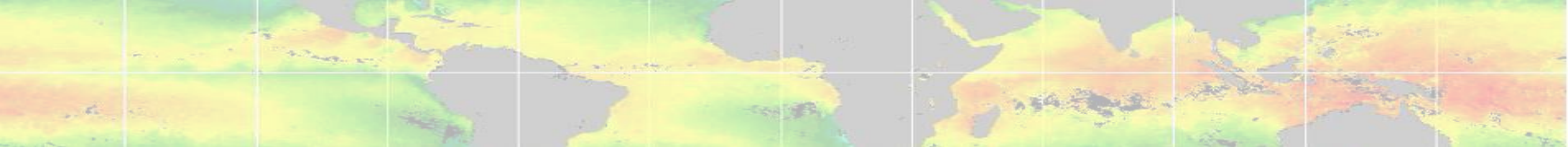

Progress in Establishing a Satellite-Derived Climate Data Record for Sea-Surface Temperature

Peter J Minnett, Malgorzata Szczodrak, Miguel Angel Izaguirre, Katherine Kilpatrick

Rosenstiel School of Marine and Atmospheric Science, University of Miami

&

R. Michael Reynolds
Remote Measurements and Research Inc. Seattle.

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FRM4STS International Workshop
16-18 October 2017. NPL, UK

pminnett@rsmas.miami.edu

FRM4STS Motivation

- The successful application of all satellite-derived fields depends on confident knowledge of their accuracies.
- Several sources of error and uncertainties impact the satellite measurements and the geophysical variables derived from them.
- Determine the accuracies by comparing the satellite-derived temperatures with **independent surface based measurements of equal or better accuracy**.
- This approach integrates the errors and uncertainties from all sources.
- Satellite SST requirements for climate research:
  - Accuracy = 0.1K
  - Stability = 0.04 K/decade

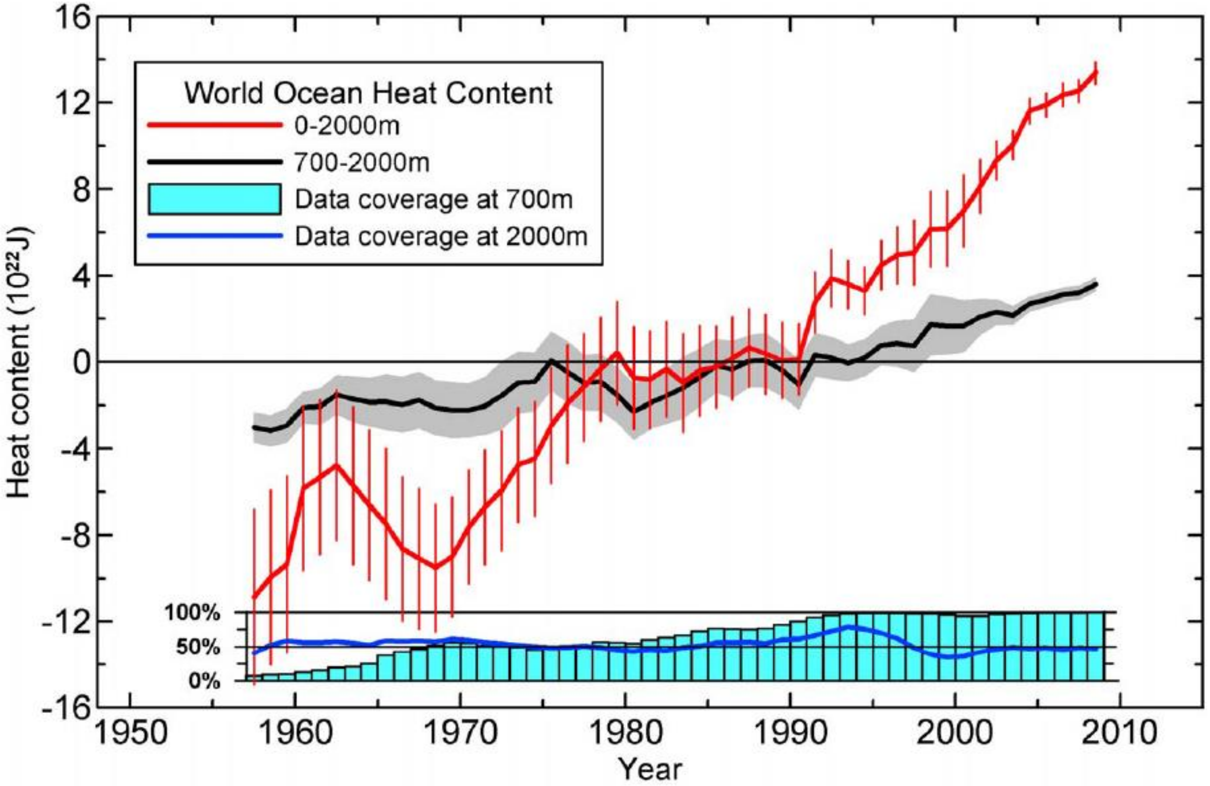
Ohring, G., et al. (2005). "Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop." Bulletin of the American Meteorological Society **86**(9): 1303-1313.

Ocean heat content is increasing

Time series of ocean heat content (10^{22} J) for the 0-2000 m (red) and 700-2000 m (black) layers based on running pentadal (five-year) analyses. Reference period is 1955-2006.

Red bars and grey-shading represent ±2 standard errors.

The blue bar chart represents the percentage of one-degree squares (globally) that have at least four pentadal one-degree square anomaly values used in their computation at 700 m depth. Blue line is the same as for the bar chart but for 2000 m depth. (Levitus et al., 2012).



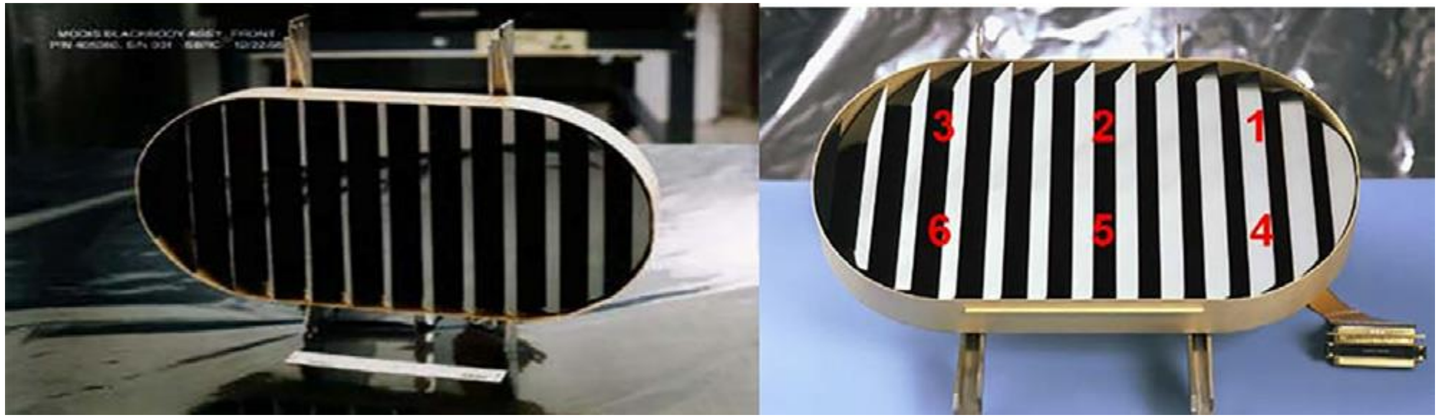
The heat content of the World Ocean for the 0–2000 m layer increased by 24.0 ± 1.9 10^{22} J (± 2 S.E.) corresponding to a rate of 0.39 Wm^{-2}.

A mean increase of temperature of 0.09^{o}C.

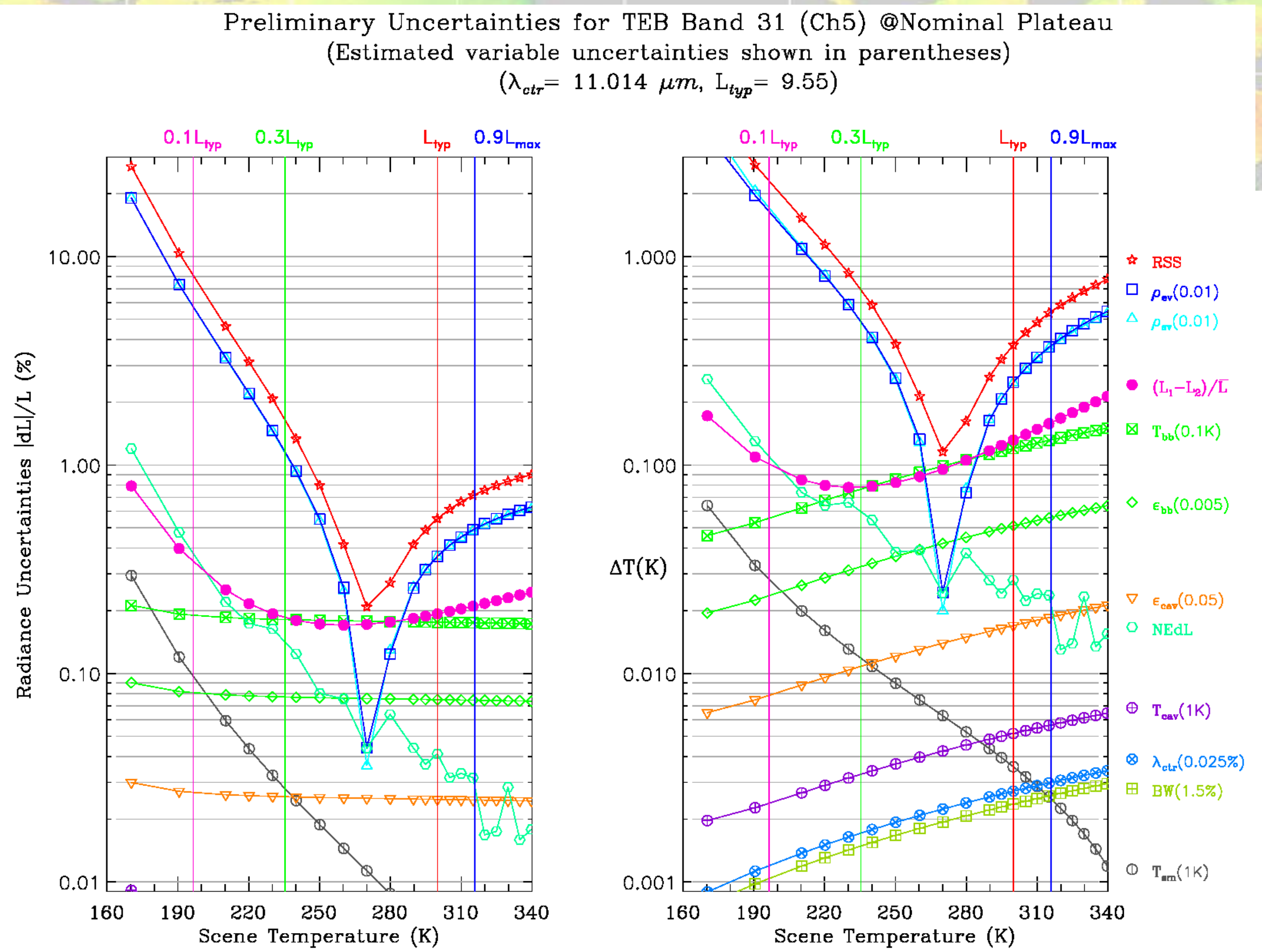
Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S., & Zweng, M.M. (2012). World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters 39*, L10603. 10.1029/2012GL051106

On-orbit calibration – MODIS & VIIRS

- Two-point linear calibration using space view and measurement of black body emission.
- Non-linearities determine prior to launch, and monitored using warm-up cool-down of black bodies.
- MODIS and VIIRS use same black body design.



From: X. Xiong, J. Butler, A. Wu, et al., Comparison of MODIS and VIIRS onboard blackbody performance, in: R. Meynart, S.P. Neeck, H. Shimoda (Eds.), Proc. SPIE 8533, Sensors, Systems, and Next-generation Satellites XVI, 853318, November 19, 2012. http://dx.doi.org/10.1117/12.977560.



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Validation by Comparison with Surface Measurements

Buoys

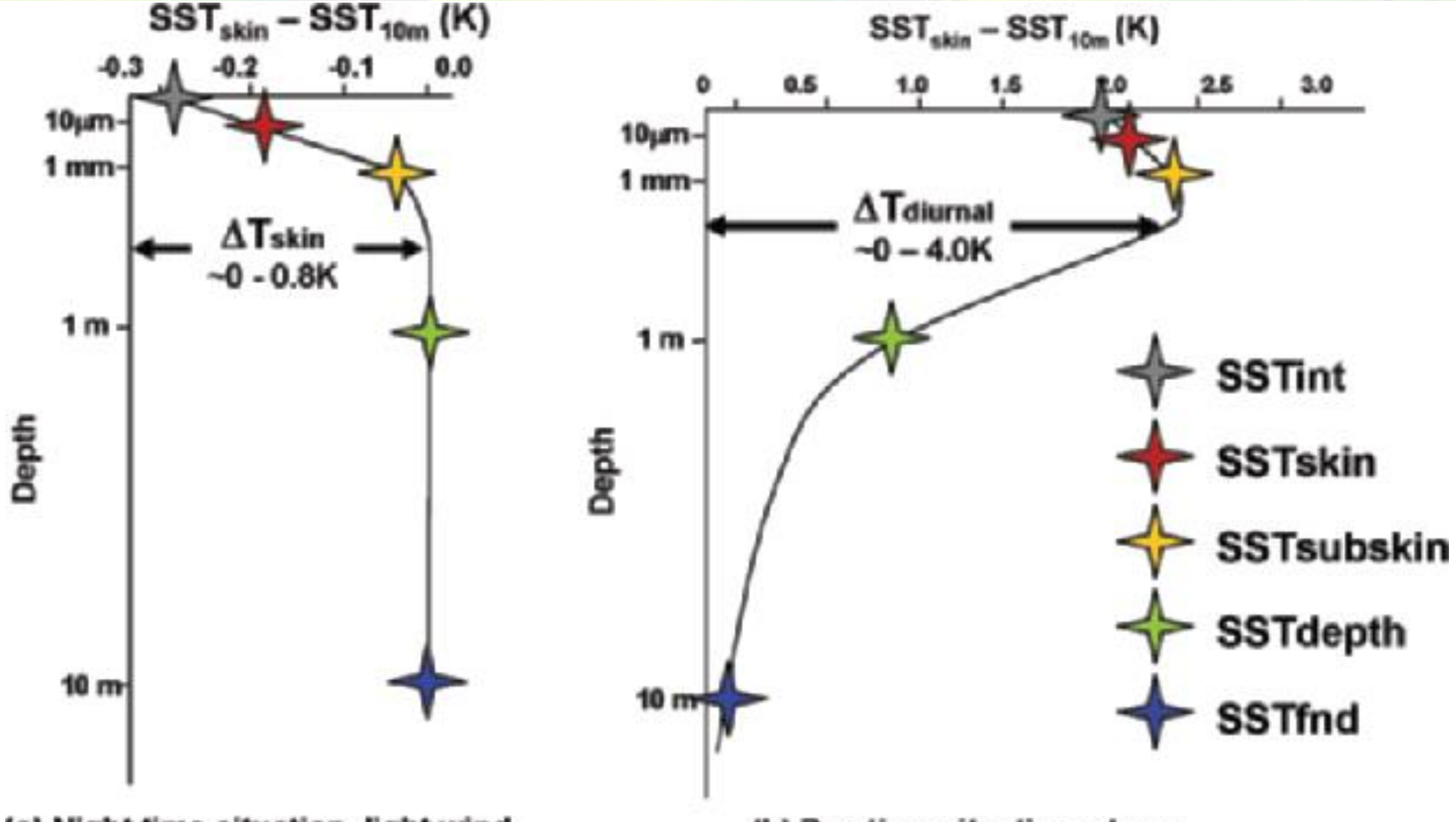
- Numerous, but not uniformly distributed in space or time.
- Long time series, starting in early 1980s.
- Subsurface measurement.
- Calibration issues.
- Not a comparison of like-with-like.

Radiometers

- Fewer, and not uniformly distributed in space or time.
- Began in mid-1990's.
- Skin SST measurement.
- Very good calibration, repeatable and traceable to SI-standards.
- Is a comparison of like-with-like.

Best approach to use both

Schematic Temperature Profiles



(a) Night time situation, light wind

(b) Day time situation, strong solar radiation and light winds

Donlon, et al. (2007). The Global Ocean Data Assimilation Experiment High-resolution Sea Surface Temperature Pilot Project. *Bulletin of the American Meteorological Society, 88, 1197-1213*

Drifting buoys

Before & After

Drifting Buoy Calibration Experiment

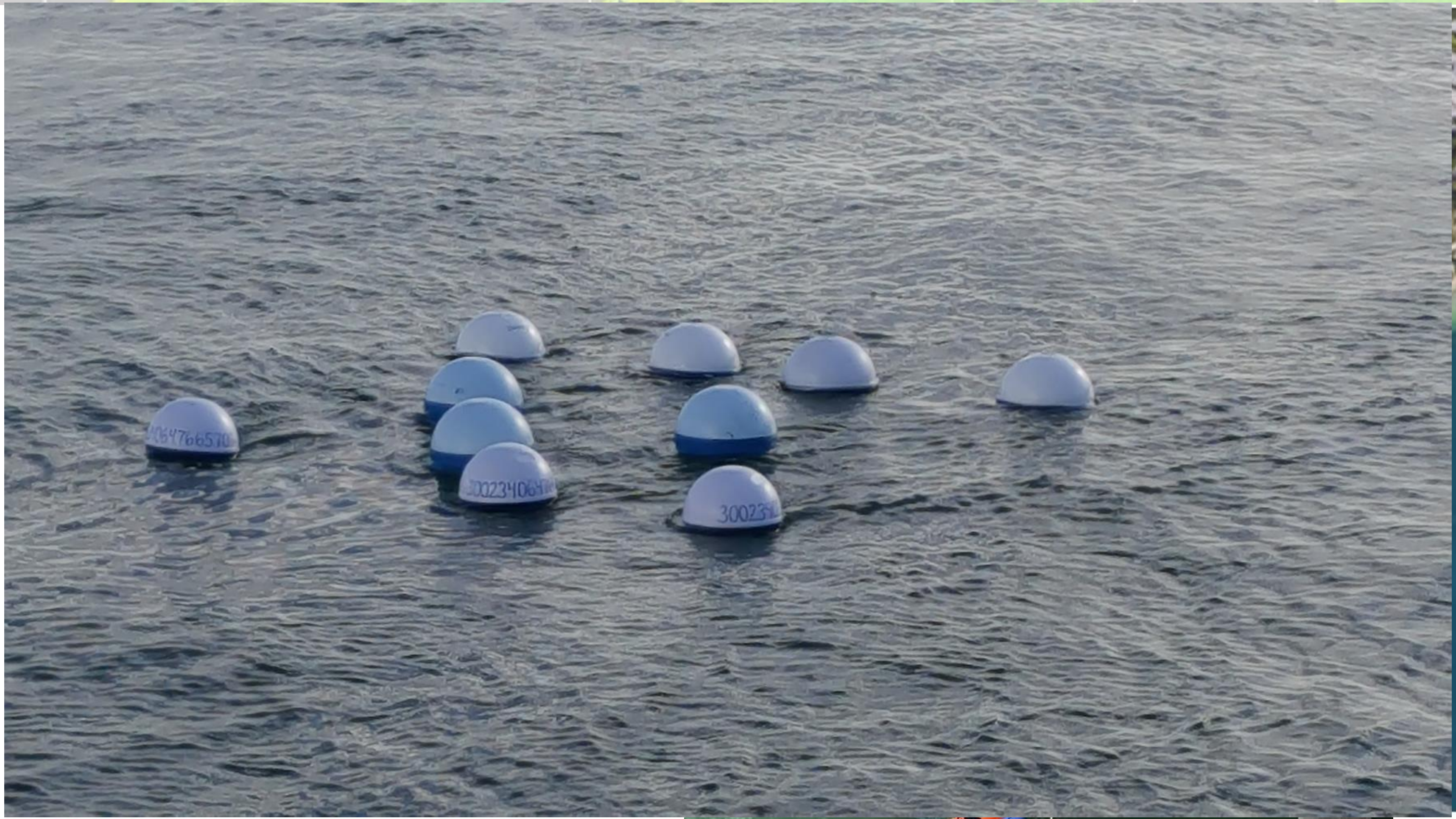
Objective: to assess any calibration drift in drifter thermometers by long-term monitoring in realistic conditions.

An array of drifters is moored off RSMAS. Data sent to SIO via Iridium, and to NOAA/AOML so data flow is the same as deployed drifters.

Data are not distributed beyond SIO, AOML and RSMAS.

Drifter types:

- Pacific Gyre
- Data Buoy Instrumentation
- SIO



In collaboration with Luca Centurioni (SIO) and Rick Lumpkin (NOAA/AOML).

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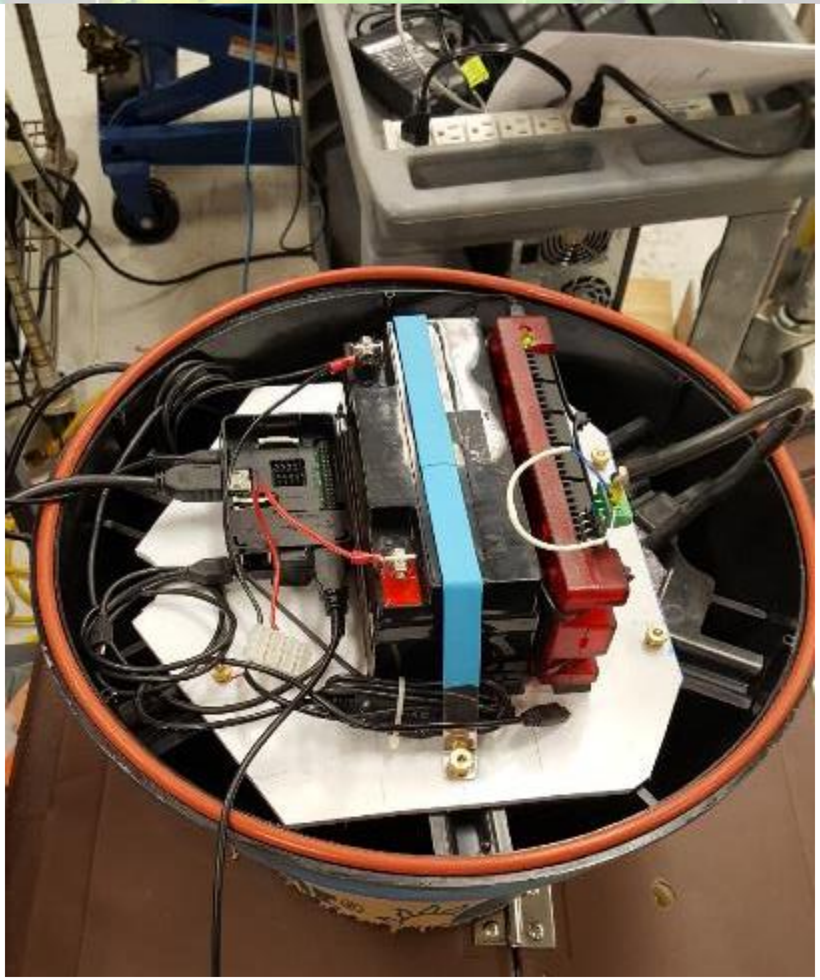
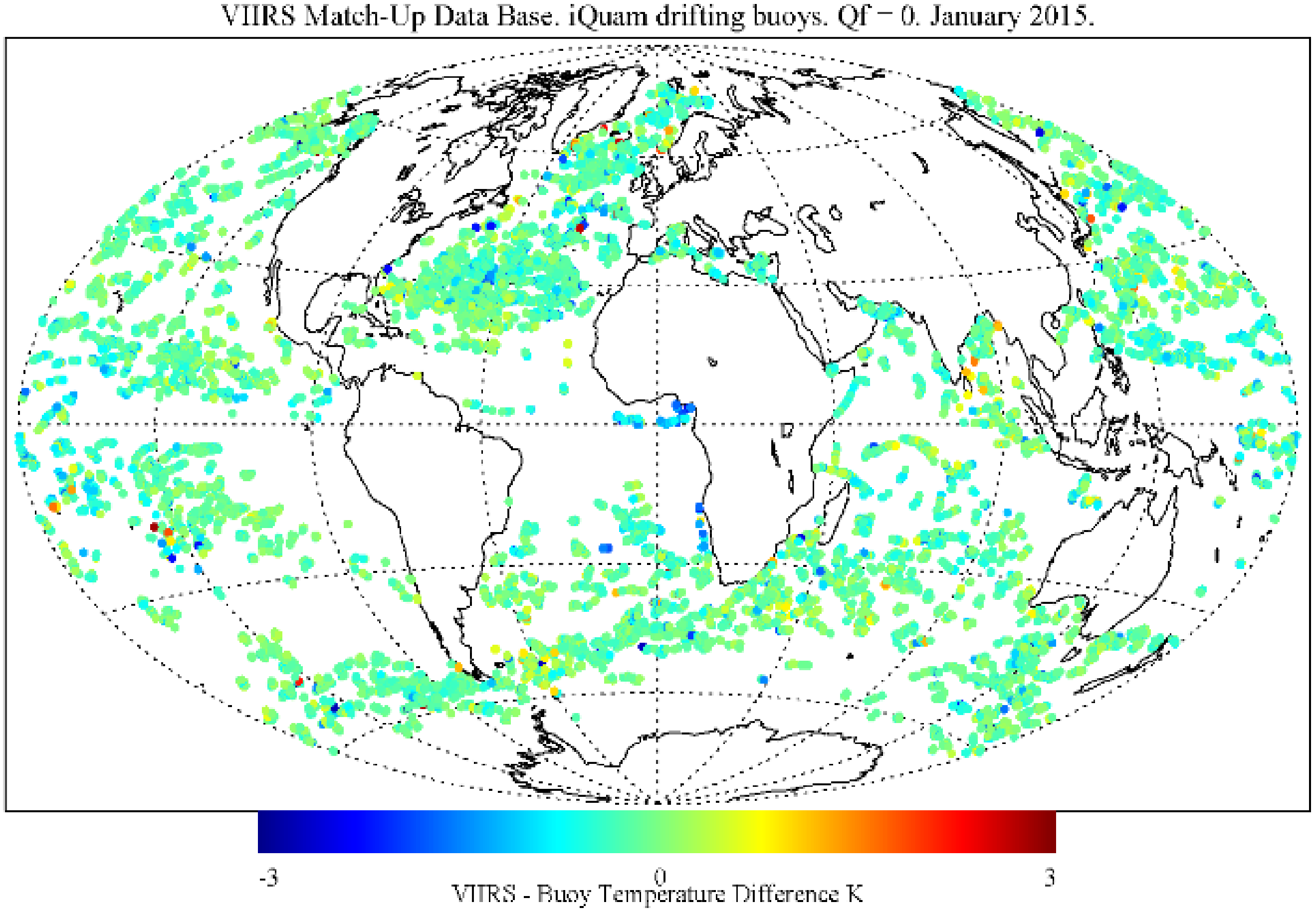
Reference Drifter

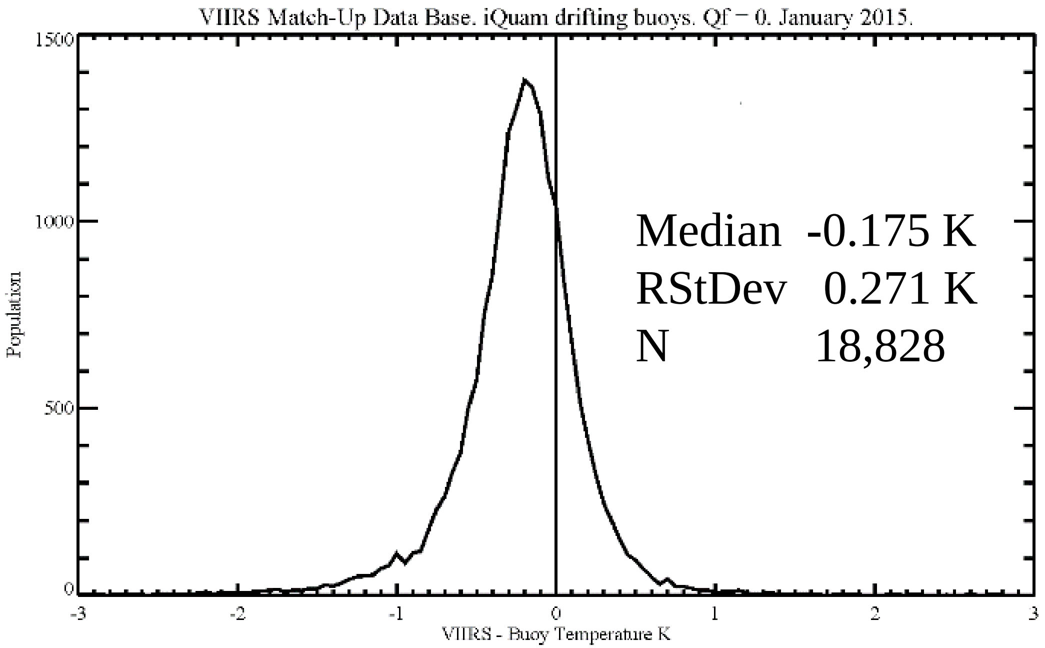
An SIO drifter has been rebuilt to have a reference thermistor and internal data logger. This is brought into the lab periodically for the data to be downloaded and recalibrated.

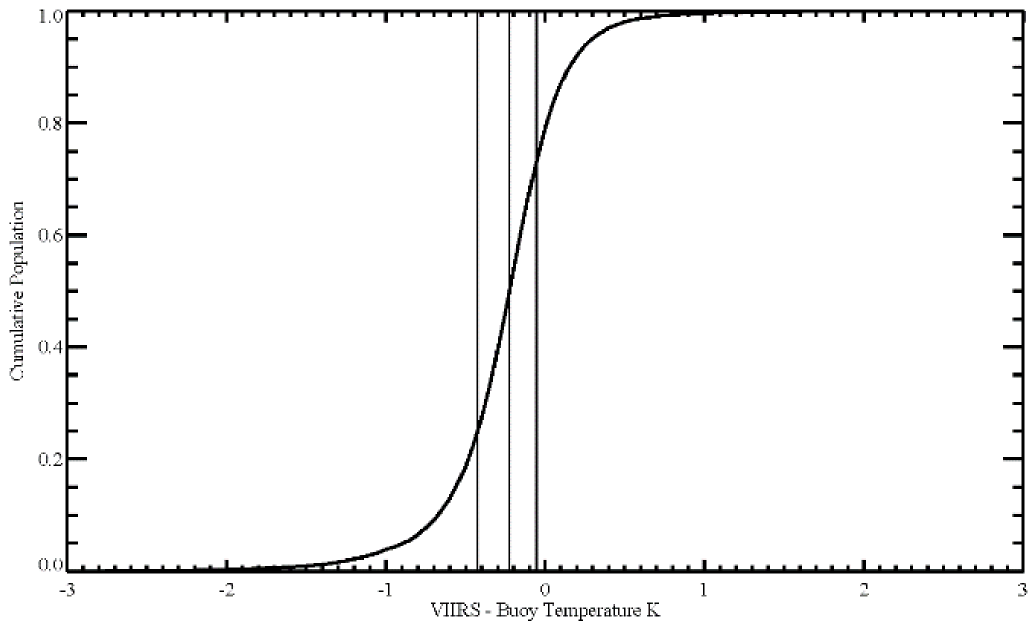


VIIRS SST Accuracies wrt Drifters



January, 2015





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RSMAS Ship Radiometers

M-AERI

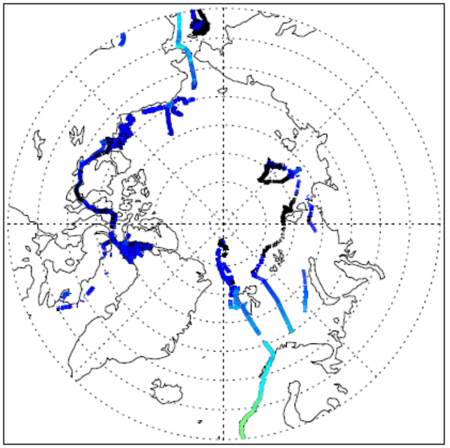
- M-AERI is a very well-calibrated and stable sea-going Fourier Transform Infrared Interferometer.
- At sea calibration by two internal blackbody cavities with thermometers with NIST-traceable calibration.
- Calibration sequence before and after each cycle of measurements.
- Calibration before and after deployments using NIST-designed water-bath blackbody calibration target at RSMAS. Uses SI-traceable thermometers at mK accuracy.
- Periodic radiometric characterization of RSMAS water-bath blackbody calibration target by NIST TXR and NPL AMBER.

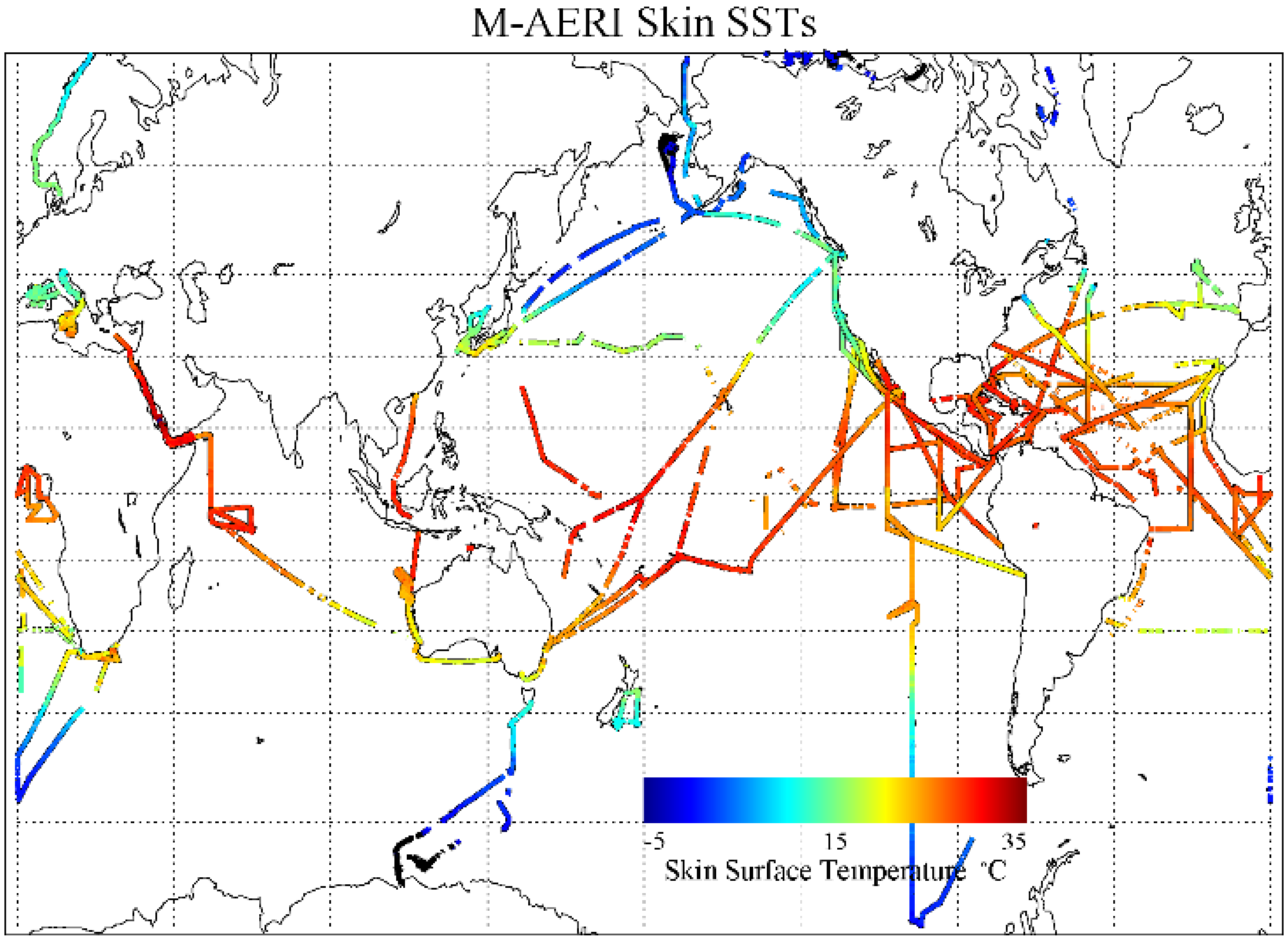
ISAR

- ISAR is a very well-calibrated and stable sea-going filter radiometer.
- At sea calibration by two internal blackbody cavities with thermometers with SI-traceable calibration.
- Calibration sequence before and after each cycle of measurements.
- Calibration before and after deployments using NIST-designed water-bath blackbody calibration target at RSMAS or UW-APL. Use SI-traceable thermometers at mK accuracy.
- Periodic radiometric characterization of RSMAS water-bath blackbody calibration target by NIST TXR and NPL AMBER

Research Ship Radiometer Deployments

M-AERI Cruises





Explorer of the Seas

Explorer of the Seas: near continuous operation December 2000 – December 2007.

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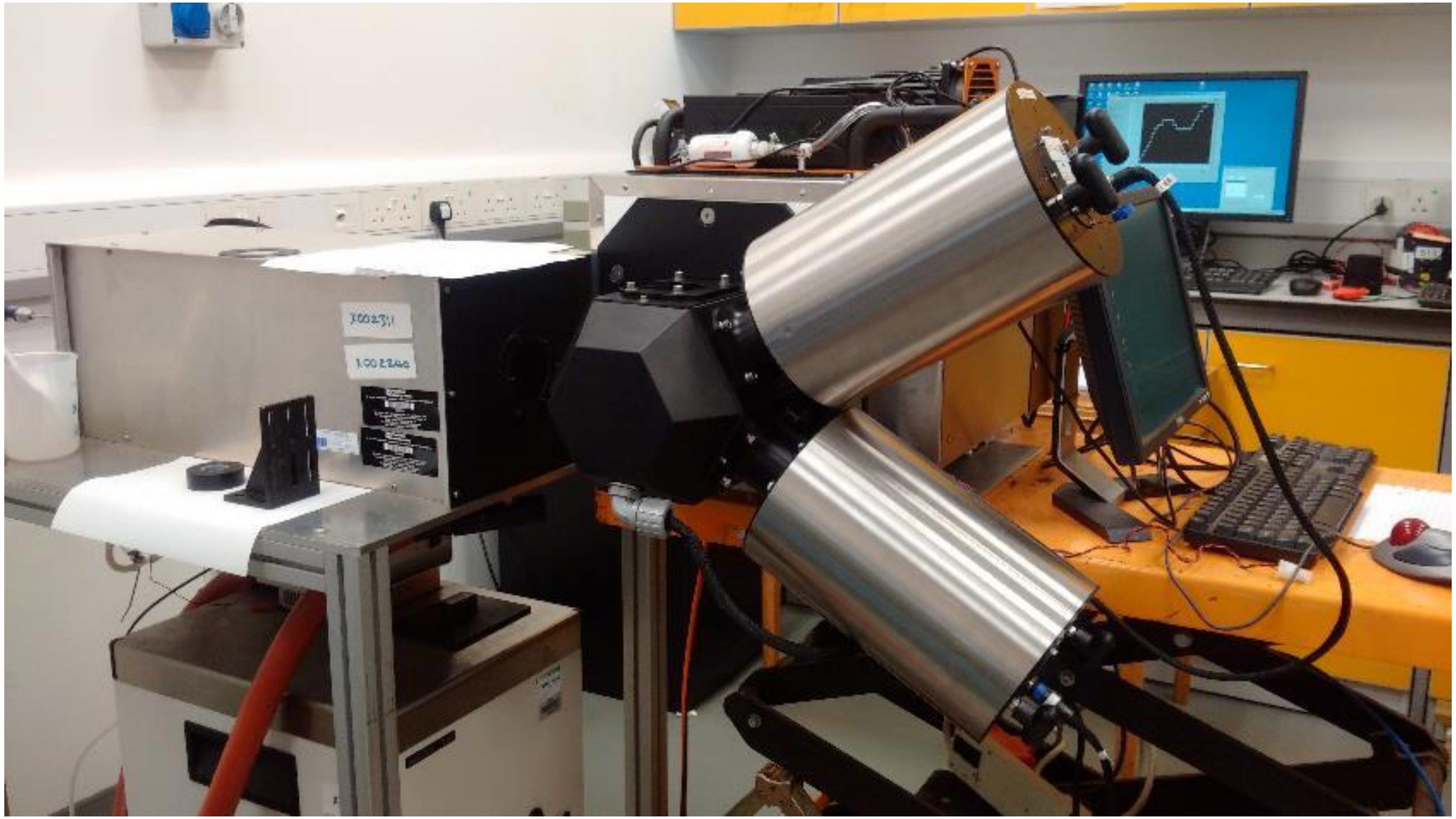
Current Cruise Ship Deployments

Collaboration with Royal Caribbean Cruise Lines

Adventure of the Seas installation in January 2018.

Fiducial Measurements for Surface Temperatures Workshop – NPL, June 2016.

Fiducial Measurements for Surface Temperatures Workshop – NPL, June 2016.



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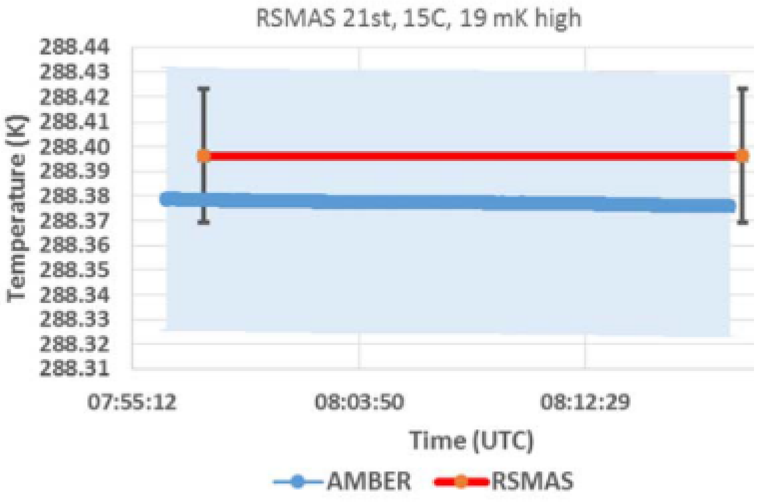
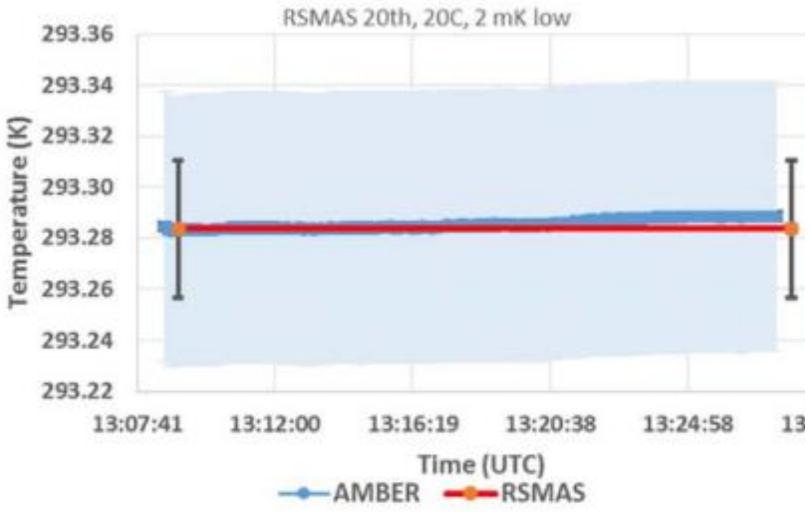
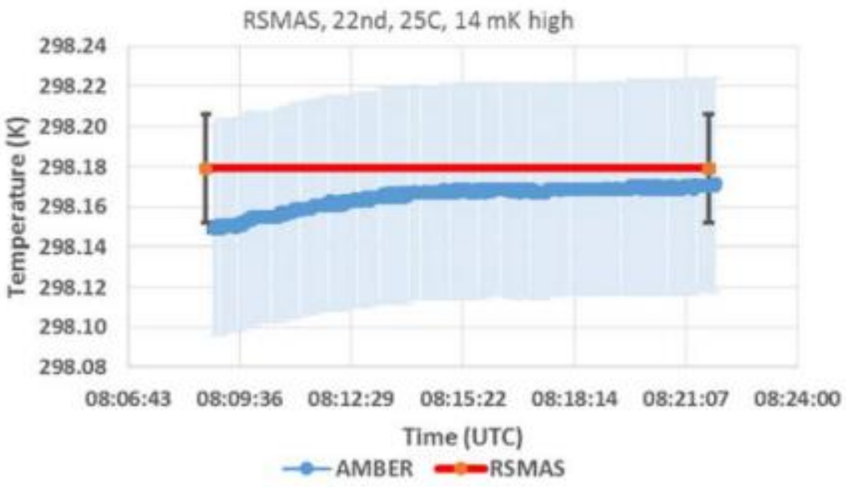
Error Budget of Miami Water-bath Blackbody Target

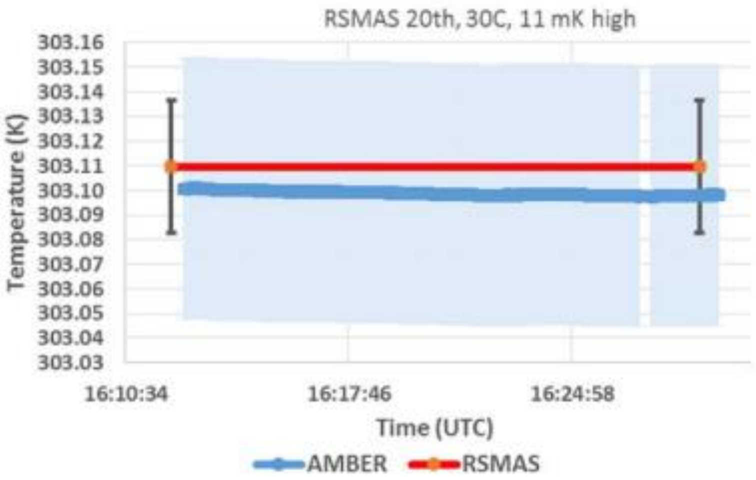
Uncertainty Contribution	Set point temperature							Comments
All values in mK	288	293	298	303	308	313	318	
Thermometer calibration	4.24	4.24	4.24	4.24	4.24	4.24	4.24	Average of two thermometers, each with uncertainty (k=2) of 6.0 mK (Fluke calibration reports, 5 April, 2016)
Blackstack thermometer resistance measurement	0.54	0.12	0.35	0.42	0.13	0.35	0.19	k=2. Fluke calibration report.
Conversion of resistance to temperature	0.35	0.23	0.08	0.07	0.19	0.27	0.30	k=2. Fluke calibration report.
Stability of the water bath	0.16	0.16	0.17	0.17	0.18	0.19	0.17	k=2. 2x standard error of temperature measurements at set points.
Emissivity uncertainty	50.0	50.0	50.0	50.0	50.0	50.0	50.0	Fowler, 1995; Rice et al, 2004. Upper bound. (k=2)
Temperature drop across copper cone	0.5	0.0	0.5	1.0	2.6	2.2	2.8	Fowler, 1995; Table 4. (k=2)
Spatial temperature gradients in cavity	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Thermal imager – no gradients detectable with FLIR SC3000 with sensitivity of 20mK
Radiative heat exchange with environment	15.0	15.0	15.0	15.0	15.0	15.0	15.0	Assumes uncertainty in knowledge of ambient temperature of 0.5K and uncertainty in cone reflectivity of 0.0003; Fowler, 1995.
Convective heat exchange with environment	1.0	1.0	1.0	1.0	1.0	1.0	1.0	From uncertainty budget of NPL Gallium reference BB

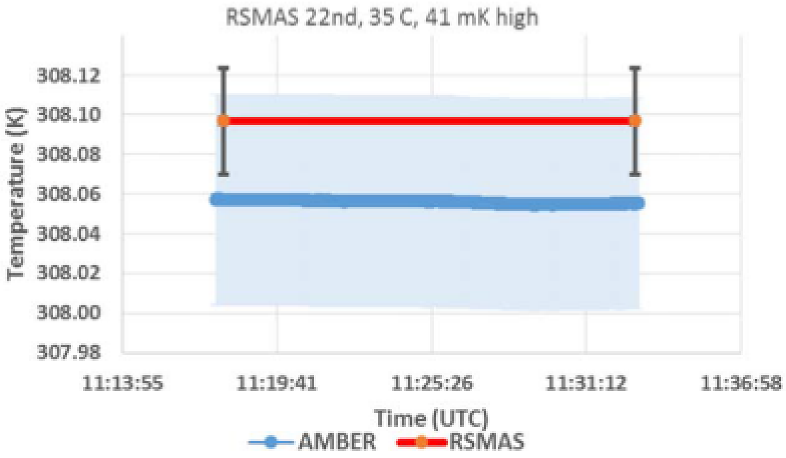
RSMAS Water-bath Blackbody *vs* AMBER



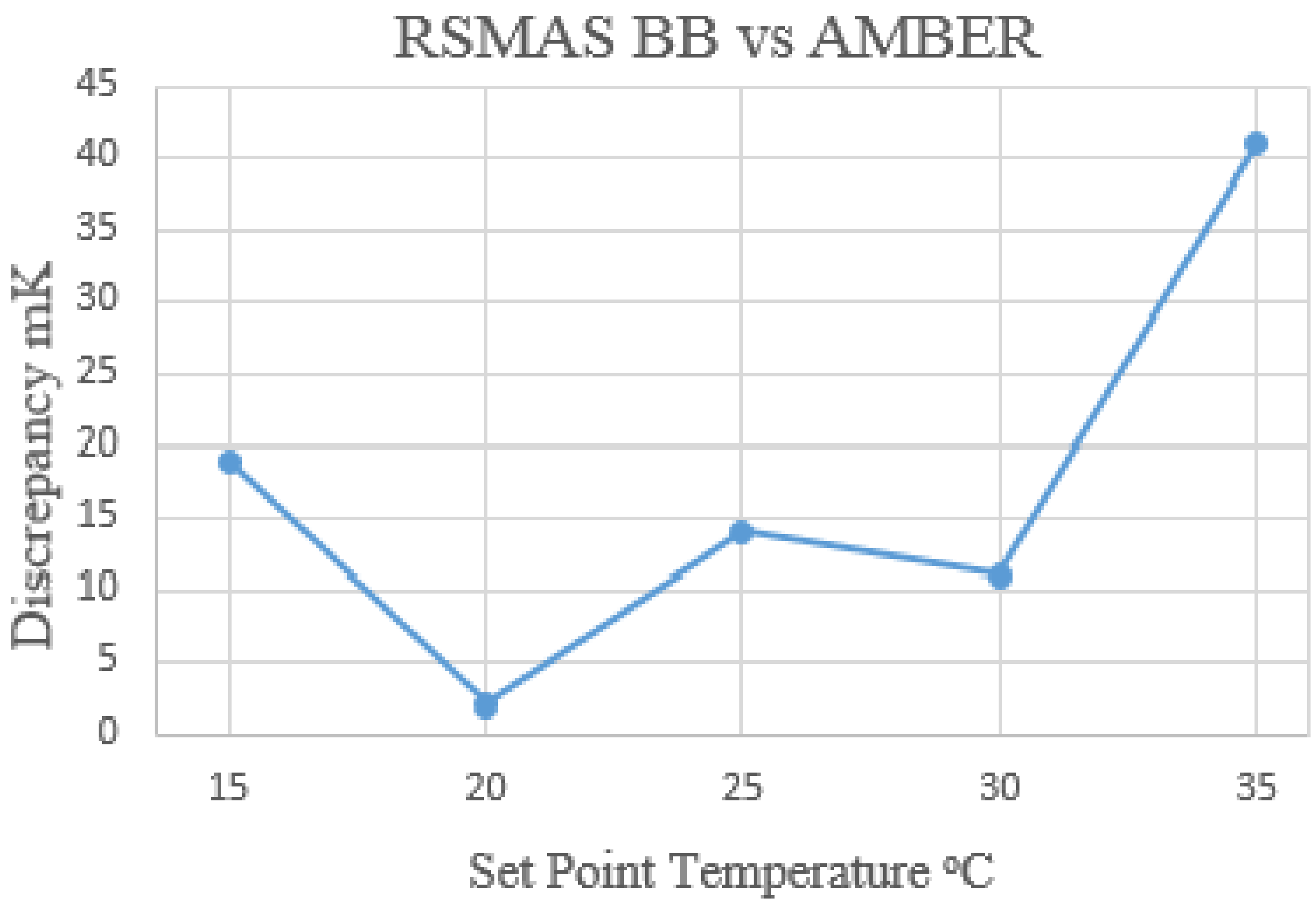








RSMAS Water-bath Blackbody *vs* AMBER



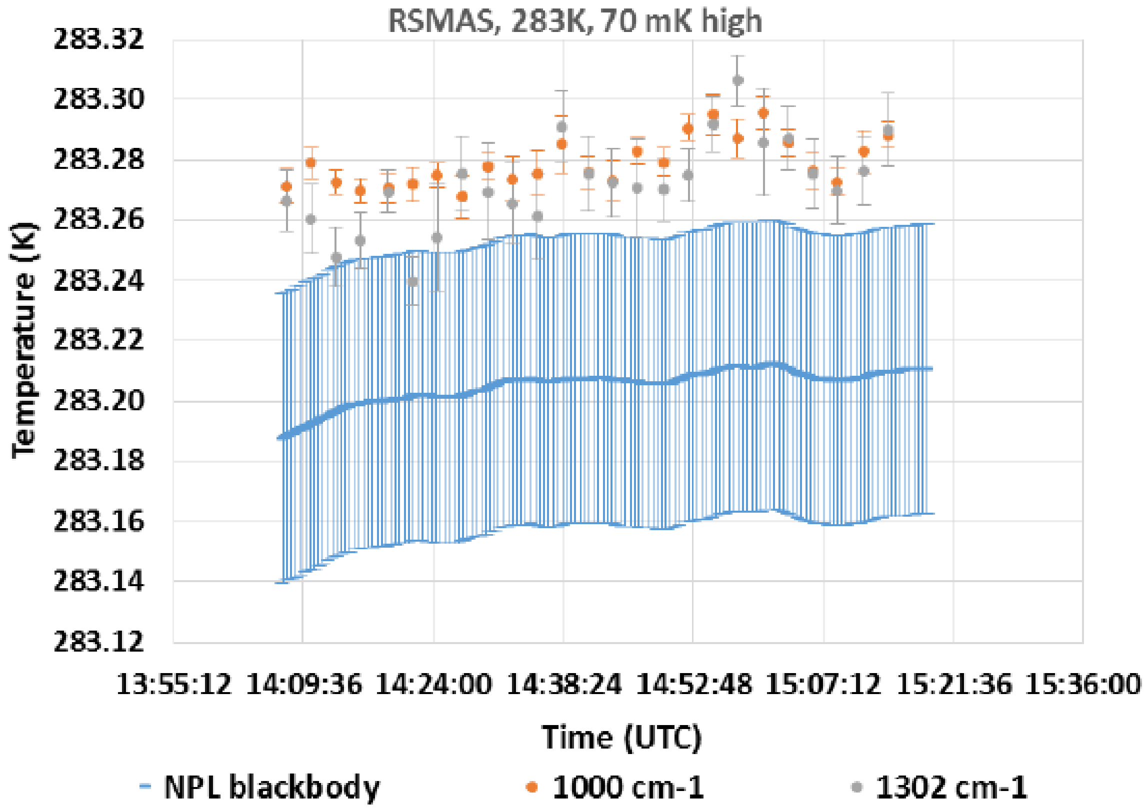
Note: discrepancies are within uncertainties of AMBER reference radiometer.

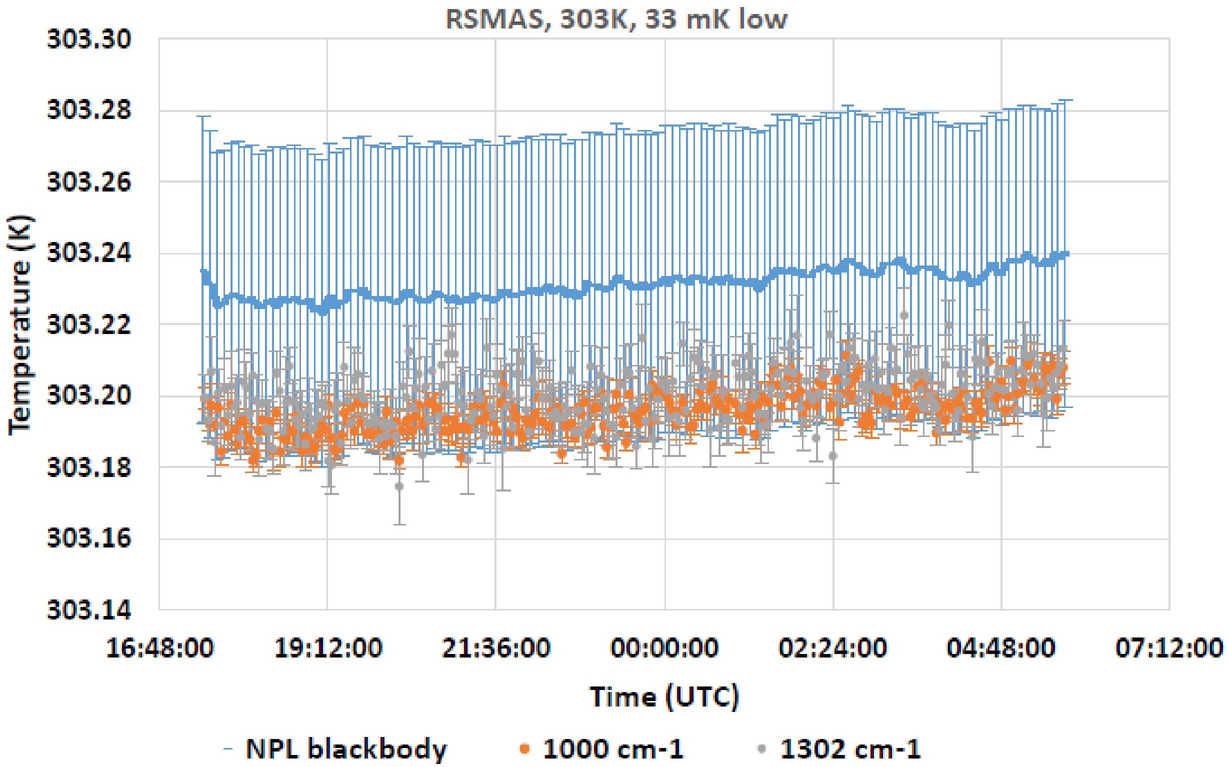
Error Budget of M-AERI measurements

At λ= 10.0 µm (1000 cm^{-1})			
Parameter	Type A Uncertainty in Value [K]	Type B Uncertainty in K	Uncertainty in Brightness temp K
Repeatability of Measurement	0.014		0.014
Reproducibility of Measurement	0.0058 (0.0035)		0.0058 (0.0035)
Linearity of radiometer		0.0003	0.0003
Primary calibration		0.0097	0.0097
Drift since calibration			0
RMS total	0.0152 (0.0144)	0.0102	0.0182 (0.0176)

At λ= 7.7 µm (1302 cm^{-1})			
Parameter	Type A Uncertainty in Value [K]	Type B Uncertainty in K	Uncertainty in Brightness temp K
Repeatability of Measurement	0.0349		0.0349
Reproducibility of Measurement	0.0178 (0.0089)		0.0178
Linearity of radiometer		0.0003	0.0003
Primary calibration		0.0086	0.0086
Drift since calibration			0
RMS total	0.0392 (0.0360)	0.0091	0.0402 (0.0372)

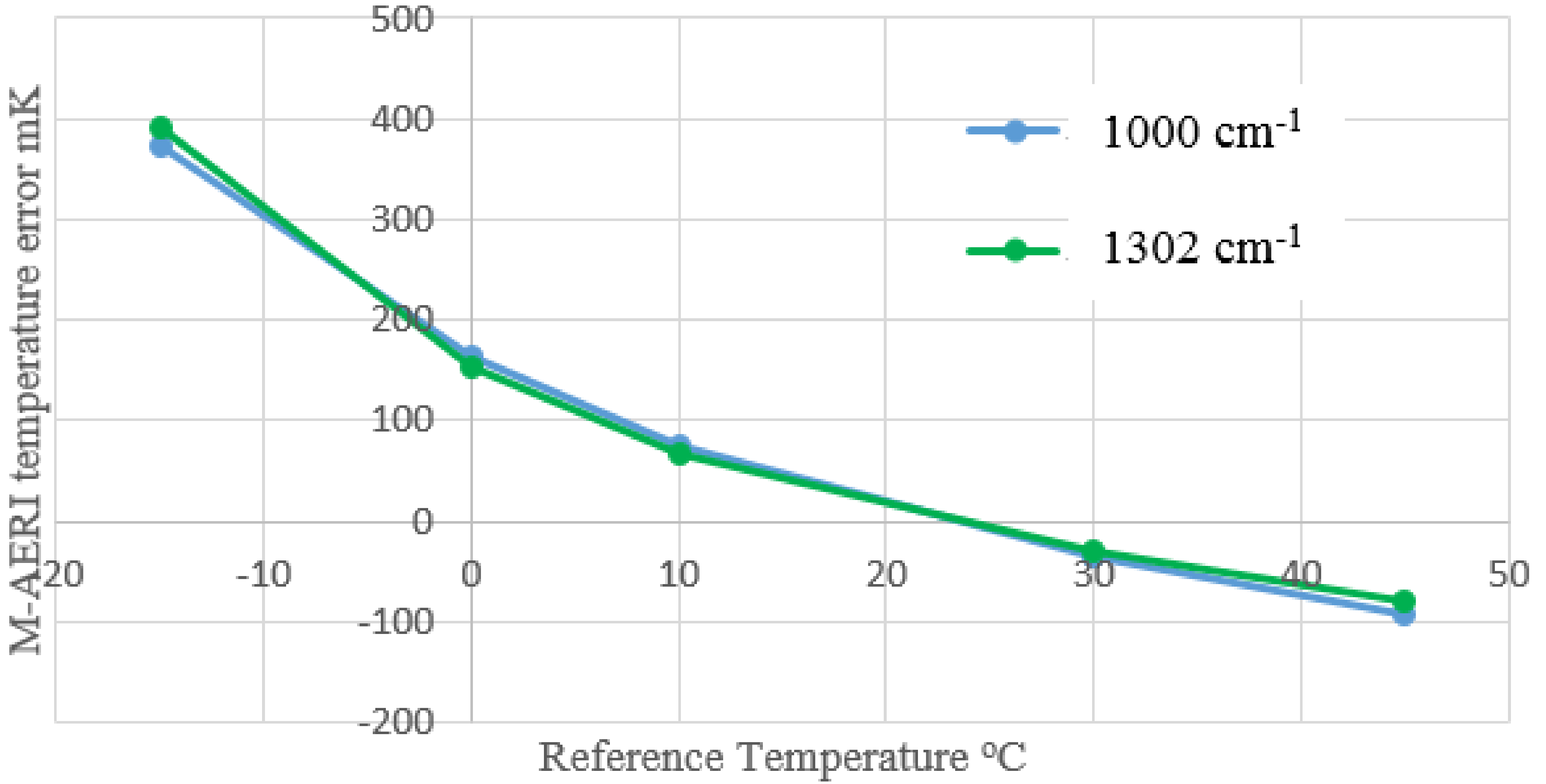
M-AERI *vs* NPL Reference Blackbody





From: Theocharous, E., Barker-Snook, I., & Fox, N.P. (2016). 2016 comparison of IR brightness temperature measurements in support of satellite validation. Part 1: Blackbody Laboratory comparison. NPL REPORT ENV 12. pp. 104. Teddington, Middlesex, UK: National Physical Laboratory

M-AERI *vs* NPL Reference Blackbody



M-AERI vs RSMAS Blackbody

R_m is measured radiance from the RSMAS WB BB cone, which is:

$R_C = [R(T_{BB})*\varepsilon_{BB} + (1-\varepsilon_{BB})*R(T_{amb})]$.

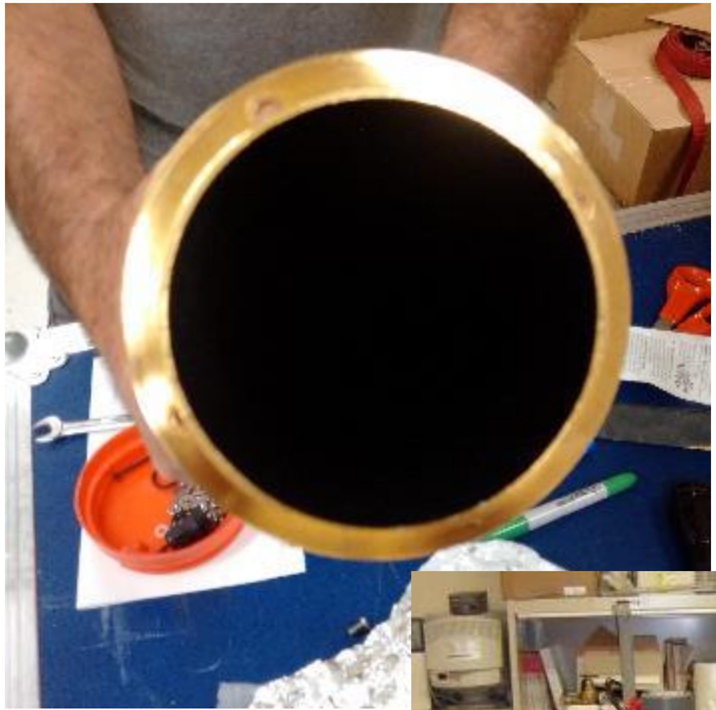
Error is $R_m - R_{C}$.

Wavelength dependence treated explicitly.

Measurements taken at a range of set point temperatures.

Measurements include a third M-AERI BB mounted on the zenith view port of the M-AERI.

ε_{BB} is adjusted to minimize dependence of the error on the target temperature



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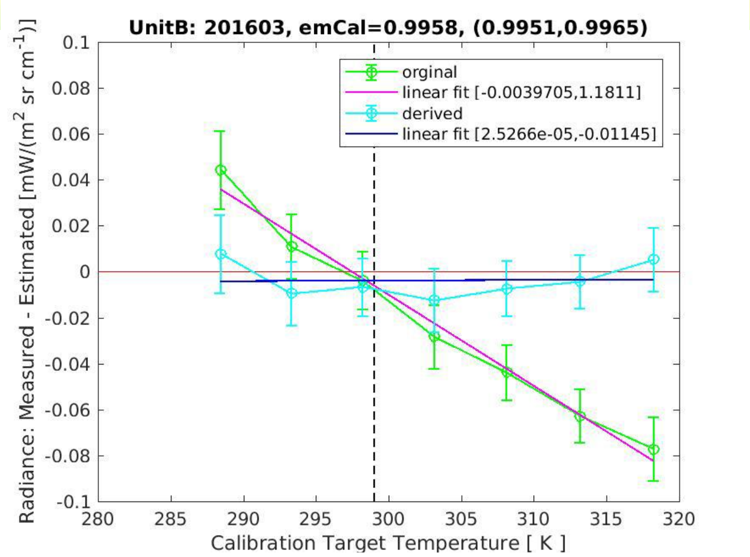
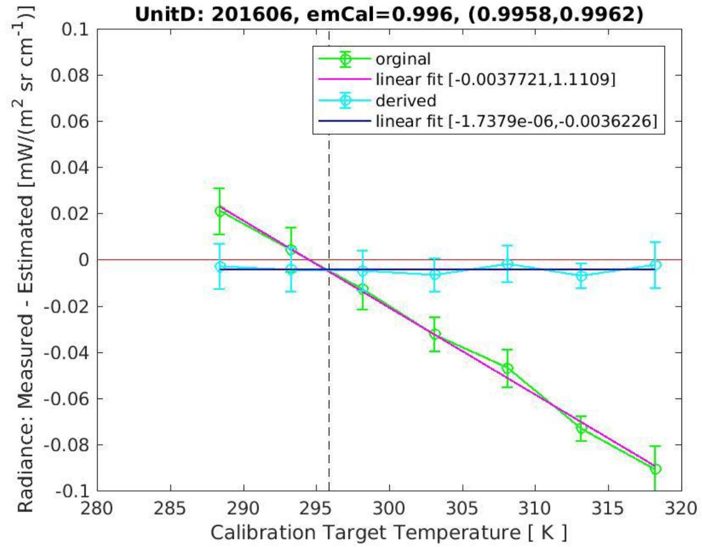
Estimates of Cone Emissivity





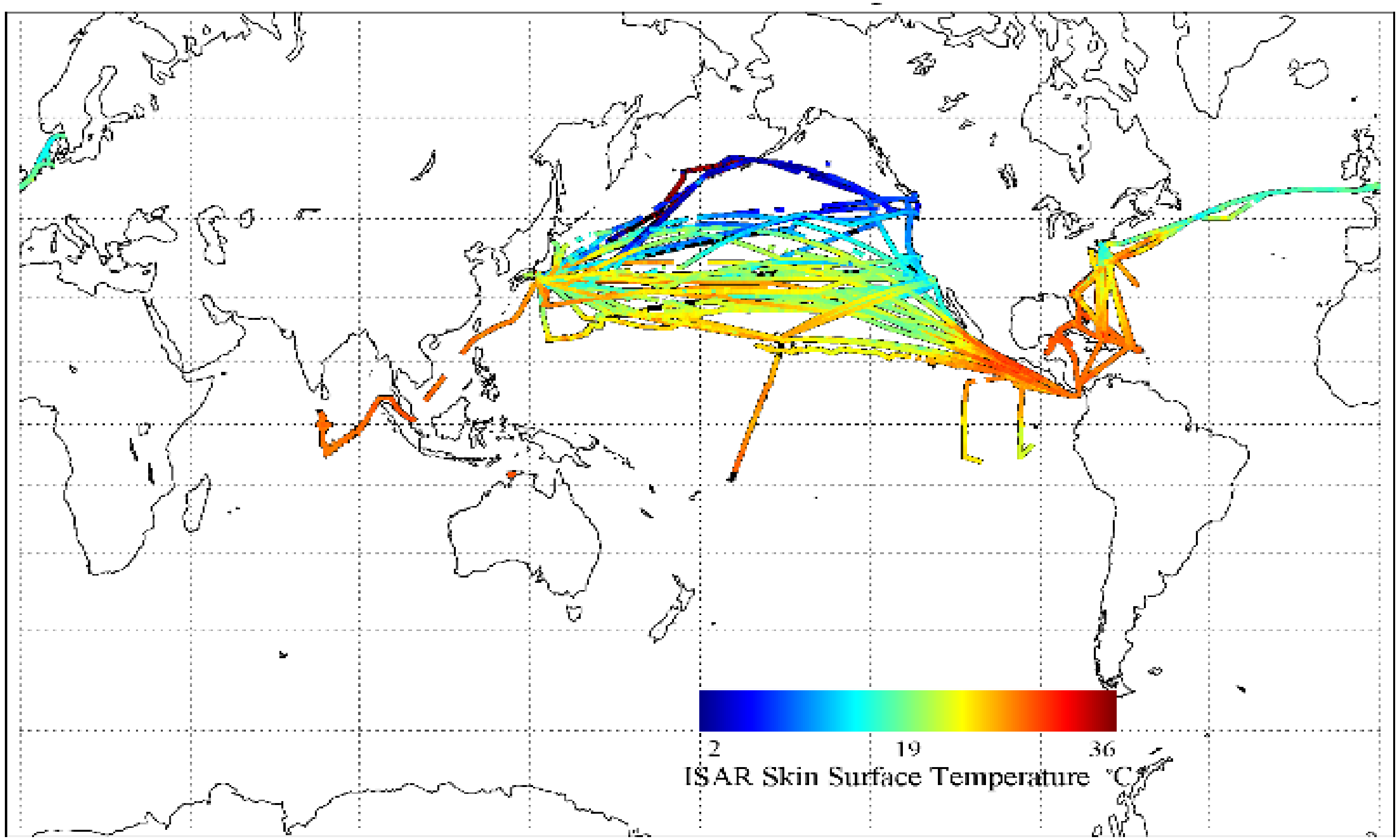
Date	Unit	1300 cm^{-1}	1000 cm^{-1}
2015/03	A	1.0000	1.0000
2015/05	A	1.0000	1.0000
2016/02	A	1.0000	1.0000
2016/02	A	0.9982	0.9989
2017/04	A	0.9982	0.9981
2017/04	A	0.9997	0.9993
2016/03	B	0.9985	0.9984
2016/03	B	0.9958	0.9959
2014/02	C	0.9967	0.9969
2014/02	C	0.9957	0.9955
2015/10	D	0.9963	0.9964
2016/02	D	0.9962	0.9961
2016/02	D	0.9966	0.9964
2016/06	D	0.9961	0.9961
2016/06	D	0.9960	0.9960
2017/06	D	0.9939	0.9937
2017/09	D	0.9946	0.9947
Average		0.9972	0.9971

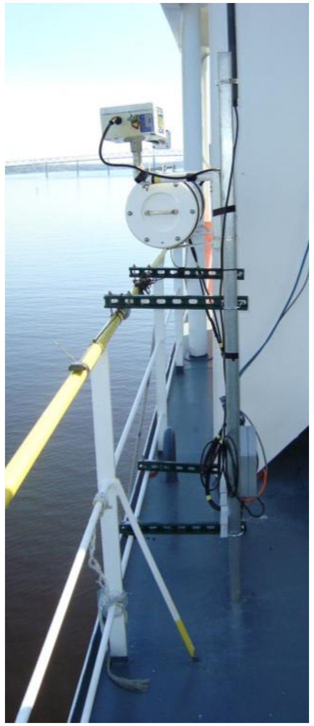
Four M-AERIs show very similar results for the cone emissivity.

These results are for new or recently cleaned mirrors.

Is this a reasonable approach?

RSMAS ISAR Deployments





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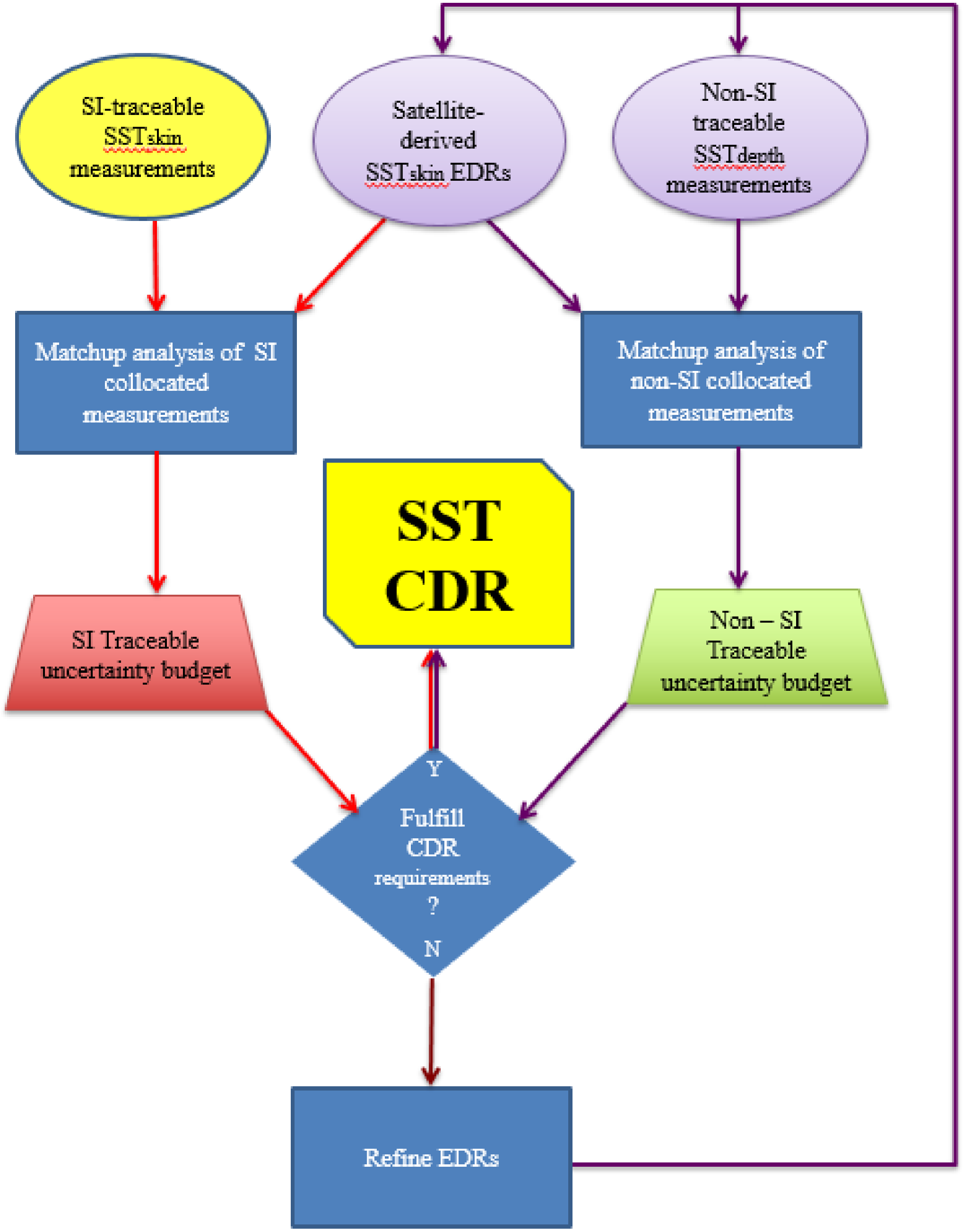
MODIS SSTs & Ship Radiometers

MODIS Skin SST vs M-AERI and ISAR Skin SST. Temperatures in K					
Satellite and Algorithm	Mean	Median	Standard Deviation	Robust St. Deviation	Number
Terra SST Day	0.082	0.080	0.567	0.409	1025
Terra SST Night	0.048	0.034	0.467	0.337	2454
Terra SST4 Night	0.016	0.023	0.339	0.244	2467
Aqua SST Day	0.105	0.107	0.666	0.480	910
Aqua SST Night	0.020	0.027	0.489	0.353	1752
Aqua SST4 Night	-0.010	0.016	0.396	0.285	1858

Generating an SST CDR

- Ship Radiometers Measure skin SST and are SI-traceable.
- But are few in number.
- Buoys measure sub-surface SST, and are not SI-traceable.
- But are numerous, even if not uniformly distributed.



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Outstanding issues

- Better cloud screening and atmospheric correction algorithms.
- Developing full error and uncertainty budgets for satellite-derived SSTs.
- Assess sampling errors in drifting buoy data and ship radiometer measurements.
- The SSES (Sensor Specific Error Statistics) for each SST product should be revisited.
- Improved modeling of thermal skin effect is needed.
- And much more….

Summary

- Target accuracies and decadal stability requirements for SST are very demanding, and challenging to verify.
- Comparison with ship-board radiometers provides a primary mechanism for ensuring satellite SSTs have an SI-traceable reference.
- SI-traceability permits the generation of SST Climate Data Records.
- Experiment to assess thermometer calibration drift in (moored) drifters has started at RSMAS.

Conclusion

the ONION SEARCH

National Science Foundation: Science Hard

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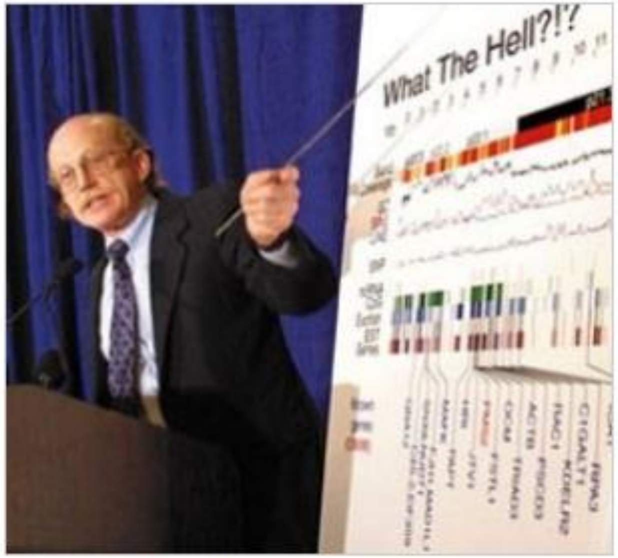
INDIANAPOLIS—The National Science Foundation's annual symposium concluded Monday, with the 1,500 scientists in attendance reaching the consensus that science is hard.



Farian explains the NSF findings.

"For centuries, we have embraced the pursuit of scientific knowledge as one of the noblest and worthiest of human endeavors, one leading to the enrichment of mankind both today and for future generations," said keynote speaker and NSF chairman Louis Farian. "However, a breakthrough discovery is challenging our long-held perceptions about our discipline—the discovery that science is really, really hard."

"My area of expertise is the totally impossible science of particle physics," Farian continued, "but, indeed, this newly discovered 'Law of Difficulty' holds true for all branches of science, from astronomy to molecular biology and everything in between."

And bear in mind….

"God made the bulk; surfaces were invented by the devil."

Wolfgang Pauli

Acknowledgements

- Funding from NASA Earth Science Division & Physical Oceanography Program, NOAA/NESDIS/STAR, U. Miami, RSMAS.
- International Space Science Institute, Bern, Switzerland.
- Royal Caribbean Cruise Lines.
- NYK Lines.
- Captains, officers and crews of many research vessels.
- Michael Reynolds, RMRCo, & Andy Jessup at U. Washington APL.
- Support from Ocean Biology Processing Group at Goddard, and PO.DAAC at JPL.
- Colleagues at RSMAS:
  - Miguel Izaguirre, Katherine A. Kilpatrick, Guillermo P. Podestá, Goshka Szczodrak, Susan Walsh and Elizabeth Williams.

Thank you.