

TECHNICAL REPORT

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with EOS/MODIS

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**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. This effort includes 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 radiative transfer modeling, evaluation of atmospheric correction methodologies, undertake field campaigns, analysis of field data, and participation in MODIS meetings.

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 1997

Activities during the past six months have continued on the previously initiated tasks. There have been specific continuing efforts in the areas of (a) radiative transfer modeling, (b) continued work on IR calibration/validation as part of the MODIS Ocean Science Team cruise effort, (c) analysis of consequences of imperfect pre-launch characterization of the MODIS infrared channels, and (d) test 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) Radiative transfer modeling to refine the at-launch SST algorithm..
- 2) Continue analysis of measurements from the DOE/NOAA/NASA ARM Combined Sensor Project cruise in the Tropical Western Pacific in the spring of 1996.
- 3) Construction of a marine FTIR instrumentation for cal/val applications by UW/SSEC via subcontract .
- 4) Pathfinder in a research cruise in the Pacific Ocean on the *R/V Roger Revelle*.
- 5) Participation in the 'CASOTS' Workshop.
- 6) Negotiate for ship-time for post-launch validation, and explore options for long-term validation from fixed platforms.
- 7) Wide area networking

B.1.1 Radiative Transfer Modeling

As described in the SST ATBD, the MODIS SST retrieval algorithm will be built on the form found to be very successful in the NASA/NOAA AVHRR Pathfinder program. This is based on the AVHRR "split-window" channels with wavelengths corresponding to ~10.5 and 11.5 μ m. Although the form of the MODIS algorithm is the same as that for the AVHRR, the coefficients must be refined to match the spectral characteristics and NEAL's of the MODIS bands (31 and 32).

The RAL (Rutherford Appleton Laboratory) line-by-line radiative transfer model was used with a global dataset of 1200 quality-controlled radiosondes over 5 zenith angles and 5 atmosphere-surface temperature differences to generate a database of 30000 brightness temperatures in each of MODIS bands 31 and 32. Colleagues at RSMAS have developed the Miami Pathfinder SST (mpfst) algorithm, which is the basis for the MODIS V.2 pre-launch SST algorithm:

$$modis_sst = ((c_2 * T_{31}) + (c_3 * T_{3132}) + (c_4 * secterm) + c_1)$$

$$secterm = ((1 / (\cos ((\text{satz} * \pi) / 180)) - 1) * T_{3132}$$

T_{30} is the band 31 brightness temperature (BT). (Comparable to AVHRR Channel 4)

T_{3031} is (Band32 - Band31) BT difference (Comparable to AVHRR (Channel 4 - Channel 5)).

The algorithm differentiates atmospheric vapor load using the difference between the brightness temperatures (T_{3132}) for the 11 and 12 micron bands (MODIS bands 31 and 32). Coefficients are determined for T_{3132} greater or less than 0.7°C. In application, the coefficients are then weighted by measured T_{3132} .

The 30000 point database was run through a robust regression to fit the *modis_sst*. Data are weighted according to the residuals, discarding data more than one Standard Deviation from the basic regression. A subsequent regression derives the coefficients. Residuals of that regression increased notably for Arctic and Antarctic terrestrial stations with surface temperatures below -2°C, which would be unrealistic temperatures for marine atmospheres. Excluding those extremely cold

data, the series of regressions were re-run. MODIS V.2 pre-launch *modis_sst* coefficients were delivered with a predicted RMS error of 0.337K about zero mean error.

	$T_{30} - T_{31} \leq 0.7$	$T_{30} - T_{31} > 0.7$
c_1	1.228552	1.692521
c_2	0.9576555	0.9558419
c_3	0.1182196	0.0873754
c_4	1.774631	1.199584

While the radiosonde database was somewhat biased toward warmer SST's and clearer atmospheres, this bias was reduced by the statistics-based rejection of outliers. The plot of modeled band 31 vs. band 32 resembles the distribution of previously collected Pathfinder data. Residuals showed no major trend vs. zenith angle or SST. Residuals are greatest at high latitudes.

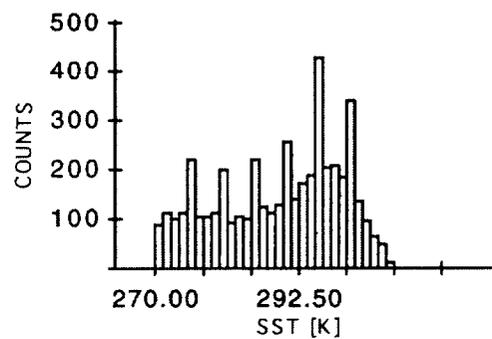


Figure 1. The modeled brightness-temperature database, filtered to remove surface temperatures below -2°C , is show fairly uniform distribution versus surface temperature.

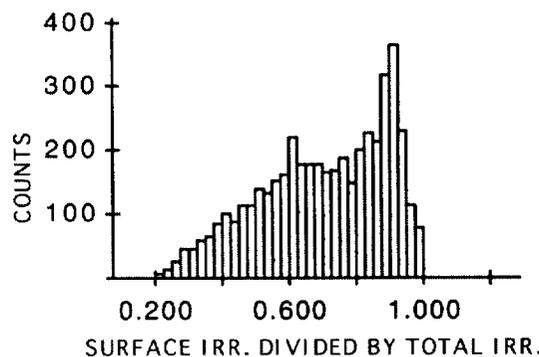


Figure 2. The modeled brightness-temperature database, filtered to remove surface temperatures below -2°C , is show fairly uniform distribution versus atmospheric clarity, represented as fraction of surface-leaving irradiance divided by total satellite-viewed irradiance in band 31.

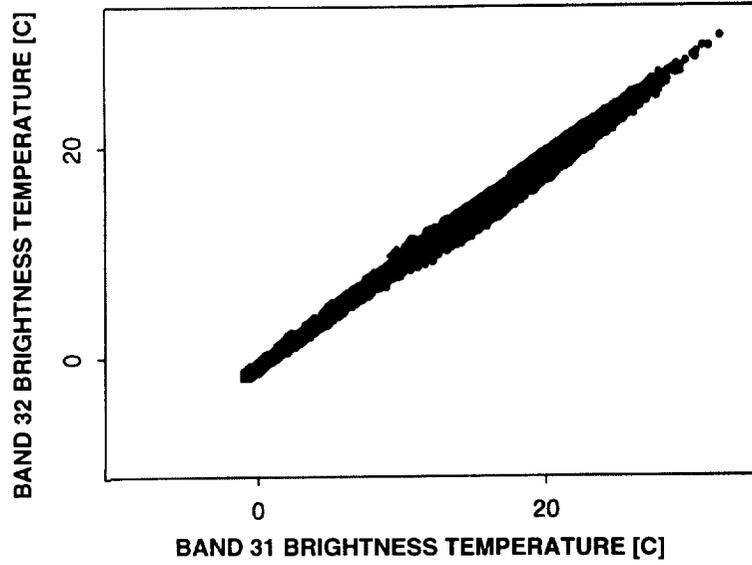


Figure 3. Modeled modeled brightness-temperatures for band 31 (11 μm window) versus band 32 (12 μm window) shows a spreading of values above 15°C, which is typical of measured Pathfinder data.

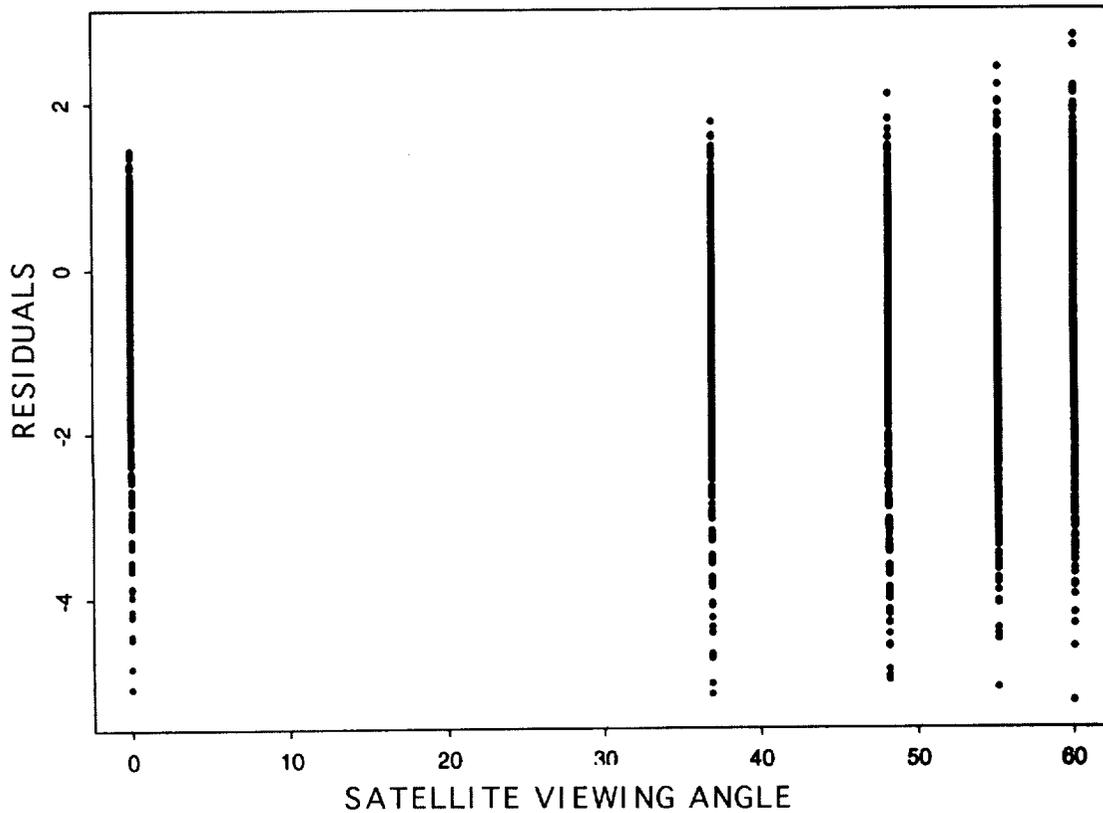


Figure 4. Residuals from the least-squares regression for the MODIS V.2 pre-launch algorithm show no major trends versus satellite zenith angle. (Surface temperatures $> -2^\circ\text{C}$)

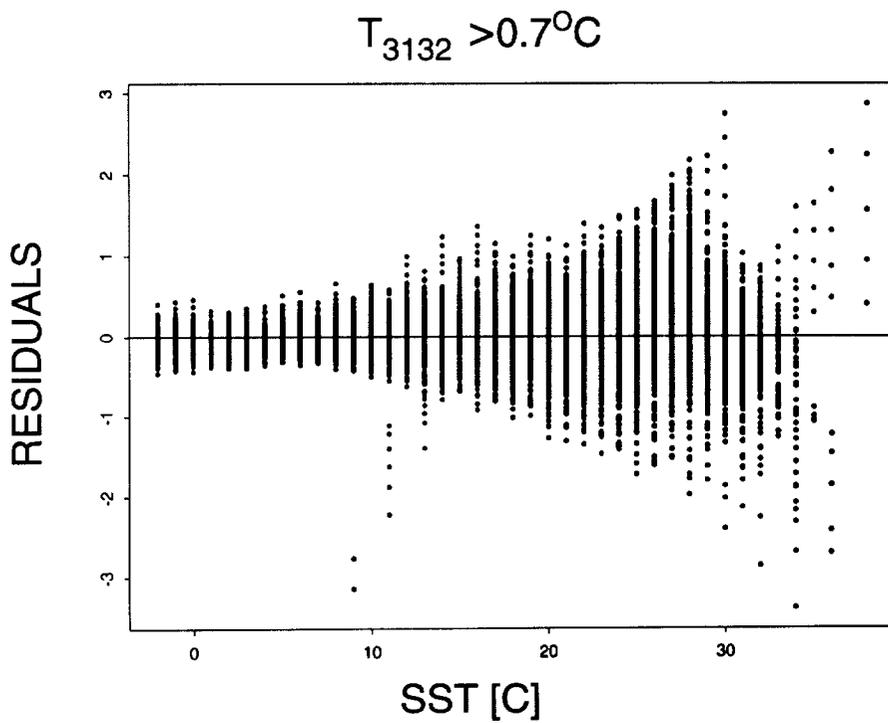
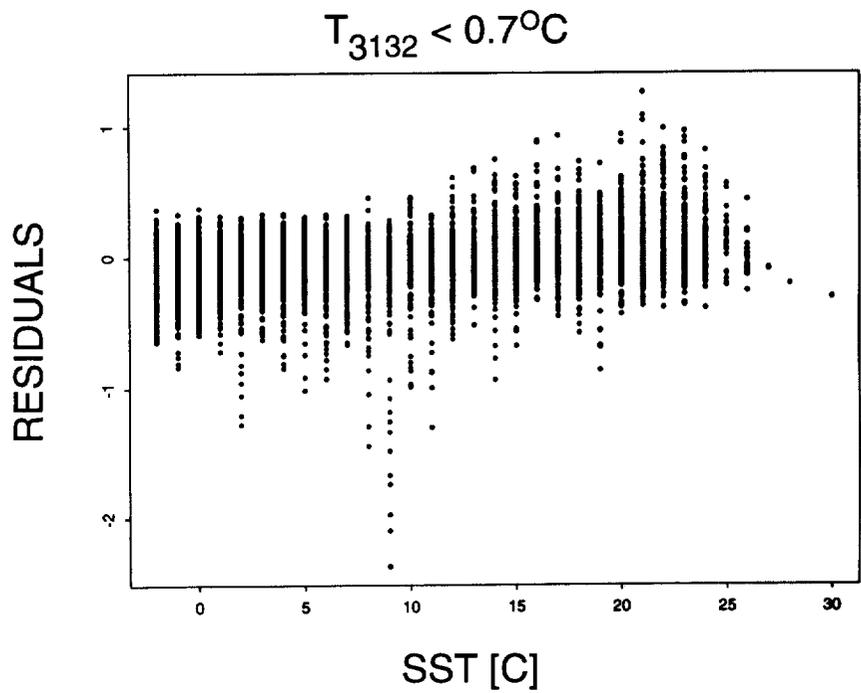


Figure 5. Residuals from the least-squares regression fit for the MODIS V.2 pre-launch algorithm show no major trends versus SST, with T_{3132} greater or less than 0.7°C . (Surface temperatures $> -2^{\circ}\text{C}$)

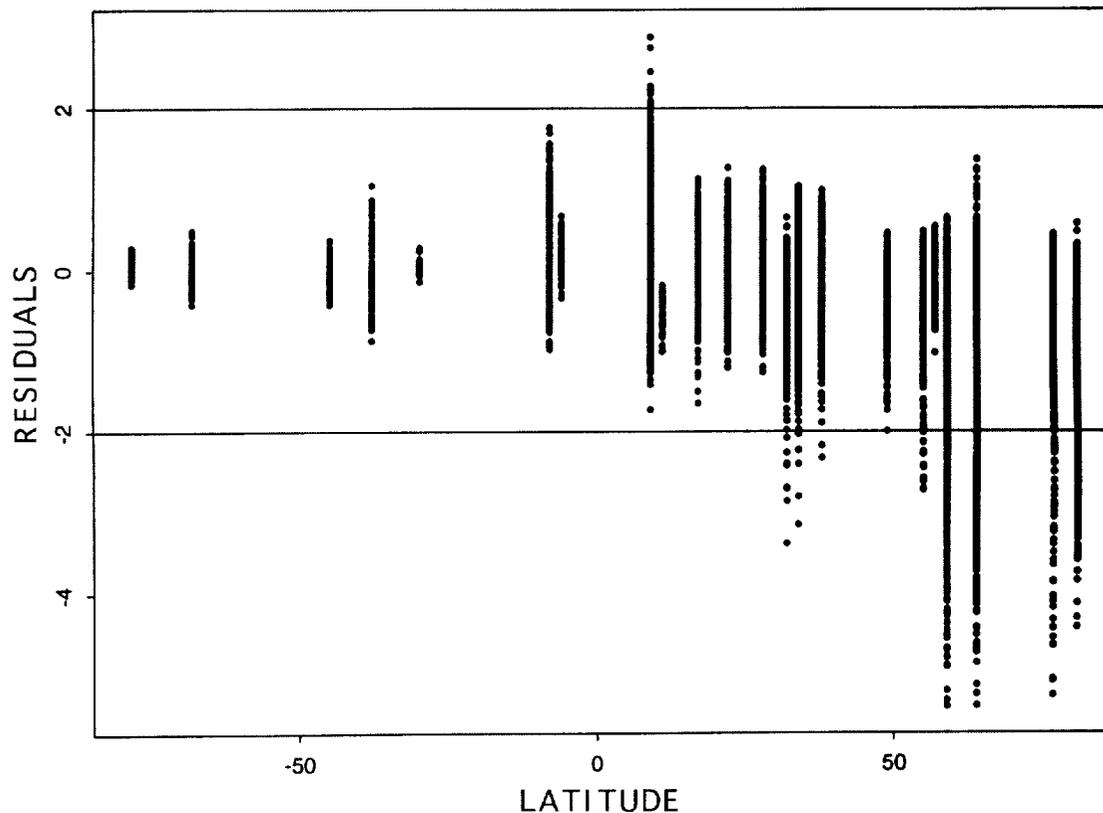


Figure 6. Residuals from the least-squares regression for the MODIS V.2 pre-launch algorithm are greatest at high latitudes. (Surface temperatures $> -2^{\circ}\text{C}$)

B.1.2 The Combined Sensor Cruise of the NOAA ship *Discoverer*

As described in earlier reports, the Combined Sensor Cruise in the Tropical Western Pacific in March–April 1996, generated an unprecedented array of measurements of atmospheric boundary layer and sea surface temperature.

Attention has been focused on the quality assurance of the prototype M–AERI skin SST retrievals to generate a final, clean time series. Jennifer Hanafin (graduate student) visited SSEC, University of Wisconsin - Madison, to work on the identification of suspect retrievals. The final data set has subsequently been released. Peter Minnett presented an invited paper on these measurements at the AGU Fall Meeting in San Francisco.

B.1.3 M-AERI

The M–AERI–01 was delivered to RSMAS in April and was set up to run in the lab. The control computer was put on to the RSMAS network to allow the specialists at SSEC to monitor the state of the instrument. The only cause for concern was instabilities in the current being drawn by the Stirling cycle cooler, which chills the detectors to $\sim 78^{\circ}\text{K}$. This behavior has not been seen in other coolers, but does not appear to cause fluctuations in the detector temperature. The M–AERI–01 functioned well in the lab until it was shipped to Hawaii for the *R/V Revelle* cruise.

M–AERI–02 was delivered at the start of the cruise of the *R/V Roger Revelle* in late September. It

was installed on the ship next to M-AERI-01 and both instruments functioned well during the cruise (see below).

B.1.4 R/V Revelle Cruise

B.1.4.1 Introduction

The cruise of the R/V Revelle from Hawaii to New Zealand presented us with the opportunity to test the use of Marine Atmosphere Emitted Radiance Interferometers (M-AERI's) in a realistic environment prior to their use in the post-launch validation of the infrared bands of MODIS

Two M-AERI's were operated side-by-side with the objective of comparing co-located skin temperature measurements from two independently calibrated instruments, test different sampling strategies by varying integration times and scan mirror sequences on one while maintaining a 'default' scheme on the other, and to provide redundancy should one M-AERI fail during the cruise.

Additional instruments were also deployed on the ship to characterize the conditions under which the skin temperature measurements were taken.

B.1.4.2 Cruise Details

The original cruise plan included a series of stations along the way to collect geological samples from the ocean floor, but these plans were subsequently abandoned. The result being that the cruise was several days shorter than initially expected. Apart from reducing the total number of days during which we could collect data this revision to the cruise plans did not adversely affect our activities.

The ship sailed from the University of Hawaii Marine Facility in Honolulu on September 28 at about 4:30 p.m. local time, and arrived at Lyttleton at about 8:00 a.m. local time, on October 13, after a transit made at speeds in the 10-12 knot (5-6 ms⁻¹) range. The cruise track crosses both northern and southern hemisphere trade wind zones, the Equatorial region including the inter-tropical convergence Zone, and the westerlies ('roaring forties') of the southern hemisphere. The ship's track is shown in Figure 7.

Details of the ship itself can be found on the WWW at the URL:
http://sio.ucsd.edu/supp_groups/shipsked/revelle

B.1.4.3 Instrument Deployed

A brief summary of the instruments used during the cruise is given in Table 1. The positions on the ship at which the instruments were deployed around the ship are shown in Figure 8.

The two M-AERI's were mounted on the starboard side on the 02 deck, with M-AERI-01 being forward of M-AERI-02. Both were mounted high enough so that they viewed undisturbed water, ahead of the ship's bow-wave with a view angle of 45° and greater (measured from nadir). The cables were run along the exterior of the ship into the main scientific laboratory two decks lower. The prevailing winds throughout the cruise, with the exception of the southern hemisphere westerlies, were from the port side of the ship and the M-AERI's were in the lee of a crane on the 02 deck. During strong wind conditions when the risk of salt spray entering the instruments was high, and during heavy rain, the M-AERI's were covered by tarpaulin sheets for protection, and no data were collected. Similarly, when there was evidence of direct sunlight entering the aperture, a shield was used which obscured some of the environmental views at the affected mirror angles. Otherwise, the instruments were run around the clock.

R/V Roger Revelle. 28 Sept. - 14 Oct. 1997

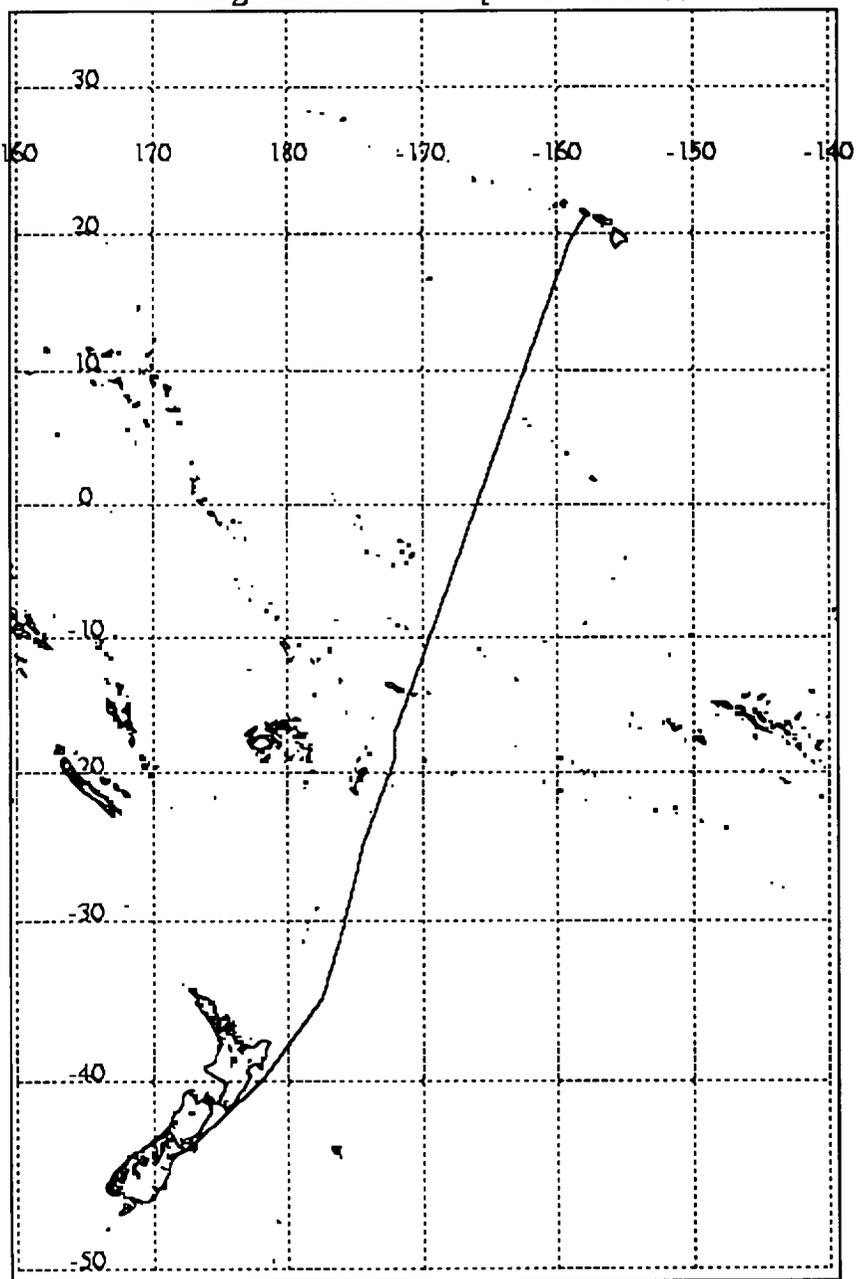


Figure 7. Track of the *R/V Revelle*

A meteorological station was mounted on the forward rail of the 02 deck. This measured relative wind speed and direction, air temperature and humidity, and hemispheric downwelling short (0.28 to 2.8 μm) and longwave (3 to 50 μm) radiation. These radiometers were mounted on gimbals to reduce the effects of ships' motion, and more importantly, mean tilts.

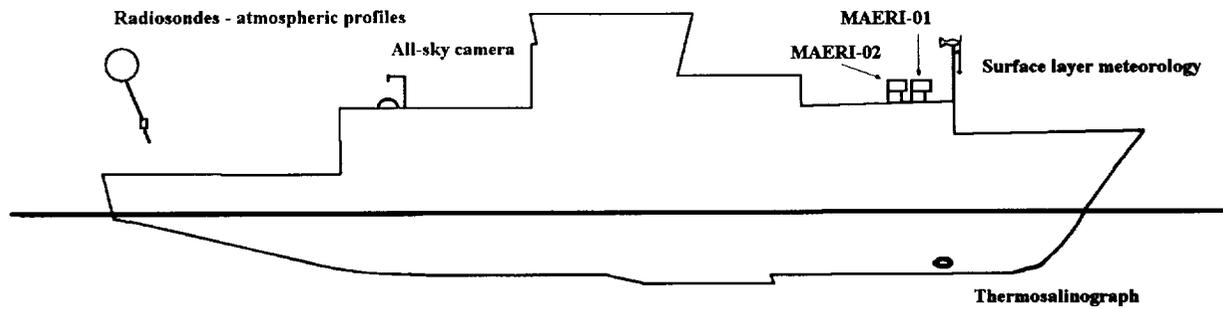


Figure 8. Schematic diagram showing the placement of instruments on the *R/V Revelle*.

Table 1. Measurements taken during the cruise of the *R/V Revelle*

Variable	Sensor	Comments
Skin Sea Surface Temperature	M-AERI	Continuous measurements
Skin Ice Surface Temperature	M-AERI	Continuous measurements
Infrared spectra of surface emitted radiation	M-AERI	Continuous measurements over range of angles. Pitch and roll measured to monitor ship's motion
Broad band LW↓ & LW↑	Heimann IRT, $\delta\lambda= 9.6-11.5\mu\text{m}$	Continuous measurements
Bulk SST	Ship's thermo-salinograph	Continuous measurements
Air Temperature	Thermistor	Continuous measurements
Relative humidity	Vaisala "Humicap"	Continuous measurements
Wind speed	R. M. Young anemometer	Continuous measurements
Wind direction	R. M. Young anemometer	Continuous measurements
Barometric pressure	Digital barometer	Continuous measurements
Insolation (SW↓)	Eppley pyrometer	Continuous measurements Sensors gimballed to compensate for ship's motion.
Incident thermal radiation (LW↓)	Eppley pyrgeometer	Continuous measurements Sensors gimballed to compensate for ship's motion.
Cloud type and cover	All-sky camera	Continuous measurements
Atmospheric humidity profiles	Radiosondes	Few per day
Atmospheric temperature profiles	Radiosondes	Few per day

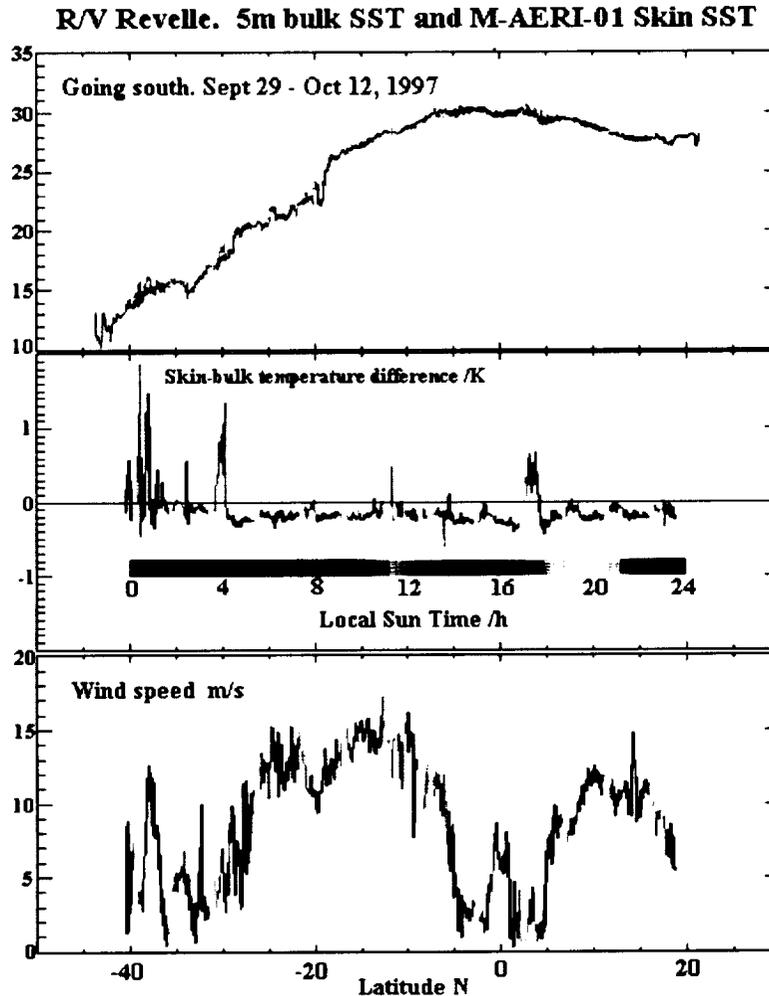


Figure 9. Latitudinal section of surface temperature measured at 5m depth (bulk) shown as black, and by the M-AERI (skin) color coded according to the time of measurement from Hawaii to New Zealand (top). The difference between the skin and bulk temperatures is shown in the middle panel with the color code showing time. Wind speed, corrected for the effects of ship motion, is shown in the lower panel using the same color coding.

The Heimann Infrared Radiation Thermometers (IRTS) were mounted close to the M-AERI's and viewed the sea surface (ahead of the bow wave) at 55° to zenith. They were sampled at 0.1 Hz throughout the cruise to provide higher frequency measurements of the emitted radiance from the sea surface and stay in the 10.6 to 11.5 μ m wavelength interval.

An all-sky camera was mounted on the 02 deck aft of the bridge. This is a TV camera, mounted looking down on a hemispheric mirror which provides a view of the dome of the sky, connected to a time-lapse video recorder programmed to capture one frame every 17 seconds. This provides a record of the cloud conditions under which the measurements were taken. This is important as part of the radiance measured in the direction of the sea surface by the M-AERIs and IRTS is reflected radiation having its origin in the sky. In cases of broken cloud the sky radiance correction may be imperfect if the cloud conditions change between the sky and sea measurements.

Radiosondes were launched throughout the cruise from the fantail of the ship to provide measurements of the temperature and humidity profiles. These measurements will be used with a

numerical radiative transfer model to determine the effects of the atmosphere on co-located infrared measurements from satellite radiometers (see below). The details of the radiosonde launches are given in Table 2.

Table 2: Radiosondes launched during the *R/V Revelle* cruise.

Date	Time (UTC)	Latitude N	Longitude E	Comments
1 October 97	20:15	8.67	-162.90	Failed at 879 hPa
1 October 97	20:40	8.59	-162.97	Reached 95 hPa
2 October 97	21:25	4.10	-164.50	Reached 95 hPa
3 October 97	01:43	3.39	-164.79	Reached 38 hPa
4 October 97	00:24	-1.35	-166.43	Data capture failed
4 October 97	02:25	-1.50	-166.50	Reached 30 hPa
5 October 97	02:48	-6.66	-168.31	Reached 35 hPa
6 October 97	03:15	-11.71	-170.09	Reached 39 hPa
7 October 97	00:49	-15.58	-171.58	Reached 40 hPa
7 October 97	21:48	-19.72	-172.35	Reached 36 hPa
8 October 97	02:40	-20.60	-172.70	Reached 35 hPa
8 October 97	21:20	-24.26	-174.28	Reached 28 hPa
9 October 97	01:03	-24.90	-174.44	Reached 32 hPa
9 October 97	21:00	-29.30	-175.60	Reached 49 hPa
10 October 97	01:24	-29.85	-175.75	Reached 29 hPa
10 October 97	21:58	-34.00	-177.20	Reached 39 hPa
11 October 97	02:05	-34.80	-177.42	Reached 35 hPa
11 October 97	05:59	-35.39	-177.97	Reached 31 hPa
11 October 97	21:01	-37.48	180.00	Reached 39 hPa
11 October 97	23:19	-38.15	179.70	Reached 32 hPa
12 October 97	02:23	-38.50	179.30	Reached 32 hPa
12 October 97	04:37	-39.95	178.98	Reached 35 hPa
12 October 97	07:11	-39.31	178.60	Reached 46 hPa

Measurements of the bulk temperature of the near-surface layer of the ocean were provided by the ship's thermosalinograph system, mounted in the bow-thruster intake at a depth of about 5m. The system was calibrated in July 1997, and the absolute accuracy should be better than $\pm 0.01\text{K}$. These provide the in-situ measurements against which the M-AERI skin temperature measurements can be compared.

The ship's position was recorded using GPS in each of the M-AERI data streams, and also by the ship's navigation system, which also provides measurements of ship's speed and course at 15 second intervals.

B.1.4.4 Satellite Data

The M-AERI skin temperatures will be compared with measurements from several infrared radiometers on spacecraft. These include the AVHRR (Advanced Very High Resolution Radiometer) on the NOAA polar-orbiting satellites, the ATSR-2 (Along Track Scanning Radiometer) on the European ERS-2, and the VISSR (Visible Infrared Spin-Scan Radiometer) on the Japanese geostationary meteorological satellite (GMS). The AVHRR data have been extracted from the Global Area Coverage (4km resolution) at RSMAS and 1km data have been requested from the New Zealand Meteorological Service. ATSR data have been requested from the ATSR

project in the UK. The GMS data are available through Minnett's activities in the DOE ARM (Atmospheric Radiation Measurements) program.

B.1.4.5 M-AERI Sampling Strategies

The M-AERI scan mirror is now under the control of the system's computer and a series of mirror possibilities are programmed which are repeated continuously. At the start of each new (UTC) day the system computer reboots itself and clears any incomplete or damaged files resulting from pathological situations. It also determines that enough free disc space exists for the data from the forthcoming day: if not old data files are deleted until enough free space exists. It is presumed that the deleted files will have already been archived to other storage media.

The default sequence of mirror positions are given in Table 3. This sequence was used on the M-AERI-01 throughout the cruise and forms a bench-mark for the alternative schemes that were tried on M-AERI-02.

The number of interferograms averaged is determined by the need to reduce the NE Δ T of the detector noise in the spectra to $\ll 0.1$ K (actually ~ 0.03 K). More are needed for the sky view to ensure that the measurements taken in the most transmissive part of the spectra (and therefore lead to very cold temperatures) are not dominated by detector noise. The skin surface temperatures are derived from the 55° measurements, as these are close to the Brewster angle at which the reflectivity of the ocean is at a minimum and the contribution to the measurement of reflected sky radiation is therefore least. The 75° measurements are used to retrieve air temperatures close to the sea surface. This sequence takes about 20 minutes to complete (2.82 per hour); skin SST and air temperature are retrieved once per sequence.

The detectors on M-AERI-02 have much lower noise levels than those of M-AERI-01, and the number of interferograms averaged per mirror position was reduced without drastic loss of signal-to-noise ratio. By averaging 12 interferograms on all but the sky view at zenith (46) the sequence time was reduced to 7.3 minutes (8.2 per hour). Further reductions are feasible in principle, but in reality it was found that the control software was crashing for faster sequences. Also the full benefit of shorter averaging times was not being realized as there appears to be more software 'overhead' than can be accommodated in the mirror movement intervals.

The two M-AERI system computers were attached to the ship's LAN and the M-AERI data were copied onto disks on the ship's computer system before archiving on 4mm DAT tapes (2 copies). Critical data files were also copied onto the hard drive of a laptop PC (also attached to the ship's LAN) and an additional copy made on an external disk drive.

Table 3 - Mirror Position Sequence

View	Angle, relative to Zenith	Number of Interferograms
Hot calibration target	60°	46
Ambient temperature target	120°	46
Sky view	0°	90
Sea view (45°)	225°	46
Sky view (45°)	315°	46
Sea view (55°)	235°	46
Sky view (55°)	305°	46

View	Angle, relative to Zenith	Number of Interferograms
Sea view (75°)	255°	46
Sky view (75°)	285°	46
Repeat Sequence		

B.1.4.6 Preliminary Results

The skin sea surface temperatures are retrieved from the 55° sea and sky view data using measurements in a narrow spectral interval at 7.7 μ m, where the atmosphere is only moderately transparent. This means that the correction for sky radiation is less dependent on the cloud conditions than it would be in more transparent spectral intervals, as nearly all of the reflected sky radiation has its origin in the lower troposphere. The calibration data are provided by using the views of the black body targets at both the start and end of each scan mirror sequence.

The sampling rates given above are for conditions that lead to no data loss, such as when the instruments are under covers, have a contaminated scan mirror, having the mirrors cleaned, or where measurements are contaminated by an operator looking down the field of view to check that the mirror is clean. In addition, in light rain the mirror is driven to a 'safe mode' position (viewing the ambient temperature black body calibration target), and when such periods are short the sequence is resumed without significant data loss. When such intervals are longer, the instrument calibration may not be sufficiently stable so that the calibration measurements taken before the mirror entered safe mode may not be applicable to the measurements taken between leaving safe mode and the next calibration data, leading to a reduction in accuracy of the SST retrieval. In the results presented below we have tried to identify the SST measurements contaminated by any extraneous effects, but closer examination may reveal reasons for rejecting more data (hopefully outliers in the current data set), such as those contaminated by spray on the scan mirror.

B.1.4.7 M-AERI-01 vs. M-AERI-02 SST retrievals

Before mounting on the R/V Revelle the calibrations of both M-AERIs were tested by measuring the temperature of a third black body target at a known temperature. Both M-AERIs measured the temperature of this target to an accuracy of <0.03K.

The two instruments have slightly different cycle times, determined by the speed of the moving mirror in each interferometer, and thus it was impossible to synchronize the two data sets even when both instruments were using the same scan mirror control sequence, and to compare the skin SST retrievals the time series from M-AERI-02 was interpolated to the measurement times of those from M-AERI-01. Daily averages of the differences in skin SST's from both instruments are given in Table 4 together with their standard deviations. It can be seen that the correspondence is remarkably good. These measurements are independent in the sense that each instrument has its own interval calibration. This agreement is better than anticipated given the design goals (<0.1K) and what were believed to be the inherent uncertainties in key components of the instrument (e.g., emissivity of black body calibration targets; accuracy of thermistors in the black body targets).

Table 4

M–AERI Skinn SST comparisons
 R/V Revelle section, Hawaii to New Zealand
 55° incidence angle, $\lambda=7.7\mu\text{m}$
 M–AERI-2 data interpolated to times of M–AERI-1 measurements
 24h data segments

Date – UTC	Mean ΔT K	Std. Dev. ΔT K
Sept 30	0.016	0.036
Oct 1	0.006	0.038
Oct 2	0.004	0.142
Oct 3	0.035	0.167
Oct 4	0.016	0.068
Oct 5	0.012	0.270
Oct 6	0.018	0.045
Oct 7	0.012	0.056
Oct 9	-0.001	0.069

B.1.4.8 Skin v.s. bulk temperature

The latitudinal section of surface temperature measured by the ship (bulk) and M–AERI–01 (skin) is shown in Figure 9, upper panel. The difference between the skin and bulk temperatures is given in the lower panel together with a key for the color coding which is for the local time of the measurement. It can be seen that in nearly all cases the skin temperature is cooler than the bulk measurements, as is to be expected. Those cases where the reverse is true tend to be in the local afternoons in situations of low wind speed and are indicative of the presence of a diurnal thermocline which raises the in-situ temperature just below the sea surface to values much higher than at the depth of the ship measurement. Even the presence of a cool skin leaves the skin temperature warmer than the bulk temperature measured by the ship’s system. Similar diurnal effects are to be seen in the data on other days, even in the trade winds’ region although the amplitude is sufficiently reduced so that the skin-bulk temperature difference does not change sign. Nevertheless, there remains a diurnal modulation of the skin-bulk temperature difference with a peak-to-peak value of 0(0.1K).

B.1.4.9 Wind speed dependence

A scatter-plot of the measured skin temperature difference against measured surface wind speed (corrected for the ship’s motion) reveals an envelope of points that becomes narrower with increasing wind speed (Fig. 10). The color coding in this figure indicates the local sun time of the measurements, and it can be seen at low wind speeds a widening of the distribution include positive values during the afternoon. This is the effect of the generation of a diurnal thermocline in the top few meters of the ocean, which makes the skin temperature appear to be warmer than the 5m bulk measurements. In reality, the skin remains cooler than the bulk measurement at a depth of a few centimeters. During the night, and for higher wind speeds the skin is about $0.2\text{K} \pm 0.2\text{K}$ cooler than the bulk temperature.

B.1.4.10 Satellite validation

At the time of writing this report, no comparisons with satellite data have been made. The results of these comparisons will be discussed in subsequent quarterly reports of the project.

B.1.4.11 Conclusion

The initial conclusions are very positive. They show the M-AERIs capable of making accurate skin temperature measurements, and of operating in a shipboard environment in very hot ambient conditions. Long (180 ft.) cables were used and, apart from the difficulty of man-handling such bulky cables on the ship, this did not lead to any obvious loss of quality in the data compared to those taken with prototype M-AERIs using much shorter cables.

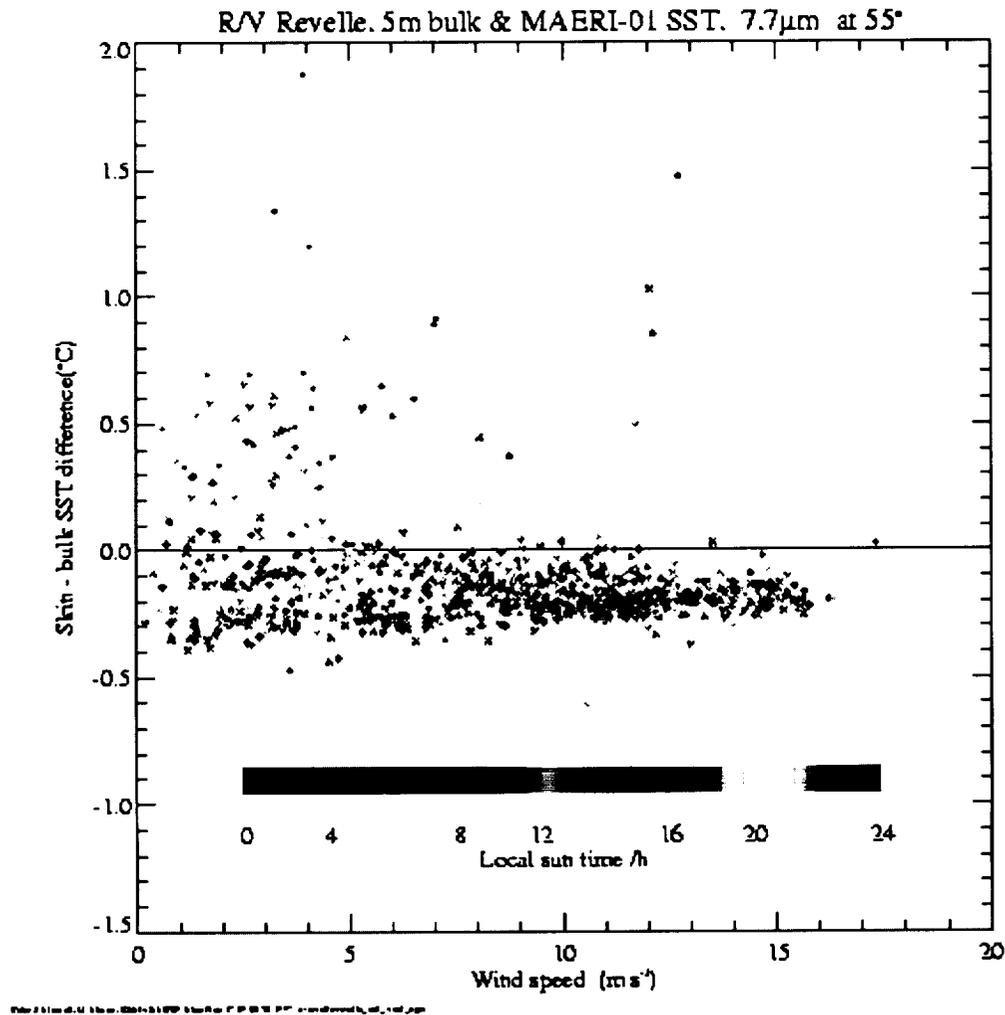


Figure 10. Wind speed dependence of the skin-bulk temperature difference.

A number of issues have been identified that will receive attention before the use of the M-AERIs for MODIS validation. These include:

- a) upgrading the CPUs of the system computer so that the speed of SST retrieval is not CPU limited, but detector noise limited;
- b) increasing the size of the hard disks on the system computer to ensure no data are lost at the “start-of-day” procedures when “old” data are deleted to make way for the new day’s measurements;

- c) improved weatherproofing and baffles around the aperture to keep the mirror clean by avoiding spray deposition;
- d) improved rain and spray detection software for automatic mirror "safe-mode" operation; and,
- e) improved software for flagging data that might be contaminated by mirror "safe-mode" operation and by covering the instrument by tarpaulins. This will lead to better and more rapid quality assurance of the data.

B.1.5 CASOTS Workshop

The CASOTS (Combined Action to Study the Ocean's Thermal Skin) group is funded by the European Community "Framework 4 Environment and Climate Programme," to coordinate study of the ocean surface thermal skin, with the objectives of improving the knowledge of the physics of the ocean skin and of understanding how the skin temperature difference influences the validation of satellite measurements of sea-surface temperature (SST). A workshop was held in October 1997 and Dr. Minnett was invited to attend.

The CASOTS group has a WWW page at <http://www.soc.soton.ac.uk/SUDO/RES/CASOTS/index.html>

The workshop was the second of the series, the first having been held in Southampton in the UK in June 1996, and is described at <http://www.soc.soton.ac.uk/SUDO/RES/CASOTS/workshop1.html>. One of the main activities at the first workshop was a comparison of the performance of several infrared radiometers used, or intended for use, to validate satellite measurements of SST.

The objectives of the Second Workshop were:

- Review the improvements in field measurement methodology arising from the first workshop, additional bilateral visits and fieldwork collaboration.
- Examine the data catalogue and identify gaps in coverage.
- Compare the performance of different predictive models for delta T.
- Plan a program of further study required to enable delta T to be accurately predicted.
- Prepare an advisory paper to the CEO concerning the effect of delta T on the monitoring of global SST from space.
- Prepare the Workshop Proceedings, which will include recommendations for the further development of the subject.

The participants at the Second Workshop are given below.

The workshop consisted of a series of sessions which began with a number of presentations that led into general discussions amongst the participants. The sessions were:

Introduction & Welcome: Ian Robinson & Walter Eifler
 Introduction to the Space Applications Institute at JRC, Dr Rudolf Winter, Director of SAI
 Session 1: Keynote Address: Dr. Kristina Katsaros
 Session 2: Discussion: The role of SST in climate change and climate monitoring
 Session 3: Presentations: Update on recent progress in thermal skin research
 Session 4: Discussion: Defining and measuring delta T
 Session 5: Presentations and discussion: Ship-borne Radiometry.
 Session 6: Discussion: Calibration / validation of satellite SST

Session 7: Discussion: The way forward for skin layer research.
Session 8: Workshop Conclusions

Peter Minnett gave a presentation in Session 3, which included M-AERI measurements from the Combined Sensor Cruise and from the recently completed sections from Hawaii to New Zealand on the *R/V Roger Revelle*.

One of the outcomes from the meeting was a statement reached by the consensus of the participants on the relevance of the ocean thermal skin to climate studies, air-sea exchanges, and validating satellite SST retrievals. This is what was agreed upon:

The relevance of the thermal skin of the ocean for climate studies

There is clear evidence in the literature from the past 20 years, confirmed by recent measurements, that there is a significant difference between the radiometrically measured skin temperature of the ocean (SSST) and the bulk sea surface temperature (BSST) as measured typically from ships and buoys. The magnitude of this difference, Delta T, is typically for the skin to be 0.3 K cooler than the bulk, but it can vary considerably over the ocean. In conditions of local diurnal warming SSST can become several K warmer than BSST measured a few metres below the surface.

This phenomenon should be of concern for climate scientists for a number of reasons:

1. Sea surface temperature (SST) is used as a parameter for monitoring climate change. Its increase globally is an indicator of global warming, and the change in its geographical distribution can be a sensitive indicator of climate change.
2. SST is a parameter which appears explicitly, and controls heat fluxes and evaporation rates, in the coupled ocean-atmosphere models used to predict climate change. Measurements of SST can be used to validate and possibly to drive such models.
3. SST is required for the parameterisation of air-sea gas fluxes and is therefore crucial for understanding the processes which control the global carbon dioxide budget.

Given the importance of SST as a climate parameter, and the size and variability of Delta T, the distinction between SSST and BSST should not in future be neglected by climate scientists. The magnitude of the uncertainty resulting from failing to address the difference between them is too large to be tolerated in the circumstances outlined above. The following recommendations are therefore made for future use of SST in the climate context:

1. SSST and BSST should be treated as two distinct variables. For many purposes, SSST is the most useful and appropriate indicator. It represents a physically definable property. It is the temperature which drives most of the air-sea interaction processes. It is also the variable which is directly measured by earth orbiting satellites. In general SSST is likely to be more variable spatially and temporally than BSST and contains information about changes in air-sea interaction processes. However, the historic climate record is based on BSST and continuity of its recording is essential. BSST approximates to the ocean's mixed layer temperature and is therefore a better indicator of the heat stored in the upper ocean, although it is important to standardise the depth to which the BSST refers.

2. Both BSST and SSST should be monitored independently. BSST must essentially be obtained by in situ measurements, while SSST is measured radiometrically from satellites, aircraft or ship-borne radiometers. It is inappropriate to measure BSST by remote sensing. However, when sufficiently long overlapping records of BSST and SSST have been accumulated, it will be possible to explore the relationship between the two, and thus provide an approximate continuity between satellite-derived time series of SSST and the historic archive of BSST.
3. From a physical basis, SSST appears to be the most appropriate variable to use in coupled models of air-sea interaction. It is recommended that experiments be performed using high resolution process models which use SSST rather than BSST, in order to study whether there is a significant difference in the predicted outcome of such models in comparison with those using BSST.
4. Although SSST is the most appropriate variable on which to base estimates of air-sea fluxes, it will not be practicable to do so until new bulk parameterisations of heat, momentum, and gas fluxes are derived. There is therefore an urgent need for experiments to derive bulk parameters based on SSST.
5. If SSST is to be used as the driver for air-sea interaction processes (see (3) and (4)), there is also a need to examine the effect of cloud cover on SSST lest the clear-sky requirement for satellite measurements of SSST introduce a bias.

Another outcome of the workshop was a recognition that there needs to be further comparisons between the radiometers that are used to study the skin effect and to validate satellite SST measurements, and plans were made for such a workshop to take place at the University of Miami in the spring of 1998. It was also recognized that the black-body targets used in the calibration of these radiometers should be compared with each other and, if possible, with a standard reference target provided by a Standards Institute. Also it was agreed that a workshop should be held to attempt to coordinate satellite validation exercises by the various groups around the world, especially given the expectation of several new infrared spacecraft radiometers becoming operational in the next few years. It was decided that it would be wise to take advantage of the concentration of scientists active in this field at the Miami Radiometer Workshop, and the Validation Workshop should be held in conjunction with this. These workshops will take place from March 2-6 at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami. The validation Workshop will be held under the auspices of the CEOS Working Group on Calibration and Validation. Details of these workshops can be found on the WWW page <http://www.rsmas.miami.edu/ir>.

B.1.6.1 *NOAA Ship Ronald H. Brown*

Space has been offered on the NOAA Ship *Ronald H. Brown* on the forthcoming cruises from Miami to the Canary Islands and back in January-February 1998. Two berths will be available on each cruise. The first is a non-stop transit and the second will include over 130 oceanographic stations. In total these cruises include over six weeks of sea time. A M-AERI will be installed on the ship and operate in a continuous mode. The retrieved M-AERI skin temperatures will be used to validate the AVHRR Pathfinder atmospheric correction algorithm (a close analogue of the MODIS SST algorithm), with 1km AVHRR data being captured at the NASA Wallops Island facility (Western Atlantic) and at a receiving station at the University of La Laguna, Canary Islands (eastern Atlantic). Details of the cruise are available at <http://www.aoml.noaa.gov/phod/24n>

B.1.6.2 *CCGC Pierre Espirit Radisson*

The Canadian research agency NSERC has funded the scientific voyages of the Canadian ice-

breaking research vessel *Pierre Espirit Radisson*, (which replaces the CCGC *Louis S. St. Laurent*) to the north of Baffin Bay (see earlier reports). Berths have been made available to Dr. Minnett on all four of the cruises, beginning late March 1998 and continuing through July, in order to make M-AERI (and other) measurements. This will provide the opportunity to collect M-AERI data over a wide range of Arctic conditions. These will be used to validate AVHRR sea-surface temperatures through very dry, cold atmospheres. AVHRR data will be collected using satellite data receiver on the ship itself. Plans are being made to mount a smaller expedition to the same course in summer 1999, which will provide an opportunity to validate MODIS SST retrievals (Minnett's participation in these cruises is supported, in part, by another NASA grant – AVHRR validation – and by NSF- measurements of the surface heat budget).

B.1.6.3 NOAA OACES Cruise

In May-July 1998, the NOAA ship *Ronald H. Brown* will be used to conduct an observational program northwest of the Azores in the North Atlantic as part of the Ocean-Atmosphere Carbon Exchange Study. Dr. P. Minnett was successful in obtaining NOAA funding to participate in this cruise. This will provide a further opportunity to use the M-AERI at sea. Use will also be made of the transit cruises between Miami and the Azores. These data will complement the winter-season data to be collected in the Atlantic in January and February.

B.1.6.4 USCGC Polar Sea

Confirmation that space will be available for a M-AERI group on the USCGC Polar Sea on the long transect from Seattle to Antarctica (or at least to the last port before Antarctica) has been given. This cruise, in November-December 1998, will provide the first MODIS trans-oceanic validation opportunity.

B.1.6.5 RV *Mirai*

Japanese collaborators at JAMSTEC (Japanese Marine Science and Technology Center) have offered space for M-AERI and ancillary instruments and operators on the *RV Mirai* during summer 1999. This will be part of the planned US-Japan collaborative research in the warm pool of the Pacific Ocean.

B.1.6.6 PFS *Polarstern*

The Alfred-Wegener-Institute for Polar and Ocean Research has approved a proposal by Minnett to mount a M-AERI and ancillary instruments on their ice-breaking research vessel "*Polarstern*" on the voyage in the Atlantic Ocean from Bremerhaven to Cape Town in December 1999. This will provide another dataset for MODIS validation spanning a wide range of climate regimes, comparable to that from the Polar Sea in the Pacific Ocean.

B.1.7 Wide Area Networking

Since the last report a second gigaswitch ATM has been added; the two switches are being interconnected using OC12 (622Mbs) links. Additional hardware to populate the second switch and workstation interfaces were acquired. These changes allow the existing ATM network to be expanded to cover at-launch requirements. Work continues with NASA and NSF to connect RSMAS to the vBBNS (very high speed Broad Band Network System).

C. Investigator Support

July	W. Baringer J. Brown O. Brown P. Evans G. Goni	A. Li A. Mariano R. Sikorski J. Splain
August	W. Baringer J. Brown O. Brown P. Evans	G. Goni A. Li A. Mariano R. Sikorski
September	W. Baringer J. Brown O. Brown M. Framinan	G. Goni A. Mariano R. Sikorski
October	W. Baringer J. Brown O. Brown P. Evans M. Framinan G. Goni	R. Jones A. Li A. Mariano R. Sikorski J. Splain
November	P. Evans G. Goni	R. Jones A. Mariano
December	A. Li A. Mariano J. Splain	

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. Organize radiometer and validation workshops
- e. Continue radiative transfer modeling using RAL code
- 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.

D.3 AGU Meeting

Dr. Peter Minnett has been invited to present a paper at the Spring meeting of the American Geophysical Union in May in Boston, in the Special Session on "The Measurement of Sea Surface Temperature from Satellites and Algorithm Intercomparisons." He has also been invited to present a paper at the 1998 IEEE International Geoscience and Remote Sensing Symposium in Seattle in July. The special session is entitled, "Infrared Remote Sensing of the Sea Surface: measurement techniques and applications to air-sea interaction."

E. Problems

No new problems to report.

F. Publications and Presentations

Post, M.J., C.W. Fairall, J.B. Snider, Y. Han, A.B. White, W.L. Ecklund, K.M. Weickmann, P.K. Quinn, D.I. Cooper, S.M. Sekelsky, R.E. McIntosh, P.J. Minnett, and R.O. Knuteson, 1997. The Combined Sensor Program: An air-sea science mission in the central and western Pacific Ocean. *Bull. Am. Met. Soc.*, **78**, 2797-2815.

Minnett, P.J. Infrared interferometric measurements of the ocean skin temperature. Invited presentation at CASOTS Workshop, Joint Research Centre, Ispra, Italy, October 28, 1997.

Minnett, P.J., R.O. Knuteson and O.B. Brown. Measurements of near-surface vertical temperature gradients in the Tropical Pacific Ocean. Invited presentation at AGU Fall Meeting, San Francisco, December 8, 1997.

APPENDIX – Participants at CASOTS Workshop

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