A Status Overview of Earth Observation Calibration/Validation for Terrestrial Applications

Review Paper/Article de synthèse

by P.M. Teillet

RÉSUMÉ

La synthèse de certains des principaux sujets d'intérêt dans le domaine de l'étalonnage/validation (étal/val) permet d'identifier des secteurs où des améliorations devront être apportées à la procédure cal/val pour atteindre un niveau opérationnel du point de vue de l'utilisateur. Des axes spécifiques de recherche et de développement sont discutés dans le domaine optique notamment en ce qui concerne l'étalonnage radiométrique des capteurs, la correction atmosphérique, la caractérisation spectrale et l'influence des effets géométriques sur la radiométrie de l'image.

SUMMARY

An overview of some of the main issues in Earth observation calibration/validation (cal/val) for terrestrial applications identifies areas where cal/val needs improvement to attain operational status from the perspective of both science and general users. Specific research and development perspectives are discussed in the solar reflective optical domain with respect to radiometric sensor calibration, atmospheric correction, spectral characterization, and geometric effects on image radiometry.

INTRODUCTION

At a recent workshop, the President of the International Society for Photogrammetry and Remote Sensing (ISPRS) noted that, in the eye of the public, the scientific community has a credibility gap when it comes to the accuracy and quality of data used to study and predict terrestrial phenomena and that, consequently, standards and calibration activities are of critical importance to Earth observation technology and the information derived from it (Fritz, L.W., Opening Remarks, ISPRS Joint Workshop on Sensors and Mapping From Space, Hannover, Germany, 29 September 1997). At a time when it is increasingly needed, Earth observation technology continues to advance, but it also continues to struggle to mature, partly because it is a complex and costly endeavour and partly because it has not yet managed to provide whole products that are readily available, easy to use, consistent in quality, and backed by sound customer support. In analogous fashion, remote sensing calibration and validation (cal/val) have also known significant technological advances and struggled to become more operational, with mixed results.

The international Earth observation community has come to an agreement on the definitions of calibration and validation via the Committee on Earth Observation Satellites (CEOS):

- *calibration* is the process of quantitatively defining the system response to known, controlled signal inputs;
- *validation* is the process of assessing by independent means the quality of the data products derived from the system outputs (CEOS, 1995).

These definitions are often used in the remote sensing context to refer specifically to radiometric sensor calibration and geophysical data product validation. However, they are sufficiently general to refer to any given measurement system or process. Indeed, there are calibration and validation aspects to many of the components in an end-to-end system. Thus, as a combined expression, calibration/validation has also become synonymous in remote sensing with the entire suite of processing algorithms used to convert raw data into accurate and useful geophysical

• P.M. Teillet is with the Canada Centre for Remote Sensing, 588 Booth Street, Ottawa, Ontario, K1A 0Y7

quantities on the surface of the Earth that are verified to be self-consistent. This latter definition provides a more practical way of considering cal/val for the present purpose. It is in this practical sense that validation is included in the title of this paper, even though data product validation is not addressed to any notable extent, partly because it is a product-specific or algorithm-specific activity and partly because it is at a less advanced stage compared to calibration. It deserves to receive much more attention in the context of remote sensing in the future.

Remote sensing calibration and validation are critical aspects of Earth observation measurements and methods if they are to show terrestrial processes as they really are and if they are not to be compromised by sensor and data processing effects. The challenge is to ensure that the measurements and methods yield self-consistent and accurate geophysical parameters, even though the measurements are made with a variety of different instruments under different observational conditions and the methodologies vary. Even the majority of remote sensing users, whose product requirements do not directly involve cal/val, want imagery and data products that are consistent in quality over time. Thus, a stable instrument with well-understood characteristics is important in any event for reliability and quality of data products and derived information. This will be an important consideration as the size and cost of satellite sensors decrease substantially in the near future.

This article provides an overview of some of the key cal/val issues today and proposes research and development areas that can help bring cal/val to a more operational status. Within the framework of the process of surface reflectance retrieval in the optical spectral domain, specific aspects of cal/val are briefly discussed with respect to current capabilities and issues or challenges needing attention if the potential of forthcoming satellite sensor systems is to be fully realised. Each aspect is a subject unto itself and so only a few key points are highlighted. The main aspects considered are radiometric sensor calibration, atmospheric correction, spectral characterisation and geometric effects on image radiometry. Aspects dealing with geometric calibration and polarization considerations are not addressed.

The state of the art in remote sensing calibration and validation has been captured in definitive ways in relatively few monograms, review articles, and special publications. Appendix 1 lists a selection of literature references that have a primary emphasis on remote sensing calibration and validation and that provides a state-of-the-art perspective. A closer look at the relevant literature over the past twenty-five years indicates that there has been a healthy number of research papers on particular aspects of radiometric sensor calibration and atmospheric correction, but considerably fewer on spectral characterization and geometric effects on image radiometry. The chief deficiencies in cal/val research and development have been in the areas of validation and investigations into the role of cal/val in end-user applications.

Radiometric Sensor Calibration

Radiometric sensor calibration, the most fundamental part of the cal/val process, is a broad and complex field that imposes the greatest limitations on quantitative applications of remote sensing (Teillet *et al.*, 1997). The methods and instrumentation involved can be grouped into three domains (Dinguirard and Slater, 1997): on the ground prior to launch, onboard the spacecraft post-launch, and vicarious or indirect approaches using Earth scenes imaged in-flight. Whereas preflight methods encompass a vast array of painstaking sensor characterizations (e.g., Guenther *et al.*, 1996), onboard and vicarious calibrations are devoted primarily to the monitoring of the radiometric responsivities of sensor spectral bands over time. Advantages and disadvantages of these three categories of approaches have been discussed by Dinguirard and Slater (1997).

In all cases, the objective is traceability of calibrated data accuracies to absolute SI units for science users and data products with consistent quality for the broader user community. Recent developments in detector-based radiometers used in metrology as calibration transfer standards show excellent promise toward reducing the number of steps in the traceability chain and reducing calibration uncertainties (Fox *et al.*, 1997; Slater *et al.*, 1996).

To date, Earth observation satellite sensors have been susceptible to significant post-launch changes in their performance characteristics. These changes arise as a result of many factors, including the rigours of the launch itself, the space environment in Earth orbit in general, the operating environment of the spacecraft, and aging of the sensors and their subsystems. Thus, even well-built, stable, and well-characterized sensors require evaluation and monitoring of changes in the months immediately following launch especially, but also over the lifetime of their operation. Although future Earth observation sensors will benefit from better technology, it is very likely that significant post-launch changes will still arise. Moreover, many forthcoming systems will have fewer if any onboard calibration systems in order to reduce costs. Hence, there will continue to be a need for several independent methodologies for the in-flight characterization of sensors. Equally important will be the operational infrastructure needed to integrate the results from these independent methodologies (Slater *et al.*, 1996) and to ensure that users benefit fully and in a timely fashion from the post-launch updates (Teillet *et al.*, 1997). Science users may want to know the details, but the majority of users will want access to ready-to-use data from stable and well-characterized sensor systems in such a manner that calibration is essentially transparent to them.

The calibration of satellite-based geophysical data was recently reviewed by an international workshop panel (Guenther *et al.*, 1997), where the emphasis was on global, long-term data sets, but high spatial resolution sensors were also addressed. The workshop report provides a good snapshot of current calibration issues in the context of atmosphere, ocean, and land remote sensing. Key findings and recommendations for the future are documented in the categories of programmatic support, preflight calibration, in-flight calibration, data set continuity and consistency, and combining remote sensing and in-situ data. Brest *et al.* (1997) also conclude that current uncertainties in sensor calibration changes are generally much larger in magnitude than real decadal changes in the Earth system, which therefore cannot be reliably detected without significant improvements in sensor calibration.

The current status of radiometric sensor calibration is that, with few exceptions, it is not operational. **Table 1** provides an assessment of the radiometric calibration of three key optical sensors in use today, the NOAA Advanced Very High Resolution Radiometer (AVHRR), Landsat Thematic Mapper (TM), and SPOT Haute résolution visible (HRV) sensors. The success criteria are considered to be: (1) radiometric calibration built into the program, (2) systematic absolute calibration updates, (3) users benefit from calibration updates, and (4) solid customer support on radiometric features of data products. Although some of the table entries may be subject to debate, it is undeniable that radiometric calibration efforts and associated infrastructures have been inadequate overall. A notable counter-example is the significant effort by NASA to ensure the best possible calibration and validation of EOS sensors and date products for science users.

Table 1.

A high-level assessment of the optical radiometric calibration story for three of the most widely used earth observation sensors.

	NOAA AVHRR	Landsat TM	SPOT HRV
Radiometric calibration designed into program	NO ☹	YES ☺	YES ☺
Systematic absolute calibration updates	POOR[1] ☹	FAIR[2] 😐	GOOD ☺
Users benefit from calibration updates	GOOD ☺	POOR[3] ☹	GOOD ☺
Solid customer support on radiometry	POOR[4] ☹	POOR[4] ☹	POOR[4] ☹

1 The adopted methodology for absolute calibration updates, aircraft underflight campaigns, is costly, difficult and used very infrequently.

2 The principal methodology for absolute calibration updates, vicarious calibration campaigns at White Sands, is labour-intensive and used on an irregular basis.

3 Calibration results based on White Sands indicate sensor gain changes not captured by the onboard Internal Calibration system (Thome et al., 1994), but data suppliers are not advised systematically of these changes and data production has not allowed for them.

4 Data suppliers generally cannot respond quickly and effectively to user questions about radiometric calibration and related product characteristics.

In the absence of sensor calibration and atmospheric correction information, some investigators necessarily resort to the use of empirical techniques that provide data calibration to surface reflectance, usually based on assumptions about the radiometric characteristics of pseudo-invariant reference targets or based on field measurements. Such approaches are limited in applicability to specific projects and data sets, and involve effort and resources that cannot be directed to the application of interest.

The need for several independent calibration methods has been documented by Slater (1988). When there are multiple approaches to sensor calibration, there also needs to be a plan for the use of these techniques over the lifetime of the sensor, as well as an algorithm for the weighted integration of the results from the various techniques into a single set or sequence of calibration coefficients for operational use (Slater *et al.*, 1996). There has been very little experience with this type of integration process. For postlaunch calibration of the NOAA AVHRR instruments, the most common approach has been to give equal weight to different calibration results (Che and Price, 1992) or to use results from one or two methods only (Brest and Rossow, 1992; Teillet and Holben, 1994; Cihlar and Teillet, 1995) for consistency in the absence of a detailed evaluation of the various approaches. Postlaunch radiometric calibration of the SPOT HRV instruments is based on a weighted blend of relative and absolute methods (Gellman *et al.*, 1993) and is deemed quasi-operational, although the details of the recipe have not been made available.

Because of the importance of calibration test sites, any additional information on their characteristics is worth consideration, including remotely sensed data acquired at other wavelengths, such as in the thermal infrared or in the microwave portions of the electromagnetic spectrum in the case of shortwave optical test sites. However, such data sets are seldom acquired. One example is a multi-temporal series of C-band ERS-1 Synthetic Aperture Radar (SAR) images obtained for three optical calibration sites: White Sands in New Mexico, and the Lunar Lake and Railroad Valley playas in Nevada (Teillet *et al.*, 1995). The study reports on an initial examination of multi-temporal SAR image data sets generated for the three test sites and focuses on the significant pattern changes observed in the scenes, largely due to surface roughness, soil moisture, and run off. At C-band, backscatter from most natural targets comes primarily from the surface layer (5 to 8 cm). The investigation is currently being extended to include imagery from the Canadian Radarsat C-band SAR system. These kinds of remote sensing data sets from other wavelength domains can contribute to a baseline understanding of ground targets and provide insight into the usefulness of such targets for in-flight calibration of optical sensors.

The main points on radiometric sensor calibration may be summarised as follows.

- The improved accuracies in the radiometric calibration needed by science users may be achieved in the near future by new developments in metrology.
- The majority of users will want access to ready-to-use data from stable and well-characterized sensor systems in such a manner that calibration is essentially transparent to them.
- Radiometric calibration efforts and associated infrastructures have been inadequate overall and the current status of radiometric sensor calibration is that, with few exceptions, it is not operational.
- Multiple independent calibration methodologies, particularly post-launch, are important and require new algorithms for the

weighted integration of the results from the various techniques into operationally useful calibration coefficients.
- Remote sensing data sets from other wavelength domains can contribute to a baseline understanding of ground targets used for optical sensor calibration.

Atmospheric Correction

Consider the example in **Figure 1**, which plots the Normalized Difference Vegetation Index (NDVI) based on data from the NOAA-11 AVHRR for averaged vegetation targets in Canada during part of one year. It illustrates the improvements achieved by calibrating and correcting AVHRR channels 1 and 2 prior to computing NDVI. The dynamic range of NDVI is slightly increased and the values approach a typical ground-based value for representative vegetation.

Compensation for atmospheric effects in satellite sensor imagery is clearly an indispensable component in the process of surface reflectance retrieval. However, the current status of atmospheric correction is that, with few exceptions, it is not operational. In addition to the need for image data that are very well calibrated radiometrically, the most important key to operational atmospheric correction is timely and ready access to information on atmospheric variables such as aerosol optical depth (AOD) and atmospheric water vapour content (WVC) for input to atmospheric codes. This is highlighted in **Figure 2**, which is a block diagram of an operational atmospheric correction scheme. **Figure 2** also highlights the dark target approach as one of the main methods for estimating AOD (Kaufman *et al.*, 1997a; Teillet and Fedosejevs, 1995), as well as the validation role played by automated sunphotometer networks (O'Neill *et al.*, 1997; Holben *et al.*, 1997). A notable counter-example to the lack of operational status is that of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) now in use for quantitative ocean applications.

Although there is presently no standardisation as to which atmospheric radiative transfer code should be used, most of the predominantly used codes tend to disagree significantly only for large aerosol optical depths and large off-nadir angles of 60 degrees or more (Royer *et al.*, 1988). Therefore, the proper use of a given atmospheric code should be of greater concern than which code to use, although the choice of code is an important factor in the correction of high spectral resolution data (Staenz *et al.*, 1994). Monochromatic computations should not be used (Teillet, 1989) and band-pass calculations based on relative spectral response profiles with 0.005 micrometer spacing or better are recommended. For application to regional and global data sets, the atmospheric correction of images must be fast and relatively straightforward. For more localised coverage at higher spatial resolution, computation time can still be an issue, even with today's computers, because of the large number of image pixels.

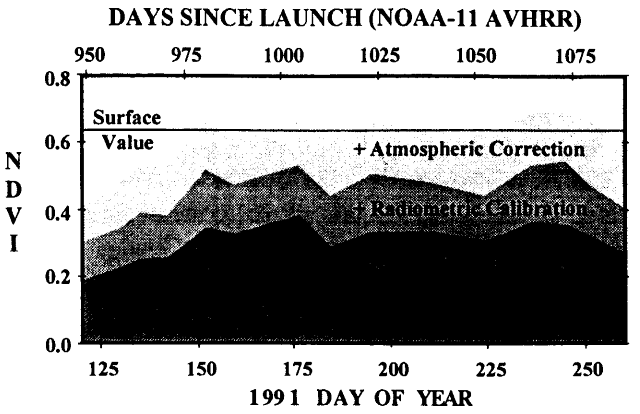

Figure 1.
1991 NOAA-11 AVHRR NDVI for averaged vegetation targets are plotted as a function of time for various radiometric correction treatments. In all cases, the NDVI computation took the form (channel 2 – channel 1)/(channel 2 + channel 1). However, for the lowest, middle, and uppermost curves, the channel data consisted of raw digital signal levels, top-of-atmosphere reflectances, and surface reflectances, respectively. The horizontal line is a typical ground-based value of NDVI = 0.64 for representative vegetation (not adjusted for seasonal variation) based on surface reflectance measurements in spectral channels corresponding to NOAA-11 AVHRR channels 1 and 2.

Variations in terrain elevation give rise to different atmospheric path lengths, which in turn leads to variations in the effect of atmospheric scattering and absorption transmittance on retrieved surface reflectances and derived NDVI values (Teillet, 1992; Teillet and Staenz, 1992; Running *et al.*, 1994). Study results indicate that the effects of terrain elevation are significant and increase with decreasing vegetation density. The terrain elevation effect is also smaller for NDVI based on spectral bands on the forthcoming (EOS) Moderate-resolution

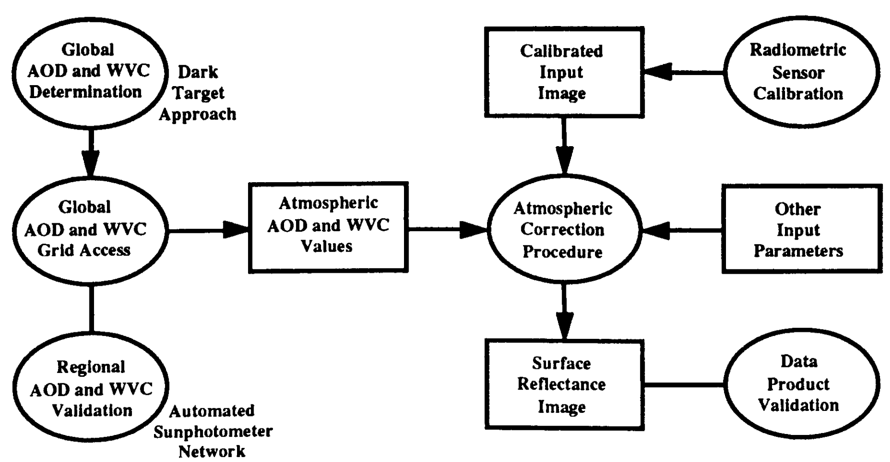

Figure 2.
An operational atmospheric correction scheme, where AOD = aerosol optical depth and WVC = water vapour content.

Imaging Spectroradiometer (MODIS) than for AVHRR-based NDVI because of the spectral bandwidth differences between the two sensor systems (Teillet and Staenz, 1992).

The main points on atmospheric correction may be summarised as follows.

- The current status of atmospheric correction is that, with few execptions, it is not operational.
- Operational atmospheric correction will depend on the ready availability of atmospheric parameters needed to run atmospheric radiative transfer codes and the efficient implementation of those codes or derived results in a cost-effective image correction framework.
- The proper use of a given atmospheric code should be of greater concern than which code to use, except in the case of the correction of high spectral resolution data.
- Terrain elevation effects should be taken into account.

Spectral Characterization

Although it receives relatively less attention than radiometric sensor calibration and atmospheric correction, spectral characterization is an important aspect of surface reflectance retrieval, regardless of how wide or narrow the spectral bands may be. Spectral bands are designed for specific applications and data products are susceptible to variations in spectral band-passes that can occur after launch. Clearly, if the spectral bands have changed in position or width or there are uncertainties as to their characteristics, there is a direct impact on radiometric and atmospheric processing, as well as on data and information products (Flittner and Slater, 1991; Teillet, 1990; Suits *et al.*, 1988). These impacts need to be assessed on a more routine basis using both onboard systems and data analysis approaches. New developments such as the Spectroradiometric calibration assembly (SRCA) on the forthcoming EOS MODIS (Guenther *et al.*, 1996) is a step in the right direction, but the SRCA is an expensive and sophisticated device that will not likely be replicated often on future missions. Another new approach is planned for the Medium-Resolution Imaging Spectrometer (MERIS) on the forthcoming European Envisat, where a diffuser plate doped with rare earth will be used to generate spectral lines for reference (M. Lewis, personal communication).

The issue arises in a significant way in the processing and analysis of high spectral resolution data, although relatively few studies have examined the impact of these effects (Goetz *et al.*, 1995; Teillet and Irons, 1990). The requirements for high spectral resolution are driven by water and vegetation studies in the visible and near-infrared spectral regions and by the needs for vegetation biochemistry and mineralogical mapping in the shortwave infrared (Vane and Goetz, 1993).

Use of vegetation indices will span the lifetime of multiple sensors of a given type and also encompass several different sensor types. Nevertheless, study of the impact of radiometric, spectral, and spatial sensor characteristics on such indices has only begun recently (Qi *et al.*, 1994; Teillet *et al.*, 1996; Guyot and Gu, 1994). One faces the important and difficult task of ensuring that the same vegetation information can be obtained from all of these sensor systems. The key perspective to adopt for the future is that spectral characteristics of sensors and natural surfaces should be sufficiently well understood to allow the generation of similar geophysical and biophysical products from dissimilar measurement methods and systems.

The main points on spectral characterization may be summarised as follows.

- Spectral characterization has received insufficient attention.
- The spectral characteristics of sensors and natural surfaces should be sufficiently well understood to generate similar geophysical products from dissimilar measurement systems

Geometric Effects On Image Radiometry

Another area that has received relatively less attention is that of the role of geometry on image radiometry. It is true that bidirectional reflectance effects have been studied extensively, but they remain challenging to deal with in an operational setting and there are many other geometric effects to consider.

The anisotropy of surface reflectance as a function of illumination and viewing geometry (see, for example, Gauthier *et al.*, 1991; Staenz *et al.*, 1995) is best described in terms of the Bidirectional Reflectance Distribution Function (BRDF). In the analysis of remotely sensed data, BRDF effects should be taken into consideration, by correcting for them where necessary and/or by taking advantage of anisotropic behaviour to improve target discrimination. Multi-temporal composites of AVHRR imagery suffer from BRDF artefacts, even after radiometric calibration and atmospheric correction. The BRDF can be modelled but it is presently impractical to apply models that are land cover type specific on an operational basis, although this may become possible in the future (see, for example, Cihlar *et al.*, 1994). Even approximate BRDF information for broad classes of land cover can improve atmospheric correction computations (Kaufman *et al.*, 1997b).

Increasingly, users will be integrating data from different remote sensing systems and from different non remote sensing sources, most if not all of which sample the Earth's surface in different ways. Even a given sensor acquires data in ways that vary significantly. It will be critical to establish the validity of, and provide accuracy assessments for, data fusion products.

Essentially, remote sensing instruments acquire imagery in very specific modes and geometries that have direct impact on the radiometric character and information content of derived products, which in turn has implications with respect to the widespread acceptance and utilisation of Earth observation technology. As more quantitative and better quality information is sought from Earth observations, the restricted and uneven manner in which remotely sensed data sample terrestrial surfaces is coming under increasing scrutiny.

For AVHRR, panoramic distortion and Earth curvature transform 1.1 km nadir pixels to ever larger and overlapping foot-prints as a function of scan angle, reaching dimensions of about 1.5

km by 2.5 km at scan angles of ± 45 degrees and about 2 km by 5 km at scan-angle extremes of ± 55 degrees. The solution to this problem has generally been to avoid using AVHRR data beyond about 40 degrees off nadir for quantitative analysis. In the MODIS framework, the 1 km resolution channels will use ten-detector arrays to image the Earth, such that swaths will overlap rather than individual pixel footprints. This phenomenon and other scan-angle effects for MODIS have been described by Fleig (1994) and Kalb and Goff (1993). Although a given pixel's digital signal level and geographic location may be known in computer storage, the interpretative use and any two-dimensional image representations of these data will be far from straightforward if they are to be correct and quantitatively useful. In a product such as a mosaic or temporal composite, the intrinsic spatial resolution cannot be inferred from the position of a pixel in the final image product.

Also of concern is the selection of an image resampling kernel for multi-temporal and/or multi-source data integration into a common, usually map-based data set. Nearest neighbour resampling is being used for the global AVHRR data sets currently being generated (Townshend *et al.*, 1994), ostensibly to preserve the radiometric character of the landscape that has been imaged. It can be argued that, given the gridded nature of rectified image space, and also the topographic variations in some locations, nearest neighbour resampling will actually give rise to an incorrect spatial distribution of the terrain's reflectance information content in the so-called integrated data set (B. Guindon, personal communication).

A brief summary of topographic influences on image radiometry has been presented by Teillet *et al.* (1982) and Teillet and Staenz (1992). The chief difficulty in practical terms will be the lack of global availability of terrain elevation data at sufficiently high spatial resolution to carry out such topographic corrections (Running *et al.*, 1994).

The main points on the role of geometry on image radiometry may be summarised as follows.

- The role of geometric effects on image radiometry has received insufficient attention.
- Bidirectional reflectance effects have been studied extensively, but they remain challenging to deal with in an operational setting and there are many other geometric effects to consider.
- The proper and accurate integration of retrieved geophysical parameters will require greater consideration of a variety of geometric effects on image radiometry.
- Topographic effects should be taken into account and their correction will depend on the ready availability of terrain elevation data at sufficiently high spatial resolution.

A Future Perspective

Earth observation is a wonderful though costly endeavour that makes quantitative measurements and is much more than a mere extension of photointerpretation (MacDonald, 1997). An essential part of this measurement capability is the accurate retrieval of geophysical quantities on the Earth's surface, such as reflectances, temperatures, backscatter coefficients, etc. An equally essential part is the routine derivation of valuable information from these quantities for use in mainstream information systems and applications, an aspect that remains rudimentary overall. Earth observation technology will be deemed successful in the long run only if it routinely provides information of value to society (Teillet *et al.*, 1997; MacDonald, 1997; Moran *et al.*, 1997).

Although Earth observation calibration technologies and methods are not yet operational from the user perspective, the critical role they play in terrestrial applications is now well recognized and must be considered an essential part of future satellite sensor programs. In the years to come, the process of Earth observation sensor calibration and the computation of key surface parameters will have to become increasingly transparent to users. Science users will want to know the details, but the vast majority of users will not, demanding instead product consistency, in some instances accompanied by a seal of approval or a certification of some kind. Users will also want a growing selection of higher-level and value-added products that are of consistent quality, easy to use, and reliably available (Teillet *et al.*, 1997). For this to be possible, data product validation and quality considerations will have to receive much more attention than they have in the past.

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