

DRAFT - FOR DISCUSSION

Basic Strategy for the Post-launch Calibration and Characterization of Visible and Near-Infrared Meteorological Satellite Sensors

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1. Introduction

Post-launch calibration and characterization of the in-orbit performance of satellite sensors is crucial to the generation of accurate long-term records of geophysical parameters which are free of spurious trends in time, and are smoothly continuous during the transition from one satellite to the next, or when data from different satellite sensors have to be blended to generate a desired geophysical product. Thus, the importance of post-launch calibration of satellite sensors to the attainment of the objectives of national and international programs dedicated to the study of the Earth system, such as the World Climate Research Programme, the International Geosphere Biosphere Programme, World Weather Watch, the satellite component of the global climate, ocean, and terrestrial observing systems(G3OS), Mission to Planet Earth, the National Polar-orbiting Operational Environmental Satellite System (U.S.A.) and the NOAA/NASA Pathfinder Program can hardly be exaggerated. Against this background, we shall briefly describe a strategy to characterize the in-orbit performance of meteorological satellite sensors, and to ensure compatibility among different sensors designed to yield the same geophysical product. We will confine our attention to broad-band sensors in the visible and near-infrared regions of the spectrum ($\leq 2\mu\text{m}$) which are employed to measure and establish long-term records of important Earth system characteristics such as atmospheric aerosols over oceans, aerosol radiative forcing, insolation at the ground, vegetation cover, drought, desertification, and cloud morphology. Central to the proposed strategy are: (a) the development of vicarious calibration techniques to characterize a sensor when there are no onboard calibration devices as in the case of the visible and near-infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) flown on the Polar-orbiting Operational Environmental Satellites (POES) operated by the National Oceanic and Atmospheric Administration (NOAA), U.S.A., or the visible channels of the various imagers flown on several of the geostationary spacecraft operated by different national agencies, (b) establishment of procedures to monitor the performance of on board calibrators as in the case of the Along-Track Scanning Radiometer (ATSR) flown on the polar orbiters operated by the European Space Agency (ESA); and © incorporation of reliable on board calibration devices in sensors which are in the concept and design stages. It should also be noted that any strategy that is developed should take into account issues specific to the polar and geostationary platforms. Thus, as a rationale for the proposed strategy, we shall first describe activities underway at the NOAA/NESDIS Office of Research and Applications (ORA) in the area of post-launch calibration of satellite sensors,

grouping the sensors by platform to bring out the platform-specific issues clearly.

2. Sensors on polar platforms

2.1 General

The basis for some of the elements of the proposed strategy for the calibration of sensors on polar platforms can be best illustrated with the work done to date to calibrate, both in the retrospective and real or quasi-real time modes, the visible and near-infrared channels (≈ 0.63 , and $0.84\mu\text{m}$) of the AVHRR which have no onboard calibration devices, and of the ATSR-2 (≈ 0.56 , 0.66 , and 0.87 , and $1.6\mu\text{m}$) which have onboard calibration devices.

2.2 Retrospective calibration

As we acquire increasing amounts of satellite data, and as our requirements to extract geophysical information from the same get more sophisticated, the need for continuous retrospective calibration of the sensors, especially of the AVHRR-type, will be keenly felt. Thus, considerable effort was spent on the development of an appropriate vicarious calibration procedure for the calibration of the data obtained with the AVHRRs on the NOAA-7, -9, and -11 spacecraft under the NOAA/NASA AVHRR Pathfinder Program (Rao et al. 1993); the data covered the period 1981-1994. This activity provided insights into the attainable vicarious calibration accuracies, and methods to improve the same. As part of this activity, the potential and limitations of three vicarious calibration techniques listed below were studied in detail. The three techniques are:

(a) Analysis and interpretation of long-term records of top-of-the-atmosphere albedo over radiometrically stable desert calibration sites to determine relative degradation in orbit; radiometric stability implies that the top-of-the-atmosphere albedo does not vary in time; thus, slight departures from radiometric stability are propagated as small but finite errors in the relative degradation rates. The method requires a few seasonal cycles of data (about three to four years) to yield reliable relative degradation rates, and also requires independent absolute calibrations at least at one or two points in time during the operational life of a sensor to render the relative degradations absolute (Staylor 1990; Rao et al. 1995; Brest and Rossow 1992; Kaufman and Holben 1993);

(b) Matching the AVHRR output to model simulations of the radiation emerging at the top of the atmosphere in the spectral intervals of interest, with the model simulations using measured values of atmospheric and surface parameters (e.g., gaseous and particulate constituents, surface albedo, surface bidirectional reflection function, etc.) to different degrees to derive absolute calibration. The absolute calibration thus determined is very sensitive to the departure of the model atmosphere/surface from the actual atmosphere/surface at the site of observation (Mitchell et al. 1992; Teillet et al. 1990); and Matching the AVHRR output to the congruent path radiance measured by a calibrated spectrometer on board a high altitude (≈ 18 km) aircraft (ER-2) to derive absolute calibration; this technique imposes stringent requirements on collocation of satellite and airborne spectrometer observational geometry; in addition, the cost and logistics of this technique may discourage its wide use (Abel et al. 1993).

After a thorough examination of the above techniques, it was decided that retrospective calibration of AVHRR, and AVHRR-type sensors is best achieved by combining the method mentioned in (a) with the results of (c), obtained at several points in time during the life of a sensor. Using this approach, absolute calibration of the AVHRRs on the NOAA-7, -9, and -11 spacecraft has been derived as a function of elapsed time in orbit, and inter-sensor calibration has been established for the three sensors (Rao and Chen 1995). Recent work by Vermote and Kaufman (1995) has indicated that the very infrequent aircraft-based absolute calibrations could be supplemented by model-based absolute calibrations (technique b) with a fair amount of success. It is expected that absolute calibration accuracies of the order of 5 per cent can be achieved using these vicarious techniques. However, these calibrations cannot be directly traced to any of the national radiometric standards.

2.3 Real time calibration

The ATSR has an onboard calibration assembly which uses the Sun as an external source of calibration. The response of the instrument to sunlight reflected off a Russian opal diffuser provides the calibration, and the stability of the calibration assembly is monitored in terms of the response of a stable silicon photodiode to sunlight as seen through the same. Smith et al. (1997) have recently reported on the characterization of the ATSR onboard calibrator, using the vicarious technique of analysis and interpretation of top-of-the-atmosphere albedo over a radiometrically stable site in the Libyan desert; a ten-year (1981-1991) record of top-of-the-atmosphere albedo measurements with the AVHRR has established that this site is closest to being radiometrically stable. The results of this activity can be taken as an illustration of the benefits to be derived from inter-sensor comparison, and of the role that vicarious calibration has even in the presence of onboard calibration devices.

The results of the NOAA/NASA AVHRR Pathfinder calibration were utilized to identify and characterize several sites around the globe which can be considered to be radiometrically stable. A technique has been developed to obtain quasi-real time calibration of the visible and near-infrared channels of the AVHRR on the NOAA-14 spacecraft, using the radiometrically stable sites as calibration sources (Rao and Chen 1996). This activity has shed light on the impact of the small but finite natural variability of the top-of-the-atmosphere albedo over any given site, assumed to be radiometrically stable, on our ability to predict the radiometric performance of the sensor in orbit. However, because of the global coverage of the polar orbiters, the vicarious calibration of the sensors on board, using radiometrically stable calibration sites, can be rendered very robust by using multiple calibration sites, with top-of-the-atmosphere albedos ranging from 20 to 70 percent.

It has been suggested that the moon could also be used as a stable calibration source for satellite sensors on polar orbiters (Guenther et al. 1996). However the requirement that the entire spacecraft may have to be maneuvered in orbit so that the sensor may be able to look at the moon may inhibit the extensive use of this technique to calibrate sensors on polar orbiters..

3. Sensors on geostationary platforms

The visible channel of the imagers/radiometers flown on various geostationary

platforms to date are generally very broad, encompassing the entire visible region of the spectrum, and have no onboard calibration devices. Thus, of necessity, we have to use vicarious calibration techniques to characterize the in orbit performance. As mentioned earlier, the logistics and cost of making congruent path high altitude ($\approx 18\text{km}$) aircraft/satellite radiance measurements to derive absolute calibration coefficients may discourage the use of this technique, especially since such measurements may have to be made over different sites with distinct spectral signatures to account for the impact, if any, of site-specific optical characteristic over the broad spectral bandwidth of the sensors. Use of less expensive, low-altitude aircraft would entail the incorporation of corrections for the effects of the atmosphere over the aircraft which in turn could introduce uncertainties in the derived calibration coefficients for reasons mentioned in Section 2.2 (Kriebel 1981; Kriebel and Amman 1993). Thus it looks attractive to use techniques based on the analysis of long-term records of the geostationary sensor measurements over radiometrically stable calibration sites, where practicable, to derive relative degradation rates in orbit both in the retrospective and quasi-real time modes, and render the same absolute by comparison with another calibrated satellite instrument such as the AVHRR (Rao et al. 1998). Model simulations of the top-of-the-atmosphere albedo or radiance measured by the geostationary sensor have also been extensively used to derive absolute calibrations (Arriaga and Schmetz 1998; Frouin and Simpson 1995; Koepke 1982).

However, the applicability of the technique of using radiometrically stable calibration sites to derive relative degradation rates varies from the optimum to adequate for different geostationary sensors because of the differences in the geographical regions covered which in turn determine the availability of well-characterized calibration sites. We have shown in Table 1 the location of potential vicarious calibration sites for different geostationary platforms. Based on the results of a calibration site survey presently underway at NOAA/NESDIS/ORA, we feel that the calibration sites available for METEOSAT are the optimum, while those available for INSAT, GOMS, GOES, and FY-x range from good to adequate. Presently, we cannot comment upon the Australian sites for GMS. The assessment of radiometric stability was based on AVHRR and ATSR measurements over a period of three years.

The feasibility of using the top-of-the-atmosphere albedo measured in the visible ($\approx 0.63\mu\text{m}$) channel of the AVHRR, whose in-orbit performance has been independently characterized, as the calibration standard for the visible sensors on the geostationary platforms is presently being investigated (Rao et al. 1998); the impact of the differences in the spectral characteristics of the two sensors, and of the differences in the illumination and observational geometry is being studied through radiative transfer model simulations. It has also been suggested (Bremer et al. 1998) that stars may serve as radiometric calibration sources for geostationary visible sensors.

Table 1. Visible Sensors on Geostationary Platforms and Potential Vicarious Calibration Sites

| Spacecraft | Operating Country/ Agency | Sensor (Spectral Interval) | Operational Longitude | Potential Vicarious Calibration Sites |
|------------|---------------------------|--|-----------------------|---|
| METEOSAT | ESA | Imager ($\approx 0.40\text{-}1.10\mu\text{m}$) | 0° | Various desert sites in Algeria, Libya, and Sudan |
| | | AVHRR | 74°E | Arabian desert, the Great |

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|-----------|--------|---|--------|---|
| INSAT* | India | VHRR ($\approx 0.55\text{-}0.75\mu\text{m}$) | 93.5°E | Indian desert Gobi desert, the Great Indian Desert |
| GOMS* | Russia | STR ($\approx 0.46\text{-}0.70\mu\text{m}$) | 76°E | Arabian desert, the Great Indian desert |
| FY-x* | China | MCRS ($\approx 0.50\text{-}1.05\mu\text{m}$) | 105°E | Gobi desert, China; Great Indian desert; Thangoo and other sites in Australia |
| GMS | Japan | VISSR ($\approx 0.50\text{-}0.75\mu\text{m}$) | 140°E | Hay, Amburla, and other sites in Australia |
| GOES-East | U.S.A | Imager ($\approx 0.55\text{-}0.75\mu\text{m}$) | 75°W | Sonora (U.S.A., Mexico) Sechura (Peru) |
| GOES-West | U.S.A | Imager ($\approx 0.55\text{-}0.75\mu\text{m}$) | 135°W | Sonora (U.S.A., Mexico) Sechura (Peru) |

Note 1. * It is expected that the future platforms in these series will have the same, or very similar, orbital characteristics as the current, or most recent member of the series.

Note 2. STR: Scanning Television Radiometer

VHRR: Very High Resolution Radiometer

MCRS: Multi-Channel Scanning Radiometer

VISSR: Visible and Infrared Spin-Scan Radiometer

4. Inter-Sensor Calibration

The inter-comparison of the AVHRR and ATSR time series of the clear-sky top-of-the-atmosphere albedos over different sites, and of the visible channels of the AVHRR and the GOES Imagers, presently underway at NOAA/NESDIS /ORA has provided valuable insight into the impact of differences in sensor spectral characteristics, of gaseous and particulate absorption and scattering, and of the spectral dependence of surface reflection properties on the inter-calibration of satellite sensors. In order to develop simple procedures to represent this impact, we wish to expand the inter-sensor calibration/comparison to include other sensors which are either operational or will be in orbit in the near future; some examples are the Moderate-resolution Imaging Spectrometer (MODIS); Advanced Along-Track Scanning Radiometer (AATSR), Medium Resolution Imaging Spectrometer (MERIS), and the SCanning Imaging Absorption SpectroMeter for Atmospheric Cartography (SCIAMACHY), all to be flown on the Environmental Satellite (ENVISAT); and the Sea-viewing Wide-Field-of-View Sensor (SeaWiFS). It is expected that this activity will lead to the development of robust, generic procedures for inter-sensor calibration.

It has been suggested that the climatology of satellite-derived geophysical products

could be utilized to inter-calibrate satellite sensors, especially in the retrospective mode; an example is the utilization of the Normalized Difference Vegetation Index (NDVI) to inter-calibrate the AVHRRs on different NOAA polar orbiters. This approach should be viewed with caution as algorithm-specific effects, and the natural variability of the product over a long period of time may lead to product-specific calibration of a given sensor.

5. Bases for a Calibration Strategy

The calibration strategy outlined in the next section is based on our experience to date with the ATSR, and AVHRR which are typical of broad-band meteorological sensors in the visible and near-infrared with and without onboard calibration devices, and with the imager on the GOES platform, which has served as a model for other visible sensors on geostationary platforms. We have also drawn heavily from the results of the NOAA/NASA Pathfinder Program.

6. Strategy for Satellite Sensor Calibration

The main objective of an effective satellite sensor calibration strategy should be to satisfy the current and anticipated sensor accuracy and precision requirements of the user community, while pragmatically taking into account the constraints imposed by current, established technology, and the risks associated with experimental technology. The requirements of ensuring the accuracy, and long-term continuity of geophysical records should be central to any strategy that is developed. Accordingly, we have listed below the main elements of the proposed strategy for the post-launch calibration of the visible and near-infrared sensors.

a. Onboard calibration

Onboard radiometric and spectral(if necessary) calibration should be a mandatory requirement for all future satellite sensors in the concept and design stages. The feasibility of retrofitting onboard calibrators to sensors which are scheduled for production, but which will not be in orbit until the latter part of the next decade, should be studied. While current, established technology should be utilized to design onboard calibration systems that would meet the current user requirements, innovative, new technologies should be studied with zeal to improve attainable calibration accuracy and precision.

b. Vicarious calibration

Vicarious calibration should be an integral part of the post-launch characterization of satellite sensors. As mentioned earlier, vicarious calibration serves to monitor the performance of onboard calibrators, and as replacement in the event of failure of the latter. Hybrid vicarious calibration procedures, based on the three techniques outlined in Section 2.2, should be developed to enhance the attainable accuracies. Central to this activity is the utilization of radiometrically stable sites as calibration sources, and characterization of the same in terms of the optical and radiative properties of the surface, and the overlying atmosphere.

c. Site characterization

Regional vicarious calibration sites should be identified, and fully instrumented facilities should be set up to measure the spectral reflection properties of the surface, and radiatively important atmospheric parameters such as columnar ozone, aerosols, precipitable water, and cloud cover so that calibrations based on model simulations of the upwelling radiation may be rendered more realistic; to the extent practicable, available satellite-derived information on these parameters should be incorporated into the site data. If pragmatic considerations prevent the establishment of permanent instrumented facilities, field campaigns should be conducted frequently. This element should draw upon the experience gained under the satellite-based site characterization activity at NOAA/NESDIS/ORA, the site characterization activity in Australia (CSIRO); in the People's Republic of China (National Satellite Meteorological Center, Beijing), the Atmospheric Radiation Measurement (ARM) program of the Department of Energy, U.S.A., and the various vicarious calibration activities planned for MODIS.

d. Inter-sensor comparison/calibration

Inter-sensor comparison/calibration is essential to meet the user requirement for blended or fused records of geophysical parameters derived from different sensors. In addition, this activity will be central to rendering vicarious calibration results robust.

e. Involvement of the National Radiometric Standards Laboratories

National radiometric and spectral standards laboratories [e.g., National Institute of Standards and Technology (NIST), U.S.A.], National Physical Laboratory (NPL), United Kingdom] have a vital role to play in the calibration of satellite sensors. They should be involved in all stages of the concept, design, and fabrication of onboard calibration devices, and in the testing of the same in the pre-launch calibration phase; they should ensure the traceability of sensor calibration to national and international radiometric and spectral standards.

f. Utilization of the International Space Station

In principle, the International Space Station provides a unique platform to perform vicarious calibration, traceable to NIST standards, with active human involvement. Calibration scientists at NOAA/NESDIS/ORA are working closely with NIST to explore the use of space-based radiometry for satellite sensor calibration, utilizing the technique of congruent path radiance measurements.

g. Involvement of the User Community

There should be continuing interaction between the sensor and user communities so that product requirements are properly translated into sensor calibration requirements, subject to the constraints imposed by technology. This would also lead to pragmatic revisions of user requirements, if warranted.

7. Implementation of the Strategy

Implementation of the strategy requires firm commitment of needed resources by the various operating countries/agencies. It is expected that such commitment

would be forthcoming since the CGMS membership is also actively involved in international activities such as the IGBP, WCRP, and the G3OS the success of which to a large extent depends upon proper satellite sensor calibration to ensure data continuity and accuracy. The Working Group on Calibration and Validation (WGCV), Committee on Earth Observation Satellites (CEOS), which has already initiated, albeit on a pilot scale, studies of some of the elements of the proposed strategy, should play an important role in the coordination of plans to implement the proposed strategy at the international level. Thus, proper liaison must be established between the Coordination Group for Meteorological Satellites (CGMS) and CEOS/WGCV to address the specific issue of satellite sensor calibration.

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