." It is likely that these authors drew from the many ship reports available to them at the time.

There are numerous documented accounts of milky seas dating back to the early 1800's. In 1832 the crew of the ship *Clive* believed they were in extreme peril when their ship entered a large area of glowing-white water between Bombay and the Arabian Gulf--obscuring the line of horizon and eliminating all visual indications of forward movement. The crew of the *Moozuffer*, transecting these same Indian Ocean waters in 1849, described their ship "forcing her way through molten lead" while the stroke of the paddle wheel churned liquid resembling patches of "thick milk or cream." In 1854, the *Shooting Star* reported crossing an ocean surface shining bright enough to illuminate objects on deck and gave the appearance of an aurora on the horizon. En route to Bombay in 1856, the steamship *Singapore* encountered an ocean glowing with such brilliance that its captain thought that distant clouds (their bases being

illuminated by the glowing seawater) were in fact far-off land features, and that they had somehow drifted far off of their planned course!

According to the compilations by Herring and Watson (1993), there are at least 235 similar encounters that have been logged by captains and crew since 1915. Most of the events have occurred in the waters of the northern Indian Ocean (171 reports) and near Indonesia (40 reports). While these reports predominantly derive from laymen sources and under the extreme and unusual circumstances of may be expected to contain subjective and exaggerated descriptions, accounts of the milky sea phenomenon are surprisingly consistent. Finally in 1985, a research vessel surveying the western Arabian Sea happened upon a milky sea in progress (Lapota et al., 1988). Water samples from the ~72 hour event (viewable only at night) suggested the cause to be a bloom of the luminous bacteria strain *Vibrio harveyi*, which were found to be colonizing upon the brown/green alga *Phaeocystis*, perhaps in the form of a surface slick. This previous study remains as the lone scientific account of a milky sea. Due largely to the remote, episodic, and transient nature of these events, being at the right place at the right time to conduct further experiments on these white waters has been something akin to chasing Captain Ahab's Moby Dick. This paper describes the unlikely events which resulted in the first detection of a milky sea from low-earth-orbiting satellite—offering new hope for detecting and responding to events as they occur.

### **Different Forms of Bioluminescence**

Although there are still more questions than answers, the leading hypothesis for what produces milky seas is marine bioluminescence. Bioluminescence is a special class of chemical luminescence (chemiluminescence) that takes place within a living organism. Here, light is produced as the by-product of a luciferase-catalyzed oxidation of reduced flavin mononucleotide and a long-chain aldehyde. In contrast to the more common and familiar bioluminescence events produced by dinoflagellates which produce a localized bright flash of light in response to disturbed waters (e.g., breaking waves along the sea shore during red tide blooms, or in the turbulent wake behind ships), the glow emanating from a milky sea is reportedly constant, opaque, widespread, and entirely independent of mechanical stimulation. As such, the most likely explanation for milky seas is luminous bacteria (consistent with the observations of Lapota et al., 1988) which are known to produce a faint but steady glow (see Figure 1) when they reach a critical concentration. Requirements for this process to occur are (i) an abundance of oxygen in the water, (ii) a sufficiently high concentration of autoinducer, and (iii) an extremely high concentration of bacteria (e.g., about  $10^8$  cells•mL<sup>-1</sup>). Autoinducer is a chemical that is produced and detected by the organisms via a cell-to-cell communication process known to as 'quorum sensing', which tells the colony when to begin emitting light.



**Figure 1: Luminous bacteria (*Vibrio fischeri*), grown in a nutrient-rich broth, producing ~500 nm light upon reaching a critical population.**

To human observers, the light levels produced by even the most intense of milky seas would be rather faint by absolute standards. Under low-light viewing conditions (scotopic vision), the rod cells of the human eye's retina operate as the primary photodetectors and are capable of detecting the faint light produced by luminous bacteria. Unlike the cone cells we use under brighter illumination conditions, which provide three distinct visible band-passes (blue/green/red), the rod cells do not provide this same color discrimination capability. For this reason, even though the central wavelengths for most bioluminescent light emissions are near 500 nm (blue/green light) a milky sea would appear white (or in the most extreme cases, perhaps having a hint of cyan as suggested Figure 1). Although the absolute value of luminescence is very low, its contrast against dark, moonless skies would be perceived by the dark-adjusted human eye as bright against the black-space backdrop.

The purposes for bioluminescence (a costly practice from an energy budget standpoint) vary from organism to organism, but in the context of visual communication the ultimate goal likely would be one of attraction or repulsion. In contrast to dinoflagellates, which produce a bright and transient flash of light to ward off predators (by attracting still larger predators, higher in the food chain, to the area), prokaryotes such as luminous bacteria are thought to glow for the opposite purpose—they actually want to be ingested! It so happens that the gut of a fish is a preferred habitat for these bacteria. When they gather in a sufficient concentration (e.g., colonization upon a small piece of organic matter) they take advantage of their ability to emit light as a community in order to solicit themselves to potential hosts. Under normal conditions, this might occur on an isolated piece of material, making it stand out in contrast to its dark surroundings. In the case of milky seas, the uniqueness factor obviously would be lost for the sheer numbers of colonized substrata glowing simultaneously.

## **Research Origins**

The chain of events leading up to these findings began oddly enough as a lunchtime chat among meteorology and engineering colleagues attending an American Meteorological Society conference in Seattle. Our conversation centered on the anticipated capabilities of the forthcoming "Day/Night Band" (DNB), a new sensor being developed for the National Polar-orbiting Operation Environmental Satellite System (NPOESS) Visible/Infrared Imager/Radiometer Suite (VIIRS). We knew that the DNB would offer unique nighttime imaging capabilities similar to its heritage sensor, the Defense Meteorological Satellite

Program (DMSP) Operational Linescan System (OLS). The latter employs a photomultiplier tube (PMT) to amplify extremely low levels of light (occurring at four to five orders of magnitude below the limits of other visible-light detectors designed for daytime observations). The high sensitivity provided by the PMT enables detection of cloud and snow cover at night by way of reflected moonlight. It also can detect both natural (e.g., forest fires, lightning, aurora) and artificial (e.g., city lights, oil refinery gas flares, fishing fleets) sources of light. The OLS, however, is based on 1960's technology. We were curious as to whether the next-generation NPOESS VIIRS/DNB, with its superior spatial and radiometric resolution, would find other kinds of weak/fine-scale light features.

To our knowledge at the time, there were no documented cases of OLS-detected bioluminescence, presumably due to the small spatial extent and low levels of light produced by typical events. Could the DNB do better here? Stepping back, and perhaps naively so, we pondered whether certain bioluminescent events ever occurred at scales sufficient to "fill" a typical satellite pixel (i.e., of order 1 km, thereby increasing their chances of detection), such that even the OLS might stand a chance of spotting them. The odds seemed extremely slim, especially in light of the poor radiometric resolution of the OLS and the likely proximity of any bioluminescent signal to the sensor noise floor, but it was an idea at least worth checking out.

And so, as any noble scientist of the 21<sup>st</sup> century might do, we ran a 'Google' search that included such key words as 'bioluminescence', 'ocean', and 'extensive', just to see what the search engine might dig up. This exercise led us to (among many other irrelevant things) a report submitted by James P. Briand, then Captain of the British merchant vessel S.S. Lima, to the journal *The Marine Observer* (Briand, 1996) The following excerpt from that report marked our formal indoctrination to the fascinating topic of milky seas:

"25 January 1995: At 1800 UTC on a clear moonless night while 150 n.mile east of the Somalian coast a whitish glow was observed on the horizon and, after 15 minutes of steaming, the ship was completely surrounded by a sea of milky-white colour with a fairly uniform luminescence. The bioluminescence appeared to cover the entire sea area, from horizon to horizon [...] and it appeared as though the ship was sailing over a field of snow or gliding over the clouds [...] The bow waves and the wake appeared blackish in colour and thick black patches of oil were passing by. Later, the Aldis lamp revealed that the 'oil patches' were actually light green kelp, amazingly black against the white water."

In addition to supplying specific information on the date, time and location of the event, Capt. Briand's report went on to include the Lima's course and temperature/pressure/wind data. Realizing that the National Geophysical Data Center (NGDC) began archiving OLS data (in a "smoothed" format having approximately 2.8 km pixel resolution) in 1992, we were optimistic about the prospects of obtaining coverage over the Lima's location by one or more of the contemporary DMSP constellation members.

Our Internet search tactic proved faithful once again in guiding us to several bioluminescence experts whose input would add both substance and context to our observations. Also among those contacted were experts in the field who had dismissed altogether, based on common-sense arguments and previous failed attempts, the prospect of any possible detection by way of the current satellite technology. Realizing the many challenges we faced from an observing system standpoint, it would be nearly impossible for us to counter their arguments with anything short of clear and definitive proof to the contrary. So, we set common sense temporarily to the side and proceeded with our inquiry.

### **Murphy's Law Breaks Down**

It turned out that several candidate OLS orbits providing coverage of the waters off the Horn of Africa were available in the NGDC archive for the days surrounding the 25 January 1995 Lima report, including one evening pass collected within an hour of the actual sighting. The sighting occurred during a favorable portion of the lunar cycle (close to the new moon) when the OLS sensor would be applying its highest gain settings. Despite this good fortune, we realized that our chances of detecting above the noise the very

low light signals of a milky sea remained slim, hinging on an opportune positioning of the feature within the sensor's 3000 km swath.

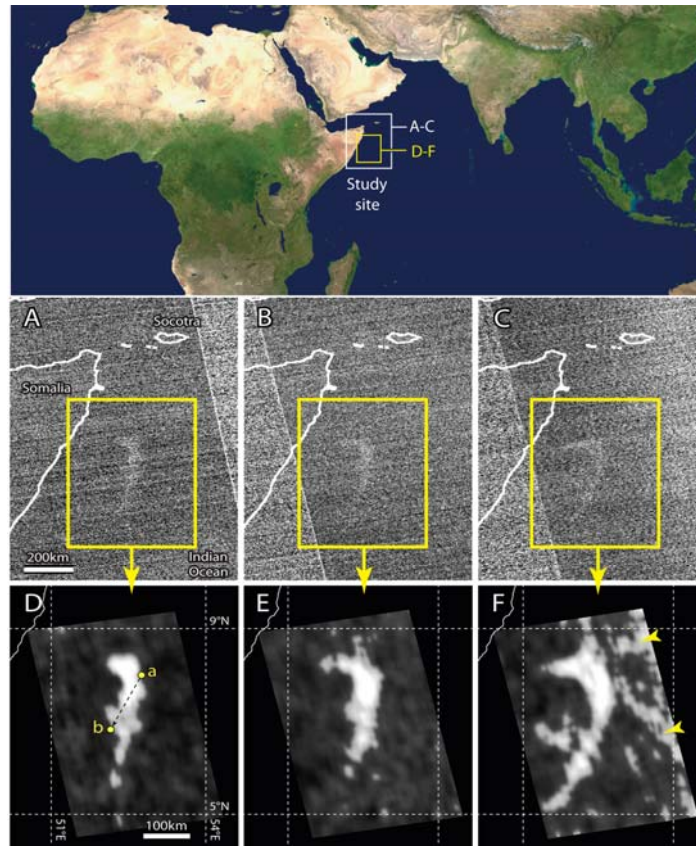
The OLS implements a pendulum-like cross-track (whisk-broom) scanning motion to image a scene, meaning that its 'footprint' (the projection of the detector element onto the surface of the earth) grows with increasing angle off nadir (similar to the spot-size of a flash light pointed at the ground). In an attempt to preserve a nearly constant spatial resolution across the entire swath, the OLS mechanically reduces the physical size of its detector (and hence, its projected footprint upon Earth's surface) at discrete points with increasing scan angle. At about +/- 766 km off nadir, the first of these switches takes place, and is clearly evident when viewing the imagery in a low-end enhancement (manifesting in the imagery as a sudden jump to a higher noise floor). The regions of the imagery swath just prior to the first detector size reduction offer larger detector footprints, signal-to-noise ratios, and dwell times (owing to the pendulum motion) than pixels closer to nadir and pixels beyond the switching point. Hence these regions would offer the best opportunity to detect a low-light signal if it were indeed distributed uniformly over a wide enough spatial extent.

In what seemed to be a case of extreme luck, our target area of interest fell repeatedly within this ideal sensing region of the various OLS-pass swaths on four consecutive nights, beginning with the night of the Lima milky sea observation. In addition, the detailed coordinates provided in Capt. Briand's account allowed for the assignment of entry/exit glowing water boundaries on the event that would prove invaluable to the data analysis to follow. The best of all possible scenarios in terms of both timing and location with respect to the available satellite observations bred hope for a positive outcome.

### **A Finger Smudge**

Even with such good fortune, we would still need to rely on some amount of digital enhancement to isolate any features of interest from the considerable PMT noise present on the low-end of the detector's sensitivity range. The enhancement consisted of first subtracting out the mean intensity of each scan line (removing striping), then applying along-track and cross-track filters. This retained the slightly brighter/coherent structures while serving to reduce random noise.

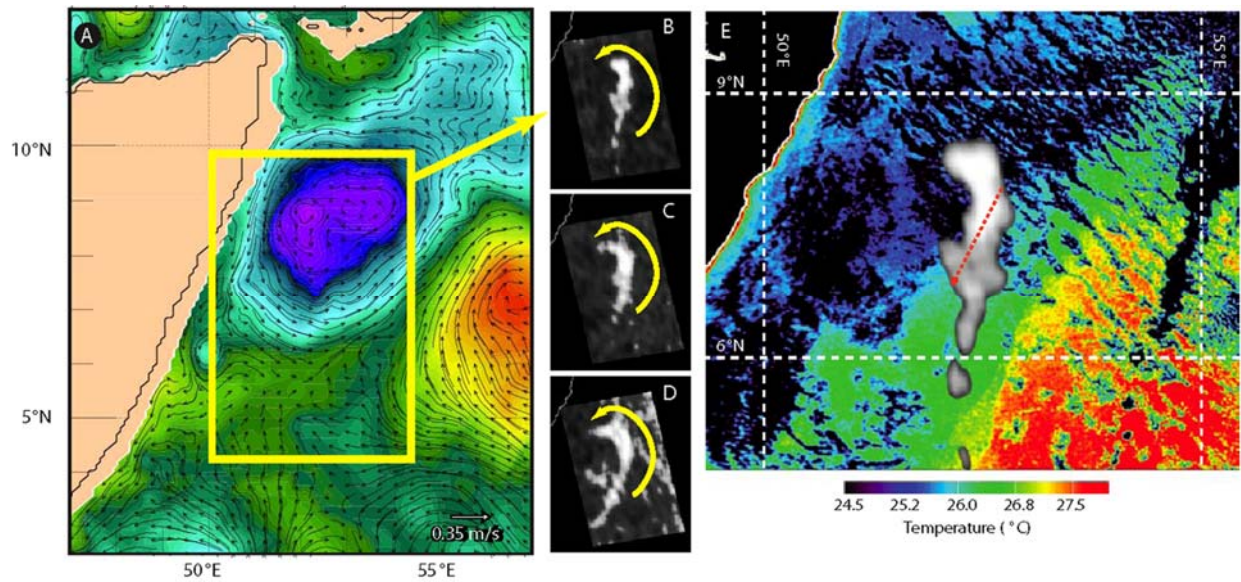
At first glance, the faint features present in the 25-27 January 1995 imagery sequence (Figure 2A-C) could easily have been mistaken for a faint finger smudge on the display. It became evident only after digital enhancement (Figure 2D-F) that the coherent feature, spanning a region approximately 50 km wide by 300 long (an area roughly the size of Connecticut), was not an artifact of random noise but retained its general structure for at least three consecutive nights. The reported positions of the Lima at both entrance and exit from the glowing waters were then overlaid (Figure 2D), showing a nearly perfect match with the boundaries of the peculiar comma-shaped feature appearing in the enhanced OLS imagery—the first detection from space of a milky sea.



**Figure 2: DMSP/OLS detection of a milky sea off the Horn of Africa on 25-27 January (A-C) along with digital enhancement (D-F). The dotted line (a → b, in panel D) shows the path of the S.S. Lima on the night of 25 January 1995. From Miller et al. (2005).**

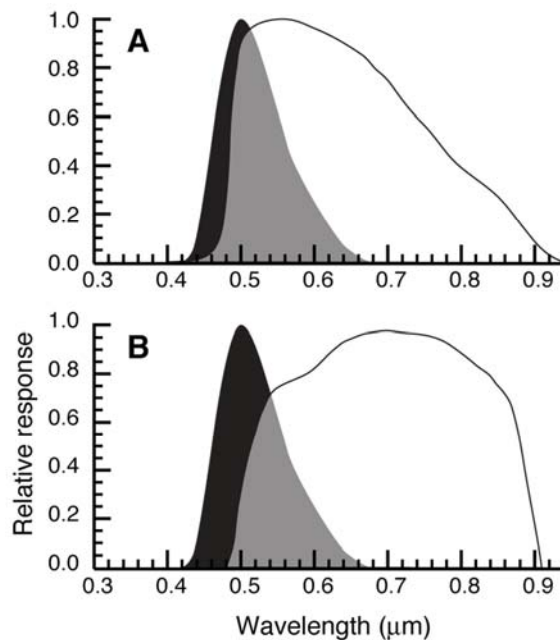
### Associated Environmental Parameters

Several previous milky sea accounts mention accompanying conditions offering potential clues to understanding the environmental state. For example, several reports cite large sea surface temperature (SST) gradients and a sudden calming of winds when entering milky seas. These SST gradients often correspond to oceanic fronts. The cooler sides of these fronts produce a stable boundary layer which serves to decouple the surface from any stronger winds present aloft (e.g., Chelton *et al.* 2000). This decoupling could result in a potentially rapid decrease of winds when crossing into the cooler waters—consistent with some accounts of a marked calming of winds and ocean state in the midst of milky seas. Although the Lima did not report any notable SST or wind speed changes along its milky sea transect, we conducted a retrieval of SST from Advanced Very High Resolution Radiometer (AVHRR) data and sea surface currents from the NRL Layered Ocean Model (NLOM; 1/16° resolution, courtesy of the NRL Stennis Space Center) in order to better understand the broad-scale environmental conditions.



**Figure 3: Navy Layered Ocean Model (NLOM) surface currents (A) showing a cold gyre in the vicinity of the milky sea, explaining the observed counter-clockwise flow of the pattern over three night's time (B-D). AVHRR-derived sea surface temperatures (E) show the orientation of the milky sea with respect to an oceanic front. Dotted red line corresponds to the S.S. Lima track. From Miller et al. (2006).**

Figure 3A depicts the NLOM sea surface current field, revealing the presence of a large cool-water gyre just off the Horn of Africa. Knowledge of this eddy's existence proved key to understanding the temporal evolution of the milky sea feature (Figures 3B-D), whose northern "head" appears to wrap in a counter clockwise fashion around the eddy—linking the glowing feature unequivocally to the ocean surface. Figure 3E depicts the AVHRR-derived SST field (black patches correspond to clouds masked out prior to conducting the retrieval). Overlaying the Lima's track upon the milky sea feature, we note that despite the presence of a strong northwest/southeast gradient in SST the ship's course ran parallel to it. The additional satellite analysis helped to explain the lack of an observed SST gradient for this particular Lima case while not discounting the potential importance of oceanic fronts to the formation of milky seas.



**Figure 4: Emission spectra of luminous bacteria (solid black) in comparison to the sensor response functions for the DMSP/OLS (A) and the VIIRS DNB (B) showing overlap (solid gray). From Miller et al. (2005).**

Although the OLS data are not calibrated, the sensor's minimum detectable signal (MDS) at high-gain mode is known, allowing for a conservative estimate on total light production. Using this MDS as a baseline, we attempted to calculate the total bacteria population potentially involved in the S.S. Lima event. Because the OLS sensitivity range and the bacterial light emission spectra (Figure 4A) do not overlap completely, we computed an adjustment factor (describing how much additional light would need to be produced by the bacteria in order to yield the same signal as an emission source having full overlap with the OLS response curve). Knowing the per-cell light emission rate for luminous bacteria (based on measurements conducted in the laboratory), we computed the minimum population of cells in the near-surface water column required to produce light levels equaling this adjusted MDS. Finally, using the satellite-inferred spatial extent we extended this to compute the total bacterial population.

Following the above procedure, the MDS and adjusted MDS values were  $4 \times 10^{-5} \text{ W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$  and  $1.8 \times 10^{-4} \text{ W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$ , respectively, the per-cell light emission was  $1.2 \times 10^3 \text{ phot}\cdot\text{s}^{-1}\cdot\text{cell}^{-1}$ , the minimum detectable population was  $1.9 \times 10^8 \text{ cells}\cdot\text{mL}^{-1}$  (within the top 10 cm of water), and the milky sea surface area (for 25 January, 1995) was  $15.4 \times 10^3 \text{ km}^2$ . This resulted in a conservative total population estimate of  $4 \times 10^{22}$  bacteria. The sheer enormity of this figure, representing nearly the same number of bacteria as are estimated to occupy the upper 200 m of the all the world's open oceans (non-coastal) under normal conditions, might be put into context in the following way: if each bacteria cell were represented by a grain of sand, this milky sea could form a 10 cm thick layer covering the entire earth!

## Prospects and Conclusion

There are many questions outstanding on the topic of milky seas. What series of events could culminate in such a massive bacteria population explosion? Do these special circumstances tell us something important about the current/future states of the marine ecosystem (do they correlate with climate change)? Do they occur exclusively in association with algal blooms, or might other sources of nutrients (e.g., deep water upwelling common in these highly productive waters) play an important role? Laboratory work ongoing at NRL in Washington DC and the University of Maryland, including the set up of *Vibrio harveyi* / *Phaeocystis* co-cultures, may help determine preconditioning requirements and the nature of bacterial



“super blooms.” In addition, proposals are in the works to rapidly respond with in situ sensors to satellite-detected events in progress, based in part on the current constellation of ocean color and nighttime low-light satellite sensors.

The ability of contemporary satellite sensors like the DMSP/OLS to observe the weak signal of milky seas requires a special alignment of circumstances that are almost as uncommon as the events themselves. Among planned satellite observing systems, the VIIRS/DNB offers the only realistic opportunity for pursuing this research further. One potential challenge, as depicted in Figure 4B, is that despite the improved fidelity of the DNB compared to the OLS, its spectral band pass provides slightly less overlap with the bioluminescent emission spectra for bacteria thought to be responsible for milky seas. The hope is that the higher fidelity of the DNB will help to overcome this challenge. For example, with the dynamic selection from three stages of gain, the DNB will be able to provide more opportunities for milky sea detection than the OLS (whose gain setting is tied in part to the lunar cycle).

The greater challenge may turn out to be one of temporal sampling. While the 1995 milky sea and the one reported by Lapota *et al.* (1988) ten years earlier were observed to persist over several nights time, other reports indicate more transient events (including cases of sudden instantaneous cessation). Also, cloud obscuration at the time of one satellite overpass may obscure an event observable by an earlier/later overpass. With the deletion of the mid-morning (0930/2130 local time) NPOESS orbit from reorganized program, we lose the orbit closest to the one which detected the 1995 S.S. Lima event (and currently provided by DMSP F-15 and F-16). A study of the lunar cycle indicates that in addition to temporal sampling benefits, the mid-morning orbit provides about 55 additional nights of detection (without risk of moon-glint contamination off the sea surface) on the waning side of the cycle (i.e., when the moon has not yet risen at 2130). The European operational polar orbiter program, which will provide the mid-morning coverage via the Metop series, does not presently contain a low-light channel. Given the considerable benefits of nighttime visible observations to the detection and characterization of other environmental parameters (Lee *et al.* 2006), and in the spirit of the International Joint Polar System (IJPS) which provides a concept for cooperation among agencies working toward a Global Earth Observing System of Systems (GEOSS), perhaps there is cause for hope that a DNB could be added to a future mid-morning orbit on the international constellation.

Until then, we will continue responding on an ad-hoc basis to any and new leads on possible milky sea events. The maritime record, based on a sparse sampling and biased predominantly to major shipping routes, gives little insight to the full spatial extent, global distribution, and temporal variability of milky seas. The phenomena apparently are not limited to the Arabian Sea—there have been sightings from cruise liners off the coast of Brazil, the waters west of central Mexico, throughout the Arabian Gulf, and in the Mergui Archipelago of Indonesia. It is entirely possible that milky seas occur in other regions, less frequented by sea vessels, as well. We encourage those who believe they may have encountered a milky sea during their travels to contact us immediately.

To scientists and laymen alike, it is refreshing to be confronted with evidence that Earth remains a place brimming with natural mysteries. Even as we look to other planets, solar systems, and the cosmos beyond as the new frontiers of science discovery, we are humbled by evidence that such frontiers still exist in our own backyard. As we prepare for the NPOESS era, the prospect of a new frontier in scientific research emerging by virtue of improved remote sensing technology is truly exciting. The adventure begins with the launch of the NPOESS Preparatory Project (NPP), slated for late 2009.

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