Final Report for Grant #NAG5-6595

Earth Remote Sensing Center of Excellence at Scripps Institution of Oceanography

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We developed advanced communications and networking capability and satellite reception systems for Earth science to improve the ability of scientists at Scripps Institution of Oceanography (SIO) to conduct interdisciplinary research. With matching funds from the SIO Director's office we implemented a "virtual center" utilizing modern networking hardware and software to enhance access for researchers and students to unique satellite and in situ data sets. The center provides facilities and data access to graduate students as well as research scientists at SIO, and outside SIO. Our private sector partners installed and testes and advanced X-band data acquisition system for satellite data capture relevant for Earth science research and applications. Some of the commercial applications of these partners have been developed (or are under development) with NASA SBIR resources. The X-band system collected RADARSAT, ERS-2 and MODIS imagery. Perhaps most importantly, this COE brought together – for the first time - an interdisciplinary team of SIO scientists with interests in Earth remote sensing. The collaboration extended beyond our infrastructure and research accomplishments leading to a dialog that resulted in a report with strong recommendations to the SIO community for enhancing satellite remote sensing at SIO (see Appendix 1).

The center's regional focus was on environmental and geophysical assessment for the Southern Ocean and the California Current regions where the PIs and their commercial partners have on-going research activities combining advanced *in situ* and satellite observation networks (UV monitoring network, AARC antenna systems, CalCOFI; SeaSpace antenna systems).

The five main elements of the project, and accomplishments, are summarized below.

1. Upgrade an X-band antenna at SIO developed with NASA SBIR funding;

This element complemented a previously funded NASA SBIR to SIO and SeaSpace, Inc. The funds in the NASA COE grant allowed upgrading the reception to include the MODIS direct broadcast from Terra. The basic system architecture is summarized in Figure 1.

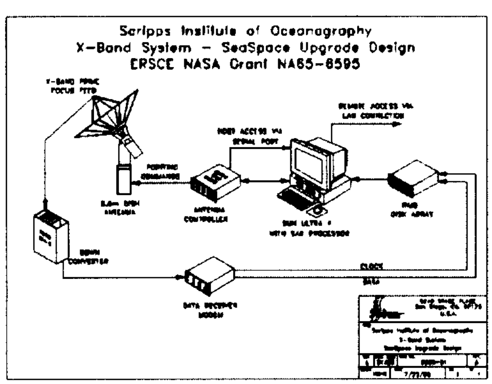


Figure 1. Architecture of X-Band data reception antennae at SIO.

2. Initiate a full operational backup archive of the unique AARC data, deliver to NSIDC;

Under the leadership of co-Investigator Dan Lubin, SIO has collaborated with SeaSpace, Inc. since 1989 to acquire thousands of satellite passes of the NOAA and DMSP polar orbiter environmental satellites. All data had been archived on aging 2GB DAT tapes. This data housed at the Arctic and Antarctic Research Center (AARC) serves dozens of research scientists, students and policy makers at SIO and outside SIO. Thus, the integrity of the unique data set was at risk since the tape media was aging. With funds from this NASA COE, new SUN servers and DLT tape systems were purchased to allow the transfer of all archived tapes to more modern media.

3. Create browse and archive facility for data collected by the SIO X-band and the AARC.

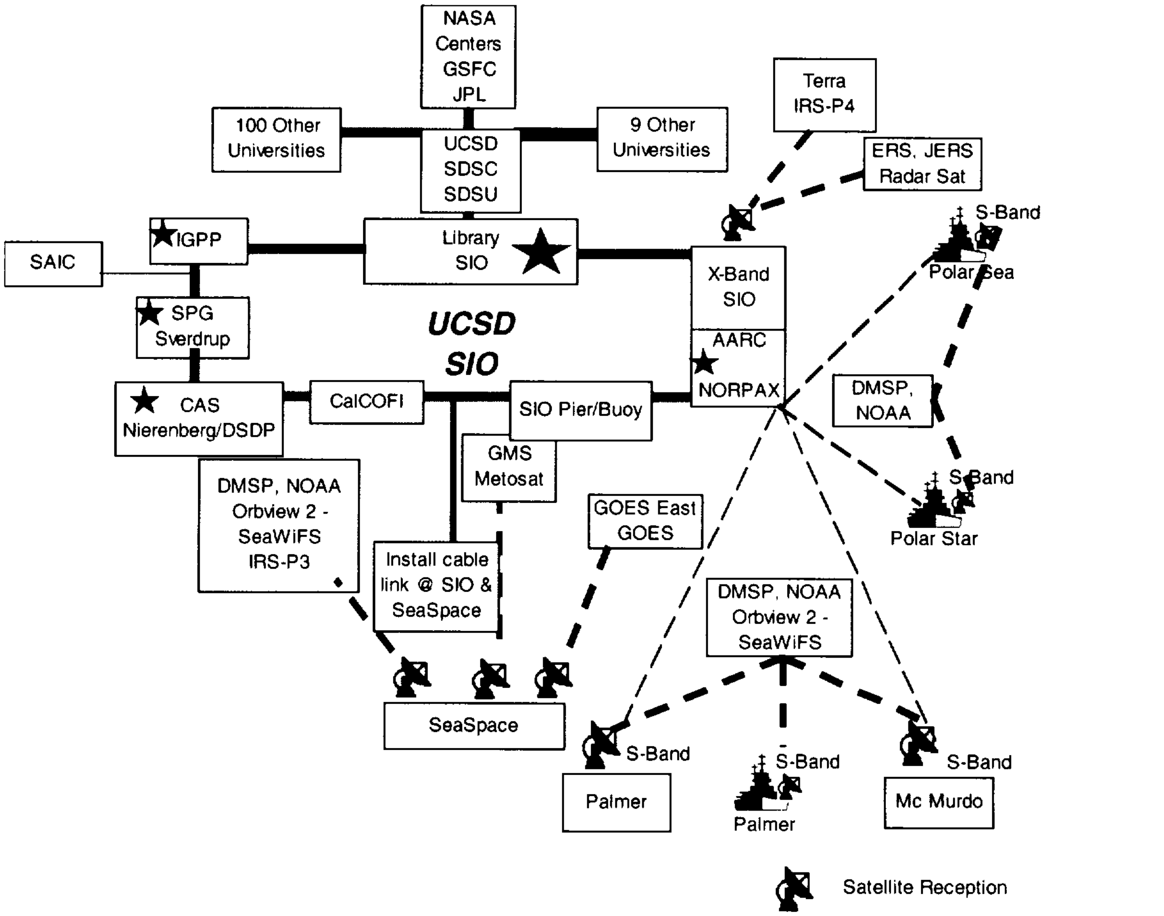
Access to data at the AARC was cumbersome due to its limited availability on tape with no browse system. Therefore, funds from this COE grant were used to make browse images of all captured passes as the tapes were read and transferred to DLT tape as part of Task 2. The browse capability has greatly enhanced access to this unique data set.

4. Augment the SIO curriculum and computational laboratories for remote sensing education;

The co-Investigators of the COE met and developed a plan for enhancing the curriculum at SIO for remote sensing applications. We raised our concerns at the highest level of the institution and were requested to prepare a report on enhancing satellite applications for Earth science research and education at SIO. Attached (Appendix 1) is the report we prepared. Several explicit accomplishments derived from this initiatives were the addition of a course on the physics of radiation in the Earth's atmosphere and oceans, a course on satellite physical oceanography, and a course, and hiring of new faculty whose research has an emphasis on satellite data analysis. While it is not reasonable to assign credit for all these accomplishments directly to this NASA COE, the co-Investigators on this project were also the leaders on recommendations to the university, and specific, tangible accomplishments like data access, networking, X-Band antennae, etc. were elements of the overall transformation of the philosophy at SIO. Thus, this project, which brought an interdisciplinary team of SIO scientists with satellite interests together for the first time, played a pivotal role at the inception of our effort to encourage this dramatic institutional transition.

5. Enhance data access within and outside SIO including researchers and students;

A key element of this task was the creation of the browse files for AARC data holdings summarized under Task 2. We also partnered with SIO Director's office through SIO matching funds and funds provided from the COE to implement a new high speed network infrastructure at SIO summarized in Figure 2.



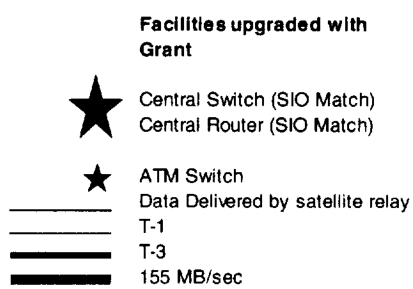


Diagram of satellite and *in situ* observing networks for regional studies of the Antarctic and Southern California. The NASA Centers of Excellence grant allowed installation of the facilities summarized below:

Figure 2. Hardware and network infrastructure improvements at SIO that are critical to the success of our NASA COE. The SIO administration provided matching funds to install the central switch and router that now serve the entire institution. The grant provided switches for several key buildings to upgrade the system to ensure 100MBS access to most students and researchers at SIO. Prior to this upgrade, all SIO shared a single T-1 line.

Appendix 1. Satellite Remote Sensing IRDAC Thrust Committee Report

Co-Chairs: Francisco P. J. Valero and B. Greg Mitchell
Contributors: P. Flatau, D. Lubin, B. Minster, V. Ramanathan, D. Sandwell, D. Stammer, D. Stramski

Among the most important goals for modern Earth science is to understand of how the major systems are coupled (i.e. ocean and atmosphere dynamics, biogeochemical processes, climate, and ecology). Advances will require both better models and exploitation of advanced observational tools such as satellite sensors. The first 40 years of satellite observations, which began during the International Geophysical Year, have profoundly changed our perspective of the Earth and have led to significant new scientific understanding. The next few decades will offer major advancements in sensors and spacecraft providing the ability to observe phenomena as diverse as Antarctic sea ice dynamics, El Nino forcing of sea surface temperature and chlorophyll distributions, deep ocean circulation, radiative forcing by anthropogenic aerosols, transport of volcanic aerosols, terrigenous mineral dust transport which fertilizes the oceans, the role of tidal mixing in the deep oceans, and resolution of mesoscale eddy processes which force biogeochemical responses in the global oceans. Scripps Institution of Oceanography (SIO) scientists have already used a variety of satellite observations to make major discoveries. The committee believes that this research tool is so important that SIO needs to become a leading institution in satellite oceanography to complement their already strong shipboard capabilities. Establishing SIO as a recognized leader in satellite remote sensing will require:

- academic hiring of scientists with remote sensing expertise;
- a more coherent remote sensing curriculum, and
- improved infrastructure (i.e. data acquisition and access, data management and networking)

Satellite remote sensing missions have a long lead-time, and therefore national agencies of spacefaring countries are already making final plans for missions a decade from now. SIO scientists should play a lead role in developing these missions to guarantee high priority is given to the most important measurements. Thus, SIO must move in this direction now to lead in the scientific application of satellite remote sensing 10-20 years from now. It is important that we build the intellectual, educational, and research infrastructure to ensure that we can achieve our goals. Such leadership will come not only from hiring experts who exploit satellite observations, but also scientists who study the processes governing the observational patterns, and modelers who are capable of assimilating observations and predicting patterns based on a sound definition of the governing processes.

Academic recruitment

The other scientifically oriented IRDAC thrust groups have separately reported essential scientific goals that SIO should pursue. Those reports demonstrate that satellite remote sensing is a priority for some of the scientific goals SIO should pursue. Therefore, we recommend that academic hiring be motivated primarily by the scientific priorities of the disciplinary and interdisciplinary science elements of SIO. The satellite observational priorities of those groups will then ensure an expansion of expertise in satellite remote sensing at SIO. The evaluation of potential academic hiring should therefore include consideration of scientists who are experts in using satellite data in their research, and capable of teaching our graduate students not only the scientific applications, but also the foundations of satellite remote sensing measurement and systems. SIO has several experts in satellite remote sensing applications, but relative to the size of the institution, and the importance of this observational tool, the committee feels we should strengthen this research area. Furthermore, our curriculum in this field is not well defined or coordinated. We lack critical expertise to achieve the breadth in both research and teaching that will be necessary if SIO is to develop into an international leader in scientific applications of satellite remote sensing. We propose that SIO define a strategic plan to hire exceptional scientists within the various disciplinary and interdisciplinary elements who have a proven ability to utilize satellite remote sensing data in their research.

We have narrowed the highest priority hiring recommendations to experts who will either complement or expand existing expertise in satellite remote sensing at SIO and who would contribute to the curriculum that we believe must be developed to properly train our graduate students. No priority order is implied by the following enumeration which is used to simplify subsequent reference to these proposed hiring initiatives.

1. Small-scale physical-biogeochemical interaction, including mixing and vertical transport of nutrients to support ocean primary production and the flux of gas across the ocean-atmosphere interface, is a research area of great interest. This research area requires process studies of fluid dynamics, and an interdisciplinary collaboration with biologists, chemists or air-sea boundary experts concerned with small-scale processes that take place especially near boundaries and on the continental shelves. Many modern ocean models that address this scale of the flow field have to exploit a combination of in situ data and satellite-derived surface fields (e.g., wind and sea surface elevation) to improve and constrain physical-biological models. We recommend hiring a physical oceanographer with expertise in physical-biological and/or shelf models and with a record of interdisciplinary collaboration with biologists, chemists or air-sea boundary experts concerned with small-scale ocean dynamics of other system elements.

2. Colored aerosols, including terrestrial dust, and anthropogenic soot are poorly characterized in terms of detailed optical and chemical properties but are of great scientific importance for biogeochemical processes including trace mineral input to the oceans and radiative forcing of the atmosphere. Clouds play an important role in global radiative budget and their bulk and spectral properties have to be resolved and understood on many scales. Modern multi-spectral satellite sensors (passive and active) will have the potential to dramatically improve our observational capability of colored aerosols and clouds. We should ensure that SIO has the capability to integrate that information with advanced process studies and models of biogeochemistry and climate. We recommend hiring a physical optics expert with strong foundation in radiative transfer theory, scattering by non-spherical particles and experience in applications of satellite data to research on colored aerosols and/or clouds.

3. Significant research will continue on approaches to better constrain the various components of the Earth's carbon cycle. In a scenario of continuing emission of anthropogenic carbon dioxide, it is crucial to quantify the role of the ocean as a sink or source in the global carbon budget. Estimating phytoplankton pigments and global ocean primary production from satellite ocean

color over the last two decades have been relevant to this research, as well as to the more classical issues relating local, regional and basin scale primary production to ecological processes. Satellite remote sensing is presently gaining new significance for research on the carbon dioxide problem and the ocean's role in climate as novel satellite-based approaches are being developed to determine organic carbon reservoirs in the ocean, export of carbon from the surface ocean to the ocean's interior, and the rate of gas transfer across the air-sea interface. SIO has strength in both theoretical and applied ocean optics with an emphasis on detailed understanding of in situ observations and optical processes (including photosynthesis) that underlie ocean color remote sensing. We recommend hiring an expert on applications of satellite-derived passive solar reflectance whose research will combine models and data from the many ocean color satellites on orbit or soon to be launched to study oceanic carbon reservoirs and fluxes at regional or global scales.

4) At large time and space scales, a frontier of ongoing oceanic research is to understand the mass budget of the ocean, including its exchange with the atmosphere and the land system, variations in surface salinity (and temperature) and redistribution of mass within the ocean. Progress in this area will fundamentally contribute to our understanding of how the large-scale wind-driven and thermo-haline circulation of the oceans is coupled to climate and to the Earth's hydrologic cycle. The mass of water stored in glaciers and sea ice, evaporation and precipitation, and the temporal/spatial dynamics of these are all of fundamental importance to ocean circulation, heat storage and climate. We recommend hiring a scientist with expertise in the hydrologic cycle of the climate system who has proven capability using satellite data in the study of glacial or sea ice dynamics, quantitative precipitation and related surface temperature and salinity estimates, and the combination of in situ and satellite observations with models of the hydrologic cycle.

Our recommendations summarized above are complimentary with the following elements of other IRDAC thrust committees reports:

The Geosciences thrust group defined a priority hire in the broad area of geodynamics that includes modeling combined with data from proposed satellite missions to constrain ice volume change and quantify the annual and interannual hydrologic cycle on a global scale. However, their advertisement is broad enough to also include modeling of mantle and tectonic processes in the oceanic and continental lithosphere. Our recommendation #4 is more narrowly focused on the hydrologic cycle and sea ice element because we feel this focus has a closer affinity with atmospheric dynamics, climate, physical oceanography, and ocean biogeochemistry. We also recognize that many of the sensors and data analysis methods that we wish to apply to Earth science are relevant in the exploration of other planets and their moons. The Geosciences group recommended that SIO consider research in comparative planetology and the potential exploration of the ocean of Europa. Such an initiative is appropriate for the new mode of university-led satellite missions that NASA has begun to implement. We feel that the best strategy to pursue such opportunity would be to establish SIO as a world leader in scientific research using satellite remote sensing data.

The Physical-Biological-Chemical Interactions thrust group has emphasized the need to improve our understanding of nutrient cycling and nitrogen fixation for basin and global scale biogeochemistry. This will require better knowledge of transport of terrigenous minerals through the atmosphere to the central oceans, chemical transformations of minerals in the upper ocean, the rate of vertical mixing and the dynamics of nutrient cycling and nitrogen fixation. Eventually, the integration of these physical, chemical, biological and meteorological processes for ocean primary production and biogeochemical cycles will be required at large time and space scales. Our hiring recommendations #1, 2, and 3 are relevant to the goals of this separate thrust group. We concur with their focus on small scale mixing, process studies, nutrient dynamics and modeling of these but also recommend that consideration be given to those areas of satellite observations that will be essential to extend the smaller scale understanding to the basin and global scale.

The Coastal Ocean Science thrust group has outlined the need for interdisciplinary research in the coastal zone that addresses the important time and space scales of variability. A combination of observations and modeling is viewed as essential to address their scientific goals. While specific mention of satellite remote sensing is not included in their recruitment summary or draft advertisements, they do identify time and space scales of variability that are difficult to resolve with traditional in situ observations, modern rapid survey tools or new surface observational systems. Their recommendation of hiring a numerical modeler whose models are capable of assimilating relevant observational data could easily be compatible with our recommendation #1. We believe that various new and existing satellite sensors, including high spatial and spectral resolution sensors, synthetic aperture radar, scatterometers, altimeters, ocean color and sea surface temperature will prove valuable to coastal ocean science and management. Development of models capable of assimilating these data sets might be considered an important priority.

The Large-scale Coupled Systems thrust group summarized requirements to improve our understanding of the hydrologic cycle, to integrate chemistry and biology into coupled system models and to assimilate observations, including satellite data, into modern models. We concur with their recommended wording of draft advertisements specifically emphasizing that expertise in the use of satellite remote sensing data as an observational tool will be one criterion used to evaluate applicants. Explicit inclusion in advertisements that satellite remote sensing experts are encouraged to apply is strongly recommended by our committee.

In summary, the various scientific thrust groups converge on some common themes including combining both traditional and modern observational technologies with interdisciplinary data assimilation models. Some of the specific recommendations of the scientific thrusts emphasize the need to use satellite remote sensing to attain the goals that have been outlined. We concur with this broad philosophy and recommend that the advertisements that are generated for academic recruitment include specific mention of satellite remote sensing as one of the observational tools of high priority. We also recommend that the search committees for the various positions endeavor to ensure that appropriate balance is attained through the searches for in situ and remote observations, and modeling. Clearly, we would be disadvantaged if a good balance of scientists with diverse observational and modeling approaches were not recruited through the IRDAC process.

Curriculum

Among the most important aspects of our recommendation is that SIO develop a more coherent remote sensing curriculum that cuts across, but is also integrated with, the various science curricular groups. Such a curriculum would attract the best students and prepare them to exploit modern satellite technology. Moreover, since many of our students will be developing and using data from satellite systems of the future, they should understand the fundamentals of remote sensing from a broad perspective. We propose to develop an interdisciplinary curriculum, which first stresses physical principles of remote sensing and radiative transfer. Topics include: propagation dispersion and reflection of electromagnetic waves, thermal emissions and radiative transfer, ocean and land spectral reflectance and scattering, electro-optical systems, passive microwave systems, active lidar and radar systems, satellite orbits/platforms and image processing techniques. From this point, the students will branch to disciplinary courses taught within the traditional curricular groups. Examples include geology/geodynamics, satellite physical oceanography, climate, synoptic meteorology, ocean carbon cycles and even comparative planetology.

SIO already has few researchers and faculty with expertise in satellite remote sensing. Based on the recommendations of the other IRDAC scientific thrust groups and existing academic searches, one expects that the remote sensing expertise will be broadened. However, we lack a commitment to teach the foundations of satellite remote sensing, which is concerned with radiative transfer, the interaction of electromagnetic radiation with Earth system components and fundamental applications courses. These courses should be complemented by practical courses in measurement, modeling and applications. Elements of a remote sensing curriculum are provided below.

Foundation courses

- Physical Principles of Remote Sensing (Sandwell and others)
- Foundations of Radiative Transfer (new hire)
- Atmospheric Radiation (new hire)
- Ocean Optics (Stramski)

Applications

- Climate (Ramanathan)
- Satellite Physical Oceanography (Stammer)
- Satellite Geodesy and Crustal Dynamics (Bock and Sandwell)
- Ocean Color Remote Sensing (Stramski)
- Hydrologic Cycle Remote Sensing (new hire)
- Applications of Remote Sensing (broad lecture series including many research staff)

Our recommendation is that the existing faculty teach most of this basic curriculum. However, the field is becoming so large and diverse that we need to grow in this area. As a minimum, we believe a new faculty member is needed to teach the foundations of radiative transfer and the hydrological cycle classes and coordinate this with other elements of a basic curriculum. In general, this proposed curriculum will be coordinated by the existing curricular groups.

Moreover, the institution should encourage existing research scientists with appropriate expertise to teach lecture or seminar courses on specialized topics. Indeed, research scientists have taught several remote sensing classes but there is a concern that their teaching contributions are not properly considered during academic review. SIO needs to define a formal policy for compensation and academic review of researchers who contribute to teaching of SIO students.

Finally we should explore formal coordination of an Earth science curriculum with UCSD upper campus, where many of the courses we envision might be of great interest to upper level undergraduates and graduate students on upper campus. Such a strategy would ensure sufficient student enrollment to teach the various specialized classes, as well as garner a greater allocation of UC funds proportionate to the undergraduate teaching effort.

Infrastructure

There is less consensus among the committee regarding the best strategy for infrastructure improvement as compared to our consensus to recommend that SIO expand its academic research and curriculum for satellite remote sensing scientific applications. However, there is unanimous agreement that if we are to become a leading institution in the application of satellite data, there will need to be significant improvement in infrastructure. Some of this should occur in the context of start up funding allocated to new hires. Separate from the needs of individual new hires is the need for efficient campus wide networking, computational systems, and access to data provided from external sources, or unique data acquired by the newly developed X-band antennae. We feel that a careful study of the needs of both the satellite remote sensing experts, and the non-experts who simply wish to use the data, must be carried out to define a consensus recommendation for infrastructure improvement. Such a study will take more time that we have had for the development of this report, and should consider the needs of all SIO academics and students. We recommend that a satellite remote sensing infrastructure study be undertaken.

Summary Recommendations

1. SIO should strive to lead - rather than follow – in the application of satellite data to important Earth science questions.

2. Recruitment to strengthen satellite remote sensing science should be achieved in the context of scientific recruitment. Advertisements should encourage applications from scientists with remote sensing expertise:

> "scientists who exploit a wide range of observational strategies, including, ... and satellite remote sensing."
>
> "development of interdisciplinary models that include data assimilation of in situ and satellite observations...."
>
> Search committees should consider experts in scientific applications of satellite remote sensing and modelers with demonstrated expertise in satellite data assimilation

3. A coherent remote sensing curriculum should be developed.
   - Create an interdisciplinary curriculum coordinated by existing curricular groups
   - Teach foundations of electromagnetic radiation interaction with Earth's systems
   - Hire new faculty appointments in radiative transfer and applications
   - Utilize research scientists to ensure breadth of curriculum
   - Partner with UCSD upper campus in Earth Science curriculum

4. Remote sensing data analysis infrastructure should be improved.
   - Allocate resources for new hires for specific infrastructure requirements
   - Make satellite data more accessible to all SIO researchers and students
   - Carry out study of specific infrastructure recommendations
   - Improve networking, mass storage, and data management