Calibration, Validation, and Quality Assurance In Remote Sensing: A New Paradigm

Technical note/Note technique

by P.M. Teillet • D.N.H. Horler • N.T. O'Neill

RÉSUMÉ

Au sens large, la procédure d'étalonnage/validation (étal/val) comprend toutes les étapes requises pour convertir des données brutes au capteur en quantités géophysiques ou biophysiques précises et utiles dont on peut démontrer la cohérence inhérente. De ce point de vue, la procédure étal/val ne peut être considérée comme opérationnelle. Cet article établit le concept que la procédure étal/val peut jouer un rôle essentiel dans la démarche permettant à la télédétection d'accéder à la consommation de masse dans une société basée sur l'information, pourvu qu'elle soit intégrée à une stratégie d'assurance de la qualité. On présente un modèle de marché pour le cas spécifique de la télédétection qu'on utilise ensuite pour démontrer que la mise en place d'une procédure d'assurance de la qualité est la clef qui permettra de faire le lien entre les utilisateurs précoces de la technologie et les marchés de masse. L'article poursuit en proposant un suivi semi-permanent des sites de référence pour l'assurance de la qualité et de la stabilité (QUASAR) en tant que première étape essentielle vers une infrastructure étal/val destinée aux utilisateurs de masse. Des ensembles de données hyperspectrales à basse altitude acquises pour les sites de suivi seront utilisés pour générer des résultats dans les bandes spectrales des capteurs les plus courants dans le but de les rendre rapidement et facilement disponibles sur une base répétitive.

SUMMARY

In the larger sense, calibration/validation (cal/val) includes all of the steps required to convert raw sensor data into accurate and useful geophysical or biophysical quantities that are verified to be self-consistent. From that perspective, cal/val cannot be considered operational. The paper introduces the concept that cal/val can play an essential role in bringing remote sensing to mainstream consumers in an information-based society, provided that it is an integral part of a quality-assurance strategy. A market model for the specific case of remote sensing is introduced and used to demonstrate that quality assurance is the key to bridging the gap between early adopters of technology and mainstream markets. The paper proposes the semi-continuous monitoring of quality assurance and stability reference (QUASAR) sites as an important first step toward a cal/val infrastructure beneficial to mainstream users. Low-altitude hyperspectral data sets acquired for the monitoring sites will be used to generate results in the spectral bands of commonly used sensors and make them rapidly and easily available on a frequent basis.

INTRODUCTION

Interest in the calibration/validation (cal/val) aspects of terrestrial remote sensing has been on the rise and significant resources are being devoted to relevant areas of research and development. However, while capabilities in cal/val have continued to improve, sensor calibration remains difficult and data product validation has received relatively less attention. Thus, the challenge to provide operational data products with proper cal/val has only partially been met. Rather than considering the specifics of any given method, this paper looks at cal/val from a larger perspective and addresses issues that have more to do with infrastructure and information than with techniques. Attention is confined to the optical solar reflective domain.

The paper also attempts to relate advances in cal/val technology to the needs of users. A case is made that remote sensing in general has achieved little penetration of mainstream markets. Initiatives are proposed in terms of quality assurance and standardization. Experimental work is proposed with a view to helping present-day users while waiting for cal/val technology currently under development to become operational and for the quality assurance perspective of the future to

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

• D.N.H. Horler is with Horler Information Inc., 275 Slater Street, 9th Floor, Ottawa, Ontario, K1P 5H9

• N.T. O'Neill is with Centre d'Applications et de Recherches en Télédétection (CARTEL), Université de Sherbrooke, Sherbrooke, Québec, J1K 2R1

evolve. The concept involves the routine and systematic monitoring of quality assurance and stability reference (QUASAR) sites and the timely dissemination of results.

A list of acronym definitions is provided at the end of the paper.

The Status Of Calibration/Validation Methodologies

The list of planned Earth observation satellite sensors for the coming years is impressive, indicating that, despite the current economic climate, satellite remote sensing is considered to be a strategically important technology. It is anticipated that the capabilities of these new sensors will make it possible to provide better information more frequently about the Earth's surface. Many of them will be characterized by higher spatial resolution as well as by more and narrower spectral bands. The increased frequency of coverage and higher spatial resolutions by themselves have the potential to go a long way toward fulfilling the promise of remote sensing technology, which has so often fallen short of expectations. Also, there will continue to be advances in coarser-resolution sensors that provide broadscale coverage of the globe on a daily basis.

While each of the forthcoming satellite sensors will probably find a niche in terms of providing special data sets and information that only it can provide, there will also be certain geophysical and biophysical parameters that many of them will be called upon to provide despite significant differences in sensor characteristics. The most common denominators in this regard are likely to be surface reflectance and derived parameters such as vegetation indices, from which a variety of other quantities can be derived. In all cases, in order to take full advantage of advanced sensor systems, data and information products must be inherently sound and not significantly affected by by-products of the technology itself. This implies an ongoing need for calibration, validation, stability monitoring, and quality assurance.

The international Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) defines calibration and validation as follows (CEOS, 1995): *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. These definitions refer specifically to sensor calibration and data product validation. However, as a combined expression, calibration/validation has also become synonymous in the context of remote sensing with the suite of processing algorithms that convert raw data into accurate and useful geophysical or biophysical quantities that are verified to be self-consistent. This latter statement provides a useful and holistic way of considering cal/val for the present purpose.

One can envisage a range of calibration/validation users (**Figure 1**). There are the **specialist** users, who have high accuracy requirements and are prepared to, and indeed prefer to, run the image correction steps themselves. These specialists are often the key scientists that actually develop the algorithms in the first place. There are the **operational** users, who need good cal/val for their work, but who do not want to be concerned with the details, as long as the remote sensing products they use are quantitatively self-consistent and have an accuracy certification. These users depend on a transfer of algorithm technology from research to operational status, and that is something that is taking far too long these days. Then there are the majority of remote sensing users, who are not really interested in cal/val, but who 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. This will be an important consideration as the size and cost of satellite sensors decrease substantially in the near future.

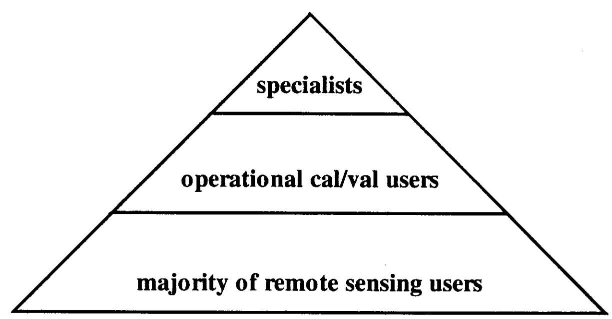

Figure 1.
Categories of calibration/validation (cal/val) users: (1) *specialist* users have high accuracy requirements and prefer to use their own preprocessing algorithms; (2) *operational users* need good cal/val but the details must be transparent to them; (3) *the majority of remote sensing* users seldom need cal/val but stability and quality of data are always important.

It can be argued that existing calibration/validation algorithms do not meet the quantitative needs of operational users and that only specialist users are able to, or are prepared to, use them (Teillet, 1997). Moreover, if these algorithms become more operational and feasible to use, a greater number of specialists will adopt them, but the majority of operational users will likely still avoid them. Such users want ready-to-use data and information products, and even operational calibration/validation will still require some complex and time-consuming steps. Where there is a need for calibration/validation, value-added industry should be able to provide it once operational.

Future Directions For Calibration/Validation Methodologies

How the technology for calibration/validation evolves will depend on the user constituencies being addressed. It is assumed that scientific users will establish the state-of-the-art whereas the majority of users will want operational, ready-to-use self-consistent products. Thus, the main challenge is to build data processing systems and value-added industries that can successfully take advantage of state-of-the-art techniques to make available quantitative remote sensing products and derived information to applications users. This will be a difficult task given the complexity of calibration/validation, the variety and variability of sensor characteristics, and the different number of processing steps users are or are not prepared to undertake or pay for. A case in point is the struggle to standardise the data and processing elements involved in the generation of self-consistent vegetation indices such as the Normalized Difference Vegetation Index (NDVI) from a multiplicity of sensor systems (Teillet *et al.*, 1997).

Some of the most important considerations may be summarised as follows (Teillet, 1997).

(i) With respect to radiometric calibration of sensors, 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.
(ii) The spectral characteristics of sensors should be sufficiently well understood to generate similar geophysical and biophysical products from dissimilar measurement systems.
(iii) Atmospheric correction will depend on the operational availability of atmospheric parameters needed to run atmospheric codes and the efficient implementation of those codes or derived results in a cost-effective image correction framework.
(iv) Proper and accurate integration of retrieved surface reflectances into self-consistent data sets will require consideration of a variety of geometric effects on radiometry.

Calibration/Validation User Requirements From A Market Perspective

One of the main driving forces for the current interest in cal/val is global change research, for which it is necessary to characterize the environment over long time periods and vast areas using many sensors. This work is carried out by scientists who are sophisticated users of remote sensing technology. The cal/val needs of this group, and of research scientists working on other applications of remote sensing, are already fairly well represented in fora such as the CEOS WGCV. It is likely that the development of cal/val technology will remain driven by these kinds of users for the near future. The challenge is to relate the advances in cal/val technology to the needs of the majority of remote sensing users who are generally not knowledgeable about cal/val issues. Therefore, it is worthwhile to consider a market-driven approach to identifying the needs for cal/val.

Cal/val is a basic and pervasive issue in remote sensing that needs to be examined from a strategic viewpoint. The purpose of this section is to characterize remote sensing markets in a way that relates to cal/val and that can be used to establish priorities and directions. The market model presented is based on the general marketing model for technological products described by Moore (1991) and consists of an initial development of that model for the specific case of remote sensing. As will be shown, cal/val is a scientific concept that, when viewed from a market perspective, translates to the concept of data quality.

The General Market Model

Two elements of the technology market model are outlined here, the *technology adoption life cycle* and the *value proposition*.

Markets pass through several stages of development for any technology. The market requirements do not evolve progressively through the cycle, but are discontinuous and radically different from one stage to the next. Most notably, there is a "chasm" between the Early Adopters of a technology and the Early Majority that are the first type of mainstream customer (**Figure 2**). Some of the characteristics of these two groups are compared in **Table 1**.

The second element of Moore's marketing model that is relevant to this paper is the concept of the *value proposition*, which postulates that a given product or service provides value to a user for an application. In order to cross from the Early Adopter market segment to the Early Majority segment, there

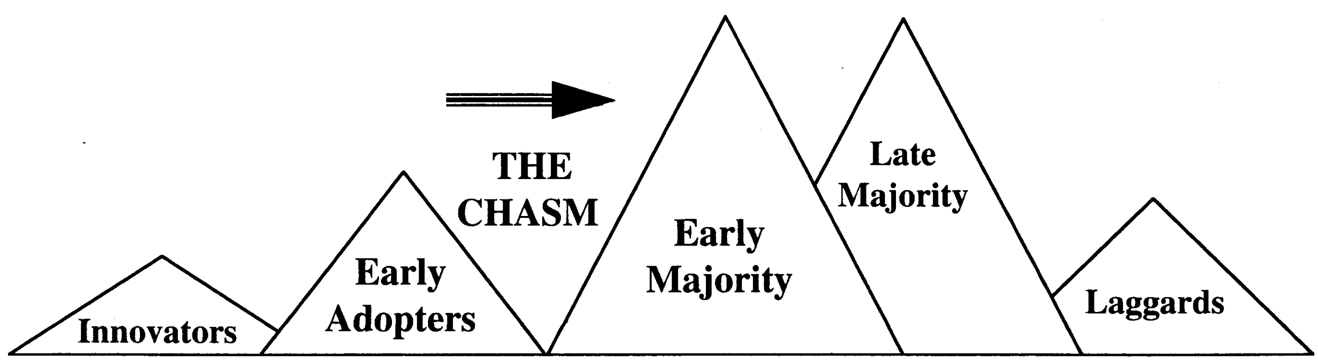

Figure 2.
The revised technology adoption life cycle (Moore, 1991; Horler and Teillet, 1996).

Table 1.
Some characteristics of Early Adopters and Early Majority customers (based on Moore (1991)).

Early Adopters	Early Majority
• technology enthusiasts	• pragmatists
• looking for a fundamental breakthrough, not merely incremental improvement	• looking for incremental, measurable, predictable progress (not quantum leaps)
• willing to accept high risk for the potential of high return	• low risk tolerance; want assurances about product quality, infrastructure of supporting technology, reliability of service, etc.
• easy to sell but hard to please: -have a project orientation -have high expectations	• hard to win over, but loyal once won
• relatively low price-sensitivity	• like to see competition, to keep costs down and to have alternative supply sources ·
• tend to communicate laterally, across industry boundaries	• tend to communicate with peers in their industry; require proof of success before buying

has to be a compelling reason to buy; that is, the end user receives benefits that are strategic to the sponsoring organization and cannot be achieved by any other reasonably comparable means. In contrast to Early Adopters, mainstream users have little interest in the technology, in itself. They see technology more as a source of risk than as a source of opportunity.

Project Versus Infrastructure Applications

Applications using remote sensing have, for the most part, been at the level of individual projects, and this body of knowledge is documented in over two decades of empirical research papers. We can refer to this as the *project* use of remote sensing, which often equates to the qualitative or semi-quantitative applications. Standardization in remote sensing is still somewhat *ad hoc*, and is applied, if at all, at the level of the individual sensor and/or project and requires significant technological knowledge on the part of the user.

Attempts are being made to use remote sensing as a data input to information systems where the spatial and temporal continuity of consistent information is of primary concern. An example in Canada is the Crop Information System (Brown *et al.*, 1993). We can think of such uses of remote sensing as being at the *infrastructure* level, where remote sensing is required to provide a reliable data input to an information system (Anderson, 1992). It is at the infrastructure level that the needs for cal/val are brought to the forefront. Further, a proliferation is occurring in sensors and space programs, which have the potential to operate synergistically, but only if there is appropriate standardization.

Locating Remote Sensing in the Technology Adoption Life Cycle

Several characteristics of the historical and existing remote sensing market support the contention that remote sensing is primarily in the Early Adopter phase of the technology adoption life cycle. Many users in mainstream markets have not embraced or have actually avoided remote sensing because of the deficiencies of the technology and the fact that they often have alternative ways of getting the same, or similar, information. Basically, remote sensing has failed to meet their needs. The technology has not delivered the *whole product* that is needed to create the compelling value proposition that can win over this market. The *whole product* means not just the radiometric image or thematic product that is the output of the technology, but the surrounding elements of quality, reliability, standardization, third party support, complementary products and so on that will give pragmatists the confidence to make a business decision to buy into this solution.

Market surveys by other authors support the aforementioned points. Sweet *et al.* (1992) reported on a study intended to identify research needs to encourage the growth of the Earth observation applications market. From a survey of users, it was concluded that the value of the information derived from Earth observation data is limited by several bottlenecks, of which the following relate to cal/val:

(i) corrections, including atmospheric corrections, registration /geocoding, and bidirectional reflectance corrections;
(ii) quality control problems, including poor calibration of sensors, loose control of the interpretation process, no systematic validation with collateral data, little or no traceability of processing;
(iii) poorly developed standards for data formats, media, processing systems and applications;
(iv) automated interpretation techniques that are inflexible, unreliable and not robust to changes in scale, amongst other problems (it is also difficult to assess the accuracy of their output);
(v) data integration problems within a geographic information system, because of heterogeneity in format, geometric and radiometric properties, temporal sampling rate, and lack of digital terrain data (integrating vector and raster data sets and multi-resolution merging are particular problem areas).

A telephone survey of US value-added remote sensing companies was carried out by Merry and Tomlin (1992) in the context of developing a commercialization policy for Earth Observing System (EOS) data. The survey included a question on the problems experienced in obtaining existing remote sensing data. Among the problems cited were data format changes and discrepancies, lack of standardization of the product, and noisiness and radiometric problems with the data.

Caibration/Validation as a Quality Assurance Issue

Quality assurance (QA) has been defined as "all those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality"; quality is "the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs" (ISO, 1992). The recognition of the need for and the rapid adoption of the ISO 9000 series of standards by the private and public sectors attest to the need for quality assurance in many industrial and governmental processes, including those in geomatics. QA in remote sensing data processing gives the user some assurance of the reliability of the information and therefore its suitability for a particular use. For remote sensing QA to be optimal and widely applicable operationally, it should be preceded by the fundamental steps of calibration and validation.

ISO 9000 standards are usually voluntary although they are increasingly becoming a source of competitive advantage and a basis for contractual situations. They seem to be popular in a wide variety of industries and government services that have important quality implications but are not covered by laws or regulations. Regulatory standards are expensive to monitor and are usually only applied in areas of the economy on which society places high values, such as those involved with money, health, safety or basic services.

Remote sensing presently operates in a market that has no regulatory or generally accepted QA framework. Up to now, the implicit philosophy in remote sensing has been "user beware", a philosophy that could only have endured in a technology-driven field. However, remote sensing is starting to produce information with significant impacts on people's lives and the operations of organizations. This trend is certain to continue. As the processing and applications of the data become more complex and more important, the existing state of affairs cannot continue. There are reliability and responsibility issues that increasingly arise as Earth observation data become an integral part of decision making information systems. Therefore, it is perhaps opportune for the remote sensing community to start contemplating a self-imposed quality assurance framework.

The Case for Standardization

The concept of *plug-and-play* is key in order for remote sensing data to penetrate mainstream markets. The main characteristic of *plug-and-play* data is that all the issues associated with data format and data quality are standardized or handled by the technology without the user having to be aware of them. The user can concentrate on the content of the information, rather than trying to read the data and transform it into a useable form. By the same token, *plug-and-play* implies that data become a commodity, interchangeable and interoperable. One data type should be substitutable for, or blendable with, another data type that has the same specifications. To be successful, the standards should be public-domain, not proprietary.

The feasibility of international standardization on spectral wavebands should be explored for all operational sensors. In the long run, in response to or in anticipation of customer demands, it should be possible to include a limited number of standard sets of spectral bands on every operational satellite sensor regardless of any other sensor capabilities. A strong case can be made for such a standardization in order to promote inter-sensor compatibility and data product continuity and consistency. Changes in spectral bands of sensors should be carefully weighed against the benefits of inter-sensor standardization. For example, we do not know how comparable will be vegetation indices generated by the many future sensors to be launched during the next five years (Teillet et al., 1997). Initially, the principle of standardization would apply to broad-band sensors but not to emerging technologies such as imaging spectrometry (hyperspectral sensors).

Recommendations

The term *cal/val* represents a set of scientific concepts and procedures of which the ultimate objective is to assure data quality. Until now, remote sensing has failed to deliver quantitatively dependable data on a systematic and reliable basis, or data whose errors and limitations are clearly appreciated by a broad base of users. Thus, remote sensing has been limited to *project* applications where the use of the data is constrained by the limits of the project and the data are well validated. *Infrastructure* applications will remain restricted until the data can be plugged into information systems with guarantees as to their reliability and accuracy. Given the historical evolution of remote sensing, meeting these requirements is a major challenge.

Cal/val has not been given proper importance during the historical development of remote sensing. It needs to be raised to a higher level of management awareness and organizational structure. There is a need for organizations (logically federal government agencies in Canada's case and likely in the case of most countries) to fulfill an on-going operational mandate in cal/val. The role of remote sensing QA support should be to encourage the uses of remote sensing consistent with the best possible practice and with the capabilities of given remote sensing technologies.

The following measures could be pursued in the area of QA: (i) develop a detailed specification of what a data quality plan means in the remote sensing context; (ii) develop quality plans for specific organizations or projects on a pilot basis; (iii) later, consider delivery mechanisms for quality audits, process or supplier certification, and/or product quality specifications. These measures need to be implemented carefully to ensure that they are technically and organizationally viable. They have to be perceived as supportive and to be sensitive to the risk of appearing bureaucratic or threatening. The QA initative should be tried out on a voluntary and confidential basis. It is beyond the scope of this paper to address the management strategies for implementing these measures.

Another linked aspect is standards development for remote sensing data. This is a function where national agencies have to link to data providers nationally and internationally. CEOS is the obvious body to play this role. The primary objective should be to view standardization as a prerequisite for market growth. Promoting research and developing new technology should be balanced by delivering reliable and consistent data. A strong case can be made for a basic level of standardization of spectral bands and of such parameters as instantaneous field-of-view (the Canadian concept of pixel sizes that are multiples (Guertin *et al.*, 1985)), orbit cycles to optimize temporal coverage, data formats, and standard data selection and processing options for certain applications. Much could be done in helping to ensure that compatible data are produced by the multitude of different sensors that are emerging.

A Proposal For Quality Assurance And Stability Reference Sites

From the technical perspective, there remains a significant challenge to build data processing systems and value-added industries that can successfully take advantage of state-of-the-art cal/val techniques so that quantitative remote sensing products are made available to operational applications users. From the market perspective, in response to customer demands for data quality, it may be possible in the long run to expect the availability of standardized geophysical and biophysical parameters, whose equivalencies have been validated and guaranteed to known accuracy, regardless of the sensors and methods used to generate them. A more practical though still challenging cal/val approach in the interim would be the routine production of benchmark data sets from surface monitoring sites, in the spectral bands of the commonly used sensors, and the rapid availability of results on the Internet world-wide web and other media.

On a trial basis initially, plans are in place to acquire and correct low-level airborne sensor coverage on a frequent and systematic basis to yield wall-to-wall reference data for a spatially extensive test area at a reasonably detailed spatial resolution. The intent is that such sites should serve as QUASAR sites in a modest, repetitive fashion rather than as high-accuracy sensor calibration sites (**Figure 3**). With time and increased effort, some of the sites could evolve into pure calibration sites or validation sites for a variety of data parameters and information products relative to the appropriate regional biome. The focus to begin with is the provision of useful results in a timely and readily available way. In order to achieve the greatest utility for the quality assurance of Earth observation data, the airborne sensor should be as flexible as possible in order to simulate the signal levels and spectral bands of present and future sensors. Thus, the airborne sensor should be an imaging spectrometer with trade-off capabilities in spectral, spatial, and radiometric sampling domains.

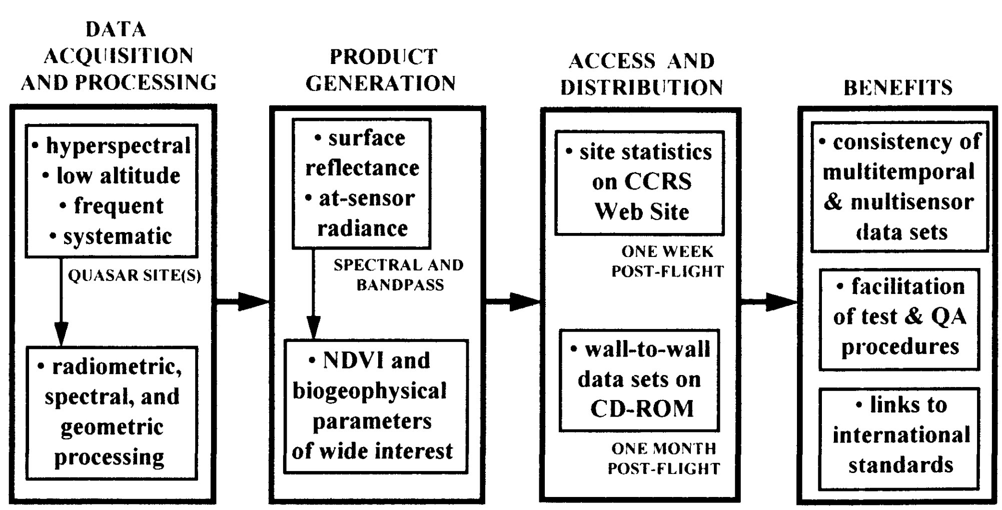

Figure 3.
The QUASAR concept.

Data Acquisition

A hyperspectral sensor candidate for wall-to-wall coverage of monitoring sites is the Canadian Compact Airborne Spectrographic Imager (*casi*) system (Anger *et al.*, 1996). The advantages of using *casi* are that it is relatively easy to use on light aircraft platforms, it costs much less than most other imaging spectrometer systems, and it has considerable flexibility in terms of selectable spatial and spectral modes of data acquisition. The disadvantages of *casi* are that it covers only the visible and near-infrared spectral regions and the geometric rectification is non-trivial. Data acquisition by the Canadian Shortwave-infrared (SWIR) Full Spectrum Imager (SFSI) (Neville *et al.*, 1995) can also be considered, although, unlike the *casi*, only one such system exists and its regular availability could be a problem. An alternative would be to boresight a visible, near-infrared and shortwave-infrared spectrometer with the *casi* to acquire at least a nadir profile in the SWIR (P. Slater, personal communication).

Initially, the complement of core ground-measurements should be realistic and feasible. Basic observations to facilitate adequate atmospheric correction and geo-referencing are envisaged. The site should be instrumented with an automated CIMEL sun photometer and thus included in the Canadian aerosol monitoring network (AEROCAN) (O'Neill *et al.*, 1997), which is part of NASA's global Aerosol Robotic Network (AERONET) (Holben *et al.*, 1997). Additional ground-measurement components can be added by other investigators over time. These extensions can contribute to improving the operational nature of the program or they can be more experimental in nature as long as the routine procedures are not compromised.

Site Considerations

Apart from being as uniform, flat and horizontal as possible, the monitoring site(s) should be large enough (10 km by 10 km, say) for use with respect to many satellite sensors, including those with large footprint sizes. Additional site characteristics under consideration include the frequency of cloud cover and the presence of nearby features that make the site(s) easy to locate. Prairie grasslands and rangeland in western Canada are under investigation as the prime candidate targets. The phenological changes that such areas undergo are not considered to be a significant drawback in the QUASAR concept, which is intended to provide extended ground reference data on a frequent basis. These Canadian targets will be supplemented by an annual overflight of the Nevada playas that are increasingly being used by the international community as Earth observation calibration sites. Although this adds considerably to the cost, it will provide a critical cross-calibration of sensors and methods to international standards.

While uniformly vegetated and very flat croplands exist in the Canadian prairies, they are limited to 1.6 km by 1.6 km or less in size and such sites exhibit high rates of phenological change at times. Native rangeland provides potentially uniform vegetation cover with more slowly varying phenology. However, the cultivation of flatter and more productive rangeland and the incursion of petroleum exploration into unspoiled rangeland diminish the chances of finding extended regions of undisturbed and flat native rangeland. Nevertheless, based on visual examination of NOAA AVHRR imagery, aerial photographs, and topographic maps for south-eastern Alberta, two sites have been selected for initial QUASAR studies. A more systematic search using a homogeneity window operator and AVHRR imagery of Canada is in progress.

The Newell County Site (**Figure 4**) is located north-west of Medecine Hat, Alberta, and the Cutbank Creek Site (**Figure 5**) is located near the Alberta-Saskatchewan-U.S.A. border south-east of Medecine Hat. Neither site is as large as the desired 10 km by 10 km area, the former being 8.2 km by 8.2 km in size and the latter 9.8 km by 4.6 km in size. Additional site descriptors are given in **Table 2**.

Central Nevada contains many dry lake playas of various sizes and two have received increasing attention as calibration sites from the international community: the Lunar Lake playa and the Railroad Valley playa (**Table 3**). Lunar Lake playa (**Figure 6**) is smaller and more suitable for the calibration of high-resolution sensors such as Landsat TM, SPOT HRV, and EOS ASTER, for example. The Railroad Valley playa (**Figure 7**) extends over a larger area and lends itself better to the calibration of coarser-resolution sensors such as NOAA AVHRR, EOS MODIS, Envisat MERIS, SPOT Vegetation, and ADEOS-2 GLI, for example.

Like the Lunar Lake playa, the often-used calibration site at White Sands, New Mexico, lends itself well to the calibration of higher-resolution sensors (Slater *et al.*, 1987). Although the alkali flats at White Sands cover a large area (some tens of kilometres across) (**Figure 8**), they can be difficult to use for the calibration of larger pixel data since the portion unaffected by frequent standing water and occasional vegetation is fairly small (Wheeler *et al.*, 1994; Teillet *et al.*, 1990).

Processing, Analysis, and Output Products

The basic elements of processing should include spectral calibration, radiometric calibration of the airborne imagery to radiance at sensor altitude, atmospheric correction to retrieve surface spectral reflectance, and geometric rectification as required. Core analysis should include the generation of spectral band reflectances for commonly used sensors as well as the computation of geophysical and biophysical parameters of interest based on these sensor bands. Maximum turnaround speed is envisaged whereby the results are to be made available within days of data acquisition. Clearly, this ambitious schedule will be difficult to meet initially, but it is nevertheless the target to aim for if significant progress is to be made. To facilitate access, the results would be put on the Internet world-wide web site at the Canada Centre for Remote Sensing (CCRS). Estimated surface reflectances and derived surface products will be reported routinely, whereas at-satellite predictions will be provided occasionally. Site statistics for the whole block for spectral bands and parameters of wide interest will be made available on the CCRS web site. The wall-to-wall data sets with full-spectral coverage will be available on CD-ROM by purchase/subscription or provided directly to stake-holders.

The QUASAR site program should benefit commercial data providers by facilitating quality control procedures used with their data products and algorithms. The same QUASAR approach can be used to validate data sets in different terrain locations and applications requiring consistency of multi-temporal and multi-sensor data sets should also be beneficiaries. While helping to monitor the quantitative status of satellite sensors internationally, the program should also enhance Canadian hyperspectral data acquisition and analysis capability.

Research Questions and Issues

Despite the desire for a simple and robust program of activities, there are many research questions and issues to be addressed. A complete error budget needs to be developed. What is the minimum area extent needed for QUASAR sites and how well can their location be determined in satellite imagery? What is the finest spatial resolution needed for the airborne imagery? How well does the airborne sensor have to be calibrated radiometrically? What approach to atmospheric correction is both feasible and sufficiently accurate? How can the directional reflectance properties of the site be characterized? What spectral and spatial sampling techniques should be used to simulate the various types of satellite data? What biogeophysical parameters are of greatest interest and how can they be validated? The procedures involved in each step of the activity need to be validated.

Infrastructure Questions and Issues

Although perhaps fewer in number, the infrastructure questions and issues may be just as daunting as the research ones. What is the cost of semi-continuous monitoring with an airborne sensor? Is the activity sufficiently promising to attract funding or in-kind participation and/or contributions by other agencies in Canada and internationally? What infrastructural support can be expected from the CEOS Working Group on Calibration/Validation?

Related Efforts and Initiatives

Surface observations and monitoring stations are commonly used in many scientific disciplines, invariably at significant cost and often under difficult logistical circumstances. A small minority of such efforts are routine and operational, in meteorology and climatology, for example. Ground reference measurements in support of remote sensing have typically been one-time efforts for specific experiments (Teillet, 1995). Nevertheless, there are promising signs that the value of cal/val test sites is being recognised, that more systematic activities can be expected in the future, and that significant resources are being made available for such efforts. A few examples are cited as follows.

(i) Significant efforts are being devoted to cal/val by NASA's EOS program in general and by the EOS MODIS Science Team in particular. Test site elements of these activities are gaining momentum but it will take years before they become of routine and practical use to more than just the key EOS scientists involved. Two international field campaigns for vicarious calibration have been held at Nevada test sites in the United States in

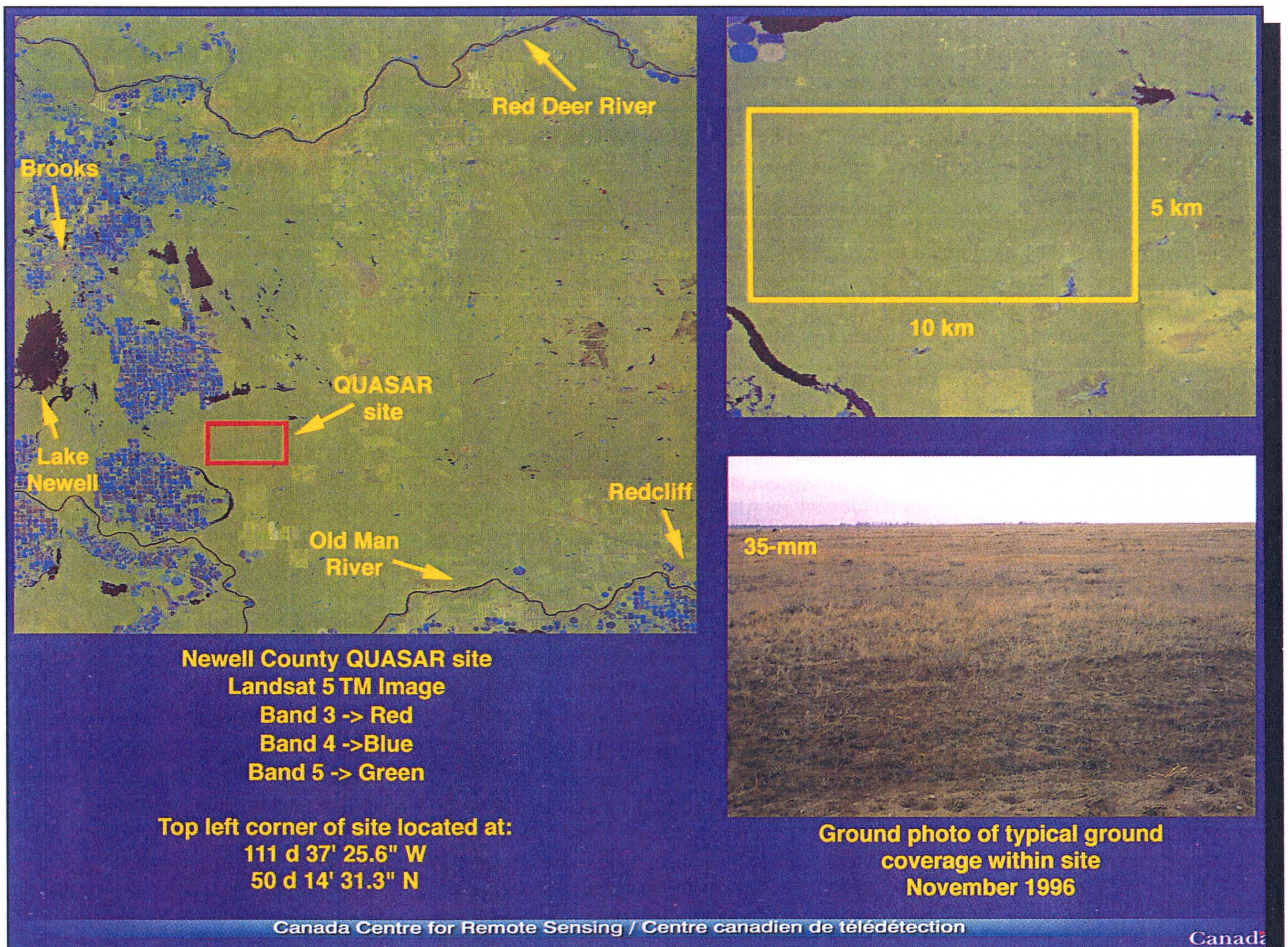

Figure 4.
The Newell County QUASAR site in Alberta.

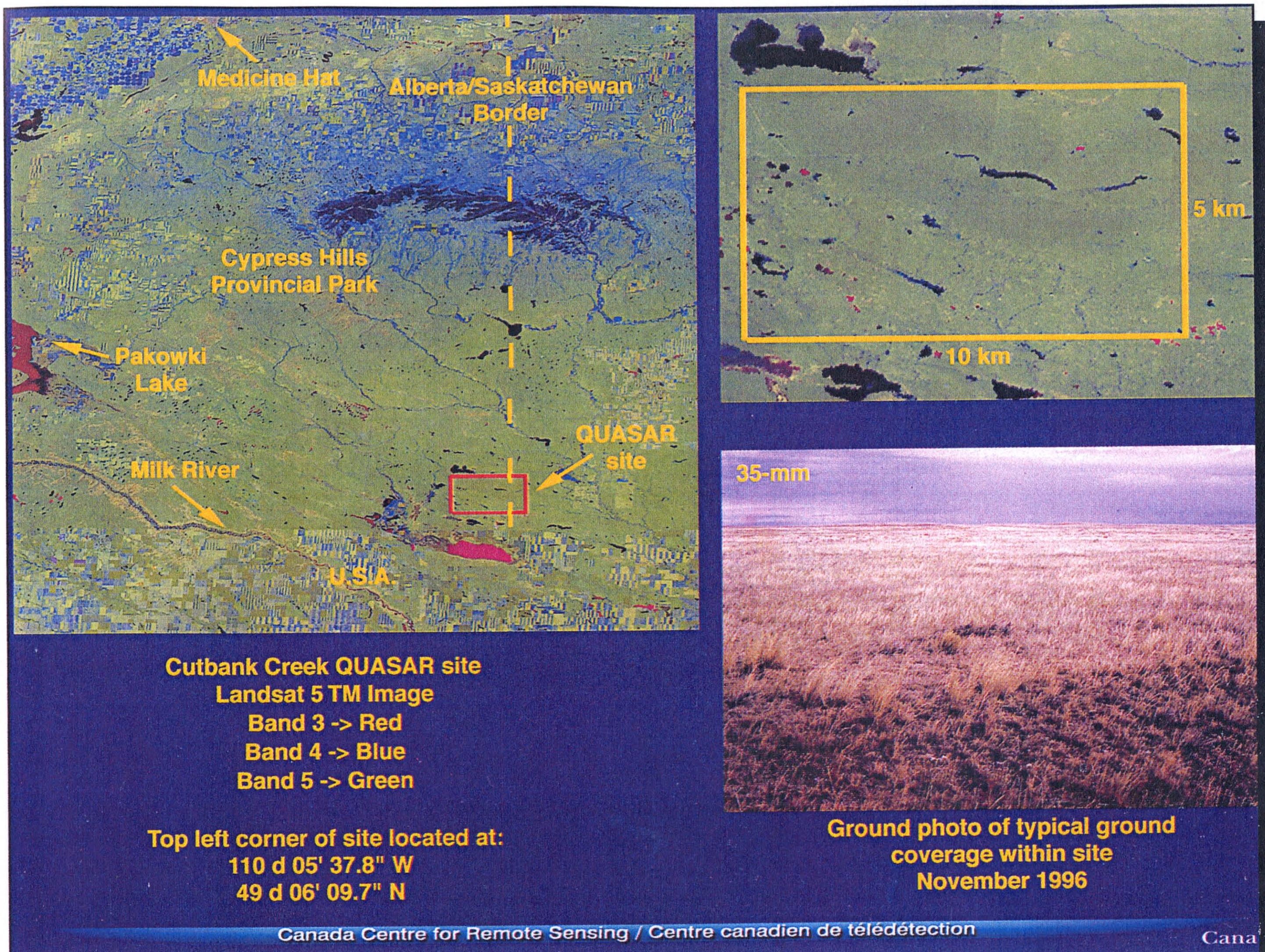

Figure 5.
The Cutbank Creek QUASAR site in Alberta.

Table 2.
Characteristics of the Newell County and Cutbank Creek QUASAR sites in Alberta.

Feature	Newell County Site	Cutbank Creek Site
Lat-Long Location (North-West Corner)	North Lat 50 deg 20 min 0.7 sec West Long 111 deg 36 min 11.8 sec	North Lat 49 deg 06 min 9.7 sec West Long 110 deg 05 min 37.8 sec
UTM Location (North-West Corner)	5575889 m Northing 457065 m. Easting, (Zone 12)	5439267 m Northing 566143 m. Easting, (Zone 12)
Airborne Coverage Block Size	10 km (E-W) by 5 km (N-S)	10 km (E-W) by 5 km (N-S)
Mean Terrain Elevation	750 m ASL	879 m ASL
Terrain Elevation Standard Deviation	4.5 m ASL	10.3 m ASL
Average Slope	0.1 deg	0.3 deg
Maximum Slope	0.9 deg	1.2 deg
Terrain Character	flat to sloping or long rolling	sloping to moderate rolling
Wetland Inclusions	< 1% (< 100 m. in size)	< 2% (< 200 m. in size)
Remarks	significant petroleum development	no petroleum development

Table 3.
Characteristics of the Lunar Lake playa and Railroad Valley playa QUASAR sites in Nevada.

Feature	Lunar Lake Playa Site	Railroad Valley Playa Site
Lat-Long Location (North-West Corner)	North Lat 38 deg 23 min 45 sec West Long 115 deg 59 min 35 sec	North Lat 38 deg 27 min 40 sec West Long 115 deg 40 min 44 sec
UTM Location (North-West Corner)	4250000 m Northing 587950 m. Easting	4257800 m Northing 615260 m. Easting
Airborne Coverage Block Size	5 km (NE-SW) by 2 km (NW-SE)	12 km (NW-SE) by 4 km (NE-SW)
Mean Terrain Elevation	1750 m ASL	1435 m ASL
Terrain Character	flat	flat
Standing Water	seasonal, primarily at North end	seasonal, primarily in peripheral areas
Remarks	Lunar Lake playa fully within airborne coverage block	airborne coverage block fully within Railroad Valley playa

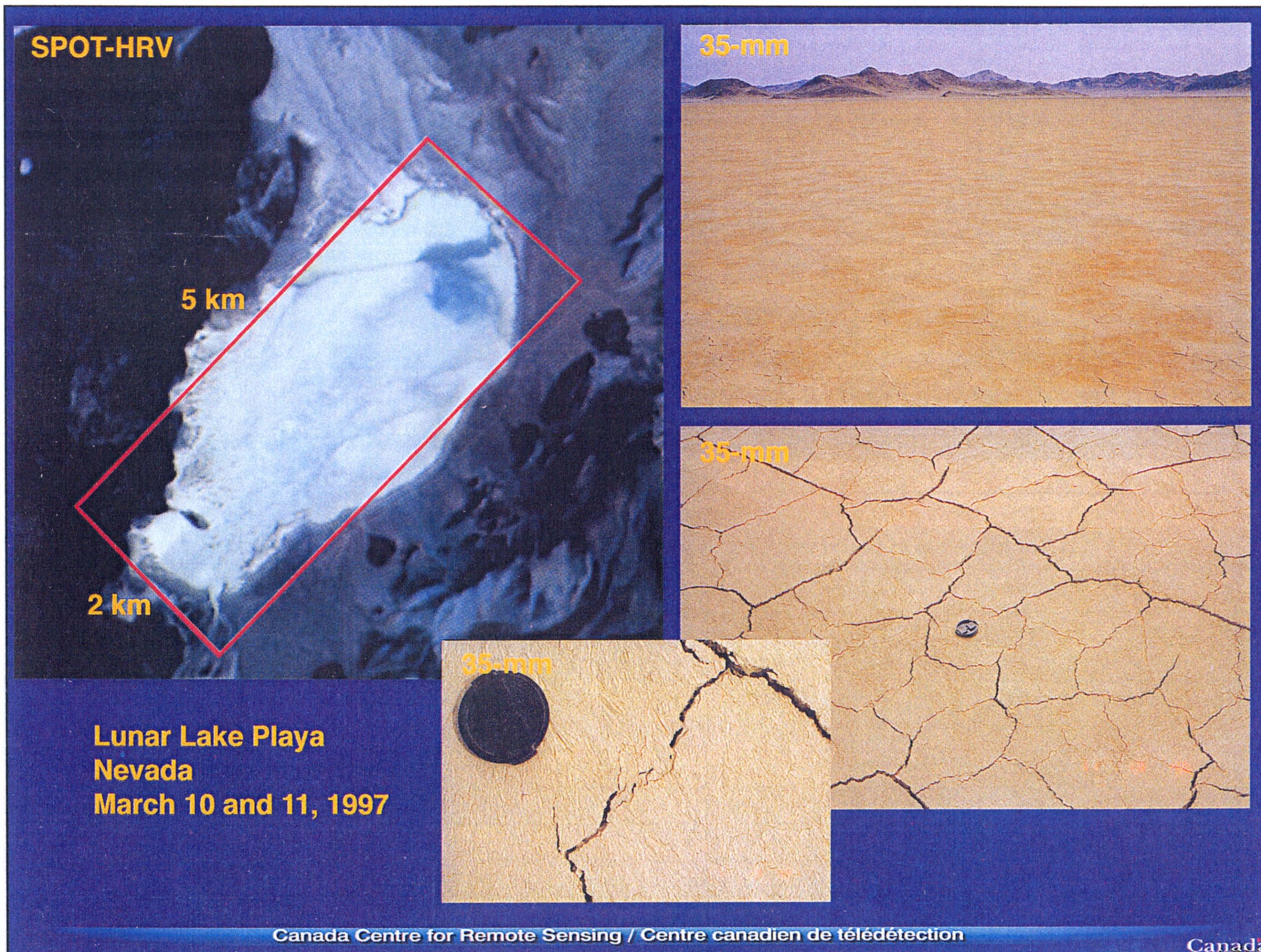

Figure 6.
The Lunar Lake playa calibration site in Nevada.

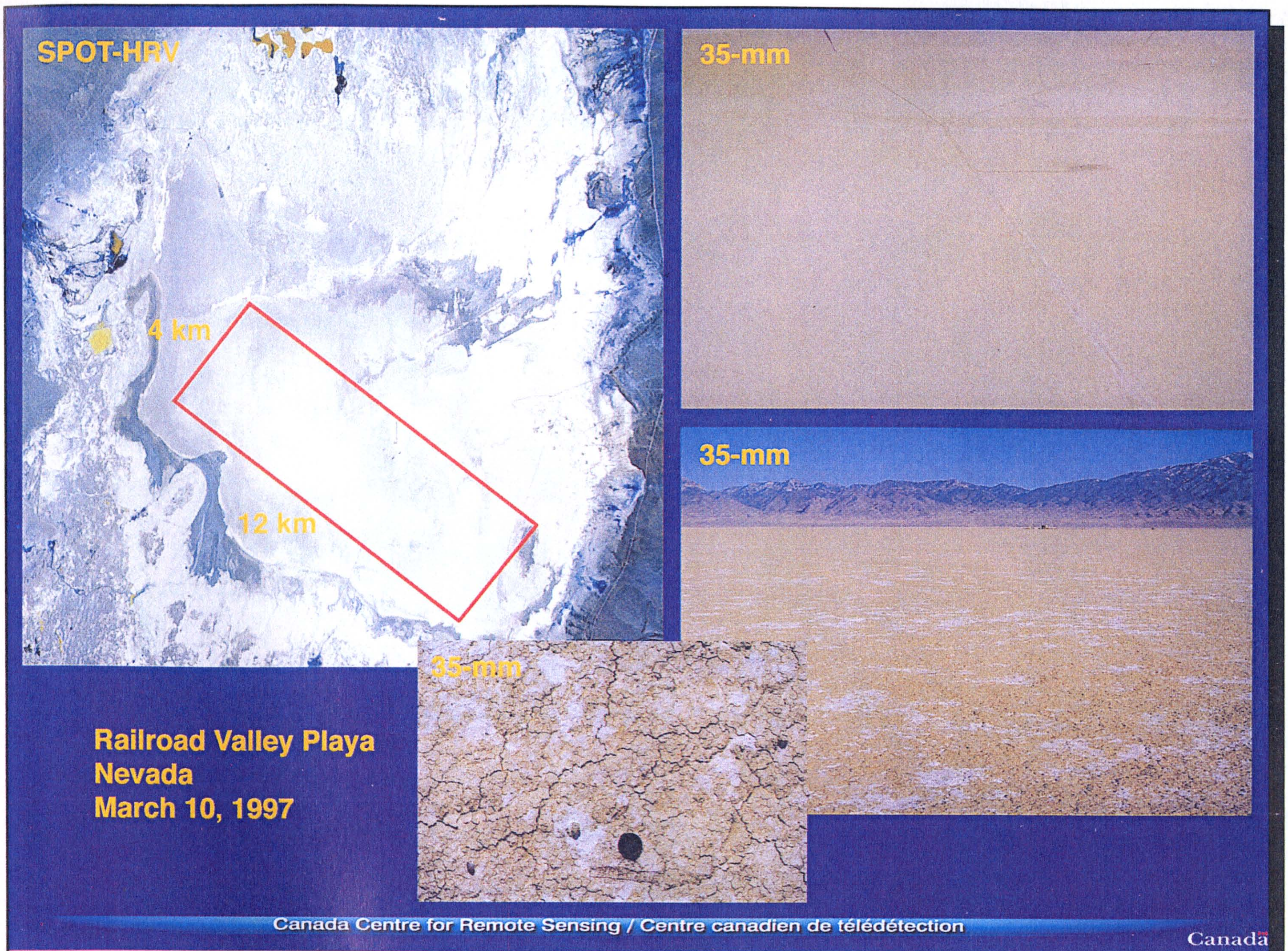

Figure 7.
The Railroad Valley playa calibration site in Nevada.

May/June 1996 and June 1997, respectively. Co-ordinated by the University of Arizona, these international efforts have been primarily but not exclusively focused on the comparison of methods for the vicarious calibration of EOS AM-1 sensors to be launched in 1998. EOS validation activities are ramping up as a result of a recent NASA Research Announcement of Opportunity (NRA-MTPE-97-03).

(ii) The International Geosphere-Biosphere Programme's (IGBP) Data and Information System is developing validation strategies in the context of the global 1-km land cover data sets based on NOAA-AVHRR data (Belward, 1994).

(iii) Stable desert areas in North Africa have been studied and used for monitoring the calibration of NOAA AVHRR, Meteosat and SPOT HRV sensors (Cosnefroy *et al.*, 1996).

(iv) The Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia has recently established a Continental Integrated Ground-truth Site Network (Prata *et al.*, 1996). Two of three scientific recommendations made by a review panel to Australia's recently formed CSIRO Earth Observation Centre are to (1) establish Australian algorithm development and validation working groups and (2) support calibration/validation activities. Various test sites are under consideration (Mitchell *et al.*, 1997).

(v) China has recently established a calibration site in the Gobi desert (Wu *et al.*, 1997) and is developing a national project for the related equipment procurement, field measurement programs, and data analysis (G. Xu, personal communication)

In developing its test site strategy, the EOS program has espoused the principles of coordination, collaboration and cost-sharing, and has expressed a special interest in international participation in measurement campaigns. With respect to the EOS Integrated Test Site Classification (Starr *et al.*, 1996), Canadian QUASAR sites can be considered to be in the "Tier 4" category – Globally Distributed Test Sites. Tier 4 sites are

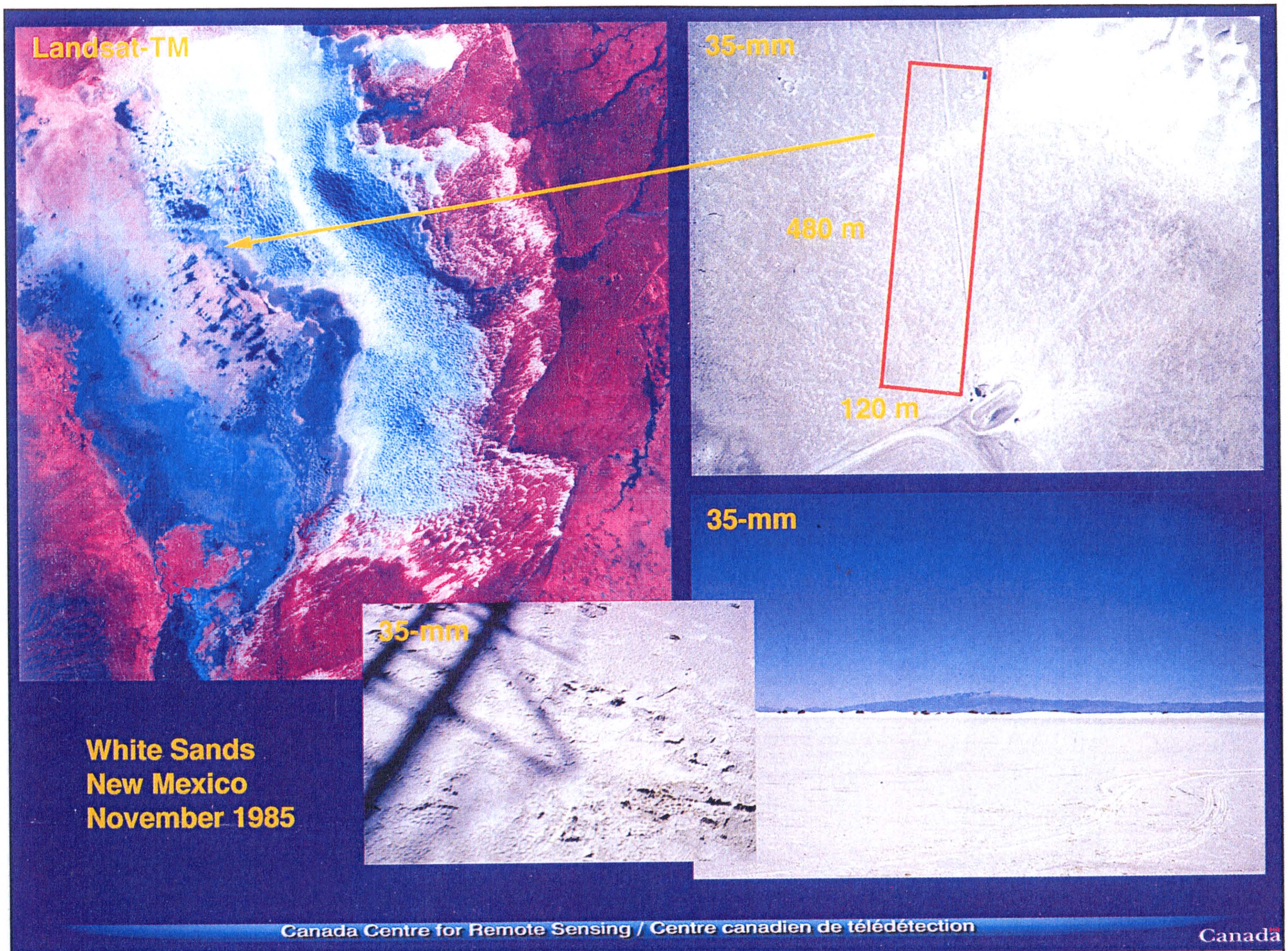

Figure 8.
The White Sands calibration site in New Mexico.

permanent, focused on specific measurement sets and user communities, and concern a limited number of variables. In the EOS classification scheme, the data sets acquired at QUASAR sites will be a combination of Measurement Suites "C" (field measurements needed to support radiometry) and "D" (aircraft measurements).

Concluding Remarks

In this paper, calibration/validation is considered to encompass all of the necessary steps to convert raw sensor data into accurate and useful geophysical or biophysical quantities that are verified to be self-consistent. The concept that cal/val can play an essential role in bringing remote sensing to mainstream consumers is introduced and market-oriented, quality-assurance and standardization initiatives are recommended. Out of a concern for helping present-day users while awaiting the results of advanced cal/val technology and the quality assurance perspective of the future, the realistic and timely monitoring of quality assurance and stability reference (QUASAR) sites is proposed. Systematic acquisition of low-altitude hyperspectral data sets for the monitoring sites will be used to generate ground reference data in the spectral bands of commonly used sensors and make the results rapidly and easily available on a frequent basis.

Acknowledgements

The authors wish to thank Karl Staenz, Robert Gauthier, Gunar Fedosejevs, Tom Lukowski, Josef Cihlar, Ron Brown, and Bert Guindon of the Canada Centre for Remote Sensing, as well as John Miller of the Institute for Space and Terrestrial Science and Philip Slater of the University of Arizona for helpful information and discussions. The authors also wish to thank Véronique Allard (University of Ottawa) for technical assistance with the illustrations. The opinions expressed herein are solely those of the authors and are not necessarily those of any organization.

ACRONYMS

ADEOS	Advanced Earth Observing System (Japan)
AEROCAN	Canadian Aerosol Sunphotometer Network (CCRS and Université de Sherbrooke)
AERONET	AErosol RObotic NETwork (NASA Goddard Space Flight Center)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (Japan; EOS)
AVHRR	ADvanced Very High Resolution Radiometer (NOAA)
casi	Compact Spectrographic Airborne Imager (Canada)
CCRS	Canada Centre for Remote Sensing (Canada)
CEOS	Committee on Earth Observation Satellites
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
EOS	Earth Observing System (NASA)
GLI	GLobal Imager (ADEOS)
HRV	Haute Résolution dans le Visible (SPOT)
ISO	International Standards Organisation
MERIS	MEdium-Resolution Imaging Spectrometer (Envisat)
MODIS	MODerate-resolution Imaging Spectroradiometer (EOS)
NASA	National Aeronautics and Space Administration (U.S.A.)
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration (U.S.A.)
QA	Quality Assurance
QUASAR	QUality Assurance and StAbility Reference (CCRS)
SFSI	Shortwave-infrared Full Spectrum Imager (Canada)
SPOT	Système Probatoire d'Observation Terrestre (France)
TM	Thematic Mapper (Landsat)
WGCV	Working Group on Calibration and Validation (CEOS)

REFERENCES

Anderson, N.M., 1992, "The Role of Geomatics in Developing the Environmental Information Infrastructure", *Environmental Monitoring and Assessment* (Kluwer Academic Publishers, The Netherlands), 20:167-173.

Anger, C., Achal, S., Ivanco, T., Mah, S., Price, R., and Busler, J., 1996, "Extended Operational Capabilities of *casi* ", *Proceedings of the Second International Airborne Remote Sensing Conference*, San Francisco, California, pp. 124-133.

Belward, A. (Editor), 1994, "The IGBP-DIS Global 1 Km Land Cover Data Set: A Validation Strategy Proposal", IGBP-DIS Land Cover Validation Working Group, Joint Research Centre - TP441, I-21020 Ispra (Varese) Italy, 28 pages.

Brown, R.J., Korporal, K.D., Pokrant, H.T., and Erickson, A.D., 1993, "Operational Use of AVHRR Data for Vegetation Monitoring in Canada", *Proceedings of the International Symposium on Operationalization of Remote Sensing*, The Netherlands, 10 pages.

CEOS, 1995, *Leadership to Ensure High-Quality Earth Observation Data: A Strategic Vision.* Committee on Earth Observation Satellites, Working Group on Calibration and Validation, 32 pages.

Cosnefroy, H., Leroy, M., and Briottet, X., 1996, "Selection and Characterization of Saharan and Arabian Desert Sites for the Calibration of Optical Satellite Sensors", *Remote Sensing of Environment*, 58:101-114.

Guertin, F.E., Friedmann, D., Simard, R., Brown, R.J., and Teillet, P.M., 1985, "Multiple Sensor Geocoded Data", *Adv. Space Res.*, 5(5):81-90.

Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.J., Nakajima, T., Lavenu, F., Jankovwiak, I., and Smirnov, A., 1997, "Automatic Sun and Sky Scanning Radiometer System for Network Aerosol Monitoring", *Remote Sensing of Environment*, in review.

Horler, D.N.H., and P.M. Teillet, 1996, *Workshop on Canadian Earth Observation Calibration and Validation, Workshop Report*, Canada Centre for Remote Sensing, Ottawa, Ontario, K1A 0Y7, Canada, 59 pages.

ISO, 1992, *ISO 9000 International Standards for Quality Management*, 2nd edition, International Organization for Standardization, P.O. Box 56, CH-1211 Geneva 20, Switzerland, ISBN 92-67-10172-2, 244 pages.

Merry, C.J., and Tomlin, S.M., 1992, "Commercial Potential of Remote Sensing Data From the Earth Observing System (EOS) Platform", *Geo-Information-Systems*, 5(2): 1-7.

Mitchell, R.M., O'Brien, D.M., Edwards, M., Elsum, C.C., Graetz, R.D., and Simpson, J.J., 1997, "Selection and Preliminary Characterization of a Bright Calibration Site in the Strzelecki Desert, South Australia", *Canadian Journal of Remote Sensing*, this issue.

Moore, G.A., 1991, *Crossing the Chasm: Marketing and Selling Technology Products to Mainstream Customers*, Published by Harper Business, a division of Harper Collins Publishers, ISBN 0-88730-519-9, 223 pages.

Neville, R.A., Rowlands, N., Marois, R., and Powell, I., 1995, "SFSI: Canada's First Airborne SWIR Imaging Spectrometer", *Canadian Journal of Remote Sensing*, 21(3):328-336.

O'Neill, N.T., Royer, A., Romanov, P., Teillet, P.M., Fedosejevs, G., and McArthur, B., 1997, "The AEROCAN Sunphotometer Network: A Component of a Cal/Val Strategy for Consistent Image Correction", *Proceedings of the 19th Canadian Symposium on Remote Sensing and the International Symposium on Geomatics in the Era of Radarsat*, Directorate of Geographic Operations, National Defence, Ottawa, Ontario, Canada, K1A 0K2, on CD-ROM, 7 pages.

Prata, A.J., Cechet, R.P., Grant, I.F., and Rutter, G.F., 1996, "The Australian Continental Integrated Ground-Truth Site Network (CIGSN) - Satellite Data Calibration and Validation, and First Results", *Proceedings of the Second SEIKEN Symposium on Global Environmental Monitoring from Space, SEIKEN Symposium Vol. 16*, Tokyo, Japan, pp. 245-261.

Slater, P.N., Biggar, S.F., Holm, R.G., Jackson, R.D., Mao, Y., Moran, M.S., Palmer, J.M., and Yuan, B., 1987, "Reflectance and Radiance-Based Methods for the In-Flight Absolute Calibration of Multispectral Sensors", *Remote Sensing of Environment*, 22:11-37.

Starr, D.O'C., Justice, C.O., Wickland, D.E., and Suttles, J.T., 1996, "Summary Report of the EOS Test Sites Meeting - March 18-19, 1996", EOS Project Science Office, Code 900, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A., 60 pages.

Sweet, R.J.M., Elliott, J.C., and Beasley, J.R., 1992, "Research Needs to Encourage the Growth of the Earth Observation Applications Market. Remote Sensing: From Research To Operation", *Proceedings of the 18th Annual Conference of the Remote Sensing Society*, edited by P.A. Cracknell & R.A. Vaughan, University of Dundee, U.K., pp. 399-407.

Teillet, P.M., 1997, "A Status Overview of Earth Observation Calibration/ Validation for Terrestrial Applications", *Canadian Journal of Remote Sensing*, this issue.

Teillet, P.M., Staenz, K., and Williams, D.J., 1997, "Effects of Spectral, Spatial and Radiometric Characteristics on Remote Sensing Vegetation Indices of Forested Regions", *Remote Sensing of Environment*, 61:139-149.

Teillet, P.M., 1995, "The Role of Surface Observations in Support of Remote Sensing", *The Canadian Remote Sensing Contribution to Understanding Global Change,* edited by E. LeDrew, M. Strome and F. Hegyi, Department of Geography Publication Series, No. 38, University of Waterloo, Waterloo, Ontario, pp. 333-351 and 408-415.

Teillet, P.M., Slater, P.N., Ding, Y., Santer, R.P., Jackson, R.D., and Moran, M.S., 1990, "Three Methods for the Absolute Calibration of the NOAA AVHRR Sensors In-Flight", *Remote Sensing of Environment*, 31:105-120.

Wheeler, R.J., LeCroy, S.R., Whitlock, C.H., Purgold, G.C., and Swanson, J.S., 1994, "Surface Characteristics for the Alkali Flats and Dunes Regions at White Sands Missile Range, New Mexico", *Remote Sensing of Environment*, 48:181-190.

Wu, D., Yin, Y., Wang, Z., Gu, X., Verbrugghe, M., and Guyot, G., 1997, "Radiometric Characterization of Dunhuang Satellite Calibration Test Site (China) and First Test Using SPOT Data", *Proceedings of the Seventh International Symposium on Physical Measurements and Signatures in Remote Sensing*, Courchevel, France (in press).