Extending GSICS to Inter-Calibrate Satellite Radiances to an Absolute Scale

Tim Hewison[1], Dave Doelling[2], Constantine Lukashin[2], Dave Tobin[3], Viju John[1], Xiuqing Hu[4], Likun Wang[5] , Dorothée Coppens[1]

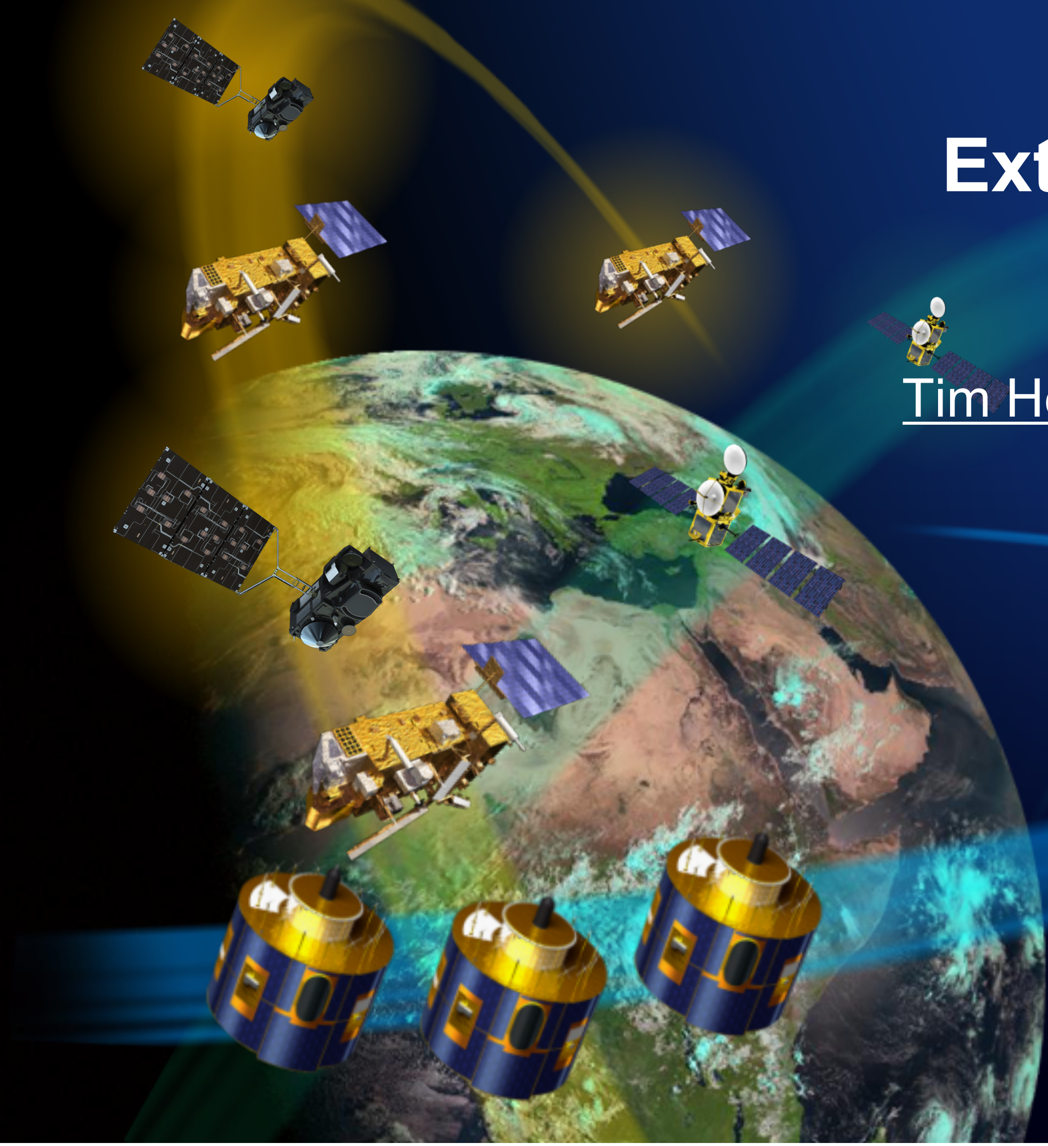
[1]EUMETSAT, [2]NASA-Langley, [3]UWISC-SSEC, [4]CMA-NSMC

[5]Riverside Technology Inc at NOAA,

Presentation for GSICS/CEOS Workshop on

SI-Traceable Space-based Climate Observing System

NPL, 2019-09-09



Outline of Presentation/White Paper

- Introduction to GSICS & products
- Review GSICS products for GEOstationary Imagers
- Application of traceability concept
- How to tie GSICS products to absolute scale
- Conclusions

Global Space-based Inter-Calibration System

What is GSICS?

- Global Space-based Inter-Calibration System
- Initiative of CGMS and WMO
- Effort to produce consistent, well-calibrated data from the international constellation of Earth Observing satellites

What are the basic strategies of GSICS?

- Improve on-orbit calibration by developing an integrated inter-comparison system
  - Initially for GEO-LEO Inter-satellite calibration
  - Being extended to LEO-LEO
- Best practices for calibration & characterisation

This will allow us to:

- Improve consistency between instruments
  - Towards Interoperability
- Reduce bias in Level 1 and 2 products
- Support Cal/Val of new instruments
- Provide traceability of measurements
- Retrospectively re-calibrate archive data
- Better specify future instruments

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GSICS Principles

Systematic generation of inter-calibration products

- **for Level 1 data from** satellite sensors
- **to** compare**,** *monitor* **and** correct **the calibration of *monitored* instruments to community references**
- **by generating calibration corrections on a routine operational basis**
- **with specified uncertainties**
- **through well-documented, peer-reviewed procedures**
- **based on various techniques to ensure consistent and robust results**

Traceability = Unbroken Chain of Comparisons with Associated Uncertainties

Delivery to users

- **Free and open access**
- **Adopting community standards**

GSICS Products

- **Currently empirical corrections to operational calibration coefficients (or alternative cal coeffs)**
  - **Defined in Radiance-space (could also be spectral)**
- **Promote greater understanding of instruments' calibration, by analysing the root causes of biases**
- **Allow Inter-operability:**
  - **Near real-time application for more accurate weather forecasting products**
  - **Re-Analysis application for improved understanding of climate processes**
  - **Re-Calibration of archive data to generate Fundamental Climate Data Records**

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GSICS Corrections for GEO imagers' IR channels

DIRECT INTER-CALIBRATION

Collocate in Space, Time, Angle

- Collect **S**imultaneous **N**adir **O**verpasses (SNOs)
- Tie to contemporary reference instrument
- with very small uncertainty

Hyperspectral Reference (IASI)

- Convolve IASI spectrum with **S**pectral **R**esponse **F**unction (SRF) monitored instrument
- Can diagnose SRF errors

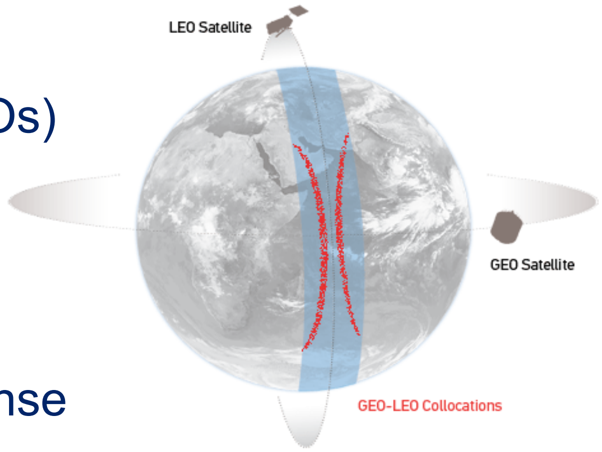
Compare

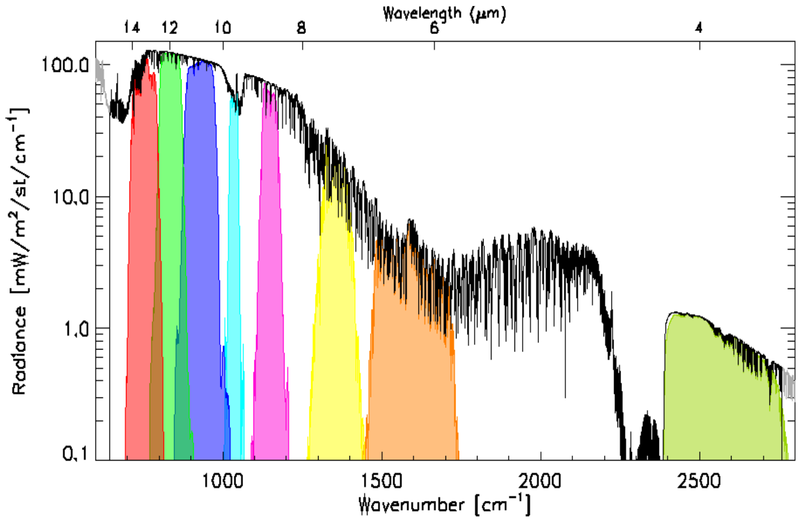
- Apply weighted regression to collocated radiances
- Evaluate uncertainties

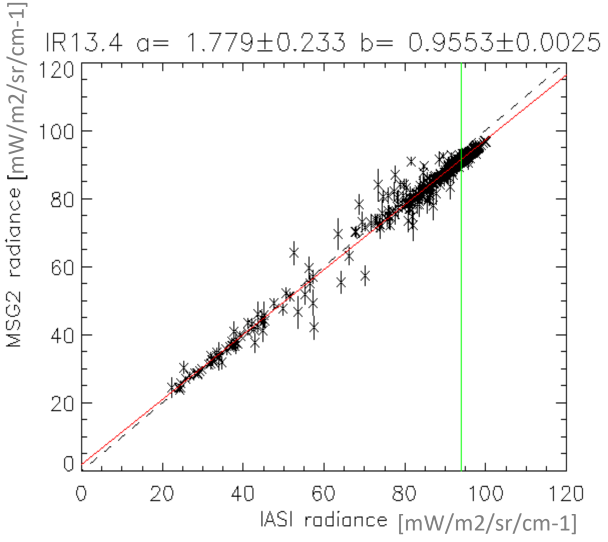
Generate GSICS Correction

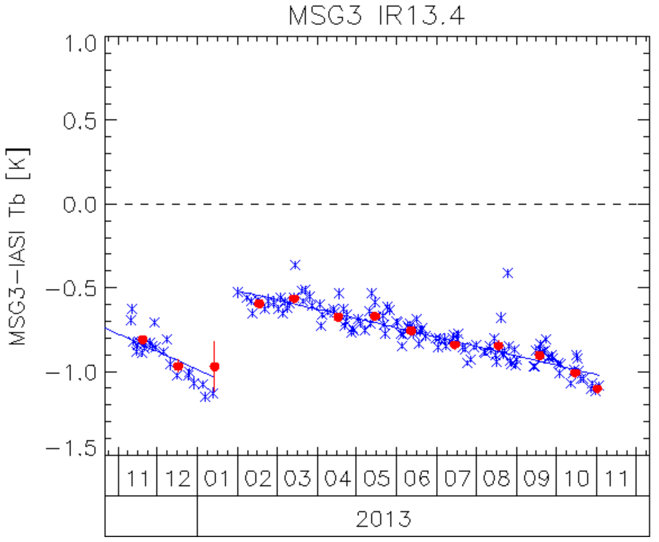
- Update daily
- Distribute via EUMETSAT GSICS Server

Evaluate & Monitor Bias









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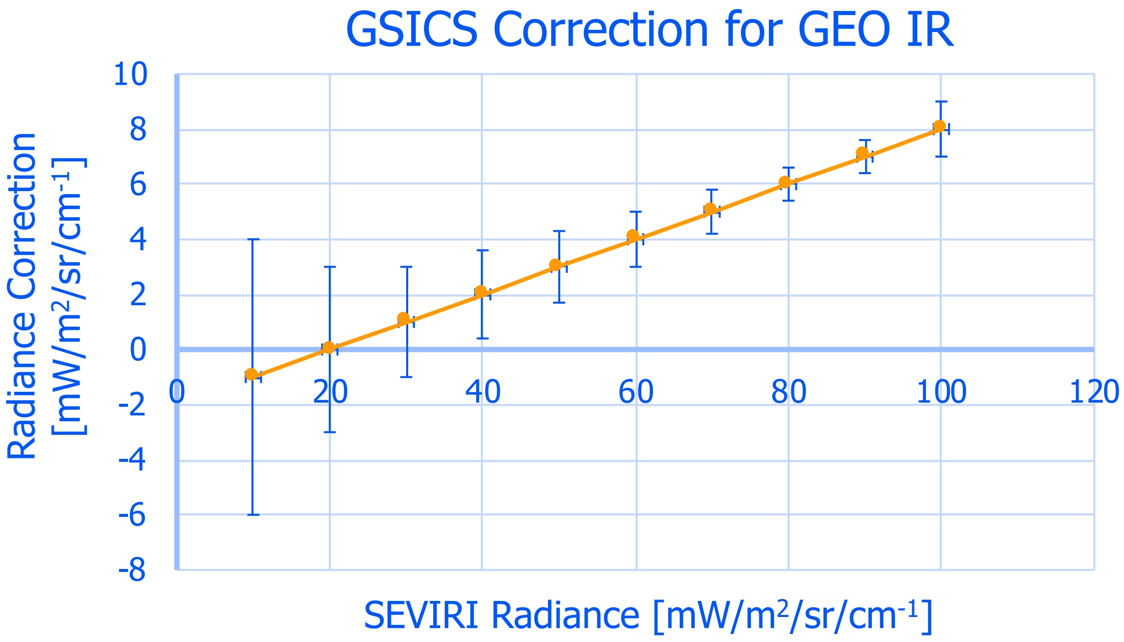
GEO-LEO IR GSICS Corrections

Global Space-based Inter-Calibration System

GEO-LEO IR GSICS Corrections

- Empirical functions fitted
  - in radiance-space of *monitored* instrument
- Each tied to single *reference* sensor
- *Harmonisation* not homogenisation
- Linear functions of scene radiance
- Provided with image-to-image uncertainties
  - Based on propagation through linear regression
  - Validated against Type-B error budget analysis
- Traceable to single *references*
- Updated daily using a monthly window,
- For Near-Real-Time & Re-Analysis



Schematic illustration of typical GSICS Correction applied to 13.4μm channel of Meteosat-9, based on inter-calibration with IASI.

Correction is radiance-dependent.

Uncertainties increase for extreme radiances.
Radiance Units: mW/m²/sr/cm⁻¹

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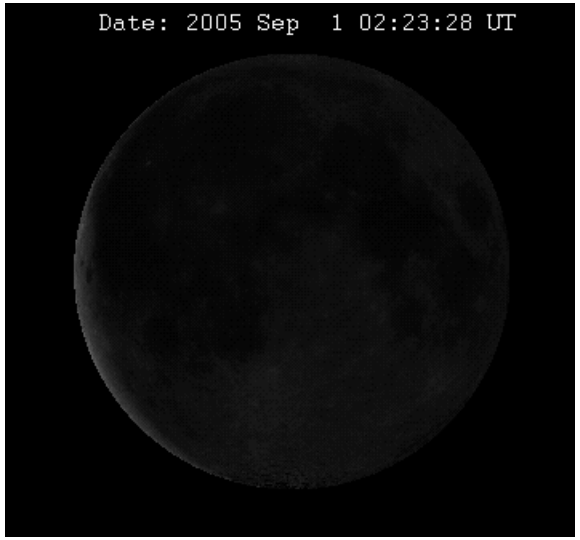
GSICS Calibration of GEO imagers' VIS/NIR channels

INDIRECT INTER-CALIBRATION, using

- *Pseudo Invariant Calibration Targets* (PICTs) = Sites (PICS) + Moon + DCC + …
- To transfer calibration from single reference instrument
  - Currently NOAA-20/VIIRS
  - Over a static period (when reference calibration is stable)
- But no suitable hyperspectral reference covering full VIS/NIR band
  - Need Spectral Band Adjustment Factors (SBAFs)
- Uncertainties derived from statistics of invariant targets' time series
  - Difficult to propagate uncertainties through RTMs

GSICS Calibration for GEO imagers' VIS/NIR channels = Blend of methods:

- Deep Convective Cloud (DCC)
  - Globally available in equatorial band
  - Selected based on IR, SZA, VZA thresholds - Invariant Reflectance – up to ~1μm
  - Long-term stability unknown – needs monitoring
- Moon
  - Based on GSICS Implementation of ROLO lunar irradiance model (GIRO)
  - Applicable between 350 and 2500nm, Phase angles ~±(2-90)° - See Tom Stone presentation
- Deserts – potentially, in the future



Introduction - *Prime GSICS Corrections*

- Comparison of two IASI references -

- GSICS products derived from different reference instruments give slightly different results

- Aim to anchor to ONE reference
- Check references' relative stability
- Combine results from multiple references
- Correct Systematic Differences
- Using *Delta Corrections*
  - from double differences
- Used in *Prime GSICS Corrections*

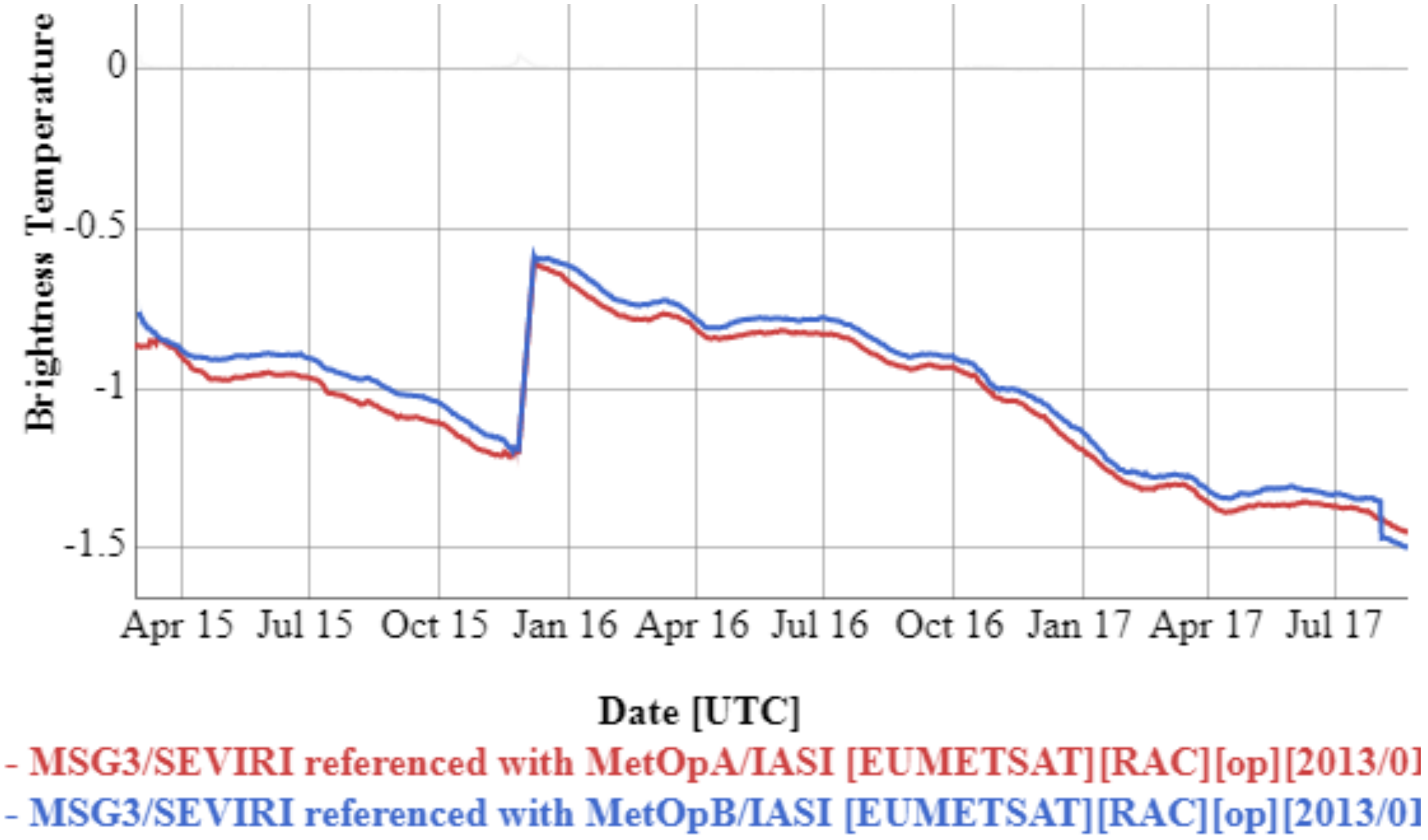
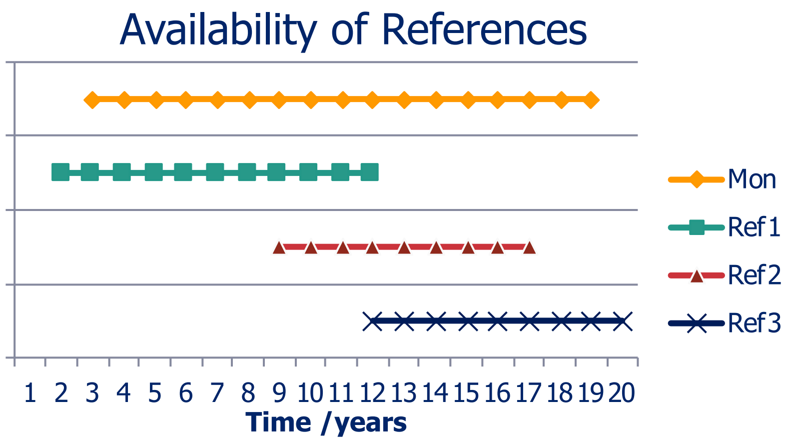
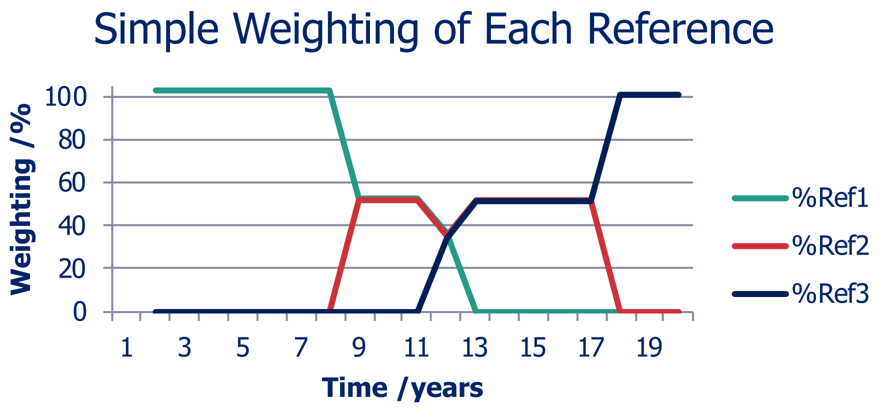


Figure: Time-series of bias in 13.4μm channel of SEVIRI on Meteosat-10 relative to Metop-A/IASI and Metop-B/IASI 2015-2017

Concept – *Prime GSICS Corrections*

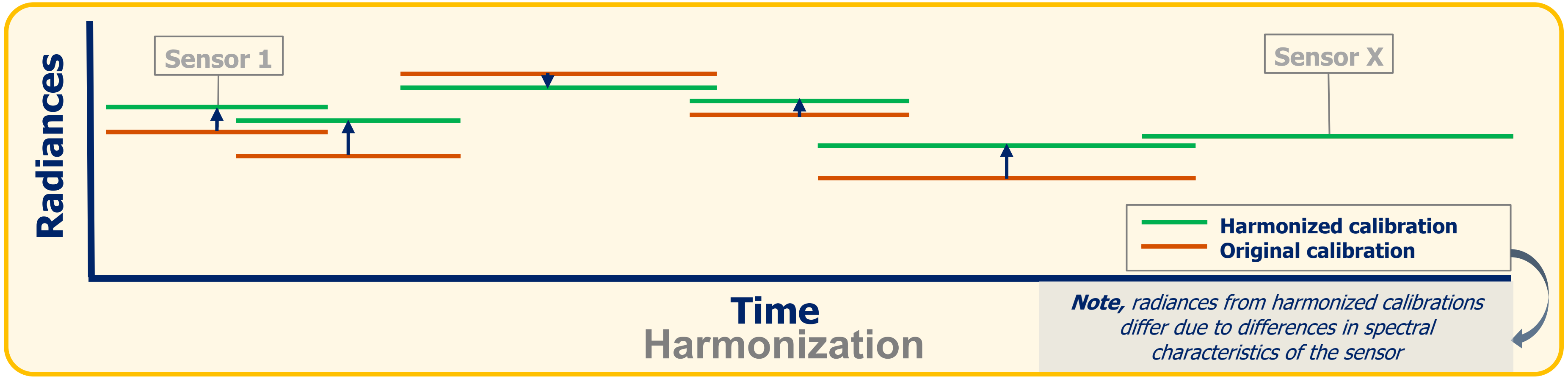
- Prime corrections aim to correct for biases between different reference instruments and combine them
- Define one *Anchor GSICS Reference*
  - For each spectral band/application
  - By consensus agreement within GSICS
- Use other references as *Transfer References*
- Construct *delta corrections* from double-differences
- Apply to GSICS Corrections from each reference
- So they are consistent with the anchor reference
- **Blend** modified corrections, accounting for uncertainties
- Ensures long-term continuity without calibration jumps
- Traceability back to single *Anchor GSICS Reference*
- Propagate uncertainties from all constituent parts
- But how to account for possible drifts outside overlaps?





Example – *Prime Corrections*

- Applying Prime Corrections to create a Fundamental Climate Data Record -



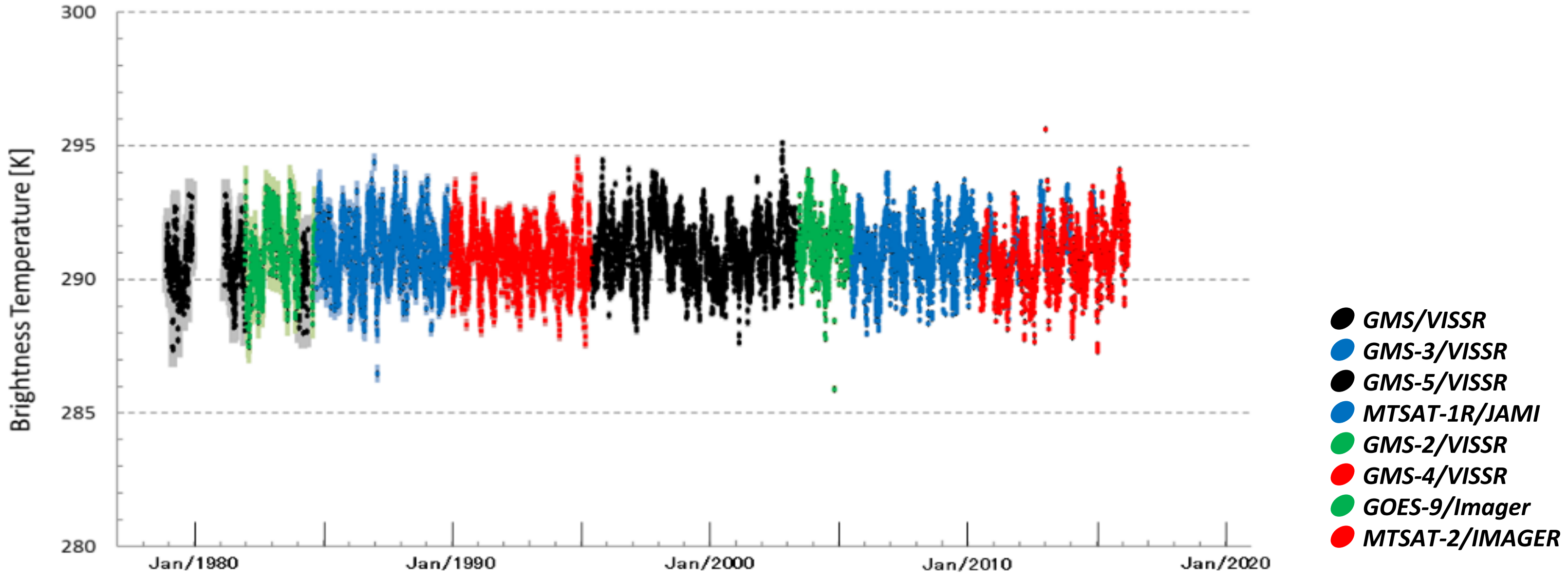


Figure : *Harmonized time-series of GMS, GMS-2, GMS-3, GMS-4, GMS-5, GOES-9, MTSAT-1R and MTSAT-2 of infrared clear sky radiances using Metop-A/IASI as Prime Reference (Tabata et al. 2019, Remote Sensing)*

Applicability of Prime GSICS Correction to FCDRs

- Previous slide showed Prime GSICS Correction approach applicable
  - to re-calibration of Japanese geostationary imagers
  - to generate for Fundamental Climate Data Records
  - using historical references
  - based on a series of double-differences
  - to tie whole time series to CLARREO-like reference at one point in time
  - Demonstrated in [Tabata et al. 2019] and [John et al. 2019]
  - See also Samuel Hunt presentation

- Drifts in reference satellites' bias before/after overlaps are difficult
  - So far, assumed this bias is time-invariant – based on analysis of overlap
  - Also assume no diurnally varying biases in GEO radiances
    - Spin stabilised GEOs may play key role as bridges
    - because 3-axis stabilised GEOs may have diurnally varying biases

GSICS IR Reference Traceability & Uncertainty Report

- Aims
  - To support choice of reference instruments for GSICS
  - To provide traceability between IR reference instruments (IASI, AIRS, CrIS)
  - To seek consensus on uncertainties in absolute calibration of reference sensors
  - By consolidating pre-launch test results and various in-flight comparisons

1. Error Budget & Traceability
   - Focus on radiometric and spectral calibration – for AIRS, IASI, CrIS
   - Analysed following common approach [Tobin *et al.*, 2013] – see next slide
   - To generate directly comparable error budgets for all reference sensors

2. Inter-comparisons
   - Introduction: Pros and Cons of each method
   - Direct Comparisons: Polar SNOs, Tandem SNOs (AIRS+CrIS), Quasi-SNOs,
   - Double-Differencing: GEO-LEO, NWP+RTM, Aircraft campaigns
   - Bin all results in common spectral/radiance intervals to allow direct comparisons – see following slide

Suomi-NPP CrIS Radiometric Uncertainty Estimates – D. Tobin

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Global Space-based Inter-Calibration System

Differential error analysis of the calibration equation, aimed at providing a useful estimate of the absolute accuracy of the mean of a large ensemble of observations. Input parameter uncertainties are based on the design of the sensor and engineering estimates of the calibration parameters; i.e. no external information via external "Cal/Val" used.
Tobin et al. (2013), Suomi-NPP CrIS radiometric calibration uncertainty, JGR Atmos.

Simplified On-Orbit Radiometric Calibration Equation:

$$R_{Earth} = \mathcal{Re}\{(C'_{Earth} - C'_{Space}) / (C'_{ICT} - C'_{Space})\}\, R_{ICT}$$

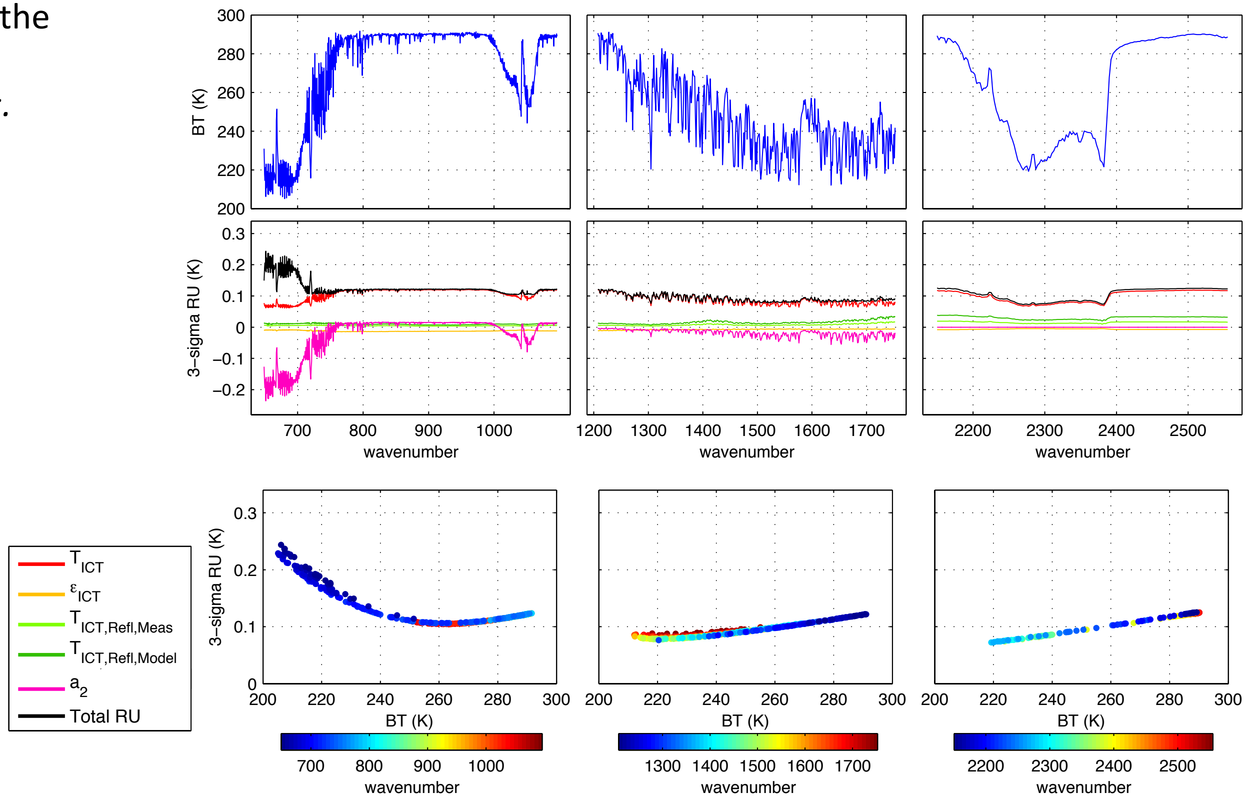
with:

Nonlinearity Correction: $C' = C \cdot (1 + 2\, a_2 V_{DC})$
ICT Predicted Radiance:

$$R_{ICT} = \varepsilon_{ICT} B(T_{ICT}) + (1-\varepsilon_{ICT}) [0.5\, B(T_{ICT,\, Refl,\, Measured}) + 0.5\, B(T_{ICT,\, Refl,\, Modeled})]$$

Parameter	Nominal Values	3-σ Uncertainty
T_{ICT}	280K	112.5 mK
ε_{ICT}	0.974-0.996	0.03
$T_{ICT,\, Refl,\, Measured}$	280K	1.5 K
$T_{ICT,\, Refl,\, Modeled}$	280K	3 K
a_2 LW band	0.01 – 0.03 V^{-1}	0.00403 V^{-1}
a_2 MW band	0.001 – 0.12 V^{-1}	0.00128 – 0.00168 V^{-1}

Example 3-sigma RU estimates for a typical warm, ~clear sky spectrum:



- RU is generally 0.2K 3-sigma or less, and similar results for JPSS-1 CrIS
- Currently working to include (relatively small) polarization effects into the calibration algorithm and corresponding RU estimates
- See also Tom Pagano presentation

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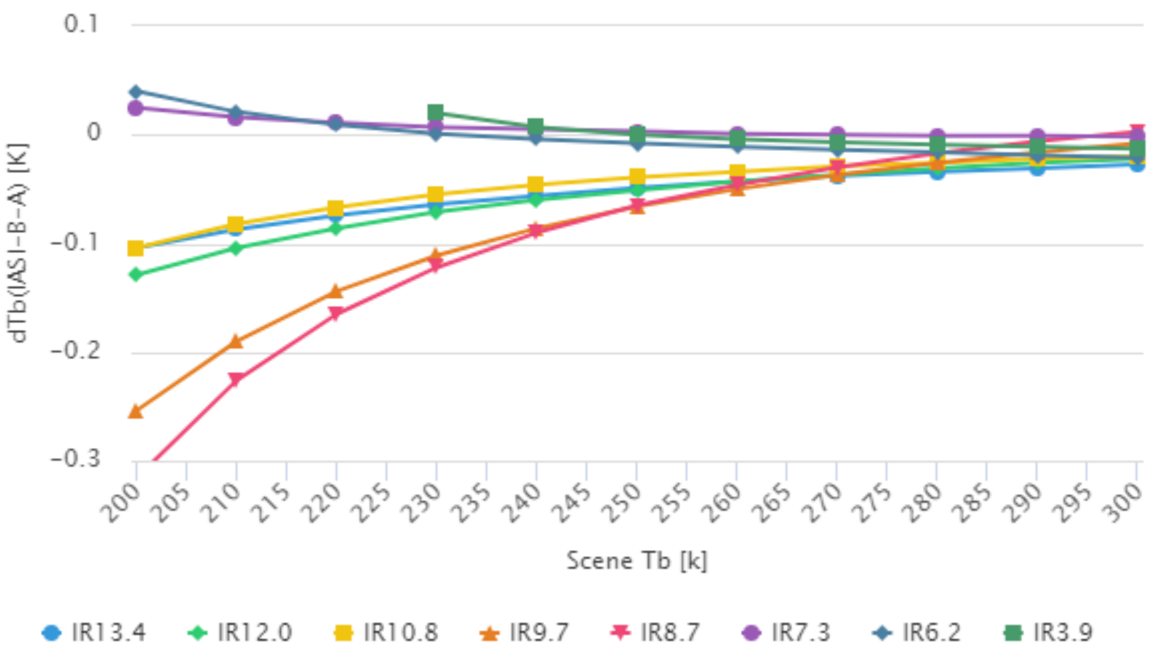
IR Reference Sensor Inter-Comparisons

- Form consensus on relative calibration
  - Re-binning results of existing comparisons
- Biases with respect to Metop-A/IASI
  - With standard uncertainties (k=1)
- At common spectral resolution
  - In 10cm-1 bins within AIRS bands
  - Or average results over broad-band channels
- Converted into Brightness Temperatures
  - For specific radiance scenes 200-300K
- For all viewing angles
  - and/or for specific ranges - e.g. nadir ±10°
- Over specific period
  - Common 4-year period from IASI-B start
- Easy to inter-compare and Calculate Double-Differences

			Mean Difference dTb [K]					
		Pseudo Channel [cm-1]	200	220	240	260	280	300
Start date	2013-08-01	655	-0.11	-0.10	-0.08	NaN	NaN	NaN
End date	2016-06-30	665	-0.09	-0.08	-0.08	NaN	NaN	NaN
Start time	21:53	675	-0.06	-0.07	-0.06	NaN	NaN	NaN
End time	23:21	685	-0.05	-0.05	-0.05	NaN	NaN	NaN
Min Latitude [°]	-74.31	695	-0.05	-0.05	-0.04	NaN	NaN	NaN
Max Latitude [°]	74.31	705	-0.10	-0.05	-0.03	NaN	NaN	NaN
Min Longitude [°]	-179.87	715	-0.11	-0.07	-0.03	NaN	NaN	NaN
Max Longitude [°]	180	725	-0.11	-0.10	-0.05	-0.02	NaN	NaN
Min Scan Angle [°]	0	735	-0.11	-0.10	-0.05	-0.01	NaN	NaN
Max Scan Angle [°]	3.5	745	-0.12	-0.12	-0.06	-0.03	NaN	NaN
		755	-0.11	-0.12	-0.08	-0.04	-0.01	NaN
Collocation method:	Big circle SNO	765	-0.11	-0.12	-0.08	-0.05	-0.04	NaN
Collocation dist [km]	50	775	-0.11	-0.12	-0.08	-0.04	-0.04	-0.50
Collocation time [s]	1200	785	-0.11	-0.11	-0.08	-0.05	-0.03	-0.15
Collocation sec(theta)		795	-0.11	-0.11	-0.07	-0.04	-0.04	NaN
Filtering applied	see ref	805	-0.10	-0.10	-0.07	-0.04	-0.04	-0.24
		815	-0.10	-0.10	-0.07	-0.04	-0.03	-0.17
Algorithm Ref	JGR Tobin 2016	825	-0.11	-0.11	-0.07	-0.04	-0.03	-0.18
Dataset Ref		835	-0.11	-0.11	-0.07	-0.04	-0.03	-0.18
Monitored Instrument	IASI-A L1C	845	-0.11	-0.10	-0.06	-0.04	-0.03	-0.16
Processing Version	latest	855	-0.11	-0.11	-0.06	-0.04	-0.03	-0.16

IR Reference Sensor Inter-Comparisons

- Form consensus on relative calibration
  - Re-binning results of existing comparisons
- Biases with respect to Metop-A/IASI
  - With standard uncertainties (k=1)
- At common spectral resolution
  - In 10cm-1 bins within AIRS bands
  - Or average results over broad-band channels
- Converted into Brightness Temperatures
  - For specific radiance scenes 200-300K
- For all viewing angles
  - and/or for specific ranges - e.g. nadir ±10°
- Over specific period
  - Common 4-year period from IASI-B start
- Easy to inter-compare and Calculate Double-Differences



- Mean Double Difference IASI B-A – wrt Meteosat/SEVIRI
  - Plotted where uncertainty < 0.1K
  - Difference increase for colder scenes in all channels
- SWIR: V. small positive differences (<<0.1K)
- MWIR: V. small positive differences (<<0.1K)
- LWIR window: Small negative differences (<~0.1K)
- LWIR absorption: Larger negative differences (<~0.3K)

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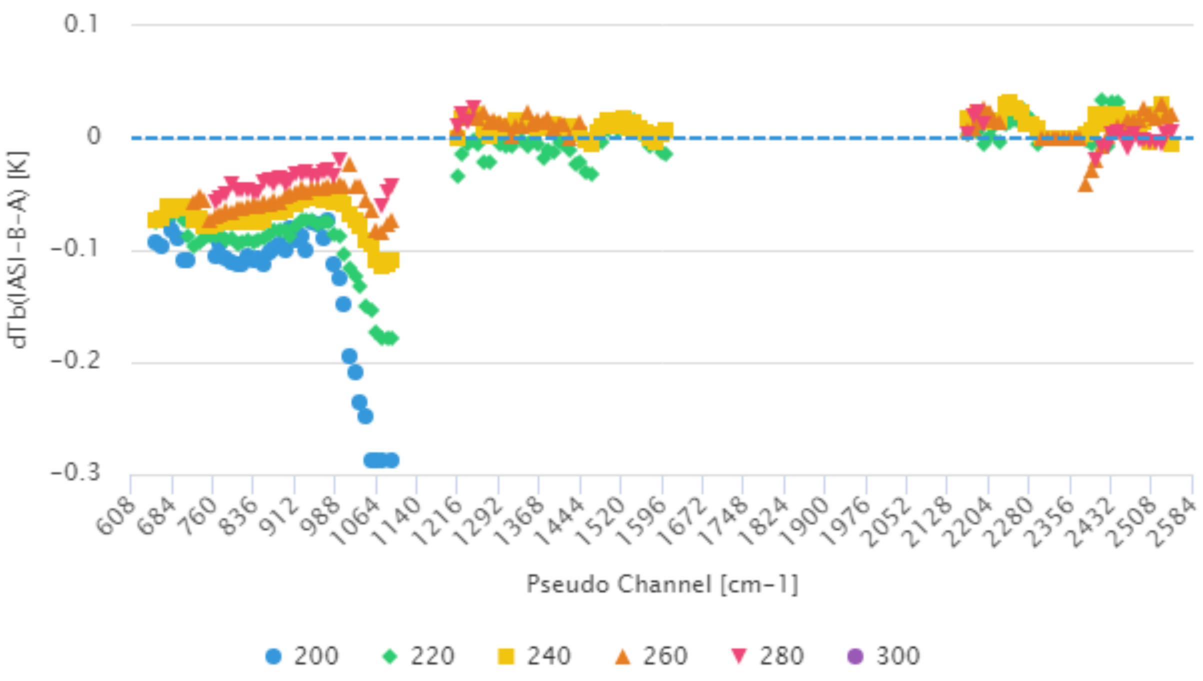

- Mean Double Difference IASI B-A – wrt S-NPP/CrIS
  - Plotted where uncertainty < 0.1K (0.15K for 200K)
  - Difference increase for colder scenes in all channels
- SWIR: V. small positive differences (<<0.1K)
- MWIR: V. small positive differences (<<0.1K)
- LWIR window: Small negative differences (<~0.1K)
- LWIR absorption: Larger negative differences (<~0.3K)

IR Reference Sensor Inter-Comparisons

GSICS Global Space-based Inter-Calibration System

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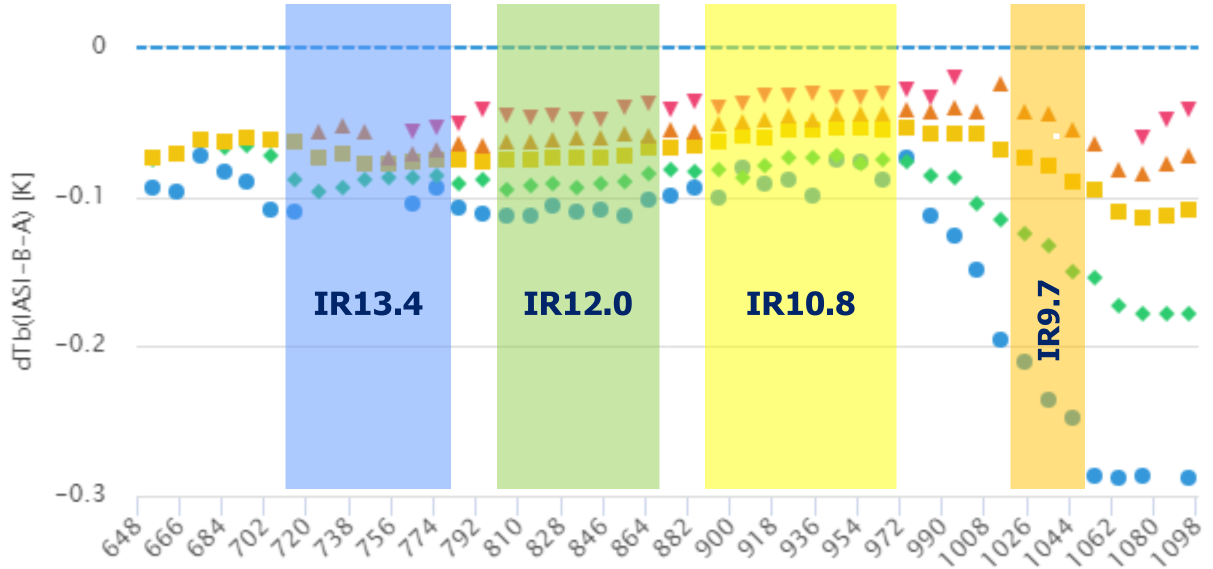

SEVIRI-CrIS DD	200	220	240	260	280	RMSD	
IR13.4	0.00	0.02	0.02	0.02	0.02	0.016	K
IR12.0	-0.02	0.01	0.01	0.02	0.01	0.015	K
IR10.8	-0.02	0.01	0.01	0.01	0.01	0.012	K
IR9.7	-0.03	-0.01	-0.01	-0.01	-0.03	0.020	K
IR8.7							
IR7.3		0.02	-0.01	-0.01		0.013	K
IR6.2		0.01	-0.01	-0.01		0.010	K
IR3.9		0.03	-0.01	-0.01	-0.01	0.018	K
r.m.s. Double Difference IASI-B-A derived from SEVIRI and CrIS						0.016	K

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Tying GSICS Products to Absolute Scale

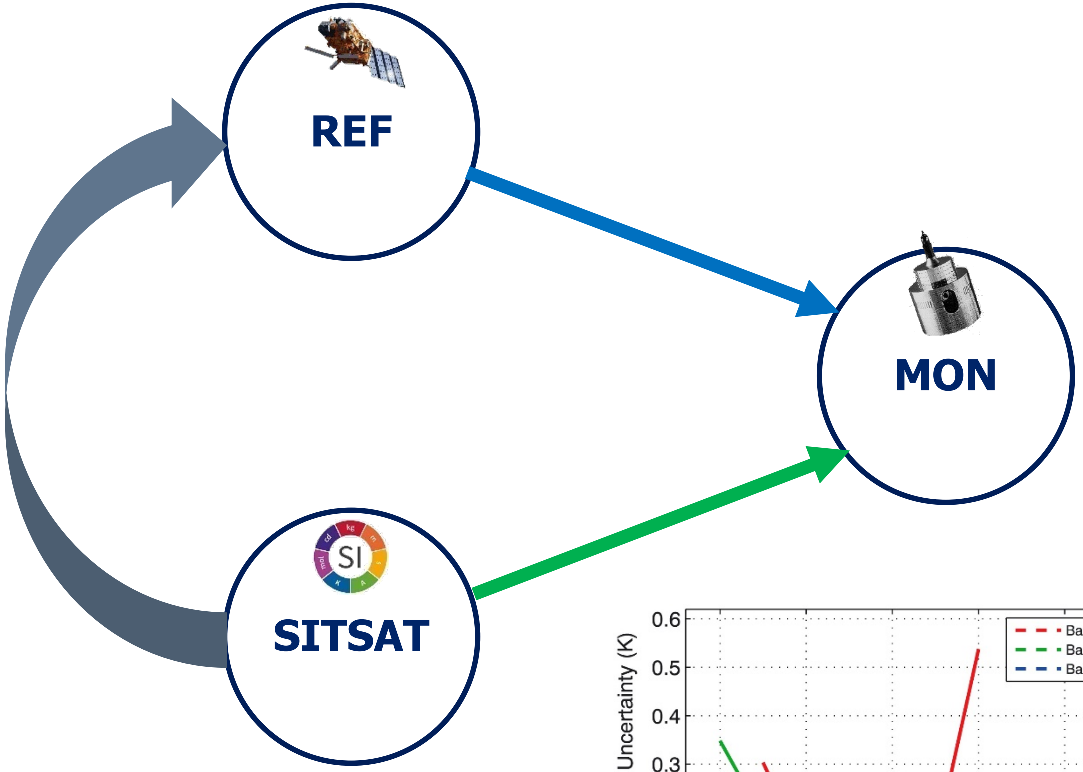
- Pre-launch instrument tests against SI standards
  - See Paul Green presentation
  - CEOS+GSICS Workshop 2020 on pre-flight characterisation/calibration
- Traceability chain may be compromised during launch
  - due to uncontrolled changes to the instrument and its operating environment
- GSICS endorses establishing of a Space-based Climate Observing System
  - with calibration directly traceable to SI-standards on-orbit
  - e.g. CLARREO, its Pathfinder, or TRUTHS
  - Generically referred to here as *SI-Traceable Satellite* instruments (SITSATs)
  - to act as an inter-calibration reference,
  - which could be used to anchor inter-calibration products to an absolute scale
  - Ideally hyperspectral with non-synchronous orbit
    - To cover all reference instruments, Characterise diurnal variations, Viewing/Solar Geometry
  - Long-term aim of GSICS

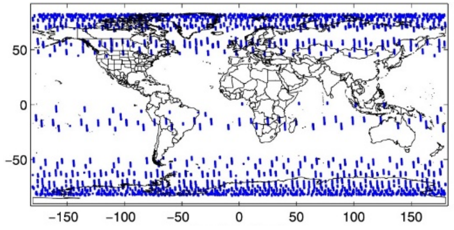
Tying GSICS IR Products to Absolute Scale

Direct Inter-Calibration Method (SNO for IR, Ray-matching VIS/NIR)

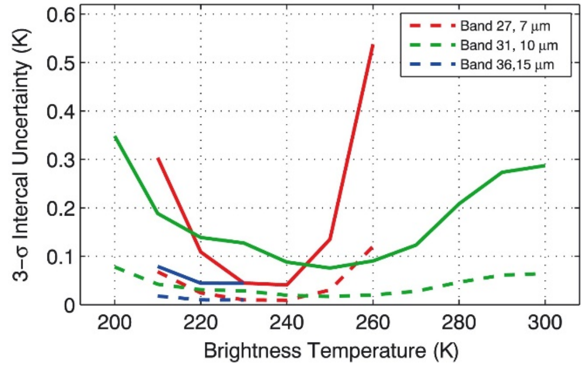
- Use SITSAT as direct reference:
  - To inter-calibrate Monitored instrument (MON)
  - By direct inter-calibration (“SNO”)
  - Instead of Reference Instruments (REF)
  - Coverage limited:
    - few collocations (design-dependent)
    - short-lived – cannot apply retrospectively

- Use SITSAT as indirect reference:
  - To inter-calibrate Reference Instruments (REF)
  - By direct inter-calibration (SNO)
  - Anchor for time series
  - Transfer to other references
  - Through double differences (*Prime Correction*)
  - Needs coordination with SITSAT operator
  - See also Dave Tobin presentation





Distribution of SNOs for CLARREO-Sounder for 1 year and 1 polar orbit CLARREO. One CLARREO FOV every 20 s and 3621 SNOs. From Tobin et al, 2016

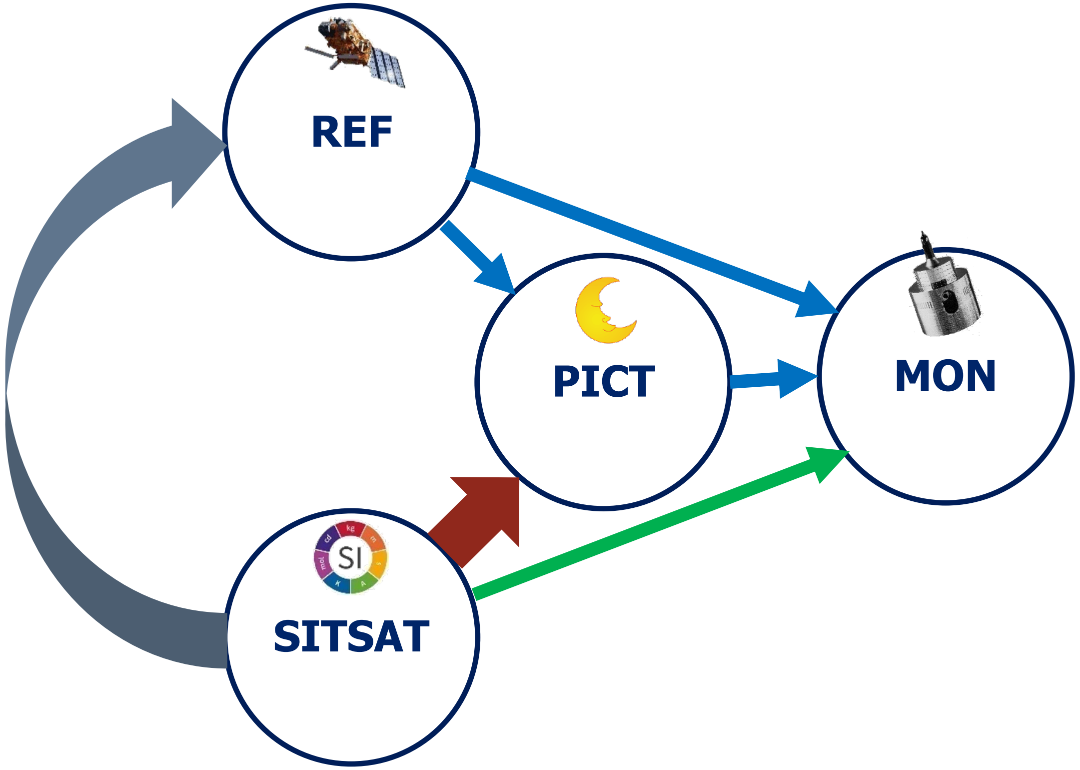


CLARREO-CrIS intercalibration uncertainty using 1 year of SNOs. Solid: single spectral channels. Dashed: averages of 20 spectral channels. From Tobin et al, 2016

Tying GSICS VIS/NIR Products to Absolute Scale

Indirect Inter-Calibration Method (Pseudo Invariant Calibration Targets)

- Use SITSAT as indirect reference:
    - To inter-calibrate Reference Instrument (REF)
    - By direct inter-calibration (“*Ray-matching*”)
    - Need to match solar and polarisation angles
    - Needs coordination with SITSAT operator
    - To target match-ups
- Use SITSAT to characterise PICTS:
    - Ideally over full range of conditions
    - VZA, SZA, season, Moon phase, libration, …
    - Replace current reference instrument
    - Still need long-term monitoring (also for IR)
    - Careful handling of atmosphere, aerosol, cloud
    - Needs coordination with SITSAT operator
    - to optimised target acquisitions
    - see also Gorroño, Helder, Stone presentations



Different approaches to provide traceability of inter-calibration products for a Monitored instrument (MON) to an SI-Traceable Satellite instrument (SITSAT);

1. Direct Inter-Calibration: Using SNO-like approach to transfer calibration of Reference Instrument (REF);

2. Indirect Inter-Calibration: Using a Pseudo Invariant Calibration Target (PICT) to transfer calibration of REF or SITSAT to MON;

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Conclusions

- Advantages of tying inter-calibration products to absolute scale:
  - Provision on an irrefutable reference
  - More uniform retrievals in space and time ➔ Inter-operability
  - Resilience against gaps/drifts outside overlaps between reference instruments
    ➔ Robust and harmonised Fundamental Climate Data Records
  - Additional benefits depend on SITSAT design:
    - Ability to resolve residual dependencies in calibration of other sensors:
    - Scan angle, Non-linearity, Diurnal variations, Spectral (Gap-filling, SBAF)

- Challenges:
  - Extending to other spectral bands
  - Optimising inter-calibration algorithms
    - e.g. handling atmospheric contributions
    - Trade-off depending on SITSAT design
    - Prioritising PICTs to characterise
  - *Cooperation between GSICS and SITSAT designers/operators?*
  - Priority is to establish usable and accurate SI-traceable references for LEO and GEO sensors!
    - Push for continuity

Thank you for your attention and contributions towards making this a reality!