World Meteorological Organization

Coordination Group for Meteorological Satellites

Implementation Plan for a Global Space-Based Inter-Calibration System (GSICS)

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Table of Contents

1 Executive Summary 3
2 Background 5
3 Overarching Goal, Objectives, and Overall Approach 7
3.1 Overarching Goal 7
3.2 Objectives 7
3.3 Enabler 7
3.4 Users 7
3.5 Current status 8
4 Expected Benefits 9
5 Overview of Satellite Instrument Calibration 10
6 Components of a Global Space-Based Inter-Calibration System 12
6.1 GSICS Executive Panel 12
6.2 The GSICS Coordination Centre (GCC) 13
6.3 The GSICS Processing and Research Center (GPRC) 14
6.3.1 Intercalibration activity 14
6.3.2 Distributed research component 16
6.4 Calibration Support Segments 17
6.4.1 Pre-launch Calibration 17
6.4.2 Earth-based Reference Sites 19
6.4.3 Extra-terrestrial Calibration Sources 22
6.4.4 Model Simulations 23
6.4.5 Benchmark Measurements 23
6.4.6 GSICS Organizational Chart 26
7 Agency Roles 27
8 Timetable 28
9 Coordination with Other Programs 29
10 References 29

1. Executive Summary

Requirements for more accurate information products from operational environmental satellites are rapidly growing. As numerical weather prediction models become more reliable, their appetite for more accurate data input steadily increases. As the requirements for monitoring global climate become clearer – temperature changes as tiny as a few tenths of a degree per decade, ozone trends as small as 1% per decade – the measurements become more demanding.

Calibration ties a satellite instrument's readings to physical quantities such as units of radiant energy. Intercalibration of instruments achieves comparability of measurements from different instruments. To deliver the more accurate observations needed by modern day weather forecasting and to permit early detection of climate change, it is vital that satellite instrument calibration is of the highest quality and that a capability exists to intercalibrate the satellite sensors. This is the motivating force for the establishment of the Global Space-Based Inter-Calibration System (GSICS).

The concept and strategy for a Global Space-based Inter-calibration System were submitted by WMO and endorsed by the Coordination Group of Meteorological Satellites (CGMS) at its 33rd meeting (CGMS-XXXIII) held in Tokyo, Japan, on 1-4 November 2005. The goal is to achieve operational inter-calibration of the space component of the World Weather Watch's Global Observing System (WWW's GOS) that addresses the climate, weather forecasting and other environmental needs of WMO Members.

This Implementation Plan describes the components of GSICS, the roles of participating agencies, a timetable for implementing the program, and coordination with other international programs.

The GSICS consists of a GSICS Executive Panel, GSICS Coordination Centre (GCC), and GSICS Processing and Research Centers (GPRCs). GSICS also includes critical calibration support segments (CSS). Some CSS are performed directly by GSICS participating agencies while others are performed by external contributing entities.

The GSICS Executive Panel, to be established by the WMO, will be responsible for Monitoring and Evaluation of GSICS and will conduct annual progress reviews of the program. To assist in the coordination, planning and implementation of the research and data management activities of GSICS, the WMO will also form a GSICS Research Working Group and a GSICS Data Working Group.

The GSICS Coordination Centre (GCC) will be co-located with one of the participating GPRCs (TBD). The GCC will coordinate the specifications for collocated data requirements (satellite-to-satellite, satellite-to-reference sites), specifications on collocation criteria, sampling frequency, formats, reporting times, methodology for instrument intercomparisons, and archiving and access of collocated data. The GCC will transmit satellite collocation times and locations to satellite operators, it will receive intercalibration results and reports from satellite agencies and reference sites and will maintain a central archive for the intercalibration collocations. All data will be accessible by the GPRCs.

A GSICS Processing and Research Center (GPRC) will be located at each operational satellite agency. The GPRC will have access to all data collected by the GCC. The GPRCs will conduct instrument calibration and validation activities, which includes pre-launch characterization. Each GPRC will focus on calibration activities based on priorities established by their respective satellite agencies. Inter-satellite calibration will use collocated satellite observations and overlapping satellite records to achieve comparability of sensors on different satellites. Pre-launch characterization and calibration will engage the national standard laboratories of participating countries to insure that pre-launch calibrations are traceable to the accepted international standards. Each GPRC will also support research activities in the framework of the distributed research component of GSICS, coordinated by the GSICS Research Working Group (GRWG)

The GSICS Calibration Support Segments (CSS) will be carried out by participating satellite agencies, national standards laboratories, major NWP centers, and national research laboratories. CSS activities are:

- **Earth-based reference sites,** such as stable desert areas, long-term specially equipped ground sites, and special field campaigns, will be used to monitor satellite instrument performance.
- **Extra-terrestrial calibration sources,** such as the sun, the moon, and the stars, will provide stable calibration targets for on-orbit monitoring of instrument calibration
- **Model simulations** will allow comparisons of radiances computed from NWP analyses of atmospheric conditions with those observed by satellite instruments
- **Benchmark measurements** of the highest accuracy by special satellite and ground-based instruments will help nail down satellite instrument calibrations

WMO, CGMS, satellite agencies, national standards institutes, national data centers, major NWP centers, and national research laboratories will carry out the GSICS.

The WMO will organize a number of implementation planning activities – including obtaining commitment from participating agencies - that will culminate with the first GSICS Annual Operating Plan in March 2007 and the initiation of GSICS operations in April 2007.

Successful implementation of GSICS will result in substantial benefits to the ultimate user communities of operational environmental satellite observations – the weather and climate communities – in the form of more accurate weather forecasts and reliable climate monitoring.

2. Background

The following paragraphs introduce the concept and strategy for a Global Space-based Inter-calibration System (GSICS) that was submitted by WMO and endorsed by CGMS at its 33rd meeting (CGMS-XXXIII) held in Tokyo, Japan, on 1-4 November 2005. The goal is to achieve operational inter-calibration of the space component of the World Weather Watch's Global Observing System (WWW's GOS) that addresses the climate, weather forecasting and other environmental needs of WMO Members.

Previous to CGMS-XXXIII, a meeting was held at EUMETSAT's Headquarters Darmstadt, Germany on 21 and 22 July 2005 in order to have an open discussion for such a concept and strategy. Participants were asked to review a draft concept and strategy paper and provide feedback and ideas with the goal to develop the present draft concept and strategy at the meeting.

Requirements for more accurate satellite information products are steadily increasing. As numerical weather prediction models become more reliable, their appetite for more accurate data input steadily increases. As the requirements for monitoring global climate become clearer – temperature changes as tiny as a few tenths of a degree per decade, ozone trends as small as 1% per decade – the measurements become more demanding. To create the stable long-term data sets needed for monitoring climate change it becomes vital to inter-calibrate sensors on similar and different satellites. Also important is intercalibration of satellite observations with in situ observations. Additionally, the NWP community has demonstrated that assimilation systems could contribute to an international effort and assist in the following continuous activities: relative calibration; channel validation and satellite radiances monitoring as reported on the Internet at various web sites. Also demonstrated by the assimilation community was the need for absolute calibration.

The Global Earth Observation System of Systems (GEOSS) is an international collaboration with the aim of integrating information from various Earth observing systems to provide better information and understanding, which then enables the public, private sector, and governments to benefit from informed decision-making. GEOSS addresses nine societal benefits:

- reducing loss of life and property from disasters
- understanding environmental factors affecting human health
- improving management of energy resources
- understanding, assessing, predicting, mitigating and adapting to climate variability and change
- Improving water resources management through understanding of the water cycle
- Improving weather information, forecasting and warning
- Improving the management and protection of terrestrial, coastal and marine ecosystems
- Supporting sustainable agriculture and combating desertification

- Understanding, monitoring and conserving biodiversity

Satellite observations are a major contributor to GEOSS. A single satellite in sun synchronous low earth orbit (LEO) provides global coverage with two observations per day (12 hour separation) for most locations on the earth. Geostationary satellites provide hourly or better coverage of the Earth over a fixed region. The WWW's GOS geostationary constellation of 6 satellites provides global coverage between +/- 60 degrees latitude, while the polar constellation of more than four LEO satellites provides hourly coverage near the poles. It is clear that multiple satellite systems are needed to provide observations with adequate temporal resolution covering the Earth in order to achieve an integrated information-based system that meets the nine societal objectives discussed above. The establishment of an operational global space-based inter-calibration system will also provide a means to retrospectively inter-calibrate satellite data.

To integrate observations and products from different satellite systems, the measurements must be inter-calibrated. Without inter-calibration of the space-based component of the WWW's GOS and of GEOSS, the full benefit of the observations will not be realized. For climate applications, the data cannot be used because jumps (systematic biases) can occur in a time series constructed from different sensor observations. For weather predictions, biases between different satellites are often resolved by computing differences between measured observations and those simulated from a model analysis or forecast. However, the radiance bias adjustments often do not identify the different sources of the biases. A much better scientific approach to account for instrument-to-instrument biases is to directly compare observations from different instruments. The number of satellite-based Earth observing systems is going to increase significantly - data volume by 5 orders of magnitude- during this decade and beyond. Additionally, an operational global space-based inter-calibration system will also serve to inter-calibrate in situ observing systems that would further improve assimilation systems. Thus, an operational global space-based inter-calibration system would be a critical step towards a total inter-calibration system.

Therefore, there was a compelling need for a concept and strategy for a global space-based inter-calibration system endorsed and implemented by space agencies with guidance from the WMO Space Programme. Here, the purpose of inter-calibration is to quantitatively relate the radiances from different sensors to allow consistent measurements to be taken over the globe by all elements of the space-based observing system. A Global Space-based Inter-calibration System would be part of an end-to-end capability consisting of: rigorous prelaunch calibration, on-board calibration devices (e.g., black bodies, solar diffusers); in situ measurements of the state of the surface and atmosphere (e.g. the Cloud and Radiation Test-bed (CART) site, aircraft instruments with SI traceable (e.g NIST)) calibrations; calibrations using extraterrestrial sources such as sun, moon and stars; radiative transfer models that enable comparison of calculated and observed radiances; and assimilation systems that merge all measurements into a cohesive consistent depiction of the Earth-atmosphere system.

3. Overarching Goal, Objectives, and Overall Approach

3.1 Overarching Goal

The overarching goal of the GSICS is to ensure the comparability of satellite measurements provided at different times, by different instruments under the responsibility of different satellite operators.

3.2 Objectives

The objectives for the operational Global Space-based Inter-calibration Systems (GSICS) are:

- To ensure that instruments meet specification, pre-launch tests are traceable to SI standards, and the on-orbit satellite instrument observations are well calibrated by means of careful analysis of instrument performance, satellite intercalibration, and validation with reference sites

- To improve the use of space-based global observations for weather, climate and environmental applications through intercalibration of the space component of the WWW's GOS and GEOSS
- To provide for the ability to re-calibrate archived satellite data using the GSICS intercalibration system to enable the creation of stable long-term climate data sets

3.3 Enabler

- An operational global space-based inter-calibration system to better characterize space-based observations by measuring, documenting, understanding and accounting for differences between different sensors - analyses of the differences will provide for recommended actions to achieve the benefits described below

3.4 Users

- Climate, NWP, and related environmental application areas

3.5 Current status

- ***Current capability*:** Operational inter-calibration, as described above, presently does not exist for the WWW's GOS as an overall total system but rather only for components of the satellite system
- ***Requirement stated by*:** CGMS-XXXII, Sochi, Russian Federation, May 2004, EUMETSAT/WMO/GCOS/CM-SAF, July 2004 and CBS-XIII Evolution of the GOS, February 2005
- ***The Gap:*** An overall system-wide operational inter-calibration system for WWW's GOS

4. Expected Benefits

The benefits resulting from the establishment of a Global Space-based Inter-calibration System are:

High-level

- Enhanced usefulness of satellite products to observe climate variability and trends, and to support reanalysis projects.
- Improved utility (ease of use) of satellite radiances in NWP
- Reduced cost-benefit ratio from an optimized global system of satellites

Technical

- Consistent calibration of space-based radiometers
- Significantly improved characterization of space-based radiometers
- Improved overall performance by moving towards absolute calibration (this would also necessitate a reference measurement network)
- Improved understanding of physical processes in atmospheric models (requires absolute calibration)
- Improved detection of climate trends, by tying entire intercalibrated system to absolute SI standards and ensuring that any drift of the entire intercalibrated system truly reflects changes of the Earth System.
- Improved assessment of sensor performance to validate that contractors meet the performance standards in their SOW.

In addition to these immediate benefits, analysis of the discrepancies between satellite sensor measurements will provide important data on sensor calibration and drift which could be used to adjust and thereby extend utilization of “drifting” space-based sensors and to improve the development of future sensors.

5. Overview of Satellite Instrument Calibration

Calibration is the process that enables an instrument's readings to be converted to physical units - in the case of satellite instruments, units of radiant energy. In the field of satellite meteorology, the term cal/val is frequently used. Cal refers to calibration of the instruments, and val refers to validation of the geophysical products generated from the instrument's observed radiances. Satellite instrument calibration activities take place throughout the lifetime of the instrument - and beyond through retrospective calibration.

Prior to launch, instruments are calibrated in laboratories against known sources of radiant energy. Pre-launch calibrations are sometimes changed in space because of suboptimal pre-launch characterization, the effect of launch shock and the harsh environment on the instruments. However, despite such calibration shifts, pre-launch calibration is still critical to mission performance. Pre-launch calibration provides and validates the radiometric performance of on-board calibrators, determines filter in-band and out-of-band spectral response, detector linearity, stray light, instrument thermal response, and other performance attributes which are critical for on-orbit performance assessment and calibration correction.

Calibration continues while the instrument is in space. Most instruments have on-board calibration devices. For those without on-board calibrators, e.g., operational visible and near infrared imagers, changes from pre-flight calibration can be monitored by viewing constant external sources. Such sources include natural targets on the Earth's surface such as deserts, and the sun, moon, and stars.

Intercalibration of satellite instruments involves relating the measurements of one instrument to those of another. Instruments can be intercalibrated when they are viewing the same scenes at the same times from the same viewing angles. Or, for satellite time series data in an archive, the overlapping records of two satellite instruments can be compared. Generally, the time series of large-scale spatial and temporal means are intercalibrated. The result of an intercalibration is the consistency and the absence of any bias of one instrument's measurements with respect to the other's.

A highly intercalibrated system not tied to international standards based on the SI system of units is prone to drift over time. The magnitude of such drift is hard to predict, but for climate measurements where small changes are of prime interest, it may become an issue for future generations trying to track changes over several decades. Therefore, development of procedures for linking the observations to the international SI system of units is highly desirable.

There are a number of other tools that can be used to nail down satellite instrument calibrations and intercalibrations. Radiances and derived products – geophysical variables retrieved from the satellite measurements - can be compared with those of reference observing sites. Such sites include long-term specially equipped ground sites, such as those of the DoE's ARM program and the Chinese calibration sites in NW China, intensive field campaigns, special aircraft observations, highly accurate radiosonde measurements, ozone observations, etc. One powerful tool that has received little attention is the comparison of radiances computed from NWP model analyses with observed radiances. The major NWP centers make these comparisons on a daily basis for the instruments that are assimilated in the models. Although the NWP model and its associated radiative transfer system have their own biases, the model calculations can be used a transfer scheme. Model versus observation comparisons can be used to determine the bias of one instrument relative to another or the stability of an instrument over time.

The measurement capabilities of an instrument are captured by three attributes: Accuracy (also called absolute accuracy, bias, or systematic error), precision (also referred to as random error, scatter, noise, or repeatability), and stability (sometimes labelled instrument drift or time dependent bias (short and long term)). An additional attribute, the RMS error (also referred to as total error or uncertainty), which combines the accuracy and precision into one number, is sometimes used.

Precision is the uncertainty in a measured quantity resulting from random errors; it is defined as the standard deviation of the observations about its mean.

Accuracy is defined as the "closeness of the agreement between the result of the measurement and the true value of the measurand" (ISO, 1993). It may be thought of as the closeness to the truth and is measured by the bias or systematic error of the data, that is, the difference between the short-term average measured value of a variable and the truth. The short- term average is the average of a sufficient number of successive measurements of the variable under identical conditions such that the random error is negligible relative to the systematic error.

Long-term stability (or, for short, stability) may be thought of as the extent to which the accuracy remains constant with time. Stability is measured by the maximum excursion of the short - term average measured value of a variable under identical conditions over a period of time; for long term climate monitoring, a decade is commonly used. The smaller the maximum excursion, the greater the stability of the data set.

For NWP, both precision and accuracy are important. Current NWP data assimilation systems correct for instrument bias by comparing the satellite observations with simulated observations calculated from the model variables. Mean differences are assumed to be due to the bias in the satellite observations (the model and its radiative transfer calculation are assumed to have no bias). The larger the instrument bias the greater the error using this method. In any case, increasing instrument accuracy is critical to moving away from the perfect model assumption.

For climate studies, accurate measurements of climate variables are vital for understanding climate processes and changes: just as in NWP, accurate values are needed in equations describing the climate system. However, it is not as necessary for monitoring long-term changes or trends as long as the data set has the required stability. And, when it comes to building satellite instruments, stability appears to be less difficult to achieve than accuracy. The difficulty in connecting the data of one satellite instrument with another satellite instrument arises because of the many known and unknown systematic uncertainties that are to be accounted for in the calibration of the instrument on ground to establish its absolute accuracy and transfer and monitor the calibration on orbit. Stability on the other hand is the measure of repeatability and reproducibility of the metrological characteristics of each satellite instrument with time. Thus, the key requirements for the climate data are long-term stability of the measuring instruments and their SI traceable absolute on orbit calibration and validation to insure comparability of data from one satellite to another.

6. Components of a Global Space-Based Inter-Calibration System

The major components of GSICS are the GSICS Executive Panel, the GSICS Coordination Centre (GCC), the GSICS Processing and Research Centres (GPRCs), and Calibration Support Segments (CSS).

6.1 GSICS Executive Panel

The GSICS Executive Panel, to be appointed by WMO, will monitor and evaluate the evolution and operations of the GSICS. The Panel will also provide guidance and advice on the development and enhancement of the GSICS. The Panel will consist of representatives from WMO and each satellite agency. The GSICS Executive Panel will conduct annual progress reviews of the GSICS. The WMO will also form a GSICS Research Working Group (GRWG) and a Data Working Group (GDWG) to assist in the coordination, planning and implementation of GSICS research and data management activities. The GRWG will consist of scientists and the GDWG of data management experts representing the participating agencies.

Table 1 Executive Component and Working Groups

Task No.	Task	Implementer
1.1	Establish GSICS Executive Panel	WMO
1.2	Organize annual meeting of GSICS Executive Panel	WMO
1.3	Publish and distribute annual reviews by the GSICS Executive Panel	WMO
1.4	Form GSICS Research Working Group and GSICS Data Working Group	WMO

6.2 The GSICS Coordination Centre (GCC)

The GSICS Coordination Centre (GCC) will be collocated with one of the participating GPRCs (TBD). The GCC will coordinate the definition of technical specifications such as: satellite-to-satellite or satellite-to-reference sites collocation or overlap criteria (viewing angle, temporal or horizontal window), sampling frequency, data exchange formats, reporting times, methodology for instrument intercomparisons, archiving strategy for collocated data, and intercalibration results. The GCC will transmit satellite collocation data (times and locations) to the satellite agencies, and it will receive and archive intercalibration results from satellite agencies and reference sites. All data will be accessible by the GPRCs. The GCC will coordinate the development of appropriate software tools to be used in all GPRCs and at the GCC.

The GCC will archive, distribute, and respond to requests for GSICS calibration information, including all relevant data and results obtained by the GPRCs and CSS.
It will serve as a one-stop source for information on all satellite instruments. The GCC will provide easy, near real-time access to calibration information via its (links) website; a mirror-site could be established at the WMO. From time to time the GCC in consultation with GPRCs will issue special assessment reports of instrument trends or other results of general interest. The GCC will also communicate to satellite agencies GSICS guidance on satellite instrument calibration. To inform and unify the satellite calibration and user community, the GCC will publish and distribute an electronic GSICS Quarterly Newsletter with news and notes on satellite calibration activities throughout the world.

Table 2 GSICS Coordination Component

Task No.	Task	Implementer
	Coordination:	
2.01	Coordinate the definition of technical specifications such as collocation or overlap criteria (satellite-to-satellite, satellite-to-reference sites), sampling strategy, comparison methodology, archiving strategy, data exchange formats and modalities	GCC
2.02	Monitor the overall GSICS activity and provide feed-back	
	Collocation	
2.03	Develop, maintain and run software for computing satellite collocations time and geolocations	GCC
2.04	Transmit request including satellite collocation times and geolocations to GPRCs for data extraction and processing	GCC
2.05	Provide report on collocated data completeness and timeliness	GCC

	Software tools development	
2.06	Develop or coordinate the development of common software tools for computing satellite-satellite intercalibration statistics and make the software available to all GPRCs	GCC
2.07	Develop software for computing large scale means and analyzing satellite/satellite differences for overlapping time series	GCC
	Guidance on methodology	
2.08	Provide guidance on calibration methodology	
2.09	Issue special assessment reports on instrument behavior in space	GCC, GPRC
	Information	
2.10	Create a website for easy, quick access to real-time calibration information on all satellite instruments	GCC, GPRC
2.11	Publish GSICS Quarterly Newsletter	GCC
2.12	Organize international workshops to discuss intercalibration algorithms, results, and applications	GCC,GPRC, CGMS,WMO
	Archive	
2.13	Collect and archive GSICS calibration results along with relevant metadata	GCC
2.14	Respond to user requests for archived calibration information	GCC

6.3 The GSICS Processing and Research Center (GPRC)

A GSICS Processing and Research Center (GPRC) will be located at each operational satellite agency.

6.3.1 Intercalibration activity

The GPRC will have access to all data collected by the GCC. The GPRC will conduct instrument calibration and validation activities, which includes prelaunch characterization. Each GPRC will focus on calibration activities based on priorities established by their respective satellite agencies.

Inter-satellite calibration involves inter-calibrating similar instruments on different satellites. Instruments can be inter-calibrated when they are viewing the same scenes at the same times from the same viewing angles – the collocation technique. Or, for satellite time series data in an archive, the overlapping temporal records of two satellite instruments can be compared - the satellite overlap technique.

LEO/LEO and LEO/GEO collocation technique

The data needed for satellite inter-calibration are collected from simultaneous collocation of observations. For LEO to LEO, this has been demonstrated at NOAA/NESDIS using a new technique called Simultaneous Nadir Observations (SNO) and Simultaneous Conical Observations (SCO) that collocates sensor data from different NOAA, DMSP and NASA instruments. For LEO to GEO, simultaneous observations from collocations between a LEO and all GEO sensors have been used on a routine basis for more than 20 years within WCRP's International Satellite Cloud Climatology Project (ISCCP) as a means to inter-calibrate GEO satellites. Conversely, for GEO to LEO, an instrument with high accuracy, precision and stability in geostationary orbit can be used as a means to inter-calibrate all LEO sensors. Additionally, collocated high spectral resolutions observations (e.g. AIRS, IASI, CrIS) are important for validating and vicariously calibrating broader-band radiometers (HIRS, MODIS). All collocated observations for satellite inter-calibration must be archived with metadata as well as inter-satellite calibration coefficients, and be freely and openly exchanged. Space Agencies should share responsibility in providing satellite observation data for inter-calibration. The GSICS Coordination Centre - should provide collocation (location and time) events for various satellite intersections.

Table 3 LEO/LEO and LEO/GEO Collocation Technique

Task No.	Task	Implementer
3.1	Receive GCC requests for collocated datasets (satellite pairs, instruments/channels, time and geolocations)	GPRC
3.2	Extract samples of observations at satellite intersections according to agreed specifications	GPRCs
3.3	Process the pairs of collocated data sets with harmonized processing tools : compute satellite-satellite collocation statistics and determine calibration coefficients matching, relative bias and uncertainty in relative bias	GPRCs
3.4	Transmit results to GSICS Coordination Center (GCC)	GPRCs
3.5	Contribute to develop software for computing large scale means and analyzing satellite/satellite differences for overlapping time series	GPRCs
3.6	Archive collocated data sets and metadata	GPRCs
3.7	Address discrepancies between instruments through detailed analysis of the measurement system, including re-measurement of witness artifacts such as apertures and filters.	National standards laboratories

Satellite overlap technique

In the satellite overlap technique, archived satellite data – either radiances or derived products – are used to compare overlapping time series records of two instruments. In contrast to the collocation technique, in which pairs of observations at satellite intersections are analyzed, the satellite overlap method inter-compares large scale temporal and spatial means of two instruments. The collocation and satellite overlap technique each has its pros and cons. Collocation permits comparison of observations of the same scene at the same time at the same viewing angle. But the number of such exact matchups is limited, and, in the case of two polar orbiting satellites, occurs mainly in polar areas. The amount of data available for analysis in the satellite overlap technique is substantially greater than in the collocation method and depends on the length of the overlap period. In practice, this period has ranged from a few months to several years for operational satellites. Care must be taken to account for possible differences in local observing time of polar or geostationary satellites, when comparing the time series of large scale means from such records. The basic assumption of this method is that the large scale means of the two satellite records will be the same even though the observations are not collocated, to the extent that the sampling of diurnal or seasonal cycles are equivalent in the two series. The satellite overlap method has been invaluable for addressing biases when different series numbers of the same satellite type are compared, such as NOAA 16 and 17. The compared sensors are essentially the same and thus many potential sources of discrepancy between the two sensors cancel in the comparison. A new suggested strategy of replacing satellites upon failure to lower costs will reduce the number of such comparisons that can be made. Ideally, agencies will work together to ensure that there is always full satellite coverage for critical climate variables. In addition, agencies should ensure that there will always be sufficient satellite overlap between old and new sensors, even if the sensors are different.

Table 4 Satellite Overlap Technique

Task No.	Task	Implementer
4.1	Develop list of satellite pairs and time periods for analysis	GCC
4.2	Extract data from archive	GPRC
4.3	Perform intercalibration of datasets pairs from overlapping records	
4.4	Transmit results to GCC	GPRC
4.5	Develop the capability to recalibrate archived satellite data	GPRC

6.3.2 Distributed research component

The GSICS Research component will be distributed. Each GPRC will support research activities which are coordinated by the GSICS Research Working Group (GRWG). The GRWG will have representation from each GPRC and other relevant scientific entities (e.g.,CEOS CalVal Working Group,GEWEX Radiation Panel). A GSICS research plan will be developed by representatives of satellite agencies, national standards laboratories, and national research laboratories active in satellite cal/val activities. NWP and climate community representatives should also participate. Potential research objectives include developing improved capabilities at national standards laboratories and space/satellite agencies for performing and validating pre-launch calibrations, more accurate on-board calibration techniques, enhanced capabilities to exploit extraterrestrial sources, improved algorithms for intercalibrating satellite instruments, additional surface and satellite benchmark observations, and how to build instruments whose calibration does not change on orbit from the prelaunch value. Principal investigators will report on their research at annual workshops held in conjunction with the annual meetings of the GSICS Executive Panel.

Table 5 Research Component

Task No.	Task	Implementer
5.1	Organize Workshop to Develop Plan for GSICS Research Component	WMO and GSICS Planning Committee
5.2	Individual research projects at Satellite Agencies	Satellite Agencies
5.3	Individual research projects at national standards laboratories	National standards laboratories
5.4	Individual research projects at participating agency laboratories	National agency laboratories
5.5	Organize annual international workshops to review and discus research progress	WMO

6.4 Calibration Support Segments

6.4.1 Pre-launch Calibration

Satellite instrument calibration begins in the laboratory where the instrument views a target whose radiative characteristics are known by independent measurements. The pre-launch component of GSICS will engage the national standard laboratories of participating countries to ensure that pre-launch calibrations are traceable to the accepted international standards - international standards, ideally based on the SI system of units-rigorously validated through international comparisons.

Pre-launch characterization requires extensive calibration tests to properly characterize instruments and ensure that calibrations are traceable to SI standards. Ideally instruments should meet thresholds for spectral coverage and resolution, and radiometric performance (accuracy, precision and long-term stability). Instruments meeting these thresholds can then be used to anchor instruments that do not. All pre-launch instrument data must be archived with metadata and be freely and openly exchanged. In particular, pre-launch calibration includes fully and publicly documented pre-launch radiometric characterization, calibration, and uncertainty analysis traceable to SI standards as maintained by the world's national metrology institutes. Prelaunch characterization should have uncertainty estimates associated for individual components (e.g, measurements of spectral response functions and antenna patterns). For the ultimate accuracy a system-level calibration should be performed with radiometric standards that mimic as closely as possible the spectral and spatial optical radiative properties of the expected Earth targets and with environmental conditions that mimic as closely as possible the temperature and vacuum conditions found in space. Onboard calibration utilizes radiometric standards (blackbodies, solar reflectance, etc.) to determine and correct the drift in the pre-launch calibration of the instrument while on orbit. The performance of the standards should be assessed during the pre-launch calibration. How these standards drift under the harsh radiation environment of space needs to be understood. (National Physical Laboratory of UK has been studying the stability of polytetrafluoroethylene (PTFE) plaque reflection standards under harsh ionizing radiation environments.)

Some national standards laboratories have developed transportable standards for calibrating, or checking the calibration of, satellite instruments in the vendor's or space agency's test chambers. These transportable facilities are used to relate an instrument's readings to international standards, by providing highly accurate measurements of target source characteristics. An example of such a facility is the US NIST's Spectral Irradiance and Radiance Calibrations with Uniform Sources (SIRCUS) facility. Implementation of the GSICS will permit inter-calibration of all international satellite agency instruments prior to flight by tying them to the same international standards based on the SI system of units. For most visible and near-infrared radiometric measurements, the absolute standard is based on cryogenic radiometry in which optical power measurements are tied to electrical power standards based on the watt SI unit. At longer infrared wavelengths, near unity emissivity blackbodies are used to tie optical measurements to temperature standards based on the Kelvin SI unit. Ideally, the calibration configuration will match as closely as possible the spatial, spectral, and temporal conditions experienced on orbit. SIRCUS transfers the watt (cryogenic radiometer) and meter (aperture area) scale to remote sensing instruments realizing spectral irradiance or radiance.

The national standards laboratories should aid vendors to establish ISO 17025 type quality systems to improve measurement quality. Such a quality system documents the process, the traceability chain, uncertainty analysis, and validation procedures used by the vendors. The national metrology institutes have implemented such a system for all of their calibration services.

National standards laboratories are encouraged to improve their capabilities. With the advent of hyperspectral satellite sensors more realistic targets are needed. Hyperspectral image projection provides the ability for calibrating sensors against realistic targets, with spatial, spectral, and temporal profiles matching that seen on orbit. Such calibration will allow the full testing of the instrument, from measurement to climate variable determination. Individual testing of components to get the full system behavior is non-ideal since it is dependent on the modelling of component couplings, such as stray light.
Current traveling SIRCUS-like facilities have minimal capabilities; there is a need to develop an advanced UV-IR capability for use off-site at specialized test chambers.

Advanced tunable LED sources may also allow less expensive routes to achieve SIRCUS-like capabilities.

Table 6 Pre-Launch Tasks

Task No.	Task	Implementer
6.1	Develop improved portable calibration facilities	National standards laboratories, Space Agencies
6.2	Develop realistic targets for hyperspectral sensors	National standards laboratories, Space Agencies
6.3	Aid vendors to establish ISO 17025 type quality systems to improve measurement quality	National standards laboratories, Space Agencies
6.4	Validate vendor calibrations	National standards laboratories, Space Agencies
6.5	Provide traceability to international standards	National standards laboratories, Space Agencies
6.6	Provide estimates of instrument accuracy and precision	National standards laboratories, Space Agencies

6.4.2 Earth-based Reference Sites

Use of earth-based reference sites involves comparing a satellite instrument's observed radiances or derived products with collocated surface measurements, or with observations from long-term specially equipped ground sites, and intensive field campaigns, special aircraft observations, highly accurate radiosonde measurements, ozone observations, etc.

Surface sources

Earth surfaces whose reflective properties are not expected to change significantly with time are used to monitor the stability of visible and near infrared radiometers lacking on-board calibration devices. Instrumental drift is determined from analysis of time series of the instrument's observations of these sources. Desert sites are preferred because of their relatively high and constant (in time) surface reflectivities, and dry atmospheric conditions, which reduce the effect of water vapour variations on the observed radiances Atmospheric effects can be more accurately accounted for with radiative transfer modelling, if there are measurement of aerosols and water vapour at the site. NOAA uses the Libyan Desert to monitor the AVHRR and the Chinese use a Gobi desert site to monitor instruments on its polar orbiting satellites. Some of these sites are also characterized by ground instruments. In a more robust technique, the ISCCP has assumed that the Earth's surface reflectance as a whole does not change from year to year and has monitored the stability of the visible and near infrared channels of the AVHRR by analyzing the changes if its clear sky global averages over time.

Table 7 Surface Sources Technique

Task No.	Task	Implementer
7.1	Monitor VIS and NIR instrument drift using stable natural surface sources or Earth as a whole	Satellite Agencies
7.2	Transmit calibration results to GCA	Satellite Agencies

Long-term ground-based sites

Observations from a number of long-term ground sites are used to calibrate satellite instruments.

The Chinese Meteorological Administration operates radiometric calibration sites in the Gobi Desert, located west of Dunhuang in northwest China's Gansu Province, and at Qinghai Lake in northwest China's Qinghai Province. The Gobi Desert site is a very uniform and flat area of about 30 km by 50 km (Liu et al. 2004). The standard deviation of surface reflectance across the central portion of this area is less than 2%. The site has no vegetation and thus the surface reflectivity remains constant throughout the year, except for rare events of rainfall and snowfall (the mean annual precipitation is 34 mm). It is far from major sources of air pollution, but reasonably close to Dunhuang city, facilitating logistics. Many high-resolution samples (400 nm–2500 nm) of surface spectral reflectance and bidirectional reflectance distribution function (BRDF) by ground-based and air-borne spectrometers are available for this site. It has not only been used to monitor the calibration of individual instruments but also to intercalibrate satellite sensors (Liu et al. 2004).

NOAA’s Marine Optical Buoy (MOBY) provides values of water-leaving radiance for the calibration and validation of satellite ocean-color instruments. Located in clear, deep ocean waters near the Hawaiian Island of Lanai, MOBY measures the upwelling radiance and downwelling irradiance at three levels below the ocean surface plus the incident solar irradiance just above the surface. These observations have been used in the calibration of ocean color sensors, which have bands in the visible and near-IR.

The DoE’s Atmospheric Radiation Measurement (ARM) Program establishes and operates field research sites, called cloud and radiation testbeds, to study the effects of clouds on global climate change. Three primary locations—Southern Great Plains, Tropical Western Pacific, and North Slope of Alaska—representing a range of climate conditions conduct a wide variety of measurements with instruments such as radiometers and interferometers, radars and lidars, and a balloon-borne sounding system.

Other long term sites include a number of measuring networks that could be used for monitoring satellite instrument drift, including the GCOS Upper air Network (GUAN), the Baseline Surface Radiation Network (BSRN), the Global Atmosphere Watch (GAW), drifting ocean buoys, and the Network for the Detection of Stratospheric Change (NDSC).

Table 8 Long-Term Ground-Based Sites Technique

Task No.	Task	Implementer
8.1	Monitor satellite calibration using Gobi Desert Site, MOBY, ARM sites, GUAN, BSRN, GAW, ocean buouys, and NDSC	Satellite Agencies and participating national agency laboratories
8.2	Transmit calibration results to GCA	Satellite Agencies and participating national agency laboratories
8.3	Calibration and validation of supporting field measurements	Satellite Agencies and participating national agency laboratories, National Standards Laboratories

Special field campaigns

A number of agencies have capabilities and instruments to conduct special field campaigns to help calibrate satellite sensors.

- The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Programme operates the NPOESS Aircraft Sounder Testbed (NAST) aircraft. NAST is instrumented with a hyperspectral IR sounder and a microwave sounder, and can underfly satellite sensors.
- The DoE's ARM program conducts special field observations is support of satellite instrument calibration. These observations have been used to calibrate the AIRS instrument as well as instruments on NASA's Aura satellite. The ARM also has an Unmanned Aerospace Vehicle (UAV) that can be instrumented for satellite calibrations.
- NASA's Hydrospheric and Biospheric Sciences Laboratory at its Goddard Space Flight Center has valuable observing capabilities.. These include innovative scanning aircraft microwave radiometers operating through the 1 - 1000 GHz spectrum; transportable weather radars; airborne lidars that measure ice cap, sea ice, and coastal topography; and other lidar systems for ocean biology. These remote sensing measurements are buttressed by a focused in-situ sensing program that includes highly innovative UAVs and autonomous ocean sensing systems.
- NOAA's Global Monitoring Division has high quality radiosondes, frost-point hygrometer temperature and moisture instruments, and in-situ ozone instruments for balloon measurements synchronized with satellite overpasses.

Table 9 Special Field Campaigns Technique

Task No.	Task	Implementer
9.1	Conduct special field campaigns for satellite instrument calibration: NPOESS NAST, DoE ARM, NASA GSFC	Satellite Agencies and participating national agencies
9.2	Launch special ozone , radiosonde, and frost point hygrometer balloon observations synchronized with satellite overpasses	NOAA and other national agency laboratories
9.3	Transmit calibration results to GCC	Satellite Agencies and participating national agency laboratories
9.4	Instrument calibration and validation	Satellite Agencies and participating national agency laboratories, and national standards laboratories

6.4.3 Extra-terrestrial Calibration Sources

Extraterrestrial objects such as the moon and stars can be used as stable sources of radiant energy to calibrate or monitor the stability of satellite instruments. The sun is used as a stable source for on-board calibration of instruments observing various parts of the earth-reflected solar spectrum, e.g., the SBUV on NOAA"s POES series. Several instruments, e.g., the NASA's MODIS and SeaWIFS, have viewed reflected sunlight from the moon to monitor changes in their visible and near-infrared channels (Sun et al., 2003; Barnes et al., 2001). Although the Moon has been found it to be an effective tool for assessing instrument drift, it cannot yet be used for absolute calibration. Absolute high-spectral resolution measurements of the Moon and other targets are needed to provide absolute radiometric scales for the intercalibration and comparison of satellite measurements. Time series of observations of stellar sources have been used to monitor the degradation of visible sensors on the GOES satellites (Chang et al., 2005). The USGS with support from NASA has developed the Robotic Lunar Observatory (ROLO). ROLO has led to the development of a high quality model of the **relative** reflectivity of the Moon at moderate spectral resolution. (Kieffer, et al.)

Table 10 Extra-terrestrial calibration sources technique

Task No.	Task	Implementer
10.1	Calibrate satellite sensors against the moon and stellar sources	Satellite Agencies

10.2	Transmit calibration results to GCA	Satellite Agencies and participating national agency laboratories
10.3	Conduct absolute high-spectral resolution measurements of the moon to provide absolute radiometric scales	National standards laboratories

6.4.4 Model Simulations

The major NWP centers around the world continually monitor satellite radiance observations by comparing radiances computed from the model's output with the observations. The model's output consists of an analysis of atmospheric conditions based on assimilating all available observations. In current operations, these comparisons are made only for IR and microwave channels and only for clear sky conditions. Analysis of the differences between the observed and modelled radiances yields the relative bias of the instrument with respect to the model and time series of these differences can reveal drifts in satellite instruments.

Table 11 Model simulations technique

Task No.	Task	Implementer
11.1	Continuously monitor satellite instrument performance by comparing NWP model simulations with satellite observations	International NWP Centers
11.2	Specify format of model/satellite calibration results	GCC
11.3	Transmit calibration results to GCC	International NWP Centers

6.4.5 Benchmark Measurements

Benchmark observations are very high quality measurements that serve as the gold standard for measuring a particular variable and that could be applied to calibrating other observations of the same variable. Benchmark passive microwave-to-UV satellite measurements of the Earth must refer to the measured radiances (including polarization and spectral distributions) and not to derived climate variables such as sea-surface temperature since the latter depends both on other measurements and modeling, such as, for instance, a radiative transfer model of the atmosphere. In the context of long-term climate monitoring, benchmarks have the following characteristics:

- Accuracy that extends over decades, or indefinitely
- Global observations of a variable that is critical to defining long-term climatic change

- Measurements that are tied to irrefutable standards, usually with a broad laboratory base

- Observation strategy designed to reveal systematic errors through independent cross-checks, open inspection, and continuous interrogation

- Minimal dependence on supporting models in which the critical input parameters or underlying theories are poorly known or understood

Goody et al. (2001) have identified a number of potential satellite measurements that could be used as benchmarks:

- GPS occultation measurements for precise monitoring of upper tropospheric and lower stratospheric temperatures
- Total solar irradiance measurements for monitoring variations in solar forcing of the Earth's climate
- Absolutely calibrated, spectrally-resolved measurements of radiance emitted by the Earth to space for information on variations in both climate forcings and responses
- A SAGE-type instrument for upper-tropospheric and stratospheric ozone, volcanic aerosols, water vapor, and other minor atmospheric constituents
- A high-precision, scanning multi-spectral polarimeter for tropospheric aerosol measurements

Except for the absolutely calibrated spectrally resolved radiance measurements, all of these instruments have flown in space. GSICS will use these observations to calibrate and intercalibrate the operational satellite instruments. GSICS will also champion long term continuity of measurements of these instruments as well as the development and launch of absolutely calibrated, spectrally-resolved radiance instruments to measure radiance emitted and reflected by the Earth. These latter instruments, obtaining benchmark measurements of the complete emitted and reflected spectrum of the Earth would be ideal for calibrating any passive operational radiometer or spectrometer.

Surface-based benchmark measurements can also be used monitor satellite instrument. calibration. For example, NOAA's Global Monitoring Division operates staffed atmospheric baseline observatories at Barrow, Alaska; Trinidad Head, California; Mauna Loa, Hawaii; Samoa; and the South Pole from which numerous in situ and remote atmospheric and solar measurements are conducted. Continuous observations are made of greenhouse gases, ozone, aerosols, and radiation fluxes. The 16-station GMD Cooperative Dobson Network is a significant portion of the global Dobson network making ground-based, column-ozone measurements. All GMD network stations and almost all of the global network stations are linked to the world calibration standard maintained by GMD. Six of the Dobson instruments are automated to provide ozone vertical profiles using the Umkehr technique and eight balloon-borne ozonesonde stations, including the South Pole, provide ozone profiles to an altitude of ~32 km.

Consideration is also being given to the creation of a benchmark balloon network for long term, high accuracy, stable observations of some of the critical atmospheric climate variables (Seidel, 2005). One possibility is the measurement of temperature and humidity profiles with balloon borne sensors whose calibration is enhanced to meet the standards of a benchmark observation.

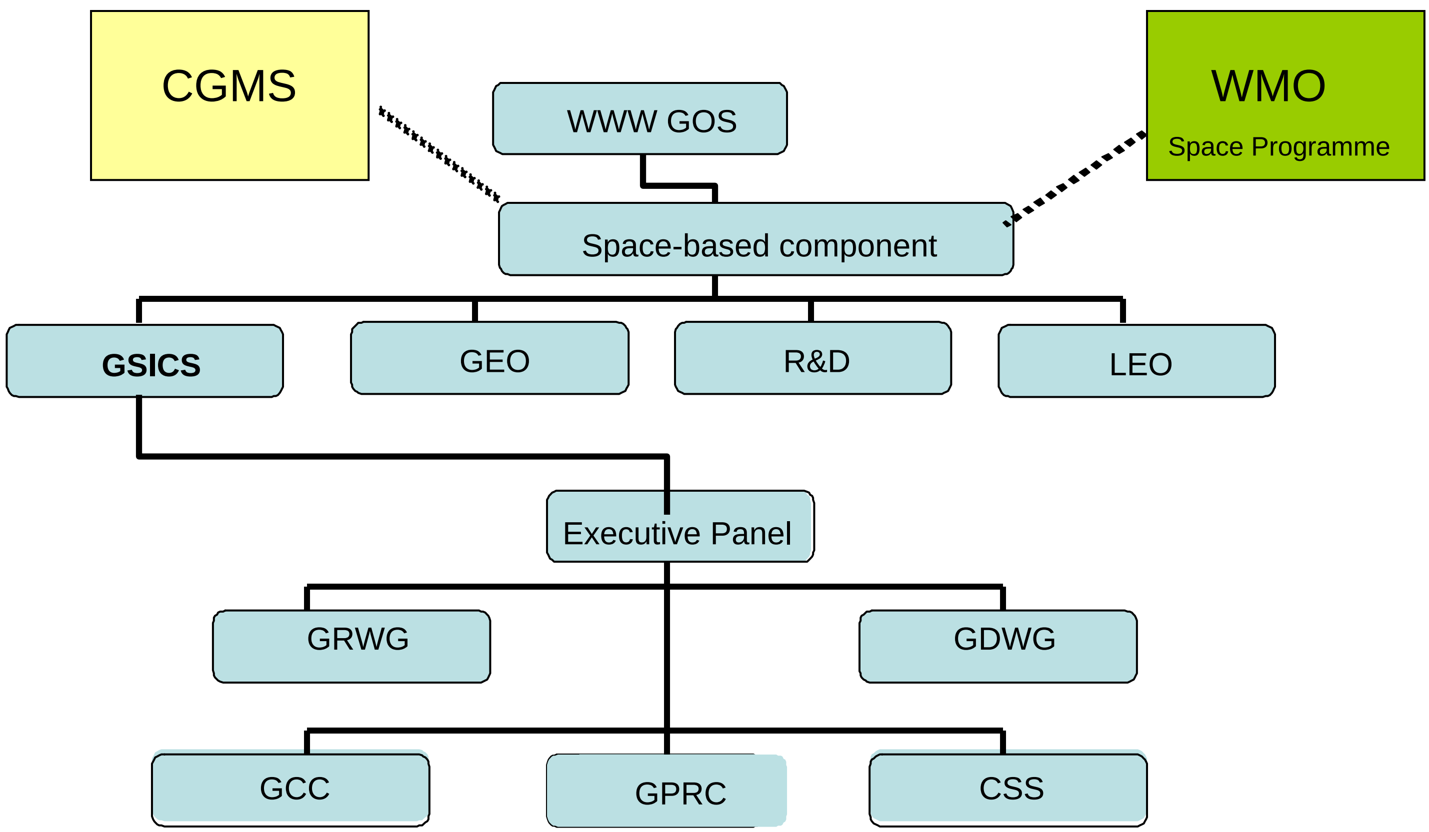
Comparing these benchmark measurements, and/or top of the atmosphere radiances computed from them, with satellite derived products or observed radiances would provide additional checks on satellite instrument calibration and drift. Since use of surface benchmark measurements requires application of a radiative transfer model – which may have its own absolute bias - this technique provides only limited information on satellite instruments bias but substantial data on satellite instrument stability if long term time series are analyzed.

Table 12 Benchmark measurements

Task No.	Task	Implementer
12.1	Exploit satellite benchmark measurements (GPS, SAGE) to calibrate satellite instruments	Satellite Agencies
12.2	Transmit calibration results to GCA	Satellite Agencies
12.3	Champion continued flight of benchmark instruments and development/flight of absolutely calibrated, spectrally-resolved measurements of radiance emitted and reflected by the Earth to space	CGMS
12.4	Use NOAA's benchmark observatory observations to calibrate satellite observations	NOAA
12.5	Champion development of a benchmark balloon network for long term, high accuracy, stable observations	WMO

6.4.6 GSICS Organizational Chart

The GSICS Organizational Chart shows the components of GSICS and how they will be organized and illustrates how GSICS fits into the Space-based Component of the WMOWorld Weather Watch (WWW) Global Observing System (GOS).



7. Agency Roles

The GSICS is a coordinated, distributed, international system aimed at achieving an Overarching Goal of ensuring the comparability of satellite measurements independent of time, instrument, and satellite operator.. Participants include the WMO, CGMS, national satellite agencies, national standards laboratories, national data centers, major NWP centers, and national agency laboratories. Roles of the participating organizations are outlined below.

WMO. The WMO, through the WMO Space Programme (WMO SP), will facilitate the evolution of the GSICS by providing general guidance and secretariat support, establishing the GSICS Executive Panel, organizing workshops, preparing documents, and securing GSICS participation commitments from member governments.

CGMS. The Coordination Group for Meteorological Satellites (CGMS) is the coordination body of satellite operators for the implementation of satellite missions contributing to the space-based component of the World Weather Watch (WWW) Global Observing System (GOS). GSICS will report to CGMS through its Executive Panel.

National satellite agencies. Participating national satellite agencies will collect samples of satellite observations for the LEO/LEO and LEO/GEO inter-satellite calibrations and participate in other parts of the GSICS distributed calibration component. They will collect and process observations samples in the GSICS Processing and Research Center (GPRC), which will be established in their respective satellite agencies. The satellite agencies will transmit to the GCC calibration results from their participation in the GSICS distributed calibration component. The satellite agencies will also conduct projects as part of the GSICS research component.

National standards laboratories. Participating national standards laboratories will execute a number of tasks to improve pre-launch calibrations and to tie these to the international system (SI) of units, facilitating comparability of instruments. They will also conduct a program of observations aimed at characterizing the absolute radiometric scale of the moon. The standards laboratories will also address discrepancies between instruments through detailed analysis of the measurement system, including re-measurement of witness artifacts such as apertures and filters. The standards laboratories will thus contribute to GSICS CSS and also conduct projects as part of the GSICS research component.

National data centers. Participating national data centers will extract time series of satellite data selected by the GSICS for inter-satellite calibration using the satellite overlap technique. They will transmit the data sets to the GPRCs.

Major NWP centers. Participating major NWP centers will continuously monitor satellite instrument performance by comparing NWP model simulations with satellite observations and transmit their results to the GCC.

National agency laboratories. Participating national agency laboratories will perform tasks under the distributed calibration component, transit results to the GCC, and conduct projects as pat of the GSICS research component.

8. Timetable

The Table below summarizes the actions needed to implement the GSICS, the responsible party, and the target dates for completion of actions.

Table 13 Timetable of Actions to Implement GSICS

Action No.	**Action**	**Responsibility**	**Target Date**
13.1	Submit GSICS Implementation Plan to CGMS heads of delegation for approval.	WMO	4/15/06
13.2	Approval of GSICS IP	CGMS	5/15/06
13.3	Transmit invitations to CGMS satellite agency members to attend GSICS implementation meeting (at the same time of WMO EC LVII meeting) with the aim to receive commitments for participation and nomination to the GSICS Executive Panel (EP).	WMO	5/15/06
13.3	Convene GSICS Executive Panel (establish working groups, terms of reference) and GSICS organizational workshop	WMO	10/11-14/06
13.4	Convene GSICS Data Management WG	GSICS	12/1/06
13.5	Construct first draft of GSICS Annual Operating Plan	GSICS	2/1/07
13.6	Approval of GSICS AOP at second Meeting of GSICS Executive Panel	GSICS	2/15/07
13.7	Begin GSICS Initial operations	GCC & GPRCs	4/1/07

9. Coordination with Other Programs

GSICS will be coordinated with other programs to prevent duplication of efforts, maximize productivity from available resources, and create a synergistic international effort. As a new element of the space-based component of the WMO WWW GOS, GSICS will be coordinated through the WMO Space Programme with other relevant WMO programmes or WMO co-sponsored programmes. In particular, proper articulation will be established with the WCRP/ISCCP in order to gain lesson learned in ISCCP calibration activities and provide the maximum mutual benefit towards ISCCP and GSICS objectives.

Under the guidance of the GSICS Executive Panel, relationship will be established with relevant international activities such as:

- GCOS
- CEOS and its Cal/Val working group
- GEOSS
- CIPM and BIPM (International Committee of Weights and Measures & Bureau of Weights and Measures—International organizations which tie together the world's national standards laboratories)

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