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Fine Spatial Resolution Land Observations: IKONOS Example

Acquisition of Earth Science Remote Sensing Observations from Commercial Sources: Lessons Learned from the Space Imaging IKONOS Example

Running Title – IKONOS: Lessons Learned

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ABSTRACT

Over the last decade, NASA and other federal agencies have been increasingly encouraged to explore commercial sources of land remote sensing data, rather than pursuing government-funded sources of these measurements (Executive, 2003). The science and applications users have been skeptical of this move to commercial sources of observations both because of uncertainty over the capabilities of the private sector and the unsatisfactory outcomes of previous efforts to commercialize satellite-acquired land remote sensing observations. In an effort to more fully explore the potential of commercial remotely sensed land data sources, the NASA Earth Science Enterprise (ESE) implemented an experimental Scientific Data Purchase (SDP) that solicited bids from the private sector to meet ESE-user data needs. The SDP activity spanned nearly 5 years, and supplied many US and international researchers with sources of land remote sensing observations that had not been previously available. The images from the Space Imaging IKONOS system provided a particularly good match to the current ESE missions such as Terra and Landsat 7 and therefore serve as focal point in this analysis.

Throughout the SDP process, there have been many lessons learned concerning interactions between US industry, government agencies and the science user community. . The specifics of the Space Imaging IKONOS experience under the NASA SDP are most valuable with respect to possible future uses of commercial vendors to supply NASA ESE user needs for space-acquired land observations. Areas where valuable lessons were learned included the technical, scientific, proprietary, and management aspects of the interactions. As this activity has evolved, user confidence in the technical and scientific qualities of the IKONOS measurements has increased substantially. There are still areas where further progress could be achieved, with respect to proprietary and management aspects of scientific commercial data buys.

To date, the NASA scientific and applications users who have examined the IKONOS imagery have found the data to be of high quality, providing substantial value to their specific pursuits. They have found that the novel attributes of IKONOS, particularly in the spatio-temporal domain have introduced new analysis challenges not previously experienced with EOS sensors such as Landsat and MODIS. The technical qualities of the observations have been substantially improved during the SDP activity as a result of independent validation and verification by the Joint Agency Commercial Imagery Evaluation (JACIE) of the IKONOS observations.

The experience gained from the Space Imaging IKONOS SDP activity, suggests that US private sector is technically capable of meeting the needs of NASA ESE science and application users . The future success of such interactions between industry, government and users appears to be far more dependent on the organizational and legal aspects of such arrangements than technical capabilities of the data providers.

1. Introduction

The NASA Scientific Data Purchase (SDP) experiment to acquire scientific-quality satellite-acquired remotely sensed Earth observations from private industry suppliers, conducted under the NASA Scientific Data Purchase (SDP), has provided valuable and important lessons, which will prove useful for the potential future success of commercial remote sensing systems in satisfying the needs of US terrestrial scientists.

Of the private industry vendors selected for the SDP (Birk et al., 2003), Space Imaging presents the best case study for describing how well US industry may be able to fulfill the role, historically filled by US government laboratories (particularly the NASA Goddard Space Flight Center), of supplying space-acquired remotely sensed land measurements. The experience with the Space Imaging IKONOS system, launched successfully in September 1999, now encompasses over 4 years and provides a useful foundation to consider what processes have worked, and which might be improved.[1]

2. The Space Imaging IKONOS Mission

Details concerning the specifics of the Space Imaging IKONOS observatory are covered elsewhere in the issue (Dial et al., 2003). From the perspective of the NASA Earth Science Enterprise (ESE) community, the following are considered interesting characteristics of the IKONOS observatory:

The four multispectral bands closely approximate three of the visible and the near infrared spectral measurements of the Landsat Thematic Mapper (TM), the Earth Observing System (EOS) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the French HRV-SPOT systems (Fig. 1, Table 1). The red and near infrared measurements are also comparable to red and near infrared spectral measurements from the Advanced Very High Resolution Radiometer (AVHRR), the EOS Moderate resolution Imaging Spectrometer (MODIS) as well as the French VEGETATION instrument as well as several other sensors (see table 1 in (Townshend & Justice, 2002))

- The pixel area of the multispectral measurements is more than a factor 50 improvement over Landsat 7 ($16m^2$ versus $900m^2$), and the 1m panchromatic band is over 200 times better than the 15m-pan band on Landsat 7. This substantial increase in spatial resolution helps provide the types of detailed spatial measurements needed to assess scaling issues encountered when moving from local to global-scale observatories (Woodcock & Strahler, 1987) (Fig. 2)

[1] It is interesting to note that a portion of Space Imaging's heritage originates in EOSAT, the corporation that was created to commercially operate Landsats 4 & 5, as well as build, launch and operate Landsat 6. For many reasons, this earlier Landsat commercialization was not successful, and the Landsat mission was returned to government management in 1992 (Sheffer, E.J. 1994)

- The radiometric precision of the IKONOS sensor, with its 11-bit analog to digital data conversion, is a factor of 8 improvement compared to the 8 bit radiometry for Landsat 7's ETM+, providing a comparable improvement in radiometric measurement precision that IKONOS supplies spatially. Potentially, this combination of radiometric precision and spatial detail could provide the high quality means needed to validate the lower resolution measurements from Landsat and other systems.
- The orbital equatorial crossing time is also nearly the same as Landsat, Terra, EO-1 and SPOT, although the IKONOS system's nadir, repeat frequency is much lower at ~ 140 days, a necessary trade-off for the increased spatial resolution of the IKONOS system. With platform agility it can revisit most locations with 3 days within ±30° from nadir (Dial et al., 2003).

As a result, IKONOS supplies an important step in multi-scale land remote sensing, one that is most closely associated with field measurements and ground "truth".

The similarities in spectral measurements and orbit that exist between IKONOS and other systems, combined with the increased radiometric precision and spatial resolution of the IKONOS satellite, make it a valuable tool in comparing and evaluating higher and lower resolution systems. Thus, the IKONOS images offer significant potential in providing the validation and local assessments needed to support regional and global scale studies of the Earth system, using Landsat, SPOT, ASTER, MODIS, AVHRR and VEGETATION as the primary observatories.

3. Science Community Perspective on Commercially-Acquired Scientific Measurements

The significance of the IKONOS data purchase for the U.S. science community can best be appreciated from the context of their previous experiences with the U.S. (foreign) private sector U.S. scientists have noted several aspects of commercial observations that might limit their value for scientific query (National Research Council, 2001, 2002). These can be broadly categorized as follows:

- **Technical**: The research community believes that the commercial remote sensing sector is targeting markets where the visual quality of the imagery is valued more highly than the spectro-radiometric precision of the pixel level measurements. Experience with sensors such as the Landsat Return Beam Vidicon (RBV) and the NOAA Advanced Very High Resolution Radiometer have demonstrated how limited observatory quality can impact the scientific quality of remotely sensed measurements (Teillet & Holben, 1993). Because scientists and engineers consider commercial systems "black boxes" containing many unknowns and therefore of uncertain value, they tend to be skeptical of using measurements from such systems.

- **Scientific**: Each new observatory brings new capabilities and new challenges. How best to exploit such systems requires a significant investment in time and resources. However researchers must continue to make successful progress on their current research goals, if they are to have any hope of winning renewed funding for their research based. Consequently it is frequently difficult for research teams to dedicate the effort needed to develop applications of new observatories without targeted support for these efforts.

- **Proprietary**: Commercial providers often reluctant or even unable to reveal details concerning sensor design, acquisition procedures, or pre-processing of imagery. In the commercial marketplace, proprietary advantages may add significant revenue potential. Added to this profit concern are the increasing governmental pressures not to export advanced US technologies outside the US. On the other hand, the science community, in fulfilling its research goals, expects both full disclosure of observatory and data specifications as well as participation in the discovery and resolution of identified observatory problems. Science community experience has also shown that as data sets age, much of the original knowledge base used to create and operate an observatory is quickly lost and not recoverable. Researchers worry that the inherent long-term value of the original observations can be lost through a failure to originally document the mission specifications.

- **Organization and Management Processes**: Access to and shared use of commercial remote sensing data is a major concern for scientific applications researchers that utilize these images. The vendor's approach to these issues is reflected in their data licensing and mission operations strategies.

    - Mission Management - Satellite observatories that exclusively serve science interests have mission operation strategies that are specifically targeted to science needs (Arvidson et al., 2001). For example, when a research team has staff in the field collecting ground measurements, mission operations can place highest priority on acquisition of that site. However, with a commercial system, where scientists are but one of several types of customer, coordination of acquisition schedules to meet specific scientific goals may either be quite costly or impossible. This may suggest that more automated ground measurement systems may be needed in the future.

    - Data Licensing - A difficult lesson learned from Landsat commercialization resulted from the highly restrictive licensing agreements associated with the data imposed by EOSAT; they nearly eliminated scientific exploration of the new Thematic Mapper data (Marshall, 1989a; Marshall, 1989b). Inability to share data among researchers is a fundamental problem within the context of the scientific method that depends, in part, on repeatability and traceability of experiments and analyses.

The scientific community's previous concerns about receiving remotely sensed data from the private sector originated from both a lack of understanding of how the commercial approach could be tailored to meet science needs, as well as prior failed attempts to partner with private industry. The 1980's Landsat privatization and the SEAWIFS ocean color observation procurement are examples the science community considers when evaluating commercial suppliers of remotely sensed scientific measurements(National Research Council, 1985, 1995). The NASA SDP differ from the earlier Landsat "privatization" effort in that under the SDP NASA is buying data from an existing commercial provider rather attempting to commercialize an existing NASA science mission (National Research Council, 2002).

4. Lessons Learned

From 1999 to present, the NASA SDP procured approximately 2400 IKONOS data products (550 GB), costing over $11 million, for NASA's Earth Science Enterprise researchers. These data sets have been used to support a wide range of Earth science applications, as noted by the papers published in this special issue.

There is no question that NASA-funded researchers have enjoyed the access to these novel observations that has been provided under this experimental NASA Scientific Data Purchase. Analysis of these observations has posed some new challenges, but they have also provided new insights about land cover properties. Many of the early concerns that the NASA ESE community of users had about the measurements have been alleviated through working with the actual data.

An observatory as novel as IKONOS takes some time to adjust to both in terms of getting used to the new perspective provided as well as becoming comfortable with the technical characteristics of the observations . As stated in the JACIE paper (Zanoni et al., 2003), it took a large team of engineers and scientists from US government laboratories and universities, over 3 years to complete a detailed assessment of metric properties of the imagery supplied by Space Imaging . The extent of the IKONOS validation is consistent with prior validation experiences with government-funded ESE science missions. It takes time to develop full confidence in the output of new observatories. Having a team of scientists and engineers working on such system validation is vital to mission scientific success (Goward & Masek, 2001; Justice & Townshend, 1994, 2002).

4.1. Technical Assessment

Overall, NASA and affiliated researchers, in conjunction with Space Imaging engineers and technicians, believe that the <u>IKONOS system supplies high quality, high spatial resolution multispectral imagery that is suitable to support the research goals and requirements of NASA–supported Earth scientists</u>. Validation and independent scientific assessment of the IKONOS observations extended over 4 years. <u>A scientifically comprehensive validation takes considerable time and effort</u>. After 4 years there are few technical questions related to sensor performance and Space Imaging-applied, post-acquisition processing that remain to be addressed. Technical areas that have been evaluated and required detailed attention include:

- Sensor Radiometric Calibration:
  Initial radiometric calibration information supplied by Space Imaging for the multispectral observations, was found to have an error that increased with increasing spectral wavelength, when compared with the independent JACIE evaluation (Goward et al., 2003; Pagnutti et al., 2003). Space Imaging is employing a calibration procedure that is relatively novel to the Earth science community involving use of stellar observations to periodically calibrate the measurements (Bowen, 2002). Space Imaging employed the JACIE results to adjust their calibration information.

  The detector-to-detector calibration is remarkably good. The only artifact that was seen in early products, across the nearly 3000 detectors, was the contrast noted between adjacent arrays (Pagnutti et al., 2003). Space Imaging later adjusted for this effect.

- Sensor Geometric Properties:
  Overall the image geometry is exceptionally good with only minor problems noted. This is especially noteworthy given that the sensor often captures images at angles substantially different from nadir by tilting the spacecraft (Helder et al., 2003). A minor error in the processing algorithm was identified that when addressed, further reduced geometric errors by 50%, to nominal levels (Helder et al., 2003). Interestingly, in the process of discovering this latter problem, the current basis for one of the Federal Geographic Data Committee standards are called into question (Helder et al., 2003).

- Image Modulation Transfer Function Compensation (MTFC):
  Modulation transfer function compensation is an image enhancement technique that is rarely used in the Earth sciences although there may be some real value in doing so (Huang et al., 2002; Townshend et al., 2000). Initial examination of the imagery metadata, at NASA Stennis revealed the phrase "MTFC applied: Yes"(Ryan et al., 2003). This was surprising, since such processing had not been requested as part of the NASA SDP. Discussions with Space Imaging revealed that MTFC is a standard part of Space Imaging's data production process, with the prime objective of making the visual appearance of images sharper to the user. JACIE analyses revealed that the MTFC, as applied, introduces some noise as a result of over-compensating the data, though this occurs for much less than 1% of the observed pixels (e.g. (Goward et al., 2003; Pagnutti et al., 2003; Ryan et al., 2003). Further assessment at the Stennis Space Center showed that the MTFC processing kernel had been rotated 90 degrees, sharpening the across-track direction more than the along-track direction . This resulted in in the "over-compensation" observed in the initial empirical analyses (Ryan et al., 2003).

- On-board Compression:
  To achieve adequate satellite to ground telemetry of these high-volume observations, Space Imaging uses a proprietary data compression scheme developed by Kodak. Although this introduces uncertainties in the ground-based calibrations methods employed by the JACIE team since it violates the linearity assumptions upon which such methods are based, the JACIE team found little evidence of detrimental effects resulting from this compression. The 11 bit data, even with compression, provides more dynamic range than the 8 bit systems used on sensors such as Landsat ETM+.

The JACIE technical assessment of the IKONOS data revealed specific technical measurement uncertainties that, if not discovered, could have reduced the value of IKONOS as a source of scientific measurements. These uncertainties were addressed in an open collaboration between industry, government and the research community. This collaborative activity converged on effective answers that resolved and validated the qualitative and quantitative integrity of the measurements, observatory and post-acquisition processing procedures.

It is clear from the JACIE experience that successful adoption of commercial remote sensing data by the land science community necessitates open dialogue between the systems developers and the scientists and engineers who use the data. An unanticipated outcome of this JACIE activity was the increased trust that developed over time between representatives from industry, research and government involved in the technical assessment of the IKONOS data. These analyses produced benefits for all involved and demonstrated that all parties could work together in a constructive framework. It also demonstrated that the development of such a successful working relationship requires a substantial commitment of time and resources from all sides.

4.2. Scientific Assessment

The availability of IKONOS imagery to the terrestrial science community has generally been greeted with considerable enthusiasm (Andréfouët et al., 2003; Goetz et al., 2003; Hurtt et al., 2003; Masuoka et al., 2003; Morisette et al., 2003; Sawaya et al., 2003; Seelan et al., 2003; Small, 2003; Thenkabail et al., 2003). The IKONOS observatory provides a valuable source of spatially detailed land visible and near infrared measurements that may be used to validate and evaluate coarser spatial resolution multispectral visible and near infrared measurements acquired by NASA observatories such as Landsat and MODIS. This is particularly true for foreign investigations, where access to fine resolution imaging is often difficult, if not impossible, to achieve (Figs 2&3). Space-acquired high spatial resolution measurements overcome serious problems encountered with using aircraft-based sensors relative to both restricted airspace and unfavorable flying conditions. An IKONOS-type system substantially improves global access to such high spatial resolution multispectral measurements.

There are some novel aspects of an IKONOS–type observatory that introduce new interpretation challenges not previously encountered with systems such as Landsat and MODIS. The IKONOS observatory basically follows the same polar, sun-synchronous orbit as Landsat and Terra. However the basic observation image is approximately 11 km by 11 km. In order for the observatory to provide reasonable repetitive coverage for most land areas, it is an extremely agile observatory, having the capacity to point off nadir up to at least ±60° and in any azimuthal direction relative to the ground track (Dial et al., 2003). The IKONOS near-nadir repeat cycle (±1°) is better than 140 days, but with its agility, IKONOS can observe any land location within 3 days and look angles between ±30°, assuming that the particular land area is cloud free at that time. This operational configuration introduces several interpretation issues.

- The time delay between acquisitions of adjacent scenes for a given land region can be as large as several months, introducing significant variations across adjacent scenes, as a result of sun angle and vegetation phenology and other temporal changes, such as tide stage. Such delays can make analysis of adjacent scenes exceptionally difficult, if not impossible (Andréfouët et al., 2003; Seelan et al., 2003) (Fig. 4). Similar timing problems are experienced with moderate resolution systems such as Landsat, Aster and SPOT again demonstrating the trade-offs between spatial and temporal resolution with contemporary satellite remote sensing systems.

- The limited areal extent of a scene, combined with persistent cloud cover and other demands for the observatory, have made coordination between satellite observations and ground measurements quite difficult (Helder et al., 2003; Morisette et al., 2003; Pagnutti et al., 2003)

- Specular reflectance as a result of sun glint from local water bodies, can be a major problem, depending upon the relation between solar zenith and azimuth angles, relative to the view zenith and azimuth angles, preventing some applications of the measurements (Sawaya et al., 2003, Dial et al, 2003).

- Scene contamination with haze and cirrus-type clouds (Fig. 5), when they had met the "clear scene" criteria for SDP was found to be a problem in several locations around the globe (Sawaya, et al, 2003, Goward, et al, 2003)

- A few investigators(Hurtt et al., 2003) also note the need for a shortwave infrared (e.g. 1.65 μm) measurement particularly in forestry applications, based on their experiences with Landsat, MODIS and SPOT-HRV. This poses significant challenges to sensor design, since it would likely lead to more costly high spatial resolution array technology using non-silicon detectors. Hopefully in the near future this will become more feasible.

Overall, the NASA ESE scientific experience with IKONOS imagery has been positive. Access to these high spatial resolution, digital multispectral measurements is yet another major step forward in our capacity to observe the Earth's land areas over a wide range of spatial and temporal scales.

It is worth noting that most of the scientific concerns with IKONOS observations result from the necessary technical trade-offs that must be made to produce such a high spatial resolution system. As with any new technology, the learning curve for the science community for this new high spatial resolution satellite has been steep and more time will be needed to develop a full scientific understanding of this new observation resource. Certainly this first step under the NASA Scientific Data Purchase has provided and excellent start.

4.3. Proprietary/ITAR Factors

Over time, one of the more interesting changes that occurred during the SDP IKONOS evaluation was that Space Imaging became less and less "proprietary" about their system configuration and operations.

In the development of commercial remote sensing private industry is facing the challenge that small technical differences can result in a significant competitive advantage. Also this an area of technology, where the political system is becoming increasingly concerned about the export of advanced US technologies overseas. Based both on concerns about their own competitive advantages as well as government regulations placed on them during licensing under current US ITAR (International Traffic In Arms Regulations), companies such as Space Imaging are either unable or quite reluctant to reveal the details of their observatory design to user communities, particularly those that are technically and scientifically well informed.

In initial discussions of sensor radiometric calibration, sensor performance characteristics and other mission characteristics were considered proprietary and were not made available for distribution to the broad user community. As more questions were posed concerning mission performance, information gradually began to flow. By the first High Spatial Resolution Commercial Imagery Workshop in 2001, Space Imaging was publicly offering descriptions of systems design and mission operations. This release of information helped to develop substantial confidence within the user community regarding the quality of the acquired data.

A primary goal of partnerships between government and commercial entities aimed at supporting the science community, should be to keep the "proprietary" knowledge needed to understand an observatory and its measurements at an absolute minimum. The role of government scientists and engineers, serving as moderators of the interactions between private industry and the science community facilitated a dialogue that led to effective interactions. The government staff served as a neutral agent assuring industry that their proprietary and ITAR interests would not be violated, while at the same time assuring users that best engineering and science practices were being followed. This brokering role may be critical to future efforts to pursue such industry/science community interactions.

4.4. Administrative Considerations

The science community holds the view, based on years of working with NASA Earth observation missions, that the practices restricting access to knowledge of mission operations and data licensing limit the value of such data sets for scientific purposes. This might appear to raise significant barriers preventing the use of commercial sources for science measurements, but present experience with reference to Space Imaging IKONOS data suggests they can be overcome.

4.4.1. Mission Operations

Many of the science users were quite disappointed with the length of time between image acquisition, when they were notified of this event and finally when the data were delivered. As a model, many of the users have become accustomed to the ready access to such information supplied by the USGS EROS Data Center for Landsat 7. The Landsat-7 acquisition schedule is placed on the EROS web site a few hours prior to acquisition, and within 48 hours a JPEG of each acquired image can be viewed. Such an approach keeps the user well informed and significantly reduces time-consuming communications between users and suppliers (Morisette et al., 2003; Sawaya et al., 2003). This appears to be an easily resolvable administrative issue.

4.4.2. Data Licensing

A more complex problem is encountered in data licensing and costs. Under the NASA Scientific Data Purchase, NASA Stennis acted as broker for individual NASA ESE principal investigators for the acquisition of approximately $11 million of Space Imaging IKONOS data products. NASA Stennis negotiated a licensing agreement with Space Imaging that permitted sharing these data freely among NASA-affiliated researchers, which includes virtually anyone currently funded through the NASA Earth Science Enterprise. Users are very positive about the fact that the data can be shared among NASA investigators.

The US science community has become increasingly aware that the single government agency license negotiated for access the IKONOS data did not address a fundamental activity, that has applied to most previously acquired NASA earth observations, archival preservation at the USGS EROS Data Center (National Research Council, 2002).. Most, if not all land observations originally acquired by NASA, ultimately migrate to the archival repository at the USGS Earth Resources Observation System (EROS) Data Center. A fundamental criterion for data sets which are archived at EROS is that they are publicly available to any interested users. Based on the original licensing agreement on IKONOS data between NASA and Space Imaging, submission to the EROS data archive under these terms will be impossible for data acquired under the NASA SDP . In fact, this is problem not unique to the IKONOS data purchase but all licensing agreements, with the exception of the Earth Satellite Corp, (Birk, et al, 2003), developed under the NASA SDP. This archival issue simply was not considered in these deliberations. This is a fundamental lesson learned that extends well past that learned from working with Space Imaging alone.

4.4.3. Future Data Costs

Under the NASA SDP, individual investigator's procurement of these observations, was through a modest proposal process that was approved by NASA Headquarters. There was no realized cost to individual investigators for IKONOS data products other than writing the proposal. Thus under the NASA SDP individual investigators viewed these IKONOS observations as "free" to their funded research activities. This process is quite similar to access to other NASA EOS observations, with the exception of Landsat data.

However, as the NASA investigators considered continued use of IKONOS data to support their scientific goals, that they recognized that they could probably not count on continued "free" access the NASA Scientific Data Purchase. After reviewing NASA negotiated data costs, most of the investigators concluded that they could not afford, within their grant budgets, to purchase many such data sets. This suggests that if use of such commercial resources are to be considered for scientific research in the future that negotiated arrangements between NASA and other federal agencies and individual companies will most likely be needed to make the costs acceptable to individual users.

These issues of data licensing and who should bear the direct costs for access to commercially supplied remotely sensed data are at the heart of the clear cultural differences between the open-access expectations of the government-funded scientific community and the proprietary, commercial concerns of private industry. How these cultures are ultimately integrated is well beyond the scope of this current assessment but has been well exposed in NRC evaluations of the NASA SDP of IKONOS data (National Research Council, 1997, 2001, 2002). Areas that need further consideration include legal factors related to intellectual property rights and data cost issues, including how the fees should be paid and the specific costs that are acceptable to both industry and users. These are complex questions that are the crux of relations between the US government, industry, and academia. Answering these questions may prove difficult, but addressing them will ultimately be critical to successfully meet the goals of all partners involved.

5. Summary and Conclusions

The NASA Scientific Data Purchase activity was directed to evaluate whether the US private sector, in place of the government, is capable of supplying remotely sensed land imagery to science users that meet their needs. In this activity, Space Imaging, space-based IKONOS mission, accheived this goal, demonstrating that a private industry financed satellite observatory is capable of meeting some of the observation needs of the US science community.

The primary conclusion that can be reached from the SDP IKONOS experience is that US private industry, in this case Space Imaging, is technically able to supply useful remotely sensed digital imagery to the US science community. This overcomes a major concern of the science community that typically commercial observatories are not of sufficient technical quality to meet science needs. There are several considerations that should be given further attention in any future efforts by NASA or others to procure scientific measurements from the commercial sector.

5.1. Some Guidelines for Future Scientific Data Purchases

There are specific lessons learned from the SDP IKONOS experience that should be recognized when future efforts to acquire scientific measurements from the US private sector to support government-funded researchers are to be considered. These include:

- *Independent assessment and validation of acquired measurements is a critical part of the acquisition process.* This assessment could be performed either by individual investigators or by an oversight team, such as the NASA/USGS/NIMA JACIE team used in the SDP activity, or even by an independent group such as the National Institute of Standards and Technology (NIST) or Underwriters Laboratories Inc. (UL) evaluators. There are some real advantages in using the single organization point of contact for these activities because critical technical and intellectual resources are in short supply. Focusing these resources produced reasonably quick (1-3 year) turnaround on the results.

- *An open dialogue between industry and ultimate data users is essential to ensure that the best outcome is achieved in the industry/science community interaction.* Some of the difficulties the science community experienced with Space Imaging may have occurred as a result of the organizational arrangements made by the government entities. For example, the uncertainties concerning acquisition schedules could have been easily resolved if Space Imaging and/or the responsible government agency simply had a web site where interested users could check on the status of their requests.

- *Finding a balance between the perceived necessity of full disclosure in the science community and the restrictions in disclosure caused by competitive and ITAR concerns of the private sector should be a major goal in interactions between government and industry.* The Space Imaging experience has shown that as trust and confidence develop, these issues have become substantially less problematic; each realizing that the overarching goal is to satisfy everyone's best interests. There also is a further need for appropriate government agencies to review and evaluate the importance of ITAR restrictions in protecting national security relative to the substantial negative impact such restrictions have on scientific and technical developments. With the advent of foreign systems, the topic will need considerable further attention. History has shown that to the degree possible, open-access has the largest benefits for all involved.

- *Workable data licensing procedures are still difficult to achieve in satellite land remote sensing.* Industry's desire to preserve the economic potential and of the observations though strict copyrighting, so they can benefit from repetitive sales tends to conflict with the user community's interests in preserving the scientific value of the observations through sharing and long-term repetitive access. This is an area where industry, government agencies and science community representatives need to work together to seek effective compromises that satisfy each community. For example, a possible alternate licensing agreement could include some type of a time-limit clause, where after for example 5 years the observations acquired under a commercial data buy would revert to the public archive and be made generally available to the scientific community. It will probably take more time for the commercial market place to evolve before a rational long-term answer to this issue will emerge. However, it is likely useful to continue experiments such as the NASA SDP to encourage emergence of new insights into the appropriate licensing arrangments.

Much of what has been revealed in this effort by NASA and Space Imaging jointly to meet NASA ESE scientists' data needs reinforces what had been previously discovered in earlier efforts in this direction (National Research Council, 1985; Pace et al., 2000; Pace et al., 1999). Moving away from government sources to commercial sources of scientific land remote sensing observations is not simple and will require further efforts to refine the models of this interaction that have been employed to date.

Not withstanding remaining uncertainties, the NASA Scientific Data Purchase of Space Imaging IKONOS high spatial resolution, multispectral, satellite-acquired imagery, has served as a successful step forward by NASA and Space Imaging in moving towards commercial sources of valuable scientific data. The particular lessons learned in this NASA SDP activity should be of value to the Landsat Data Continuity Mission (LDCM) procurement that is now underway.

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Table 1: Spectral Band Passes for IKONOS and Lansat-7 visible and near-infrared bands

Spectral Band	IKONOS Spectral Range	Lansat-7 Spectral Range
Blue	445 – 516 nm	450 – 515 nm
Green	506 – 595 nm	525 – 605 nm
Red	632 – 698 nm	630 – 690 nm
NIR	757 – 853 nm	750 – 900 nm

List of Figures

Figure 1. The spectral band passes of IKONOS versus Landsat 7. Note the differences particularly in the near infrared. This leads to a divergence in spectral measurements from the two systems (see Goward, et. al., this issue for further details)

Figure 2: Comparison of IKONOS (left); acquisition date: 04/02/2001, image upper left corner latitude/longitude: 45.45/12.38, and Landsat 7 (right); acquisition date: 08/26/2001, image upper left corner latitude/longitude: 47.0/11.12 observations for the city of Venice, Italy. The differing spatial resolution of the two sensors is clear. The trade off is that Landsat systematically monitors all land areas of the Earth seasonally whereas the IKONOS system can only sample small portions of the Earth's land areas each year.

Figure 3. a) IKONOS imagery from Antarctica; acquisition date: 10/05/2000; image upper left corner latitude/longitude: -65.25/-60.89. b) IKONOS image of Kerguelen Island in the Indian Ocean; acquisition date: 09/24/2002; image upper left corner latitude/longitude: -49.09/70.54. These observations demonstrate the value of a space-based high spatial resolution observatory. Acquisition of such detailed imagery from aircraft would have been quite difficult and very expensive. A space-based system such as IKONOS provides ready access to all areas of the Earth's land areas, an important attribute for an observation system that is used to study global changes.

Figure 4: Seasonal changes recorded between adjacent IKONOS scenes acquired from an area in Maryland just north of Washington D. C.; one acquired on 04/07/2000, image upper left corner latitude/longitude: 39.36/-77.16, and one acquired on 04/06/2000, image upper left corner latitude/longitude: 39.33/-77.02. Note that at this time of the year, vegetation foliage are rapidly growing so that the scene from the early date shows much less green foliage than the later date (THIS ALL DEPENDS ON THE SCENE PAIR FINALLY SELECTED).

Figure 5: Impact of haze and cirrus clouds on observation quality for two images acquired of Congo, Africa. Note the significant loss of contrast in the image on the right, acquired on 03/26/2001, image upper left corner latitude/longitude: 1.19/16.01, due to haze and clouds (the image without the haze and cirrus clouds, on the left, was acquired on 10/23/2000).

Figure 1.

Spectral Response Curve Comparison

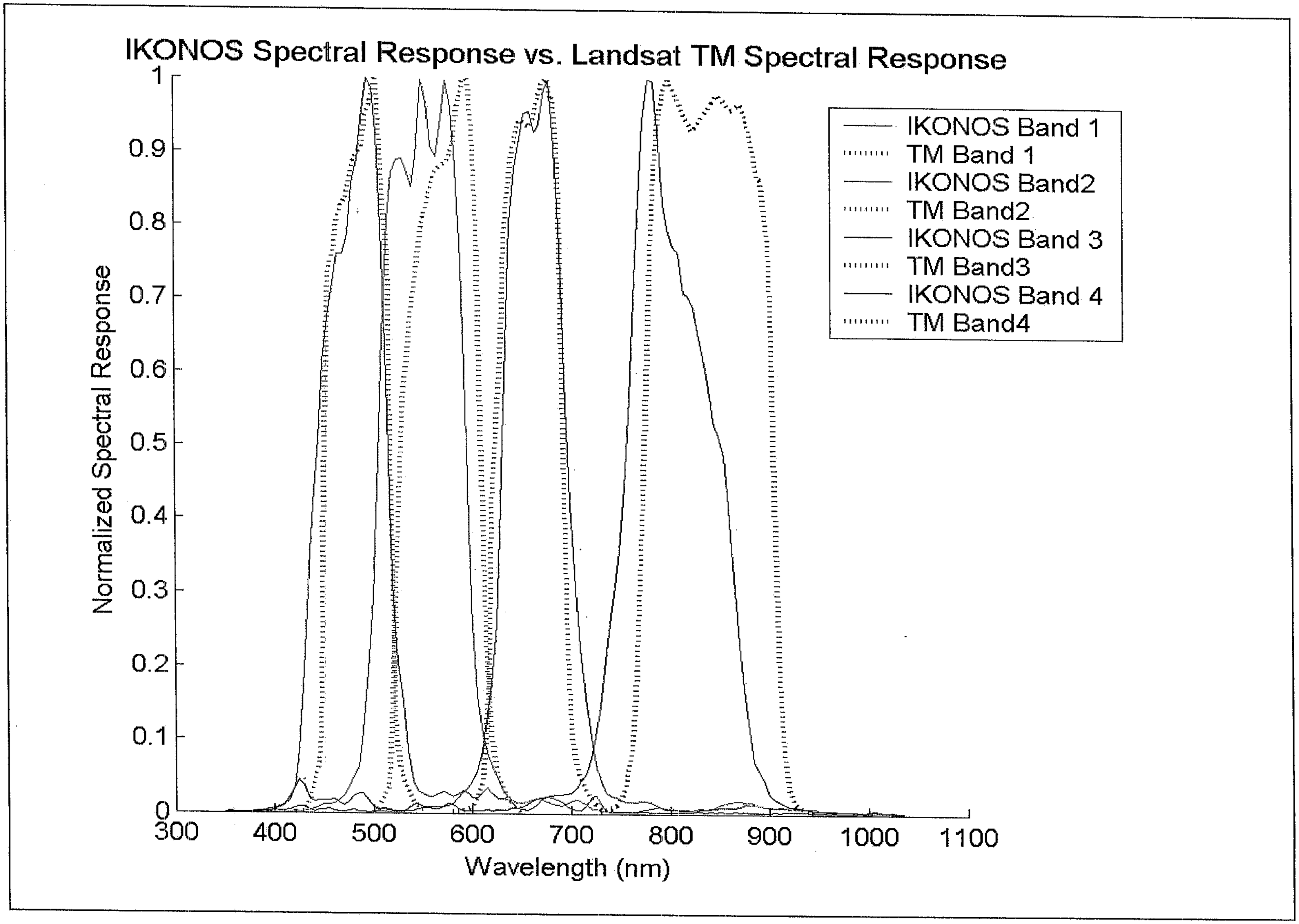

Figure 2.

Spatial Resolution

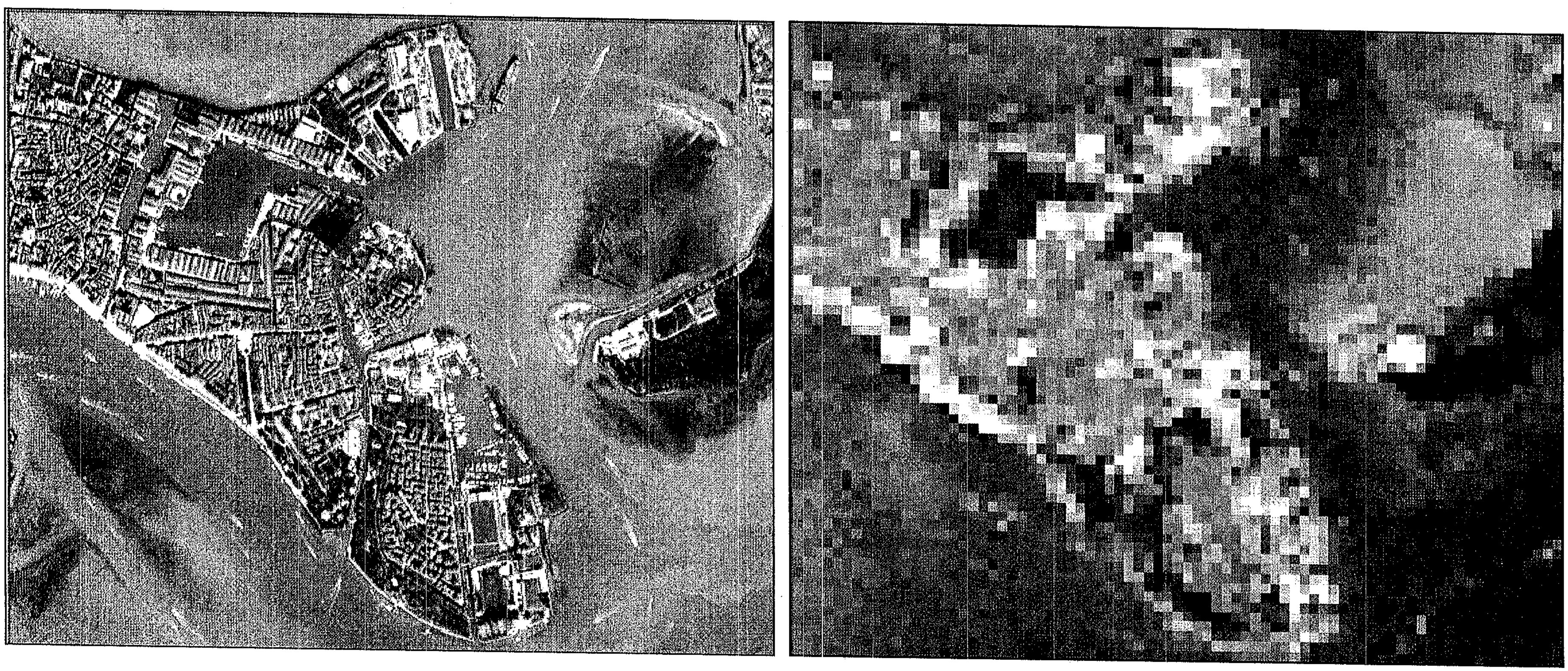

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Figure 3.

International Images

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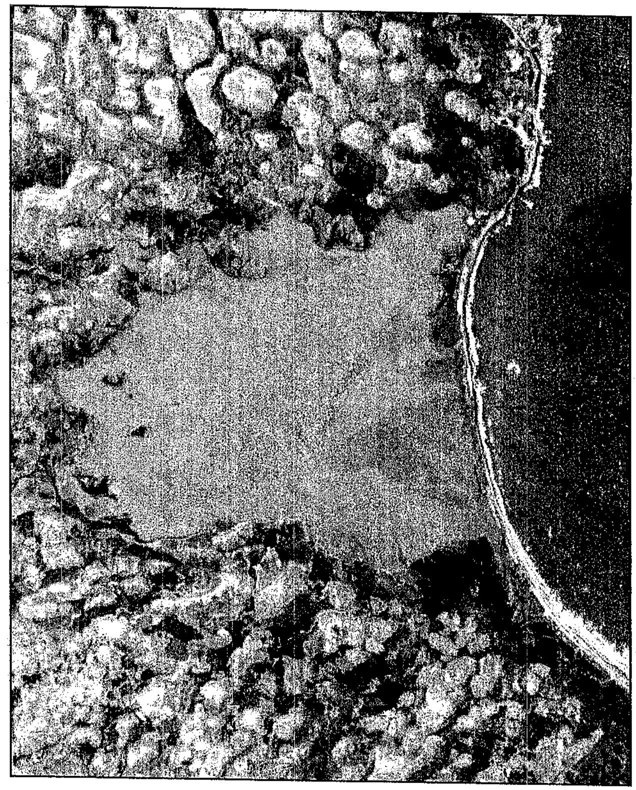
(a)



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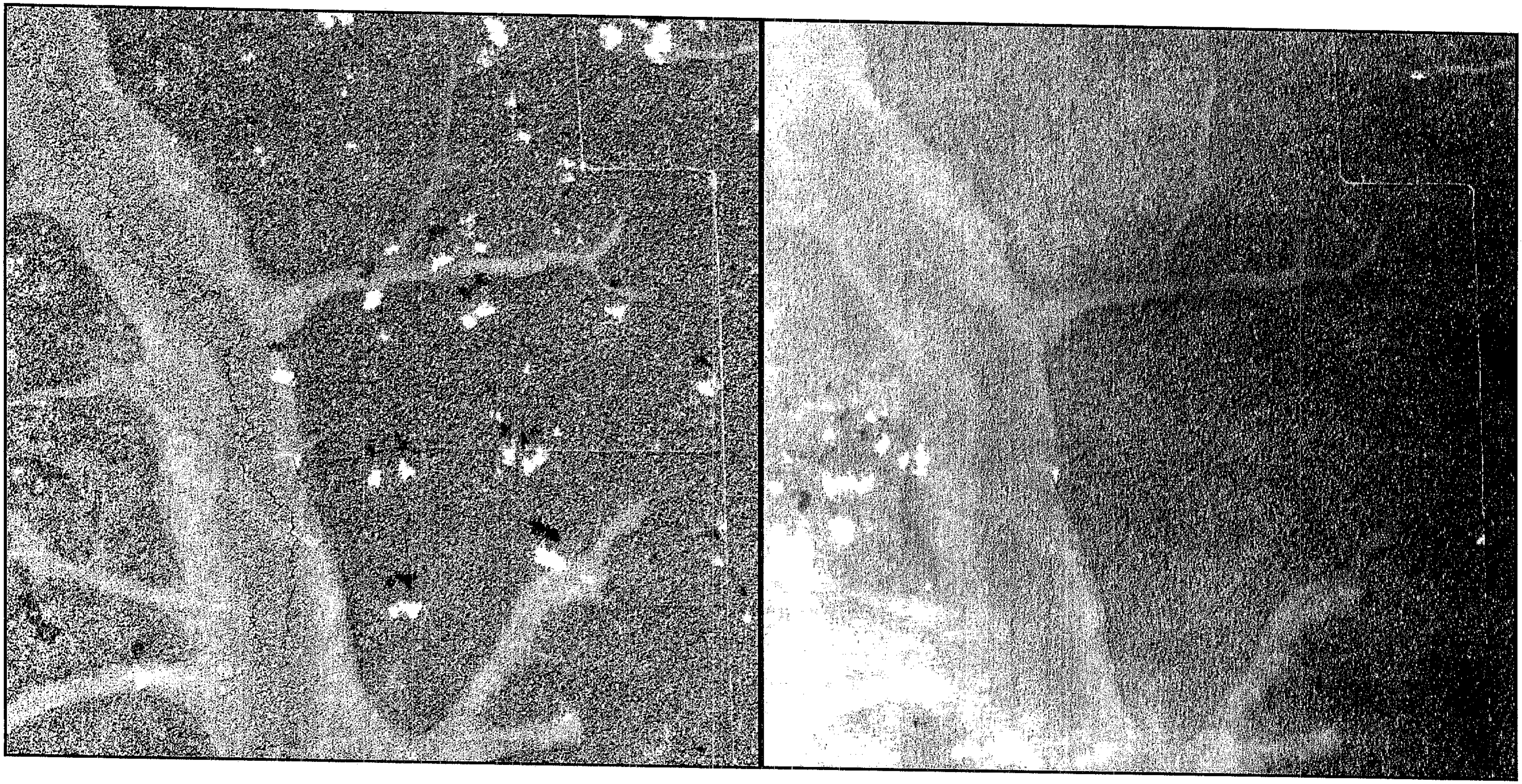
(b)

Figure 4.

Time Delay Problem

Figure 5

Cirrus Clouds and Haze



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