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# Workshop Report

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

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This section introduces products of the Global Space-based Inter-Calibration System (GSICS) and addresses how they could be tied to an absolute scale using comparisons with SI-Traceable Satellite instruments, with short, well-documented traceability chains, that are verifiable on-orbit.

### Introduction to GSICS and its Products for Geostationary Imagers

The Global Space-based Inter-Calibration System (GSICS) is an international collaborative effort, which aims at ensuring consistent measurement accuracy among space-based observations worldwide for climate monitoring, weather forecasting, and environmental applications [1]. This is achieved through a comprehensive calibration strategy, which involves routine monitoring of instrument performances, operational inter-calibration of satellite instruments, tying the measurements to absolute references and standards, and recalibration of archived data.

One part of GSICS’ strategy involves direct comparisons of collocated observations from pairs of satellite instruments, which are used to systematically generate calibration functions to compare and correct the biases of monitored instruments to references. This is currently applied to inter-calibrate the infrared (IR) channels of geostationary (GEO) imagers to hyperspectral sounders on Low Earth Orbit (LEO) satellites, which are used as references to generate *GEO-LEO IR GSICS Corrections*. These are derived by various satellite operating agencies from a commonly-agreed algorithm [Hewison *et al*., 2013], similar to the Simultaneous Nadir Overpass (*SNO*) method originally developed for LEO-LEO comparisons [Cao *et al.*, 2004], but extended to include a range of view angles. This algorithm is based on the comparison of collocated simultaneous observations from pairs of satellite instruments with similar viewing geometries, using a weighted linear regression. Because a hyperspectral reference instrument is used as a calibration reference for contemporary satellites, it is possible to accurately synthesise the equivalent radiance of the multispectral monitored instrument by convolving its spectral response function with the observed scene radiance spectra. However, some reference instruments, such as CrIS and AIRS, do not provide complete or contiguous spectral coverage of all monitored instruments’ IR channels. Algorithms have been developed to compensate for spectral gaps [Xu et al., 2018], which introduce additional, but quantifiable, uncertainties into the GSICS product.

An extension of the SNO approach, sometimes known as *Ray-matching*, can be applied to inter-calibrate counterpart channels in the reflected solar band (VIS/NIR). However, GSICS currently applies a complementary, indirect approach whereby the observations of *Pseudo Invariant Calibration Targets* (PICTs) [ref], such as the Moon or Deep Convective Clouds (DCCs) [ref], are used to transfer the calibration of the reference instrument to the monitored instrument. These observations need not be simultaneous, but need to be made under directly comparable conditions - for example, viewing and solar geometry. However, in the former case, it is also possible to use a lunar irradiance model to account for changes due to the Moon’s phase and libration [Wagner *et al.*, 2016]. There is, however, currently no hyperspectral satellite instrument covering the full spectral band of GEO imagers’ visible and near-infrared channels that would make a suitable reference. So instead, GSICS have selected S-NPP/VIIRS as a multispectral reference instrument due to its spectral characteristics, calibration stability and good quality of its characterisation [Xiong et al., 2016]. This necessitates the use of *Spectral Band Adjustment Factors* (SBAFs) [Scarino *et al.*, 2016] to account for the radiance differences introduced by the monitored and reference instruments’ equivalent channels having non-identical spectral response functions.

Similar approaches have also been proposed for thermal infrared and microwave - e.g. using the Moon as a reference [Niu and Chen, 2018].

These methods are used to derive effective calibration corrections (or, equivalently, new calibration coefficients), which are distributed as GSICS *products* to facilitate interoperability and allow for accurately integrating data from multiple observing systems into operational near real-time processing, as well as for re-analysis applications.

### Applying the Concept of Traceability to GSICS products

While the concept of traceability can mean different things to different communities, when applied to GSICS Products, it refers to the ability to relate the corrected radiance of the monitored satellite instrument to the community-defined reference instruments through an unbroken chain of comparisons, with stated uncertainties. Naturally, the different levels of uncertainty associated with each comparison will affect the overall quality with which the end product is traceable back to the reference.

### Traceability Concept Applied to Direct Inter-Calibration

For GSICS products derived by direct inter-comparison of a monitored instrument to a single reference instrument, the traceability chain is established by constructing an uncertainty budget. For example, [Hewison, 2013] considers all processes contributing to the uncertainty on the comparisons and propagates these through a model of the comparison in a Type-B uncertainty analysis, following the CIPM *Guide to the Expression of Uncertainty in Measurement* [GUM, 2008]. The GSICS GEO-LEO IR inter-calibration algorithm includes provision of the estimated random uncertainty for each correction by propagating noise and scene variability through the weighted regression used to generate them. These estimates can be validated using a Type-A analysis of their time series.

However, it is often desirable to use multiple reference instruments - for example, to provide greater robustness, to improve diurnal coverage by using platforms with different equator crossing times, and to extend the period over which inter-calibration is possible beyond the lifetime of a single reference instrument. This allows us to ensure the full range of the monitored instrument’s operating conditions are covered. In these cases, it is still possible to establish a traceability chain by selecting one reference instrument as an *Anchor Reference*. Results derived from other references are then adjusted to be consistent with those from the anchor by constructing a series of double differences between them and using these to define *delta corrections*, which are applied to each time series before they are combined. Uncertainties provided with each component correction and its delta correction are used as a weighting in the composite product, which is referred to as a *Prime GSICS Correction* [EUMETSAT, 2016].

It is important to test the relative stability of the products derived from each reference instrument before they are combined, as the delta correction is defined over the whole overlap period between each pair of reference instruments. So continuous monitoring of their double differences is critical. However, any drift in relative difference between reference instruments before or after the overlap cannot be accounted for.

The Prime GSICS Correction approach can be applied to combine results from historical references used for Fundamental Climate Data Records (FCDRs). This was illustrated by [Tabata et al. 2019], who applied the concept to recalibrate the water vapour and infrared channels of Japanese geostationary imagers using Infrared Atmospheric Sounding Interferometer (IASI), Atmospheric Infrared Sounder (AIRS), and High-resolution Infrared Radiation Sounder/2 (HIRS/2) as reference instruments.

**GSICS Infrared Reference Uncertainty and Traceability Report**

GSICS is currently in the process of developing a report, to support the choice of hyperspectral reference instruments (IASI, CrIS and AIRS) to inter-calibrate channels in the thermal infrared, and the use of Metop-A/IASI as the anchor reference. This represents an update of the *GSICS Traceability Statement for IASI and AIRS* [EUMETSAT, 2011]. This report first reviews each reference instruments’ error budget and considers the traceability of their in-flight calibration to absolute (SI) scale. The report then consolidates the results from multiple in-flight comparisons of the reference instruments by different authors, including direct inter-comparison by “SNO”, as well as indirect comparisons by double-differencing against GEO imagers and NWP bias monitoring. The report expresses the instruments’ error budgets and inter-comparisons for common sets of dates, spectral bands (both hyperspectral and broadband averages) and scene radiance (or brightness temperature). This readily allows their comparison to form a consensus on the reference instruments’ relative calibration.

It is expected that similar reports will be generated in the future to support the traceability of GSICS products for other spectral bands by reviewing the calibration uncertainty of candidate reference instruments.

### Traceability Concept Applied to Indirect Inter-Calibration

Because the use of Pseudo Invariant Calibration Targets (PICTs), including the Moon, does not require simultaneous observations from the monitored and reference instruments, a single reference instrument can be applied to any point in time - assuming the PICT itself to be stable. In this case, the reference instrument’s observations of the PICT are used to characterise its reflectance over the full range of conditions for which it is to be applied - e.g. solar and viewing geometries, seasonal or lunar variations. Typically, this is performed over a period of several years, usually soon after launch, when the reference instrument’s calibration is believed to be more reliable and this period defines the reference itself.

Even the best current reference sensors with channels in the visible band do not have perfectly stable calibration, due to unaccounted optical degradation of mirrors and detectors, not monitored by onboard calibration systems. So careful monitoring is needed and considered in the selection of this reference period. For terrestrial PICTs we know there are short term temporal drifts only because they are shorter than the sensor record. However, these are unknown on decadal and longer time scales.

Traceability of the GSICS products could be established by propagating their inputs’ variability and uncertainty through a measurement model representing the inter-calibration algorithm (including SBAFs) and simplified uncertainties are provided with the products. This can be especially challenging where Radiative Transfer Models are used, as although it is possible to propagate uncertainties in the model’s inputs, it is much more difficult to quantify the uncertainties in the model itself. Currently, VIS/NIR GSICS products are provided with uncertainty estimates based on a Type-A analysis of their time series.

### Tying GSICS products to an absolute scale

Many satellite missions attempt to calibrate their instruments against SI standards before launch. GSICS, working together with CEOS, aims to define best practices to characterise satellite instruments pre-launch using SI-traceable references to tie them to an absolute radiance scale. However, this traceability chain may be compromised during launch, due to uncontrolled changes to the instrument and its operating environment. For this reason, GSICS endorses the establishment of an observing system with calibration directly traceable to SI-standards on-orbit to act as an inter-calibration reference, which could be used to anchor inter-calibration products to an absolute scale - a long-term aim of GSICS.

A satellite mission, such as CLARREO Pathfinder with HyperSpectral Imager for Climate Science (HySICS) [Kopp et al., 2017], or TRUTHS [cross-ref TRUTHS section], in which an instrument is launched, whose SI-traceability is verifiable in orbit could be used as a reference to achieve this goal. These are generically referred to here as SI-Traceable Satellite instruments (SITSATs).

In the simplest case, such a SITSAT can be used as a reference in direct inter-calibration of the monitoring instrument by SNO/Ray-matching instead of the current reference instruments for the IR case, or the PICTs in the VIS/NIR case. However, the coverage of the available collocations can be limited, depending on the design of the SITSAT – and the duration of such inter-calibration products is limited to its operating lifetime.



*Figure: Different approaches to provide traceability of inter-calibration products for a Monitored instrument (MON) to an SI-Traceable Satellite instrument (SITSAT);
Left: Direct Inter-Calibration: Using SNO-like approach to transfer calibration of Reference Instrument (REF) and direct inter-calibration of MON using SITSAT by SNO/Ray-matching (green arrow);
Right: Indirect Inter-Calibration: Using a Pseudo Invariant Calibration Target (PICT) to transfer calibration of REF or SITSAT to MON (red arrow).*

### Tying GSICS Infrared products to an absolute scale

Alternatively, direct inter-calibration methods, as used in current GSICS GEO-LEO IR products, the hyperspectral reference instrument itself can be inter-calibrated with such a SITSAT. For example, the SNO method can be applied to compare it with a sun-synchronous reference instrument’s calibration with a *k*=3 uncertainty <0.1K within 2 months of collocations, which would span a range of latitudes [Tobin et al., 2016]. A correction would then be derived to transfer the reference instrument to the on-orbit SI-standard, which would be applied in addition to the current GSICS product.

This approach can be combined with the *Prime GSICS Correction* to extend support to FCDR generation, based on a series of double-differences to tie the whole time series to the SITSAT reference at one point in time, following the principle demonstrated by [Tabatha et al, 2019] and also in [John et al. 2019].

### Tying GSICS Reflected Solar Band products to an absolute scale

The same approach can be applied to inter-calibrate reference sensors used for indirect inter-calibration methods, such as used in the current GSICS GEO-LEO VIS/NIR products using a SITSAT with hyperspectral VIS/NIR bands. This would then be transferred to GSICS products derived either from PICTs or direct comparisons with current reference instruments. [Roithmayr et al. 2014] suggests a steerable SITSAT would be able to meet requirements for on-orbit direct inter-calibration of VIIRS’ reflected solar band channels’ with a *k*=2 uncertainty of 0.3% within 1 year. However, this capability depends on the polarisation sensitivity of the monitored instrument, which would require additional constraints on the inter-calibration sampling [Lukashin et al., 2013].

Another approach can be considered for indirect inter-calibration methods, in which the PICTs themselves are characterised by the SITSAT. If these observations covered the full range of viewing conditions, it would be possible to transfer the SITSAT calibration based on the PICT. The particular challenges for terrestrial targets include consistent PICT identification to ensure that the atmospheric, aerosol and residual cloud column is observed in a standard way, such that their contributions to the comparison’s uncertainty do not compromise its traceability. Further analysis, following Lukashin et al., 2019] suggests that operating CLARREO Pathfinder on the ISS would yield approximately 30 samples/year of terrestrial targets, such as Libya-4. As these are near-nadir, it is difficult to use this approach to fully characterise the site - although it may be possible to tie BRDF models constructed using SITSAT referenced sensors to such observations. However, such a SITSAT could observe the Moon with good coverage of the phase/libration cycle within 1 year [ref] and these observations could tie an existing model to the absolute scale – although a longer period would be needed to derive an entirely new lunar irradiance model.

A final option would be to use the SITSAT as a reference to directly inter-calibrate the GEO or LEO imagers - although that is obviously only applicable to the operational lifetime of the SITSAT.

However, any of these approaches to tie GSICS products for VIS/NIR channels to SITSAT would benefit from careful coordination with its operators to ensure its observing strategy provides sufficient sampling to achieve the required uncertainty in the inter-calibration product. In practice, GSICS will investigate a multi-method approach, combining the direct inter-calibration of the reference instrument, and the characterisation of multiple PICTs. The balance between these approaches will depend on specific needs for each PICT and the capabilities of the available SITSAT, and will evolve as different SITSATs become available.

### Conclusions on Improving Global Inter-Calibration

The benefits of being able to inter-calibrate satellite instruments to an absolute scale include the resilience against gaps between reference instruments and drifts in their calibration outside their overlap period. This would allow construction of robust and harmonized data records from multiple satellite sources to build Fundamental Climate Data Records, as well as more uniform environmental retrievals in both space and time, thus improving inter-operability.

Additional benefits may be realised depending on the design of the SI-traceable reference instrument and its operating platform. In particular, hyperspectral instruments covering the full spectral band of popular channels in the visible, near-infrared and thermal infrared could accurately simulate their radiances, making an ideal reference instrument. Such hyperspectral instruments could also be used to validate any SBAFs or similar algorithms to compensate for spectral gaps in other reference instruments, as well as characterise the spectral characteristics of various PICTs. Furthermore, by covering its full dynamic range, it could be possible to resolve reference instruments’ nonlinearity. Finally, by operating such an instrument on a non-sun-synchronous platform, any diurnal variations in the monitored instruments calibration could be accounted for, multiple reference instruments could be inter-calibrated, and terrestrial PICTS could be characterised over the full range of solar geometries.

However, a number of challenges remain for GSICS. Primarily, the approaches described above need to be refined and applied to other inter-calibration methods. In particular, careful consideration needs to be made to how different SITSAT observing strategies could be exploited to monitor the degradation of sensor optical components not resolved by onboard calibration systems. For example, scan angle dependence of the scanning mirrors and polarization, fully characterise scan-angle dependence in the calibration of other satellite instruments. This also requires that GSICS prioritise which PICT targets to characterise. Thus, to optimise the benefits of such a SI-traceable reference would benefit from cooperation between GSICS and it operators to ensure sufficient acquisitions are available.

But ultimately, the ability to inter-calibrate satellite instrument to an SI-standard provides irrefutability of scientific observations. So the priority for the satellite calibration community should be to establish suitable reference satellite instruments with SI-traceable calibration on-orbit. While there would still be a need for continuous monitoring to validate the instruments’ calibration and ensure consistency, multiple SITSATs may eventually provide sufficient spectral, geometric and temporal coverage and long-term continuity to replace the role of current reference instruments used in GSICS inter-calibration products.

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