TECHNICAL REPORT

Contract Title:	Infrared Algorithm Development for Ocean Observations with EOS/MODIS
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Principal Investigator:	Otis B. Brown RSMAS/MPO University of Miami 4600 Rickenbacker Causeway Miami, Florida 33149-1098

INFRARED ALGORITHM DEVELOPMENT FOR OCEAN OBSERVATIONS WITH EOS/MODIS

Abstract

Efforts continue under this contract to develop 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, development and evaluation of processing and networking methodologies for algorithm computation and data accession, evaluation of surface validation approaches for IR radiances, development of experimental instrumentation, and participation in MODIS (project) related activities. Activities in this contract period have focused on field campaigns, analysis of field data and the organization of and participation in two workshops held at RSMAS in early March.

MODIS INFRARED ALGORITHM DEVELOPMENT

A. Near Term Objectives

A.1. Continue algorithmic development efforts based on experimental match-up databases and radiative transfer models.

A.2. Continue interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST pre-launch calibration activities.

A.3 Continue evaluation of different approaches for global SST data assimilation and work on statistically based objective analysis approaches.

A.4 Continue evaluation of high-speed network interconnection technologies.

A.5 Continue development of *in situ* validation approaches for the MODIS IR bands.

A.6 Provide investigator and staff support for the preceding items.

B. Overview of Current Progress

B.1 July-December 1998

Activities during the past six months have continued on the previously initiated tasks. There have been specific efforts in the areas of (a) IR calibration/validation as part of the MODIS Ocean Science Team cruise effort, (b) a theoretical assessment of the MODIS instrument errors on the retrieval of SST; and (c) testing and evaluation of an experimental wide area network based on ATM technology. In addition, previously initiated activities, such as team related activities, continue.

Special foci during this six-month period have been:

1) Continue analysis of measurements from: the DOE/NOAA/NASA ARM Combined Sensor Project cruise in the Tropical Western Pacific in the spring of 1996; the cruise of the R/V Roger Revelle in the Pacific Ocean in the autumn of 1997; the research cruise at 24^{o}N in the Atlantic Ocean on the NOAA S Ronald H. Brown, January-February 1998; the research cruise to the Canadian Arctic on the CCGS Pierre Radisson, March – July 1998; and the Ocean-Atmosphere Carbon Exchange Study cruise in the North Atlantic Ocean on the NOAA S Ronald H. Brown, May-June 1998 (Table 1).

2) Preparation and participation in the cruise of the *NOAA S Ronald H. Brown* from Miami to Newport, Oregon (Panama Transit).

3) Preparation and participation in the cruise of the *R/V Melville* in the Eastern Pacific

4) Refinement of marine FTIR instrumentation for cal/val applications by UW/SSEC through a subcontract.

5) Continue negotiations for ship-time for post-launch validation, and explore options for long-term validation from fixed platforms.

6) Refinement of the radiative transfer model used to simulate the MODIS infrared measurements and the derivation of the atmospheric correction algorithm for SST retrieval.

7) Derivation of the pre-launch algorithm for SST retrievals using the mid-infrared MODIS bands.

8) MODIS-PFM IR Pre-launch characterization interactions.

9) Discussions with personnel at NIST and Hart Scientific Inc. on the construction of a high stability, high accuracy water-bath black body calibration target for the M-AERIs.

10) Discussions with researchers at the Institute of Atmospheric Physics and the University of Rome on collaborative field experiments on the effects of aerosols on the retrievals of SST from space-borne infrared radiometry.

11) Submission of proposals to ESA for access to *Envisat* data in the EOS post-launch period.

12) Wide area networking.

<u>B.1.1 Completed M-AERI cruises.</u>

The M-AERI research cruises (Figure.1; Table 1) in a wide range of climatic regimes has produced a unique data set for the study of the oceanic thermal skin layer and its response to surface forcing. The knowledge gained from analysis of these data sets will be important in understanding the results of the post-launch MODIS SST validation measurements. In addition to the continuing scientific analyses of these data, work has begun on constructing a database for the archival and retrieval of the cruise data. While the M-AERI measurements are a consistent data set, the ancillary measurements (surface meteorology, radiosondes, *etc*.) are less so, depending on the instrumentation already installed on the ship or installed by other cruise participants. Importing these diverse data sets into a uniform database will aid efficient data access and analysis in the MODIS post-launch period.

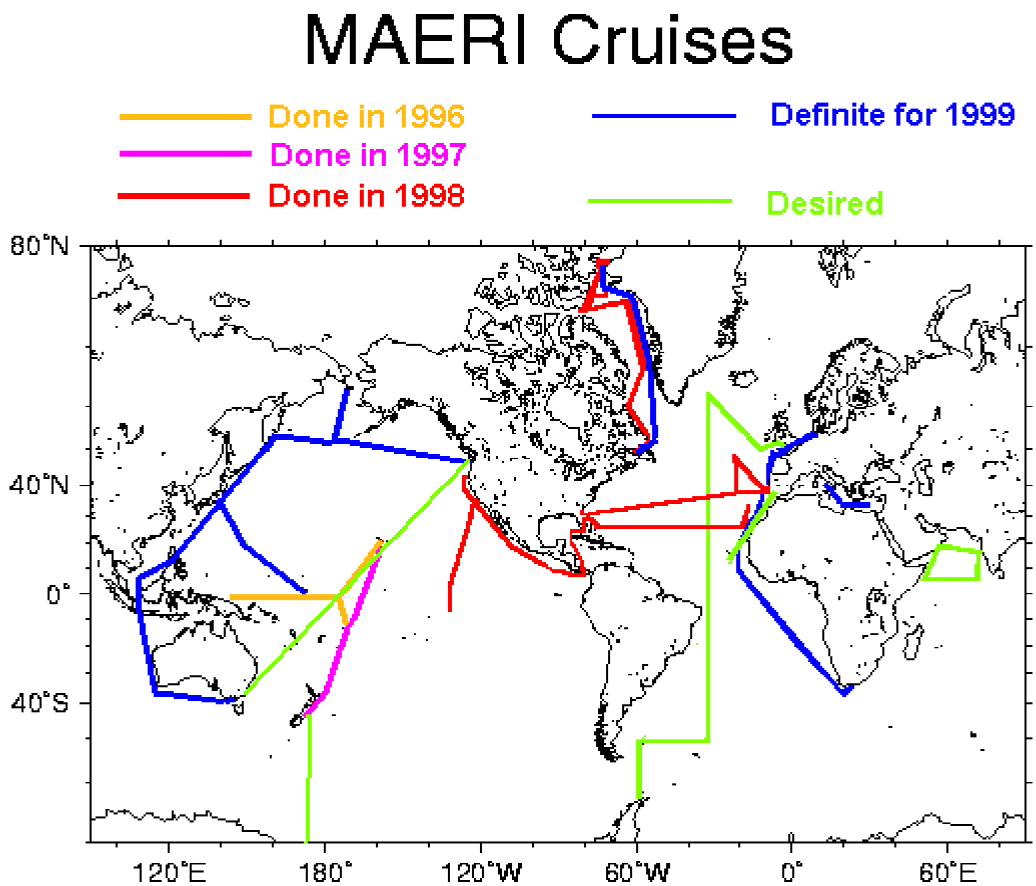


Figure 1. Schematic cruise tracks of M-AERI deployments.

Table 1. Completed M-AERI cruises

Project	Ship	Dates	Ports
Proof of concept	R/V Pelican	15-17 Jan 95	LUMCON, LA
Combined Sensor Cruise	NOAA S Discoverer	14 Mar – 13 Apr 96	Pago-pago, American Samoa. Honolulu, HI
Hawaii - New Zealand Transect	R/V Roger Revelle	28 Sept - 14 Oct 97	Honolulu, HI. Lyttleton, NZ
OACES 24 N Section	NOAA S Ronald H. Brown	8 Jan. - 24 Feb 98	Miami, FL. Las Palmas, Canary Islands. Miami, FL
NOW 98	CCGS Pierre Radisson	26 Mar - 28 Jul 98	Quebec City, Canada. Nanisivic, Canada
OACES Gasex-98	NOAA S Ronald H. Brown	2 May - 7 Jul 98	Miami, FL. Lisbon & Ponta Delgada, Portugal. Miami, FL
Panama Transit	NOAA S Ronald H. Brown	12-27 Jul 98	Miami, FL. Newport, OR
PACS-Mooring recovery	R/V Melville	8-29 Sept 98	San Diego, CA

B.1.2 The Panama Transit of the *NOAA S Ronald H. Brown*

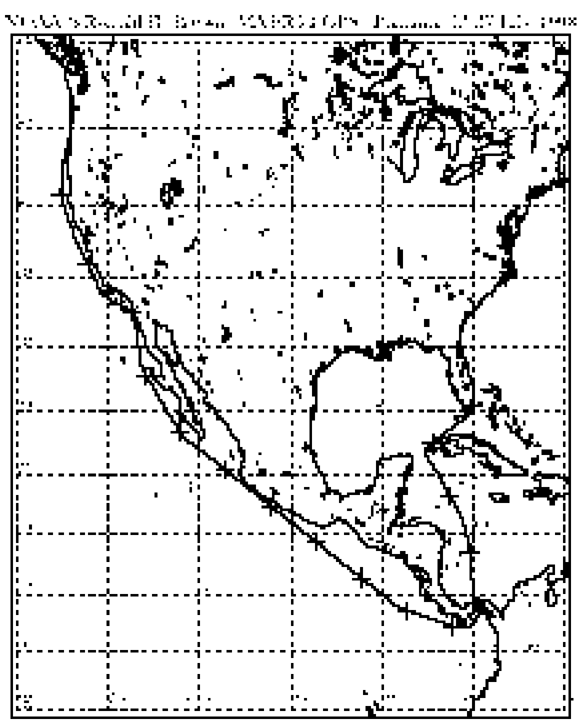


Figure 2. Cruise track of the NOAA*S Ronald H. Brown* for The Panama Transect, beginning in Miami and ending in Newport, Oregon. Midnight UTC is indicated by '+' markers.

Following the NOAA OACES (Ocean Atmosphere Carbon Exchange Study) GASEX-98 cruise in the North Atlantic Ocean (see last semi-annual report), NOAA offered space on the ship to the M-AERI team to continue to make measurements on the transit from Miami to Newport, Oregon, through the Caribbean Sea, Panama Canal and eastern Pacific Ocean (Figure 2). This opportunity to make measurements through tropical and mid-latitude conditions was grasped. These are important situations as they include cases where the marine environment is influenced by continental air masses and the underlying oceanographic signals, *e.g.* cool filaments associated with upwelling off the western US coast, are of importance. HRPT data covering the cruise tracks were provided by colleagues at the University of South Florida (Caribbean) and SeaSpace Inc. (Pacific Ocean). The M-AERI performed well during this transit and produced a high rate of data return (Figure 3).

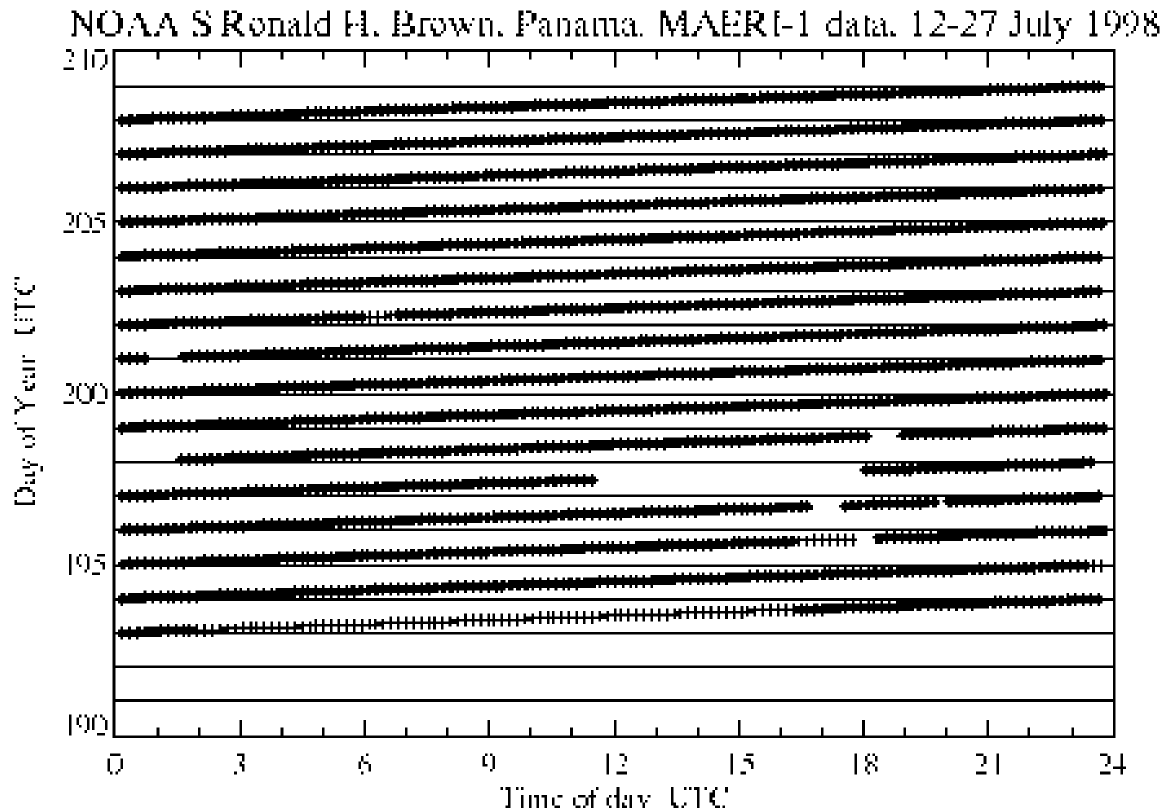
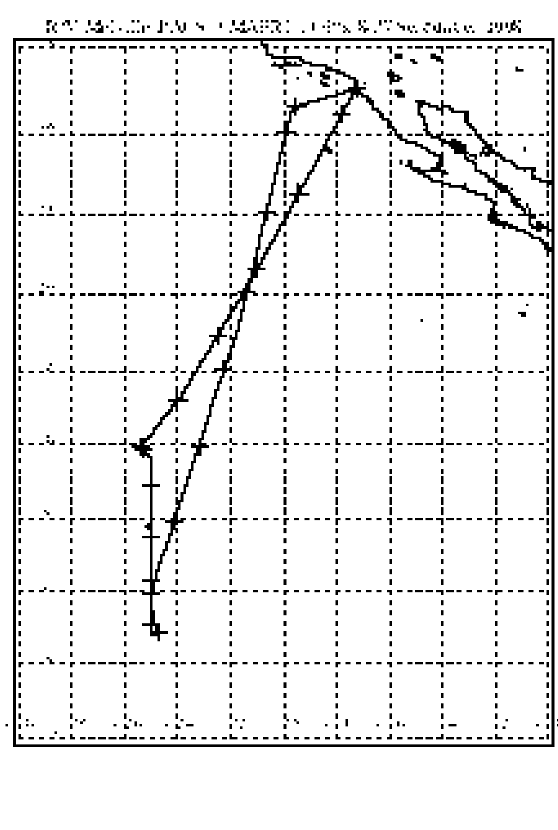


Figure 3. Data return from the M-AERI during the GASEX-98 cruise. The gaps result from periods when hardware or computer problems were encountered, or when the instrument was shut down for maintenance. Crosses without dots show where the M-AERI was functioning well, but the data are contaminated, either because the instrument was covered by a tarpaulin in bad weather, or the field of view was obscured. Day 130 is May 10 and 190 is July 9, 1998. (Preliminary data).

B.1.3 The PACS cruise of the *R/V Melville*.



Dr. Peter Minnett was invited to participate in the PACS (Pan-American Climate Study) cruise of the *R/V Melville* in the eastern Pacific Ocean in September 1998 (Figure 4). One of the objectives of PACS is the study of the sea surface temperature field in the eastern tropical Pacific. The SST here exhibits strong asymmetry about the equator and high levels of annual and interannual variability. (For the scientific background see http://tao.atmos.washington.edu/pacs/ and http://uop.whoi.edu/pacs/pacstxt.html). San Diego was the departure and return port and the cruise extended to the moorings just south of the Equator at 125^{o}W. A M-AERI and ancillary instruments were embarked on the Melville for the cruise and the skin temperature and surface meteorological variables were measured continuously. The M-AERI data return is shown in Figure 5.

Figure 4. Cruise track of the *R/V Melville*. Midnight UTC is indicated by '+' markers.

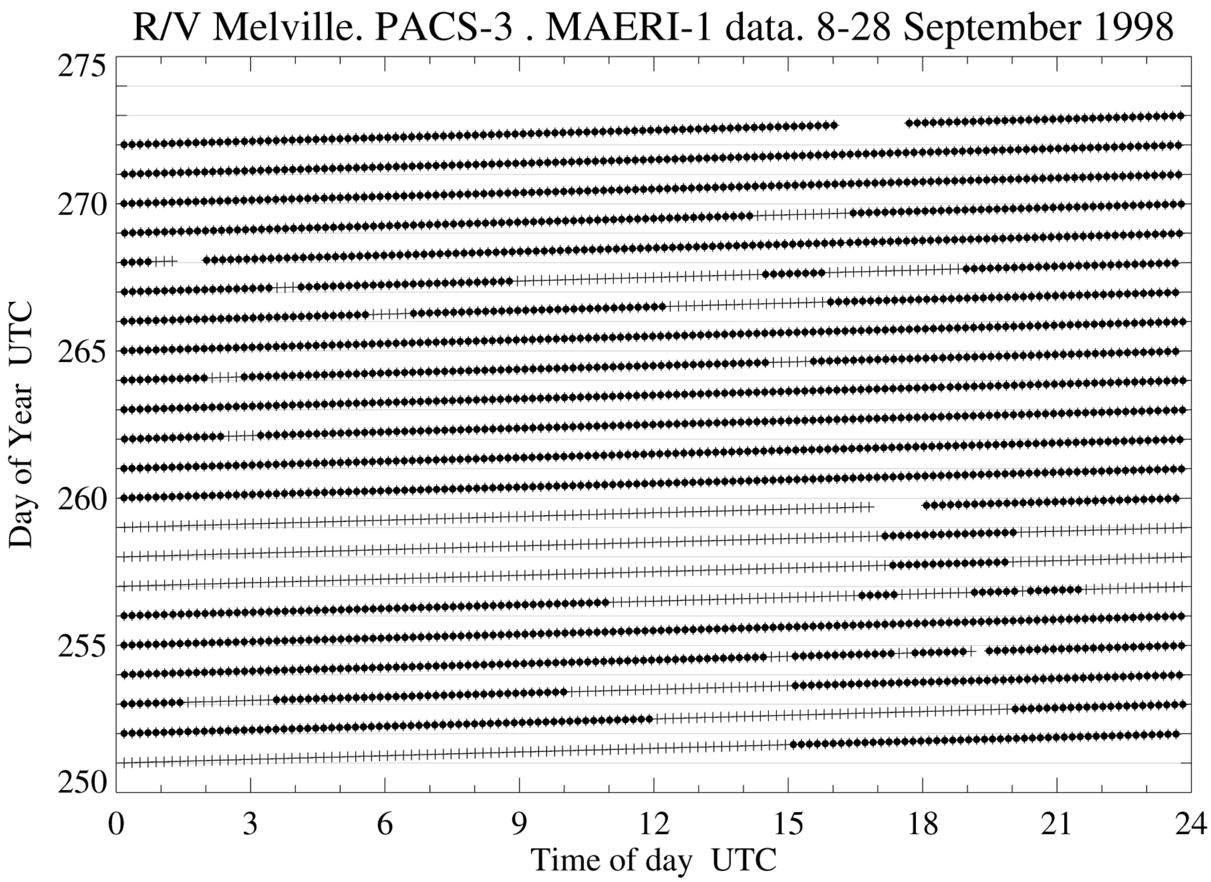


Figure 5. As Figure 4., but for the *R/V Melville* cruise. Day 250 is 7 September.

<u>B.1.4 Refinement of the M-AERI.</u>

In addition to generating new and important scientific data, the extensive sea-going use of the M-AERIs is providing the experience needed to improve the physical characteristics of the instrument. In collaboration with the group at the Space Science and Engineering Center at the University of Wisconsin-Madison, where the instruments were constructed, the electronics and computer racks have been repackaged. Together with the replacement of the standard CRT video monitors by light-weight flat-screen LCD monitors this has resulted in the compression of the rack units into a single half-rack, instead of two. This is beneficial in reducing the volume and weight of the equipment that has to be shipped for each cruise, reducing the amount of space required on board, and reducing the number of cable connections that have to made for each installation. This new configuration was tried on the newly delivered M-AERI 3, and once shown to be a practical improvement, was implemented on the other two M-AERIs, which were also refurbished at the same time at SSEC.

Discussions have begun with a local computer services company on the conceptual redesign of the M-AERI system that would remove the need for the large umbilical cable linking the external equipment with the electronics rack and computer. This cable is heavy and ungainly (having 93 conductors) and poses a problem each time the M-AERI is installed on a ship. Because of its size it is usually laid externally and is open to the elements and susceptible to chaffing on hard edges. Signs of wear are already apparent on those cables already used for several deployments. The connectors on the cables are weak points of the system design and the majority of cases of at-sea data loss have resulted form connector damage or corrosion. The new design approach would be to move the electronics half-rack to an enclosed, thermally controlled container to be mounted close to the interferometer unit, and link this with an armored CAT-5 cable to a computer system in the ship's lab space. Thus, for each deployment, the long cable runs would be reduced to the CAT-5 and a power cable. This would lead to improved reliability of the system and easier installation on ships.

B.1.5 Validation cruises

As a result of the delay in the launch of the EOS AM-1 platform several cruises, which were planned for post-launch MODIS validation, will now take place before MODIS becomes operational on orbit. In addition to those described in earlier reports, a new cruise opportunity has arisen in 1999 on board the *R/V Urania* in the Mediterranean Sea (see B.1.10 below). Also the planned Pacific section on the USCGC Polar Sea, intended for the autumn of 1998 has been postponed to the spring of 1999.

Currently planned M-AERI cruises are:

a) *USCGC Polar Sea* March-May 1999. Pacific Ocean, from Australia to Seattle.

b) *R/V Mirai* -- summer 1999. Tropical Western Pacific Ocean.

c) R/V Urania – autumn 1999. Mediterranean Sea.

d) *PFS Polarstern* -- December 1999. Atlantic Ocean from Bremerhaven to Cape Town.

The tracks of completed and planned cruises are shown in Figure 1. Web pages have been set up showing the cruises planned for 1999 (http://www.rsmas.miami.edu/ir/MAERI99.html) and completed deployments (http://www.rsmas.miami.edu/ir/MAERI95-98.html)

B.1.6 Refinement of the radiative transfer model

Dr Albin Zavody spent six weeks at RSMAS in October – November. He is the author of the forerunner of the radiative transfer model used in the simulations of the MODIS infrared measurements, which has been used for simulations of AVHRR and ATSR. During his visit he worked closely with Drs Richard Sikorski and Peter Minnett on refining the MODIS model. These improvements include incorporating the latest model for the anomalous water vapor continuum absorption, extending and updating the spectroscopic data base to cover all of the MODIS infrared window bands that can be used for SST measurements and improving the code for a more realistic simulation of aerosol effects.

B.1.7. At-launch algorithms

The radiative transfer model used for the MODIS simulations was updated with the recently published Clough model for the continuum spectra for water vapor anomalous absorption properties. The revised model was used with a global dataset of ~1000 marine and coastal atmospheric profiles, derived from radiosondes, to simulate satellite-viewed brightness temperatures (BTs) for the currently available response functions (RSRs) for MODIS PFM infrared bands. For the 11 and 12 µm bands (31 and 32), RSRs were evaluated for uncertainty, variability, and cross-talk in order to predict the impact on SST error budgets. For the 3 and 4 µm bands (20, 22, and 23), new algorithms were developed for SST retrieval, and new relationships were observed for retrieval of total column water vapor.

The SST algorithm for MODIS 11 and 12 µm bands (31 and 32) is based on the Pathfinder algorithm, and takes this form:

$$\text{mpfsst} = ((c_2 * T_{31}) + (c_3 * T_{31,32} * \text{refsst}) + (c_4 * \text{secterm}) + c_1)$$
$$\text{secterm} = 1 / (\cos(\theta) - 1) * T_{31,32}$$

where:

T_{31} is Band 31 brightness temperature (BT). (Comparable to AVHRR Ch4)
$T_{31,32}$ is Band31-Band32 BT difference. (Comparable to AVHRR Ch4-Ch5)
refsst is the reference SST
and θ is the satellite zenith angle.

The coefficients are evaluated for two sets of conditions determined by $T_{32,31}$, which appears to be acting as a surrogate for the atmospheric water vapor content. The mpfsst residual rms uncertainty is 0.337K at nadir (see previous report) and ~0.48K at a satellite zenith angle of 45^o.

Recent information from the MCST show that both of these bands (31 and 32) have significant instrumental uncertainties, and these propagate through the MODIS SST retrieval algorithm to produce amplified errors in the SST. When these are added (RSS) to the uncertainties introduced by atmospheric variability, we get a range of uncertainties in the derived SST that depend on the degree of correlation between the sources of instrumental error, and the atmospheric path length. These are (1σ):

Uncorrelated errors:
- At nadir: $\varepsilon(SST) = 1.09$ to 1.42K.
- At 45^o, $\varepsilon(SST) = 1.16$ to 1.62K

Correlated errors:
- At nadir, $\varepsilon(SST) = 0.45K$
- At 45^o, $\varepsilon(SST) = 0.56K$

We have also modeled brightness temperatures for MODIS bands 20, 21, and 23, for a zenith-viewing angle in order to develop an SST algorithm for these bands. Simulations are underway for a range of satellite zenith angles, and what follows is for the nadir view only. The algorithm is based on a simple channel difference, with the refinement of a seasonal correction, with an optional embedded latitude correction:

$$SST = a + b * T_i + c * T_j + f(x)$$

where the seasonal term, based on solar declination:

$$f(x) = m * \cos(2\pi(x + n)/365) + p$$

a, b, c, m, n, p are coefficients
x(northern hemisphere) = days after 173 (summer solstice)
x(southern hemisphere) = days after 357 (winter solstice)
Ti and Tj are any pair of MODIS bands 20, 22 and 23.

For MODIS Bands 22 and 23:

Algorithm: Bands 22, 23	coefficients			ε(SST)
	a	b	c	
No seasonal	-4.42966	1.83049	-0.804068	0.311
	m	n	p	
Seasonal	-0.221255	-24.2229	-0.0845033	0.255
Seasonal+zonal:	m	n	p	
Lat: 23.45S - 23.45N	-0.155476	-28.3669	-0.0212811	0.269
23.45 - 46.9 N or S	-0.268708	-28.7625	-0.115324	
Poleward of 46.9 N or S	-0.221255	-24.2229	-0.0845033	

For MODIS bands 20 and 22:

Algorithm: Bands 20,22	coefficients			ε(SST)
	a	b	c	
No seasonal	-2.45285	-0.293750	1.31549	0.319
	m	n	p	
Seasonal	-0.183720	-25.6533	-0.0793516	0.264
Seasonal+zonal:	m	n	p	
Lat: 23.45S - 23.45N	-0.112998	-26.5060	-0.0079824	0.285
23.45 - 46.9 N or S	-0.213912	-31.8919	-0.140964	
Poleward of 46.9 N or S	-0.183720	-25.6533	-0.0793516	

For MODIS Bands 20 and 23:

Algorithm: Bands 20,23	coefficients			ε(SST)
	a	b	c	
No seasonal	-7.71579	0.151332	0.890689	0.400
	m	n	p	
Seasonal	-0.239423	-28.1987	-0.0681934	0.340
Seasonal+zonal:	m	n	p	
Lat: 23.45S - 23.45N	-0.155810	-32.8452	0.0112498	0.387
23.45 - 46.9 N or S	-0.237422	-26.0701	-0.220756	
Poleward of 46.9 N or S	-0.239423	-28.1987	-0.0681934	

The number of data points in the zone poleward is too few to make a stable estimate of the coefficients, so the global set are used (*pro tem*) in this zone. This contributes to the increase in ε(SST) when the data are partitioned into latitude zones, as does the presence of a few outliers that are excluded from the coefficient derivation, but are included in the estimation of the accuracy. It is expected that when the database is expanded with additional high latitude profiles that this anomaly will be resolved and the residual errors will decrease.

Initial regressions showed a strong viewing angle dependence, which has not yet been incorporated into the algorithm. The increase in the ε(SST) observed in all channel pairs, when an explicit latitude dependence is included, is thought to result from the inadequate way high latitudes are treated as a result of insufficient atmospheric profiles from those areas.

Analyses during algorithm development revealed that certain band differences are a good proxy for total column water vapor. Plotting the regression residuals *vs*. radiosonde total vapor, the relationship is best for |T20-T22| < 1K *vs* 0 to 6 g cm^{-2} precipitable water. It is similar, but noisier (especially drier atmospheres), for T20-T23 = 2 to -0.5K *vs* 0 to 6 g cm^{-2} precipitable water.

The T_{22}-T_{23} difference shows virtually no dependence on precipitable water slope.

B.1.8 MODIS-PFM IR Pre-launch Characterization

Drs. Peter Minnett and Otis Brown provided input to the Project and Program management concerning pre-launch characterization issues associated with the MODIS-PFM instrument. They recommended that the instrument have additional thermal vacuum chamber characterization after circuit board re-work due to the previous electronic cross-talk invalidating prior characterization. It was determined that two potential activities should be undertaken (B. Guenther): response versus scan angle and relative spectral response tests. These recommendations were presented to management, but rejected due to risk, cost, and schedule impacts. Lack of additional characterization ensures that the PFM instrument will not meet SST specifications: Brown and Minnett have asked for a waiver of these specifications since they cannot deliver the contracted accuracy with the PFM instrument.

B.1.9. M-AERI calibration facility

The results of the RSMAS Infrared Workshop held in March 1998 (see previous semi-annual report, http://www.rsmas.miami.edu/ir) show that the absolute calibration of the M-AERI spectra is very good. Discussions have begun with NIST and Hart Scientific on the construction of a water-bath blackbody M-AERI calibration target, following the NIST design. Construction of such a water bath blackbody will permit pre- and post-cruise calibration of each M-AERI and long term maintenance of a calibration history for validation observations.

B.1.10 Collaboration with the Institute of Atmospheric Physics, Italy.

Discussions have begun with researchers, Drs E. Böhm and R. Santolieri, at the Institute of Atmospheric Physics, Rome, Italy on possible future collaborative studies on the influence of aerosols on satellite remote sensing. The prospects are favorable for collaborative research in the central Mediterranean in 1999 using island-based instruments during the summer, and also for a joint cruise on the Italian ship *R/V Urania* in the autumn. Both efforts will provide the opportunity of studying the effects of African terragenous aerosols.

B.1.11 ESA Envisat Mission

Dr. Peter Minnett is the lead P.I on a proposal on behalf of a number of US investigators submitted a to the European Space Agency for the validation of the SST retrievals from the Advanced Along-Track Scanning Radiometer (AATSR) on the European *Envisat* satellite planned for launch in May 2000. For details of the *Envisat* mission see http://envisat.estec.esa.nl. This proposal has been accepted. This is an important development for this project as it ensures access to the AATSR data, which will be valuable in facilitating satellite-to-satellite comparison in the post-launch validation.

Peter Minnett is also a Co-PI on another *Envisat* proposal, lead by Dr. Craig Donlon of the European Joint Research Center, to study the ocean-atmosphere interfacial properties. This proposal was also successful.

B.1.12 Wide Area Networking

The DS3 circuit to vBNS via FloridaNet continues its operation. A second T1 to NSI was installed and is also in operation. We are currently testing both paths and characterizing the vBNS link to NASA/GSFC via NASA/MSFC. This path limits maximum data exchange rates to the 5Mbs-8Mbs range, which is from 50% to 80% of requested capacity. Our understanding is that a new circuit is being installed between NASA/GSFC and the SPRINT PoP in Chicago: it hoped this will permit operation at needed rates.

C. Investigator Support

July	W. Baringer E. Böhm J. Brown O. Brown K. Kilpatrick	R. Kovach A. Mariano M. Szczodrak J. Splain S. Walsh
August	W. Baringer E. Böhm J. Brown O. Brown K. Kilpatrick	R. Kovach A. Mariano J. Splain M. Szczodrak S. Walsh
September	W. Baringer J. Brown O. Brown K. Kilpatrick R. Kolaczynski	R. Kovach A. Mariano J. Splain M. Szczodrak S. Walsh
October	W. Baringer O. Brown M. Framinan	J. Hargrove A. Mariano
November	W. Baringer O. Brown M. Framinan J. Hargrove R. Kolaczynski K. Kilpatrick	R. Kovach A. Mariano J. Splain M. Szczodrak S. Walsh
December	W. Baringer O. Brown M. Framinan K. Kilpatrick R. Kolaczynski	R. Kovach A. Mariano J. Splain M. Szczodrak S. Walsh

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. Analyze data taken at radiometer and validation workshops
- e. Continue radiative transfer modeling
- f. Continue analysis of research cruise data
- g. Continue to study near-surface temperature gradients
- h. Continue planning of post-launch validation campaigns
- i. Validation Plan updates (as needed)
- j. EOS Science Plan updates (as needed)
- k. Define and implement an extended ATM based network test bed
- l. Continued integration of new workstations into algorithm development environment
- m. Continued participation in MODIS Team activities and calibration working group

D.2 Investigator support

Continue current efforts.

E. Problems

The decision by NASA management not to proceed with adequate prelaunch calibration and characterization for the MODIS infrared bands poses a serious problem to the SST retrieval project. The uncertainties in the derived SSTs, resulting directly from uncertainties in the instrument properties, are such that the stated, required accuracies are not likely to be attained (see B.1.8 above). This has ramifications on the scientific applications of data, which is a loss to the community as a whole, and, from the point of view of this specific project, reduces the post-launch validation campaign to an experimental determination of the SST accuracy in a temporally and geographically constrained fashion, rather than an attempt to increase our understanding of the atmospheric and oceanic processes that impose the limits on satellite remote sensing.

F. Publications and Presentations

Minnett, P.J. O.B. Brown, R. J. Sikorski, A. Kumar. K. Kilpatrick and A.M. Zavody. MODIS SST retrievals- algorithm derivation, error budget and plans for validation. MODIS Science Team Meeting. University of Maryland Conference Center. December 15 1998.