

Earth Observation Sensor Calibration Using A Global Instrumented and Automated Network of Test Sites (GIANTS)

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ABSTRACT

Calibration is critical for useful long-term data records, as well as independent data quality control. However, in the context of Earth observation sensors, post-launch calibration and the associated quality assurance perspective are far from operational. This paper explores the possibility of establishing a global instrumented and automated network of test sites (GIANTS) for post-launch radiometric calibration of Earth observation sensors. It is proposed that a small number of well-instrumented benchmark test sites and data sets for calibration be supported. A core set of sensors, measurements, and protocols would be standardised across all participating test sites and the measurement data sets would undergo identical processing at a central secretariat. The network would provide calibration information to supplement or substitute for on-board calibration, would reduce the effort required by individual agencies, and would provide consistency for cross-platform studies. Central to the GIANTS concept is the use of automation, communication, co-ordination, visibility, and education, all of which can be facilitated by greater use of advanced *in situ* sensor and telecommunication technologies. The goal is to help ensure that the resources devoted to remote sensing calibration benefit the intended user community and facilitate the development of new calibration methodologies (research and development) and future specialists (education and training).

Keywords: sensor radiometric calibration, test sites, *in situ* sensing

1. INTRODUCTION

There are growing expectations on the use of Earth observation data to support key decisions by governments and industries concerning the sustainable development of our resources and the good stewardship of our environment¹. This puts increasing pressure on advanced technologies to deliver information that can be proven to be reliable. The measurements concerned may document small changes in key terrestrial parameters and they may extend over many years. Careful characterisation of the sensor systems used to make these measurements becomes a critical element.

Approaches to sensor radiometric calibration in particular have been well-documented² and new methodologies continue to evolve.^{3,4} Consistency between different sensors starts with uniform calibration of the individual sensors, including the development of a stable sensor, detailed and traceable prelaunch characterisation, and standardised on-orbit calibration. Post-launch radiometric calibrations can be based on reference to onboard standards, solar and lunar illumination, and/or ground-based test sites. With reliable sensor radiometric calibration in place, it then becomes possible to tackle other steps such as atmospheric correction, spectral characterization, and corrections for geometric effects on image radiometry. The objective is to enable the generation of consistent geophysical and biophysical products from dissimilar measurement methods and/or

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systems.^{5, 6} The Committee on Earth Observing Satellites Working Group on Calibration and Validation (CEOS WGCV) was established as an entity to help meet this objective (<http://www.wgcvceos.org/>).

It is the task of the Bureau International des Poids et Mesures (BIPM), in conjunction with the world's National Metrology Institutes (NMIs), to ensure world-wide uniformity of measurements and their traceability to the International System of Units (SI). Resolution 4 of the 21st Conférence Générale des Poids et Mesures (the governing body of BIPM and the SI system of units), organised by the BIPM in October 1999, recommends that:

“those responsible for studies of Earth resources, the environment, human well-being and related issues ensure that measurements made within their programmes are in terms of well-characterised SI units so that they are reliable in the long term, are comparable world-wide and are linked to other areas of science and technology through the world's measurement system established and maintained under the Metre Convention.”

Whereas there are a number of historical examples of space-borne Earth observation missions with less than satisfactory accuracy, calibration, consistency and stability of the higher level data products (representing geophysical variables), in recent years several space agencies have responded to the more stringent requirements in this respect. Pathfinder projects were initiated to improve long-term historical time series and satellites with exceptional calibration were launched. A striking example of this was the seamless transition from the European Space Agency's ERS-1 to ERS-2 operation in terms of radar image calibration (level-1) and wind/wave products (level-2). This practise will be continued for the upcoming Envisat mission. NASA also has put great emphasis on calibration during the development of its SeaWiFS program (SeaWiFS is on-board Orbimage's OrbView-2 satellite) and the Terra spacecraft sensor systems. In particular, NASA engaged the support of the National Institute of Standards and Technology (NIST), the US national standards laboratory, to work with it and the instrument teams to develop and adopt a consistent and appropriate method of assessing and presenting uncertainties. They also developed dedicated transfer standards in order to carry out “round-robin” comparisons between the various instrument calibration teams, both within the US and elsewhere, so as to ensure equivalence. As a result of these activities, NASA now has a high level of confidence in the likely performance of the instruments.

While prelaunch sensor characterisation helps in evaluating the extent to which a sensor meets specifications, it is in the post-launch environment that the issue of radiometric calibration and traceability to SI units becomes critical. Data providers have an interest in ensuring that their data products are of the highest quality available in terms of accuracy and reliability. The user community would like to have reliable information on the uncertainty associated with satellite-measured radiances so that they can assess the accuracy of products generated by their algorithms and whether such products are useful in Earth resource studies. The optimal fashion in which the users' objectives can be attained is through early and sustained co-operation between the instrument makers, the national standards laboratories, product generation organisations, and the data users right from the instrument concept design stage. While this is highly desirable, it does not always happen. The SIMBIOS project (<http://simbios.gsfc.nasa.gov/>) has established a calibration network for satellite-derived ocean products⁷, but a similar program does not exist for land remote sensing.

Among the various approaches to ensuring long-term radiometric consistency of data records and information products is the systematic and timely use of a small number of well-instrumented calibration test sites permanently established to acquire benchmark data sets. This kind of activity has become known as vicarious or ground-look calibration but, to date, it has been labour intensive and far from systematic, standardized or permanent. This paper presents general specifications for an advanced vicarious calibration capability through the implementation of a global instrumented and automated network of test sites (GIANTS). The domain of interest is post-launch calibration of sensors observing in the visible and near-infrared portions of the electromagnetic spectrum (~ 0.4 to 2.5 micrometers). The proposed measurement program would capture radiometric, spectral, spatial, and temporal aspects of each test site, using standard measurement protocols for data acquisition by common traceably calibrated instruments and central/identical data processing. Although emphasis is placed on autonomous *in situ* sensors and wireless telecommunication, webcasting and telepresence can also be exploited to improve the effectiveness of measurement campaigns deployed in support of remote sensing calibration. GIANTS would also facilitate efforts towards a next-generation Earth observation capability by means of improved coordination of activities world-wide, innovation through a higher degree of interaction and synergy, and greater awareness of the critical role of calibration.

2. A GLOBAL NETWORK OF INSTRUMENTED CALIBRATION BENCHMARK SITES

2.1 The Approach

Sensor and telecommunications technologies have developed to the point where it should be feasible to support a small number of well-instrumented benchmark test sites and data sets for remote sensing calibration. These would provide post-launch calibration information to supplement or substitute for on-board calibration, would reduce the effort required by individual agencies, and would provide consistency for cross-platform studies and related product generation.

GIANTS would consist of one or more test sites for each continental region, providing a variety of brighter and darker targets and options for year-round coverage. While the agencies involved would certainly want to and indeed should use independent methodologies and acquire other data, it is proposed that a core set of sensors, measurements, and protocols be standardized across all participating benchmark test sites. The measurement data sets would undergo identical processing, perhaps at a central location, and there would be periodic inter-calibration of the common sensors using solar radiation-based techniques.^{8, 9} An example of such a network is AERONET¹⁰ and federated networks such as AEROCAN¹¹ deployed for the characterization of atmospheric aerosol properties.

The focus of the GIANTS program would be on traceability, coordination and common elements (participating agencies could handle everything else of local interest). Automated data acquisition would be the norm, supplemented by periodic sorties. Such visits could be used to carry out international joint measurement campaigns followed after suitable time intervals by technical workshops.

The ideal requirements for benchmark test sites include:

- a history of data records
- large, flat homogenous areas
- nearly lambertian and nearly flat spectral reflectance
- high percentage of clear skies and dry conditions
- primarily bright targets, but a few low reflectance targets as well
- year-round availability of test site but with “controlled” human or animal disturbance.

Table 1 lists land test sites visited and used on a regular basis for radiometric calibration of Earth observation satellite sensors at visible and near-infrared wavelengths. Many of these sites satisfy the requirements identified above most of the time. Year-round availability is a difficult criterion to meet due to rain or snow that can occur even in regions that are almost always clear. However, having a global network of essentially interoperable test sites obviates this. The Newell County rangeland site is an experimental one that has only recently been studied.^{3,12,13} Although it is a vegetated target, it has potential as a darker reference surface at visible wavelengths with good spatial uniformity characteristics. Although Table 1 is not an exhaustive one, it suggests that additional test sites are needed to achieve a more global distribution.

2.2 *In Situ* Measurements

Properties that would be measured include a core measurement set acquired at satellite overpass time and a supplementary measurement set acquired when feasible (Table 2). Surface spectral reflectance would be obtained using diffuse reflectance panel measurements interspersed at no longer than 10-minute intervals between sequences of target measurements. For such a limited number of sites, it may also prove possible to supplement the spectral reflectance data with upwelling spectral radiances to allow direct comparison with aircraft and satellite sensors. Sensor selections would be predicated on a balance between automation, low cost, robustness, precision, and accuracy.

Vicarious calibration using instrumented benchmark test sites is essentially a special case of the use of *in situ* sensing in support of remote sensing. *In situ* sensing can be defined as a group of techniques to acquire information about an object by detecting energy reflected or emitted by that object when the distance between the object and the sensor is comparable to or smaller than any linear dimension of the sensor. A short dictionary-based definition for *in situ* sensing could be “sensing in place”. Because many measurements or observations are made from nearby locations that are not strictly speaking *in situ*, the expression proximal sensing has been adopted in a wide variety of disciplines. A short dictionary-based definition for proximal sensing could be “sensing from close range” (as in close-range photogrammetry, for example). For the present purposes and in practice, *in situ* sensing is considered to encompass proximal sensing.

Table 1. Land test sites visited and used on a regular basis for radiometric calibration of Earth observation satellite sensors at visible and near-infrared wavelengths.

Site	Latitude (Degrees)	Longitude (Degrees)	Altitude (Meters Above Sea Level)	Approximate Size	Landsat WRS Path/Row
White Sands, New Mexico, USA	+32.23	-106.28	1196	40 km x 40 km	33/38
Chuck Site, White Sands, New Mexico, USA	+32.92	-106.35	1196	0.5 km x 0.5 km	33/37
Railroad Valley Playa, Central Nevada, USA	+38.48	-115.66	1435	10 km x 10 km	40/33
Lunar Lake Playa, Nevada, USA	+38.40	-115.99	1750	1.5 km x 2.5 km	40/33
Ivanpah Playa, Nevada/California, USA	+35.50	-115.40	242		39/35
Rogers Dry Lake, Edwards Air Force Base, California, USA	+34.96	-117.86	694	1 km x 2 km	41/35
Newell County Rangeland, Alberta	+50.30	-111.64	750	7 km x 7 km	40/25
Tinga Tingana, Strzelecki Desert, South Australia, Australia	-29.00	+139.83	100	19 km x 19 km	97/80
Uardry, Hay, New South Wales, Australia	-34.39	+145.31	94		93/84
La Crau, France	+43.84	+4.87		0.4 km x 0.4 km	
Dunhuang, China	+40.20	+94.43	1160	25 km x 25 km	137/32

Networks of *in situ* sensors have been in place for decades in a variety of contexts, perhaps the most prevalent being meteorological stations. However, these networks continue to evolve as unattended sensor and wireless telecommunication technologies advance at a rapid pace and new applications are invented. It is becoming increasingly feasible to provide quality-controlled network-wide data to users via the Internet in near real time and information products from data assimilation into models within hours.

Given the increasing importance of *in situ* data and their assimilation into models that also use remote sensing data, the Canada Centre for Remote Sensing (CCRS) has initiated an *In Situ* Sensor Measurement Assimilation Program (ISSMAP) towards the increased use of advanced *in situ* measurement technologies and assimilation in remote sensing. In collaboration with interested partners, the program will focus on intelligent sensor networks for *in situ* data acquisition, methods to assimilate *in situ* and remote sensing data into models, and integration of *in situ* sensor data into geospatial data infrastructures¹⁴. The program will also look ahead to the use of sensor webs and sensor pods, as technology moves towards the concept of a global virtual presence as described by Delin and Jackson.^{15, 16}

Table 2. Core and supplementary measurement sets.

CORE MEASUREMENT SET	SUPPLEMENTARY MEASUREMENT SET
Surface directional spectral reflectance: <u>Spectral coverage:</u> <ul style="list-style-type: none"> • 0.4 to 2.5 micrometers • 0.005 micrometers spectral resolution • 0.0025 micrometers spectral sampling interval <u>Spatial coverage:</u> <ul style="list-style-type: none"> • 5 meters spatial sampling interval • 30 centimeters instantaneous field-of-view <u>Angular coverage:</u> <ul style="list-style-type: none"> • satellite observation geometry • 10 degrees angular resolution 	Surface directional spectral reflectance: <u>Spectral coverage:</u> <ul style="list-style-type: none"> • 0.4 to 2.5 micrometers • 0.005 micrometers spectral resolution • 0.0025 micrometers spectral sampling interval <u>Spatial coverage:</u> <ul style="list-style-type: none"> • at locations representative of the test site • 30 centimeters instantaneous field-of-view <u>Angular coverage:</u> <ul style="list-style-type: none"> • +75 to –75 degrees angular range • solar principal plane and perpendicular plane • 10 degrees angular resolution • 15 degrees angular sampling interval
Total and diffuse downwelling irradiance: <ul style="list-style-type: none"> • hemispherical • broadband and multispectral 	Radiance and irradiance: <ul style="list-style-type: none"> • broadband and multispectral • total and diffuse downwelling irradiance (hemispherical) • upwelling and downwelling radiance (directional)
Atmospheric state: <ul style="list-style-type: none"> • instantaneous measurements • aerosol optical depth • integrated water vapour content • wavelengths 0.380, 0.500, 0.870, 0.940, 1.02 micrometers 	Atmospheric state: <ul style="list-style-type: none"> • Langley plot measurements • aerosol optical depth • integrated water vapour content • wavelengths 0.380, 0.500, 0.870, 0.940, 1.02 micrometers
Environmental parameters: <ul style="list-style-type: none"> • air pressure, temperature, and relative humidity • wind speed • soil moisture at several depths • webcast and videography of general conditions 	Environmental parameters: <ul style="list-style-type: none"> • air temperature and relative humidity • wind speed • soil moisture at several depths • webcast and videography of general conditions
Temporal coverage: <ul style="list-style-type: none"> • all measurement sets centered on satellite observation times 	Temporal coverage: <ul style="list-style-type: none"> • on satellite overpass days between core measurements as time and weather permit • on clear days with no satellite overpasses at high, medium, and low solar illumination angles as time and weather permit

2.3 Usage of Telecommunication Tools

Modern telecommunication tools can be categorized by distinguishing between real-time and archival modes and the directionality of the information communication (Table 3). While most telecommunication media inherently involve two-way communication, routine low-level hand-shaking and control commands are not considered to be two-way communication in this context. Some of the tools listed in Table 3 are clearly not new, but their use has developed in proportion to the increasing availability of satellite links and decreasing costs. Material available in the archival mode will generally be dynamic and not static over time.

Table 3. Different usage contexts of advanced telecommunication tools.

	Real Time	Archival Mode
One-way Communication	<ul style="list-style-type: none"> • Live webcasting • Automated <i>in situ</i> sensors 	<ul style="list-style-type: none"> • Web sites • Digital libraries
Two-way Communication	<ul style="list-style-type: none"> • Teleconferencing • Telepresence 	<ul style="list-style-type: none"> • Interactive modules • Case studies

For GIANTS, several modes of telecommunication are envisaged. Emphasis would be placed on unattended measurements using automated *in situ* sensors, wireless telecommunication, and Internet web access and control. When field sorties take place, live webcasting would be used to broadcast calibration activities to collaborators not on site and to other interested parties including academic institutions. Two-way communication via telepresence would be used to provide interactive communication between locations and groups, again including academic institutions. The remote locations of calibration test sites would dictate that the wireless telecommunication be satellite-based, although it is expected that line-of-site RF communication between sensors would be part of the data acquisition repertoire at each test site. In all cases, measurements would be communicated to a central location for quality control and archiving in a digital library that is part of the growing global spatial data infrastructure (GSDI).

2.4 Facilitating Remote Sensing Calibration

Efforts towards a next-generation calibration capability would be facilitated by GIANTS among other initiatives by means of improved coordination of calibration activities world-wide, innovation through a higher degree of networking and synergy, and greater promotion and visibility of the critical role of calibration in remote sensing.

In addition to multi-sensor calibration and traceability to the International System of units (SI), GIANTS would facilitate the accessibility of teams of world-class scientists and engineers in action via the Internet. This would contribute to the following important areas.

- Standardization of measurement methodologies and protocols
- Remote technical support of instruments
- Lower-cost and wider participation in resource-intensive activities
- University-level education
- Training of highly-qualified personnel

Following posted schedules, live webcasting and telepresence would provide experiment-oriented or pedagogical coverage of the calibration measurement activities. Successful examples of these kinds of initiative include the Jason project (<http://www.jasonproject.org/>) and the programs of the American Museum of Natural History (<http://www.amnh.org/rose/hope/>) among others. Issues and controversies about measurement methodologies can be outlined during broadcasts. Time can also be built into broadcast schedules to allow for remote technical support of instrumentation by specialists not on site. At the very least, calibration activities should be captured on video occasionally and subsequently made available on the Web for broader use.

3. GIANTS PROOF OF CONCEPT PROPOSAL

3.1 Field Trials

Vicarious calibration has been pioneered to a significant extent by the Remote Sensing Group at the University of Arizona's Optical Sciences Center.^{17, 18} Using desert and dry lake test sites in the southwestern USA, it has developed new techniques and provided radiometric calibration updates for sensors onboard Landsat, NOAA, SPOT, Earth Observing System (EOS) Terra and several other Earth observation satellites of wide interest. Other groups have developed their own vicarious calibration capabilities at test sites in different countries and on different continents (Table 1), in most cases modeled after the Arizona model.

During the next few years, the Arizona group will be undertaking almost continuous field campaigns at a variety of test sites in support of the calibration of several satellite sensor systems. These will include Landsat-7 Enhanced Thematic Mapper Plus (ETM+), EOS Terra MODIS (Moderate Resolution Imaging Spectroradiometer) and Advanced Spaceborne Thermal Emission and Reflective Radiometer (ASTER), and Earth Observing-1 (EO-1) sensors, among others. Initial trials of

GIANTS sensors could take place at two of the Arizona group's test sites, the Pima County Fair Grounds (PCFG) just outside Tucson, Arizona and at the Railroad Valley Playa in central Nevada (RVPN). The proximity of the PCFG test site to an urban area makes it possible to work out some of the details while still providing access to actual EOS vicarious calibration efforts in progress. The RVPN test site is one of the most used vicarious calibration sites and it would provide a good telecommunications test given its remote location.

3.2 GIANTS Secretariat

The establishment of a central office or secretariat for the international coordination of network activities, standardized data processing, and archiving and dissemination of data is a role more suited to a government agency than an academic group. The CEOS WGCV could act as the entity under which GIANTS is organized. This would help integrate the network into the calibration activities of the CEOS members. However, for practical purposes, the actual office would have to reside within a specific agency. In the spirit of using existing expertise and infrastructures wherever possible, CCRS could serve as the GIANTS secretariat if suitable external resources can be identified. The Data Acquisition Division and the Applications Division of CCRS have strong records of remote sensing research and development and CCRS' GeoAccess Division is leading the development of the Canadian Geospatial Data Infrastructure (CGDI), part of the growing GSDI. Technical support in terms of organization of comparisons and maintenance of instrumentation calibration could be provided by a specialist NMI such as the National Physical Laboratory (NPL) or NIST so as to ensure that full traceability is maintained.

3.3 Recommended Steps

The following steps are proposed to move towards implementation of the GIANTS concept.

- Form a very small working group to develop a more complete proposal and a strategic plan.
- Continue to promote the GIANTS concept to the international remote sensing calibration community in general and the CEOS WGCV in particular.
- Seek funding support for experimental core sensor packages, test site programs, database infrastructures, and coordination efforts.
- Establish an Internet Web site for network development and coordination.
- Put together and deploy prototype sensor packages at selected test sites.
- Develop efficient software to handle and process automated *in situ* sensor data.
- Upgrade data analysis software for more streamlined generation of calibration results based on field measurements.
- Work with the satellite data providers to institute automated acquisition, archiving and availability of image chips for the network calibration sites for every overpass opportunity.
- Follow up initial results with funding initiatives for more permanent installations at network test sites and a secretariat.
- Use benchmark data sets and accumulated statistical data sets to reveal biases and problems with current calibration methodologies.
- Continue research on new calibration methodologies.

4. METRICS FOR SUCCESS

4.1 Research and Development

The science community looks to long-term data records to help address strategic science questions and, in particular, global change studies. Satellite-based records as for all records must be traceable to a common radiometric scale with documented accuracy. The following items are proposed as an initial list of outputs indicating GIANTS progress and success from the research and development perspective.

- Test site deployment of prototype sensor and telecommunication packages.
- Completion of proof-of-concept trials, including Internet Web enablement and geo-access to trial benchmark data sets.
- Statistically meaningful improvements in agreement between calibration results obtained by different agencies.
- Increased commonality between measurement methodologies and protocols used by different agencies.
- Inter-agency reports on sensor calibration agreement and methodology standardisation.

4.2 Operational Calibration

The broader user community looks to remote sensing technology to provide information solutions. From this mainstream perspective, remote sensing calibration must become part of the essentially invisible quality assurance infrastructure that supports any form of advanced technology. GIANTS would provide only one step in this direction. Nevertheless, the following items are proposed as an initial list of outputs indicating GIANTS progress and success from the operational perspective.

- Demonstration of interoperability and statistical similarity of calibration updates based on benchmark data sets obtained from at least three of the network test sites.
- Trial incorporation of GIANTS outputs in operational data product generation by a commercial data provider.
- The generation of initial specifications for a self-imposed quality standards framework by the remote sensing community, definitely involving traceability to SI standards and a certification process of some kind.

4.3 Education and Training

Given the scientific and mainstream requirements for accurate calibration and quality assurance, the time has come to enlarge the scope of remote sensing calibration curricula. While GIANTS is not intended to address this issue directly, it should contribute to education and training as noted earlier. The development of interactive pedagogical tools involving benchmark sites and data sets would be a notable output of GIANTS activities.

5. CONCLUDING REMARKS

Although calibration is a very specialised aspect of remote sensing, it constitutes a critical core component of Earth observation technology. With GIANTS, it is proposed that advanced *in situ* sensor and wireless telecommunication technologies be exploited to improve the effectiveness of surface measurements acquired in support of remote sensing calibration. Specifically, the advanced technologies would be used both to improve approaches to vicarious calibration measurements and to facilitate coordination and pedagogical efforts related to calibration.

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