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# International Teams in Space Science

# Generation of Climate Data Records of Sea-Surface Temperature from Current and Future Satellite Radiometers

**Report of the First Workshop**

**March 26-30, 2012**

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# Abstract

This report summarizes the presentations and discussions at the First Workshop of the International Team on the *Generation of Climate Data Records of Sea-Surface Temperature from Current and Future Satellite Radiometers*. The Workshop was held at the ISSI from March 26 to 30, 2012. The purpose of the presentations was to ensure that all of the Team Members were all cognizant of the current state of the field, irrespective of their own specialties. The discussions were focused on how best to move forward with establishing the justification of the term Climate Data Record when applied to Sea-Surface Temperatures derived from measurements of satellite radiometers. A number of particular research areas that need attention were identified.

## Disclaimer

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# 1 Workshop Participants

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|---|---|
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| Dr Gary Wick | NOAA Earth System Research Laboratory, USA |
| Mr Werenfrid Wimmer | University of Southampton, UK |
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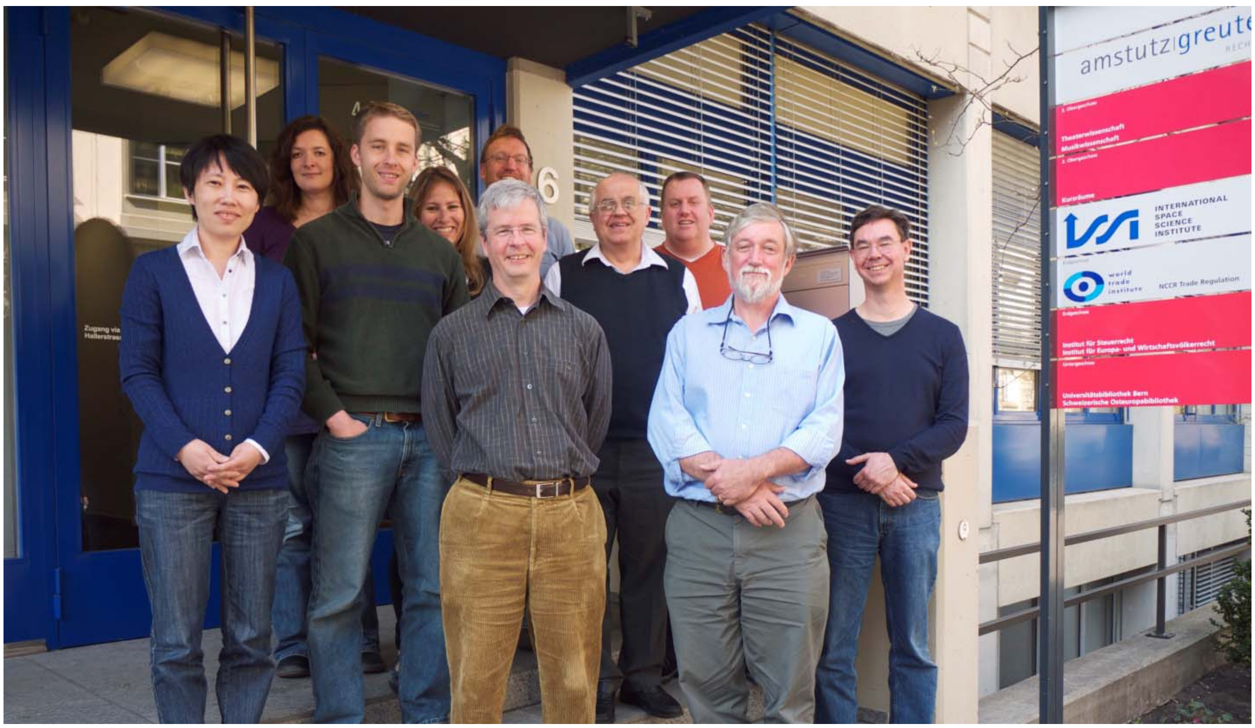



Participants (left to right): Lei Guan, Anne O’Carroll, Chris Wilson, Sandra Castro, Werenfrid Wimmer (behind), Gary Wick, Theo Theocharous, Gary Corlett, Peter Minnett, and Tim Nightingale.

# 2 Introduction

The first Workshop of the ISSI Study Project on the *Generation of Climate Data Records (CDRs) of Sea-Surface Temperature (SST) from current and future satellite radiometers* was held at the ISSI in Bern, Switzerland on March 26-30, 2012. The goals of this ISSI Study Project are to:

1. Review the results of the three Miami infrared workshops and lay the groundwork for the next series of workshops to be held in the USA or Europe.
2. Review the current "state of the art" of satellite SST retrieval uncertainties, and identify the contributions to the satellite-derived uncertainty budget from the validating radiometers, and from the method of validation.
3. Revisit the specifications for future SST validation radiometers.
4. Establish and publish a Best Practices Handbook for validation of satellite-derived SSTs.
5. Ensure the steps to establishing SST CDRs are rigorous and well-understood by those involved in this activity.
6. Make longer term, coordinated plans to validate new satellite radiometers – VIIRS on NPP and JPSS, and SLSTR on Sentinel-3.
7. Coordinate the validation of the satellite-derived SSTs within the framework of the CEOS QA4EO.
8. Examine the initial validation results of the VIIRS on NPP.
9. Finalize publications arising from the Study Projects.

Much of the fundamental research and field programs that provide the framework of the ISSI Study Project are funded from national sources. The research and the transition of results into the operational community is facilitated through the Group for High Resolution SST (GHRSST; Donlon et al., 2009) in which any of the participants in the Study Project are active. A newly constituted SST Science Team, formed under aegis of the NASA Physical Oceanography Program, provides a loose framework and discussion forum for a large group of active researchers. The role of this ISSI Study Project is to coordinate the effort and facilitate activities of a small subgroup of the satellite SST community concerned with the generation of CDRs of SST.

Unlike many critical parameters in the earth's climate system, the SST is a well-defined variable with a correspondence to an SI standard unit. It has been declared an Essential Climate Variable. Thus, the generation of Climate Data Records of SST is both of great importance and also tractable, at least in principle. In practice a pathway exists if the SST retrieval uncertainties are determined using accurate ship-based radiometers with calibration traceable to National Metrology Institute (NMI) standards, such as those maintained by the National Physical Laboratory (NPL) in the UK and the National Institute of Standards and Technology (NIST) in the USA.

Time series of measurements intended for use in Climate Research are referred to as "Climate Data Records" (CDRs), which have been defined as "a data set designed to enable study and assessment of long-term climate change, with 'long-term' meaning year-to-year and decade-to-decade change. Climate research often involves the detection of small changes against a background of intense, short-term variations" (NRC, 2000). It is important to continue validation efforts over the lifetimes of the spacecraft sensors to ensure that the effects of degradation of the instruments in orbit are not misinterpreted as being caused by environmental signals (NRC, 2000). In generating time series of surface temperatures that span several satellite missions, the role of validation includes providing the necessary continuity in the derived fields.

The ISSI Study Project builds on a series of three infrared radiometers workshops held at the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, in collaboration with the US NIST to cross-calibrate ship-mounted, self-calibrating infrared radiometers used to validate the satellite SST. Another objective was to provide traceability of calibration to NMI SI standards. At these workshops, the radiometers were calibrated in the laboratory against black-body calibration devices that were in turn characterized by the NIST Transfer Radiometer (TXR; Rice and Johnson, 1998). The measurements of the radiometers were then compared in the field, either from the RSMAS jetty, or, in the 2001 workshop, on the RSMAS research vessel, the R/V *Walton Smith*. The most recent workshop was held in Miami in May 2009, in coordination with a laboratory blackbody calibration comparison held at the UK National Physical Laboratory (NPL).

# 3 Workshop Objectives

The main Workshop Objectives were to address the list of the Study Project objectives, listed above, and to formulate the contents of the Best Practices Handbook for validation of satellite-derived SSTs using ship based radiometers. The meeting was held partially in plenary, during which presentations were made with open discussions involving all, and partially in break-out groups for more specialized discussions and writing. The workshop agenda is given in the Appendix.

The plenary sessions were intended to ensure all participants were aware of the current state of the field with presentations on the characteristics of satellite radiometers, including those scheduled for launch in the next several years, of ship-board radiometers, and of in situ, sub-surface thermometers. The plenary sessions also included a discussion of the requirements of a CDR, and specifically an SST CDR.

# 4 Background

There are uncertainties associated with all measurements, and the magnitude of the uncertainties imposes restrictions on how the measurements should be applied or interpreted. The uncertainties can result from a variety of causes that relate to the nature of the variable being measured, and how the measurements are made. Furthermore, the techniques employed to assess the magnitude and characteristics of the uncertainties are also prone to error, and thus contribute to the overall uncertainty budget, which is conventionally attributed as a satellite SST retrieval error.

For SST derived from measurements taken by infrared radiometers on earth-observing satellites, the sources of uncertainties can be divided into those that result from the characteristics of the radiometer, and how well the measurements are calibrated, and those that arise from imperfections in the atmospheric correction algorithm that is applied to remove the effects of the intervening atmosphere, including identifying the effects of clouds and aerosols.

The application with the most demanding accuracy requirement is “climate research” where a multi-decadal time series of global SSTs is required to detect small changes that are expected to reveal the response of the climate to changing radiative forcing. Analysis of a time-series of SSTs to search for signatures of climate change will not lead to a convincing result if the uncertainties associated with the measurements are larger than the anticipated signal, which is likely to be <0.2K decade$^{-1}$. This requires 15-20 years of consistent and accurate SSTs with uncertainties <0.3K (Ohring et al., 2005).

The radiance measured in space by infrared radiometers has its origin in the skin layer of the ocean and not in the body of the water below, the "bulk temperature" of which is what is measured by in situ thermometers below the surface. The near-surface temperature gradients result from three distinct processes: the absorption of insolation, the heat exchange with the atmosphere and levels of subsurface turbulent mixing. In conditions of low wind speed, the heat generated in the upper ocean by the absorption of solar radiation is not well mixed through the surface layer, but causes thermal stratification with temperature differences between the uppermost layer of the ocean and the water below. There is a strong diurnal component to the magnitude of these temperature gradients, as well as a dependence on cloud cover, which modulates the insolation, and, importantly, wind speed which influences the turbulent mixing (e.g. Price et al., 1986; Fairall et al., 1996; Gentemann and Minnett, 2008). The surface, skin layer of the ocean, much less than one millimeter thick (Hanafin and Minnett, 2001), is nearly always cooler than the underlying water because the heat flux is nearly always from the ocean to the atmosphere. The heat flow, supplying energy for both the turbulent and radiant heat loss to the atmosphere, is accomplished by molecular conduction through the aqueous side of the interface and this is associated with a temperature gradient in the surface skin layer. The relationship between skin and bulk SSTs just below the surface (at ~5cm) is reasonably well behaved (Minnett et al., 2011). The relationship with deeper bulk temperature, at depths of a few meters where many bulk SST measurements are taken, is the same on average during the night, and during the day for wind speed conditions of >~6ms$^{-1}$ (Donlon et al., 2002). But under low winds the relationship is very variable - vertically, horizontally and temporally (Minnett, 2003; Ward, 2006). The difference between the skin temperature and that measured by a bulk, in situ thermometer is strongly dependent on the depth of the bulk measurement. Use of the bulk temperature for satellite-validation introduces these near-surface gradients into the error budget of the satellite retrieval and leads to an over-estimate of the uncertainties (Kearns et al., 2000). Physical models of the growth and decay of the diurnal thermocline (e.g.Woods and Barkmann, 1986; Price et al., 1986;Schiller and Godfrey, 2005; Gentemann et al., 2009) require high temporal resolution forcing fields to produce reliable predictions, and this is a limitation on their use in relating bulk to skin temperatures for the validation of satellite-derived SSTs.

Given that CDRs of SST span several satellite missions, ensuring that the validating measurements are themselves accurate over the CDR period is of prime importance. Without this assurance, systematic changes in the characteristics of the data sets used to validate the satellite SSTs could be misinterpreted as systematic changes in the upper ocean, and the climate. The only way of ensuring this stability in the calibration of the sensors used to provide the validation data is to have a traceable calibration chain to a national SI temperature standard.

The validation of SSTs with infrared radiometers can be done using instruments mounted on ships (e.g. Kearns et al., 2000; Noyes et al., 2006). For the highest quality data to be used in the validation of satellite SSTs, the ship-based radiometers must be mounted on the ships so they have a clear view of the sea surface ahead of the ship's bow wave. Otherwise they do not take measurements of the skin SST undisturbed by the presence of the ship. Because the emissivity of the sea surface is not unity, a small component of the signal measured by the radiometer when it is directed at the sea surface is reflected sky radiance. To correct for this a measurement of the downwelling atmospheric radiance is required and thus, the validating instrument must be able to view the sky at the same angle to zenith as the sea view is inclined to nadir. The radiometers on the ships must be calibrated throughout the field deployment using internal calibration targets; and the calibration procedure should be checked using laboratory facilities before and after each deployment. Consistency of practice by all groups taking such measurements is important to ensure the generation of accurate and compatible data.

The key to the generation of SST CDRs lies in the calibration of the ship-based radiometers. The path to national temperature standards for satellite-derived SSTs, therefore, is through the calibration of the radiometers used to validate the satellite retrievals, and this requires, and provides, radiometric traceability to national standards. The national reference standards are maintained by the NPL in the UK and NIST in the USA.

As part of the pre-launch characterization of the satellite radiometers, they are carefully calibrated in thermal-vacuum chambers to replicate the conditions on orbit. The pre-launch calibration is traceable to national standards, but the satellite radiometers are never recovered at the end of the mission for recalibration and re-characterization. To ensure traceability to NIST standards, an infrared calibration facility has been set up at RSMAS at the University of Miami. Three international workshops have been held at which many of the ship-board radiometers used to validate satellite-derived SSTs were calibrated using a water-bath blackbody calibration target, built to a NIST design (Fowler, 1995). The internal calibration of ship-board radiometers is assessed by pointing them into the cone of the water-bath blackbody calibration target. The radiation emerging from the cone depends not only on its temperature, as given by the thermometers in the water bath, but also on its emissivity. The emissivity was determined, and hence the calibration system characterized, by the NIST Transfer Radiometer (TXR; Rice and Johnson, 1998), which is the infrared radiometric standard for the NASA Earth Observing System program (Rice and Johnson, 1996). The TXR was also used to characterize the laboratory blackbody calibrators used elsewhere to check the internal calibration of the ship-deployed radiometers (Rice et al., 2004).

# 5 Discussions

## 5.1 Linkage to QA4EO

It is recognized than any effort to develop protocols for producing SST CDRs will have to be made in concert with CEOS WGCV IVOS (Committee on Earth Observation Satellites Working Group on Calibration and Validation Infrared and Visible Optical Sensors), in particular the QA4EO (Quality Assurance Framework for Earth Observation) guidelines. This will require proper and well-documented traceability to SI standards. This renders problematic the practical solution of reliance on the measurements of buoys to assess the uncertainties in the satellite-derived SSTs. This because as at present and certainly in the past, there has been little emphasis on establishing SI-traceability, although there is currently a movement towards rectifying this shortcoming. Theo Theocharous alerted us to the new program focused on "metrology in space" with ~4M€ budget for competitive awards.

## 5.2 Additional satellite SST sensors

Several satellite sensors that have not been widely considered as sources of satellite-derived SSTs were briefly discussed.

Chinese satellites in both polar and geostationary orbits have SST measurement capabilities. The polar orbiting Hai Yang-1B (HY-1B), as its predecessor HY-1A, carries COCTS (Chinese Ocean Color and Temperature Scanner) which has actively cooled thermal infrared ($\lambda$ = 10.3-11.4μm and 11.4-12.5μm) bands with a nadir 1.1 km resolution. Further details can be found at https://directory.eoportal.org/web/eoportal/satellite-missions/h/hy-1b.

The polar-orbiting HY-2A satellite which became operational on March 2, 2012, has a suite of active and passive microwave sensors including an imaging microwave radiometer with low frequency channels sensitive to SST. The spatial resolution at 6.6 GHz is 100km, and 62km at 10.7 GHz. Further details can be found at https://directory.eoportal.org/web/eoportal/satellite-missions/h/hy-2a.

The FengYun-3 (FY-3) polar orbiting meteorological satellite series began in May 2007 with two experimental satellites intended to lead into an operational series beginning in 2013. Part of their payload is a 10-band scanning whisk-broom VIRR (Visible and Infrared Radiometer) that includes infrared channels at 3.55-3.95, 10.3-11.3 and 11.5-12.5 μm. These are standard infrared bands for SST retrievals. The spatial resolution at nadir is 1.1 km on a swath of 2800 km (FOV=±55.4°) which is comparable to AVHRR, although the stated NEΔT at 0.2K is larger than similar imagers. Further details are given at https://directory.eoportal.org/web/eoportal/satellite-missions/f/fy-3.

The FengYun-2 (FY-2) series of geostationary satellites has been operational since October 2004. These are spin-stabilized satellites and carry an S-VISSR (Stretched - Visible and Infrared Spin-Scan Radiometer) which has a single infrared channel with a 10.5 - 12.5 μm bandpass. Without the possibility of a robust atmospheric correction algorithm based on multiple infrared bands, it is unlikely that these data can contribute to an SST CDR.

## 5.3 Additional validation sensors

With funding from NASA, a second generation M-AERI has been developed and is currently being tested. It is also a Fourier-Transform Infrared interferometer with very stable blackbody cavities for internal calibration with the same spectral range and resolution as the original M-AERI. It is smaller and less massive than the original M-AERI and therefore easier to deploy on ships. Taking advantage of developments, including miniaturization of electronics and computers, all of the electronics and the control computer are mounted at the deck unit, with a real-time data display and archiving of data being achieved by a laptop computer connected by an internet cable. It is planned that three of these will be deployed on cruise ships of Royal Caribbean Cruise Lines.

Additional conventional subsurface thermometers that could be used to provide more accurate validation data are a new generation of drifters with temperature resolution, and eventually accuracy, of 0.01K are being developed and deployed. Some Argo profiles have been equipped with a second set of unpumped sensors that function as the profilers break surface and therefore take measurements to within centimeters of the interface and provide measurements of near-surface vertical temperature gradients, and are better suited for satellite SST validation than the standard Argo profilers that cease making measurements at depths between 5 and 10 meters.

Additional sources of potentially high quality validation data that could be used are those provided by the thermometers that are attached to some Continuous Plankton Recorders that are towed by ships in the North Atlantic Ocean and North Sea, and by the thermometers attached to marine mammals and birds.

5.4 Methodology of generating an SST CDR.

The methodology outlined by Minnett and Corlett (Minnett and Corlett, 2012), shown in Figure 1, was used as a starting point for the discussions.

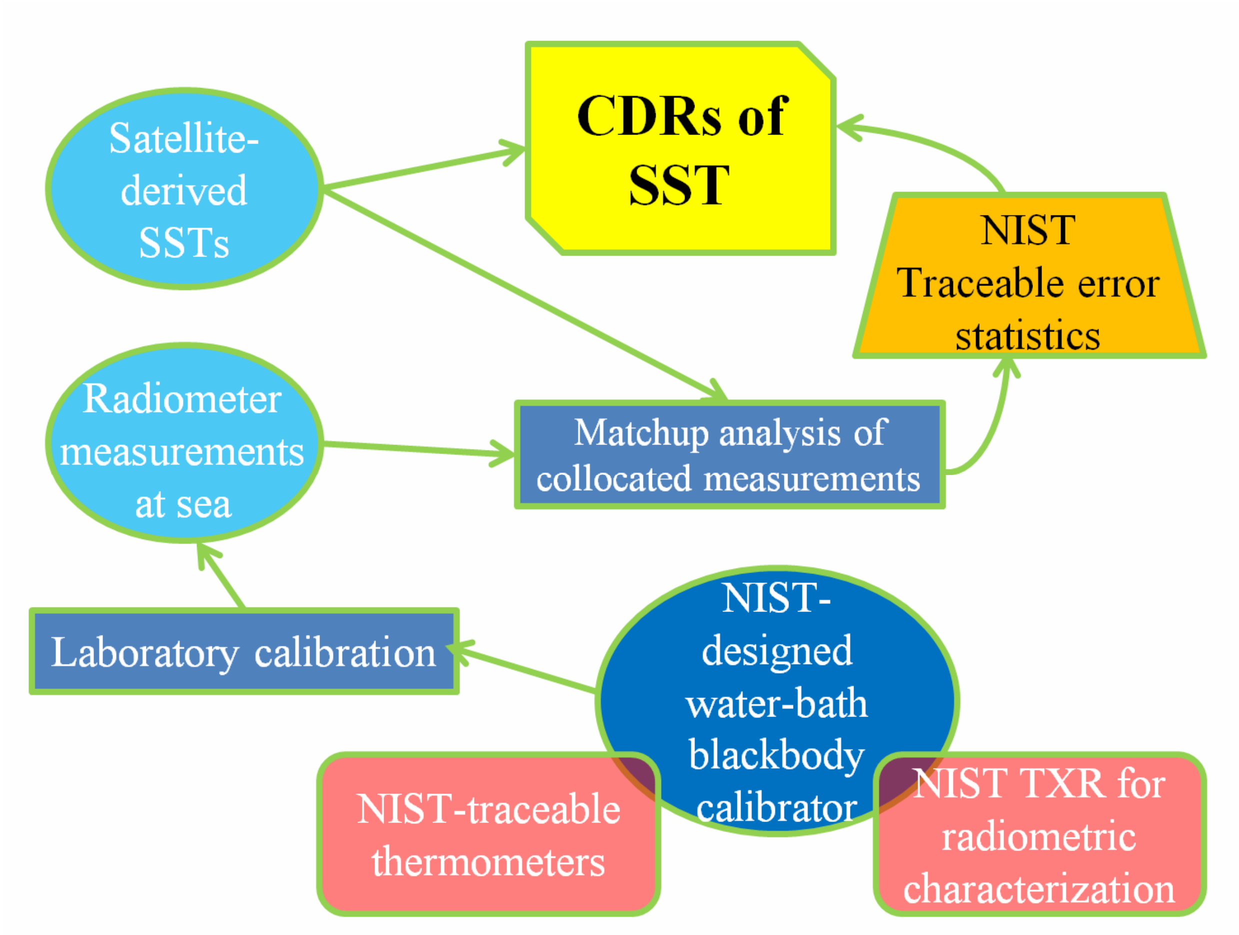



*Figure 1 Schematic flow diagram for the generation of satellite-derived SST CDRs. From Minnett and Corlett, 2012.*

In the course of the discussion it became apparent that there are many steps in this framework that ought to be explicitly shown, and this resulted in the schematic in Figure 2, with a brief summary version, as shown in Figure 3.

The new scheme makes use of satellite-derived SST uncertainties based on match-ups with in situ measurements from drifting buoys and other sources, as these provide a much larger sampling of varying conditions. The crux of the scheme is assessing in a quantitative fashion whether there are significant differences between the error characteristics determined by SI-traceable radiometers, and by comparisons with other non-SI traceable sources.

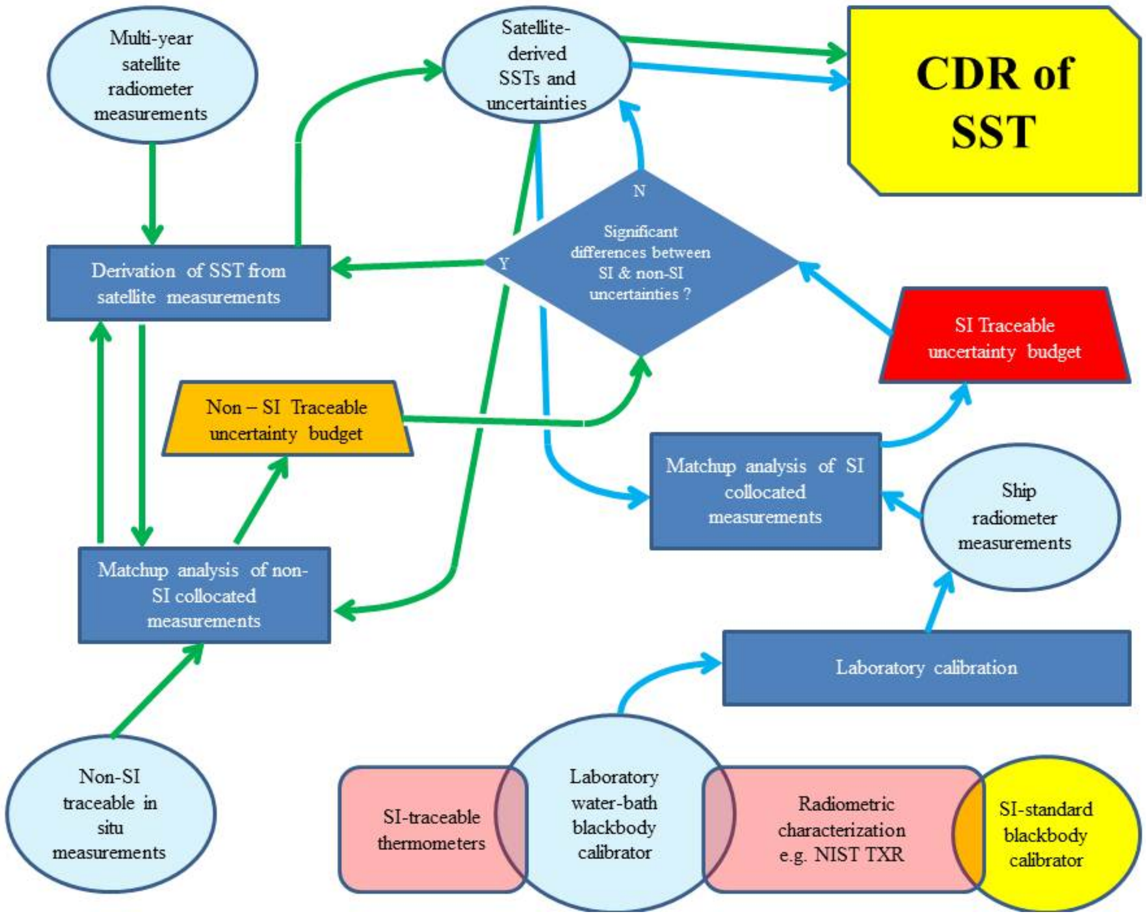



*Figure 2. More complete form of the schematic for generating SST CDRs from satellite and n situ data.*

Theo Theocharous stressed that a clear chain of uncertainty assessment to SI references is a pre-requisite for meeting QA4EO requirements.

To provide continuity between successive satellite missions, a period of overlap long enough to allow meaningful statistics to be generated by three-way matchups is necessary. Gary Corlett pointed out that this is not so straightforward as even with the ATSR series, overlap between ATSR-2 and AATSR is feasible as they are in similar orbits, but there is a day separating the overlaps of orbits between ATSR-1 and ATSR-2.

Gary Wick suggested that the VOS-Clim data could be used to bridge gaps between missions (see 6.2 below), but it was acknowledged that the lack of NIST traceability could be a problem. On a positive note, it was pointed out that the stability of the statistics of the differences between AATSR SSTs and temperatures measured from drifters is encouraging.

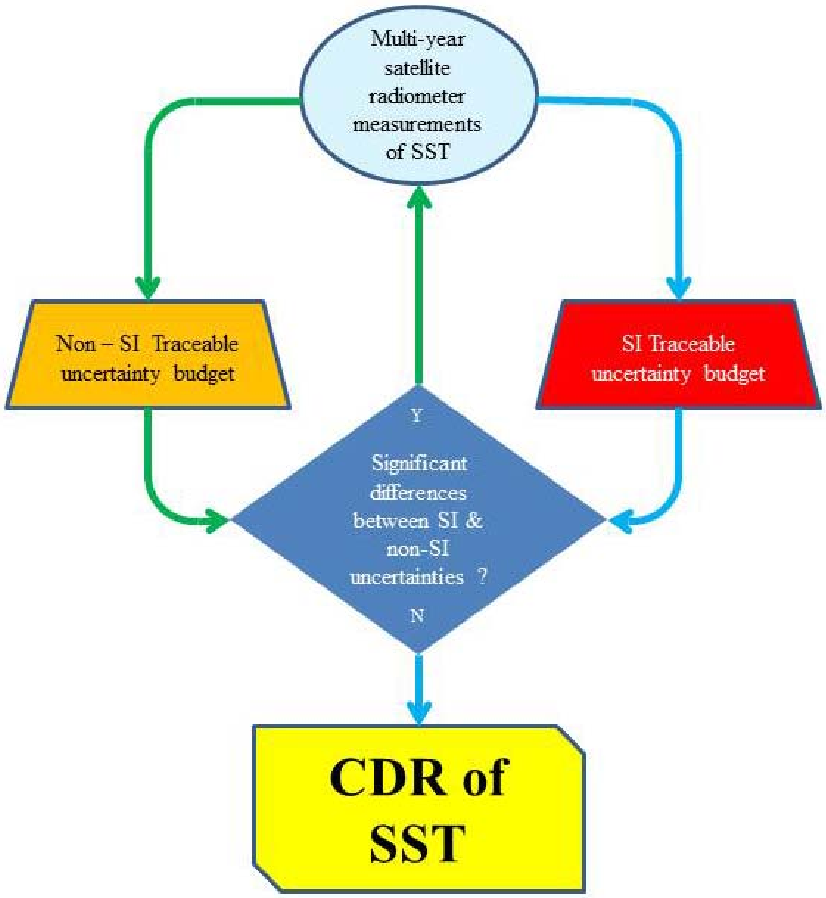



*Figure 3. Simplified schematic for the generation of SST CDRs*

Anne O'Carroll urged us to consider using IASI (Infrared Atmospheric Sounding Interferometer on the EUMETSAT METOP polar orbiting satellites) as a transfer radiometer through Simultaneous Nadir Overpasses (SNOs) with other imaging radiometers. IASI is well-calibrated and has a 12km field of view with 8461 spectral bands which can be averaged according to the relative spectral response function of other filter radiometers to match top-of-atmosphere spectral radiances and brightness temperatures.

### 5.5 Requirements of a Data Archive

An important aspect of an SST CDR is an archive of not only the satellite measurements, but also those of the instruments used in determining the uncertainty characteristics and the traceability to SI standards. These include the measurements of the ship-board radiometers and their presence, and all of the ancillary information, will allow the re-assessment of the uncertainties of the satellite-derived SSTs as new knowledge is brought to the field. This is likely to be in the form of better atmospheric correction algorithms, better models of the skin effect and diurnal thermoclines, and processing of the ship-board measurements.

The data sets would therefore include not only the at-sea measurements but also the pre- and post-cruise calibration measurements taken in controlled conditions in the laboratory, or at-sea using portable calibration devices. A clear chain of comparisons that lead back to SI standards is also an important part of the information to be archived. Copies of reports and publications related to these aspects should also be included.

An important consideration is how to keep track of dataset revisions through reprocessing and file-naming to avoid mistaken use of obsolete data sets. The use of a DOI system should also be considered.

An obvious place to host the Data Archive would be the National Oceanographic Data Archive in the USA which serves as the GHRSST community as the Long Term Stewardship and Reanalysis Facility (LTSRF) to provide data stewardship in perpetuity.

# 6 Research Areas

Several research areas requiring urgent attention were identified and discussed in the Breakout Groups.

## 6.1 Satellite - in situ matchup criteria.

A research topic based on satellite/in situ data matchup criteria has been summarised by the ISSI project. Five areas have been identified by the ISSI team, and these have been described in terms of key scientific questions, potential research tasks, and benefits, below:

### *6.1.1 Sub-pixel variability (4 dimensions)*

Key scientific questions:

- What size observation box is needed to study variability e.g. 11×11 (used by CCI for ATSR data as the minimum size for cloud masking) or perhaps 50×50 (maybe constrained by resources);
- How does the variability within a box relate to other parameters;
- What is the uncertainty contribution for point (in situ) to areal (satellite) collocations;
- How do the uncertainties change with depth and time;
- What are the optimal collocation criteria for matchups in terms of time, distance, and depth differences?

Potential research tasks:

- Use a combination of an n×n MMD of more than one satellite SST source (with differing spatial resolutions or one averaged sensor) and a radiometer transect(s) to study the SST variability of within a box and how it relates to cloud, water vapour, aerosol, SZA, the standard deviation of SSTs in the box;
- Use a combination of GEO, Argo, and ship-board radiometers/moored buoys to analyse variability of uncertainties through depth and time;
- Utilisation of air-borne radiometric measurements to get spatial scales of skin and comparisons with high-resolution surface ship and sub-surface measurements over time.

Benefit:

- Understanding of how constraints based on time difference, differences in depth between comparisons, and spatial collocation can influence the uncertainties of the collocations, and to be able to recommend optimal collocation criteria for matchups in terms of time, distance, and depth.

### *6.1.2 Recommended skin to depth method*

Key scientific questions:

- What is the best skin effect model to use to convert a satellite skin temperature to sub-skin for comparison with in situ data;
- How do limitations of input model data such as wind-speed and fluxes affect the uncertainty contribution of the skin effect model.

Potential research tasks:

- Assess the use of skin effect models (e.g. Fairall et al, 1996, and others) and corrections (e.g. Donlon et al, 2002) including an assessment of the influence on uncertainties of using low-wind speed data (<6m/s) with a -0.17K offset;
- Tuning of skin effect models (e.g, Embury et al., 2012; Horrocks et al, 2003) using skin SSTs from radiometers and $SST_{depth}$ information;
- Use model data and radiosonde profiles and surface measurements to assess uncertainty contributions from different model input data.

Benefits: Recommendation of method of skin effect adjustment in SST CDRs matchup procedure.

### *6.1.3 Recommended diurnal adjustment methodHorrocks et al., 2003*

Key scientific questions: Which model is most appropriate to use for match-ups e.g. POSH (), Kantha-Clayson (Kantha and Clayson, 2004), or others; The recommended model should be appropriate for the input conditions and data, for example, a model based on a basic wind-speed and time function may be the most appropriate where there is no detailed input data.

Potential research tasks: Continuation of work coordinated by the GHRSST-DVWG; Ensure that the analysis is consistent with products available in the CDR framework, for example, where there is 6-hourly NWP input, uncertainties should be consistent with this.

Benefits: Recommendation of method of diurnal adjustment for CDRs.

### *6.1.4 Time difference adjustment*

Key scientific questions: Skin to sub-skin models are applied to the satellite SST data, which are then compared to in situ data taken at a different time, therefore it is necessary to relate the time of the in situ measurement to the time of the satellite measurement, and the best practice for this process should be defined.

Potential research tasks: Use a diurnal variation model coupled with the satellite skin to in situ sub-skin differences over a defined time window to understand the variation of uncertainties of the diurnal model with time; Explore potential to do uniform generalised time depth comparisons based on available environmental/atmospheric forcing data.

Benefits: Definition of a reference time for consistency between all CDRs; Recommend method to convert in situ time and temperature to satellite time; Understand what is the maximum time window.

#### *6.1.5 Estimation of contaminant uncertainty using variable spatial coverage*

Key scientific questions: Derive a method of estimating cloud contaminant uncertainty for use within uncertainty models.

Potential research tasks: By separating a matchup window into 1 hour blocks in a 24 hour period, analyse the statistics for a different number of clear pixels in an n×n box, with repeated validations, and produce a method for estimating the cloud contaminant uncertainty. This would be a challenging task as time and depth adjustments would have to be performed for each pixel for each hour. The method of deriving the uncertainty could then be included in an uncertainty model based on the number of clear pixels within a box.

Benefits: The method to derive cloud contaminant uncertainty can be used within an uncertainty model with input information needed based on the number of clear pixels within a box.

#### *6.1.6 Summary of high-priority tasks*

- Investigation of sub-pixel variability and uncertainty to understand spatial scales of SST through time and at different depths.
- Estimation of the cloud contaminant uncertainty.
- Assessment of uncertainty contributions from different model input data for skin to depth models.
- Perform uniform generalised time depth comparisons based on available environmental/atmospheric forcing data to define the best practice for relating the time of the in situ measurement to the time of the satellite measurement.

### 6.2 Coastal Moorings

The goal of this research area is to evaluate whether coastal moored buoys can be reliably utilized for validation of satellite SST CDR products.

#### *6.2.1 Introduction/Justification*

SST from coastal moored buoys have traditionally been excluded from satellite SST derivation/validation activities. These buoys have associated higher uncertainty levels than non-coastal moorings and drifters. Recent studies (Castro et al., 2012) suggest that, for at least US NDBC coastal moorings, this uncertainty is geophysical in origin, and might be linked to complex coastal dynamics, such as coastal currents with upwelling. In particular, NDBC moorings in the Pacific coast of the USA present high variability from May to September, coincident with the upwelling of the California Current System. NDBC buoys in the Gulf of Maine of the USA have similar seasonal variability coincident with complex dynamical processes in that region. These moorings could be of importance for validating an SST CDR, since they seem capable of resolving the small-scale coastal variability and complex ocean dynamics, offering the potential for improving poorly parameterized coastal SSTs. The moorings also have long data records that go back to the 1990's with a steady increase in annual deployments driven by need of weather warning stations in coastal regions and for initializing NWP models. Unlike tropical moored buoys, coastal moorings are serviced more regularly, and at least for the case of the coastal moorings operated by NOAA (NDBC and partners), data from the previous month undergo additional quality control in addition to the automated real time QC prior to archival. More importantly, they are the only viable source of validation data given the unique measuring challenges of the coastal environment, and the fact that drifters are rapidly flushed out of the coastal waters.

Preliminary comparisons indicate that coastal small-scale variability is largely absent from SST analyses (satellite SST L4 products), where large discrepancies are present when the analyzed fields are compared with SST measurements from coastal moored buoys. Initial comparisons with MODIS SSTs, however, indicate smaller or no discrepancies exist at finer scales. This opens many questions as to whether: (a) coastal variability has associated spatial scales that are missing from coarse resolution products, (b) coastal variability is smoothed out when multiple SST products are merged, or (c) the retrieval algorithms have deficiencies in coastal regions because of anomalous atmospheric conditions or the lack of appropriate data.

These results suggest possible directions for additional detailed research before we can state recommendations for the treatment of high environmental variability regions such as fronts and coastal areas, and hence, of higher uncertainty. General scientific questions include:

- Sources of the high uncertainty level in comparisons with coastal moored buoys: Is the high uncertainty the result of geophysical variability or compromised buoy performance?
- If coastal moored buoys are actually resolving small-scale dynamics not resolved at the resolution of the satellite SST products, can they be effectively integrated in the retrieval and validation chain and, in particular, in the validation of an SST CDR?
- What should be the recommended procedure for regions/conditions that represent a measurement challenge? Do we favor the exclusion of coastal moored buoys such is currently being done or can they be used under some careful guidelines in the future?

#### *6.2.2 Specific actions*

Detailed evaluation of time series from individual moorings:

Careful examination of the time series of individual coastal moored buoys should be performed in order to quantify uncertainty levels associated with these buoys and evaluate discrepancies with individual satellite SST products. For example, do relative biases exhibit seasonal patterns or other behavior that could be consistent with regional environmental phenomena? Different coastal buoy types might be expected to have different measurement accuracies and challenges, and each type should be considered separately. Stratification of results by individual buoy types, mooring programs, and regions has proven useful.

Identification of potential regional effects affecting the geophysical uncertainties:

Time series of the coastal NDBC moorings demonstrated that their large biases and standard deviations were not constant instrumental effects, but rather were tied to well-defined seasonal dynamical coastal processes. This study should be extended to other coastal moored buoy programs, with emphasis on those located in challenging measuring environments. Variation of data along with coincident ancillary data such as wind speed (e.g. upwelling favorable regions) should provide further insights in the geophysical nature of the high uncertainty levels in coastal moorings.

Stratification of moored statistics by proximity to coast:

In addition to the inspection of individual time series of SSTs, coastal moored buoy statistics should be stratified by different proximity values to land. The NOAA NESDIS in situ SST quality monitor (iQuam) (http://www.star.nesdis.noaa.gov/sod/sst/iquam) is a valuable resource that can be utilized for preliminary analyses.

Determine if there is a minimum resolution of the satellite product for which use of coastal moorings is valid:

The proximity of buoys to the coast and scales of physical variability may imply a limit on the resolution of satellite SST products that can be reliably compared with coastal moored buoys. Within individual proximity bands, the coarsest resolution product that can be effectively evaluated with the coastal moorings should be determined. The resolution may depend on the type of satellite radiometric measurement as sidelobe contamination and radio frequency interference issues can pose unique problems with microwave SST products near land.

### *6.2.3 Anticipated Results*

Specification of additional QC tests for coastal moorings:

Following the knowledge gained from the scientific questions formulated above and ensuing research, it should be possible to formulate quality control methods that specifically address the challenges of the coastal moored buoys. These should incorporate lessons learned from:

- Derived characteristics of individual buoy types
- Seasonal cycles identified from time series analysis
- Characterization of regional geophysical uncertainties and/or localized dynamical processes from comparisons with ancillary data
- Spatial variability and satellite resolution from multi-sensor matchup intercomparisons.

### *6.2.4 Benefits*

Potential additional in-situ data set for SST validation:

- If proven sufficiently reliable, consideration of coastal moored buoys could potentially add a significant new data source for validation of satellite SST products in important coastal regions where other in situ data (especially drifters) are lacking.

Guideline for treatment of high-variability regions and conditions:

- Whether coastal moored buoys are deemed reliable for satellite SST validation or not, these research tasks should provide guidance in the handling of high-variability regions such as coastal areas and fronts.

## 6.3 Extending satellite-derived SST CDRs before ship-board radiometers

The primary issue in extending the climate data record back in time is the loss of SI-traceable measurements for comparison against the satellite-derived SST products. Is it possible to maintain a continuous chain of traceability backward in time over different satellite sensors? The discussion focused on exploring the available resources for attempting to do this, identifying significant problems and limitations, and considering possible methods to achieve the extension.

Available resources include making use of available alternative in situ measurements, incorporating improved satellite calibration methodologies in the AVHRR era, and utilizing inter-satellite calibration techniques.

Available in situ products include drifting and moored buoys and ship-based measurements including VOS and VOSclim. While all of these are subject to increased uncertainties and lack SI-traceability, we must evaluate whether we can adequately utilize carefully characterized data with these limitations. VOSclim data have been carefully analyzed for potential use in climate applications but are very limited in spatial coverage and are only available over relatively recent periods. Buoy data are more extensive, but are subject to significant changes in their numbers and spatial coverage over time. While individual buoy measurements are subject to large uncertainties, recent analyses have suggested that the average error statistics of the full set of buoy data have remained largely stable. If the time mean of the data can be assumed to be stable extending back into the record, there is potential for the use of these data. A potential approach is discussed in more detail below.

Recent work by Jonathan Mittaz, University of Maryland and NOAA NESDIS, has demonstrated the potential to significantly improve the calibration of earlier AVHRR sensors. The argument for use of AVHRR data in a satellite-derived SST CDR could be significantly strengthened if systematic calibration of the satellite radiometric data can be demonstrated. While some significant issues remain with the availability of accurate pre-launch and spectral response data from early sensors, a path forward appears to exist for more reliable calibration of the AVHRR data record.

The most powerful tool for potential extension of the satellite-derived SST CDR back in time is the use of periods of inter-satellite overlap extending forward to the time of traceable ship-board radiometric measurements. Earlier in the meeting the point was made that one “can’t beat good overlap” of sensors. A choice must be made, however, as to how to utilize the data from the periods of overlap. Comparisons can be done in either radiometric or SST space. Methods making use of simultaneous nadir overpass (SNO) techniques enable rigorous intercomparison of radiometric data desirable for use in construction of a CDR. The techniques however are subject to significant limitations. Any difference in the spectral response of the different sensors degrades the utility of the intercomparison if high spectral resolution data from sensors such as IASI are not available. Additionally, SNO results are largely constrained to higher latitude regions where overlap between satellite swaths is greater. It is unclear whether results derived from these conditions will adequately enable use of data obtained under significantly different atmospheric profiles such as in the tropics. Comparisons in SST space are less rigorous and are subject to differences in retrieval algorithms over time, but provide more representative (though still not necessarily complete) sampling of global variability. Use of SST comparisons will also require careful definition of acceptable collocation criteria. In some cases differences in the equatorial crossing times of the different sensors may not be ideal.

Discussion suggested that studies may need to be performed to determine which approach (or some combination of the two) will enable the best results. While periods of overlap generally exist between earlier AVHRR sensors, work will be needed to determine if the length of the periods are adequate in all cases.

A fundamental limitation of use of inter-satellite overlaps is how to account for any potential sensor degradations outside the periods of satellite overlap. The problem becomes increasingly difficult the farther back in time (and over increasing numbers of sensors) one goes. In these periods it becomes necessary to make use of the available in situ data. Orbital drift is also a specific concern requiring explicit consideration of diurnal warming effects in comparison of satellite and in situ data.

A potential methodology discussed involved the use of in situ data to provide relative information on stability outside the periods of direct overlap. If the overall mean accuracy of buoy data can be assumed to be stable over time (as suggested above) then deviations in mean apparent biases between the satellite SST retrievals and buoy observations could suggest potential changes in the radiometric performance of the satellite radiometers. Careful consideration must be given to possible changes in relative biases due to changes in the spatial sampling of the in situ data with time.

Practical considerations of how to implement a methodology of this type are picked up in a best practices methodology being drafted by Gary Corlett.

### 6.4 Merging satellite SST CDRs with in situ time-series

Satellite SSTs for a potential CDR are available from 1981, with SSTs from AVHRR (with the first split-window channels). Initially the only validation in situ source for climate purposes available for the first decade of SST measurements from space are from moored buoys. Drifting buoys started to be deployed from around the mid-1980's onwards and their numbers gradually increased. From 1991, SSTs from the ATSR series became available in addition to AVHRR, with validation in situ sources available from both moored and drifting buoys. From around 1997, another validation data source became available from ship-board radiometers, with lower uncertainties than the other in situ sources, and much more appropriate for use by a CDR.

SSTs reported from ships are available through this entire period but these data are not of a high enough quality and have too high uncertainties to be used within a CDR process.

In the years following, satellite SSTs also became available from MODIS, TMI, AMSR-E, SEVIRI, IASI and VIIRS, with all having the possibility to be validated with ship-board radiometers.

In order to merge na SST CDR with in situ time-series, one of the most important considerations is how to characterize and understand the uncertainties over and beyond overlap periods of different satellites (either from similar or totally different satellite designs). A traceable data stream is required, such as those from ship-board radiometers to be able to characterize the uncertainties. However, in the period prior to the availability of ship-board radiometers other methods are required such as for the transition to ATSR-1 in 1991, and as such considerations are listed below.

### *6.4.1 Collocation methodology*

The creation of a MMD or MDB should follow GHRSST guidelines and criteria.

A Multi-Matchup Database (MMD) could follow SST CCI guidelines and should include NWP model fields, and store data around the central pixel in an n×n box.

The global standard deviation of errors can be derived from multi-matchup comparisons using n-way techniques.

### *6.4.2 Considerations*

These include:

- Orbital drift of satellites (especially AVHRR); and difference in overpass times (e.g. ATSR's).
- Use of diurnal variation models and considerations of their constraints.
- Volcanic aerosol and desert dust.
- Global, regional, temporal and observational uncertainties.

- Full analysis of overlap period and use of inter-calibration using other satellite data e.g. GSICS.
- Modelling of the skin effect and consideration of in situ measurements at different depths.
- QC of in situ data; buoy black-lists; robust statistics.
- How to deal with sparse in situ data; use of in situ masks.
- Limitations of cloud detection.
- How do uncertainties vary with water vapour and satellite zenith angle.
- Consistent and continual access to stable validation sources e.g. ship-board radiometers; moored buoys; satellite data for inter-calibration.

## 7 Acronyms

| | |
|---|---|
| AATSR | Advanced Along-Track Scanning Radiometer |
| AMBER | Absolute Measurements of Black-body Emitted Radiance |
| ATSR | Along-Track Scanning Radiometer |
| AVHRR | Advanced Very High Resolution Radiometer |
| BIPM | International Bureau of Weights and Measures |
| CDR | Climate Data Record |
| CEOS | Committee on Earth Observation Satellites |
| COCTS | Chinese Ocean Color and Temperature Scanner |
| EUMETSAT | European Organisation for the Exploitation of Meteorological Satellites |
| GPS | Global Positioning System |
| IASI | Infrared Atmospheric Sounding Interferometer |
| IVOS | (CEOS WGCV) Infrared and Visible Optical Sensors |
| JPSS | Joint Polar Satellite System |
| LTSRF | Long Term Stewardship and Reanalysis Facility |
| M-AERI | Marine-Atmospheric Emitted Radiance Interferometer |
| NDBC | National Data Buoy Center |
| NIST | National Institute of Standards and Technology (USA) |
| NMI | National Metrology Institute |
| NOAA | National Oceanic and Atmospheric Administration |
| NPL | National Physical Laboratory |
| QA4EO | Quality Assurance Framework for Earth Observation |
| SI | Système International d'Unités |
| SNO | Simultaneous Nadir Overpass |
| SLSTR | Sea and Land Surface Temperature Radiometer |
| S-VISSR | Stretched - Visible and Infrared Spin-Scan Radiometer |
| TXR | (NIST) Thermal-infrared Transfer Radiometer |
| VIIRS | Visible Infrared Imager Radiometer Suite |
| VOS | Voluntary Observing Ship |
| VOSClim | VOS Climate |
| WGCV | (CEOS) Working Group on Calibration and Validation |

## 8 References


Castro, S. L., G. A. Wick, and W. J. Emery, 2012: Evaluation of the relative performance of sea surface temperature measurements from different types of drifting and moored buoys using satellite-derived reference products. *J. Geophys. Res.*, **117,** C02029.

Donlon, C. J., P. J. Minnett, C. Gentemann, T. J. Nightingale, I. J. Barton, B. Ward, and J. Murray, 2002: Toward improved validation of satellite sea surface skin temperature measurements for climate research. *Journal of Climate*, **15,** 353-369.

Donlon, C. J., and Coauthors, 2009: The GODAE High-Resolution Sea Surface Temperature Pilot Project. *Oceanography*, **22,** 34-45.

Embury, O., C. J. Merchant, and G. K. Corlett, 2012: A reprocessing for climate of sea surface temperature from the along-track scanning radiometers: Initial validation, accounting for skin and diurnal variability effects. *Remote Sensing of Environment*, **116,** 62-78.

Fairall, C., E. Bradley, J. Godfrey, G. Wick, J. Edson, and G. Young, 1996: Cool-skin and warm-layer effects on sea surface temperature. *Journal of Geophysical Research.*, **101,** 1295-1308.

Fowler, J. B., 1995: A third generation water bath based blackbody source. *Journal of Research of the National Institute of Standards and Technology*, **100,** 591-599.

Gentemann, C. L., and P. J. Minnett, 2008: Radiometric measurements of ocean surface thermal variability. *Journal of Geophysical Research*, **113,** C08017.

Gentemann, C. L., P. J. Minnett, and B. Ward, 2009: Profiles of Ocean Surface Heating (POSH): a new model of upper ocean diurnal thermal variability. *Journal of Geophysical Research*, **114,** C07017.

Hanafin, J. A., and P. J. Minnett, 2001: Profiling temperature in the sea surface skin layer using FTIR measurements. *Gas Transfer at Water Surfaces.*, M. A. Donelan, W. M. Drennan, E. S. Saltzmann, and R. Wanninkhof, Eds., American Geophysical Union Monograph, 161-166.

Horrocks, L. A., B. Candy, T. J. Nightingale, R. W. Saunders, A. O'Carroll, and A. R. Harris, 2003: Parameterizations of the ocean skin effect and implications for satellite-based measurement of sea-surface temperature. *Journal of Geophysical Research*, **108,** 3096.

Kantha, L. H., and C. A. Clayson, 2004: On the effect of surface gravity waves on mixing in the oceanic mixed layer. *Ocean Modelling*, **6,** 101-124.

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

Minnett, P. J., 2003: Radiometric measurements of the sea-surface skin temperature - the competing roles of the diurnal thermocline and the cool skin. *International Journal of Remote Sensing*, **24,** 5033-5047.

Minnett, P. J., and G. K. Corlett, 2012: A pathway to generating Climate Data Records of sea-surface temperature from satellite measurements. *Deep Sea Research Part II: Topical Studies in Oceanography*, **77–80,** 44-51.

Minnett, P. J., M. Smith, and B. Ward, 2011: Measurements of the oceanic thermal skin effect. *Deep Sea Research Part II: Topical Studies in Oceanography*, **58,** 861-868.

Noyes, E. J., P. J. Minnett, J. J. Remedios, G. K. Corlett, S. A. Good, and D. T. Llewellyn-Jones, 2006: The Accuracy of the AATSR Sea Surface Temperatures in the Caribbean. *Remote Sensing of Environment*, **101,** 38-51.

NRC, 2000: *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: II. Implementation.* National Academy of Sciences, 82 pp.

Ohring, G., B. Wielicki, R. Spencer, B. Emery, and R. Datla, 2005: Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop. *Bulletin of the American Meteorological Society*, **86,** 1303-1313.

Price, J. F., R. A. Weller, and R. Pinkel, 1986: Diurnal cycling: observations and models of the upper ocean response to diurnal heating, cooling and wind mixing. *Journal of Geophysical Research*, **91,** 8411-8427.

Rice, J. P., and B. C. Johnson, 1996: A NIST Thermal Infrared Transfer Standard Radiometer for the EOS Program. *The Earth Observer*, **8,** 31.

——, 1998: The NIST EOS Thermal-Infrared Transfer Radiometer. *Metrologia*, **35,** 505-509.

Rice, J. P., and Coauthors, 2004: The Miami2001 Infrared Radiometer Calibration and Intercomparison: 1. Laboratory Characterization of Blackbody Targets. *Journal of Atmospheric and Oceanic Technology*, **21,** 258-267.

Schiller, A., and J. S. Godfrey, 2005: A diagnostic model of the diurnal cycle of sea surface temperature for use in coupled ocean-atmosphere models. *Journal of Geophysical Research*, **110,** C11014.

Ward, B., 2006: Near-Surface Ocean Temperature. *Journal of Geophysical Research*, **111,** C02005.

Woods, J. D., and W. Barkmann, 1986: The response of the upper ocean to solar heating. I: The mixed layer. *Quarterly Journal of the Royal Meteorological Society*, **112,** 1-27.

# 9 Appendices

## 9.1 Meeting agenda

Monday, 26 March, 2012

**Welcome**
Local Arrangements - Maurizio Falanga
Introduction of Participants – All
Objectives of the Workshop – Peter Minnett
Discuss & modify agenda - All

**Background – satellite radiometers**
Requirements of Sea-Surface Temperature Climate Data Records – Peter Minnett, Theo Theocharous
Approaches to generating SST CDRs – Peter Minnett
Characteristics of past, current and future radiometers that can contribute to the SST CDR – Gary Corlett, Peter Minnett
Summary of ESRIN Sentinel-3 Cal/Val Team Meeting, 20-22 March, 2012 – Peter Minnett, Gary Corlett

**Background – shipboard radiometers**
Characteristics of shipboard radiometers – Peter Minnett, Werenfrid Wimmer, Tim Nightingale
Calibration requirements – Peter Minnett, Theo Theocharous
Summaries of RSMAS and CEOS workshops – Peter Minnett, Theo Theocharous
Calibration histories of radiometers – Peter Minnett, Werenfrid Wimmer, Tim Nightingale
Deployment – past and future plans – Peter Minnett, Werenfrid Wimmer, Tim Nightingale

**Background – in situ measurements**
Characteristics of in situ temperature measurements - Anne O'Carroll, Gary Corlett
Deployments of in situ temperature measurements, past and future, Gary Corlett

Tuesday, 27 March, 2012

**Discussion of SST CDRs**
Can we justify calling satellite SST fields a CDR? - Peter Minnett, Gary Corlett
Does the identification of satellite uncertainties using ship-board radiometers constitute a CDR? - Peter Minnett
How can the satellite-derived SST CDR be extended back before the deployments of ship-board radiometers? - Gary Wick
How can satellite SST CDRs be merged with in situ SST time series? - Anne O'Carroll
Alignment with QA4EO. - Gary Corlett, Theo Theocharous

**Definition of Breakout Groups – Ship-board radiometry, in situ measurements and more….**

Each group to consider:

Minimum and optimal accuracy requirements and how these can be achieved and demonstrated

Contents of "Best Practices Handbooks" for measurements to be used to validate satellite-derived SSTs

Identify Research areas that need urgent attention.

Wednesday, 28 March, 2012

**Reports of Breakout Groups**

**Data Archiving and distribution**

Define the user requirements for a data archive - Peter Minnett et al

Define minimum requirements of data sets, including metadata for archival data -Tim Nightingale et al

Thursday, 29 March, 2012

**Breakouts -** All

Write sections for Best Practices Report

Write sections for Workshop Report

Develop content for Web Pages

Friday, 30 March, 2012

**Future plans**

Identify problems to be addressed, gaps to be filled - Peter Minnett, Gary Corlett

Requirements of future calibration workshops - Peter Minnett, Gary Corlett

Opportunities for coordinated ship radiometer deployments – Peter Minnett et al.

Outline of peer-reviewed publications arising from this ISSI Study Project – All

"Homework" assignments- All

Dates for next ISSI Workshop -All

## 9.2 Presentations

This section provides the slides used during the workshop. They are presented as six per page, to be read vertically.

The sequence of presentations is:

Generation of Climate Data Records of Sea-Surface Temperature from current and future satellite radiometers

## Goals and Outcomes

ISSI workshop. March 26-30, 2012

# The goals of the ISSI Study Project

1. Review of the results of the three Miami infrared workshops and lay the groundwork for the next series of workshops to be held in the USA or Europe.
2. Review the current "state of the art" of satellite SST retrieval uncertainties, and identify the contributions to the satellite-derived uncertainty budget from the validating radiometers, and from the method of validation.
3. Revisit the specifications for future SST validation radiometers.
4. Establish and publish a Best Practices Handbook for validation of satellite-derived SSTs.
5. Ensure the steps to establishing SST CDRs are rigorous and well-understood by those involved in this activity.
6. Make longer term, coordinated plans to validate new satellite radiometers – VIIRS on NPP and JPSS, and SLSTR on Sentinel-3.
7. Coordinate the validation of the satellite-derived SSTs within the framework of the CEOS QA4EO.
8. Examine the initial validation results of the VIIRS on NPP.
9. Finalize publications arising from the Study Projects.

ISSI workshop. March 26-30, 2012

# Outcomes

- A handbook of Best Practices
- Web pages for conveying results and progress
- Papers submitted to the peer-reviewed literature - potential titles are:
  - "Demonstrating traceability to SI in deriving climate data records: An example using sea-surface temperature"
  - "Accuracy of satellite-derived sea-surface temperatures derived from multi-decadal time series from multiple satellite sensors"

ISSI workshop. March 26-30, 2012

# Goal 1

Review of the results of the three Miami infrared workshops and lay the groundwork for the next series of workshops to be held in the USA or Europe.

Published papers (Miami 2):

Rice, Jet al, 2004: The Miami2001 Infrared Radiometer Calibration and Intercomparison: 1. Laboratory Characterization of Blackbody Targets. *Journal of Atmospheric and Oceanic Technology,* ***21, 258-267.***

Barton, I. J., P. J. Minnett, C. J. Donlon, S. J. Hook, A. T. Jessup, K. A. Maillet, and T. J. Nightingale, 2004: The Miami2001 infrared radiometer calibration and inter-comparison: 2. Ship comparisons. *Journal of Atmospheric and Oceanic Technology,* ***21, 268-283.***

Published Reports (Miami 3):

Theocharous, E., E. Usadi, and N. P. Fox, 2010: CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part I: Laboratory and ocean surface temperature comparison of radiation thermometers, National Physical Laboratory, Teddington, Middlesex, UK, 130 pp.

Theocharous, E. and N. P. Fox, 2010: CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part II: Laboratory comparison of the brightness temperature of blackbodies, National Physical Laboratory, Teddington, Middlesex, UK, 43 pp.

ISSI workshop. March 26-30, 2012

# Goal 2

Review the current "state of the art" of satellite SST retrieval uncertainties, and identify the contributions to the satellite-derived uncertainty budget from the validating radiometers, and from the method of validation.

This is a moving target……

ISSI workshop. March 26-30, 2012

# Goal 3

Revisit the specifications for future SST validation radiometers.

Presentations to follow on current ship-board radiometers….

ISSI workshop. March 26-30, 2012

## Goal 4

Establish and publish a Best Practices Handbook for validation of satellite-derived SSTs.

Contents to be assessed during this meeting

ISSI workshop. March 26-30, 2012

## Goal 5

Ensure the steps to establishing SST CDRs are rigorous and well-understood by those involved in this activity.

To be determined through this series of meetings. Several approaches may be feasible, desirable, or simply necessary

ISSI workshop. March 26-30, 2012

## Goal 6

Make longer term, coordinated plans to validate new satellite radiometers – VIIRS on NPP and JPSS, and SLSTR on Sentinel-3.

•On a person-to-person basis, avoid unnecessary duplication, but still allow comparative measurements.
•How to identify areas or conditions needing attention?
•Include AMSR-2 on GCOM-W
•Data sharing
•Quality assurance
•Data bases (on-line?)

ISSI workshop. March 26-30, 2012

## Goal 7

Coordinate the validation of the satellite-derived SSTs within the framework of the CEOS QA4EO.

- Outcome of these workshops

ISSI workshop. March 26-30, 2012

## Goal 8

Examine the initial validation results of the VIIRS on NPP.

- Preliminary results can be presented here

ISSI workshop. March 26-30, 2012

## Goal 9

Finalize publications arising from the Study Projects.

- Outcome of these workshops

ISSI workshop. March 26-30, 2012

# Requirements of a Climate Data Record



# Reference to SI-standards

Although it seems self-evident, it was only in 1995 at the 20th Conférence Générale des Poids et Mesures that it was recommended that "*those responsible for studies of Earth resources, the environment, human well-being and related issues ensure that measurements made within their programs are in terms of well-characterized SI units so that they are reliable in the long term, are comparable world-wide and are linked to other areas of science and technology through the world's measurement system established and maintained under the Convention du Mètre*" (BIPM 1995).

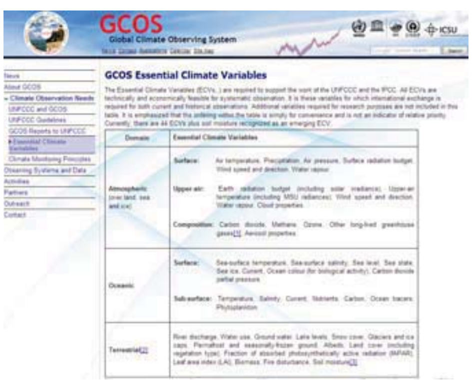
This lays the foundation for relating environmental measurements to SI (Système International d'Unités) standards, which, in the USA, are maintained by the National Institute of Standards and Technology (NIST) and in the UK by the National Physical Laboratory (NPL).

This recommendation is the basis of the feasibility Climate Data Records of SST as by following it, temperature measurements from different sources taken over a period of time can be combined in a meaningful manner.

(http://www.bipm.org/en/CGPM/db/20/1/)



# Essential Climate Variables



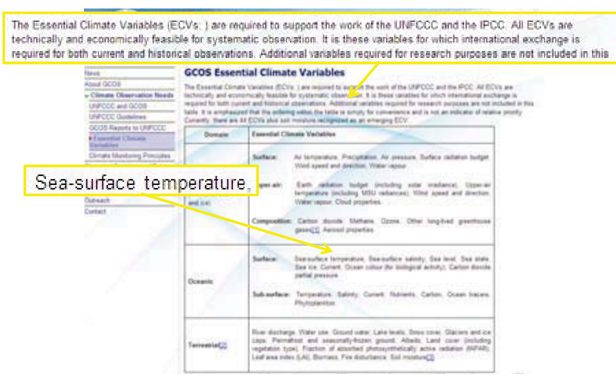



# Satellite-derived CDRs

- National Academy of Sciences Report (*NRC, 2000*): "***a data set designed to enable study and assessment of long-term climate change***, *with 'long-term' meaning year-to-year and decade-to-decade change. Climate research often involves the* ***detection of small changes against a background of intense, short-term variations***."
- "*Calibration and validation should be considered as a process that encompasses the entire system, from the sensor performance to the derivation of the data products. The process can be considered to consist of five steps:*
  - *instrument characterization,*
  - *sensor calibration,*
  - *calibration verification,*
  - *data quality assessment, and*
  - *data product validation.*"



# Essential Climate Variables






# NIST Traceability

*Long-term validation, by a suite of sensors, can best be achieved if each has traceability to a National Reference Standard*

- Satellite radiometers require validation traceability to radiometric as well as thermometric references.
- NIST traceable thermometers are off-the-shelf items - not so for radiometers.

## Desired SST CDR uncertainties

- The useful application of all satellite-derived variables depends on a confident determination of uncertainties.
- CDRs of SSTs require most stringent knowledge of the uncertainties:
  - Target accuracies: 0.1K over large areas, stability 0.04K/decade - Ohring et al. (2005) Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop. *Bulletin of the American Meteorological Society* **86**:1303-1313



## The NIST EOS TXR

Unique EOS Standard Cryogenic detectors (liquid $N_2$)
$\lambda$= 5 & 10μm

Rice, J. P. and B. C. Johnson, 1998. The NIST **EOS Thermal-Infrared Transfer Radiometer, *Metrologia*, 35, 505-509.**

**Rice, J.P. et al., 2004. The Miami2001 Infrared R**adiometer Calibration and Intercomparison: 1. Laboratory Characterization of Blackbody Targets. *Journal of Atmospheric and Oceanic Technology*, 21, 258-267

### NIST water-bath black-body calibration target

See: Fowler, J. B., 1995. A third generation water bath based blackbody source, *J. Res. Natl. Inst. Stand. Technol.*, 100, 591-599

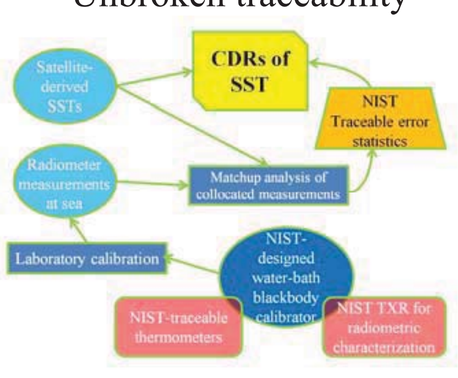


## CDR of SSTs

•Climate Data Records of SST require an **unbroken chain between the satellite measurement and an SI Temperature standard**.
•Prior to launch, the satellite radiometers are calibrated using SI-traceable standards, but post launch it is not currently feasible to check calibration drift using SI-standards.
•Drifting buoys are currently not sufficiently well calibrated for this purpose, and very few are recovered to check for calibration drift during deployment .
•A calibration chain can be established using ship-based radiometers to validate the skin SST retrievals, provided the ship-based radiometers have SI-traceable calibration.
•This is achieved using the NIST TXR or NPL AMBER to characterize the laboratory black-body calibration targets to check the internal calibration of the ship-based radiometers.



## Unbroken traceability

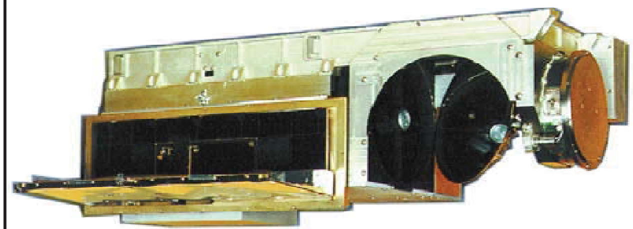



Minnett, P. J. and G. K. Corlett, 2012: A Pathway to Generating Climate Data Records of Sea-Surface Temperature from Satellite Measurements. *Deep-Sea Research II*, Accepted.

# Characteristics of spacecraft radiometers that can contribute to SST CDRs



## AVHRR- Advanced Very High Resolution Radiometer



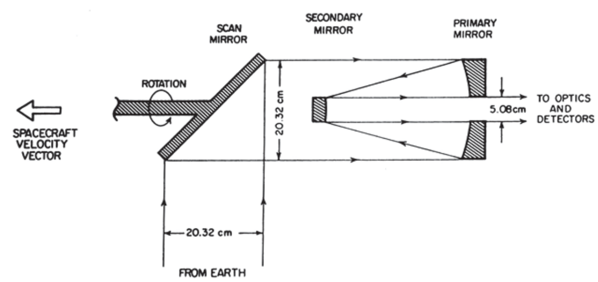


## Satellite infrared radiometers for SST – polar orbiters

| | |
|---|---|
| AVHRR - | Broad swath (>3000km), ~1km$^2$ resolution, operational, 1bb + space view for in-flight calibration, 10-bit digitization, 3 ir SST channels. |
| (A)ATSR - | Narrow swath (~500km), ~1km$^2$ resolution, "experimental", 2bb for in-flight calibration,<br>12-bit digitization, 3 ir SST channels, with two views. |
| MODIS - | Broad swath (~2330km), ~1km$^2$ resolution, pre-operational, 1bb + space view for in-flight calibration, 12-bit digitization, 5 ir SST channels |
| VIIRS- | Broad swath (~3000km), ~0.75 km resolution, operational, 1bb + space view for in-flight calibration, 12-bit digitization, 4 ir SST channels. |



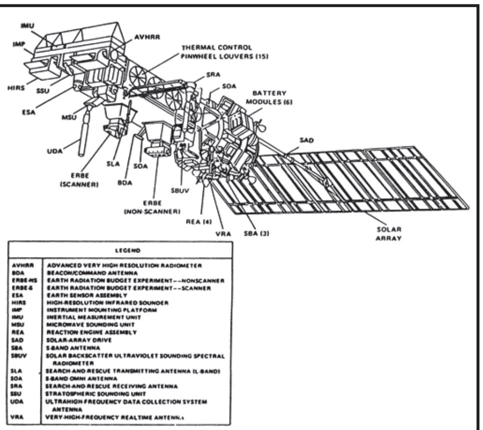
## AVHRR telescope





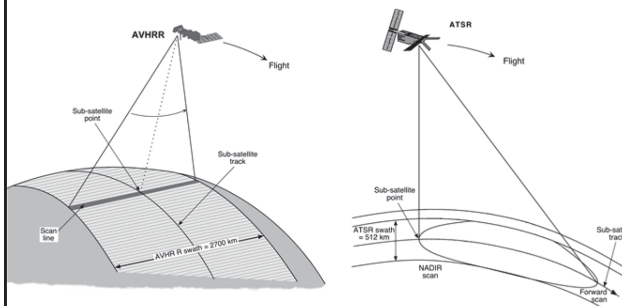

## Advanced TIROS satellite

## NOAA-n series






## Path length effects and scan patterns




From: Minnett, P. J., 2001. Satellite Remote Sensing of Sea Surface Temperature, in "Encyclopedia of Ocean Sciences" Edited by J. Steele, S. Thorpe and K. Turekian, Academic Press Ltd., London, U.K., pp 2552-2563.

## Calibration of infrared radiometers

- In-flight measurements every mirror scan of:
  - A black body at a known temperature
  - A view of cold space
  - Or of two on-board black bodies
- These give a two point calibration for converting the digital outputs of the detectors to calibrated channel radiances
- Integrals of radiance across each channel's relative spectral response functions to convert calibrated channel radiances to brightness temperatures

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## Advanced Along Track Scanning Radiometer

- **Imaging radiometer**
- **Designed to measure global sea-surface temperature (SST) at the levels of precision and accuracy required for climate research (better than 0.3° K; 1σ)**
- **~20 year record of accurate SST measurements on a global scale**

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## AVHRR system parameters

TABLE 4.3. Advanced Very High Resolution Radiometer (AVHRR) System Parameters

| Parameter | AVHRR/1 | AVHRR/2 |
|---|---|---|
| Telescope | | |
| Type | Afocal Mersenne | Afocal Mersenne |
| Diameter | 20.32 cm | 20.32 cm |
| Field of view | 1.3 mrad | 1.3 mrad |
| Ground resolution[a] | | |
| Nadir | 1.1 km | 1.1 km |
| End of scan | 2.3 × 6.4 km | 2.3 × 6.4 km |
| Scan mirror rotation | $12\pi$ rad $s^{-1}$ | $12\pi$ rad $s^{-1}$ |
| Data sampling rate | 40 kHz | 40 kHz |
| Scan line | | |
| Angle from nadir | ±55.3° | ±55.3° |
| Distance from nadir | ±1500 km | ±1500 km |
| Steps | 2048 | 2048 |
| Channels[b] (half-power points) | | |
| 1 | 0.55–0.68 μm | 0.58–0.68 μm |
| 2 | 0.75–1.10 μm | 0.725–1.10 μm |
| 3 | 3.55–3.93 μm | 3.55–3.93 μm |
| 4 | 10.5–11.5 μm | 10.3–11.3 μm |
| 5 | channel 4 repeated | 11.5–12.5 μm |
| Data rate[c] | 750 kbits $s^{-1}$ | 750 kbits $s^{-1}$ |
| Instrument size | 27 × 37 × 79 cm | 27 × 37 × 79 cm |
| Instrument mass | 30 kg | 30 kg |
| Power consumption | 29 W | 29 W |

[a] From an orbital height of 850 km.
[b] Changes slightly with satellite (see Kidwell, 1986).
[c] Kilobits per second.

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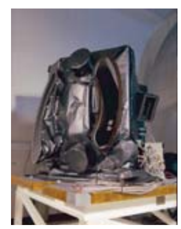
## AATSR Principles of Operation

- **7 spectral channels**
  - **3 IR (3.7 µm, 11 µm, 12 µm)**
  - **4 Vis/NIR (0.55 µm, 0.67 µm, 0.87 µm, 1.6 µm)**
- **500 km swath**
- **1 km IFOV at nadir**
- **Dual view (nadir and 55° to nadir)**
- **On board calibration**
  - **2 on-board black bodies for IR calibration**
  - **VISCAL unit for visible channel calibration**
- **Stirling Cycle Coolers, cooling low noise detectors to 80K, for optimum signal-to-noise ratios**



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## (A)ATSR

- ATSR – Along-Track Scanning Radiometer
  - ASTR on ERS-1
  - ATSR-2 on ERS-2
  - AATSR (Advanced ATSR) on Envisat
- Only spacecraft radiometer optimized for SST measurements

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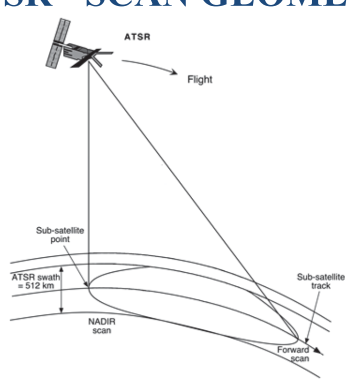
## AATSR - SCAN GEOMETRY

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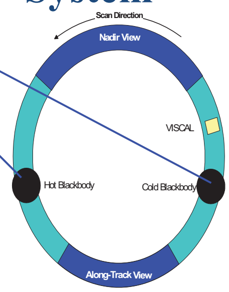
# AATSR Scan sequence – showing on-board Calibration System

Blackbodies viewed every scan.



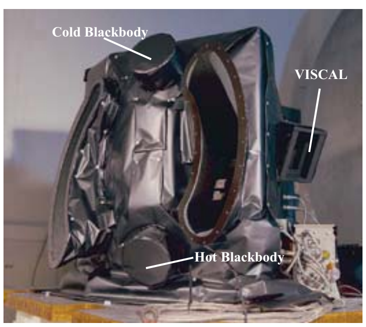



# MODIS Bands - I

| Primary Use | Band | Bandwidth[1] | Spectral Radiance[2] | Required SNR[3] |
|---|---|---|---|---|
| Land/Cloud Boundaries | 1 | 620 - 670 | 21.8 | 128 |
| | 2 | 841 - 876 | 24.7 | 201 |
| Land/Cloud Properties | 3 | 459 - 479 | 35.3 | 243 |
| | 4 | 545 - 565 | 29.0 | 228 |
| | 5 | 1230 - 1250 | 5.4 | 74 |
| | 6 | 1628 - 1652 | 7.3 | 275 |
| | 7 | 2105 - 2155 | 1.0 | 110 |
| Ocean Color/ Phytoplankton/ Biogeochemistry | 8 | 405 - 420 | 44.9 | 880 |
| | 9 | 438 - 448 | 41.9 | 838 |
| | 10 | 483 - 493 | 32.1 | 802 |
| | 11 | 526 - 536 | 27.9 | 754 |
| | 12 | 546 - 556 | 21.0 | 750 |
| | 13 | 662 - 672 | 9.5 | 910 |
| | 14 | 673 - 683 | 8.7 | 1087 |
| | 15 | 743 - 753 | 10.2 | 586 |
| | 16 | 862 - 877 | 6.2 | 516 |
| Atmospheric Water Vapor | 17 | 890 - 920 | 10.0 | 167 |
| | 18 | 931 - 941 | 3.6 | 57 |
| | 19 | 915 - 965 | 15.0 | 250 |



# AATSR – Earth-viewing face






# MODIS Bands - II

| Primary Use | Band | Bandwidth[1] | Spectral Radiance[2] | Required NE[delta]T(K)[4] |
|---|---|---|---|---|
| Surface/Cloud Temperature | 20 | 3.660 - 3.840 | 0.45(300K) | 0.05 |
| | 21 | 3.929 - 3.989 | 2.38(335K) | 2.00 |
| | 22 | 3.929 - 3.989 | 0.67(300K) | 0.07 |
| | 23 | 4.020 - 4.080 | 0.79(300K) | 0.07 |
| Atmospheric Temperature | 24 | 4.433 - 4.498 | 0.17(250K) | 0.25 |
| | 25 | 4.482 - 4.549 | 0.59(275K) | 0.25 |
| Cirrus Clouds Water Vapor | 26 | 1.360 - 1.390 | 6.00 | 150(SNR) |
| | 27 | 6.535 - 6.895 | 1.16(240K) | 0.25 |
| | 28 | 7.175 - 7.475 | 2.18(250K) | 0.25 |
| | 29 | 8.400 - 8.700 | 9.58(300K) | 0.05 |
| Ozone | 30 | 9.580 - 9.880 | 3.69(250K) | 0.25 |
| Surface/Cloud Temperature | 31 | 10.780 - 11.280 | 9.55(300K) | 0.05 |
| | 32 | 11.770 - 12.270 | 8.94(300K) | 0.05 |
| Cloud Top Altitude | 33 | 13.185 - 13.485 | 4.52(260K) | 0.25 |
| | 34 | 13.485 - 13.785 | 3.76(250K) | 0.25 |
| | 35 | 13.785 - 14.085 | 3.11(240K) | 0.25 |
| | 36 | 14.085 - 14.385 | 2.08(220K) | 0.35 |

[1] Bands 1 to 19 are in nm; Bands 20 to 36 are in µm

[2] Spectral Radiance values are ($W/m^2$ -µm-sr)

[3] SNR = Signal-to-noise ratio

[4] NE(delta)T = Noise-equivalent temperature difference



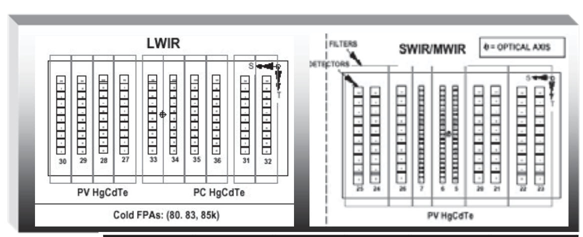
# MODIS: MODerate-Resolution Imaging Spectroradiometer

## *MODIS Technical Specifications*

| | |
|---|---|
| **Orbit:** | 705 km, 10:30 a.m. descending node (AM-1) or 1:30 p.m. ascending node (PM-1), sun-synchronous, near-polar, circular |
| **Scan Rate:** | 20.3 rpm, cross track |
| **Swath Dimensions:** | 2330 km (cross track) by 10 km (along track at nadir) |
| **Telescope:** | 17.78 cm diam. off-axis, afocal (collimated), with intermediate field stop |
| **Size:** | 1.0 x 1.6 x 1.0 m |
| **Weight:** | 250 kg |
| **Power:** | 162.5 W (single orbit average) |
| **Data Rate:** | 10.8 Mbps (peak daytime); 6.2 Mbps (orbital average) |
| **Quantization:** | 12 bits |
| **Spatial Resolution:** | 250 m (bands 1-2)<br>500 m (bands 3-7)<br>1000 m (bands 8-36) |
| **Design Life:** | 6 years |



# Characteristics of MODIS IR Focal Planes SST Product Input Bands




MODIS has 4 focal planes, each band with 10 - 1km detectors:

2 for visible

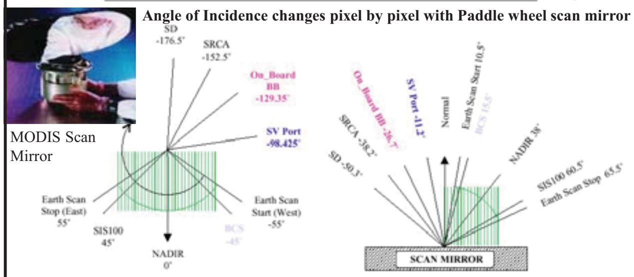
2 for IR

| Band number | Center Wavelength µm | Bandwidth µm | NEΔT at T=300K | SNR at T=300K | Saturation Temperature K |
|---|---|---|---|---|---|
| **Midwave IR** | | | | | |
| 20 | 3.7882 | 0.1826 | 0.026 | 900.0 | 333 |
| 22 | 3.9719 | 0.0882 | 0.030 | 837.5 | 328 |
| 23 | 4.0567 | 0.0878 | 0.026 | 987.5 | 329 |
| **Longwave Thermal IR** | | | | | |
| 31 | 11.0144 | 0.5103 | 0.024 | 2808.8 | 399 |
| 32 | 12.0282 | 0.4935 | 0.040 | 1824.5 | 391 |

* Averaged over ten detectors in each band

## Principal Scan Angles Mapped to Scan Mirror Angles of Incidence

**Angle of Incidence changes pixel by pixel with Paddle wheel scan mirror**

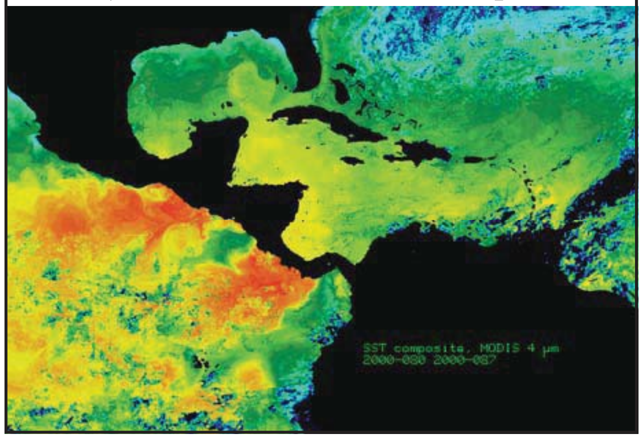



Principal Scan Angles
(Earth View: -55 to 55 )

Angles of Incidence
(Earth View: 10.5 to 65.5)

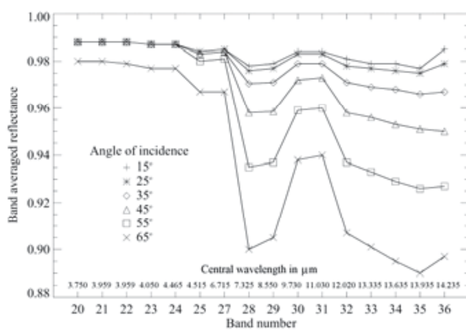


## 4µm SSTs – smaller RVS impact






## Scan Mirror Band Averaged Average Reflectance *vs* Band Number




Terra east side of scan

Note relative change in bands 31,32 (SST) as **angle of incidence** increases

Terra west side of scan



## Suomi-NPP

- Launched on 28 October, 2011.
- Equator crossing - 1:30 p.m.
- Altitude of 824 km.
- 16-day repeat cycle

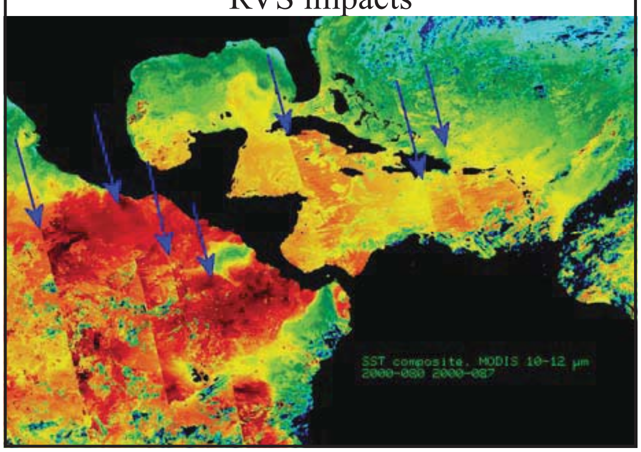
Five key instruments:

- Advanced Technology Microwave Sounder (ATMS)
- Cross-track Infrared Sounder (CrIS)
- Ozone Mapping and Profiler Suite (OMPS)
- Clouds and the Earth's Radiant Energy System (CERES)
- Visible Infrared Imaging Radiometer Suite (VIIRS)

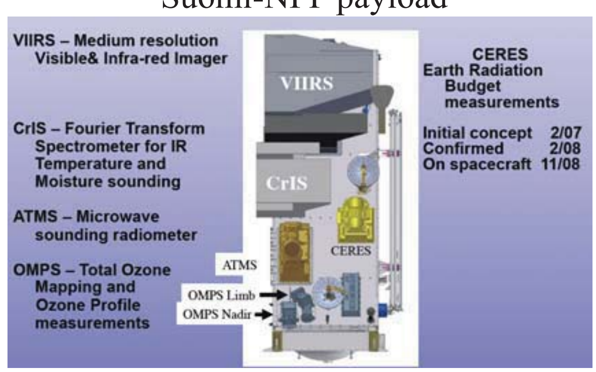
Photo courtesy Ball Aerospace.



## RVS impacts




## Suomi-NPP payload




From http://modis.gsfc.nasa.gov/sci_team/meetings/201001/presentations/plenary/gleason.pdf

# VIIRS

- Rotating telescope with “Half-Angle Mirror” foreoptics
- Spectral Bands:
  - Visible/ Near IR: 9 plus Day/Night Band
  - Mid-Wave IR: 8
  - Long-Wave IR: 4
- Imaging Optics: 18.4 cm Aperture
- 114 cm Focal Length
- Scan Range of earth view: ±56º from nadir
- Swath width: 3000 km

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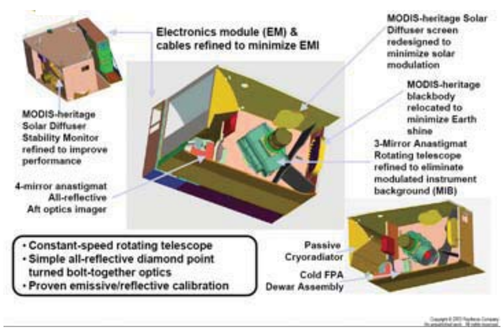
# VIIRS Components

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# VIIRS

Photo courtesy Ball Aerospace.

- VIIRS on NPP/JPSS (operational)
- VIIRS:
  - Multi-spectral scanning radiometer (22 bands between 0.4µm and 12 µm)
  - Nadir resolution ~0.75km; pixel aggregation to try to compensate for pixel growth away from nadir.
  - 12 bit digitization
  - Swath width: 3000 km
- Two “Key Performance Parameters” based on the Integrated Operational Requirements Document (IORD) II
  - **SST and Imagery**

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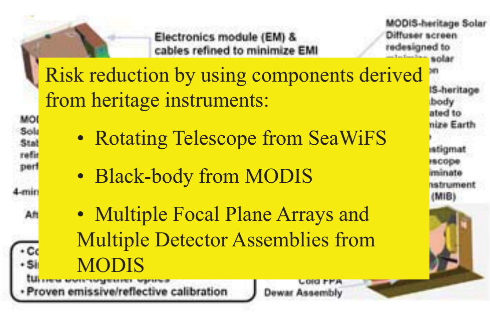
# VIIRS Components



Risk reduction by using components derived from heritage instruments:

- Rotating Telescope from SeaWiFS
- Black-body from MODIS
- Multiple Focal Plane Arrays and Multiple Detector Assemblies from MODIS

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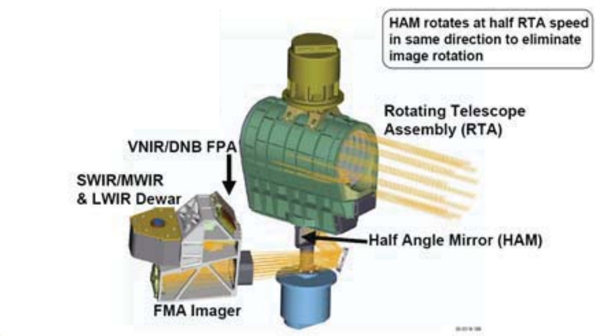
## VIIRS Compact, All Reflective Non-Image Rotating Optical Design






## VIIRS spectral bands

| | | Band No. | Wave-length (µm) | Horiz Sample Interval (km Downtrack x Crosstrack) Nadir | End of Scan | Driving EDRs | Radi-ance Range | Ltyp or Ttyp |
|---|---|---|---|---|---|---|---|---|
| | | M1 | 0.412 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 44.9<br>155 |
| | | M2 | 0.445 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 40<br>146 |
| | | M3 | 0.488 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color | Low | 32 |
| | | I4 | 3.74 | 0.371 x 0.387 | 0.80 x 0.789 | Imagery Clouds | Single | 270 K |
| | PV HgCdTe | M12 | 3.70 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 270 K |
| | | M13 | 4.05 | 0.742 x 0.259 | 1.60 x 1.58 | SST<br>Fires | Low<br>High | 300 K<br>380 K |
| LWIR | PV HCT | M14 | 8.55 | 0.742 x 0.776 | 1.60 x 1.58 | Cloud Top Properties | Single | 270 K |
| | | M15 | 10.763 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 300 K |
| | | I5 | 11.450 | 0.371 x 0.387 | 0.80 x 0.789 | Cloud Imagery | Single | 210 K |
| | | M16 | 12.013 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 300 K |

### Spectral Bands:

- Visible/Near IR: 9 plus Day/Night Band
- Mid-Wave IR: 8
- Long-Wave IR: 4

Some bands have dual gain



## VIIRS 22 EDRs

| Name of Product | Group |
|---|---|
| **Imagery *** | Imagery |
| Precipitable Water | Atmosphere |
| Suspended Matter | Atmosphere |
| Aerosol Optical Thickness | Aerosol |
| Aerosol Particle Size | Aerosol |
| Cloud Base Height | Cloud |
| Cloud Cover/Layers | Cloud |
| Cloud Effective Particle Size | Cloud |
| Cloud Optical Thickness/Transmittance | Cloud |
| Cloud Top Height | Cloud |
| Cloud Top Pressure | Cloud |
| Cloud Top Temperature | Cloud |
| Active Fires | Land |
| Albedo (Surface) | Land |
| Land Surface Temperature | Land |
| Surface Type | Land |
| Vegetation Index | Land |
| **Sea Surface Temperature *** | Ocean |
| Ocean Color and Chlorophyll | Ocean |
| Sea Ice Characterization | Snow and Ice |
| Ice Surface Temperature | Snow and Ice |
| Snow Cover and Depth | Snow and Ice |

* Key Performance Parameters:

Imagery and Sea-surface temperature



## Infrared measurements

**Table 1. Channel Characteristics of Satellite-borne IR Radiometers**

| VIIRS baseline | | MODIS | | AVHRR | | (A)ATSR | |
|---|---|---|---|---|---|---|---|
| λ,µm | NEΔT K | λ,µm | NEΔT K | λ,µm | NEΔT K | λ,µm | NEΔT K |
| 3.7 | 0.065 | 3.75 | 0.05 | 3.75 | 0.12 | 3.7 | 0.019 |
| 4.0 | 0.078 | 3.96 | 0.07 | | | | |
| | | 4.02 | 0.07 | | | | |
| 10.8 | 0.038 | 11.03 | 0.05 | 10.5 | 0.12 | 10.8 | 0.028 |
| 12.0 | 0.070 | 12.02 | 0.05 | 11.5 | 0.12 | 12.0 | 0.025 |

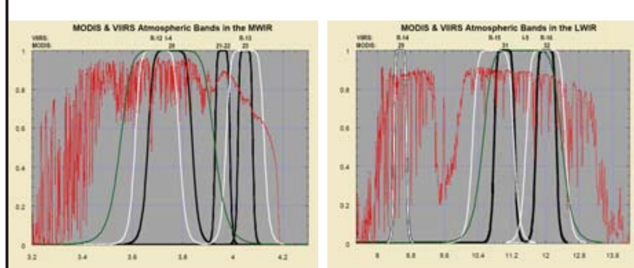


## VIIRS spectral bands

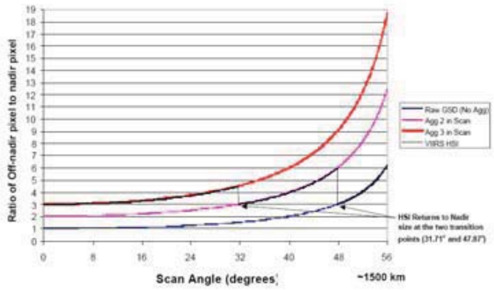
| | | Band No. | Wave-length (µm) | Horiz Sample Interval (km Downtrack x Crosstrack) Nadir | End of Scan | Driving EDRs | Radi-ance Range | Ltyp or Ttyp |
|---|---|---|---|---|---|---|---|---|
| VIS/NIR FPA | Silicon PIN Diodes | M1 | 0.412 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 44.9<br>155 |
| | | M2 | 0.445 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 40<br>146 |
| | | M3 | 0.488 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 32<br>123 |
| | | M4 | 0.555 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 21<br>90 |
| | | I1 | 0.640 | 0.371 x 0.387 | 0.80 x 0.789 | Imagery | Single | 22 |
| | | M5 | 0.672 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 10<br>68 |
| | | M6 | 0.746 | 0.742 x 0.776 | 1.60 x 1.58 | Atmospheric Corr'n | Single | 9.6 |
| | | I2 | 0.865 | 0.371 x 0.387 | 0.80 x 0.789 | NDVI | Single | 25 |
| | | M7 | 0.865 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 6.4<br>33.4 |
| CCD | | DNB | 0.7 | 0.742 x 0.742 | 0.742 x 0.742 | Imagery | Var. | 6.70E-05 |
| S/MWIR | PV HgCdTe (HCT) | M8 | 1.24 | 0.742 x 0.776 | 1.60 x 1.58 | Cloud Particle Size | Single | 5.4 |
| | | M9 | 1.378 | 0.742 x 0.776 | 1.60 x 1.58 | Cirrus/Cloud Cover | Single | 6 |
| | | I3 | 1.61 | 0.371 x 0.387 | 0.80 x 0.789 | Binary Snow Map | Single | 7.3 |
| | | M10 | 1.61 | 0.742 x 0.776 | 1.60 x 1.58 | Snow Fraction | Single | 7.3 |
| | | M11 | 2.25 | 0.742 x 0.776 | 1.60 x 1.58 | Clouds | Single | 0.12 |
| | | I4 | 3.74 | 0.371 x 0.387 | 0.80 x 0.789 | Imagery Clouds | Single | 270 K |
| | | M12 | 3.70 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 270 K |
| | | M13 | 4.05 | 0.742 x 0.259 | 1.60 x 1.58 | SST<br>Fires | Low<br>High | 300 K<br>380 K |
| LWIR | PV HCT | M14 | 8.55 | 0.742 x 0.776 | 1.60 x 1.58 | Cloud Top Properties | Single | 270 K |
| | | M15 | 10.763 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 300 K |
| | | I5 | 11.450 | 0.371 x 0.387 | 0.80 x 0.789 | Cloud Imagery | Single | 210 K |
| | | M16 | 12.013 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 300 K |



## VIIRS SST RSRs



## VIIRS pixel aggregation




GSD: Ground Sampling Distance
HSI: Horizontal Sampling Interval



## SST retrievals

- Primary KPP SST is a **skin SST**.
- Additional Environmental Data Record is a bulk SST, and the plan is to use a model to derive the bulk SST from the skin SST.



## VIIRS Daytime SST Retrieval Equation

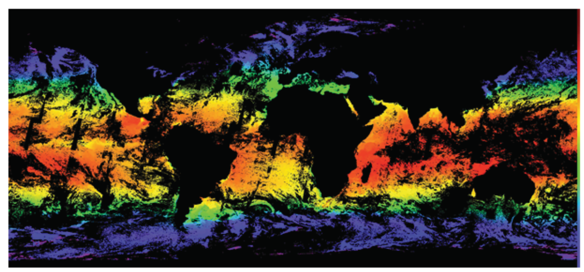
$$SST = a_0 + a_1 T_{11} + a_2 (T_{11} - T_{12}) RSST + a_3 (T_{11} - T_{12})(\sec(\theta) - 1)$$

where $a_0$, $a_1$, $a_2$, $a_3$ are coefficients derived by regression analysis, $T_{11}$ is the measured brightness temperature at 11 µm (VIIRS band M15), $T_{12}$ is the measured brightness temperature at 12 µm (VIIRS band M16), RSST is a modeled, first guess SST, and $\theta$ is the sensor zenith angle.

- Two set of monthly coefficients are determined for
  - $T_{11} - T_{12} \leq 0.8$K (temperate to polar)
  - $T_{11} - T_{12} > 0.8$K (equatorial to temperate)



## Initial SST fields from VIIRS on NPP



Global 4km VIIRS SST (3.7, 11, 12 µm; night-time) for February 4-6, 2012.
Processed at the native 0.75km resolution and a 4km output pixel generated as the average of the 'best' quality retrievals within the 4km cell.
SSTs computed using the pre-launch coefficients derived by Sid Jackson, NGST.

Courtesy Bob Evans et al.



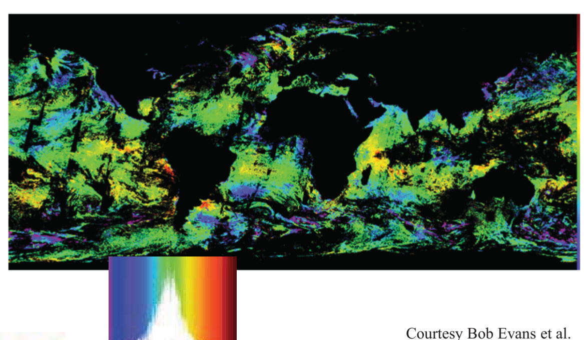
## VIIRS Night-time SST Retrieval Equation

$$SST = a_0 + a_1 T_{11} + a_2 (T_{3.7} - T_{12}) RSST + a_3 (\sec(\theta) - 1)$$

where $a_0$, $a_1$, $a_2$, $a_3$ are coefficients derived by regression analysis (different from daytime algorithm), $T_{3.7}$ is the measured brightness temperature at 3.7 µm (VIIRS band M12), $T_{11}$ is the measured brightness temperature at 11 µm (VIIRS band M15), $T_{12}$ is the measured brightness temperature at 12 µm (VIIRS band M16), RSST is a modeled, first guess SST, and $\theta$ is the sensor zenith angle.

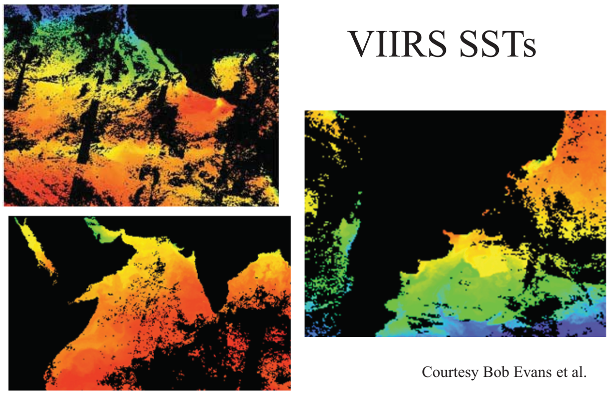


## VIIRS SST compared to “Reynolds” OI SST




Courtesy Bob Evans et al.

# VIIRS SSTs



Courtesy Bob Evans et al.



# AMSR-E: Advanced Microwave Scanning Radiometer for EOS.

Table 1. AMSR-E PERFORMANCE CHARACTERISTICS

| CENTER FREQUENCIES (GHz) | 6.925 | 10.65 | 18.7 | 23.8 | 36.5 | 89.0 |
|---|---|---|---|---|---|---|
| BANDWIDTH (MHz) | 350 | 100 | 200 | 400 | 1000 | 3000 |
| SENSITIVITY (K) | 0.3 | 0.6 | 0.6 | 0.6 | 0.6 | 1.1 |
| MEAN SPATIAL RESOLUTION (km) | 56 | 38 | 21 | 24 | 12 | 5.4 |
| IFOV (km x km) | 74 x 43 | 51 x 30 | 27 x 16 | 31 x 18 | 14 x 8 | 6 x 4 |
| SAMPLING RATE (km x km) | 10 x 10 | 10 x 10 | 10 x 10 | 10 x 10 | 10 x 10 | 5 x 5 |
| INTEGRATION TIME (MSEC) | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 1.3 |
| MAIN BEAM EFFICIENCY (%) | 95.3 | 95.0 | 96.3 | 96.4 | 95.3 | 96.0 |
| BEAMWIDTH (degrees) | 2.2 | 1.4 | 0.8 | 0.9 | 0.4 | 0.18 |

http://www.ghcc.msfc.nasa.gov/AMSR/

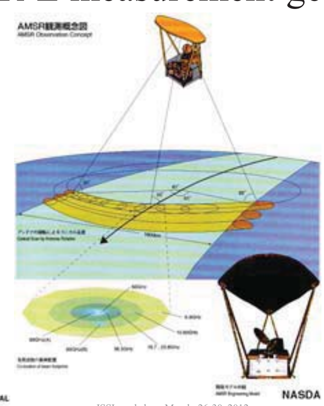


# VIIRS Summary

- Expectation is that VIIRS will provide SSTs of good quality
- Atmospheric daytime correction algorithm is the NLSST based on AVHRR & MODIS heritage
- Nighttime algorithm is also an NLSST, whereas heritage was MCSST
- Validation plans use multi-tiered approach
- Anticipated that VIIRS will extend the SST CDR into future decades

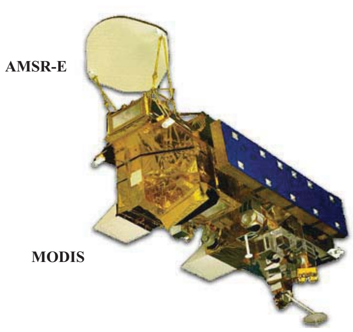


# AMSR-E measurement geometry






# AMSR-E on EOS-Aqua




*Aqua* launched 4 May 2002.

Low frequency SST sensitivity means very large antenna is needed for even moderate surface resolution.

Offset parabolic reflector, 1.6 m in diameter, and rotating drum at 40 rpm

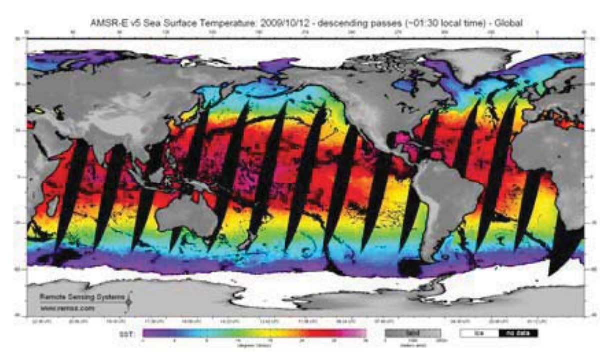
But side lobe contamination is a significant issue, especially in coastal regions.

http://aqua.nasa.gov/

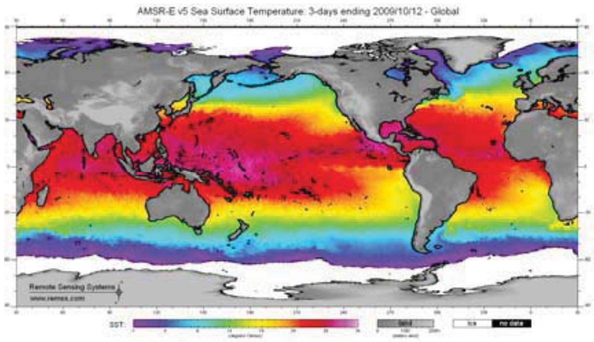
http://aqua.nasa.gov/about/instrument_amsr.php



# Global microwave SSTs



# Global microwave SSTs



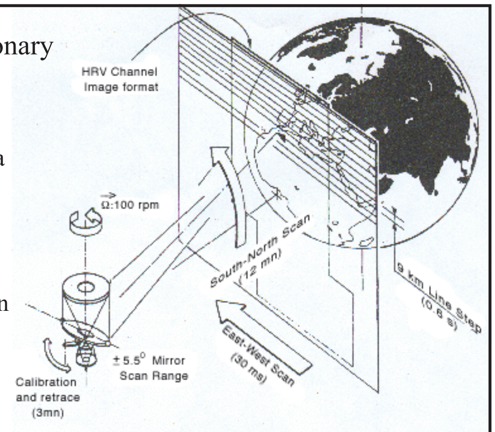

INTERNATIONAL SPACE SCIENCE INSTITUTE



# Geostationary scan

This is for a "spin-stabilized" satellite.

Scan pattern similar for 3-axis stabilized satellite




INTERNATIONAL SPACE SCIENCE INSTITUTE



# Geosynchronous Satellites

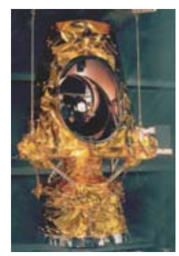
- Orbital height: 35,786 km above the earth's surface, 42,164 km radius. (About 10% of the distance to the moon.)
- Orbital period: one sidereal day - 23 hours 56 minutes.

INTERNATIONAL SPACE SCIENCE INSTITUTE



# SEVIRI

- Flown on EUMETSAT Meteosat Second Generation (Meteosat 8, 9, 10, 11)
- 12 Channels in Vis and IR
- 3km surface resolution (1km for High-Resolution Visible)
- 15 minute repeat cycle for full disk.
- 5 minute rapid sampling mode.



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# Infrared radiometers on GOES

Imager – 5 channels: 1 vis, 4 ir; 1, 4 & 8 km ground resolution; 10 bit digitization; 1bb + space for calibration

Sounder – 19 channels; 18 ir + 1vis; ~10km ground resolution; 13 bit digitization; 1bb + space for calibration

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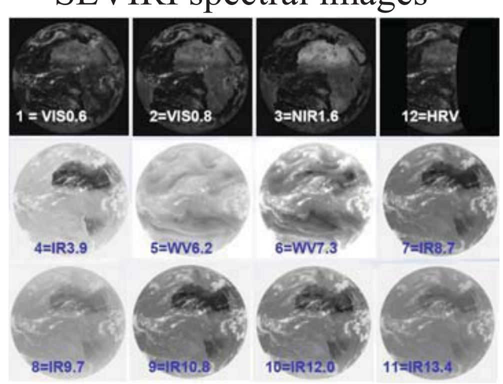
# SEVIRI spectral images

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New radiometers about to be launched:

- AMSR-2
- SLSTR

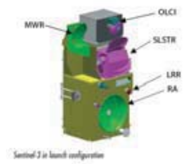
Further in the future:

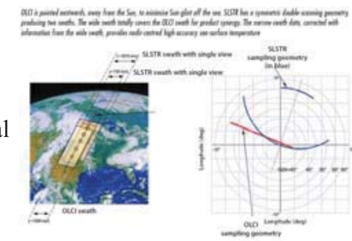
- VII on EPS-SG



# SLSTR on ESA's Sentinel 3

SLSTR on ESA's Sentinel 3. Combines dual view of (A)ATSR and multi-channel approach of conventional scanning radiometers.




From Aguirre et al. (2007) Sentinel-3. The Ocean and Medium-Resolution Land Mission for GMES Operational Services. ESA Bulletin 131:24-29



# AMSR-2

The launch date and time for the H-IIA Launch Vehicle No. 21 (H-IIA F21) with the Global Change Observation Mission 1st - Water "SHIZUKU" (GCOM-W1) onboard was decided to be at around 1:39 a.m. on Friday May 18, 2012.

http://www.jaxa.jp/projects/sat/gcom_w/index_e.html



# SLSTR on Sentinel 3

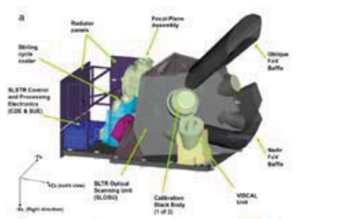


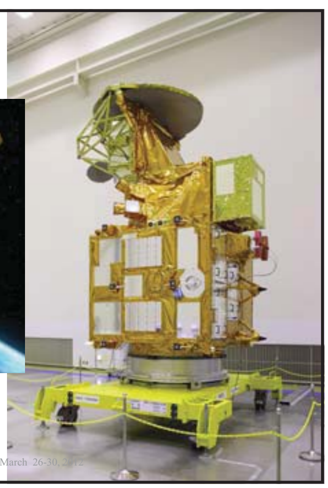


Fig. 7. (a) An overview of the Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) instrument highlighting principal components of the instrument design. (b) Photograph of the SLSTR Structural and Test Model (STM). (Credit: Selex-Galileo & Jena-Optronik).

Please cite this article as: Donlon, C., et al., The Global Monitoring for Environment and Security (GMES) Sentinel-3 mission, Remote Sensing of Environment (2012), doi:10.1016/j.rse.2011.07.024



# AMSR-2





# SLSTR Characteristics

**Table 9**
Technical characteristics of the Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR).

| | |
|---|---|
| Swath | Nadir view 1400 km Dual view 740 km |
| SSI at SSP (km) | Visible channels: 0.5 km<br>SWIR, IR and fire: 1 km |
| Calibration | Two on-board calibration reference black bodies and 1 × Visible calibration unit (VISCAL) viewed once per orbit at the South Pole ecliptic |
| Detectors | VIS: Silicon diode at 260 K<br>SWIR and MIR: HgCdTe photovoltaic (PV) elements actively cooled to 80 K.<br>TIR: HgCdTe photoconductive (PC) elements actively cooled to 80 K. |
| Optical scanning design | Along-track scanning based on two earth view scanning mirrors viewing two scan lined per revolution led to one recombination mirror with focusing optics to the detector array (field stop on the detector elements) |
| Radiometric resolution | VIS(a = 0.5%): SNR > 10<br>SWIR(a = 0.5%): SNR > 20<br>MWIR(T = 270 K): NeΔT < 80 mK<br>TIR(T = 270 K): NeΔT < 50 mK<br>Fire1 (< 500 K): NeΔT < 1 K<br>Fire2 (< 400 K): NeΔT < 0.5 K |
| Radiometric accuracy | VIS-SWIR (a = 2–100%): < 2% (BOL) < 5% (EOL)<br>MWIR-TIR (265–310 K): < 0.1 K (goal)<br>Fire1 and fire2 (< 500 K): < 3 K |
| Mass | 150 kg |
| Size | 2.116 $m^3$ |
| Design Lifetime | 7.5 years |

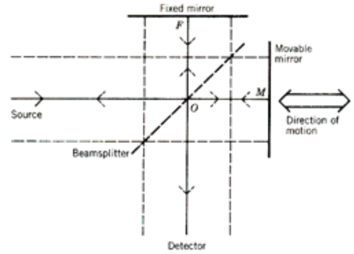
SSI is the spatial sampling interval at sub-satellite point (SSP), a is top of atmosphere albedo, T is top of atmosphere brightness temperature, SNR is signal-to-noise ratio, and NEΔT is noise equivalent difference temperature.

From Donlon, C., et al. 2012: The Global Monitoring for Environment and Security (GMES) Sentinel-3 mission. *Remote Sensing of Environment. In press.*

# Validating radiometers



# Michelson interferometer




Schematic representation of a Michelson interferometer. The median ray is shown by the solid line, and the extremes of the collimated beam are shown by the broken lines.



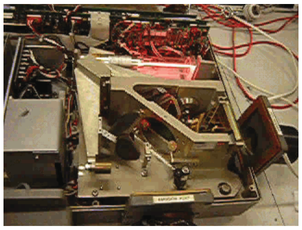
# Ship-board radiometers

- M-AERI
- M-AERI Mk 2
- ISAR
- Sister
- CIRIMS
- ……



# Marine - Atmospheric Emitted Radiance Interferometer. M-AERI

- Oscillating yoke provides a robust infrared radiometer for shipboard deployments.
- Visible laser used for wavelength calibration.
- Two blackbodies used for radiometric calibration.





# Marine-Atmospheric Emission Radiance Interferometer

The M-AERI is a Michelson-Morley Fourier-transform infrared (FTIR) interferometric spectroradiometer. These were first developed in the 1880's to make accurate measurements of the speed of light.

We use it to make very accurate measurements of the sea-surface temperature, air temperature and profiles of atmospheric temperature and humidity. We also measure surface emissivity and the temperature profile through the skin layer, which is related to the flow of heat from the ocean to the atmosphere.

THE AMERICAN JOURNAL OF SCIENCE.

AMERICAN JOURNAL OF SCIENCE.



# Marine-Atmospheric Emitted Radiance Interferometer (M-AERI)

**Specifications**

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

**Laboratory tests of M-AERI accuracy**

| Target Temp. | LW (988-985 cm $^{-1}$) | SW (2510-2515 cm $^{-1}$) |
|---|---|---|
| 20°C | +0.013 K | +0.030 K |
| 30°C | -0.024 K | -0.030 K |
| 60°C | -0.122 K | -0.086 K |

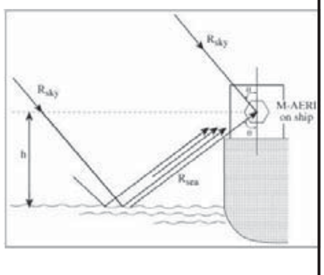
The mean discrepancies in the M-AERI 02 measurements of the NIST water bath blackbody calibration target in two spectral intervals where the atmosphere absorption and emission are low. Discrepancies are M-AERI minus NIST temperatures.

## Measurements of skin SST by ship-board radiometers

$$R_{water}(\lambda,\theta) = \varepsilon(\lambda,\theta)B(\lambda,T_{skin}) + (1-\varepsilon(\lambda,\theta))R_{sky}(\lambda,\theta)$$

$$T_{skin} = B^{-1}\langle\{R_{water}(\lambda,\theta) - [1-\varepsilon(\lambda,\theta)]R_{sky}(\lambda,\theta) - R_{\Delta}(\lambda,\theta)\}/\varepsilon(\lambda,\theta)\rangle$$

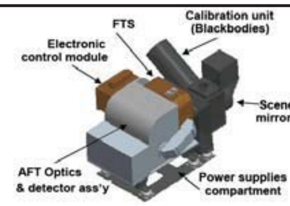
- Scan-mirror mechanism for directing the field of view at complementary angles.
- Very good calibration for ocean radiances
- Moderately good calibration at low radiances

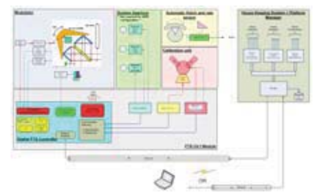





## M-AERI Mk2

Takes advantage of a decade of developments in detector technology, electronics and communications.

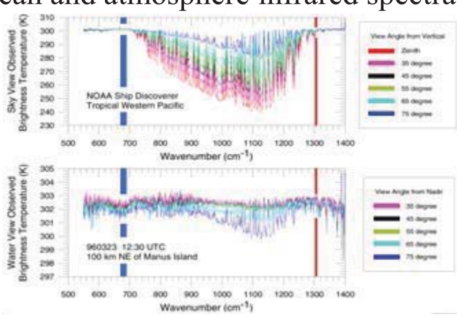




## Ocean and atmosphere infrared spectra

NB: X10 change in temperature scale

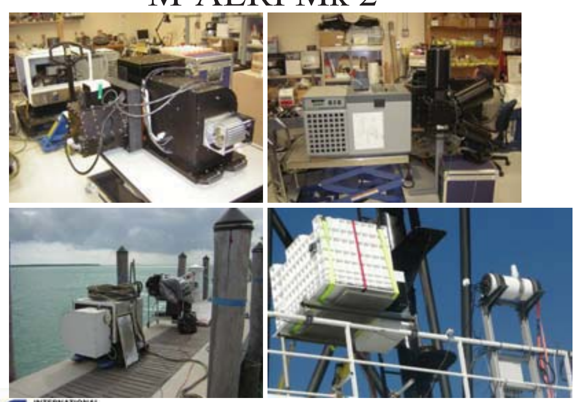



Examples of parts of spectra measured by the M-AERI, represented as temperature, and those intervals where the sky temperatures are smallest indicate where the atmosphere is most transparent. The spikes in the atmospheric spectra are caused by emission lines. The blue bar shows which spectral region is used to measure air temperature, and the red bar skin sea-surface temperature. Note the change in temperature scales of the two panels. These data were taken in the Tropical Western Pacific during the Combined Sensor Program Cruise in 1996.



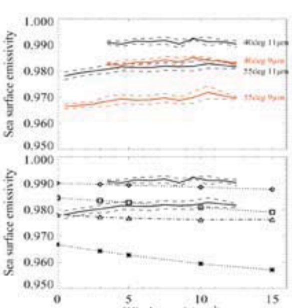
From Minnett, P. J., R. O. Knuteson, F. A. Best, B. J. Osborne, J. A. Hanafin and O. B. Brown (2001). "The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer." Journal of Atmospheric and Oceanic Technology. 18(6): 994-1013.

## M-AERI Mk 2

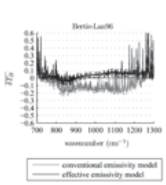




## Sea surface emissivity (ε)




- Conventional wisdom gave decreasing ε with increasing wind.
- Not confirmed by at-sea hyperspectral measurements
- Improved modeling confirms at-sea measurements.





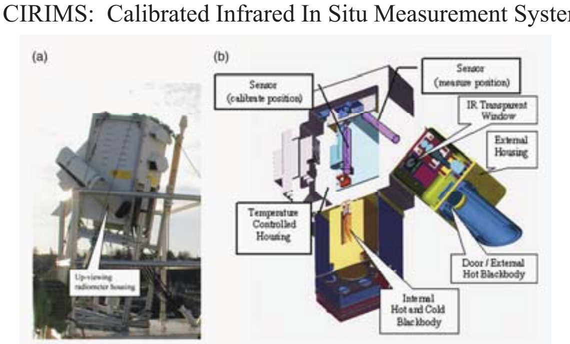
Hanafin, J. A. and P. J. Minnett, 2005: Infrared-emissivity measurements of a wind-roughened sea surface. *Applied Optics.,* ***44, 398-411.***

Nalli, N. R., P. J. Minnett, and P. van Delst, 2008: Emissivity and reflection model for calculating unpolarized isotropic water surface-leaving radiance in the infrared. I: Theoretical development and calculations. *Applied Optics,* ***47, 3701-3721.***

Nalli, N. R., P. J. Minnett, E. Maddy, W. W. McMillan, and M. D. Goldberg, 2008: Emissivity and reflection model for calculating unpolarized isotropic water surface-leaving radiance in the infrared. 2: Validation using Fourier transform spectrometers. *Applied Optics,* ***47, 4649-4671.***




## CIRIMS: Calibrated Infrared In Situ Measurement System




Andy Jessup, Applied Physics Lab, U. Washington.

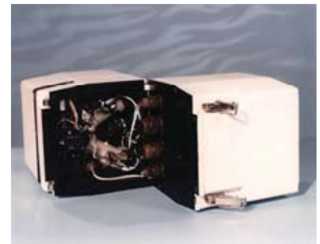
From: Jessup, A. T. and R. Branch, 2008: Integrated Ocean Skin and Bulk Temperature Measurements Using the Calibrated Infrared In Situ Measurement System (CIRIMS) and Through-Hull Ports. *Journal of Atmospheric and Oceanic Technology,* ***25, 579-597.***

## Radiometers

- Primary source of SST
  - Radiometric measurements and uncertainties are derived from a thorough understanding of the instrument characteristics and are directly traceable to national standards
  - SST measurements mediated by retrieval methods, additional uncertainties from (small) atmospheric correction, surface emissivity…
  - BUT is independent of other measurements of SST
- Basic considerations. Must be:
  - Seaworthy (and able-seaman-proof)
  - Able to maintain a calibration over a deployment
  - A method to validate the instrument calibration



## SISTeR



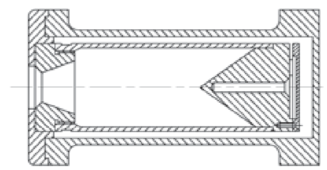


## Characteristics

- Most sea-going instruments are self-calibrating spectro-radiometers or filter radiometers
- Traceable primarily through:
  - black bodies (thermometry, emissivity)
  - spectral response
- Also need to consider:
  - linearity
  - polarisation
  - environmental sensitivity
  - many other things…



## Black bodies

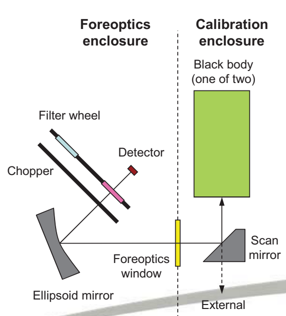


- Calculated emissivity > 0.999
- Embedded 4-wire 27Ω RhFe thermometer
- Constant power heater at cavity mounting point, near aperture
- Outer fibreglass shell with small air gap to inhibit convection
- Black body cavities calibrated complete in a specialised facility at Oxford University, against a secondary standard traceable to NPL.



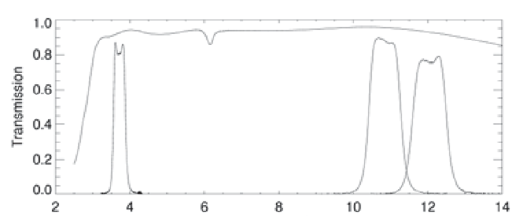
## Basic elements

- Two (or more) black bodies
  - One operated at ambient temperature, near to SST
  - One usually hotter (no condensation problems)
- Scan mirror
- Spectral selection
  - Filter
  - Spectrometer
- Detector
- Calibration at end of optical chain

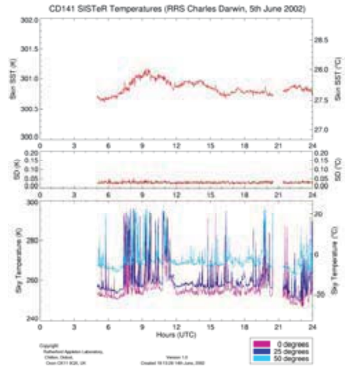





## Filters



Science & Technology Facilities Council




# CD141

RRS Charles Darwin
Indian Ocean

Science & Technology Facilities Council

Science & Technology Facilities Council

Science & Technology Facilities Council

## Ship-radiometer calibration & installation for CDR generation.



## Requirements

- Radiometers need two internal blackbody calibration targets, temperatures of which must be known to ~0.01K (?)
- Blackbodies should be well insulated and/or have large thermal mass, so temperature gradients (spatial and temporal) should be small (how small?)
- Detectors and digitizers should be stable with sufficient responsivity so as not to be quantization limited.
- Environmental measurements should be bracketed by calibration measurements of blackbodies
- Scene mirror must be protected against rain and spray
- Internal calibration of the radiometers should be periodically checked against SI-traceable lab blackbody calibrators.



## Installation

- Requires clear view of the sea ahead of the bow wave
- Requires clear view of the sky for reflected sky irradiance correction, at complimentary angle
- (Wind speed for <u>small</u> emissivity correction?)
- Subskin temperature very desirable, with usable accuracy.

# Miami IR Workshops

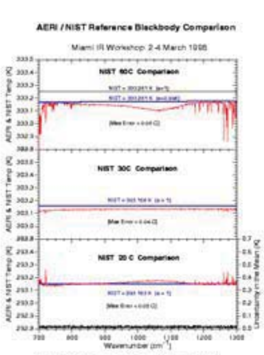


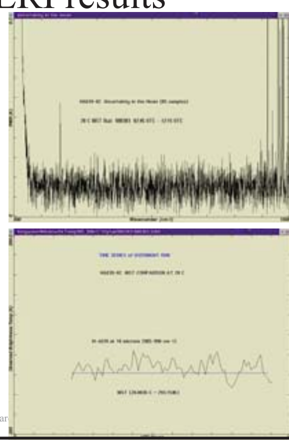
# IR Workshops

- The purpose of the Workshops is to provide a **common calibration** for instruments used to quantify the uncertainties in satellite measurements of the temperature of the sea and land surfaces.
- This is necessary to ensure satellite data are useful for **climate research**.
- The **calibration reference** instruments have been provided by the US National Institute of Standards and Technology (NIST) and UK National Physical Laboratory (NPL).
- Three workshops have been held:
  - **1998**, prior to launch of *Terra*
  - **2001**, after launch of *Terra*, prior to launch of *Aqua*
  - **2009**, prior to launch of *Suomi-NPP* (under the auspices of IVOS)



# 1998 M-AERI results



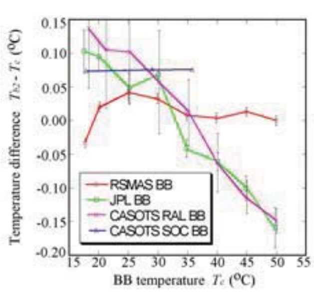





# 2001 – Blackbodies & Lab

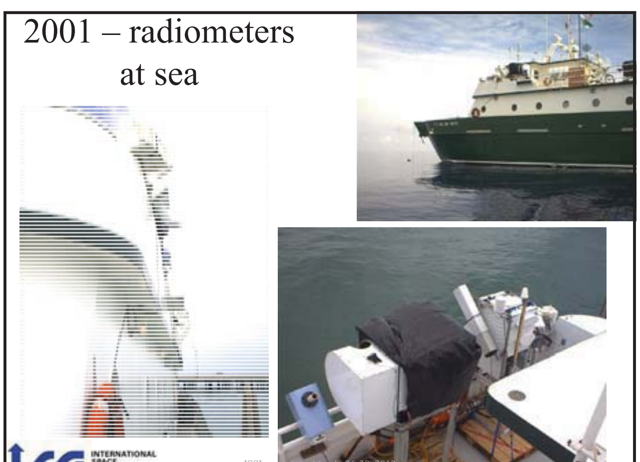


# 2001 – Black bodies




# 2001 – radiometers at sea



## 2001- Radiometers

TABLE 1. Infrared radiometers deployed on the R/V *F.G. Walton Smith*.

| Radiometer | Agency | Waveband (μm) | Detector | Sea-view angle (°) | Sky-view angle (°) |
|---|---|---|---|---|---|
| M-AERI | RSMAS | 3–18 | Cooled HgCdTe | 55 | 55 |
| ISAR-5 | JRC/EEC[a] | 9.6–11.5 | Heitronics KT15.85D[b,c] | 43 | 43 |
| SISTeR | RAL/UK[d] | 10.3–11.3 | Pyroelectric | 40, 45 | 40, 45 |
| JPL NNR | NASA/JPL[e] | 7.8–13.6 | Thermopile | 45 | No sky view |
| CIRIMS | APL[f] | Up: 9.6–11.5; down: 7–16 | Heitronics KT11.85[b] | 40 | 40 |
| DAR011 | CSIRO | 10.4–11.4 | Pyroelectric | 45 | 45 (backward) |
| TASCO | CSIRO | 8–14 | Thermopile | 45 | 45 |

[a] European Commission Joint Research Centre (JRC)
[b] The Heitronics radiation pyrometer is based on a chopped pyroelectric detector.
[c] The ISAR-5 Heitronics is modified to allow the measurement of temperatures down to −100°C.
[d] Rutherford Appleton Laboratory (RAL).
[e] National Aeronautics and Space Administration (NASA).
[f] Applied Physics Laboratory (APL), University of Washington.

TABLE 3. Means and std devs of the estimated skin SST differences between pairs of radiometers for the entire cruise period and for each half of the cruise.

| Time | 150.50–152.00 | | | 150.50–151.25 | | | 151.25–152.00 | | |
|---|---|---|---|---|---|---|---|---|---|
| Radiometer pair | Mean (K) | Std dev (K) | No. | Mean (K) | Std dev (K) | No. | Mean (K) | Std dev (K) | No. |
| MAE–ISA | 0.002 | 0.135 | 80 | 0.005 | 0.135 | 69 | −0.015 | 0.135 | 11 |
| MAE–SIS | 0.046 | 0.066 | 144 | 0.046 | 0.066 | 74 | 0.045 | 0.068 | 70 |
| MAE–JPL | 0.007 | 0.114 | 148 | 0.052 | 0.111 | 77 | −0.042 | 0.096 | 71 |
| MAE–DAR | −0.008 | 0.076 | 149 | 0.022 | 0.071 | 78 | −0.041 | 0.067 | 71 |
| ISA–SIS | 0.038 | 0.101 | 79 | 0.030 | 0.101 | 67 | 0.085 | 0.093 | 12 |
| ISA–JPL | 0.026 | 0.142 | 81 | 0.027 | 0.141 | 70 | 0.018 | 0.150 | 11 |
| ISA–DAR | 0.007 | 0.114 | 80 | 0.019 | 0.112 | 69 | −0.064 | 0.107 | 11 |
| SIS–JPL | −0.048 | 0.099 | 144 | −0.009 | 0.103 | 74 | −0.088 | 0.078 | 70 |
| SIS–DAR | −0.053 | 0.074 | 144 | −0.019 | 0.054 | 74 | −0.088 | 0.076 | 70 |
| JPL–DAR | −0.014 | 0.103 | 148 | −0.028 | 0.102 | 77 | 0.000 | 0.102 | 71 |



## 2001 - conclusions

- NIST traceability established for many radiometers, and lab calibration targets.
- Different radiometers produce measurements with statistics that agree within useful limits.
- Data from different radiometers can be combined into single data sets for satellite SST validation, and to study the physics of the upper ocean
  - e.g. Donlon, et al., 2002: Toward improved validation of satellite sea surface skin temperature measurements for climate research. *Journal of Climate,* 15, 353-369



## 2009

The objectives of the 2009 comparison were to establish the "degree of equivalence" between terrestrially based IR Cal/Val measurements made in support of satellite observations of the Earth's surface temperature and to establish their traceability to SI units through the participation of National Measurement Institutes (NMI)s.

- Included a component at NPL for lab comparisons
- Attempts to generate full uncertainty budgets for each radiometer and black-body target
- More of an emphasis on Land Surface Temperature Radiometers.
  - These have a tolerance of larger uncertainties than the SST radiometers



## 2009 measurements

- Stage 1 took place at NPL in April 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NPL reference transfer radiometer (AMBER) (Theocharous et al., 1998). The performances of 4 blackbodies were compared.
- Stage 2 took place at RSMAS in May 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NIST Thermal-Infrared Transfer radiometer (TXR). The performance of two blackbodies was completed during stage 2.



## Results *vs* AMBER

**Table 3.6.1:Difference between the temperature of the blackbody cavity provided by the participants and the brightness temperature of the same blackbody measured by the AMBER radiometer at different blackbody set temperatures.**

| Participant | Set temperature °C | Temperature "error" 21st April run mK | Temperature "error" 22nd April run mK |
|---|---|---|---|
| RAL SISTeR BB | 30 | 14 | 6 |
| | 20 | -8 | -5 |
| | 10 | -15 | -14 |
| Southampton ISAR BB | 30 | -7 | 3 |
| | 20 | -16 | -14 |
| | 10 | -19 | -18 |
| GOTA La Laguna Univ. Canary Island | 30 | -176 | -188 |
| | 20 | -152 | -181 |
| | 10 | -164 | -177 |
| DEPT Valencia University LAND P80P | 30 | -167 | -185 |
| | 20 | -143 | -166 |
| | 10 | -74 | -87 |



## Results *vs* TXR

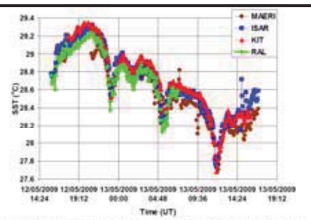
**Table 3.6.2: Difference between the temperature of the ISAR blackbody provided Southampton University minus the brightness temperature of the same blackbody measured by the TXR radiometer, at different blackbody temperatures.**

| Participant | Set temperature °C | Temperature "error" 1st measurement mK | Temperature "error" 2nd measurement mK |
|---|---|---|---|
| Southampton ISAR BB | 30 | -144 | -223 |
| | 20 | -37 | -95 |

**Table 3.6.3: Difference between the temperature of the RSMAS blackbody provided RSMAS minus the brightness temperature of the same blackbody measured by the TXR radiometer, at different blackbody temperatures.**

| Nominal temperature (°C) | Difference (°C) |
|---|---|
| 10 °C | 0.064 |
| 15 °C | 0.040 |
| 20 °C | -0.025 |
| 25 °C | -0.100 |
| 30 °C | -0.161 |

## 2009 – field measurements




## 2009 - conclusions

- Traceability to SI standards established.
- Larger spread of uncertainties than in 2001
- Evidence of significant degradation in RSMAS WB-BB target

## Calibration histories

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## Desirable developments

- For CDRs, make lab calibration data available as metadata files.

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## M-AERIs

- Calibration is checked vs RSMAS WB-BB target before and after each cruise deployment
- Uncertainties at environmental temperatures <0.1K
- Some inconsistencies recently discovered in versions of SST algorithm. Plans being made to reprocess all M-AERI data. Changes expected to be <<0.1K

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## RSMAS ISARS

- Calibration is checked vs RSMAS or UW APL WB-BB targets before and after each cruise deployment
- Uncertainties at environmental temperatures generally <0.1K, and post-cruise corrections made.
- Rain sensor or shutter malfunctions main source of data contamination or loss.

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# Ship-based deployments



# Cal/Val examples

- Use of ship-board radiometers to validate satellite SSTs from MODIS, (A)ATSR, SEVIRI and VIIRS.
- Removes sources of uncertainty in the comparison caused by variability in near-surface temperature gradients (skin effect and diurnal heating and cooling).

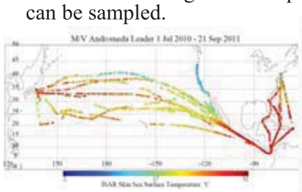
| SEVIRI SST uncertainties - comparisons with M-AERI on selected research cruises | | | | |
|---|---|---|---|---|
| Conf. level | 5 | | | Comments |
| Year | N | Mean | St Dev | |
| 2006 | 2431 | -0.087 K | 0.431 K | AMMA and PNE; small zenith angle |
| 2007 | 72 | -0.482 K | 0.616 K | PNE; small zenith angle |
| 2008 | 1238 | 0.477 K | 0.600 K | PNE & BONUS. Moderate & high zenith angle |
| 2006-08 | 3741 | 0.092 K | 0.568 K | Total |

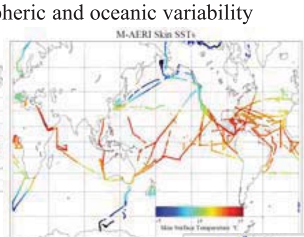
| Envisat AATSR SST uncertainties - comparisons with M-AERI on *Explorer of the Seas* in Caribbean area | | | |
|---|---|---|---|
| Data | Mean | St. Dev | N |
| Day | 0.16 K | 0.36 K | 32 |
| Night | 0.04 K | 0.26 K | 84 |
| From information in Noyes et al. 2006 | | | |

Noyes, E. J., P. J. Minnett, J. J. Remedios, G. K. Corlett, S. A. Good, and D. T. Llewellyn-Jones, 2006: The Accuracy of the AATSR Sea Surface Temperatures in the Caribbean. *Remote Sensing of Environment,* ***101, 38-51.***

# M-AERI & RSMAS ISAR

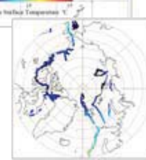
Over time full range of atmospheric and oceanic variability can be sampled.




ISAR on NYK vessel *Andromeda Leader*

M-AERI's on research ships



# CIRIMS

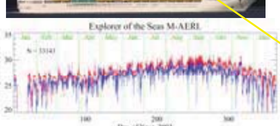
Calibrated Infrared In Situ Measurement System.

Andy Jessup, Applied Physics Lab, U. Washington.



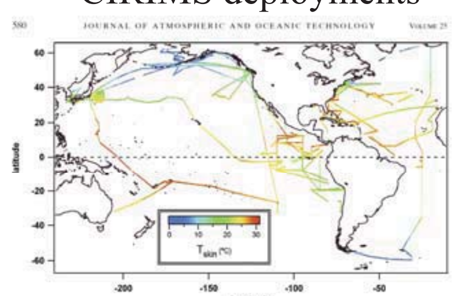

# Royal Caribbean Cruise Lines

Use of commercial cruise liners provides a cost-effective mechanism for generating long time-series of radiometric measurements of skin SST, often along repeating tracks.




M-AERI on:
*Allure of the Seas*, starting 2012;
*Explorer of the Seas*, 2000-2006, restarting in 2012.

# CIRIMS deployments




From: Jessup, A. T. and R. Branch, 2008: Integrated Ocean Skin and Bulk Temperature Measurements Using the Calibrated Infrared In Situ Measurement System (CIRIMS) and Through-Hull Ports. *Journal of Atmospheric and Oceanic Technology,* ***25, 579-597.***

## Radiometer deployment opportunities



## Research vessels

- Research ships of opportunity, e.g. Ron Brown, August 2012
  - Load in Boston August 14th.
  - DEP: 8/18/2012 Boston, MA
  - RR: 8/26/2012 St. George's, Bermuda
  - DEP: 8/31/2012 St. George's, Bermuda
  - ARR: 9/30/2012 Bridgetown, Barbados.



| **2012 NOAA Aerosols and Ocean Science Expedition (AEROSE) Ship-Based Atmospheric Measurements** | Howard University NOAA Center for Atmospheric Sciences; NOAA/NESDIS Center for Satellite Applications and Research (STAR); University of Miami / RSMAS | |
|---|---|---|
| | | |
| **Data Sample** | **Measurement Method** | **Instrument** |
| Tropospheric profiles of atmospheric pressure, temperature, humidity and wind | Balloon borne radiosondes launched ~4/day coinciding with orbital overpasses of low-earth orbit (LEO) evironmental satellites | ~130 Vaisala RS92-SGP radiosondes |
| Tropospheric to lower-stratospheric profiles of atmospheric ozone partial pressure, pressure, temperature, humidity and wind | Large-balloon-borne ECC ozonesondes interfaced with regular radiosonde packages, launched ~1/day coinciding with orbital overpasses of LEO environmental satellites | ~20 EN-SCI ECC ozonesondes |
| Multichannel solar-spectrum aerosol optical depths (AOD) | Handheld sunphotometers measuring slant-path solar attenuation | Microtops handheld sunphotometers |
| Cloud base height and boundary layer aerosol verticle distribution | Celiometer (a low-power Lidar) measurements of attenuated laser backscatter | Vasala ceilometer |
| Aerosol number density | Laser scattering measurements of airborne aerosols | laser particle counters |
| Downwelling broadband solar spectrum radiative flux (irradiance) | Passive measurements of sunlight via black coated thermopile sensor covered by a glass (solar spectrum transparent) hemispheric filter | broadband pyranometers |
| Downwelling broadband infrared spectrum radiative flux (irradiance) | Passive measurements of infrared irradiance via black coated thermopile sensor covered by a solar spectrum filter | broadband pyrgeometers |
| Aerosol mass density distribution | In situ aerosol sampling | Quartz crystal microbalance cascade impactor |
| Condensation particle number density | Optical scattering | condensation particle counter |
| In situ surface ozone, NOx, CO, VOC, and SO2 | optical absorption | trace gas monitors |
| Surface aerosol samples for organic analysis | in-line filter sampling | sequential aerosol sampler |
| Surface bioaerosol samples | In situ aerosol sampling | single-stage bioaerosol sampler |
| Surface aerosol samples - for inorganic analysis | in situ air sample aerosol measurements | multi-stage aerosol impactors |
| Upwelling and downwelling infrared (IR) spectra; sea surface skin temperature; surface air temperature; boundary layer profiles; sea surface emissivity | Fourier transform spectrometer (FTS) passive measurements of IR radiance spectra; algorithms to retrieve geophysical parameters from the radiance measurements | Marine Atmospheric Emitted Radiance Interferometer (M-AERI) |
| Meteorological surface measurements temperature, humidity, pressure, wind | Standard in situ meteorological sensor measurements | Weatherpak meteorological sensors |
| Atmospheric precipitable water, and cloud liquid water content | Passive measurements of microwave spectral radiance | microwave radiometer |
| Photographs of hemispheric sky cloud cover | Continuous digital snapshots of reflective hemispheric mirror at ~15 second intervals | all-sky camera sytem |
| Measurement of near-surface bulk sea surface temperature at ~5 cm depth | Temperature measurements via thermistor housed in a robust floatable package (a refitted "hard hat") lowered into the water during periods when the ship is holding station | in situ bulk sea surface temperature sensor (aka, the "hard hat") |



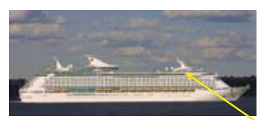
## Royal Caribbean Cruise Lines

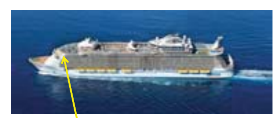
M-AERI Mk 2 installation plans:

*Allure of the Seas* – mid 2012

*Explorer of the Seas* – end 2012

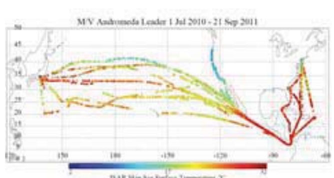
*TBC of the Seas* – mid 2013





M-AERI on:
*Allure of the Seas*, starting 2012;
*Explorer of the Seas*, 2000-2006, restarting in 2012.

## RSMAS ISAR on NYK ship *Andromeda Leader*

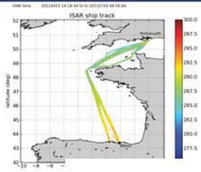


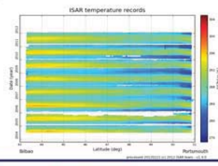

ISAR on NYK vessel *Andromeda Leader*

## ISAR installation on *Cap Finistere*

Southampton www.isar.org.uk Page 1

## Typical ISAR data





- Future Plans:
  - Continue the English Channel and Bay of Biscay data record.
  - Potential deployment of the French segment of SPURS – Strasse.

Southampton    www.isar.org.uk    Page 2

## OUC ISAR Deployment Plan in 2012 (244 days)

| | | |
|---|---|---|
| 1. | Mar. 16 – Apr. 30, 46 days | Yellow Sea & South China Sea |
| 2. | May 1 – May 23, 23 days | Bohai Sea & Yellow Sea |
| 3. | May 25 – Jul. 28, 65 days | East China Sea |
| 4. | Jul. 30 – Aug. 17, 19 days | Yellow Sea & East China Sea |
| 5. | Aug 18 – Oct. 3, 47 days | South China Sea |
| 6. | Oct. 8 – Oct. 31, 24 days | Jiaozhou Bay, Qingdao |
| 7. | Nov. 1 – Nov. 20, 20 days | Bohai Sea & Yellow Sea |

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## SISTeR

- SISTeR #1, a.k.a. "Alice", *Queen Mary 2* until further notice.
  - Usually Southampton to New York for spring to autumn, with occasional side-trips, and a "round-the-world" cruise in the winter (the last two have covered the north and south Atlantic, the Indian Ocean and the far east, but not the open Pacific).
- SISTeR #2, a.k.a. "Beth" is slowly being built up out of a pile of spare parts in the odd quiet moments and hopefully will get to sea this year.
  - There's no planned route yet, but we have a standing offer from Cunard to host further deployments.
  - Suggestions are welcome, but please bear in mind that we don't have much (or any) funding to support hard-to-reach locations!

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## Data Archiving and Distribution

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## Ship-board radiometer data

Objective is to provide an archive in perpetuity for future users to reprocess data in light of new knowledge

- What should go into an archive?
- Where should it be housed?
- List metadata?
- How should data be made available?

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## Laboratory calibration

- What should be included?
- Metadata?
- Open or limited access?
- Digest of lab results should be available in metadata of ship-radiometer data.

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## Data archiving: datasets

- Does it make sense to specify a common data format for radiometer SSTs (and possibly other in-situ SSTs)?
  - Simplified access for users
  - Guaranteed presence of basic data fields
  - Can implement standards
  - Encourages best practice (e.g. QA4EO recommendations)
- Are there any relevant existing in-situ dataset specifications?
  - Some, e.g. SAMOS (http://samos.coaps.fsu.edu), but lack some relevant metadata and data fields.

## General questions

- What mandatory variables are required?
- What optional variables are required?
- What data flags (mandatory and optional) are required?

## Dataset outline

- Suggest we borrow the common outline of GHRSST SST products
  - netCDF4
  - Follows Climate Forecast (CF) conventions
  - Implements the Attribute Convention for Data Discovery (ACDD)
  - ***Might*** lead to adoption by GHRSST: in-situ radiometer measurements would then be accessible to a large SST community in a familiar format

## Suggested mandatory variables

- **`lat, lon, (depth,) time`**
- **`sea_surface_temperature`**
- **`sst_total_uncertainty`**
- **`sst_flags`**
- **`quality_level`**
- **`view_elevation`**

## Dataset content

- Global header containing traceability and summary metadata
  - Propose to use GHRSST header without modification
  - Might need one or two additional fields to comply with (new) CF 1.6 convention for trajectories
- Coordinate variables
  - Latitude, longitude, (depth), time
- Mandatory variables
  - SSTs, SST uncertainties, quality indicators…
- Optional variables
  - Wind speed, platform speed, course, bearing…
- Experimental variables

## Suggested optional variables #1

- **`sst_random_uncertainty`**
- **`sst_systematic_uncertainty`**
- **`speed_over_ground`**
- **`course_over_ground`**
- **`speed_through_water`**
- **`true_bearing`**
- **`view_azimuth`**

## Suggested optional variables #2

- `wind_speed`
- `wind_speed_dtime_from_sst`
- `sources_of_wind_speed`

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## `sst_flags` candidates

| Bit | Common flags |
|---|---|
| 0 | 0 if thermometric, 1 if radiometric |
| 1 | 0 if night, 1 if day |
| 2 | Set if cloudy |
| 3 | Set if raining |
| 4 | Set for an instrument exception |
| 5 | Set for a processing exception |
| 6 | Set if the platform speed is low |
| 7 | Set if the wind speed is low |
| 8 | Land proximity |
| 9 | (reserved) |

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## Questions for netCDF-heads

- Should data stored types be fixed or flexible (e.g. as for GHRSST latitudes and longitudes)?
- Should (some) units be flexible (so long as they're traceable to SI and implemented in UDUNITS)?
- Can scalar values be used where a value is constant (e.g. as for CF time series latitudes and longitudes)?

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## 5.4 How can satellite SST CDRs be merged with in situ time-series?



## Estimation of global accuracies for n-way comparisons

E.g. for wind and wave see Stoffelen, 1998; Jansenn, 2008 resp.

Given three independent observation types can analyse the standard deviation of the couplets to derive estimation of standard deviation of error for each observation type.

$$\sigma_1 = \left[\frac{1}{2}(V_{12} + V_{31} - V_{23})\right]^{1/2},$$
$$\sigma_2 = \left[\frac{1}{2}(V_{23} + V_{12} - V_{31})\right]^{1/2}, \quad \text{and}$$
$$\sigma_3 = \left[\frac{1}{2}(V_{31} + V_{23} - V_{12})\right]^{1/2}.$$

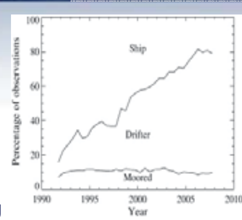
Assume errors are not correlated, and that the co-variances between the different observations because of representativity error are negligible.

**O'Carroll, Eyre, Saunders, 2008: AATSR 0.16K, drifting buoys 0.23K, AMSR-E SST 0.42K**
**Beggs, 2011: NOAA-17/AVHRR 0.16K, NOAA-18/AVHRR 0.13K, db 0.18-0.22K**
**O'Carroll, August et al, 2012: Metop-AVHRR 0.13K, drifting buoys 0.20K, IASI 0.28K**



## Summary of sensors/in situ

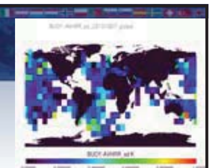
- ~1982: AVHRR + moored buoys (+ships)
- ~1991: ATSR-1 + drifting buoys + moored buoys (+ships)
- ~1997: AVHRR/ATSRs + ship board radiometers + moored buoys + drifting buoys (+ships)

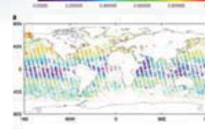


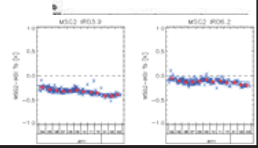



## Considerations: satellite

- Understanding spatial and temporal variations in satellite and in situ biases/uncertainties; use of observational uncertainty estimates; theoretical uncertainties
- Satellite drift in overpass time (diurnal variations)
- Volcanic aerosol e.g. Pinatubo 1991
- Inter-calibration of satellite data e.g. through GSICS....



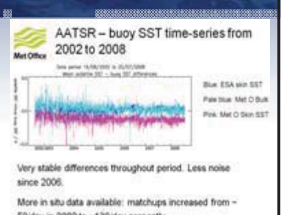






## Collocation of in situ with satellite SSTs

- Creation of matchup datasets of in situ moored and drifting buoys with satellite SSTs
- Consistent matchup criteria, in line with GHRSST recommendations
- Buoy location within satellite pixel; ±2hrs; QC of in situ data
- Statistics with night-time data only; 3-sigma statistics

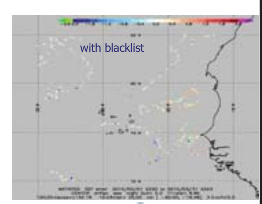



- Derivation of multi-matchup datasets; inclusion of meteorological and NWP fields



## Considerations: in situ data

- Understanding spatial and temporal variations in satellite and in situ biases/uncertainties; observational uncertainties
- Measurements at different depths
- QC of in situ data (e.g. Ingleby pp 219-224, 12th AMS Conference on Probability and Statistics in the Atmospheric Sciences. 1992.
- Buoy blacklists
- Robust statistics



## Considerations: methodologies

- Consistent and continual comparisons to stable sources e.g. Ship board radiometers; satellite spectrometers
- Modelling for different depth/skin effect/diurnal variation differences
- Wind-speed, how to deal correctly with high/low wind-speeds
- Other fields which may influence comparisons: WV, aerosol, SZA...
- Clouds: limitations of cloud detection
- What to do in regions of sparse in situ data

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## Summary

- Define in situ sources for AVHRR to ATSR-1 period in 1991
  - Tropical moored buoy arrays
  - Consider volcanic aerosol and desert dust
- Consider global, regional and observational uncertainties in both satellite and in situ SSTs
- Full analysis of overlap period and use of data from other sources e.g. GSICS
- Comprehensive quality control
- Modelling of skin effect and diurnal variations

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# Problems and gaps



# Mooring Issues

- Is elevated levels of variability in coastal moored buoys real?
- High variability missing in L4 SST products – why?
  - Sources of the high uncertainty level in comparisons with coastal moored buoys: Is the high uncertainty the result of geophysical variability or compromised buoy performance?
  - If coastal moored buoys are actually resolving small-scale dynamics not resolved at the resolution of the satellite SST products, can they be effectively integrated in the retrieval and validation chain and, in particular, in the validation of a CDR SSTs?
  - What should be the recommended procedure for regions/conditions that represent a measurement challenge? Do we favor the exclusion of coastal moored buoys such is currently being done or can they be used under some careful guidelines in the future?
- Sandra will address these questions
- Construct multi-sensor (satellite) matchups – 2008?



# SI traceability

- Continue series of workshops, not necessarily at RSMAS.
- Does pre- & post-cruise calibration ensure desired accuracy and traceability?
- Does pre- & post-cruise calibration catch "aging" and non-linear degradation?



# Drifter issues

- Assess improvements of new generation drifters.
- Assess role of ARGO profilers
- Assess sampling issues with drifters, especially as f(t); identify areas where drifters should be deployed.



# Satellite issues

- How best to deal with overlap periods & transitions to different satellites?
- Drift within satellites
- Define more fully the recommendations and best practices
- Establish accuracies of MODIS and AVHRR SSTs in a more rigorous fashion
- Assess accuracies in VIIRS SSTs
- Initial assessment of accuracies in AMSR-2 SSTs
- Improve interaction with instrument and retrieval experts



# Long term stabilty

- Ocean Site:
- Platform – power, logging, maintenance
- Siting – low cloudiness, atmospheric variability, reasonable distance from coast (GBR, ICON, ….)
- Instruments – SSTskin, SSTdepth (multiple), Met package, GPS, Radn package, currents, all-sky camera, ceilometer, surface waves,

## GPS water vapour

- Can we use GPS to derive atm humidity to useful accuracy?
- Moving platform issues?
- GoM results are +ve

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## Writing

- Develop the recommendations and best practices.

- PJM & GKC to merge input and circulate drafts

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## Timeline

- Deliver presentations to PJM for ISSI web pages - April 6.
- Deliver contributions to text – April 20
- PJM and GKC to circulate draft docs – June 1

- Iterate ….
- Publish by ?

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