Progress Report: NAG5-6463
BROADBAND IR MEASUREMENTS FOR MODIS VALIDATION

Reporting Period: 10/1/00 – 9/30/01, Supplement Period: 10/1/01 – 3/31/02

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OBJECTIVE

The objective of this research is to develop, fabricate, and deploy autonomous instrument systems for *in situ* infrared measurement of sea surface temperature to an accuracy of ±0.1 °C for MODIS validation.

SUMMARY OF PRIMARY TASKS

The CIRIMS (Calibrated, InfraRed In situ Measurement System) has been described in previous reports. The primary tasks for this grant are:

1) Fabricate 3 CIRIMS Units
2) Verify accuracy by *in situ* comparison to the M-AERI
3) Deploy over a wide range of environmental and geographic locations
4) Deliver quality controlled skin temperature data to MOCEAN for MODIS validation.

OVERVIEW OF PREVIOUS AND CURRENT PROGRESS

The first year of the grant was devoted to development and testing of a prototype instrument. In the second year, we fabricated operational units #1 and #2 and deployed them on two research cruises. In our last progress report, we set forth the following objectives for the third year:

1) Complete the fabrication of a total of 3 units
2) Validate the accuracy through side-by-side comparison with the M-AERI
3) Deploy the CIRIMS for validation of SST from MODIS.

During the reporting period, we fabricated a third CIRIMS unit, performed side-by-side field comparisons with the M-AERI, and deployed the CIRIMS extensively at sea to collect *in situ* skin temperature data for MODIS validation.

DEPLOYMENTS

At the time of my last progress report I planned to deploy the CIRIMS on 6 cruises for a total of 335 days and on a platform for a period of 1 year. The platform deployment was to be in conjunction with research under separate NASA Earth Science Enterprise funding (Dr. Eric Lindstrom, program manager). We were forced to abandon our original plan to use Platform Harvest because of concerns about tower interference. I seriously considered the Chesapeake Light Tower as an alternative platform, which was especially attractive because of the ongoing NASA-funded CERES measurements. However, we determined that logistical considerations of power and the potential for vandalism made this alternative impractical. As a substitute long-term installation, we decided to extend the deployment on the NOAA ship *R/V Ronald H. Brown* from the planned 45 day to over 10 months. Table 1 lists deployments since the last progress report, totaling over 600 days.

Ship	Dates	Location	Comments
USCG *Polar Star*	07/15/00 - 09/15/00 (62 days)	Seattle-Arctic RT	M-AERI
USCG *Polar Sea*	11/15/00 – 01/05/01 (167 days)	Seattle-Antarctica RT	M-AERI
R/P FLIP	15 Sep – 15 Oct 00 (30 days)	Off Monterey, CA	Stable platform
NOAA *R/V Brown*	24 Jan – 15 Dec 01 (324 days)	Pacific – see Figure 1	M-AERI for 3 months
WHOI *Asterias*	23 Jul – 03 Aug 01 (18 days)	Off Martha's Vineyard	Small craft, coastal location

Comparisons between the M-AERI and CIRIMS were difficult during the *Polar Sea and Polar Star* cruises because there were a number of periods when the two instruments were not both working properly at the same time. The Polar Sea cruise to Antarctica provided an opportunity to test the ability of the CIRIMS to withstand some of the harshest weather possible. The conditions during *R/P FLIP* cruise provided an excellent opportunity to test the infrared transparent window correction scheme (see below). The nearly 10-month deployment on the Brown has demonstrated the robustness of the system and provided ample data taken simultaneously with the M-AERI to evaluate the CIRMIS at-sea performance.

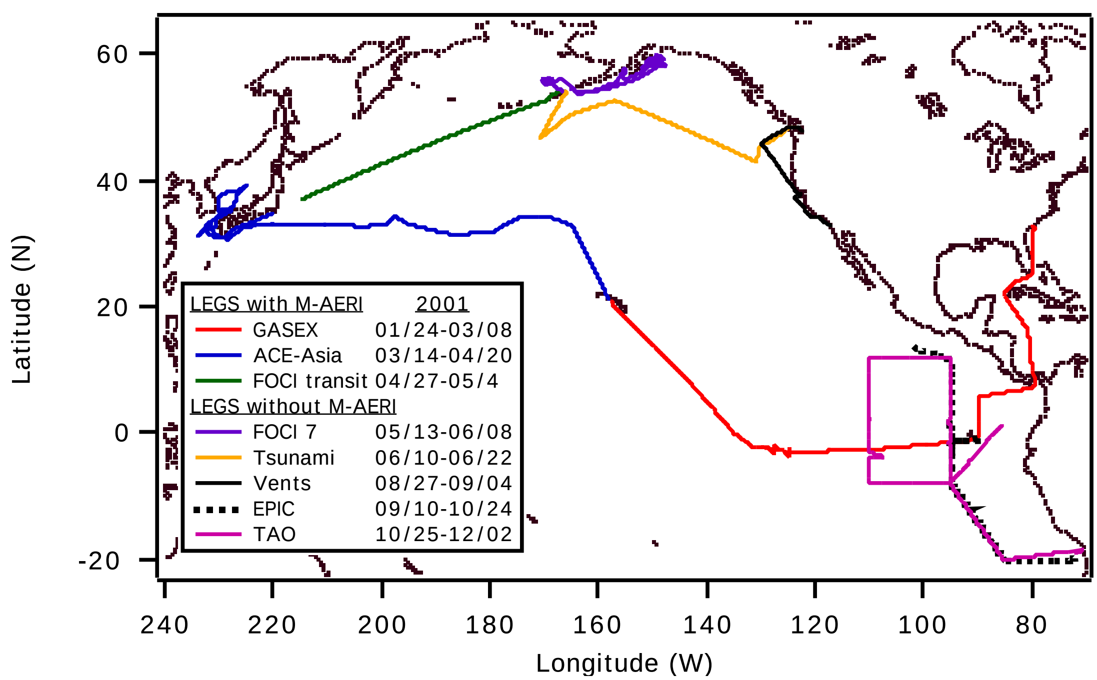

Figure 1. Ship track for *Brown* showing cruises with CIRIMS deployed totaling roughly 10 months. Simultaneous measurements with M-AERI were made for roughly 3 months.

COMPARISON WITH M-AERI ABOARD THE *BROWN*

Figure 1 shows the ship track of the *R/V Ronald H. Brown* during 2001 when the CIRIMS has been on board. The CIRIMS was installed in Charleston, SC in late January in preparation for the GasEx 2001 cruise, which began in Miami, where the M-AERI was installed. The CIRIMS and M-AERI operated continuously together from February through March (GasEx, Ace-Asia, and FOCI cruises). During this time, the *Brown* covered a wide range of water temperatures and climatic regimes as it steamed from Miami to Honolulu, Japan, and Alaska. We have worked closely with Peter Minnett and his colleagues at the University of Miami to compare our results. In this report, we will present the results for the GasEx cruise. Data from subsequent cruises are being processed and will be reported by the end of the grant period.

Figure 2 is a photograph showing the CIRIMS mounted on the bow tower of the *Brown* during the GasEx 2001 cruise, which we have found to be an ideal location for long term unattended operation. The tower platform is 20 m above the sea surface so that very little sea spray reaches the optics. It is located close enough to the bow that the field of view is forward of the bow wake.

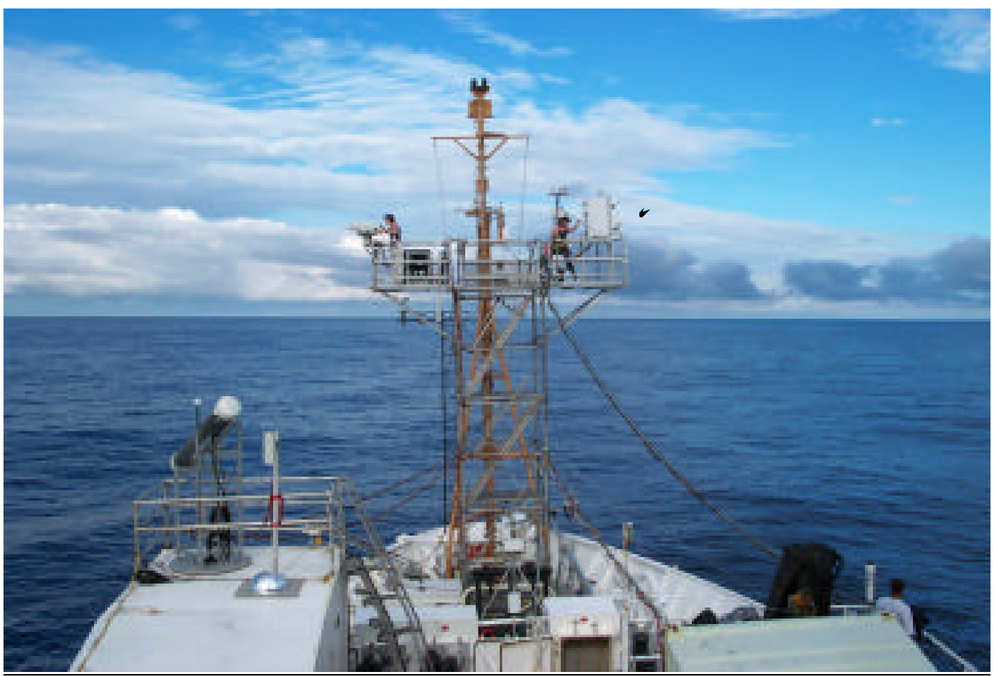

Figure 2. Photograph showing location of CIRIMS on the bow tower of the *Brown*.

Figure 3 is a histogram of the difference between calibrated, sky-corrected skin temperature measured by the M-AERI and the CIRIMS. This histogram is for all the overlapping data from the GasEx 2001 cruise and covers roughly 15 days (357 hours) over a 35-day period. The rms difference is 0.13 °C and the mean difference and (±) one standard deviation is 0.06 ± 0.11 °C. This is judged to be excellent overall agreement. Examination of time series of the simultaneous measurements show that there are extended periods of time when the agreement is significantly better than the overall statistics.

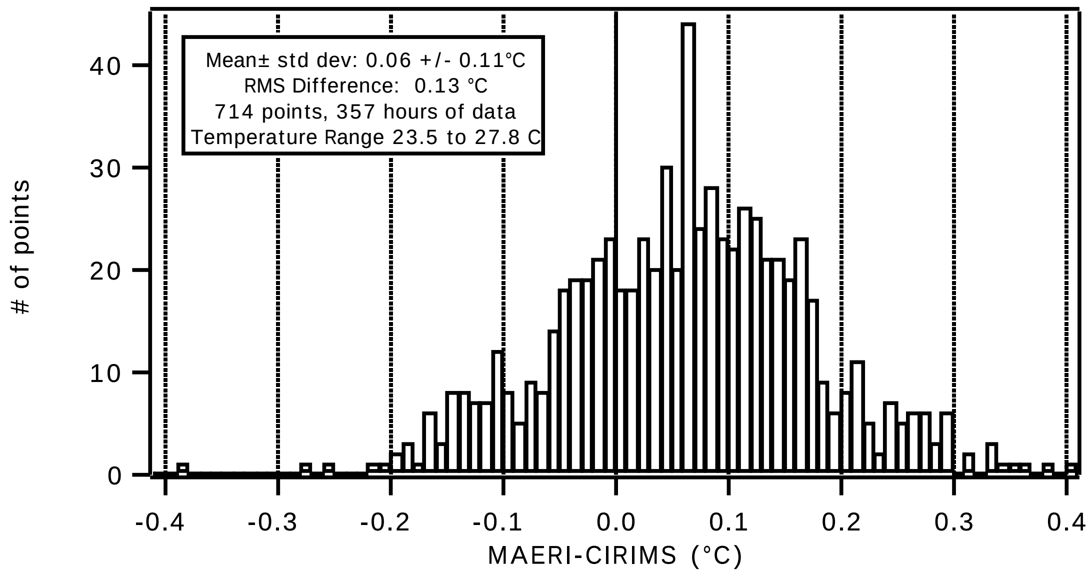

Figure 3. Histogram of difference between the M-AERI and CIRIMS measurement of skin temperature during the GasEx 2001 cruise. The rms difference is 0.13 °C and the mean difference and standard deviation are 0.06 ± 0.11 °C.

Figure 4 is a time series of SST measured by M-AERI and CIRIMS covering several days of the GasEx 2001 cruise. The agreement between the measurements is excellent over a number of extended periods, especially during the first half of the time series. Towards the end of the record, there are a number of periods where the two measurements appear offset by an amount that remains constant for a significant period. These observations suggest that some of the difference between the CIRIMS and M-AERI may be correlated with different environmental conditions.

A likely environmental source of the difference between the CIRMIS and M-AERI measurements is the effect of different cloud conditions. Both the M-AERI and the CIRIMS correct for sky reflection by making measurements of sky radiance, however the techniques employed are very different. In order to examine the comparison under different sky conditions, we sorted the data according to four categories: clear night, clear day, cloudy night, and cloudy day. Figure 5 shows four histograms of the difference between the M-AERI and CIRMIS for data collected during GasEx 2001 for different sky conditions during the day and night. Table 2 summarizes the results as a function of these conditions. The results show that the mean difference is reduced by about a factor of two for cloudy conditions compared with clear conditions.

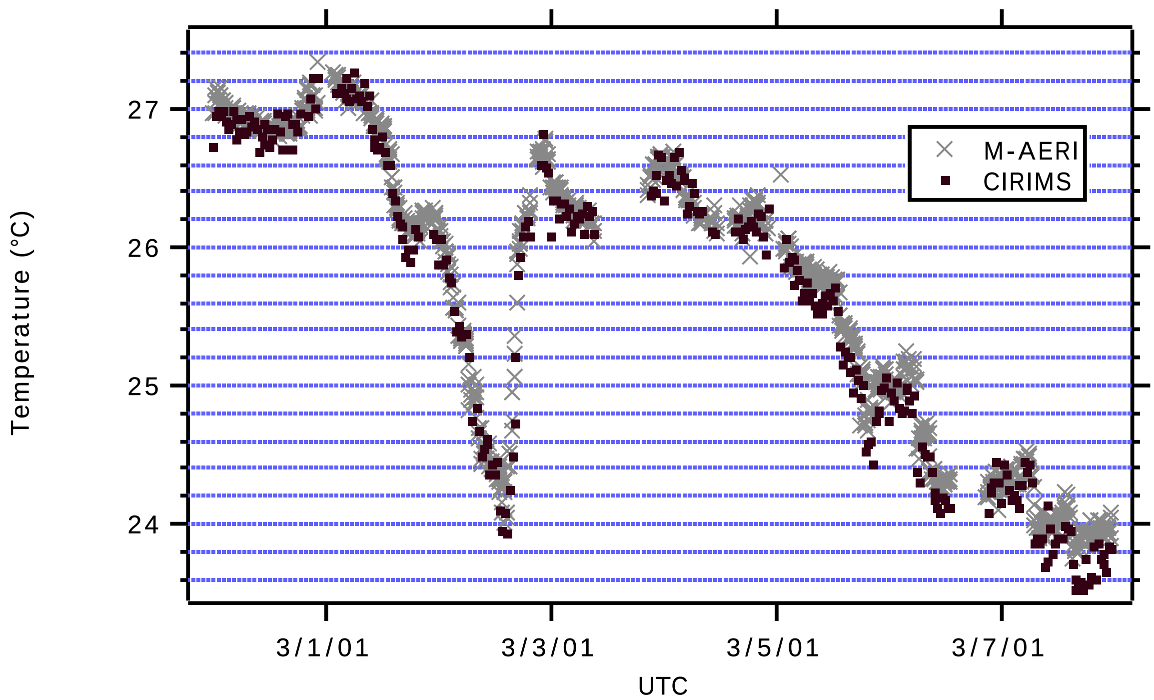

Figure 4. Time series of skin SST measured by M-AERI and CIRIMS over an 8-day period on the GasEx 2001 cruise.

Table 2: Comparison of difference between M-AERI and CIRIMS by sky condition

CONDITIONS	RMS difference	Mean difference ± standard deviation
All data	0.13 °C	0.06 ± 0.11 °C
Clear, day	0.15	0.11 ± 0.10
Clear, night	0.15	0.12 ± 0.10
Cloudy, day	0.15	0.05 ± 0.15
Cloudy, night	0.10	0.02 ± 0.10

The sky correction for cloudy conditions is not very sensitive to errors in emissivity because the radiance reflected from clouds is close to that from the ocean. In the case of overcast conditions the brightness temperature will be about the same as the actual temperature since the temperature of the clouds is relatively close to that of the ocean surface. Accuracy of the sky correction is much more important for clear skies since the radiance reflected from the sky is negligible compared to that from the ocean. Under clear sky conditions, the brightness temperature of the ocean can be as much as 0.5 °C less than the actual temperature since the clear sky can appear *O*(100 °C) cooler than the ocean surface. The case of partly cloudy conditions is even more problematic because the measurement geometry for the two instruments is not the same.

Using the M-AERI as the standard for judging the performance of the CIRIMS, the comparison to date demonstrates that the CIRIMS very nearly meets the design goal of ± 0.1 °C. The observation that the small mean offset is a function of sky conditions suggests that the CIRIMS performance can be improved by understanding the cause of the offset.

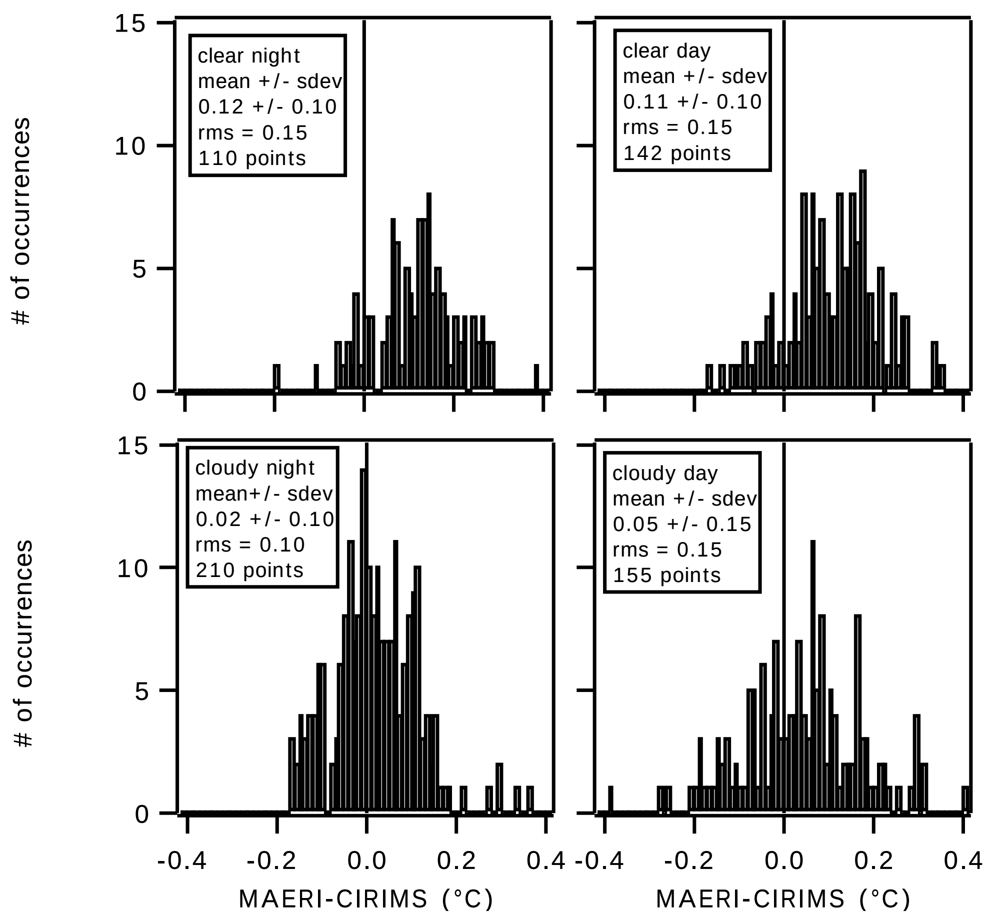

Figure 5. Histograms of difference between M-AERI and CIRIMS by sky.

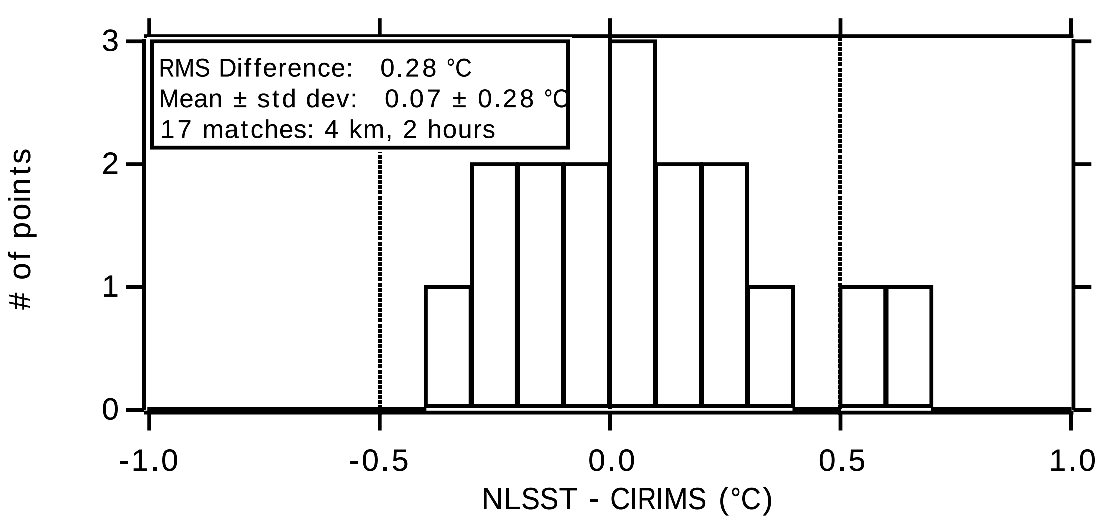

Figure 6. Histogram of difference between AVHRR-derived SST (NLSST algorithm) and CIRMIS for 17 matchups during GasEx 2001.

The main objective of this research for validation of SST from MODIS is to provide high quality *in situ* measurements to MOCEAN to supplement the ongoing M-AERI validation program. As a preliminary validation task, we have performed match-ups with AVHRR during the GasEx 2001 cruise. Figure 6 is a histogram summarizing this comparison for which the mean difference was 0.28 °C and the mean offset and (±) one standard deviation was 0.07±0.28 °C. A general conclusion regarding the comparison is premature because there were only 17 match-ups, but the differences are comparable to those reported by other investigators. We have exchanged data with Peter Minnett during times when the M-AERI and CIRIMS were deployed on the *Brown*. Data gathered on the *Brown* when the M-AERI was not deployed are being processed and will be provided to MOCEAN before the end of the grant period.

STATUS of IR TRANSPARENT WINDOW CORRECTION

A primary design goal for the CIRIMS has been to determine the practicality of using an IR transparent window to protect the optics and calibration blackbody. In order to evaluate the design, we implemented a scheme by which the CIRIMS alternately measures the ocean radiance with and without the window in place. The design also includes a two-temperature hot blackbody that can be moved into the field of view external to the window. This feature provides a method to correct for the effect of the window by making measurements of a constant temperature target with and without the window in place.

Figure 7 illustrate the window correction scheme. When the radiometer views the external blackbody without the window in place, the radiance is

$$\Phi_{no\_window} = \varepsilon_{bb}\phi_{bb} + \rho_{bb}\phi_{amb}, \qquad (1)$$

where Φ_{no_window} is the radiance without the window in place, ε_{bb} is the emissivity of the blackbody, φ_{bb} is the radiance of the blackbody, ρ_{bb} is the reflectivity of the blackbody, and φ_{amb} is the ambient temperature. When the window is in place, the measured radiance is the product of Φ_{no_window} and τ, the window transmission coefficient, plus the emission from the window itself and the reflection from window of the radiometer housing. Therefore, the radiance from the blackbody measured through the window is

$$\Phi_{window} = \tau_w \Phi_{no\_winsow} + \varepsilon_w\phi_w + \rho_w\phi_{box}, \qquad (2)$$

where the subscripts *w* denotes the window and *box* stands for the radiometer housing. The first term in (2) is known since Φ_{no_window} is measured. The second term is small and varies slowly and as the window temperature changes. The third term is small and constant since the reflectivity is small and the box temperature is fixed.

In practice, the scheme is implemented in three steps:

1. Perform a linear regression between the measurements of the external blackbody with and without the window at two temperatures. Compute the first residual, which is dominated by the second term in (2) and depends primarily on the window temperature.

2. Perform a linear regression between the first residual and window temperature, which is measured by an attached thermistor. The residual of this regression is referred to as the second resisual. It will be close to zero with an offset that corresponds to the third term in (2), which is constant.
3. The RMS of the second residual is a measure of the accuracy of the window correction.

Figure 8 summarized these steps for data taken during the deployment aboard *R/P FLIP* and demonstrates that the effect of the window can be corrected to an RMS error of 0.09 °C.

PLANS FOR THE REMAINDER OF THE GRANT PERIOD

A funded extension was granted to continue deployment on the *Brown* through the end of 2001, finish procession of existing data, and upgrade our outdoor laboratory testing facility. The outdoor facility is being used to investigate the sky correction procedure as a source of the difference between the CIRIMS and M-AERI. The APL web site is being revised and will incorporate a new CIRIMS home page with updated design and performance information. Processed data for MODIS SST validation will be provided to MOCEAN before the end of the grant period.

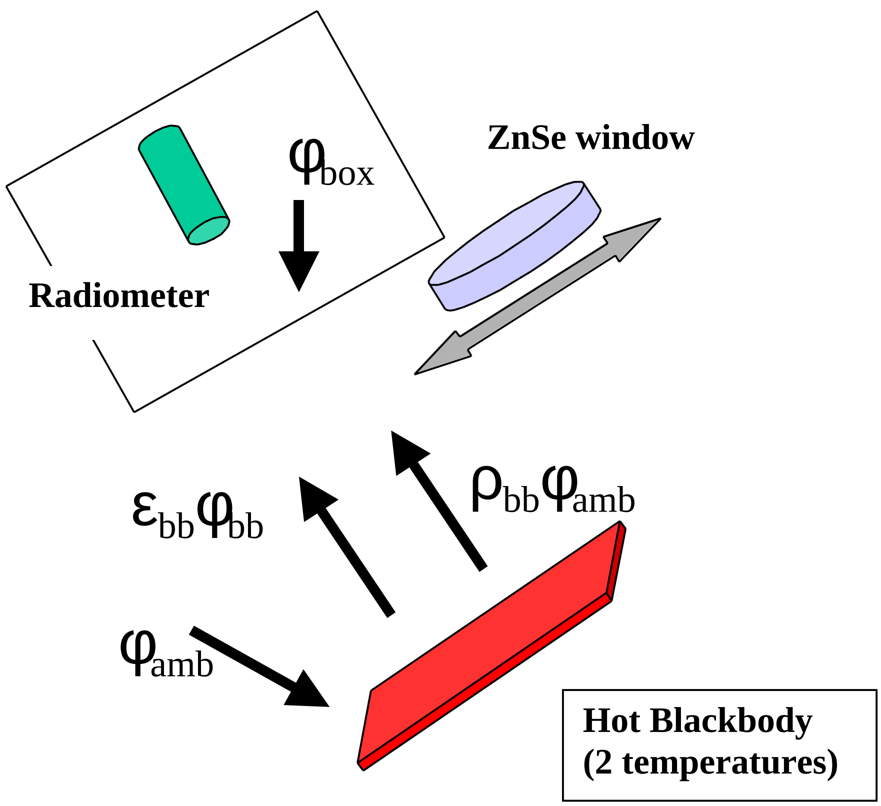

Figure 7. Schematic illustration of scheme to correct for IR transparent window made of ZnSe. An external hot blackbody at two temperatures is alternately viewed with and without the window. The window temperature is measured with an attached thermistor.

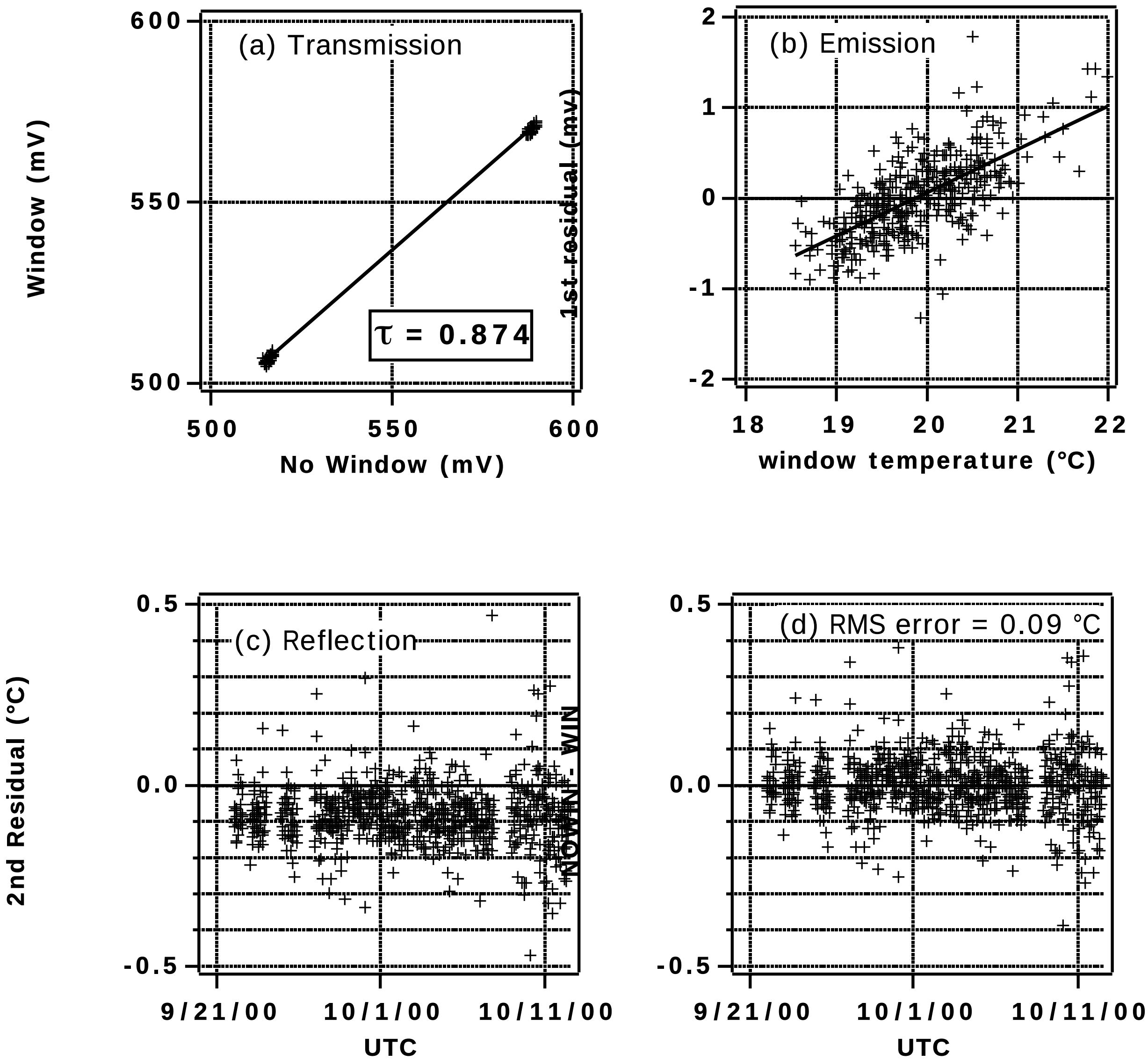

Figure 8. Example of steps in window correction scheme for data from the *FLIP* cruise. (a) Measurements of the external blackbody at two temperatures are plotted against each other and a linear regression computed. (Since the voltage output of the radiometer is proportional to radiance, the plot can be made in mV.) The dependence is dominated by the attenuation of the window material, which is confirmed by the value of the slope being equal to the transmission coefficient. (b) The first residual is plotted against window temperature because it depends primarily on emission from the window. The residual of this regression is a called the second residual. (c) The mean of the second residual corresponds to the constant effect of window reflection. (d) The rms of the second residual is a measured of the accuracy to which the effect of the window can be determined.