Overview of Intercalibration of Satellite Instruments

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***Abstract*—Intercalibration of satellite instruments is critical for detection and quantification of changes in the Earth's environment, weather forecasting, understanding climate processes, and monitoring climate and land cover change. These applications use data from many satellites; for the data to be interoperable, the instruments must be cross-calibrated. To meet the stringent needs of such applications, instruments must provide reliable, accurate, and consistent measurements over time. Robust techniques are required to ensure that observations from different instruments can be normalized to a common scale that the community agrees on. The long-term reliability of this process needs to be sustained in accordance with established reference standards and best practices. Furthermore, establishing physical meaning to the information through robust Système International d'unités traceable calibration and validation (Cal/Val) is essential to fully understand the parameters under observation. The processes of calibration, correction, stability monitoring, and quality assurance need to be underpinned and evidenced by comparison with "peer instruments" and, ideally, highly calibrated in-orbit reference instruments. Intercalibration between instruments is a central pillar of the Cal/Val strategies of many national and international satellite remote sensing organizations. Intercalibration techniques as outlined in this paper not only provide a practical means of identifying and correcting relative biases in radiometric calibration between instruments but also enable potential data gaps between measurement records in a critical time series to be bridged. Use of a robust set of internationally agreed upon and coordinated intercalibration techniques will lead to significant improvement in the consistency between satellite instruments and facilitate accurate monitoring of the Earth's climate at uncertainty levels needed to detect and attribute the mechanisms of change. This paper summarizes the state-of-the-art of postlaunch radiometric calibration of remote sensing satellite instruments through intercalibration.**

***Index Terms*—Calibration, comparison, constellations, correction, cross-calibration, Earth Observing (EO) System, infrared, intercalibration, international collaboration, microwave, monitoring, radiometric calibration, reflective solar band (RSB), satellite, satellites, thermal infrared, traceability, validation, visible.**

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I. Introduction

SATELLITE observations have become an integral part of the modern information age with dependence across all aspects of society: public, academic, commercial, and government. This places stringent requirements on agencies to ensure the availability and reliability of satellite observations. It has long been recognized that collaboration among national agencies and international organizations is needed to meet this common challenge. It is therefore imperative that data from multiple instruments be readily combined seamlessly to enable the delivery of fully operational services. This cannot be done without reliable knowledge of the relative biases between instrument outputs and correcting and/or normalizing them with a level of confidence in data quality. The Earth Observing (EO) instruments' calibration accuracy and consistency over time are critical performance parameters that directly impact the quality of the data products derived from these observations, particularly for understanding the forcing factors and forecasting the consequences of climate change. Long-term Climate Data Records (CDRs) derived from satellite remote sensing are constructed using observations made by a series of EO instruments over long time scales with broad spectral and spatial coverage and on a large temporal scale. These instruments, of the same or different types, have operated on different platforms or missions. In addition, these instruments could be developed and built with different technologies while the recognition for calibration requirements has evolved. Early instruments were built without adequate onboard calibration devices and may not have gone through a rigorous system-level prelaunch calibration process; therefore, calibration traceability or stability could not be established. Furthermore, the severe stress of launch and harsh environment of space makes it a rarity for satellite instruments, particularly those operating in the optical domain, to not change their characteristics following launch and during the lifetime of the mission. Because of this, high-quality on-orbit calibration intercomparisons among different instruments and improved calibration accuracy requirements for individual instruments have become increasingly important and demanding [1].

There have been a number of major national and international workshops with primary focus on instrument calibration and validation. Examples include the *Workshop on Strategies for Calibration* and *Validation of Global Change* and *Measurements* [2], organized in 1995 by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) on behalf of the Committee on Earth

Observation Satellites (CEOS)[1] Working Group on Calibration and Validation (WGCV), the Global Change Observing System (GCOS),[2] and the U.S. Committee on Environment and Natural Resources (CENR); and the *Workshop on Satellite Instrument Calibration for Measuring Global Climate Change*, organized in 2002 by the National Institute of Standards and Technology (NIST), National Oceanic and Atmospheric Administration (NOAA), NASA, and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) [3]. In May 2006, a follow-on workshop, i.e., *Achieving Satellite Instrument Calibration for Climate Change (ASIC3)*, was held with its primary objective to formulate a national roadmap for a calibration system that will help the remote sensing community deliver the requirements and meet the challenges [4]. A joint World Meteorological Organization (WMO)[3] and Bureau International des Poids et Mesures (BIPM)[4] workshop was organized on "*Measurements challenges for Global Observation Systems for Climate Change Monitoring: Traceability, Stability* and *Uncertainty*" in 2010 to foster communication between metrology and EO communities to deliver accurate and reliable observations of the Earth's climate [5].

Recent years have seen more and broad international efforts on using integrated satellite data to support policy and decision making within different organizations and agencies. For example, the Global Earth Observation System of Systems (GEOSS)[5] has been established as a public infrastructure, interconnecting a diverse and growing array of instruments and systems for monitoring and forecasting changes in the global environment. The accuracy of EO instruments and their associated data products has become critical as scientists and decision makers are heavily relying on them to address global environmental issues. Thus, the characterization and calibration of these instruments, particularly their relative biases, are vital to the success of the developing integrated GEOSS for coordinated and sustained observations of the Earth. To address relative biases between instruments, intercalibration and comparisons between instruments have become central in calibration and validation (Cal/Val) strategies of national and international organizations. Recent progress included the establishment of CEOS reference standard test sites and "best practice" guidance on site characterization and applications, and development of a Quality Assurance Framework for Earth Observation (QA4EO).[6] The Global Space-based Inter-Calibration System (GSICS)[7] is an international collaborative effort initiated by WMO and the Coordination Group for Meteorological Satellites (CGMS) to monitor and harmonize data quality from operational weather and environmental satellites [6]. The CEOS WGCV extends this vision to include all EO instruments and satellite operating agencies and has a major effort led by its Infrared Visible and Optical Sensors (IVOS) subgroup.

[1] http://ceos.org/
[2] http://gosic.org/gcos
[3] http://www.wmo.int/
[4] http://www.bipm.org/
[5] http://www.earthobservations.org/
[6] http://qa4eo.org/
[7] http://gsics.wmo.int/

This paper is organized into six sections: Sections I and II provide an introduction and describe the need for satellite instrument intercalibration. Section III describes general problems encountered during intercalibration, and Section IV focuses on the intercalibration methods by briefly summarizing the application of each. Section V summarizes the ongoing joint efforts, and Section VI briefly describes the challenges and future improvements and provides a summary of the work.

II. Need for Intercalibration

Current satellite instrument calibration is not traceable to *Système International d'unités* (SI) postlaunch, regardless of whether the prelaunch calibration is SI traceable. This means that measurements by different instruments not only could be different but also contain *unknown* uncertainty. Given an instrument's typical design life of about five years, the detection of decadal climate change relies on observations from a series of satellites [4]. At much shorter time scales, for example, to describe the atmospheric conditions for Numerical Weather Prediction (NWP) models, observations from multiple satellites (polar-orbiting, geostationary, and otherwise) are often needed to maximize the spatial and temporal coverage at multiple scales. If measurements by different instruments have unknown uncertainty, the ability of detecting long-term trends from a series of satellite instruments or the interoperability of concurrent instruments would be seriously compromised. Intercalibration of satellite instruments is an effective way to reduce the differences among satellite instruments and, as a minimum, to estimate the scale of any residual uncertainty. For instruments without onboard calibration, the need for intercalibration is even more obvious.

The use of the concept of "common reference scale" is only valid and useful if one is confident that the reference is stable and that it can be validated or calibrated at a later date through traceability to SI. It is expected that instruments that can achieve on-orbit SI traceability will become available in the near future. Nevertheless, it remains unlikely that all future instruments will be self-sufficient to achieve on-orbit SI traceability. Therefore, intercalibration with SI-traceable instruments will be a long-term strategy for environment monitoring. While on-orbit SI traceability is the ultimate goal, it is not yet achievable. An alternative is to make the calibration of all instruments traceable to a reference that the community considers the best standard at present. Such community standards can be stable targets on Earth (e.g., Dome C [7]) or in space (e.g., the Moon [8]), or a network of well-characterized instrumented sites that monitor surface and atmospheric conditions in detail [9], or stable and well-calibrated satellite instruments that are versatile to collocate with other satellite instruments temporally, spatially, spectrally, and geometrically. Intercalibration to these community standards can remove relative differences for now. In the future, characterization of community standards using on-orbit SI-traceable instruments will tie all instrument calibration to absolute standards.

Before performing intercalibration between instruments, it is critical to understand the definition of calibration. According to BIPM international Vocabulary of Metrology, calibration is defined as an operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication [10]. The CEOS definition of calibration is the process of quantitatively defining the system responses to known controlled signal inputs. This is the only link between what the instrument actually measures (e.g., radiance, in the form of digital counts) and what one wants to measure (e.g., radiance). Digital numbers (DNs) from one sensor have no relation to a DN from a different sensor. Conversion to at-sensor spectral radiance and/or top-of-atmosphere (TOA) reflectance is the fundamental steps to compare products from different sensors. Absolute radiometric calibration enables the conversion of image DNs to values with physical units. In general, the absolute radiometric calibration for most optical sensors is specified to an uncertainty of 5%; hence, the likely uncertainty (in reflectance units) on a measured reflectance value of, for example, 0.4 will be $\pm 5\%$ of 0.4 equal to ± 0.02.

Most satellite instruments were calibrated before launch. However, because of instrument response changes due to operating environment or aging, they must be regularly recalibrated on-orbit, several times every second for some or, for others, once a month or less frequently [11]. Postlaunch calibration is important to ensure radiometric calibration stability. Instruments that do not have an onboard calibration device need intercalibration to monitor the stability of the data they acquire. Satellite instruments are designed and used for different purposes and with various limitations. With or without onboard calibration, most of the satellite instruments were not made for climate missions, which often require uncertainties close to those currently only achievable at the National Metrology Institutes. However, in their absence, one needs to make the best effort possible to make optimum use of data from existing missions and seek, where possible, to improve performance through improved calibration, postlaunch.

Similar to any technology, capabilities for calibration and instrument performance improve over time. This has been the case in the past and will continue in the future. To benefit from future development in calibration technology and sensors, the process of intercalibration must be established, understood, and, where possible, made operational. It is difficult for most satellite instruments to claim rigorous SI traceability, as explained in Section III-A, and although ideally desirable, it will be costly and impractical for all instruments to independently establish their own calibration systems. Recognizing this critical shortcoming, a plan has been made to launch and maintain an SI-traceable "climate and calibration observatory" in space, the U. S. Climate Absolute Radiance and Refractivity Observatory (CLARREO) [12]–[14], and United Kingdom (UK) National Physical Laboratory (NPL) proposed Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) [15], [16]. The TRUTHS mission in particular will establish well-calibrated reference targets/standards to support other EO missions as well as solar and lunar observations. Once launched, these instruments would in effect become the de facto primary reference instruments (standards) for the global EO System. A "metrology laboratory in space" provision of calibration lies at the heart of these proposed missions; therefore, intercalibration is an integral and indispensable tool to maximize the benefits of the services provided by such an observatory.

Finally, it is sometimes difficult to reveal or adequately correct for the deficiency of instrument calibration by its own calibration subsystem, and intercalibration can be a powerful tool to assist in many anomaly investigations. This is a relatively new application, developed from the success and improvements made in the intercalibration processes in recent years. Examples include the improvement in the radiometric calibration of Landsat Multispectral Scanner System (MSS) [17], Thematic Mapper (TM) [18]–[20] and Advanced Very High Resolution Radiometer (AVHRR) instruments [21]–[23], correction of AVHRR infrared calibration [24]–[27]; diagnosis and correction of error in the spectral response function (SRF) of High Resolution Infrared Radiation Sounder (HIRS) [28], and Geostationary Operational Environmental Satellites (GOES) Imager 13.3-μm channel cold bias [29]–[31]; evaluations of diurnal and scan angle variations in calibration of GOES Imager infrared channels [32]; characterization of GOES Imager midnight blackbody calibration anomaly [32], [33]; confirmation of stray light contamination of GOES and validation of its removal [32]; investigation of the midnight calibration anomaly for three-axis stabilized geostationary satellites such as GOES and Multifunctional Transport Satellites (MTSAT) [34]; and the ice contamination of Meteosat Spinning Enhanced Visible Infra-Red Imager (SEVIRI) [35] and GOES [36].

III. General Intercalibration Problems

The basic premise of intercalibration is that two instruments should make identical measurements when they view the same target at the same time, with the same spatial and spectral responses and the same viewing geometry. Since these idealized conditions never occur in reality, a series of thresholds is applied to collocate the data and transform it to a comparable scale. In general, there are three broad objectives. The first objective is to quantify the relative bias, or the difference between a monitored and reference instrument, for the collocated data. This is useful because the results can then be generalized, albeit often implicitly, to measurements by the same pair of satellites even when not being directly compared. The second objective is to correct for the bias. Again, the efficacy of correction can be only validated with the collocated data but is assumed to hold for all measurements. The third objective is to find the causes of biases and eliminate them from the instrument directly; if it is not possible for the one on-orbit, at least improve future instruments. It may be that an apparent bias in the radiometric calibration is introduced by an error in another component of the system, such as the spectral response. Although ultimately the term in error should be corrected, it is also possible to compensate for its effect by applying a correction to the calibrated radiance if the biases are sufficiently small and if they can be considered linear.

For all these objectives, it is important to evaluate the bias, correction, and cause analysis, collectively or separately, under a variety of conditions. This dictates that the collocated measurements should adequately cover the normal range of system characteristics and observables likely to be encountered during operation. First, the collocations should cover all spectral bands to enable users to quantify possible spectral variation of bias. Second, the collocations should cover all scene radiances to quantify possible dynamic range dependence of bias. Next, the collocations should cover all ranges of geographic location, viewing geometry, and time of day to quantify possible geographic, geometric (angular), and diurnal variation of bias. Finally, the collocations should cover all days of the year and all stages of the satellite's age to quantify possible seasonal variation and long-term trend of bias. This requires intercalibration studies to be performed throughout the satellites' lifetimes. Throughout the intercalibration process, it is important to propagate the uncertainty introduced at each stage. This is the only way one can ensure and account for full traceability to a common reference. The Centre National d'Etudes Spatiales (CNES) has made major efforts to establish a long-term database of sensor observations over a range of targets [37] to allow detailed analysis of sensor and sensor-to-sensor responses as part of an operational calibration system [38]. Before proving a general description of problems encountered during intercalibration, it is imperative to define and understand some of the key terminology and concepts [10]. Measurement science is based on the concepts of traceability and accuracy.

A. Traceability

Calibration traceability refers to an unbroken quality-assured chain of comparisons that relate instrument measurements to a known national or international standard with stated uncertainties [10]. The quality of an individual instrument's calibration traceability is closely tied to its calibration bias, precision, and accuracy. As a result, it has a direct impact on the quality of its calibration intercomparisons with other instruments. For satellite observations, the calibration traceability established prelaunch must be transferred and maintained postlaunch. Traceability requires that the measurement can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty. Furthermore, SI traceability requires that the references used are themselves directly traceable to standards maintained by designated national or international metrology organizations/communities or standardizing bodies. For satellite instruments in orbit, the requirement for an "unbroken chain" presents a problem because many parameters of a calibration reference can change between prelaunch characterization on the ground and its operating environment.

The critical importance of traceability and data quality assurance is to enable interoperability of data from EO systems, particularly satellite instruments, which has led to a new internationally agreed upon QA4EO. QA4EO was established at the direct request of the Group on Earth Observation to support the development of its ten-year vision to establish the GEOSS. The key principle of this framework is that "all EO data and derived products should have associated with them a "quality indicator," which should be based on a documented quantitative assessment of its traceability to internationally agreed upon reference standards (ideally tied to SI units).

In this context, it is important to recognize the formal definition and meaning of "traceability": property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [10]. For bias removal, it is of course only essential that the reference standard chosen and its characteristics (in terms of the parameters being observed) are well understood and stable between the time it is defined and used, or at least during the time interval between observations by respective instruments (see Section III-B). However, the ability to extract long-term trends from climate records directly depends on the determination of systematic and/or time-dependent biases in the instruments making those measurements. Conceptually, there are two ways of doing this.

- **SI-traceable approach:** Through high-accuracy measurements performed (and tested) in-orbit and pinned to irrefutable international standards (the International System of Units, SI).
- **Reproducibility approach:** Through overlapping time series of independent instruments whose time-dependent biases are tested by frequent intercomparison and the measurement of stable pseudo-references (e.g., the moon or Earth reference sites).

However, it is a basic principle that the only reliable way to determine the magnitude of changes in a measured quantity over a long period of time is to ensure that the measurements made at the beginning and at the end of the period are traceable to standards that are themselves unchanging, i.e., they must be linked to unchanging constants of nature. Today, this means that measurements must be traceable to the SI over the whole period of the measurements. Thus, the SI-traceable approach is the ultimate goal to achieve an unequivocal low-risk long-term climate-monitoring strategy. Of course, if the references used in the "reproducibility approach" can be proven to be stable over this long period through some traceable calibration, then this is acceptable, and it is worth reflecting that without an SI-traceable (absolute) standard, time works against you, and with an SI-traceable (absolute) scale, time works for you.

1) Accuracy: Accuracy is a measure of how close a measured result is to the "true" value. As the "true" value is, by definition, unknown, accuracy is estimated by a measurement uncertainty, a combination of the standard deviation of multiple measurements (random effects) and an estimate of the size of an uncorrectable systematic bias. Any correctable systematic bias (an error) should be corrected before presenting the measured result, but the uncertainty associated with that correction is included in the measurement uncertainty. In most measurement systems, this uncertainty will include the uncertainty associated with the calibration of the instrument, that is, the uncertainty associated with the traceability to SI. In general, accuracy is a quantification of the quality of that measurement. Each step in a traceability chain increases the overall measurement uncertainty (reduces the accuracy of the measurement), and this process must be appropriately quantified (in a quality-assured manner) to obtain usable measured results. It is clear that achieving high-accuracy SI traceability for a space-based mission is extremely challenging and is probably the limiting factor in most of today's missions.

2) Precision and Repeatability/Reproducibility: Precision is a measure of the repeatability (standard deviation of multiple measurements under the same conditions) and reproducibility (standard deviation of multiple measurements with different instruments or under different conditions) of a measured value. Precision can be improved by averaging.

3) Bias and Stability: Bias is an estimate of the systematic errors, relative to the "true" absolute SI value of the measured quantity, associated with a measured result. The bias can be slowly changing with time, as described by the measurement stability. Bias cannot be improved by averaging.

4) Uncertainty: Uncertainty is the nonnegative parameter characterizing the dispersion of the quantity values that are being attributed to a measurand (quantity), based on the available information used. Where possible, this should be derived from an experimental evaluation, but it can be also an estimate based on other information, e.g., experience. Guidance on how to evaluate, express, and analyze sources and types of uncertainty can be found in QA4EO (Guideline 6), which then refers to a more detailed reference, i.e., the Guide to Uncertainty of Measurement.[8]

B. Sampling Differences

In general, the first step of any intercalibration is the comparison of observations from pairs of satellite instruments. This can either be the direct comparison of collocated observations, the comparison of their statistics over extended periods or regions, or indirect comparisons against an intermittent reference. In all cases, however, the uncertainties should be specified as part of any intercalibration process. The selection criteria used in the comparison determine the contributions to the overall uncertainty [35]. In particular, consistent differences in sampling can introduce systematic errors such as temporal, geometric, and spatial trends in the scene that will be reflected in the sampled observations; similarly, spatial and temporal changes due to variability of the atmosphere and/or surface can introduce random errors in the observations being compared. These terms are considered in the following sections.

1) Spectral: Different applications and technology developments in EO necessarily require different spectral coverage. Thus, even for the spectral bands designed to look at the same region of the electromagnetic (EM) spectrum, instrument response can be substantially different because their analogous bands may have different relative spectral responses (RSRs), which are also known as SRFs. The state-of-the-art electrooptical instruments being used for today's intercalibration applications require more complete characterization of the spectral band differences to permit small uncertainty needed for many applications. This is particularly true in the intercomparison of instruments whose RSRs are not directly comparable. The differences in spectral responses between the instruments lead to a systematic band offset when attempting the intercalibration between these instruments as the two instruments differently respond to the same EM source [39]. Because of these RSR differences, the instruments often report different values of measured at-sensor spectral radiance or TOA reflectance for spectral bands that are sometimes assumed to be directly comparable. Thus, for accurate intercalibration between these two instruments, the differences that arise from the RSR differences between the two instruments need to be resolved. This is often assumed to be constant, but evidence from intercalibration has shown that, in some cases, it can change during an instrument's operational lifetime [40]–[42]. A compensation for differences in SRFs can be made after having some prior knowledge of the spectral signature of the ground during the overpass time. This adjustment factor, needed to compensate for the spectral band differences, is known as spectral band adjustment factor (SBAF) [21], [39], [42]–[44].

2) Spatial: Moderate Resolution Imaging Spectroradiometer (MODIS) instruments provide a spatial resolution of 250 m, 500 m, and 1 km and a ground swath of 2330 km. AVHRR has a spatial resolution of 1.1 km and a ground swath of 2893 km, whereas the Landsat instruments provide a spatial resolution of 30 m and a ground swath of 183 km. The effect of spatial resolution is even more pronounced in instruments with a large swath and the capability to collect off-nadir data using high viewing angles. In general, to minimize the effect of spatial resolution and nonuniformity of the target, near-simultaneous nadir images with large homogeneous regions of interest (ROIs) are preferred for intercalibration. One important factor that characterizes the spatial resolution of the instruments is the modulation transfer function [45]. The uncertainty due to spatial resolution may not be a major contribution to the combined uncertainties in an intercalibration experiment, but the effect needs to be considered and quantified in intercalibration.

3) Radiometric Resolution: In general, data quantization for EO instruments ranges from 8 to 12 bits. Higher quantization will provide an improved sensitivity of the instruments and allow capturing the low and high radiance data that may saturate at the lower 8-bit quantization. For infrared and microwave, radiometric noise usually dominates any quantization effects. It can also include a significant contribution from noise introduced by the calibration process itself (e.g., from radiometric noise while viewing the calibration targets). A theoretical analysis of the contribution of noise and quantization to the intercalibration is usually performed by estimating the noise at individual pixels and comparing it with total noise after averaging a number of pixels.

4) Temporal and Angular: Even when imaged on the same day within a short period of time, circa 30 min and in a nadir view, changes in the solar illumination angle and changes in the atmosphere between the two instruments' measurements, combined with the bidirectional reflectance distribution function (BRDF) of the target, produce differences in the radiance at the instrument. To determine the uncertainty in the intercalibration, the contribution of these differences needs to be understood. During the 30-min difference between the acquisitions, the solar zenith angle will change by as much as 7.5°.

A change in the solar angle has several impacts on the radiance reaching the instrument. First, the change in solar zenith

[8]http://www.bipm.org/en/publications/guides/gum.html

angle changes the incident solar irradiance. This change is readily compensated by normalizing the cosine of the sun angle. Second, the path and length of the path through the atmosphere can change. Even for a constant homogeneous atmosphere, the amount of scattering and absorption and the resulting amount of direct and diffuse irradiance at the surface changes. These effects can be well modeled for known atmospheric conditions, but the atmospheric conditions are generally not well known for the image pairs when intercalibrations are being performed. Differences in the atmospheric conditions between the two solar paths and any changes in the atmospheric conditions in the target to the instrument path cause additional uncertainties. Finally, unless the target is Lambertian, changes in the angle at which the direct solar beam impinges on the target and the amount and directional distribution of the diffused component will affect the amount of light reflected off the target into a nadir viewing instrument.

C. Scene Variability

The intercalibration of satellite instruments often requires comparing observations from different instruments coincident in space, time, and viewing geometry. As these are never exactly aligned, thresholds are usually applied to define the collocations. The choice of these thresholds directly impacts the uncertainty of the comparison, partially due to the scene variability within the range of the collocation criteria. The collocation criteria represent tradeoffs between the errors on each collocation and the number of collocations available. Collocated observations from a pair of satellite instruments are not sampled at exactly the same place or time. Variations in the atmosphere and surface during the interval between their observations introduce errors when comparing their collocated radiances. The greater the collocated observations interval, the larger the contribution of the scene's variability to the total error budget.

Different types of scenes have different surface reflectance or emissive radiance spectra. Even for the same type of scenes, their surface reflectance or emissive radiance spectra may still vary with a number of factors, such as season and atmospheric conditions. To minimize uncertainties of calibration intercomparisons among different instruments, it is highly desirable that their observations be made over the same types of scenes under the same observational conditions. Special attention must be taken into account for scenes that might change their spectral or reflectance or radiance levels. Random scene variations in space and time contribute to the uncertainty in the comparison of a pair of collocated observations. Furthermore, systematic differences in the sampling time and geolocation of the monitored and reference instruments can introduce systematic errors in their collocated radiances due to small longitudinal and latitudinal mean gradients and the diurnal cycle of the temperature, humidity, cloud cover, and radiance emitted by the Earth's surface and atmosphere. Errors introduced by the misregistration of an instrument's navigation can be quantified in the same way by assuming typical values for geolocation errors.

The appearance of the ground areas in images captured by instruments may vary due to differences in instrument type, altitudes, imaging, viewing geometry, scanning times, etc. Hence, a feature simultaneously observed by two sensors can be represented by slightly different numbers of image pixels, even for instruments with same spatial resolution. This makes it very difficult to establish sufficient geometric control to facilitate radiometric comparisons on a point-by-point and/or detector-by-detector basis. The effect of viewing geometry on the appearance of images is even more pronounced in instruments with a large viewing angle. Image registration can become extremely difficult for data acquired even on the same day a few minutes apart. Thus, image registration plays a significant role in providing accurate intercalibration results and can be a major source of error when intercalibration is performed using the ROI from image pairs. In general, to minimize the effect of misregistration and spatial nonuniformity, large homogeneous regions are preferred for intercalibration. However, the uncertainty caused by image misregistration needs to be investigated for better understanding of intercalibration uncertainty among various imaging platforms.

The uncertainties introduced by these random and systematic factors should be analyzed for all intercalibration products. Hewison [35] provides an example of such an analysis for the intercalibration of the infrared channels of two instruments. A similar analysis is presented for a limited number of factors, determined to be dominant in the intercalibration of reflective solar bands (RSBs) of two optical instruments [46]. In the case of microwave instruments, radio-frequency interference can introduce highly non-Gaussian errors that need to be accounted for in the uncertainty analysis [47], [48].

D. Other Calibration Dependence

The spectral radiance reaching the instrument of different radiance or reflectance levels could be impacted by instrument response nonlinearity. In addition, calibration is often made at a fixed level of reflectance or radiance and a single scan angle. The EO instrument usually covers a wide swath with different scan angles. The solar illumination angles and correction should be made for observations made at a different scan angle. Intercalibration can allow the correction of the calibration's sensitivity to these and other factors by introducing dependence based on comparisons over a broad range of conditions.

E. Choice of Reference Instrument

In general, intercalibration involves the comparison of observations from one *monitored* instrument to another, defined to be the *reference instrument*. Observations from these reference instruments provide the *common scale* on-orbit, against which other instruments are intercalibrated. The key feature of any reference instrument is its radiometric stability as it defines the calibration's datum. However, many other factors need to be considered when defining an instrument as an intercalibration reference. Most obviously, it must be concurrently operated to allow observations to be made, which can be directly compared, but their satellite orbits must also allow coverage of the same geographic areas, ideally at the same time. The reference instrument's spectral coverage also needs to be considered, as ideally, it would cover the channels of the monitored instrument and be well matched such that minimal errors are introduced by the SBAF. For example, a hyperspectral reference instrument can allow full representation of the monitored instruments' SRF. The reference instrument itself must be also accurately calibrated consistent with other instruments and well characterized to allow better traceability.

Currently, GSICS is using the Infrared Advanced Sounding Interferometer (IASI) aboard the Meteorological Operational Satellite (Metop)-A satellite as an intercalibration reference for GSICS products [34]. This is complemented by the Advanced Infrared Sounder (AIRS) onboard Aqua as a transfer standard to expand the intercalibration opportunity into the time of the day not covered by Metop underpasses [32]. A document has been prepared to demonstrate the suitability of these hyperspectral spectrometers as intercalibration references [49]. It has been shown that IASI can be used as an excellent intercalibration reference because it has been well characterized prelaunch, and its calibration has proven to be stable in-orbit and consistent with the AIRS with uncertainties $\sim$0.1 K $(k = 1)$ [50]. This methodology is currently being extended to develop counterpart Geostationary Earth Orbit (GEO)–Low Earth Orbit (LEO) infrared products for a historical data set of geostationary radiances observed before suitable hyperspectral reference instruments were available. The HIRS is being considered as a candidate reference instrument because it has been operated in various incarnations on NOAA and Metop platforms since 1978 [28]. This requires the development of SBAFs to account for the different SRFs of the monitored GEO and reference HIRS instruments. For the RSB, the MODIS sensor provides an excellent spectral coverage and stability, and it has a robust onboard calibration strategy. Since the Aqua MODIS is more stable better calibrated than Terra MODIS [51], [52], it has been selected by GSICS as the current reference for channels in the RSB. In the longer term, reference sensors capable of establishing SI traceability onboard together with appropriate sampling and SRF characteristics are desired to underpin a climate observing system [16].

IV. Intercalibration Methods

The main cause of the relative biases between the instruments is the difficulty in characterizing individual instruments due to the lack of an SI-traceable onboard calibration reference or standard and the variable nature of biases both short-term and long-term in response to the spacecraft and instrument operating conditions. These intersatellite biases have become major concerns in constructing time series for climate change detection. As a result, a number of approaches have been developed and implemented to better quantify these intersatellite biases. The most direct approach, common with most terrestrial nonspace situations, is to use a well-calibrated instrument as a reference to intercalibrate or at least compare with other instruments viewing the same "target" under near-simultaneous conditions (or with some reliable means of providing a link if simultaneity cannot be easily obtained). This is often called "intercalibration."

Consistency between different instruments starts with sound calibration of the individual instruments, including the development of a stable instrument, comprehensive prelaunch characterization, and on-orbit calibration. Usually, postlaunch radiometric calibrations are based on reference to onboard standards, solar or lunar illumination, or ground-based test sites. Intercalibration between instruments can be based on prelaunch measurements in the laboratory using common sources or transfer radiometers at the same or different times. In addition to direct comparison of collocated observations for those missions operating during the same time periods, postlaunch intercalibration can use near-simultaneous imaging of common targets on the surface of the Earth, Moon, mutual reference to pseudo-invariant features, or data from a third instrument. Several techniques have been used to perform intercalibration of instruments as outlined here. Some of the published works on the use of intercalibration methods are summarized in Table I.

A. SNOs

Among various intercomparison methodologies involving satellite observations of the Earth view targets, the simultaneous nadir overpass (SNO) approach has proven to be very effective over a wide spectral range, including solar reflective, thermal emissive, as well as microwave spectral regions (see Table I row 1 for references). In this approach, the calibration difference for the spectrally matched channels of a given pair of instruments is determined from their observations made over the same Earth view target and at nearly the same time. Intercalibration by SNO needs many observations made at different times, different illuminating/viewing geometries, and over different reference targets; hence, the uncertainties are significantly reduced, if not completely eliminated. Although the same Earth view target is viewed by a pair of instruments involved for each SNO event, different SNO events typically occur over different targets, which may have different surface spectral characteristics. Thus, a correction that depends on the sensor's SRF and the Earth-surface type must be made (see Table I row 2 for references). In the visible and near-infrared (VNIR) spectral region, the SNO approach can yield an intercomparison uncertainty of about 1% for channels with similar SRF [21]. For any pair of instruments with no SNO opportunities, such as Terra and Aqua MODIS, a third instrument can be used to provide an intermediate reference as long as it is relatively stable during its comparisons with other instruments via SNO [22].

B. Statistical Intercalibration

Another approach to intercalibration of series of data from two or more satellites is based on homogenizing their statistical mean observations over extended periods and/or global regions (see Table I row 3 for references). This can be thought of as expanding the collocation thresholds of the SNO method, as many thousands of observations are compared. This method is most frequently used for products, which by themselves represent averages over large domains, typically for climate trend analyses. Furthermore, statistical methods are often applied to homogenize Level 2 (L2) products derived from Level 1 (L1) data sets. This has been a common practice for variables that can be retrieved as simple linear functions of the

TABLE I
SOME OF THE PUBLISHED WORKS ON THE USE OF INTERCALIBRATION TECHNIQUES

Number	Intercalibration Method	References
1	Simultaneous Nadir Overpasses (SNO)	[97], [24], [21], [22], [98], [99], [100], [101], [102], [103], [104], [105]
2	Spectral Band Adjustment	[106], [107], [39], [41], [44], [108], [109], [110], [111], [112], [21], [24], [34], [42], [101], [102], [113], [114]
3	Statistical Inter-Calibration	[53], [54], [55]
4	Examples of GEO-LEO Intercalibration	[78], [115], [116], [117], [118], [119], [120], [121]
5	Examples of LEO-LEO Intercalibration	[98], [103], [105], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [134], [135], [136] [137] [138], [139], [140], [141], [142], [143], [144], [145], [146], [147], [148]
6	Geostationary satellites	[6], [50], [149], [150], [151]
7	Series of observations from multiple satellites	[28], [53], [134], [135], [152], [153]
8	Aircraft observations	[56], [128], [154], [155], [156], [157]
9	Numerical Weather Prediction + Radiative Transfer Models	[57], [58], [124]
10	Vicarious Ground Based Calibration	[43], [88], [107], [109], [110], [137], [140], [142], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167], [168], [169], [170], [171], [172], [173], [174], [175]
11	Pseudo-Invariant Calibration Sites (PICS)	[19], [22], [37], [60], [138], [139], [176], [177], [178], [179], [180], [181], [182], [183], [184], [185], [186], [187]
12	Deep Convective Clouds (DCC)	[44], [67], [68], [70], [132], [188], [189], [190], [191], [192], [193], [194], [195], [196], [197], [198], [199], [200], [201], [202], [203], [204], [205]
13	Rayleigh Scattering	[69], [70], [206], [207], [208], [209], [210], [211], [212], [213]
14	Liquid Water Cloud (LWC)	[191], [214], [215], [195], [196], [198], [200], [201], [202], [216]
15	Sun Glint	[71], [72], [217], [218], [219], [220], [221], [222], [223], [224], [194]
16	The Moon	[8], [73], [74], [75], [76], [143], [146], [225], [226], [227], [228], [229], [230], [231], [232], [233], [234], [235]
17	The Stars	[77], [236], [237], [238],[78], [79], [239]
18	Ray-Tracing	[44], [121], [132], [189]

observations, for example, the upper tropospheric humidity retrieved from infrared water vapor channels [53] or upper troposphere/lower stratosphere layer temperatures retrieved from microwave sounding channels [54]. However, the harmonization of L2 data sets makes it more difficult to attribute the root causes of any biases in the L1 data from which they are derived.

Statistical approaches rely on a series of assumptions and approximations. For sun-synchronous polar-orbiting satellites, it is often assumed that there are no diurnal cycles in the satellite observations. Clearly, this is not the case for window channels of LEO instruments with different local overpass times, but it should not be neglected for channels in stronger atmospheric absorption bands. As with all methods, differences between the characteristics of each instrument need to be accounted for. In particular, changes in SRF, scan-angle dependence, and incidence angle can have important influences on the final intercalibrated data set [53]–[55]. The uncertainty each of these introduces to the end data set needs to be quantified.

C. Double-Differencing Methods

It is not always possible or desirable to base an intercalibration algorithm on the direct comparison of collocated measurements of two instruments as these do not always occur within acceptable collocation thresholds. In some cases, it can be advantageous to perform a "double difference" comparison of each instrument with an intermediate reference, which can be used as a calibration transfer standard. These methods allow indirect comparisons to take place over a much wider range of conditions by effectively broadening the collocation thresholds, under the basic assumption that the intermediate reference itself is sufficiently stable over the range of conditions covered by the double differencing, e.g., over a time window of several hours.

The following sections give examples of different transfer standards developed for various intercalibration applications. Although these may appear to be quite different techniques, they all rely on the basic double-differencing method. The assumed stability of the intermediate reference needs to be

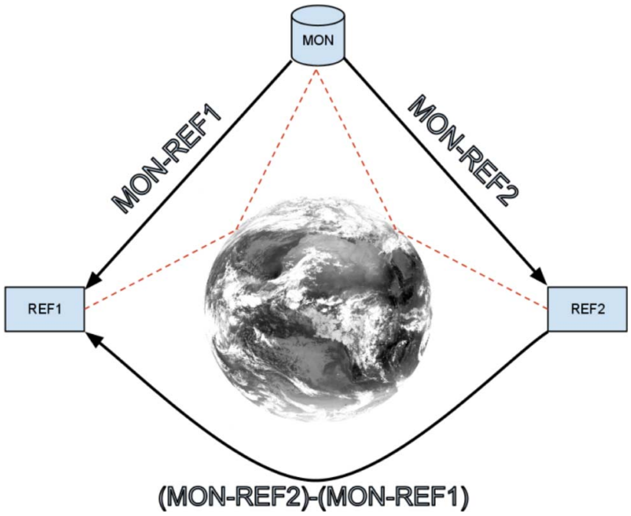

Fig. 1. Schematic showing how double differencing against a third sensor as an intermediate transfer reference can be used to intercalibrate two instruments without requiring direct comparison of their observations. Dashed red lines show collocated observations from pairs of instruments. Black arrows show calibration transfers.

quantified, as this uncertainty is an important part of the overall error budget of these intercalibration methods.

1) Intermediate Transfer Instrument: There is often a need to compare observations from satellites that do not see the same areas at the same times, either because they are in orbits that do not produce any or many collocations or because they were not operating at the same time. In these cases, it may be possible to use double-difference comparisons with a third instrument, used as a transfer radiometer to bridge the gap. This method does not require that the scene itself is stable over the range of conditions covered by the double differencing, as this will be compensated for by the measurements of the intermediate reference (see Fig. 1). However, it does require that the calibration of the transfer radiometer itself be stable over this period between the pairs of comparisons.

a) Geostationary satellites: Geostationary satellites observe part of the Earth's disk continuously with a repeat cycle that typically ranges from 5 to 60 min. This allows collocations to be found for every overpass of a LEO satellite passing within the GEO satellite's field of view. This property allows GEO instruments to be used as intermediaries between instruments on different LEO satellites. However, GEO instruments often have channels with coarser spectral and spatial resolutions than their counterparts in LEO. Direct comparisons between different instruments on different GEO platforms are often hampered by the uncertainties introduced by differences in their SRFs, particularly for channels in the strongly absorbing water vapor bands (see Table I rows 4, 5, and 6 for references).

In contrast to the LEO–LEO SNO method, where the uncertainties are limited by the small sample size, the LEO–GEO–LEO double-differencing method is limited by the stability of the transfer reference and the uncertainty introduced by the SBAF process. However, uncertainties introduced by the SBAF process tend to cancel out if the comparisons are done in the channel-space of the GEO instrument. This method has been analyzed for the AIRS and IASI, using a GOES imager as a transfer instrument. The LEO–GEO–LEO double-differencing method has been also compared with the SNO method [50], showing broadly consistent results with mean differences of < 0.1 K.

b) Series of observations from multiple satellites: An intermediate reference instrument can be used to transfer the calibration between pairs of instruments when it is not possible to perform direct comparison of their observations because the satellites are in mutually exclusive orbits or when instruments are not being concurrently operated (see Table I row 7 for references). For example, when Metop-B is launched into a polar orbit, which follows that of Metop-A by approximately half of one orbit, direct comparisons of their observations will be severely limited by the offset in the ground swath of their instruments and by the systematic and random variations of the scene radiances due to atmospheric and surface changes over the $\sim$50-min period between their observations. To transfer intercalibration products that use Metop-A IASI as a reference instrument to use Metop-B IASI, it is necessary to construct a "*delta calibration*" function based on double differencing of the intercalibration with each monitored instrument (e.g., Meteosat-9 SEVIRI). This delta calibration function is defined in the channel space of the GEO instrument and is added to the intercalibration function derived using one reference to make it metrologically compatible with the second reference. A similar approach can be adopted to transfer the calibration between a series of instruments to construct a homogeneous fundamental CDR (FCDR). For example, this approach is currently being investigated for the intercalibration of data from the many Meteosat imagers that have operated since 1981 by constructing a series of double differences between collocated observations from the series of the HIRS that has operated on NOAA and Metop LEO platforms over the same period.

c) Aircraft observations: Aircraft campaigns have been an important part of several Cal/Val campaigns supporting the launch of new satellite instruments (see Table I row 8 for references). These aircraft observations are often used as intermediate standards to transfer the calibration of a reference instrument to the satellite instrument. Sometimes this is achieved using atmospheric profile measurements sampled *in situ* by aircraft instruments or dropsondes, which are input into radiative transfer models (RTMs) to predict what the satellite instrument would see. The calibration of the satellite instrument can then be adjusted to achieve consistency. In this case, the RTM is acting as the intermediate standard, transferring the calibration of the aircraft instruments to the satellite instrument. However, the RTM can have its own errors, which are then transferred to the *monitored* instrument.

More advanced aircraft campaigns include airborne instruments similar to the monitored satellite instrument. In this case, the airborne instrument is compared to its *in situ* instruments through the RTM, which is run twice to predict the observations of the airborne instrument and the satellite instrument, accounting for the atmosphere between the aircraft and the satellite. Now, the *in situ* instruments and the RTM together act as the intermediary to transfer the calibration of the airborne reference instrument to the monitored instrument on the satellite. Any errors in the surface conditions, the RTM, and atmospheric profile (below the aircraft but not above) will be cancelled out if these do not significantly change between the two comparisons. All these factors should be quantified in the uncertainty analysis of such an intercalibration.

The concept can be further extended to the intercalibration of two satellite instruments using the aircraft instrument, *in situ* instruments, and RTM to transfer the calibration. An example of the latter is the Joint Airborne IASI Validation Experiment (JAIVEx) campaign, in which airborne interferometers were used to validate the calibration of the Metop-A IASI during flights over the Gulf of Mexico [56]. However, this was not strictly a calibration, because no adjustment was made as the band-averaged calibration of both Metop-A IASI and Aqua AIRS were found to be consistent with the airborne instruments within ∼0.1 K.

d) NWP + RTMs*:* NWP models represent the state of the atmospheric profile and surface in a continuously updated cycle and can provide global coverage at spatial resolutions comparable to some satellite instruments (see Table I row 9 for references). Hence, any satellite and NWP model fields can always be collocated with a small uncertainty, often referred to as an *error of representativeness*. In fact, many of the infrared and microwave channels of satellite instruments are routinely assimilated into NWP models to improve their representation of the initial state of the atmosphere, from which weather forecasts are derived. The first step of this process is to compare the observations with the model in observation space, requiring the application of an RTM to the NWP model fields. Bias corrections are derived from these comparisons, which are applied to the observations to ensure they are consistent with the RTM and NWP model. Analyzing trends in these biases with time or other variables provides a valuable tool for monitoring instruments' performance.

However, the bias corrections include components of the bias due to errors in the RTM and NWP model as well as the observations themselves. This problem can be overcome to a first approximation by using the NWP+RTM system as an intermediate reference to transfer the calibration from one satellite instrument to another by comparing the double differences between each satellite instrument and the NWP+RTM, as shown in Fig. 2. As with other double-differencing methods described here, this relies on the assumption that the calibration of the intermediate reference is the same for each instrument pair and does not change with time. In practice, differences in SRF and processing (e.g., cloud masking) can introduce systematic errors in the double differencing. (For more details, see [57] and [58].)

2) Vicarious Ground-Based Calibration: The term "vicarious calibration" refers to all methods that do not rely on onboard systems. Vicarious calibration is an approach that attempts to estimate the at-sensor spectral radiance over a selected test site on the Earth's surface, using surface measurements and radiative transfer code computations (see Table I row 10 for references). In the radiance-based approach, measurements of the upwelling radiance from the test site are made with a well-calibrated radiometer. Downwelling radiance at selected wavelengths can be also measured to provide basis points for modeling atmospheric transmittance. These radiances are then used to further constrain the radiative transfer code calculations to predict the at-sensor spectral radiances at the TOA, as seen by the instrument.

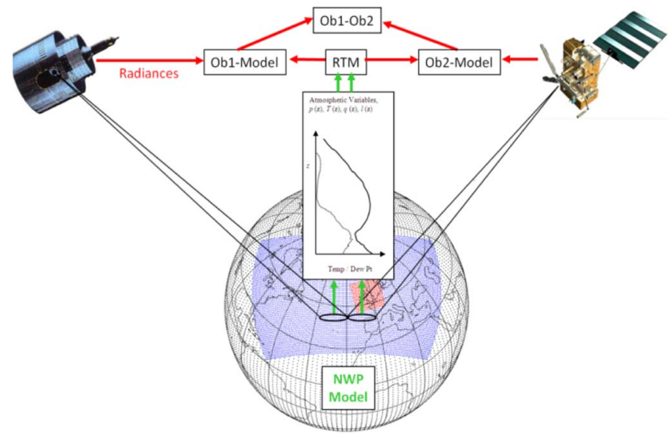

Fig. 2. Schematic of the use of NWP and RTM as intermediate transfer references for the intercalibration of observations from two satellite sensors (Ob1 and Ob2) by double differencing.

Vicarious calibration techniques provide full aperture calibrations with relatively high accuracy (but lower accuracy compared with laboratory methods). The biggest advantage of these vicarious calibrations is that the calibration is performed with the system operating in the mode in which the system collects its remote sensing data [59]. However, vicarious calibration techniques that involve field campaigns to obtain radiometric gains are expensive and labor intensive, which limits the number of such calibrations that are possible for high-quality instrument performance evaluation. Another factor limiting ground reference approaches is that the calibrations can only be performed when the system collects data over the test site. For a satellite with a 16-day repeat cycle, the maximum number of calibrations possible during a given year over a given test site is 22. The actual number will certainly be smaller due to local weather conditions. Finally, the vicarious calibration approach depends on finding a good instrumented site with minimal cloud cover. To get an accurate calibration status of Earth imaging instruments, both the vicarious and onboard calibration systems are necessary. There is a strong need for repeated calibrations of an instrument over its lifetime and for a variety of calibration methods to assess the true radiometric response of an instrument as accurately as possible.

The CEOS IVOS subgroup members worked with partners around the world to establish a set of CEOS-endorsed globally distributed reference standard test sites for the postlaunch calibration of space-based optical imaging sensors. Based on the decision from the CEOS IVOS-19 meeting (February 6–7, 2008) that was held in Phoenix, AZ, there are now eight instrumented sites and six pseudo-invariant calibration sites (PICS), shown in Fig. 3. The eight instrumented sites are Dome C, Antarctica; Dunhuang, China; Frenchman Flat, USA; Ivanpah Playa, USA; La Crau, France; Negev Desert, Israel; Railroad Valley Playa, USA; and Tuz Gölü, Turkey. The CEOS instrumented sites are provisionally being called LANDNET. These instrumented sites are primarily used for field campaigns to obtain radiometric gain, and these sites can serve as a focus for international efforts, facilitating traceability and

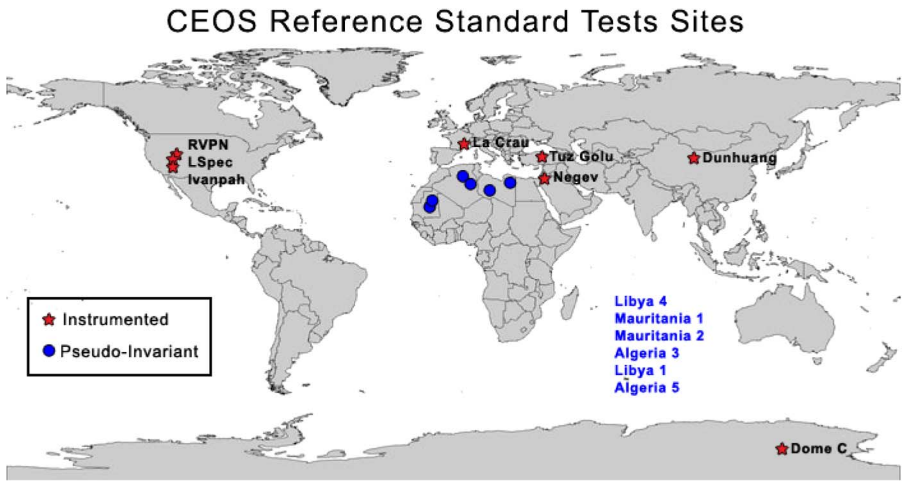

Fig. 3. Distribution of the CEOS reference standard test sites.

intercomparison to evaluate biases of in-flight and future instruments in a harmonized manner. In the longer term, it is anticipated that these sites will all be fully automated and provide surface and atmospheric measurements to the World Wide Web (WWW) in an autonomous manner, reducing some of the cost of a manned campaign. At present, three can operate in this manner. As a precursor to the selection of the CEOS reference test sites, a list of prime candidates was developed [60], and a catalog of worldwide test sites used for instrument characterization was implemented by the U.S. Geological Survey (USGS) [61]. The online catalog provides easy public access to this vital information for the global community.

3) Invariant Targets: Certain targets have been used to calibrate satellite instruments. Used alone, repeated measurements of these invariant targets can detect the instrument degradation relative to some point in time, usually the first day in orbit. If the targets have been adequately characterized by RTM, *in situ* instruments, reference radiometer, or some combination thereof, the calibration can be rendered absolute, or intercalibrated. This method has long been used to calibrate instruments in the VNIR and shortwave infrared (SWIR) part of the spectrum. Improved calibration of microwave instruments has been demonstrated using vicarious calibration over ocean [62], desert [63], and vegetation [64]. An intrinsic limitation of calibration based on the invariant targets is that it cannot detect change in the targets it depends on. Some targets are explicitly referred to as pseudo-invariant to reflect this limitation, assuming stability only during the period of calibration or since the last characterization. This also points to the benefits of using a variety of invariant targets, in hopes that the variations of the signal they generate, known or unknown, are mutually independent to some extent. Fig. 4 provides an illustration of images of various targets that are used for intercalibration studies.

a) PICS: The most widely used invariant targets are the PICS, which are typically sites in the desert (see Table I row 11 for references). Many such sites have been used in the past by various researches, but to concentrate efforts and acquisitions, CEOS has defined a subset of the best and is currently looking at further subsets for higher resolution instruments. The six CEOS reference PICS are Libya 4, Mauritania 1, Mauritania 2, Algeria 3, Libya 1, and Algeria 5. Besides the nominally good site characteristics (temporal stability, uniformity, etc.), these sites were selected by also taking into account their heritage and the large number of data sets from multiple instruments that already existed in the EO archives and the long history of characterization performed over these sites [37], [65], [66]. The PICS have high reflectance and are usually made up of sand dunes with climatologically low aerosol loading and practically no vegetation. Consequently, these PICS can be used to evaluate the long-term stability of an instrument and to facilitate intercomparison of multiple instruments. Since nothing is absolutely invariant, these sites are assumed invariant only during the period of calibration or since the last characterization, thus "pseudo-invariant." In addition, they are only assumed to be radiometrically stable in time, not necessarily spectrally invariant or with respect to varying viewing geometry. Care must also be taken to account for the scattering and absorption in the atmosphere by aerosols, dust, and water vapor, although some sites are much less affected by these uncertainties. It is thus generally recognized that a good comparison would make use of data from an ensemble of sites rather than just one.

b) DCCs: In addition to the selected land targets, another candidate for a stable Earth target is the deep convective cloud (DCC). Unlike the PICS, the DCC targets are not permanently fixed in space, but like the PICS, their reflectance is assumed to be pseudo-invariant. DCC can be used very much the same way as PICS for intercalibration, with a few important advantages. DCCs are nearly perfect solar diffusers [67], regardless of the geometrical conditions, allowing an accurate interband calibration as well as a very precise on-orbit stability monitoring (see Table I row 12 for references). DCCs have much higher reflectance than any other Earth-surface-based target and radiance since they follow the Sun. In general, DCCs are brighter than PICS in the visible spectrum, whereas PICS typically are brighter in NIR; therefore, the two complement each other to reduce the uncertainty in traditional two-point calibration. Comparing to PICS, the scattering from DCCs is closer to being Lambertian, which substantially simplifies the need to characterize the BRDF. DCCs are naturally at a very high altitude, often above 80% of the air, 99% of the atmospheric water vapor,

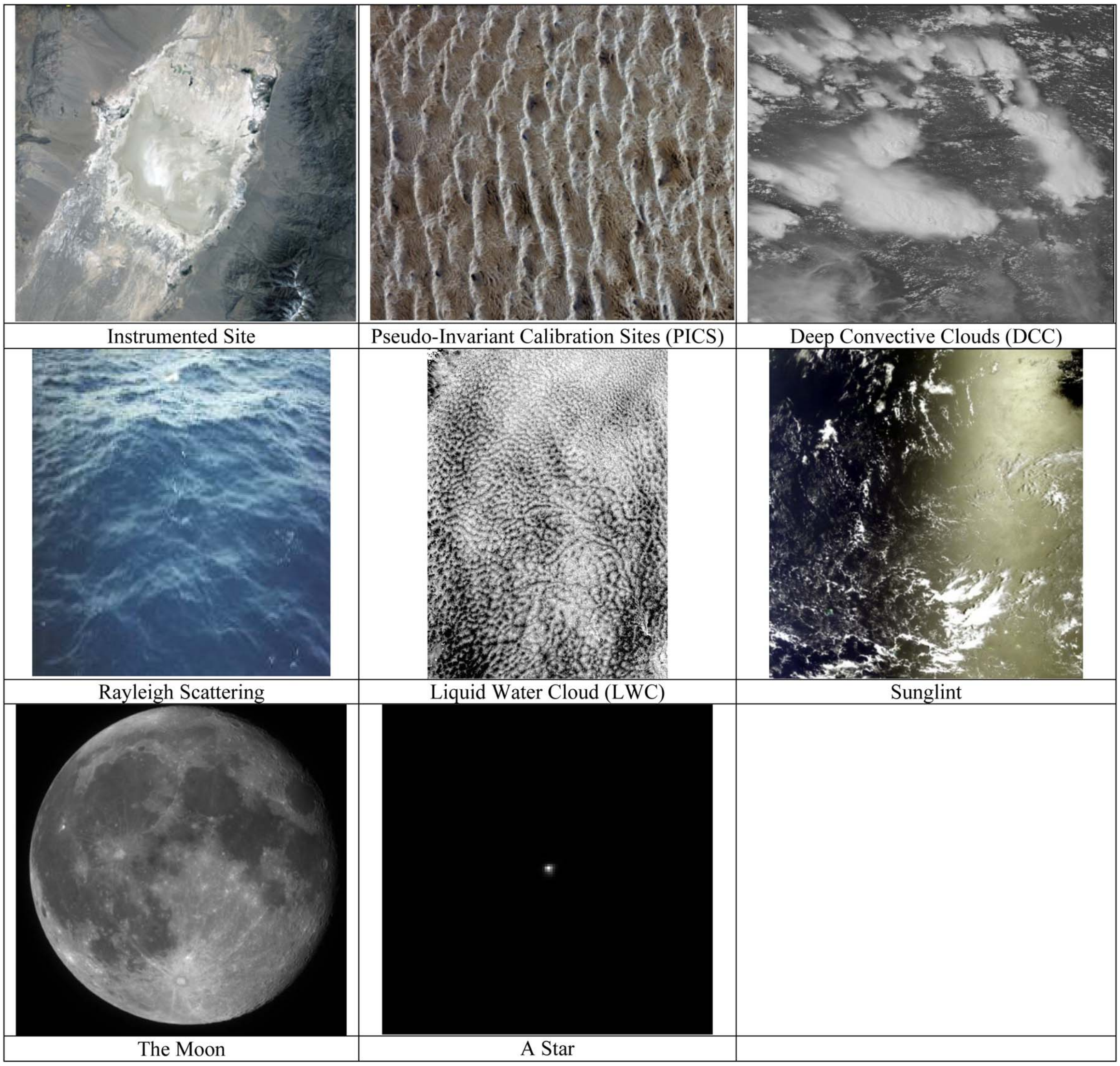

Fig. 4. Images of various targets that are used for intercalibration studies. (Note that the scales differ.) The instrumented site image is over Railroad Valley Playa, Nevada (RVPN), acquired from the L7 ETM+ 30-m sensor on May 19, 2003. The PICS image is over the Libya 4 Desert site acquired from the L7 ETM+ 30-m sensor on April 29, 2003. The DCC image (courtesy: David R. Doelling, NASA) is over Brazil acquired from a GOES-12 1-km visible image at 17:45GMT on October 23, 2009. The Rayleigh image (courtesy: Bertrand Fougnie, CNES) is a high-resolution ocean image acquired using an above-water camera over the Pacific Californian Coast on October 1, 1996 (very similar to what satellites observe). The LWC image (courtesy: B. J. Sohn, SNU) is retrieved from Aqua MODIS (MYD06, in g/m^2) at 19:20 UTC on April 29, 2011, over the East Pacific off South America. The sunglint image (courtesy: Bertrand Fougnie, CNES) is acquired over the Northern Pacific from the ENVISAT MERIS on July 15, 2004. The sunglint image shows a longer vertical shape because of the pushbroom sensor. The Moon image (courtesy: Thomas C. Stone, USGS) is a ROLO image of the Moon at 555 nm, acquired at 06:23:10 UTC on December 24, 1999, with a phase angle of 22.3°. The star image (courtesy: Thomas C. Stone, USGS) of Vega, the standard calibration star α Lyr at 550 nm, is acquired by the ROLO at 07:32:47 UTC on June 15, 2000. The star location is RA $= 18$ h $36'56.3''$, DEC $= +38\ 47'01''$.

and 100% of tropospheric aerosols. This makes DCCs free of those uncertainties. DCCs are more evenly distributed globally in the tropics. This is important for geostationary satellites, as many cannot view PICS under favorable conditions. Another noble aspect of DCCs is that the visible-channel calibration can be performed by calculating BRDF for a typical DCC once its presence is determined based on criteria of infrared window channel brightness temperature [68].

c) Rayleigh scattering: Another category of predictable targets are those whose signals do vary; however, the process is so well understood that the properties, i.e., magnitude and variation, can be accurately estimated. One advantage of using the Rayleigh scattering method is that it provides references for absolute calibration, in addition to trending (see Table I row 13 for references). This is important to validate preflight or operational calibration of satellite instruments, including those with onboard calibration. It also facilitates intercalibration among various instruments.

For example, Vermote *et al.* [69] were among the first to recognize that, in the visible spectrum and over the clear ocean, up to 90% of the radiance reaching the TOA is due to the scattering of the sunlight by the gaseous molecules. This process, known as Rayleigh scattering, is well understood. Often, targets were selected in the atmospheric subsidence zones over the subtropic oceans (see Fig. 5), where uncertainties due to aerosol scattering, back scattering by the water body, and diffuse reflection by whitecaps are small (if a threshold is introduced on sea surface wind speed to further reduce the possibility of

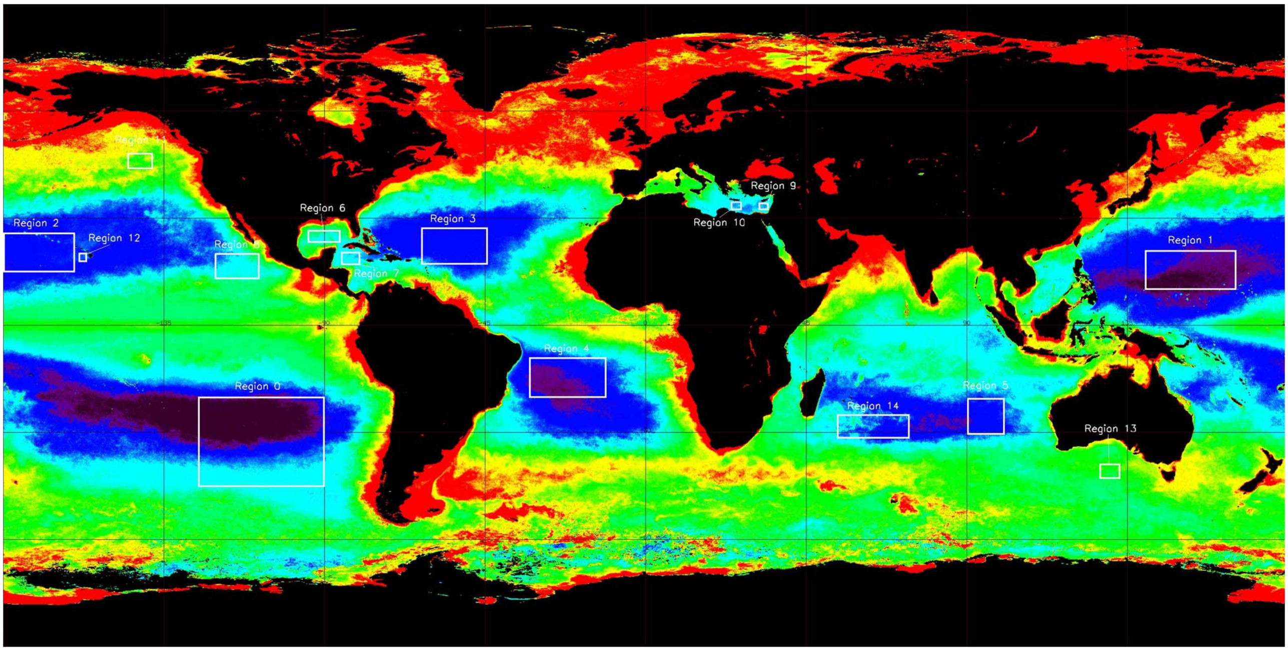

Fig. 5. Distribution of the recommended Raleigh scattering calibration test sites [211] (courtesy: Bertrand Fougnie, CNES). Based on the measurements from the SeaWiFs ocean color data, six spatially homogeneous ocean sites were recommended in the Pacific, Atlantic, and Indian Ocean.

whitecaps). In addition, the geometry of viewing the targets can be controlled to avoid specular (Fresnel) reflection or sunglint at the surface. The residual effects, and the gaseous absorption, must be accurately estimated with an RTM, using climatology data or other observations as inputs. The accuracy of calibration based on Rayleigh scattering ranges from 3% for the blue channels to 2% for channels in longer wavelengths up to the red range. Unlike the PICS and DCCs, the signals of Rayleigh scattering are about an order of magnitude lower (allowing to perform diagnostic on instrument nonlinearity), which may lead to additional uncertainty when extrapolating the calibration to instruments of full dynamic range. However, Rayleigh scattering is ideal for instruments specializing in low signals, such as ocean color instruments, for which DCCs and many PICS often saturate the instruments. For this and other reasons, the two methods are often used together.

d) LWCs: A second example of variant but known targets is the liquid water cloud (LWC). These targets are even more abundant than the DCCs, and their midrange reflectance complements the calibrations based on Rayleigh scattering on the low end and on DCC on the high end (see Table I row 14 for references). One challenge for this method is that the radiance from LWC is highly dependent on the optical properties of the LWC, which are so viable that neither climatology nor outputs from the NWP models are adequate. Therefore, although the RTM has been well known, the lack of accurate input parameters has inhibited its applications in the past.

Recently, cloud properties have been derived from advanced instruments, such as MODIS. This enabled the estimate of LWC radiance using the cloud optical thickness, cloud particle effective radii, cloud top height, and temperature from MODIS, along with atmospheric profiles from NWP models and surface BRDF. To further improve the accuracy of the RTM, one has to account for the radiative effects of 3-D clouds. These include

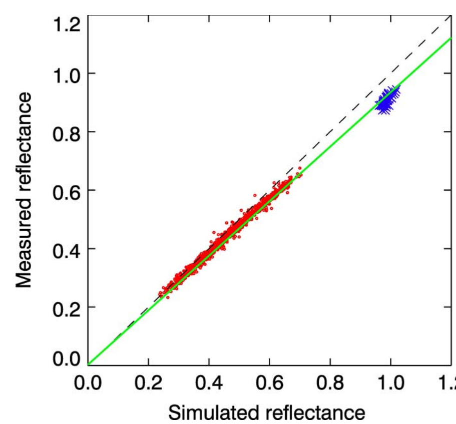

Fig. 6. Illustration of Meteosat 9 visible channel (red band, 0.640 μm) by combining LWC (red dots), DCC (blue crosses), and ray matching (green solid line) calibration methods. LWC and ray matching are based upon MODIS data, and DCC is independent. All methodological procedures are described in Ham and Sohn (2010) [191]. The results show a nice agreement among the three methods, with a suggested underestimate by SEVIRI. (Adapted by courtesy of B.J. Sohn, SNU).

the bias due to the assumption that clouds are plane-parallel and homogeneous, and the assumption that radiance from a pixel is independent of those from its surrounding pixels. Preliminary analysis shows that the accuracy of the LWC method is 2%–3%, comparable to other methods. Figs. 6 and 7 provide an illustration of visible-channel calibration using some of the methods discussed in the earlier section.

e) Sunglint: A third example of variant but known targets is the satellite measurements over the region of sunglint. This method exploits the spectral irradiance from the Sun in the SWIR spectrum (e.g., 3.9 μm), for which many meteorological satellites have a calibrated channel to measure its radiance (see Table I row 15 for references). The solar component in the measured SWIR radiance is usually very weak because the

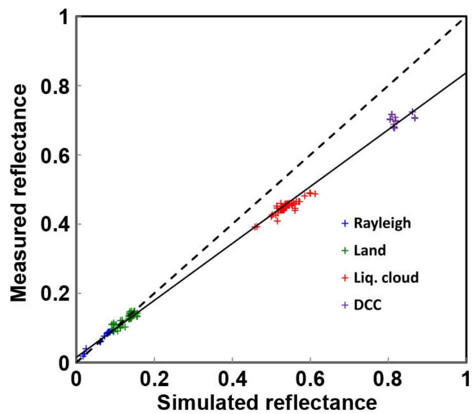

Fig. 7. Illustration of visible-channel calibration using Rayleigh scattering (blue), land targets (green), LWCs (red), and DCCs (purple). A summary of the results is provided [240]. The abscissa is the expected reflectivity from models; the coordinate is the observed reflectivity for MTSAT-1R. (Adapted by courtesy of Y. Kosaka and A. Okuyama, JMA).

surface reflectance is small. Under certain circumstances such as the sunglint, the surface reflectance is substantially enhanced, and the solar component becomes appreciable. The basic idea is to estimate the thermal emission in SWIR from the surface temperature derived from some longwave infrared (LWIR) channels (e.g., 11- and 12-μm channels), subtract the SWIR emitted radiance from the measured radiance to obtain the reflected radiance, and compute the SWIR reflectance from the ratio of the reflected radiance and the incoming solar radiance. It is assumed that the ratio between the reflectances in SWIR and visible is invariant, which enables relative calibration or trending. If the ratio is known, invariant or not, this method can be used for absolute calibration. Care must be taken to account for the surface and atmospheric effects in all visible, SWIR, and LWIR bands because the method uses quantities at the TOA and at the surface.

If in the blue part of the spectrum, the sunglint reflectance represents about 50% of the TOA signal, it reaches more than 90% for longer wavelengths (NIR and SWIR), allowing an efficient interband calibration. One spectral band can be used as a reference to estimate the sunglint contribution and predict the TOA reflectance for other spectral bands. Other contributors to the TOA signal are Rayleigh scattering, marine surface reflectance, background aerosol scattering, and gaseous absorption, depending on the considered spectral band. This target is very suitable for interband calibration and particularly to propagate the absolute calibration made in the visible range to all RSB, with a typical accuracy of 1%–2% [70]–[72].

f) Moon: A third category of invariant targets is celestial bodies, many of which are truly invariant for all practical purposes. They also offer radiometric references that are independent of the Earth surface reflectance and atmosphere, removing the potential conflict of calibrating EO instruments using Earth targets (see Table I row 16 for references). It is well known that the lunar surface reflectance property is extremely stable [8]. The Moon is a nearly ideal target that can be used because its variations in brightness due to phase angle, nonuniform albedo, distance, and the lunar librations can be accurately accounted for with a sophisticated model. Typically, when using the Moon for radiometric calibration, the brightness differences from different lunar observation geometries are corrected or normalized via a lunar model, such as the Robotic Lunar Observatory (ROLO) model developed at the USGS [73]. The correction or normalization is made in terms of lunar irradiances, spatially integrated over the entire lunar disk. Comparisons of lunar observations from different instruments have sometimes been restricted to nearly the same phase angles in attempts to minimize the uncertainties in normalizations for different lunar viewing geometries. However, this may not be the dominant source of uncertainty (e.g., [74]). For calibration intercomparisons among different sensors, the lunar model also accounts for their spectral response differences.

Special arrangements are sometimes needed to acquire lunar images with spacecraft instruments. For example, instruments on LEO sometimes can only observe the Moon in their space view. Satellite maneuvers also have been used to obtain lunar images [75], [76]. Some spacecraft perform dedicated maneuvers to acquire the desirable lunar image, but this can be prohibited for operational satellites. The Moon has been used for satellite instruments, such as Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Terra and Aqua MODIS, and Suomi National Polar-orbiting Partnership (NPP) Visible Infrared Imager Radiometer Suite (VIIRS), to track their on-orbit calibration stability in the RSB. For instruments on geostationary orbit, lunar images sometimes appear in the space adjacent to the Earth's disc, making instrument lunar calibration possible. However, the operational imaging schedules can mean the number of these free lunar images is insufficient; in these cases, dedicated observations are necessary to make lunar calibration a viable option. For future instruments such as the GOES-R Advanced Baseline Imager (ABI) that do not observe the adjacent space unless specifically commanded, plans are to be made in advance to obtain lunar images. Thus, it should be pointed out that not all satellite instruments can collect lunar data or collect enough lunar data due to their design configuration or operational constraints. For these sensors, alternative approaches must be considered for their calibration stability monitoring and intercomparisons with other sensors. Future instrument designs should consider the ability to observe the Moon for in-flight calibration. However, where instruments do observe the Moon, these observations should not be discarded, but data should be routinely archived for analysis.

g) Stars: In addition to the Moon, stars can be also used as calibration targets. Some satellite instruments, such as the Imagers aboard the three-axis stabilized GOES I-M and N-P series, routinely observe a selected set of stars for image navigation and registration (see Table I row 17 for references). The Sounder also views the stars, but with not with the same set of detectors it uses to observe the Earth; therefore, the measurements cannot be used to calibrate the Sounder instrument. Excluding known variable stars (AD Cet, AR Cet, Ψ Vir, 82 Vir, σ Oph, 39 Ori, etc. from the Yale Bright Star Catalog), one can monitor the repeated measurement of the same star to derive instrument degradation over time. Since the GOES measurements were originally intended for navigation, for which all that matters is which detector captured the star signal at which time, whereas the star signal intensity is nearly irrelevant,

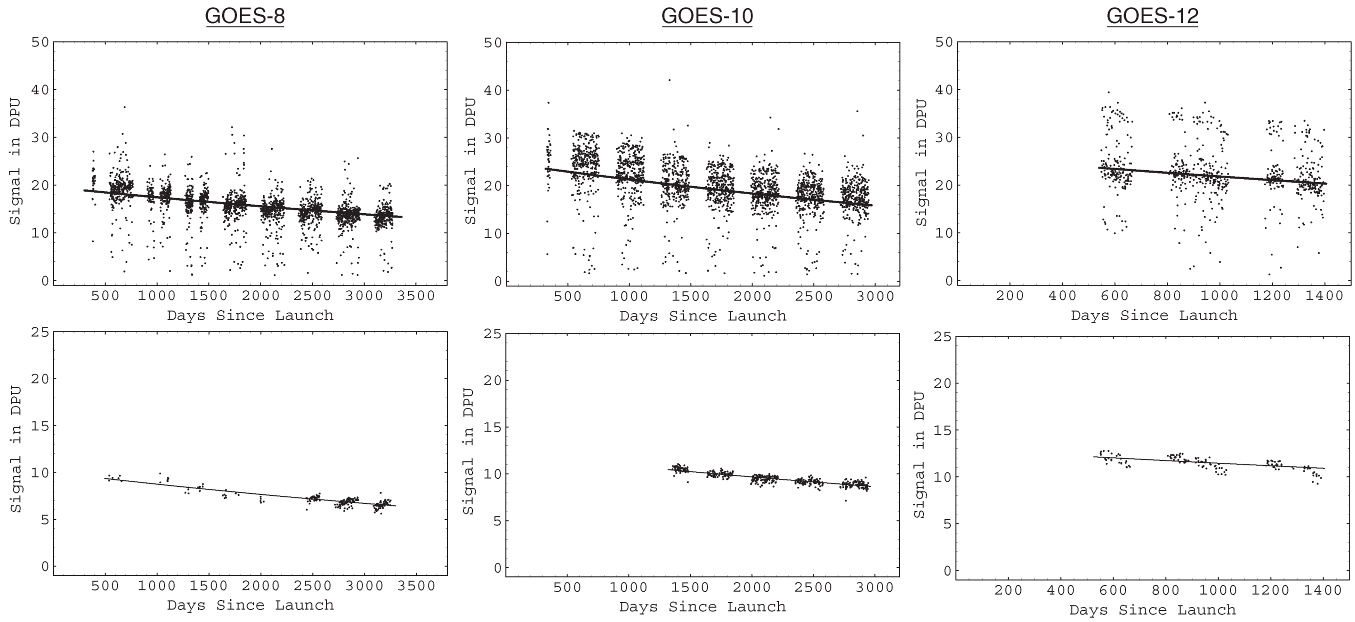

Fig. 8. Time series of instrument output (intensity) from observations of β-Cnc taken by the Imagers aboard GOES-8, -10, and -12 (in left, middle, and right column, respectively) using an initial (upper row) and an improved (lower row) method to quantify star signal intensity. GOES-8 data are obtained over the period April 10, 1995 to April 1, 2003. Day 1 is the launch date of GOES-8: April 13, 1994. GOES-10 data are obtained from March 22, 1998 to May 18, 2005. Day 1 is the launch date of GOES-10: April 25, 1997. GOES-12 data are obtained over the period January 21, 2003 to May 19, 2005. Day 1 is the launch date of GOES-12: July 23, 2001. The abscissa is time in days after launch, and the coordinate is intensity in scaled Detector Pixel Unit (DPU). One DPU is one count in imager visible-channel detector pixel measurement. (Adapted from Chang *et al.* [77]).

great effort has been made to reprocess these data for calibration purposes. With the proliferation of similar instruments used by other agencies, or more generally the acceptance of a three-axis stabilized platform for geostationary environmental satellites, it is hoped that lessons will be learned to revise the ground processing to maximize the benefits of star measurements. This has been the case for ABI, the replacement for Imager on the next generation of GOES.

On geostationary orbit, each star is observed at a different time of the day in different date of the year. On a three-axis stabilized platform such as GOES, the instruments on the satellite undergo significant diurnal thermal variations. Certain intra-annual variation is evident in the lower panels in Fig. 8, upward for GOES-8 and downward for GOES-12, which is believed to be related to the thermal variation [77]. In addition, each GOES observes a few dozen stars of various brightness and color temperatures. The linearity of the silicon detectors and studies performed using different color temperatures stars and brightness (e.g., [78, Fig. 1]) have indicated the same degradation rate is valid for all stars observed by a given instrument. Recent work [79] demonstrates that, with due considerations for all these variations, the star-based calibration can reach the accuracy comparable to other methods.

4) Ray-Tracing: Finally, some intercomparison and intercalibration algorithms have little or no requirements on whether the targets are invariant or known. The strategy is to construct measurements by two instruments that are concurrent in time, colocated in space, identical in spectrum, and matched in viewing geometry; thus, the two are bound to be equal. Some of these algorithms are referred to as "ray tracing" or "ray matching" to distinguish them from those that have no or only implied requirements on matching the viewing geometry (see Table I row 18 for references). This is an extension of the SNO method (see Section IV-A). For two polar orbiters whose ground tracks intersect at the poles, the nadir ground track transect is the SNO or ray matched location.

There are several variants in this category. Some require ray tracing to the single pixel. Others are satisfied if a small region (e.g., 0.5° of latitude and longitude) is viewed by the two instruments with approximately the same angles. In terms of stringency on ray matching, some have very loose or implied requirements, for example "near nadir." Others require only that the zenith angles of the two instruments be similar. This is often for the spectral channels for which the atmospheric absorption is significant. Similar zenith angle ensures similar path length and, assuming the optical properties of the atmosphere are isotropic, similar optical path. Yet, others require strict ray matching in both zenith and azimuth angles. This is often used in the visible spectrum, where the target's BRDF can be highly variable, complicated, and unpredictable. The strict and comprehensive requirements on both zenith and azimuth angle, together with the concurrence requirement that ensures the common illumination, minimize the BRDF uncertainty. Stringent requirements on ray matching improve the credibility of comparing a particular pair of measurements, but they tend to reduce the sample size for comparison at the same time. In some cases, either approach can be used to achieve similar accuracy. In other cases, one has to consider various tradeoffs for the optimal overall quality of intercomparison.

V. Ongoing Joint Efforts

Monitoring the global environment can be optimized by a synergistic combination of data from multiple instruments on different satellite platforms—in many cases, spanning many decades. This requires the quantization of relative biases in calibration so that their data can be equalized to allow seamless combination and interoperability. This can be achieved by international coordination among the operating agencies to intercalibrate their data and can be further facilitated by worldwide cooperative efforts, bringing together instrumentation experts to understand their calibration biases.

A. GSICS

The GSICS, sponsored by the WMO and the CGMS, is a critical component of GEOSS [6]. The overarching goal of GSICS is to ensure the comparability of satellite measurements that may be provided at different times, over different regions, by the different instruments operated under the responsibility of different space agencies. GSICS pursues this goal primarily through intercalibration that enhances the calibration of satellite instruments and validation of satellite observations. GSICS was initiated in 2006 at the WMO by the China Meteorological Administration (CMA), CNES, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), and NOAA. GSICS was later expanded to include NASA, NIST, Japan Aerospace Exploration Agency (JAXA), Indian Space Research Organization (ISRO), India Meteorological Department (IMD), Russian Federal Service for Hydrometeorology and Environmental Monitoring (ROSHYDROMET), and the USGS.

The GSICS aim of ensuring consistent accuracy among space-based observations worldwide for climate monitoring, weather forecasting, and environmental applications is addressed through a comprehensive calibration strategy, which involves monitoring instrument performances, operational intercalibration of satellite instruments, tying the measurements to absolute references and standards, and recalibration of archived data. A major part of this strategy involves direct comparison 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. These *GSICS Corrections* are needed for accurately integrating data from multiple observing systems into products, applications, and services in near-real time and for reanalysis. Another key product is the *GSICS Bias Monitoring*, which is generated from the intercalibration process and quantifies the bias of each of the monitored instruments' channels with respect to the reference. As these biases are typically scene dependent, standard scenes are defined for each channel, corresponding to typical observations. The GSICS Bias Monitoring allows instrument operators and data users to visualize the performance of each channel and identify any trends. This helps them to make decisions on whether calibration corrections or other interventions are required. The third type of GSICS product is the diagnosis of the root causes of bias. There have been several successful examples for this type of application, some of which are summarized at the end of Section II.

One of the first objectives of GSICS was to develop intercalibration products for the infrared channels of geostationary imagers [34], as they are operated by several member organizations, including CMA, EUMETSAT, JMA, KMA, ISRO, and NOAA. The sensors used as an intercalibration reference for GSICS products are summarized in Section III-E. The GSICS Research Working Group is currently working to develop similar products for the geostationary imagers' channels in the RSB. Several of the methods outlined in Section IV-C3 are being reviewed, together with the direct comparison of collocated observations of the monitored geostationary imager with the reference instrument. However, the latter *ray matching* method is limited by the need to align the incidence and solar viewing angles in both azimuth and elevation, as well as the relationship between the monitored and reference instruments' SRF and spectra of the different scene types covered.

GSICS has developed a procedure for product acceptance to certify intercalibration products that have been developed by its members as being compliant with its principles of traceability and consistency. This certification does not judge whether products are "good" or "bad," or even discriminate them based on the type of method, but it does require them to meet minimum standards for documentation of their methods, uncertainties, traceability, implementation, and data access standards. This ensures potential users can decide whether a given product will suit their needs. This procedure has been also opened up to allow the certification of intercalibration products developed outside of GSICS, if they are identified as being compliant with these requirements. The Pathfinder Atmospheres Extended (PATMOS-x) intercalibration products for AVHRR [80] are examples of this.

B. CEOS

The CEOS WGCV is a key international player in the development of high-quality satellite data to improve daily operations and to allow users to confidently study global data sets. The mission of the WGCV is to ensure long-term confidence in the accuracy and quality of EO data and products and to provide a forum for the exchange of information Cal/Val, coordination, and cooperative activities. The WGCV promotes the international exchange of technical information and documentation, joint experiments and the sharing of facilities, expertise, and resources. The CEOS WGCV group seeks to be the recognized first point of contact for the international user-community as far as Cal/Val, system technical information, and EO quality processes are concerned. The objectives of the WGCV are to enhance coordination and complementarity, to promote international cooperation, and to focus activities in the Cal/Val of EO for the benefit of the CEOS membership, the GEO, and the international user community. Much of the detailed technical work of the WGCV is carried out by its six subgroups [Atmospheric Composition (ACSG), Infrared Visible Optical Sensors (IVOS), Land Product Validation (LPV), Microwave Sensors (MSSG), Synthetic Aperture Radar (SAR), and Terrain Mapping (TMSG)], which operate as individual entities and focus on specific technical areas related to Cal/Val.

The IVOS subgroup of the CEOS WGCV is carrying out multiple international comparisons of satellite-measured TOA spectral radiance/reflectance using a common reference target.

In some cases, the target is itself independently characterized by ground/*in situ* SI-traceable methods, and in others, it is simply used as a "common target." Where ground-based measurements are being made, effort is incorporated within the comparison activity to evaluate the equivalence of measurements made by different international teams. This includes an assessment of method, sampling strategy, and instrumentation used together with its associated traceability.

1) CEOS Comparison of TOA Spectral Reflectance/ Radiance—Dome C: This activity was established by CEOS as part of GEO task DA09-01-a to carry out an evaluation of instrument biases utilizing one of the newly established CEOS reference standard test sites: Dome C in Antarctica. This site is one of eight that forms the instrumented network now called LANDNET and the basis of a future potential international calibration system for EO optical instruments. The aim of the activity was to compare several moderate- to high-resolution optical instruments over the Dome-C site in Antarctica and to determine the reflectance differences (if any) between data collected by these instruments. In this paper, there is no "correct" value or set of values for derived reflectance from an instrument. The data were collected during the period December 1, 2008 to January 31, 2009 over the instrumented Dome-C test site.

The objective was to cross-compare the satellite systems using a single methodology that removes biases due to sun-target-sensor geometry and atmospheric effects so that different instruments with different overpass times and different spatial and spectral characteristics collected on different days over the same site can be directly compared. This site has been widely used by the community for a number of years for both instrument-to-instrument comparisons and instrument stability [81]–[84]. Three papers have particular significance. The first, a study carried out by CNES to evaluate the Dome-C area as a calibration site [85], demonstrated the need to correct for the BRDF of the surface, the low surface variability, and the stability over several years. It also noted that there was a need to correct for the atmospheric variations (mainly scattering). The magnitude of the BRDF effect in the data derived from the VEGETATION instrument for nadir observations was much smaller than that observed in the study by the University of Washington [86] using a series of tower observations over two seasons (2003–2004 and 2004–2005). This latter study, the second key paper, suggested that variations in the nadir reflectance (in the blue band used) could exceed 10% over the range of solar zenith angles at the site; this is in marked contrast to the 2%–3% suggested in the CNES study [85]. Last, Cao *et al.* [7] demonstrated the usefulness of this site by comparing observations from seven satellite instruments and discussed establishing the Antarctic Dome-C community reference standard site toward consistent measurements from Earth observation satellites.

2) CEOS Comparison of Land Surface Reflectance—Tuz Gölü: The large number of terrestrial imagers being operated by multiple countries each with their own reference standards and sometimes independent routes of "traceability" creates challenges for the Earth sciences community to develop a coherent data set suitable for climate-level studies. There are various methods available for carrying out this postlaunch vicarious calibration, but one of the most common and generic approaches is to use a dedicated and characterized "test site." In such a method, ground-based measurements of surface reflectance/radiance using similar solar illumination angles and instrument view angles (or at least corrected for these) is propagated to the TOA using a radiative transfer code. For the highest accuracy, surface measurements should be made within a few minutes of the satellite overpass and the characteristics of the atmosphere at that time measured, particularly its optical depth.

Tuz Gölü in Turkey is a LANDNET site. It is endorsed by CEOS as a standard reference site for radiometric calibration of optical satellite instruments. Tuz Gölü is a salt lake located about 150 km southeast of Ankara (38°.50 N, 33°.20 E). The Tuz Gölü basin is a permanent endorheic lake in an arid plateau in Central Anatolia. It is a bright natural target, free of vegetation. It has an area of 1964 km^2 and is 907 m above sea level. It is extremely saline, and during the summer, up to 95% of the lake's water dries up and exposes a salt layer 30–80 cm thick. It is in a sparsely populated region with low aerosol content. The Tuz Gölü salt lake test site is temporarily instrumented during field campaigns and is maintained by the Scientific and Technological Research Council of Turkey (TUBITAK) UZAY.

The 2009 and 2010 CEOS-led campaigns to Tuz Gölü, Turkey, to compare techniques and instrumentation used for the vicarious calibration of optical imagers provided a unique opportunity to evaluate the state of the art of vicarious calibration using a ground-characterized test site. The campaign marked an important step for CEOS to inform the community about the sources of uncertainties associated with the reflectance-based method [87] and start the process of attributing a Quality Indicator to satellite data and further to the end products derived from satellite imagery as recommended by the new international QA4EO. The 2010 CEOS Key comparisons included the following objectives: 1) determine biases between field instrumentation using a series of laboratory and *in situ* cross-comparisons of participants' radiometers and reference panels; 2) estimate a range of values for reflectance uncertainties associated with the reflectance-based method for vicarious calibration of optical instruments; 3) evaluate differences in sampling methods used to associate a "reflectance value" or a "radiometric value" for both a moderately sized (0.03 km^2) and large-sized area (1.0 km^2); 4) document "best practices" used by the participants in the 2010 CEOS Key comparison and estimate the uncertainties associated with each of them; and 5) use the averaged values determined from the participants in the comparison to establish a reference reflectance and uncertainty for the site, using a commonly parameterized radiation transfer code to propagate values to TOA for direct comparison with satellites, with the measurements on the site being timed to match (within a few minutes) those of the instrument overpass. In addition to using ground-measured data, the site was used without ground calibration as a common reference site for instruments.

Representatives from 10 countries and 13 organizations took part in either one or both years of the campaigns. Measurements were made in the VNIR and SWIR and simulated the calibration of instruments with spatial resolutions varying from tens of meters to a kilometer. The data sets collected also permit evaluation of the precision and accuracy of vicarious calibration that are a critical part of the calibration of Earth imagers sufficient to create a long-term absolutely calibrated set of observations for the study of global change [88]. Such efforts require multiple instruments on multiple platforms with each instrument typically having its own calibration team. Most of the instrument teams include some form of vicarious calibration in their calibration plans. Thus, it is essential to ensure that different groups performing these calibrations obtain consistent results to prevent biases between different instruments while producing accurate results with SI traceability. The vicarious calibration of land imagers using the reflectance-based method [87] requires the measurement of the reflectance factor (ρ) of the site surface at the time of the satellite overpass. The terminology for reflectance quantities follows the definitions given in optical remote sensing [89]. The ρ of the test site surface is calculated from radiance measurements performed with a portable spectroradiometer typically made in comparative mode against a reference panel of known reflectance. To avoid biases due to instrument calibration when carrying out the comparison of satellite instruments, all instruments were made traceable to a common SI reference via NPL. This removed biases of up to a few percent due largely to differences in calibration methodologies [90]–[94]. Results are available on the Cal/Val portal.

3) CEOS Infrared Spectral Emitted Radiance Comparison—Miami: The measurement of the Earth's surface temperature and, more fundamentally, any temporal and spatial variation is a critical operational product for meteorology and an essential parameter and indicator for climate monitoring. Satellites have been monitoring global surface temperature for some time with good precision and through activities such as the Global High Resolution Sea Surface Temperature pilot project (GHRSST-pp) have established sufficient consistency and accuracy between in-flight instruments to claim that it is of climate quality. However, for long-term records and for the avoidance of any potential data gaps, such measurements must be fully anchored to SI units, and there must be a direct correlation with "true" surface/*in situ*-based measurements.

The most accurate of these surface Cal/Val-based measurements is derived from field-deployed IR radiometers, which are in principle traceably calibrated to SI units, often through a blackbody radiator. Such instrumentation is of varying design, operated by different teams in different parts of the globe. It is essential for the integrity of their use to provide Cal/Val data for satellites in-flight and to provide the link to future instruments so that any differences in the results obtained between them are understood through rigorous comparison to themselves and to primary SI reference standards. This knowledge will allow any potential biases to be removed, and if a fully traceable link to SI can be established and demonstrated, the data will be robust and can claim its status as a "climate data record." In the context of intercalibration, such surface reference measurements are the means to provide the link and cross-calibration between instruments using transient and temporary reference sites established wherever the ship borne radiometers observe. Satellite overpasses allow direct linkage of surface-measured skin brightness temperatures of the ocean in near-SNO conditions, and given the stability of the ship's radiometers, this can be transferred to a subsequent and different satellite in the future using the simultaneously calibrated (ship) brightness temperature, even if the exact part of the ocean is different.

The "IR Cal/Val community" is well versed in the need and value of such comparisons, having held a previous highly successful exercise in Miami in 2001 [95], [96]. However, nine years had passed, and it was timely to repeat/update the process, particularly as many of the satellite instruments originally supported were nearing their end of life. Therefore, a new comparison building from the previous exercise was organized by CEOS WGCV IVOS taking account of the new QA4EO processes. This new comparison was carried out in two phases. The first laboratory-based comparison of instruments and reference blackbodies was primarily carried out at NPL in the UK a month before the ocean-based comparison in Miami. In this first phase, all blackbodies were compared to the NPL reference blackbody at a number of temperatures using an NPL primary IR radiometer called AMBER. The comparison showed largely good consistency between participants' blackbodies, although there was a lack of clarity in the determination of the uncertainties. Following this, all participants' radiometers then viewed the NPL reference blackbody at various temperatures to determine any biases in brightness temperature measurements. This showed how seemingly good agreement at some temperatures can be misleading when lower or higher temperatures are observed.

The second phase of the comparison included some repeat of the laboratory measurements above to link instruments unable to transfer to the UK together, but this phase largely concentrated on simultaneous views of the ocean from a pier at Miami. While this comparison was not used in conjunction with any satellite overpass, the instruments themselves are normally deployed at various sites across the globe and on ships to provide validation of surface IR brightness temperature measurements from satellites and, in particular, the FCDR sea surface temperature. The results of the comparison can be found on the Cal/Val portal.

VI. Summary

Intercalibration between instruments is not only central to any future Cal/Val strategy but also the only practical means of deriving knowledge of biases between instruments and allows, at some level, a means of bridging anticipated data gaps in measurement continuity due to a lack of coexistent in-flight instruments. The most crucial aspect of monitoring activities using EO satellites is the continuity and consistency of measurements through time. Many of the changes in climate systems will only become apparent after decades or more of observations using precise instruments that have a consistent calibration basis; hence, intercalibration of the instruments is of key interest to the user community as more satellite observations are used for science applications and climate studies. The success of the proposed climate-monitoring missions such as CLARREO and TRUTHS will critically depend on significant advances in on-orbit intercalibration between instruments. The growing use of intercalibration techniques for postlaunch monitoring of satellite instrument performance with respect to other on-orbit reference instruments, selected as community standards, has made intercalibration a key component of current and future satellite instrument calibration strategies.

Although much progress has been made in recent years, major challenges remain to be overcome in order to firmly establish calibration traceability, or reference scale, among instruments and to constantly track their calibration stability throughout their entire missions. It is expected that promotion of the use of sound intercalibration techniques and "best practices" will lead to improved consistency between satellite instruments and help underpin the accurate monitoring of global change. However, achieving this goal requires the coordinated efforts and resources of the space agencies to establish the prospect of operational automatic comparison systems where a range of methodologies can be routinely applied and the results made publicly available for the benefit of the community. Such a system needs to incorporate all instruments from all organizations, including those from the private sector, and its usage and access to results should be made freely available to all. Satellite owners and operators will need to regularly acquire data over reference sites to perform trending, and an entity needs to be charged and funded to ensure continuous and long-term maintenance of appropriate infrastructure and tools. Although this may seem a long way off, projects and discussions are now taking place within CEOS, GSICS, and elsewhere to consider how to best implement such a system, and this special edition plays a role in demonstrating to the community that many of the concepts are mature, and the time is right to start building the framework that is clearly essential for climate and offers enough benefits to the EO community as a whole.

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