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BROADBAND IR MEASUREMENTS FOR MODIS VALIDATION

Andrew T. Jessup
Applied Physics Laboratory, University of Washington
206-685-2609, jessup@apl.washington.edu

SUMMARY
The primary objective of this research was the development and deployment of autonomous shipboard systems for infrared measurement of ocean surface skin temperature (SST). The focus was on demonstrating long-term, all-weather capability and supplying calibrated skin SST to the MODIS Ocean Science Team (MOCEAN). A secondary objective was to investigate and account for environmental factors that affect *in situ* measurements of SST for validation of satellite products.

We developed and extensively deployed the Calibrated, InfraRed, In situ Measurement System, or CIRIMS, for at-sea validation of satellite-derived SST. The design goals included autonomous operation at sea for up to 6 months and an accuracy of ±0.1 °C. We used commercially available infrared pyrometers and a precision blackbody housed in a temperature-controlled enclosure. The sensors are calibrated at regular interval using a cylindro-cone target immersed in a temperature-controlled water bath, which allows the calibration points to follow the ocean surface temperature. An upward-looking pyrometer measures sky radiance in order to correct for the non-unity emissivity of water, which can introduce an error of up to 0.5 °C. One of the most challenging aspects of the design was protection against the marine environment. A wide range of design strategies to provide accurate, all-weather measurements were investigated. The CIRIMS uses an infrared transparent window to completely protect the sensor and calibration blackbody from the marine environment. In order to evaluate the performance of this approach, the design incorporates the ability to make measurements with and without the window in the optical path.

A total of three CIRIMS units have been fabricated and deployed at sea for over 700 days since 1998. The performance was evaluated using extensive at-sea comparisons to the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), which is the primary *in situ* validation instrument for MODIS. The comparisons demonstrate that the accuracy of the CIRIMS is comparable to that of the M-AERI and that the CIRIMS can provide data for satellite validation.

The extensive comparison between the CIRIMS and M-AERI highlight the difficulties and limitations inherent in at-sea radiometric measurements of SST. The strengths and weaknesses of the CIRIMS design have been evaluated and recommendations for a new design for routine, long-term deployments have been established.

An archive of data for MODIS validation has been established and made available to MOCEAN. The three CIRIMS units are now being used for continuous at-sea measurements under the FY03 NOPP SST Topic. Graduate student Ruth Fogelberg was supported by this grant and will receive her MS degree in June 2003. A manuscript for submission to a peer-reviewed journal is in preparation and will be submitted after the completion of Fogelberg s thesis.

IN SITU RADIOMETRIC MEASUREMENTS OF OCEAN SKIN TEMPERATURE

This grant addressed the need identified by the MODIS Ocean Science Team for the development of low-cost measurement technology for at-sea deployment. The primary objective of this research was to develop and deploy inexpensive and robust systems for autonomous infrared measurement of SST to an accuracy of – 0.1 °C. A secondary objective was to investigate the impact on validation measurements of factors such as incidence angle, wind-induced surface roughness and sky reflection.

The radiometer system developed is the Calibrated InfraRed In situ Measurement System, or CIRIMS, and is shown in the photograph in Figure 1. Because of the *a priori* uncertainty of the best design approach, we consciously incorporated features into the CIRIMS that provided the engineering data necessary to evaluate the success of our design.

Radiometric determination of the skin temperature, T_{skin}, is based on inversion of the equation for the sea surface radiance, $L(T)$ [W m^{-2}], measured with an infrared radiometer. If the distance to the surface is small enough to neglect the effects of the atmosphere between the sensor height and the sea-surface, the radiance measured by a radiometer operating in the wavelength range $\lambda_1 \leq \lambda \leq \lambda_2$ and viewing the sea surface at an incidence angle θ is given by

$$L(T) = \int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda, \theta)L_{\lambda,b}(\lambda, T_{skin})d\lambda + \int_{\lambda_1}^{\lambda_2} \rho(\lambda, \theta)L_{\lambda,b}(\lambda, T_{sky})d\lambda \qquad (1)$$

where $L_{\lambda b}(\lambda, T)$ [W m^{-2} μm^{-1}] is the spectral radiance at temperature T given by Planck s function, $\varepsilon(\lambda, \theta)$ is the surface emissivity, and $\rho(\lambda, \theta)$ is the surface reflectivity. Under clear sky conditions, the sky reflection effect can be as much as 0.5 °K when operating in the 8-12 μm atmospheric window. The currently accepted technique is to make measurements of both the sea and sky radiance and to solve for T_{skin}. Although this technique requires knowledge of the emissivity, measuring at incidence angles near nadir minimizes the impact of the effect of surface roughness on emissivity.

The important factors that must be considered in the design of an autonomous shipboard IR radiometer system and common approaches within the community are listed in Table 1.

Table 1: **Design Factors**	**Common Approaches**
In situ instrument calibration	Two-point supplemental blackbody
Correction for sky reflection	Via (1) using up- and down-looking radiometers
Incidence angle	Near nadir is optimal, 40°-50° is practical
Radiometer bandwidth	10-12 μm (minimizes impact of water vapor in sky correction)
Environmental Protection	IR transparent window or shutter triggered by rain gauge

Reliable, long-term calibration of the *in situ* radiometer requires a two-point calibration with a high emissivity calibration target (blackbody). The most common approach is to use a combination of hot and ambient temperature targets. The final accuracy of the measured T_{skin} is dependent not only on the accuracy of the instrument itself, but also on the accuracy of the sky correction. The emissivity of seawater in the long wavelength range at nadir incidence varies from roughly 0.98 to 0.99. The emissivity depends primarily on incidence angle and surface roughness, with the roughness effect increasing with incidence angle. In practice, an incidence

angle of 40° to 50° is necessary in order to ensure that a shipboard radiometer views the sea surface where it is not disturbed by ship wake effects. A narrow bandwidth in the 10-12 μm range is generally agreed upon to be necessary to minimize the impact of atmospheric water vapor on the sky correction. Other challenging aspects of the sky correction include partly cloudy conditions and the vulnerability of an up-looking instrument to rain and condensation.

Protection of the radiometer and calibration blackbody is arguably the most challenging and debated aspect of a practical design. Two competing strategies have emerged over the past 5 years. The strategy adopted in the CIRIMS is to use an infrared transparent window to provide complete protection of the optics and the blackbody. The use of a window depends on the ability to adequately correct for the effect of the window. The second approach, adopted by C. Donlon of the Joint Research Center (Italy) in the Infrared SST Autonomous Radiometer (ISAR) [*Barton et al.,*2003], is to use focussed foreoptics that permit the use of a small aperture in combination with a shutter mechanism that is triggered by a sensor that detects rain and spray.

INFRARED TRANSPARENT WINDOW CORRECTION

The motivation behind the use of a window is to ensure complete protection under all conditions because of the inevitability of severe weather and sea conditions during a long deployment. The primary concerns regarding the use of a window are the effect of salt deposits on the transmission and the fact that the self-emission of the window is a function of ambient temperature. In the development of the CIRIMS, we put a high priority on the ability to continuously monitoring the effect of the window in order to account for changes due to contamination or environmental conditions in an ongoing fashion. The results summarized below show that there is some loss in accuracy when using a window, but we believe that a small reduction in accuracy is acceptable to ensure reliable all-weather operation.

The CIRIMS design, shown schematically in Figure 2, allows us to determine the effect of the window by measuring the radiance of a simple flat plate blackbody that is external to the window. First the CIRMS is put in a protected mode by closing a door between the optical path and the outside air. A two-point hot blackbody is on the back of the door. This design provides a method to correct for the effect of the window by making measurements of a two-point temperature target with and without the window in place while the optics and primary calibration blackbody inside the main housing remain protected.

When the radiometer views the external blackbody without the window in place, the radiance is

$$L_{no\_window} = \varepsilon_{bb}L_{bb} + \rho_{bb}L_{amb}, \tag{2}$$

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

$$L_{window} = \tau_w L_{no\_window} + \varepsilon_w L_w + \rho_w L_{box}, \tag{3}$$

where w denotes the window and the subscript *box* stands for the radiometer housing. The CIRMS window is made of ZnSe with $\tau = 0.874$, $\varepsilon = 0.025$, and $\rho = 0.101$ (clean window,

measured in laboratory). The first term on the right of (3) is the effect of attenuation due to the window. The second term, the window self-emission, is small and varies slowly with the window temperature, T_{window}, which is measured with an attached thermistor. The third term is also small but constant because the box temperature is fixed. Using two linear regressions, we can empirically remove the effects of attenuation, emission, and reflection as follows:

1. Regress L_{no_window} vs L_{window}, obtaining offset a_0 and slope a_1
   The slope a_1 is roughly equal to τ_w and the 1st residual is dominated by the second term on the right in (3) and as such is proportional to T_{window}.
2. Regress the 1st residual vs T_{window}, obtaining offset b_0 and slope b_1
   The slope b_1 corresponds to second term on the right in (3). The combined offsets from the two regressions correspond to the effect of the third term.
3. Compute the standard deviation of the 2nd residual
   The mean of the 2nd residual should be negligible and the standard deviation (std dev) is a measure of the accuracy of the window correction.

The result of these steps are shown in Figure 3 for data taken during the deployment during the Fluxes, Air-sea Interaction, and Remote Sensing (FAIRS) Experiment (see Table 2) and demonstrates that the effect of the window can be corrected with an error of 0.04 °C (the mean±sdev was 0.00±0.04 °C).

This error only applies to correction of the window effect when measuring the external blackbody, not the sea surface. In order to evaluate the error when viewing the sea, we made measurements of the sea surface with and without the window during periods when the weather conditions permitted the window to be removed without jeopardizing the optics and internal blackbody. The radiance measured through the window and corrected using the regression analysis above is given by

$$L_{corrected} = \frac{1}{a_1} \left\{ L_{window} - \left(a_0 + b_0 + b_1 T_{win} \right) \right\}.$$

The difference between T_{skin} without the window and T_{skin} through the window and corrected using this method during FAIRS showed a mean difference of –0.06 °C, a std dev of 0.07 °C, and an rms of 0.09 °C. The increased standard deviation is likely due to the fact that the measurements with and without the window were made 30 minutes apart. The increase in the mean difference may be due to inadequately characterizing the window emission because there is evidence that the external blackbody causes some additional heating of the window that is not detected by the window thermistor. Nonetheless, these results demonstrate our ability to correct for the effect of the window to better than 0.1 °C.

FIELD COMPARISIONS OF THE CIRIMS AND THE M-AERI

The deployments of the CIRIMS over the past 4 years are listed in Table 2 and cover 8 cruises for over 733 days. 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 nearly 10-month deployment on the *Brown* in 2001 has demonstrated the robustness of the system and provided ample data taken simultaneously with the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI) to evaluate the CIRMIS at-sea performance.

Table 2: CIRIMS DEPLOYMENTS			
Ship	**Dates**	**Location**	**Comments**
R/V Brown	05/07/98 - 07/07/98	Miami-Lisbon RT*	prototype testing , GasEx 1998 cruise
R/V Brown	11/01/99 -12/10/99	Seattle-equator RT	TAO array service cruise
R/V *Thompson*	01/03/00 - 02/05/00	Seattle-Honolulu RT	Student instruction cruise
USCG *Polar Star*	07/15/00 - 09/15/00	Seattle-Arctic RT	M-AERI
USCG *Polar Sea*	11/15/00 - 01/05/01	Seattle-Antarctica RT	M-AERI
R/P FLIP	09/15/00 - 10/15/00	Off Monterey, CA	Stable platform, FAIRS Experiment
R/V Brown	01/24/01 - 12/15/01	Pacific Ocean	M-AERI (3 mo.), GasEx 01, Ace-Asia, FOCI, EPIC, STRATUS
WHOI *Asterias*	07/23/01 - 08/03/01	Off Cape Cod	Small craft, coastal

*Round Trip

The CIRIMS was installed on the NOAA R/V *Ronald H. Brown* in Charleston, SC in late January 2001 in preparation for the GasEx01 cruise, which began in Miami, where the M-AERI was installed. The CIRIMS and M-AERI operated continuously together from February through March 2001 (GasEx01, 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.

During the GasEx01 cruise, T_{skin} measured by CIRIMS (combined data with and without the window) was compared to T_{skin} measured by the M-AERI for all available overlapping data (15 days, or 357 hours, over a 35-day period). The range of environmental conditions during GasEx01 was relatively narrow. The temperature was between 24 °C and 27 °C and the wind speed was less than 8 m s^{-1}. The RMS difference was 0.13 °C, with zero mean. For clear skies using only the CIRIMS data with the window, the RMS difference was 0.12 °C and the mean±std dev was –0.02 ± 0.11 °C. The degree to which the measurements agree is illustrated in the time series plot in Figure 4, which shows the M-AERI data plotted with the CIRIMS data with and without the window. This comparison demonstrates that the scatter in the CIRIMS data is comparable to that of the M-AERI.

Following GasEx01, the *Brown* traveled from Hawaii to Japan during the Ace-Asia cruise and then on to Alaska during FOCI. The range of temperature encountered during these cruises was much greater than during GasEx01, as shown in the comparison of CIRIMS and M-AERI measurements in Figure 6. There are a total of 756 hours (31.6 days) of coincident CIRIMS and M-AERI measurements over a period of roughly 50 days for the combined Ace-Asia and FOCI cruises. For all the data, the RMS difference was 0.20 °C and the mean±std dev was –0.06 ± 0.19 °C, which is a somewhat greater than during GasEx01.

The range of wind speed and wave conditions during Ace-Asia and FOCI was much greater than during GasEx01. Rough conditions can significantly affect the accuracy of the sky correction through changes in surface emissivity due to increased roughness and variation in local incidence angle due to the ship's roll. The correlation of an increase in the difference between the CIRIMS and M-AERI is illustrated in Figure 5. The inset plot shows a segment in which an increase in the difference correlates with rougher conditions, as indicated by the increase in the standard deviation of the ship's roll. An additional source of variability is partly cloudy conditions, which can enhance the effect of changes in local incidence angle. The difference is significantly reduced for a subset of the measurements from Hawaii to Alaska

during which the seas were calm and the sky was clear, with the mean difference being zero and the standard deviation of 0.15 °C. The results of the CIRIMS and M-AERI comparisons are summarized in Table 3. The comparison between the GasEx data with and without the window demonstrates the window correction is successful. The larger RMS difference for all conditions compared with calm conditions for Ace-Asia/FOCI implies that surface roughness and local incidence angle are contributing factors.

Table 3: Summary of Difference between CIRIMS and M-AERI

CRUISE: CONDITIONS	Window	RMS diff.	Mean ± Std Dev
GasEx01: All data (low wind, calm)	With & without	0.13 °C	0.00 ± 0.13 °C
GasEx01: Clear skies only	With only	0.12	-0.02 ± 0.11
Ace-Asia/FOCI: All data (high winds/rough)	Without only	0.20	0.06 ± 0.19
Ace-Asia/FOCI: Calm, uniform sky	Without only	0.15	0.00 ± 0.15

The correlation of the difference with sea state and changing local incidence angle may be due to fundamental differences in sky correction methods. The CIRIMS uses radiometers that operate in the 9.6-11.5 μm range which is relatively transparent. The M-AERI uses a narrow band centered on 7.7 μm, at which wavelength the atmospheric path length is much shorter than in the 10-12 μm range. According to *Minnett et al.* [J. Atmos. Ocean. Tech., 18,994-1013, 2001], the sensitivity of the M-AERI to changes in local incidence angle should be an order of magnitude less than CIRIMS.

Our results demonstrate the feasibility of low-cost, autonomous SST measurements from ships. The accuracy of the CIRIMS is comparable to that of the M-AERI and the CIRIMS has been used to gather a large data set for MODIS validation. The most important result is the knowledge that has been gained that can be applied to a new, simpler design for routine deployment on merchant ships. This design is the topic of a proposal in preparation for submission in 2003.

Peer-reviewed Journals

Barton, I. J., P. J. Minnett, C. J. Donlon, S. J. Hook, A. T. Jessup, K. A. Maillet and T. J. Nightingale The Miami 2001 infrared radiometer calibration and inter-comparison: Ship-board results, *J. Atmos. Ocean. Tech,* submitted, 2002

Jessup, A. T., and R. A. Fogelberg, CIRIMS: Calibrated Infrared In situ Measurement System, *J. Atmos. Ocean. Tech,* to be submitted, 2003.

Articles in Proceedings

Jessup, A. T., R. A. Fogelberg, and P. Minnett, Autonomous shipboard radiometer system for in situ validation of satellite SST, Earth Observing Systems VII Conference, Int. Symp. Optical Sci. and Tech., SPIE, Seattle, July, 2002.

Jessup, A. T., CIRIMS: Calibrated Infrared In situ Measurement System (Invited Talk), International Geoscience and Remote Sensing Symposium, Hamburg, IEEE, 1999.

Confererence Presentations

Jessup, A. T., R. A. Fogelberg, M. Welch, J. Hare, R. Weller, C. Fairall, Shipboard underway measurements of near surface temperature with through-the-hull sensors, AGU Ocean Sci. Mtg., Honolulu, 2002.
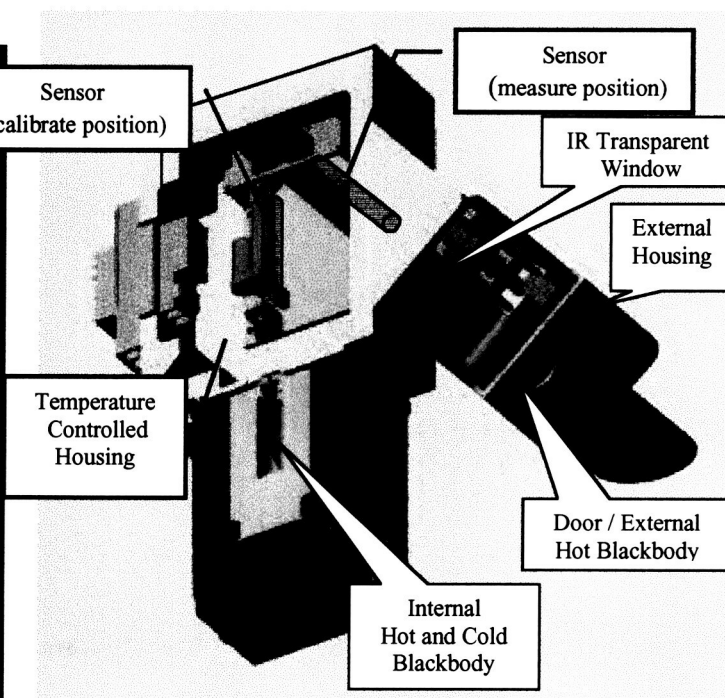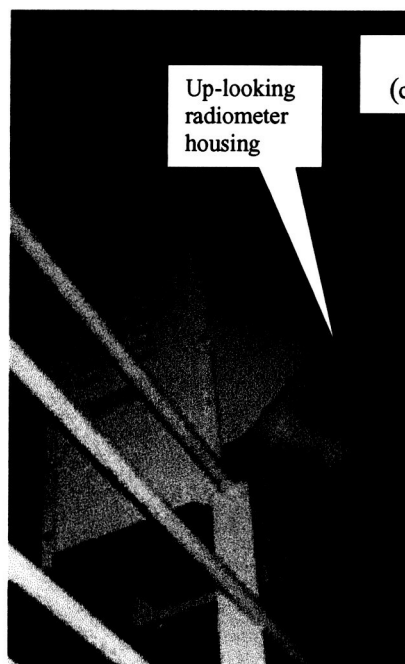
Figure. 1. Photograph of CIRIMS housing deployed along ship railing.

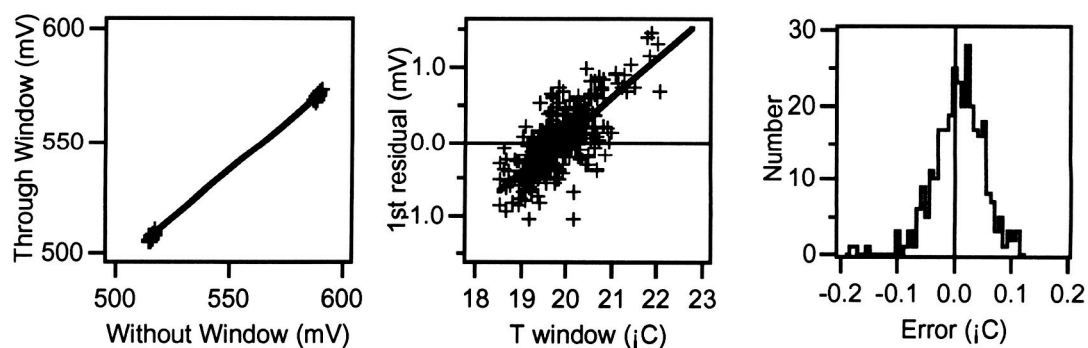Figure 2. Engineering drawing of CIRIMS showing key internal components.

Figure 3. Steps in window correction using the external blackbody. (a) Regression of L_{window} vs L_{no_window} removes attenuation, (b) regression of 1st residual vs T_{window} removes emission (slope) and reflection (offset). The standard deviation of the 2nd residual is equal to 0.04 ¡C and is a measure of the window correction.
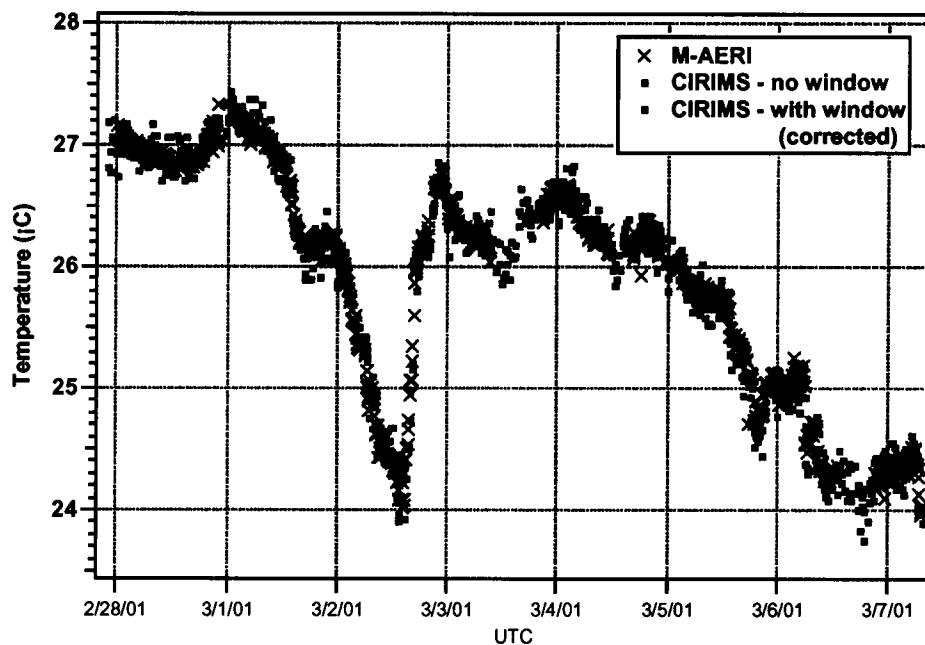
Figure 4. Time series of skin SST measured by M-AERI and CIRIMS over an 8-day period on the GasEx 2001 cruise showing results with and without the IR transparent window in use.
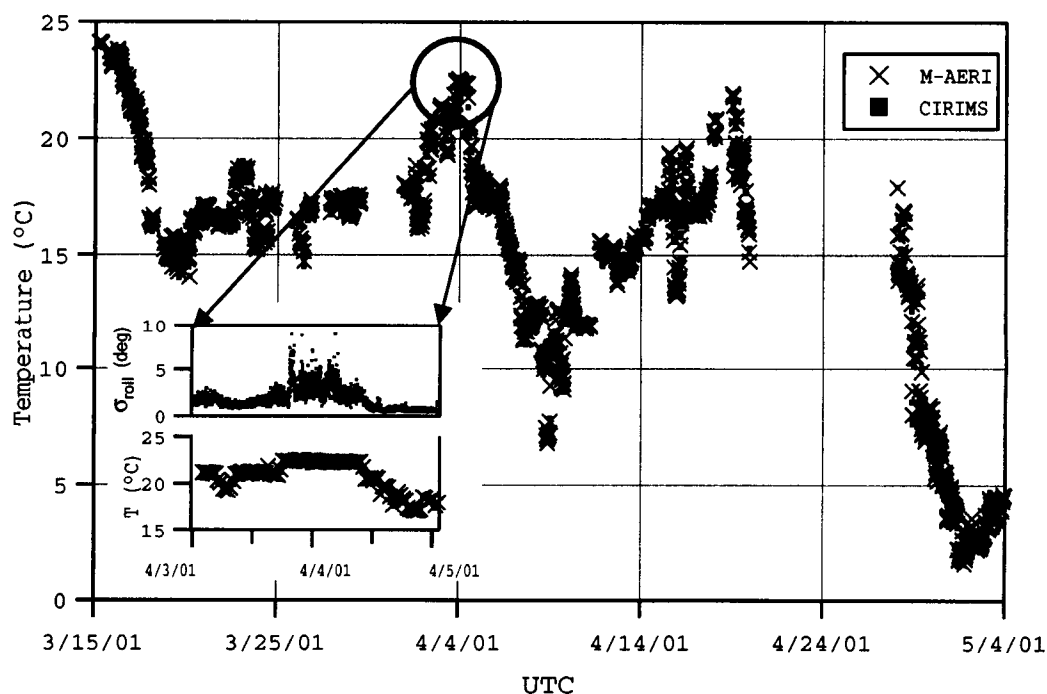

Figure 5. Time series of skin SST for M-AERI and CIRIMS over a 50-day period on the *Brown* from Hawaii to Alaska. The 2-day period of detail shows that that an increased difference is correlated with increased ship roll due to rough conditions.