Solutions Network Formulation Report

NASA's Potential Contributions in Remote Quorum Sensing and the Management of Harmful Algal Blooms

August 17, 2007

1. Candidate Solution Constituents

a. Title: NASA's Potential Contributions in Remote Quorum Sensing and the Management of Harmful Algal Blooms

b. Authors: Rose Fletcher, Kelly Knowlton, and Robert E. Ryan, Science Systems & Applications, Inc., Stennis Space Center, MS

c. Identified Partners: NOAA (National Oceanic and Atmospheric Administration)

d. Specific DST/DSS: HABSOS (Harmful Algal Blooms Observing System) developed by the NCDDC (National Coastal Data Development Center)

e. Alignment with National Application: Coastal Management and Public Health

f. NASA Research Results – Table 1:

Missions	Sensors/Models	Data Product
Aquarius/SAC-D	HSC (High Sensitivity Camera)	Night Imaging Data Will be Available at: http://podaac-www.jpl.nasa.gov/
SAC-C	HSTC (High Sensitivity Technological Camera)	Night Imaging Data Available at: http://ggt.conae.gov.ar/focos_hstc/default3.asp

g. Benefit to Society: Improved understanding and management of aquatic ecosystem hazards.

2. Abstract

This candidate solution proposes to use the night-imaging capabilities of the HSTC from SAC-C and of the HSC from SAC-D/Aquarius to detect bioluminescent events associated with HABs (harmful algal blooms). Once detected, this information could be fed to the NOAA CSCOR (Center for Sponsored Coastal Ocean Research) Harmful Algal Bloom Event Response Program, which acts quickly to fund the mobilization of research teams and to engage local agencies in a response. The HSC/HSTC data can serve as input to the HABSOS decision support system to provide information on location, extent, and duration of HAB events. Society will benefit from improved protection of the health of humans beings, aquatic ecosystems, and coastal economies. This work supports coastal management, public health, and homeland security applications.

3. Detailed Description of Candidate Solution

a. Purpose/Scope

The term “Quorum Sensing” refers to a molecular communication that occurs between tiny bacteria in response to cell density through which the cells coordinate their behavior. Some species of bacteria respond to high cell density by becoming luminous. This type of bioluminescence is seen in squid, for example, where the bacteria accumulating in the squid’s organs cause the display. This type of bioluminescence is different from the brief flashes of bioluminescence caused by mechanical stimulation in red tide.

The sustained bioluminescence related to quorum sensing can occur on scales massive enough to be detectable from space. There have been 235 reported cases of noctilucent seas since 1915, and many more cases have been recorded throughout the centuries by mariners who describe the eerie experience of sailing for night after night on an ocean that is glowing from horizon to horizon. In 1985, a Navy research vessel encountered a similar bioluminescent display that lasted three days (Lapota, 1988). Based on biological samples, the Navy concluded that the “milky seas” were primarily a sea-surface phenomena caused by a colony of light-emitting bacteria *Vibrio harveyi* in association with an algal bloom of *Phaeocystis*. Bacteria may accumulate in sufficient quantities to induce bioluminescence if living on a substrate of algae or possibly thriving as an algal bloom breaks down (Nealson et al., 2006).

In 2003, a research scientist at the Naval Research Laboratory was able to correlate one of these milky sea ship sightings with a ghostly feature in a satellite image taken over the Indian Ocean in January 1995 (Miller et al., 2005). That particular bioluminescent event was significant in that it spanned an area the size of Connecticut and lasted for several days. Miller demonstrated that it is possible to detect this kind of bioluminescent event from space, and Lapota was able to link the phenomena to an algal bloom of *Phaeocystis*. Still, the origin, ecological composition, spatial extent, temporal variability, and health implications of these phenomena are not well understood.

Phaeocystis is brown algae that often forms in high-biomass gelatinous colonies and belongs to the group of algae classed as non-toxic harmful algal blooms (Anderson et al., 1998). *Phaeocystis* colonies often result in the formation of surface organic scums and foams that cover the beaches and foul fisherman’s nets. *Phaeocystis* produces both acrylic acid and DMS (dimethyl sulfide), an important climate-cooling aerosol, but the ecological and environmental impacts of these compounds are not known (Darcey et al., 1994).

Harmful algal blooms generally cost the United States about 82 million dollars per year in fishing, recreation, health, and management costs (NOAA, 2007). These costs are escalating because the frequency, extent, and complexity of HABs has been increasing over the last several decades. In addition to health impacts, economic losses are sustained by such causes as shellfish closures and loss of aquacultural stock. Socio-cultural impacts include loss of recreational opportunities and shifts in livelihoods. Additional tools are needed to combat this growing threat. Detection of bioluminescent bacteria may offer a method for nighttime detection of some harmful algal blooms.

b. Identified Partners

NOAA provides scientific support to coastal managers faced with responding to unusual or unexpected HABs through the Harmful Algal Bloom Event Response Program. This NOAA CSCOR program operates on the principle that science is essential to making good management decisions (CSCOR, 2007). The event response program investigates the HAB event, evaluates the risks to humans/sea life, and provides training for local managers.

NOAA also sponsors HABSOS, which is a decision support tool that uses remote sensing data and other inputs to assist managers in mitigating the detrimental impacts of a bloom. HABSOS, which includes a public Web portal, currently covers the Gulf of Mexico but will be expanded to a world-wide system in the future. The HABSOS decision support tool currently has the capability of integrating NASA satellite imagery with data on harmful algal blooms to guide management decisions and actions. HABSOS includes wind data from the QuikSCAT SeaWinds instrument (NCDDC, 2006). It also uses near real-time imagery from the Jason-1, ERS-2, and GeoSat Follow-On satellites. These data are also used to develop past/present/future model products including surface current, surface current speed, sea surface height, sea surface salinity, and sea surface temperature. These products can be viewed publicly on the HABSOS Internet portal in association with HAB events and other geographic information. Hence HABSOS has the capability of both processing and displaying the HSC bioluminescence data.

c. NASA Earth-Science Research Results

Archived remote sensing data from the Defense Meteorological Satellite Program OLS (Operational Linescan System) was used to discover the patch of bioluminescent ocean described earlier. The OLS sensor collects data at a spatial resolution of 2.8 km using a photomultiplier tube with a NER (noise equivalent radiance) of about 10^{-6} $Wm^{-2}sr^{-1}$ (Elvidge et al., 1999). This sensitivity is more than four orders of magnitude higher than conventional visible-band silicon detectors, such as AVIRIS and AVHRR (Elvidge et al., 1997). Accounting for the solid angle subtended by the detector, the minimum detectable signal scene radiance is about 4 x 10^{-5} $Wm^{-2}sr^{-1}$ with a SNR (signal-to-noise ratio) of 6 (Miller et al., 2005). The OLS spectral range is 470-950 nm (full width half maximum 510-860 nm), while the bacterial emission spectrum peaks at 490 nm with half-bandwidths of 70 nm (Seliger and Morton, 1968). Consequently, only about 22% of the total energy emitted by the bacteria overlaps the spectral range of the OLS. The adjusted detection threshold radiance, integrated over the region of overlap, is 1.8 x 10^{-4} $Wm^{-2}sr^{-1}$. Assuming a photon production rate of 10^3 photons per second per cell (Hastings, 1978), the minimum bacterial population density detectable by the OLS would be 2.8 x 10^{12} cells/m^2 (Miller et al., 2005). In comparison, a population of 6 x 10^{12} cells/m^2 was measured on a phytoplankton aggregate from a plankton tow (Lapota et al., 1988). A population of this density would generate an estimated radiance of 3.9 x 10^{-4} $Wm^{-2}sr^{-1}$, which is significantly above the threshold radiance.

The DMSP OLS image was collected at 9:36 pm, January 25, 1995, on a dark night with little moonlight and with a 1-day revisit time, enabling the event to be captured on 3 consecutive nights. The HSTC in SAC-C has an ascending node of 10:21 pm and is designed to collect night imagery; however, the revisit time is 9 days. The HSC camera on the SAC-D/Aquarius satellite will be imaging along the terminator with an ascending node of 6:00 pm so it will be collecting imagery at dawn/dusk and will be less capable of detecting a faint bioluminescent signal. The revisit time for the HSC will be 7 days, which will not be conducive to a HAB monitoring effort.

d. Proposed Configurations' Measurements and Models

Ideally, a bioluminescent ocean could be detected in near-real time so that research vessels could be dispatched to the location to investigate the event. A typical colony of continuously emitting bioluminescent bacteria would shed light in the visible spectrum at a rate of about 10^3 photons per second, per cell (Hastings, 1978) with peak values at 490 nm and half-bandwidths of 70 nm (Seliger and Morton, 1968). The HSC has a spectral range of 450–850 nm, a spatial resolution of 200 to 300 m, and a noise equivalent power of 78 W (digital number = 1) (Colomb et al., 2001). With a spatial resolution of 300 m, the NER would be approximately 6.9 x 10^{-5} $Wm^{-2}sr^{-1}$ (SNR=1). If a 3x3 array of pixels was combined for a spatial resolution of 900 m, the sensitivity could be increased to about 2.3 x 10^{-5} $Wm^{-2}sr^{-1}$ (compared with 10^{-6} $Wm^{-2}sr^{-1}$ for the OLS). Although this sensitivity is less than that of the OLS, it should still be enough to detect a bacterial population such as the one described above (emitting an estimated 3.9 x 10^{-4} $Wm^{-2}sr^{-1}$). In addition, the spectral range of the HSC extends to shorter wavelengths than the OLS, increasing the fraction of emitted energy detectable by the HSC.

Algorithms will be developed to digitally enhance the HSC/HSTC data to remove noise and other artifacts from the imagery to detect the faint bioluminescence signal. Striping artifacts could be removed by subtracting the mean intensity of each scan line. Combining pixels into 3x3 arrays would increase the SNR, and histogram equalization could be applied. These processing steps would reduce random and systematic noise to increase the contrast between the dark sea surface and the bioluminescent region.

4. Programmatic and Societal Benefits

The remote sensing perspective provides coastal managers with improved ability to detect, quantify, monitor, and forecast some HAB events. Improved detection creates opportunities for scientific investigation that will shed light on a new category of HABs. Although *Phaeocystis* is considered non-toxic, during “bloom” conditions it produces very concentrated waste products because of the sheer number of algae present. When a bloom occurs, it is possible that other species of fauna can be impacted by these concentrated waste products. Furthermore, when a bloom dies, often a virus attacks the cells, penetrating the cell walls and spilling the contents of the cells into the water. These intracellular contents are attacked by local bacteria. This attack chemically is an oxidative process that uses up the oxygen present in the watermass and creates a reducing environment–or one that is depleted in oxygen (i.e., anoxia). Hence, an anoxia zone is created due to the die-off phase of a bloom. This anoxia region affects other sea life in the area.

If use of the next generation of NASA sensors is successful in improving detection of harmful algal blooms, early-warning alerts can be provided to coastal inhabitants and mitigation activities can be coordinated in a cost effective manner (HARRNESS, 2005. In particular, measures can be taken to safeguard the fishing and tourism industries from the harmful affects of *phaeocystis*. Detection of bioluminescent events also has relevance to homeland security applications concerning stealth and the movement of ships and submarines.

5. References

Anderson, D.M., A.D. Cembella, and G.M. Hallegraeff, eds., 1998. *Physiological Ecology of Harmful Algal blooms.* Springer-Verlag, Berlin, 662 p.

Colomb, R., C. Alonso, and I. Nollmann, 2001. SAC-C mission and the international am constellation for Earth Observation. *Proceedings of the 3rd International Symposium of IAA, pp. 433-437*, http://www.dlr.de/iaa.symp/archive_3/pdf/1503.pdf (accessed June 19, 2007).

CSCOR [Center for Sponsored Coastal Ocean Research], 2007. *CSCOR Harmful Algal Bloom Event Response Program*. http://www.cop.noaa.gov/stressors/extremeevents/hab/current/fact-ev_resp.html#accomp (accessed May 25, 2007).

Darcey, J.W.H., G.M. King, and P.S. Lobel, 1994. Herbivory by reef fishes and the production of dimethylsulfide and acrylic acid. *Marine Ecology Progress Series*, 112: 67–74. http://www.int-res.com/articles/meps/112/m112p067.pdf (accessed July 17, 2007).

Elvidge, C.D., K.E. Baugh, J.B. Dietz, T. Bland, P.C. Sutton, and H.W. Kroehl, 1999. Radiance calibration of DMSP-OLS low-light imaging data of human settlements. *Remote Sensing of Environment* 68:77–88.

Elvidge, C.D., K.E. Baugh, E.A. Kihn, H.W. Kroehl, and E. B. Davis, 1997. Mapping city lights with nighttime data from the DMSP Operational Linescan System. *Photogrammetric Engineering & Remote Sensing* 63(6):727–734.

HARRNESS, 2005. *Harmful Algal Research and Response: A National Environmental Science Strategy 2005–2015*. J.S. Ramsdell, D.M. Anderson, and P.M. Glibert, eds., Washington, DC: Ecological

Society of America, 96 pp., http://www.whoi.edu/redtide/nationplan/HARRNESS.pdf (accessed June 11, 2007).

Hastings, J.W., 1978. Bacterial bioluminescence: An overview. In *Methods in Enzymology: Bioluminescence and Chemiluminescence* (M. DeLuca, ed.) Academic: New York, Vol. 57, pp. 125–135.

Lapota, D., C. Galt, J.R. Losee, H.D. Huddell, J.K. Orzech, and K.H. Nealson, 1988. Observations and measurements of planktonic bioluminescence in and around a milky sea. *J. Exp. Mar. Biol. Ecol* 119: 55–81.

Miller, S.D., S.H.D. Haddock, C.D. Elvidge, and T.F. Lee, 2005. Detection of a bioluminescent milky sea from space. *Proceedings of the National Academy of Sciences of the United States of America* 102(40):14181–14184, http://www.lifesci.ucsb.edu/~haddock/abstracts/miller-milkyseas.pdf (accessed May 20, 2007).

NCDDC [National Coastal Data Development Center], 2006. *HABSOS: Harmful Algal Blooms Observing System.* National Environmental Satellite, Data, and Information Service; National Oceanic and Atmospheric Administration; http://www.ncddc.noaa.gov/habsos (accessed May 14, 2007).

Nealson, K.H., and J.W. Hastings, 2006. Quorum sensing on a global scale: Massive numbers of bioluminescent bacteria make milky seas. *Applied and Environmental Microbiology* 72: 2295–2297.

NOAA [National Oceanic and Atmospheric Administration], 2007. *Economic Impacts of Harmful Algal Blooms (HABs)*. Center for Sponsored Coastal Ocean Research, http://www.cop.noaa.gov/stressors/extremeevents/hab/current/HAB_Econ.html (accessed June 11, 2007)

Seliger, H.H., and R.A. Morton, 1968. A physical approach to bioluminescence. *Photophysiology* (A.C. Giese, ed.), Academic: New York, Vol. 4, pp. 253–314.