TECHNICAL REPORT

Contract Title: Infrared Algorithm Development for Ocean Observations with EOS/MODIS

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INFRARED ALGORITHM DEVELOPMENT FOR OCEAN OBSERVATIONS WITH EOS/MODIS

Abstract

Efforts continue under this contract to develop and validate algorithms for the computation of sea surface temperature (SST) from MODIS infrared measurements. These include radiative transfer modeling, comparison of *in situ* and satellite observations, evaluation of surface validation approaches for IR radiances, and participation in MODIS (project) related activities. Activities in this contract period have focused on analysis of on-orbit data from the SST bands of the Terra MODIS, field campaigns, analysis of field data, preparation of publications and presentations.

A. NEAR TERM OBJECTIVES

MODIS Infrared Algorithm Development And Maintenance

A.1. Algorithmic development efforts based on experimental match-up databases and radiative transfer models and inter-satellite comparisons

A.2. Interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST activities. Focus has been on analysis of the on-orbit data to determine the effects of instrumental artifacts.

A.3 Maintain and develop at-sea instrumentation for MODIS SST validation.

A.4 *In situ* validation cruises for the MODIS IR bands.

A.5 Development and population of the M-AERI Data Base, the Oceanographic and Atmospheric Archive and Retrieval System (OAARS).

MODIS SST – Scientific Research

A.6 Study thermal structure of ocean-atmosphere interface.

A.7 Development of optimal skin-SST validation strategy.

Overarching Contract Activities

A.8 Provide investigator and staff support for the preceding items.

B. OVERVIEW OF CURRENT PROGRESS

July - December 2000

Activities during the past six months have continued on the previously initiated tasks. There have been specific efforts in the areas of analysis of on-orbit brightness temperatures and cruises to acquire MODIS infrared validation data. In addition, previously initiated activities, such as team related activities, continue, as have episodic efforts associated with MODIS anomaly characterization and response.

Special foci during this six-month period have been:

1) Refinement of the SST retrieval algorithm based on simulations of the MODIS brightness temperatures.
2) Continuation of the analysis of measurements from M-AERI research cruises (Table 1).
3) Installation of equipment of on *Explorer of the Seas.*
4) Preparation and participation in the cruise of the *USCGC Polar Star* in the Western Arctic (August – September, 2000).
5) Preparation and participation in the cruise of the *USCGC Polar Sea* from Seattle to Sydney (November 2000).
6) Preparation and participation in the cruises of the NOAA ship *Ronald H Brown* in the Tropical Pacific Ocean, as part of the Gasex'01 and ACE-ASIA Campaigns (January – May 2001).
7) Maintenance of the at-sea hardware.
8) Continue development of a purpose-built computer database for validation cruise data and associated satellite measurements.
9) Implementation of various SST data assimilation approaches.
10) In collaboration with Dr B. Ward of the University of Bergen continue the study of the thermal structure of the upper ocean based on data from his micro-profiler SkinDeEP.
11) In collaboration with MODIS PI Dr Ian Barton, form the CSIRO Marine Labs in Hobart, Tasmania, plan the *2nd International Infrared Intercomparison* at the University of Miami – Rosenstiel School.

B.1. Algorithmic development efforts based on radiative transfer models.

The focus of the radiative transfer modeling and algorithm development has continued to be on the three SST bands in mid-infrared atmospheric window between 3.5 and 4.1µm wavelength (MODIS bands 20, 22,23). These have relatively invariable atmospheric transmission and offer the prospect of more accurate SST retrievals than possible in the conventional, thermal infrared window at 10-13µm wavelength (MODIS bands 31,32). However, because of sensitivity to sun-glint reflected at the ocean surface, retrievals of SST from these bands will be limited during the daytime. The form of the algorithm is:

$$SST_4 = a + b * BT + c * \Delta BT + d * \Delta BT * (\sec(\theta) - 1)$$

where SST_4 is the retrieved SST measured in the 4 µm atmospheric window, in degrees Centigrade; BT is a measured top-of-atmosphere brightness temperature, ΔBT is the difference in brightness temperatures measures in two bands in the window, θ is the satellite zenith angle, and a, b, c, and d are numerical coefficients. The inputs to the radiative transfer simulations include the relative spectral response functions of each of the MODIS bands (averaged over all of the 10 channels are used here) and a large set of representative atmospheric state vectors, that are derived from the four-dimensional data assimilation model of the ECMWF. Table 1 shows the coefficients and predicted rms uncertainty in the SST_4 retrievals (including the contributions from the sensor NEΔT, but not other instrumentally induced uncertainties).

BT	*ΔBT*	*a*	*b*	*c*	*d*	*rms*
20	22-20	2.05827	1.02039	1.42800	-1.91824	0.450
20	23-20	2.21785	1.04977	0.453908	-0.622208	0.391
20	23-22	-0.0382347	1.04786	-0.466777	-0.209102	0.371
22	22-20	2.05790	1.02041	407208	-1.91799	0.450
22	23-20	1.28466	1.02513	-0.146535	-0.391964	0.179
22	23-22	0.548027	1.01115	-0.561578	-0.255844	0.060
23	22-20	4.62743	1.03114	0.794831	-3.83250	0.933
23	23-20	2.21780	1.04976	-0.595860	-0.622200	0.391
23	23-22	0.547600	1.01113	-1.57292	-0.255732	0.060

Table 1. Coefficients and predicted rms uncertainties in SST derived from brightness temperatures in the 4 µm atmospheric window.

B.2. Interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST activities.

Intensive efforts have been underway at the University of Miami – Rosenstiel School since the delivery of the first MODIS data to develop corrections for the instrumental artifacts that appear in the MODIS SST bands after application of the on-board calibration procedures. These are apparent as detector-to-detector banding, mirror reflectivity vs. scan angle effects, and different characteristics of the two sides of the mirror. These artifacts are several times larger than can be tolerated in the SST retrieval error budget, and unless satisfactory corrections can be found, the anticipated absolute accuracy of the MODIS SSTs will be very much poorer than that of AVHRR. This is being done in close collaboration with Dr R.H. Evans (Contract NAS5-31362) and others at RSMAS on a daily basis and with MCST members and with Raytheon personnel. There has been a marked improvement in the noise characteristics of the data since switching over to the 'Side B' electronics, but this switch did not come without a penalty as much of the effort by the MCST and at RSMAS to develop corrections for the instrumental artifacts needs to be repeated as these corrections are specific to the 'Side A' electronics.

Initial results from the MODIS have been presented by Bob Evans and Peter Minnett at the Oceans from Space Symposium and at the PORSEC 2000 Symposium. Peter Minnett also gave invited seminars at the Universities of Oxford and Leicester in the UK, and an invited review of two decades of AVHRR data applications, at the Oceans from Space Symposium. He also gave presentations about validating satellite-derived SSTs at the ESA ERS-Envisat Symposium and at the PORSEC 2000 Symposium. Ajoy Kumar also presented a poster at the PORSEC 2000 Symposium on diurnal effects in the Pacific Ocean measured during the recent Polar Star cruise.

B.3 Maintain and develop at-sea instrumentation for MODIS SST validation.

Routine maintenance of the M-AERIs used in cruises for validating MODIS SSTs was undertaken during this reporting period. Other sensors deployed to provide ancillary data were also refurbished were necessary.

B.4 *In situ* validation cruises for the MODIS IR bands.

MAERI-1 was installed on the *Explorer of the Seas*, which is a very large and sophisticated cruise liner. The cruise line, Royal Caribbean Cruises undertakes weekly cruises in the eastern Caribbean Sea and Bahaman Islands (Figure 1). This provides an unprecedented opportunity to gather satellite vitiation data in a routine fashion year round. The ship returns to Miami each Saturday at which time the data are retrieved and taken to RSMAS. The data return has been very good (Figure 2).

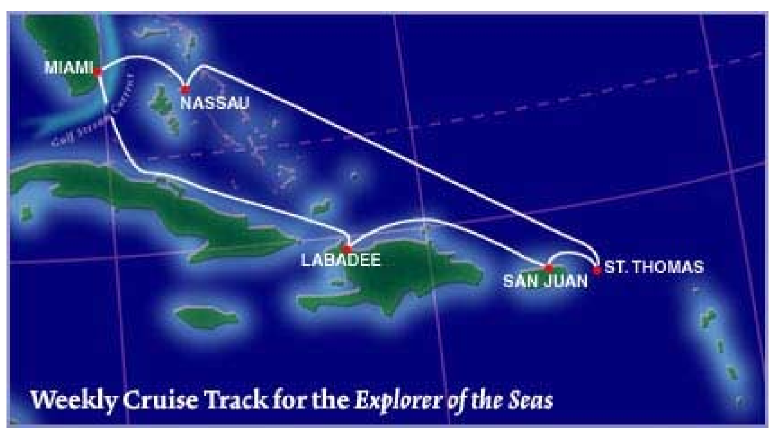

Figure 1. Weekly cruise track of the Royal Caribbean International ship *Explorer of the Seas*

Other sensors mounted on the ship include a Portable Radiation Platform (to be installed in July 2001), a total sky imager, a ceilometer, a wind profiler, a microwave radiometer, a radiosonde system (to be installed for specific measurement campaigns), an optical rain gauge and a suite of conventional weather stations measuring routine surface meteorological variables.

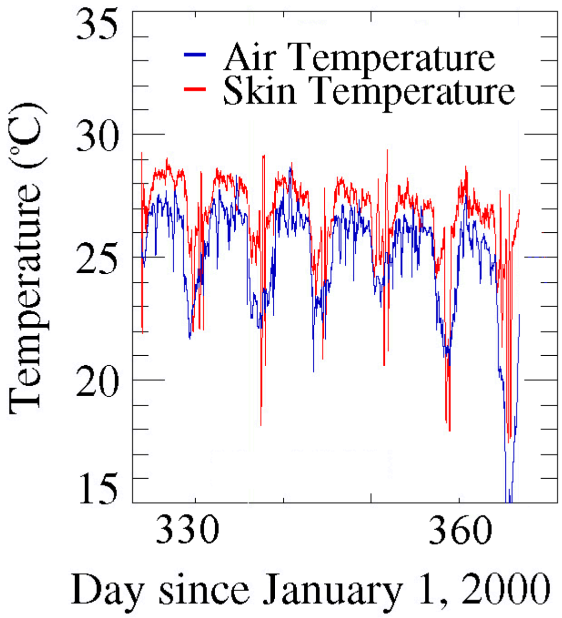

Figure 2. Skin SST and near-surface air temperatures measured by MAERI-1 on the *Explorer of the Seas*, since installation in October 2000. The repeating pattern results from the repeated cruise track, with the colder temperatures being recorded when the ship is in the Port of Miami each Saturday. The slope of the curves represents the seasonal cooling of the upper ocean and lower troposphere.

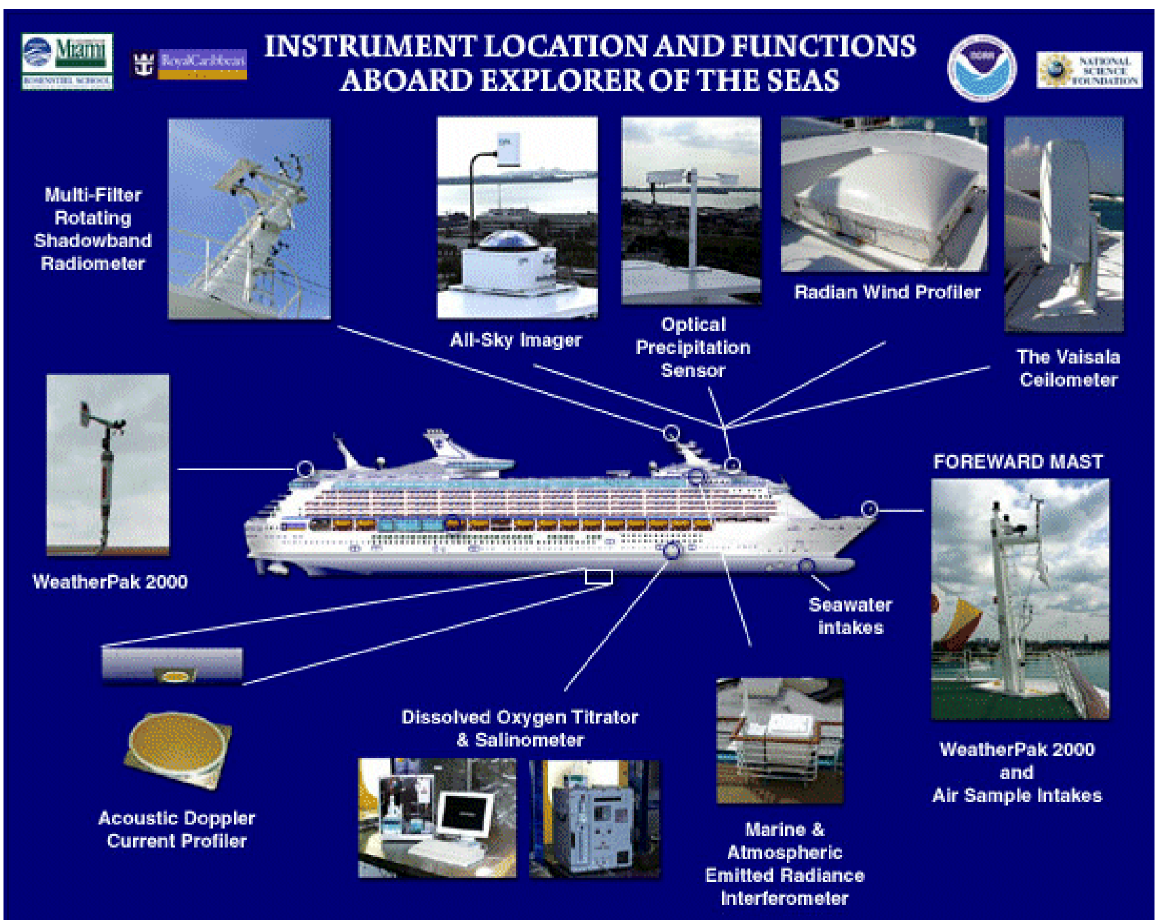

Figure 3. Instruments on the Explorer of the Seas.
From http://www.rsmas.miami.edu/rccl/facilities.html

MAERI-2 was installed on the *USCGC Polar Star* for the two-month Arctic West cruise to the north of Alaska, beginning in Seattle on July 27. The cruise track is shown in Figure 4. The M-AERI and ancillary instrument behaved very well and thereby provided a valuable data set for high latitude validation of MODIS SST in the summertime ice-free parts of the Arctic Ocean.

Following the arctic deployment, MAERI-2 was embarked on the *USCGC Polar Sea* in Seattle for the trans-Pacific passage to Sydney. Within a few days of leaving Seattle, the M-AERI computer suffered a catastrophic disk crash from which recovery during the cruise was not possible despite concerted efforts by those involved. The other sensors functioned well. The MAERI was shipped back to the US from Australia for repair and refurbishment. This is the first occasion in 17 major deployments that data collection by the MAERI was curtailed by an instrumental problem.

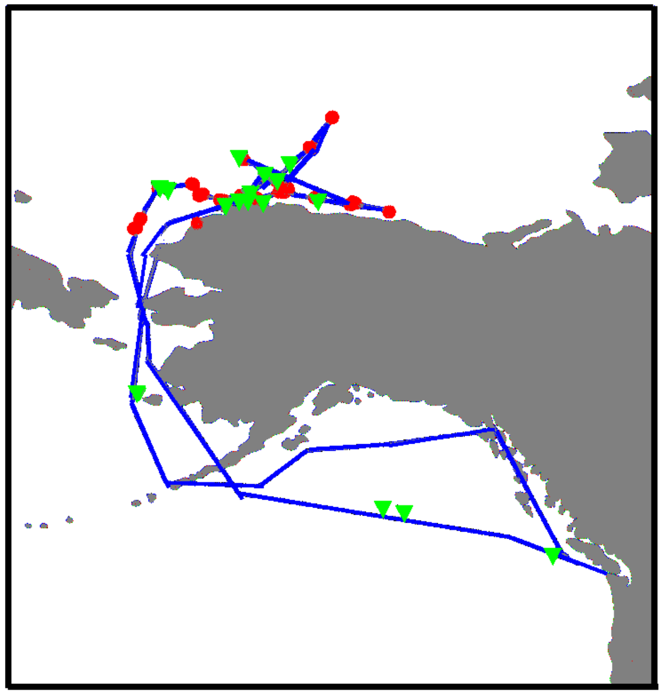

Figure 4. Cruise track of the USCGC Polar Star for the two-month Arctic West cruise. The red dots indicate where the 'hard hat' surface float was deployed to give a subsurface temperature at a depth of about 5cm, and the green triangle where radiosondes were launched to measure atmospheric temperature and humidity profiles.

B.5 Development and population of the M-AERI Data Base, the Oceanographic and Atmospheric Archive and Retrieval System (OAARS).

The OAARS database is located at http://www.rsmas.miami.edu/ir/maeri-db and is constantly being populated with new data sets. The database now contains data for 16 M-AERI cruises with nine search options available.

Table 2 is a listing of the M-AERI projects in the database and Figure 5 shows the tracks of the completed M-AERI cruises.

Project	Ship	YYYYMMDD	Start Port	End Port	Instrument
CSP1996 Combined Sensor Cruise	NOAA Ship Discoverer	19960314-19960413	Pago-Pago, Am. Samoa	Honolulu, HI	Prototype
HiNz 1997 Hawaii-New Zealand Transit	R/VRoger Revelle	19970928-19971014	Honolulu, HI	Lyttleton, NZ	M-AERI 1 and 2
24N1998 OACES 24 N Section	NOAA S Ronald H. Brown	19980108-19980224	Miami, FL	Miami, FL	M-AERI 1
NOW1998 North Water	CCGS Pierre Radisson	19980326-19980728	Quebec City, Canada	Nanisivic, Canada	M-AERI 2
GASEX1998 OACES Gasex	NOAA S Ronald H. Brown	19980502-19980707	Miami, FL	Miami, FL	M-AERI 1
PANAMA1998 Panama Transit	NOAA S Ronald H. Brown	19980712-19980727	Miami, FL	Newport, OR	M-AERI 1
PACS1998 PanAmerican Climate Studies-mooring recovery	R/V Melville	19980908-19980929	San Diego, CA	San Diego, CA	M-AERI 1
SLIP1999 Western Pacific Transect, St. Lawrence Island Polynya	USCGS Polar Sea	19990301-19990511	Adelaide, Austrailia	Seattle, Washington	M-AERI 2
NAURU1999	R/V Mirai	19990608-19990720	Yokohama, Japan	Sikenehama, Japan	M-AERI 1
NOW1999 North Water	CCGS Pierre Radisson	19990824-19991010	Quebec City, Canada	Quebec City, Canada	M-AERI 2
MODIS1999	R/V Melville	19991001-19991020	San Diego, CA	San Diego, CA	M-AERI 1
URANIA1999	NAVE Urania	19991019-19991111	Messina, Sicily	Civitavechhia, Italy	M-AERI 3
EAT1999 Eastern Atlantic Transect	R/V Polarstern	19991215-20000106	Bermerhaven, Germany	Cape Town Africa	M-AERI 3
PSTAR2000 Pacific Transect	USCGC Polar Star	20000304-20000501	Melbourne, Australia	Seattle, WA	M-AERI 2
URANIA2000 Gulf of Lions	R/V Urania	20000325-20000418	Naples, Italy	Naples, Italy	M-AERI 3
AWS2000 Arctic West Summer	USCGC Polar Star	20000727-20000922	Seattle, WA	Seattle, WA	M-AERI 2

Table 2 M-AERI Projects in the OAARS Database

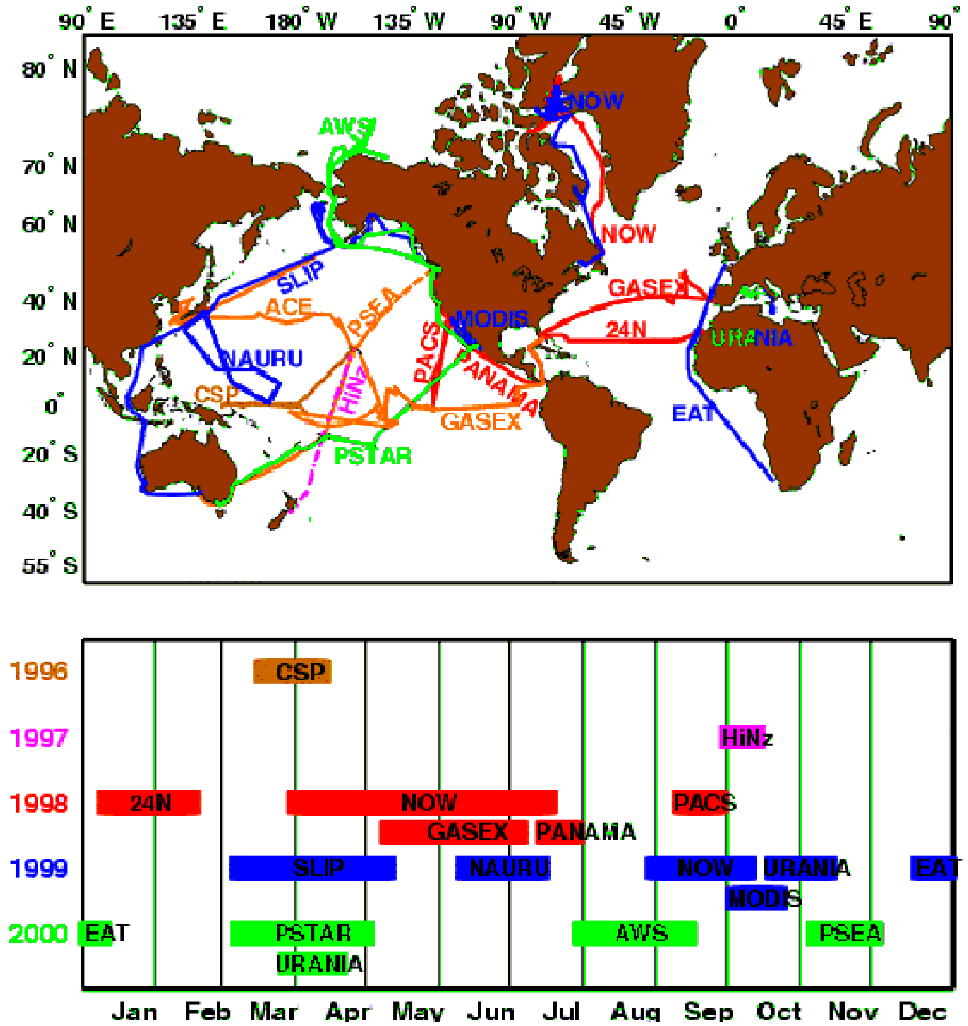

Figure 5. Completed M-AERI cruises

MODIS SST – Scientific Research

B.6 Study thermal structure of ocean-atmosphere interface.

Measurements taken by the SkinDeEP autonomous profiling buoy during the cruise of the R/V *Melville* in October 1999 are revealing the complexity of the near-surface temperature structure in low wind speed conditions. SkinDeEP, an experimental profiler developed by Dr Brian Ward, currently at the Geophysical Institute at the University of Bergen, Norway, and who participated in the *Melville* Cruise, carries microthermometers to measure temperatures at sub-millimeter resolution (Figure 6). It profiles repeatedly though the uppermost several meters of the water column, and makes measurements only on the ascending part of each cycle as the sensors pass through undisturbed water. It can make over one hundred profiles before needing recharging and the data transferred to an external computer.

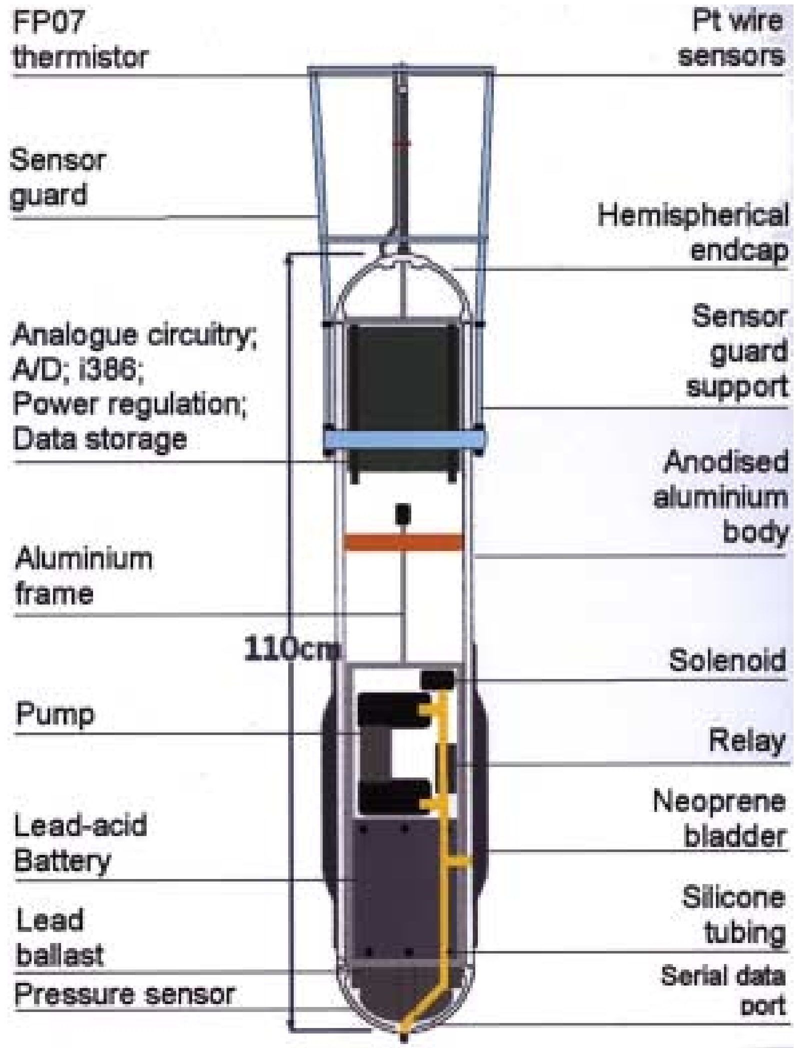

Figure 6. Schematic of the SkinDeEP autonomous buoy.

An example of a profile measured by SkinDeEP in the upper 5.5m off Baja California is shown in Figure 7. It was recorded at 1251 local time on 4 October, 1999, in low wind speed conditions. A strong diurnal thermocline has developed since sunrise, and this shows a complex structure resulting from the local, small-scale dynamics. Also shown on the profile are temperature measurements from other thermometers: the ship's thermosalinograph (green star), a surface-following float (red cross) and the skin temperature measured by the M-AERI (blue circle).

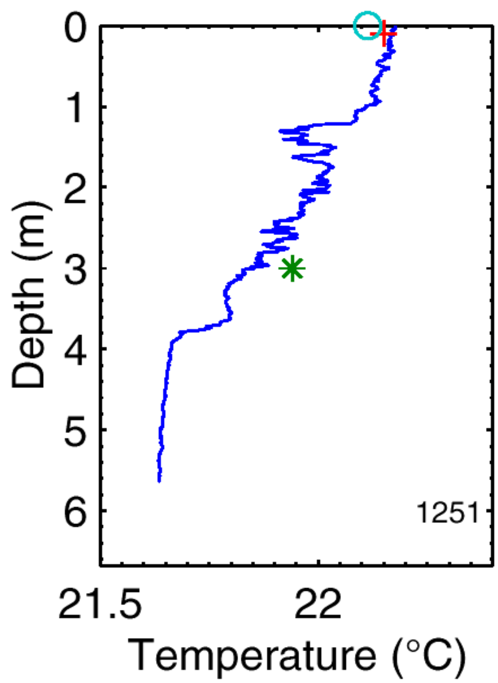

Figure 7. A temperature profile (blue) measured by a microthermometer on the SkinDeEP profiler at 12:51 (local time) on 4 October 1999. The blue circle is the skin temperature measured by the M-AERI and the red cross an in situ temperature measured at a depth of about 5cm from a surface float. The green star is the temperature measurement from a thermosalinograph on the ship at a nominal depth of 3 m. The profiler reveals significant structure in the near-surface layer not resolved by the data at discrete levels.

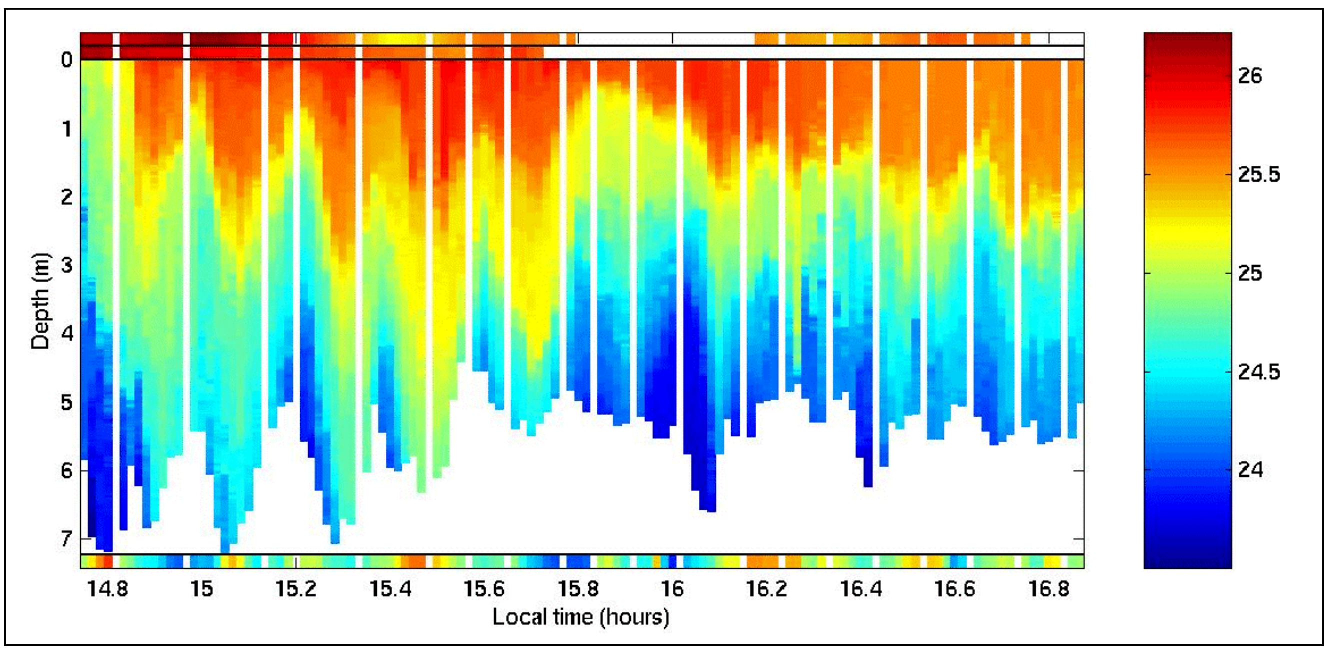

Figure 8. Time series of profiles measured by a microthermometer on SkinDeEP on 12 Ocotober 1999. The color bar at right gives the temperature scale.

The temporal development of the near-surface temperature structure revealed by the repeated profiles of SkinDeEP over a period of about two hours is shown in Figure 8. The top color ribbons show the temperatures measured by the M-AERI (skin - top) and surface float (~0.05m depth - below). The ribbon at the base of the plot shows the ship's thermosalinograph temperature at ~3m depth. The oscillatory structure, evident in the profiler data, is probably the result of Langmuir cells that were observed in the area. These temperature oscillations tend to mask the evolution of the diurnal thermocline, but the cooling of the uppermost meter of water is discernable after about 16:00. The apparent warming of the skin- and float temperatures, with respect to the shallower temperature of the profile for times before ~15:15, can be explained by the lack of collocation of the measurements; the SkinDeEP was up to several tens of meters away from the M-AERI and float measurements. The variable depth of the deepest profile measurement can be explained by the vertical velocities in the water caused by the Langmuir circulation. The complexity of the near-surface temperature structure is apparent, and the ramifications on using sub-surface temperatures to validate satellite-derived SSTs in conditions of low wind speed are great.

B.7 Development of optimal skin-SST validation strategy.

In a concerted effort to cross-calibrate all of the high-quality, ship-board, infrared radiometers planned to be used in the validation of SSTs derived form MODIS and other new-generation imaging radiometers on earth observation satellites, it is proposed to hold an international workshop in Miami in 2001. The spacecraft radiometers include those on currently operational satellites MODIS on *Terra* and others that will be launched within the year or so following the workshop. The meeting is planned for a week and will include laboratory measurements using NIST-certified black-body calibration targets, and other calibration sources, in the laboratory, and an intercomparison of the radiometers on a short cruise on board the R/V *F.G. Walton-Smith* in local waters around Miami. A proposal has been submitted to NASA for modest funding to support this effort, and a copy of this is attached to this report as an annex.

B.8 Analysis of AVHRR SSTs in the Gulf Stream area.

As an exercise to develop analysis tools for the future study of MODIS data, an investigation of the Gulf Stream, as revealed in AVHRR data has been conducted. The surface thermal front of the Gulf Stream, space-time interpolated from gappy satellite data, is represented by four hundred path positions between 76^{o}W and 45^{o}W for each two-day composite starting in April of 1982 and ending in December 1996. The dominant wavelengths of the mean path of the Gulf Stream are greater than 400 km with a peak near 900 km. The primary mode of path variability explains 46% of path variability and has a minimum between 76^{o}W to 74^{o}W with a rapid increase consisting of mostly south-north path displacements east of 70^{o}W. The second mode explains 15% of the variance and consists of south-east/north-west path movements in phase from 76^{o}W to 56^{o}W and out of phase east of 56^{o}W. This mode leads to Gulf Stream paths that are either more zonal or more to the northeast. There are three distinct dynamical regimes in frequency versus wavenumber space. A linear regime exists at lowest frequencies and wavenumbers, followed by an exponential increase in the scatter of frequencies versus wavenumbers for spatial scales greater than 150 km. There is a region of considerable energy cascade centered about spatial scales of 400 km. The e-folding wavenumber scale is about 2.5 cycles/1000 km. At the high wavenumber end, spatial scales smaller than 150 km, frequency is independent of wavenumber and Gulf Stream path variability could be modeled as a white-noise process.

The dominant sub-annual periods are broad-band and are associated with mesoscale meandering and ring-stream interactions. There is significant energy associated with an annual O(100) km south-north migration of the stream. In an average year, the Gulf Stream is southernmost at the end of winter/early spring and northernmost in late summer/early fall. However, there are years when this annual migration is six months out of phase with an average year. Our analysis finds significant interannual variability for all periods less than six years examined but there is no significant variability on interdecadal time scales, determined by including Gulf Stream path surveys from the 1940s, 1950s, and 1960s in our analysis.

This analysis indicates, that on the average, the Gulf Stream moves south as the large-scale winds increase, as sea surface temperature decreases, and the large-scale sea surface thermal gradient increases. The south-to-north displacement from the first PC time series is coherent at the 95% confidence level with (i) the root-mean-square (rms) wind stress over the Gulf Stream on time scales between nine months and six years, (ii) the rms stress south of the Gulf Stream on 5-6 year time scales, and (iii) the North Atlantic Oscillation Index on 12-18 months time scales.

The meridional component of the second principle component time series is coherent, at the 95% confidence level with the large-scale sea surface thermal gradient across the Gulf Stream on 9-18 month time scales and (ii) with the rms wind stress south, over, and north of Gulf Stream for six months to six year time scales. The results of the coherence calculations and a principle component analysis indicate that wind-forcing and buoyancy-forcing are equally important for determining the latitude of the Gulf Stream path east of Cape Hatteras on interannual time scales.

C. Investigator Support

July	W. Baringer	R. Kolaczynski	A. Mariano
	J. Brown	R. Kovach	J. Splain
	M. Framinan	A. Li	M. Szczodrak
	K. Kilpatrick	K. Maillet	S.Walsh
August	W. Baringer	R. Kolaczynski	A. Mariano
	J. Brown	R. Kovach	J. Splain
	M. Framinan	A. Li	M. Szczodrak
	K. Kilpatrick	K. Maillet	S.Walsh
September	W. Baringer	R. Kolaczynski	J. Splain
	J. Brown	R. Kovach	M. Szczodrak
	M. Framinan	A. Li	S.Walsh
	K. Kilpatrick	K. Maillet	
October	W. Baringer	R. Kolaczynski	R. Sikorski
	O. Brown	R. Kovach	J. Splain
	M. Framinan	K. Maillet	M. Szczodrak
	K. Kilpatrick		
November	W. Baringer	R. Kolaczynski	R. Sikorski
	O. Brown	R. Kovach	J. Splain
	M. Framinan	A. Li	M. Szczodrak
	K. Kilpatrick	K. Maillet	
December	W. Baringer	R. Kolaczynski	K. Maillet
	O. Brown	R. Kovach	R. Sikorski
	M. Framinan	R. Jones	J. Splain
	K. Kilpatrick	A. Li	M. Szczodrak

D. Future Activities

D.1 Algorithms

a. Continue to develop and test algorithms on global retrievals
b. Evaluation of global data assimilation statistics for SST fields
c. Participate in research cruises
d. Continue radiative transfer modeling
e. Continue analysis of research cruise data
f. Continue to study near-surface temperature gradients
g. Continue planning of post-launch validation campaigns
h. Plan for 2nd International Radiometer Intercomparison
i. Validation Plan updates (as needed)
j. EOS Science Plan updates (as needed)
k. Continued participation in MODIS Team activities

D.2 Investigator support.

Continue appropriate efforts.

D.3 Presentations and publications.

Prepare scientific results for publication in the refereed literature.

E. Problems

The instrumental artifacts in the SST bands evident in the on-orbit data from MODIS continue to be very disconcerting. Their consequences on the absolute accuracy of the SSTs are likely to result in the performance of MODIS not matching that of AVHRR. There has been an improvement in the noise levels associated with the switch to the 'Side B' electronics, but it remains imperative that the appropriate steps be taken to correct these in the FM-1 MODIS before launch.

F. Publications and Presentations

F.1 Refereed publications:

Hanafin, J. A. and P. J. Minnett, 2001. Profiling temperature in the sea surface skin layer using FTIR measurements. *Gas Transfer at Water Surfaces.* edited by M. A. Donelan, W.M. Drennan, E.S. Saltzmann and R. Wanninkhof. *American Geophysical Union Monograph. In reveiew.*

Sea surface spectral emissivity and the depth of the thermal skin boundary layer were determined using high spectral resolution measurements of the sea surface and the atmosphere taken in the field measurements by the Marine-Atmosphere Emitted Radiance Interferometer. In order to determine the sea surface emissivity, the effective incidence angle was found by minimizing the variance in the brightness temperature spectrum retrieved from the corrected upwelling radiance spectrum. Certain wavelength regions have different absorption characteristics, allowing the temperature at different levels to be retrieved from different spectral regions. In this way, the temperature gradient of the *thermal boundary layer was determined. The depth of the skin layer was then calculated by determining the depth at which the thermometrically measured bulk temperature intersects this gradient. At low wind speeds, the skin layer can be up to 0.2mm deep, getting shallower with increased wind speed and becoming very shallow (0.01-0.07mm) above wind speeds of 8ms^{-1}. These results are encouraging for application of this method to determine air-sea heat and gas fluxes in the field.*

Kearns, E.J., J.A. Hanafin, R.H. Evans, P.J. Minnett and O.B. Brown, 2000. An independent assessment of Pathfinder AVHRR sea surface temperature accuracy using the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI). *Bull. Am. Met. Soc*. **81**, 1525-1536

The remotely sensed sea surface temperature (SST) estimated from the 4-km-resolution Pathfinder SST algorithm is compared to a SST locally measured by the Marine Atmospheric Emitted Radiance Interferometer (MAERI) during five oceanographic cruises in the Atlantic and Pacific Oceans, in conditions ranging from Arctic to equatorial. The Pathfinder SST is a product of the satellite-based Advanced Very High Resolution Radiometer, while the MAERI is an infrared radiometric interferometer with continuous onboard calibration that can provide highly accurate (better than 0.05°C) in situ skin temperatures during extended shipboard deployments. Matchups, which are collocated (within 4 km) and coincident (±40 min during the day; ±120 min during the night) data, from these two different sources under cloud-free conditions are compared. The average difference between the MAERI and Pathfinder SSTs is found to be 0.07 ±0.31°C from 219 matchups during the low- and mid-latitude cruises; inclusion of 80 more matchups from the Arctic comparisons produces an average global difference of 0.14 ±0.36°C. The MAERI–Pathfinder differences compare favorably with the average mid-latitude differences between the MAERI skin SST and other bulk SST estimates commonly available for these cruises such as the research vessels' thermosalinograph SST (0.12 ±0.17°C) and the weekly National Centers for Environmental Prediction optimally interpolated SST analysis (0.41 ±0.58°C). While not representative of all possible oceanic and atmospheric regimes, the accuracy of the Pathfinder SST estimates under the conditions sampled by the five cruises is found to be at least twice as good as previously demonstrated.

Kumar, A., P. J. Minnett, G. Podesta, and R.H. Evans, 2000. Analysis of Pathfinder SST algorithm for global and regional conditions. Special Issue on the International JGOFS Symposium on 'Biogeochemistry of the Arabian Sea' *Proceedings of the Indian Academy of Sciences: Earth and Planetary Sciences,* **109**, 395-405.

As part of the Pathfinder program developed jointly by National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) a large database of in situ sea surface temperature (SST) measurements coincident with satellite data is now available to the user community. The Pathfinder Matchup Database (PMDB) is a multi-year, multi-satellite collection of coincident measurements from the Advanced Very High Resolution Radiometer (AVHRR) and broadly distributed buoy data (matchups). This database allows the user community to test and validate new SST algorithms to improve the present accuracy of surface temperature measurements from satellites. In this paper we investigate the performance of a global Pathfinder algorithm to specific regional conditions. It is shown that for zenith angles less than 45o, the best-expected statistical discrepancy between satellite and buoy data is about ~0.5K. In general, the bias of the residuals (satellite - buoy) is negative in most regions, except in the North Atlantic and adjacent seas, where the residuals are always positive. A seasonal signal in SST residuals is observed in all regions and is strongest in the Indian Ocean. The channel-difference term used as a proxy for atmospheric water vapor correction is observed to be unresponsive for columnar water vapor values greater than 45 mm and high zenith angles. This unresponsiveness of the channels leads to underestimation of sea surface temperature from satellites in these conditions.

Mariano, A.J., T.M. Chin and E.H. Ryan, R. Kovach and O.B. Brown. On Gulf Stream Path Variability. *J. Physical Ocean*. *In review.*

The surface thermal front of the Gulf Stream, space-time interpolated from gappy satellite data, is represented by four hundred path positions between 76^o W and 45^o W for each two-day composite starting in April of 1982 and ending in December 1996.The dominant wavelengths of the mean path of the Gulf Stream are greater than 400 km with a peak near 900 km. The primary mode of path variability explains 46\% of path variability and has a minimum between 76^o W to 74^o W *with a rapid increase consisting of mostly south-north path displacements east of 70° W. The second mode explains 15% of the variance and consists of south-east/north-west path movements in phase from 76° W to 56° W and out of phase east of 56° W. This mode leads to Gulf Stream paths that are either more zonal or more to the northeast.*

Minnett, P.J., 2001, Satellite Remote Sensing: Sea Surface Temperatures. *Encyclopedia of Ocean Sciences*, J. Steele, S. Thorpe, K. Turekian (eds). Academic Press, London, UK. *In review*.

The ocean surface is the interface between the two dominant, fluid components of the earth's climate system: the oceans and atmosphere. The heat moved around the planet by the oceans and atmosphere helps make much of the earth's surface habitable, and the interactions between the two, that take place through the interface, are important in shaping the climate system. The exchange between the ocean and atmosphere of heat, moisture and gases (such as CO_2) are determined, at least in part, by the sea surface temperature (SST). Unlike many other critical variables of the climate system, such as cloud cover, temperature is a well-defined physical variable that can be measured with relative ease. It can also be measured to useful accuracy by instruments on earth-observation satellites.
The major advantage of satellite remote sensing of SST is the high-resolution global coverage provided by a single sensor, or suite of sensors on similar satellites, that produces a consistent data set. By the use of on board calibration, the accuracy of the time series of measurements can be maintained over years, even decades, to provide data sets of relevance to research into the global climate system. The rapid processing of satellite data permits the use of the global-scale SST fields in applications where the immediacy of the data is of prime importance, such as weather forecasting, with the prediction of the intensification of tropical storms and hurricanes a particular example.

Minnett, P. J., R. O. Knuteson, F.A. Best, B.J. Osborne, J. A. Hanafin and O. B. Brown, 2001. The Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer. *In review.*

The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) is described and some examples of the environmental variables that can be derived from its measurements, and the types of research that these can support are briefly presented. The M-AERI is a robust, accurate, self-calibrating, sea-going Fourier-transform interferometric infrared spectroradiometer that is deployed on marine platforms to measure the emission spectra from the sea surface and marine atmosphere. The instrument works continuously under computer control and functions well under a very wide range of environmental conditions with a high rate of data return. Spectral measurements are made in the range of ~3 to ~18 μm wavelength, and are calibrated using two internal, NIST-traceable blackbody cavities. The environmental variables derived from the spectra include the surface skin temperature of the ocean, surface emissivity, near-surface air temperature and profiles of temperature and humidity through the lower troposphere. These measurements are sufficiently accurate both to validate satellite-derived surface temperature fields, and to study the physics of the skin layer.

Ward, B. and P. J. Minnett, 2001. An autonomous profiler for near surface temperature measurements. *Gas Transfer at Water Surfaces.* edited by M. A. Donelan, W.M. Drennan, E.S. Saltzmann and R. Wanninkhof. *American Geophysical Union Monograph. In review*.

This paper describes the profiling instrument SkinDeEP (Skin Depth Experimental Profiler), which measures the temperature of the water column from a depth of about 6 meters to the surface with high resolution thermometers. The instrument operates in an autonomous mode as it has the capability to change buoyancy by inflating a neoprene bladder attached to the body of the profiler. Measurements are recorded only during the ascending phase of the profile so as to minimize disturbances at the surface. Results from deployment of the profiler show strong temperature gradients within the bulk waters under conditions of high insolation. These data were compared to the skin temperatures as measured by the M-AERI, a high accuracy interferometric infrared spectroradiometer. The corresponding bulk-skin temperature differences (ΔT) were shown to have strong dependence on the depth of the bulk measurement during the daytime with low wind speeds, but at higher wind speeds, the depth dependence vanishes. One set of profiles under nighttime conditions is also presented, showing the presence of overturning and thus a heterogeneous temperature structure within the bulk.

Yang, Q., B. Parvin, A.J. Mariano, E. Ryan, R. Evans and O. Brown, 2001.Seasonal and interannual studies of vortices in sea surface temperature data. *International Journal of Remote Sensing. In review.*

We have applied an algorithm for calculating feature displacement velocities and for detecting vortices to 13 years of sea surface temperature data derived from Advanced Very High Resolution Radiometer (AVHRR) data. An unique global event database for seasonal and interannual studies of the spatial distribution of oceanic vortices was created for the years 1986-1998. The results indicate that the (1) number of vortices in each season is fairly constant from year to year in each hemisphere, however, their preferred locations change on seasonal to interannual time-scales, (2) the maximum number of vortices were detected in the summer and in the winter in all oceans and the minimum number were detected in the fall, and (3) the distribution of the spatial density function show preferred localizations such as 40°S, the tropical instability region, marginal seas, western boundary and eastern boundary current regimes.

F.2 Presentations:

Evans, R. H. and P. J. Minnett. Overview of MODIS Thermal Ocean Observations. *Oceans from Space - Venice 2000..* Venice, Italy. 9-13 October, 2000

Evans, R.H., P.J. Minnett. O.B. Brown, K. Kilpatrick, E.J. Kearns, H. Gordon, K. Voss and M. Abbott. Early Results form NASA's Moderate Resolution Imaging Spectroradiometer (MODIS): Global and Arabian Sea Regional Ocean Color and Thermal Observations. 5th Pacific Ocean Remote Sensing Conference (PORSEC2000) 5-8 December 2000, Goa, India.

Minnett, P.J. Applications of ship-board infrared interferometry. Department of Atmospheric, Oceanic and Planetary Sciences, University of Oxford, UK. July 5, 2000.

Minnett, P.J. Applications of ship-board infrared interferometry to the validation of the AATSR. Department Space Science, University of Leicester, UK, July 6, 2000.

Kumar, A. and P.J. Minnett. Diurnal variation of SST and heat fluxes in the tropical eastern Pacific Ocean. 5th Pacific Ocean Remote Sensing Conference (PORSEC2000) 5-8 December 2000, Goa, India.

Minnett, P.J Radiometric Measurements of the Sea-Surface Skin Temperature and Validation of Infrared Retrievals of Sea-Surface Temperatures From Satellite. *Oceans from Space - Venice 2000.* Venice, Italy. 9-13 October, 2000

Minnett, P.J. The Advanced Very High Resolution Radiometer - Two Decades of Applications in Oceanography. *Oceans from Space - Venice 2000.* Venice, Italy. 9-13 October, 2000

Minnett, P.J. and B. Ward. Measurements of near-surface ocean temperature variability – consequences on the validation of AATSR on Envisat. *ERS – ENVISAT Symposium "Looking down to Earth in the New Millennium"* Gothenburg, Sweden. 16-20 October 2000.

Minnett, P.J. Infrared interferometric measurements of the sea-surface temperature in the tropical Pacific Ocean. 5th Pacific Ocean Remote Sensing Conference (PORSEC2000) 5-8 December 2000, Goa, India.

Annex - Research Proposal Submitted To The National Aeronautics And Space Administration to Conduct The Second International Infrared Radiometer Calibration And Intercomparison

TITLE:	The second international infrared radiometer calibration and intercomparison
INSTITUTION:	University of Miami Rosenstiel School of Marine and Atmospheric Science Division of Meteorology and Physical Oceanography 4600 Rickenbacker Causeway Miami, FL 33149-1098
SUBMITTED TO:	Dr. James Butler EOS Calibration Scientist Code 925 Goddard Space Flight Center National Aeronautics and Space Administration Greenbelt, MD 20771 Phone: (301) 614-5942 E-mail: butler@highwire.gsfc.nasa.gov
PRINCIPAL INVESTIGATOR:	Dr. Peter Minnett
STARTING DATE:	3/1/2001
DURATION:	6 months
PROJECT COST:	$53,735

Abstract

It is proposed to hold an international workshop for the comparison and calibration of ship-board infrared radiometers that are being used to validate the skin sea-surface temperatures and land surface temperatures derived from the measurements of imaging radiometers on earth observation satellites. These include those on currently operational satellites and others that will be launched within the year or so following the workshop. The meeting is planned for a week and will include laboratory measurements using NIST-certified black-body calibration targets, and other calibration sources, in the laboratory, and an intercomparison of the radiometers on a short cruise on board the *R/V F.G. Walton-Smith* in local waters around Miami.

Aims

To calibrate and compare infrared radiometers used in the validation of the different surface temperature products derived from earth observation satellites. To assess the relative performance of each instrument and thus ensure that surface measurements used in satellite product validation are traceable to a NIST standard temperature scale.

Location

Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, Florida (http://www.rsmas.miami.edu/rsmas.html)

Timing

The workshop is provisionally planned to take place during early April 2001, about three years after the initial workshop (Kannenberg, 1998). The precise timing will depend on the availability of ship time, of the instrumentation and optimizing the participation of the workshop members, all of whom have busy schedules. A list of anticipated workshop participants is given in Appendix 1.

In terms of spacecraft radiometers, the timing of the workshop is apposite in that in addition to the long-term operational imagers (AVHRR, ATSR, GOES Imager) and relatively new sensors (VIRS and TMI on TRMM, MODIS on Terra), there will be five new sensors in orbit, and another scheduled for launch about one year later (Table 1). Even if there are unanticipated launch delays, these new sensors will be producing their initial data within months of the workshop, in the period when we will have maximum confidence in the calibration and consistency of the ship-board radiometers.

Table 1. Spacecraft radiometers designed to produce measurements of SST, which will be validated by shipborne radiometers.

Instrument	Satellite	Status
AVHRR	NOAA polar orbiters	Operational
ATSR-2	ERS-2	Operational
GOES Imager	GOES-E, GOES-W	Operational
VIRS	TRMM	Operational
TMI	TRMM	Operational
MODIS	Terra	Operational
GLI	ADEOS-II	Scheduled launch Nov 2000
AMSR	ADEOS-II	Scheduled launch Nov 2000
MODIS	Aqua	Scheduled launch Dec 2000
AMSR-E	Aqua	Scheduled launch Dec 2000
AIRS	Aqua	Scheduled launch Dec 2000
AATSR	Envisat	Scheduled launch June 2001

Background

The first inter-comparison of infrared radiometers was held at RSMAS during March 1998. This involved several high quality radiometers and some off-the-shelf devices. NIST provided their standard black body target (Fowler, 1995) for calibration of each radiometer. Other black bodies available for calibration included a NIST water-bath balck-body calibration target provided by the University of Washington, a smaller unit from JPL, the CASOTS (Combined Action to Study the Ocean's Thermal Skin) black body (Donlon *et al*., 1999), and a portable unit designed by CSIRO, Australia. Since the first inter-comparison several new radiometers have been constructed (e.g. CIRIMS, ISAR-5; see Table 2) to participate in validation activities. It is important that these radiometers be calibrated against a NIST standard as well as compared with the other radiometers. The inter-comparison and calibration will be held three years after the first exercise; this will enable any drifts in instrument calibration to be detected. Details of the first calibration and inter-comparison can be found at http://www.rsmas.miami.edu/ir/, and Kannenberg, 1998.

Methodology

The first two days will involve all radiometers viewing the available Calibration Black Bodies at a range of temperatures between 10 and 50^{o}C. The RSMAS NIST-certified black body (Fowler, 1995) will be suitable for the calibration of the radiometers allowing the measurements of each radiometer to be traced to the NIST standard. A list of candidate radiometers is given in Table 2. All except the M-AERI use filters to define the spectral band-pass of the measurements, and in several these are designed to match the relative spectral response characteristics of the spacecraft radiometers (*e.g.* Donlon *et al*.,1998). The M-AERI is a well calibrated Fourier-Transform spectroradiometer that operates in the range of wavelengths from ~3 to ~18µm (Minnett *et al*., 2000), from which accurate skin temperatures can be derived (Smith *et al*., Minnett *et al.*, 2001). A brief overview of the M-AERI is given in Appendix 2.

Several secondary black-body targets are in use at various laboratories to provide the calibration source for their radiometers (Table 3). These will be inter-calibrated during the workshop.

Following the laboratory measurements the radiometers will all be mounted on a research vessel (the *R/V F.G. Walton-Smith*, see Appendix 3) to ensure that they can operate accurately and consistently under at-sea conditions. A day will be required to both mount and dismount all the radiometers, with three days of measurements in between. Costs for 3 days of ship time are included in the budget below; the days in port before and after the experiments will not incur charges to this budget.

Table 2 Candidate shipboard radiometers for this Workshop

Instrument	Institution	P.I.
M-AERI	RSMAS, U. Miami.	P. Minnett
SISTeR	RAL,UK.	T. Nightingale
DAR011 & DAR010	CSIRO, Australia.	I. Barton & F. Prata
CIRIMS	APL, U. Washington.	A. Jessup
ISAR-5	JRC, EEC.	C. Donlon
New radiometer	AIMS, Australia.	W. Skirving
New radiometer	NOAA/University of Colorado.	J. Shaw & W. Emery
Off-the-shelf filter radiometers, e.g. TASCOs, Everests, and Heimanns.	Various	Frank Palluconi *et al*.
Infrared imagers	APL, U. Washington	A. Jessup

Table 3 Candidate black bodies for this inter-comparison:

Instrument	Institution	P.I.
NIST-Certified/NIST-Designed Black Body Target	RSMAS, U. Miami	P. Minnett
NIST-Certified/NIST-Designed Black Body Target	APL, U. Washington	A. Jessup
CSIRO Portable black body	CSIRO, Australia	I. Barton
CASOTS black body	JRC, EEC	C. Donlon
JPL Black Body Calibrator	NASA-JPLs	Frank Palluconi

Outcome

High quality radiometric measurements for the validation of satellite-derived surface temperatures are difficult to obtain, and are thus a scarce resource. International collaboration will be required to provide sufficient data to allow reliable validation of surface temperature products for MODIS, AVHRR, VIRS, GLI, and AATSR *etc* (see table 1). Following the radiometer calibration, intercomparison, and testing under field conditions, the international community will have increased confidence in the results to be provided for validation of satellite-derived surface temperatures from the above instruments.

It is intended that the findings of the workshop, in terms of the expected accuracies of the skin temperatures derived from the suite of radiometers available for the validation of satellite-derived sea-surface and land-surface temperatures, will be prepared for publication in the refereed literature.

Budget

March 1, 2001 - August 31, 2001

A. Salaries	
1. Dr. Peter Minnett, Principal Investigator, 4%	
2. M. Szczodrak, 8%	
3. R. Jones, 4%	
5. Research Coordinator, 4%	
Total Salaries and Wages	$10,711
B. Fringe Benefits	2,512
Total Salaries, Wages, Benefits (A + B)	$13,223
C. Miscellaneous Hardware	5,000
D. Other Costs	
Publication	2,000
E. Modified Total Direct Costs	$20,223
F. Shiptime 3 days @ $7800/day	23,400
G. Indirect Costs @ 50% MTDC	$10,112
H. TOTAL PROJECT COSTS	$53,735

Budget Justification

Participants will be asked to fund their own travel and subsistence to attend the inter-comparison workshop.

Dr. Peter Minnett will oversee the organization and execution of the workshop. The workshop will extend over 5-8 days, with three days allocated to ship-board measurements.

Dr. Goshka. Szczodrak, a post-doctoral associate, will be involved in the workshop, in subsequently collating data from each investigator and helping with the analysis.

Mr. Robert Jones, of the RSMAS Ocean Technology, group will assist by manufacturing special mounting brackets and cables that will be required to install the instruments on the R/V Walton-Smith.

Ms. R. Kolaczynski will coordinate the workshop activites, oversee the shipping of equipment to and from RSMAS, assist in the running of the workshop, and in preparing results for publication.

Funding is requested for miscellaneous hardware and cables that will be required to fix the instruments on the *Walton-Smith*.

Funds are also requested to cover the cost of the publication of the results in the open literature.

The workshop will include at-sea measurements with the radiometers mounted on the *R/V F. G. Walton-Smith* (Appendix 2). The *Walton-Smith* has been selected for its stability and size, being large enough to accommodate the participants and allow adequate space for the instruments. Significant shipping costs can be saved by loading the M-AERI and ancillary equipment at the RSMAS dockside. Three days are budgeted, and an additional day at each end will be provided at no charge to allow set-up and dismantling of the equipment.

References cited

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Donlon, C. J., T. Nightingale, L. Fiedler, G. Fisher, D. Baldwin, I. S. Robinson, 1999: The Calibration and Intercalibration of Sea-Going Infrared Radiometer Systems Using a Low Cost Blackbody Cavity. *Journal of Atmospheric and Oceanic Technology*: 16, 1183–1197.

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Smith, W. L., R. O. Knuteson, H. E. Revercomb, W. Feltz, H. B. Howell, W. P. Menzel, N. Nalli, P. Minnett, and W. McKeown, 1996: Observations of the infrared radiative properties of the ocean - implications for the measurement of sea surface temperature via satellite remote sensing. *Bull. Am. Meteor. Soc*., 77, 41-51.

Appendix 1

Likely workshop participants

Name	Institution
Dr. Ian Barton	CSIRO Marine Laboratories, Hobart, Australia
Dr. Jim Butler	NASA GSFC, Greenbelt
Dr. Craig Donlon	Joint Research Centre, Ispra, Italy.
Dr. Bill Emery	University of Colorado, Boulder
Dr. Mike Gunson.	NASA Jet Propulsion Laboratory, Pasadena
Dr. Simon Hook	NASA Jet Propulsion Laboratory, Pasadena
Dr. Andy Jessup	Applied Physics Laboratory, University of Washington, Seattle
Dr. Carol Johnson	NIST, Gaithersburg
Dr. Walt McKeown	U.S Navy, Norfolk
Dr. Peter Minnett	RSMAS-MPO, University of Miami
Dr. Tim Nightingale	Rutherford Appleton Laboratory, Chilton UK.
Dr. Frank Palluconi	NASA Jet Propulsion Laboratory, Pasadena
Dr. Fred Prata	CSIRO Division of Atmospheric Research, Aspendale Australia
Dr. Joe Rice	NIST, Gaithersburg
Dr. Joe Shaw	NOAA, Boulder
Dr. Tom Sheasby	EOS Group, University of Leicester, UK
Dr. Wm. Skirving	Australian Institute of Marine Science, Townsville, Australia
Dr. David Starr	NASA GSFC, Greenbelt
Dr. E. Theocharous	National Physical Laboratory, London
Dr. Gary Wick	NOAA, Boulder

Graduate Students and Post-Doctoral Fellows will also be encouraged to participate.

Appendix 2

The Marine – Atmospheric Emitted Radiance Interferometer

Laboratory tests of M-AERI accuracy

Target Temp.	LW (980-985 cm^{-1})	SW (2510-2515 cm^{-1})
20^{o}C	+0.013 K	+0.010 K
30^{o}C	-0.024 K	-0.030 K
60^{o}C	-0.122 K	-0.086 K

The mean discrepancies in the M-AERI 02 measurements of the NIST water bath blackbody calibration target in two spectral intervals where the atmosphere absorption and emission are low. Discrepancies are M-AERI minus NIST temperatures.

Specifications

Spectral interval	~3 to ~18µm
Spectral resolution	0.5 cm^{-1}
Interferogram rate	1Hz
Aperture	2.5 cm
Detectors	InSb, HgCdTe
Detector temperature	78^{o}K
Calibration	Two black-body cavities
SST retrieval uncertainty	<< 0.1K (absolute)

Appendix 3

R/V F. G. Walton-Smith

The 96-foot-long research catamaran, *R/V F. G. Walton-Smith* was commissioned in February 200. The vessel accommodates 20 people in its ten two-person staterooms and encompasses 800 square feet of laboratory space, as well as an additional 800 square feet of multi-use space astern. The layout of the ship is very well suited to the radiometer comparison, having good forward deck space to allow the mounting of many instruments viewing the sea surface ahead of the influence of the ship, laboratory facilities, an state-of-the-art scientific computer networking.

The vessel also has the capability of dynamic positioning for precise station keeping, using bow thrusters, controllable pitch propellers, and independent rudders. Other specialized instruments include a transducer suite that includes ADCP transducers for measuring ocean currents; a moon pool between the hulls for drilling or coring operations; and a notched stern to facilitate maneuvering equipment into the water using the A-frame.

For more details, see http://www.rsmas.miami.edu/support/mardep/cat/introcat.html