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The EOS Prototype Validation Exercise (PROVE) at Jornada: Overview and Lessons Learned

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The Earth Observing System (EOS) instrument teams must validate the operational products they produce from the Terra spacecraft data. As a pilot for future validation activities, four EOS teams (MODIS, MISR, ASTER, and Landsat-7) and community experts conducted an 11-day field campaign in May 1997 near Las Cruces, NM. The goals of the Prototype Validation Exercise (PROVE) included (1) gaining experience in the collection and use of field data for EOS product validation; (2) developing coordination, measurement, and data-archiving protocols; and (3) compiling a synoptic land and atmospheric data set for testing algorithms. PROVE was held at the USDA-Agricultural Research Service's (ARS) Jornada Experimental Range, an expansive desert plateau hosting a complex mosaic of grasses and shrubs. Most macroscopic variables affecting the radiation environment were measured with ground, air-borne (including AVIRIS and laser altimeter), and space-borne sensors (including AVHRR, Landsat TM, SPOT, POLDER, and GOES). The Oak Ridge Distributed Active Archive Center (DAAC) then used campaign data sets to prototype Mercury, its Internet-based data harvesting and distribution system. This article provides general information about PROVE and assesses the progress made

toward the campaign goals. Primary successes included the rapid campaign formulation and execution, measurement protocol development, and the significant collection, reduction, and sharing of data among participants. However, the PROVE data were used primarily for arid-land research and model validation rather than for validating satellite products, and the data were slow to reach the DAAC and hence public domain. The lessons learned included: (1) validation campaigns can be rapidly organized and implemented if there are focused objectives and on-site facilities and expertise; (2) data needs, organization, storage, and access issues must be addressed at the onset of campaign planning; and (3) the end-to-end data collection, release, and publication environment may need to be readdressed by program managers, funding agencies, and journal editors if rapid and comprehensive validation of operational satellite products is to occur. Published by Elsevier Science Inc.

INTRODUCTION

In 1999, NASA launched Terra, a keystone platform of the Earth Observing System (EOS). Aboard Terra are five instruments designed for simultaneous sampling of many earth system variables (Kaufman et al., 1998). Instruments for land studies include highly evolved successors to current sensors [e.g., the Moderate-Resolution Imaging Spectroradiometer (MODIS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and the Cloud and the Earth's Radiant Energy System (CERES)], as well as more experimental sensors [the Multi-Angle Imaging SpectroRadiometer (MISR)]. Once in operational mode (late spring, 2000), Terra's sensors will provide the most comprehensive view of the Earth system yet available.

Terra will also provide superior accuracy in sensor characterization, calibration, georegistration, and atmospheric correction. Since about 1990, EOS instrument teams have

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Received 15 November 1999; revised 15 February 2000.

Table 1. Spatial Resolution (in Meters) of Primary Terra Products Addressed by PROVE

<i>Sensor</i>	<i>Surface Reflectance^a</i>	<i>Albedo/ BRDF</i>	<i>LAI/FPAR</i>	<i>Vegetation Index</i>	<i>Fractional Vegetation Cover</i>	<i>Aerosol Optical Depth</i>
ASTER	15	<i>b</i>	<i>b</i>	<i>b</i>	<i>b</i>	<i>b</i>
MISR	275	275	275	<i>b</i>	<i>b</i>	17,600
MODIS	250, 500	1,000	1,000	250	1,000	10,000

ASTER=Advanced Spaceborne Thermal Emission and Reflection Radiometer; BRDF=bidirectional reflectance distribution function; LAI=leaf area index; MISR=Multi-Angle Imaging SpectroRadiometer; MODIS=Moderate-Resolution Imaging Spectroradiometer.

^aThe maximum resolution of sensor (synonymous with atmospheric correction product).

^bNot produced operationally.

worked to exploit this potential by developing operational algorithms (Table 1). For example, the MODIS Land Discipline Team (MODLAND; Justice et al., 1998) will produce routine estimates of surface reflectance, reflectance anisotropy, albedo, surface temperature, vegetation index, leaf area index (LAI), net primary production (NPP), and other parameters at various spatial and temporal resolutions. A comprehensive set of operational products is unprecedented in land remote sensing.

However, Terra's technological advancements do not guarantee highly accurate products. A well-supported and sustained validation program is needed to provide timely feedback to algorithm developers so that through iterative improvements, superior products will result. We define validation as the process of assessing by independent means the uncertainties of the data products derived from the system outputs (see URL for EOS Validation Program in Appendix 1). While previous remote sensing missions often relied on episodic checks (a field campaign) or opportunistic comparisons, the EOS program funded community validation scientists to help the sensor teams assess product accuracy.

Many techniques will be used to validate Terra products. However, direct comparison of products with field-measured data is one of the most credible techniques. To help assure an effective field measurement program, three Terra teams (MODLAND, MISR, ASTER) organized the Prototype Validation Exercise (PROVE) in a desert grassland near Las Cruces, NM in May 1997.

This overview article provides campaign and site information needed to give context to PROVE research articles. We discuss the campaign goals, organization, management (personnel and data), execution, and lessons learned in PROVE. We conclude with a summary of initial results.

BACKGROUND

MODLAND faces unique validation challenges because (1) its wide field of view ensures global coverage each day and night, and (2) its products span a great range of complexity, from low-level products generated for each pixel of each scan (e.g., surface spectral reflectance) to gridded, model-dependent annual products (e.g., NPP) to discrete thematic variables (e.g., land-cover type; Justice

et al., 1998). To meet these challenges in an economical manner, MODLAND plans to link episodic field campaigns to ongoing measurements at existing research sites (Running et al., 1999; Privette et al., 1999).

The episodic campaigns will involve comprehensive ground measurements together with aircraft remote sensing. By anchoring the spatial characteristics detected by aircraft sensors to stationary but continuous background measurements (e.g., albedo), the latter can be extrapolated over statistically significant areas throughout the year. By choosing sites that represent the world's major ecosystems, an effective validation program should result. Because some details of this approach are not well known, MODLAND initiated various prelaunch activities, including PROVE, to improve the program's effectiveness.

OBJECTIVES

PROVE was designed to prototype an EOS episodic validation campaign. The primary objectives were three-fold, including: (1) to gain experience in the collection and use of field data for EOS product validation; (2) to develop the coordination, measurement protocols, and data-sharing networks required for a global validation program; and (3) to collect a synoptic land and atmospheric data set to aid development of remote sensing algorithms.

The Landsat-7 Science Team joined the Terra teams in developing PROVE. Several non-EOS groups, primarily from universities and government agencies, also participated. These community experts filled critical measurement gaps and helped educate EOS teams on the latest capabilities and field techniques. The Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) joined to test data ingest and distribution methods.

CAMPAIGN DESIGN

Scope

Satellite products are most readily validated when equivalent parameters are simultaneously measured on the ground. However, some products cannot be sampled adequately in short campaigns (e.g., NPP; Running et al., 1999). In other cases, parameters in addition to the Terra



Figure 1. A landscape view of Jornada Experimental Range during PROVE.

product must be simultaneously measured. For example, validation of the surface reflectance (atmospheric correction) algorithm and product requires accurate information about the atmosphere. Without it, differences between field-measured surface reflectance and the satellite product cannot be attributed to algorithm problems—they could instead be caused by the erroneous aerosol values. Furthermore, all land biophysical values from Terra products are “effective,” meaning they represent the spatial mean of the variable over the resolution of the product. Thus, in heterogeneous areas, several field parameters may be required to scale point measurements to the resolution of the EOS product.

Figure 2. Location of the Jornada Experimental Range (JRN) and the Chihuahuan Desert.



Location

After assessing various North American field sites [particularly those in the National Science Foundation’s Long Term Ecological Research (LTER) program], MODLAND chose the USDA-Agricultural Research Service (ARS) Jornada Experimental Range (hereafter referred to as Jornada) for PROVE. Initial planning with Jornada personnel began in January 1997.

Jornada consists primarily of flat, desert grassland and is located 40 km north of Las Cruces, NM (Fig. 1) (Havstad et al., 2000; Rango et al., 2000). The ecosystem represents the northern extent of the Chihuahuan Desert, which, at more than 10.5 million ha, is the largest of the North American deserts (Fig. 2). Because arid and semiarid systems represent about 40% of Earth’s total land surface (Walton, 1969), Jornada clearly represents a major global ecosystem.

Jornada had several helpful attributes for validation work. First, its infrastructure includes a 30-m-high fixed tower and an on-site truck with an extendable boom capable of reaching heights up to 30 m (Fig. 3). These were useful for collecting fixed point measurements of surface

Figure 3. The 30-m boom extended from the truck at the transitional land-cover area. At the top of the boom are two instruments for measuring sky and surface radiance, a modified Cimel sunphotometer (NASA GSFC), and PARABOLA III (JPL).



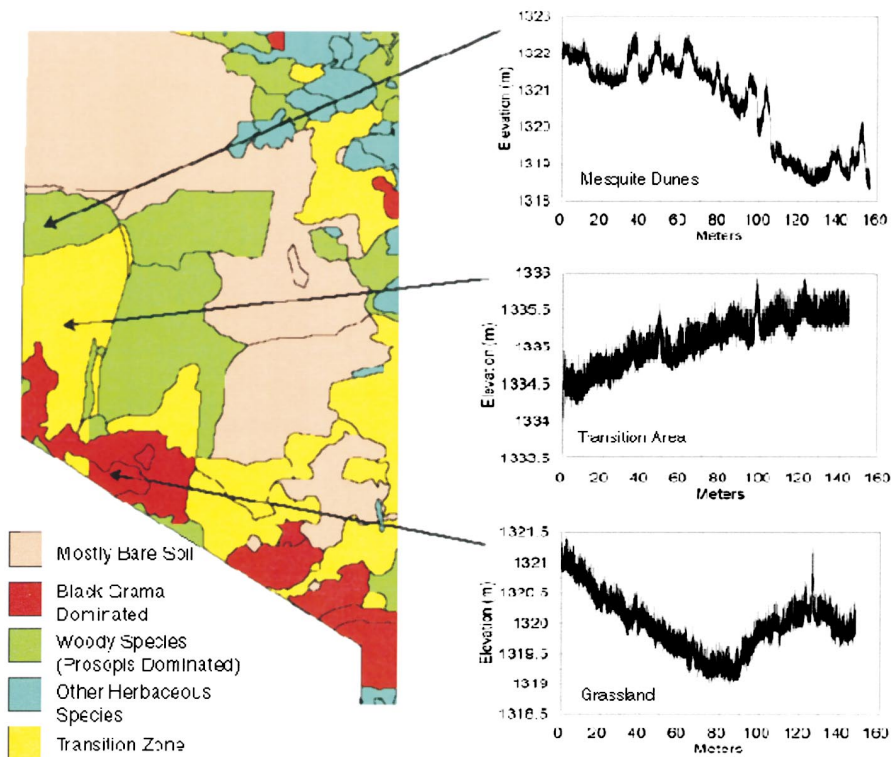
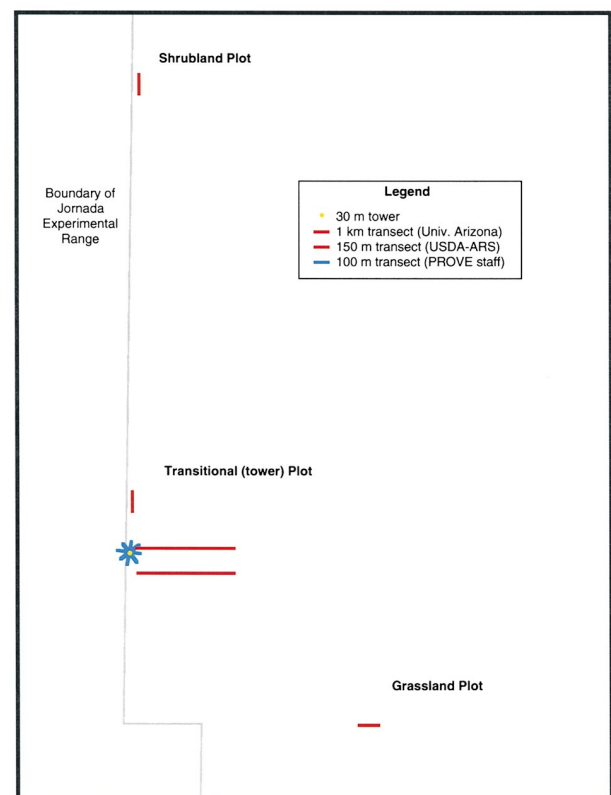


Figure 4. A land-cover map and associated laser altimeter data (Rango et al., 2000) for the shrubland (top), transitional (middle), and grassland (bottom) measurement plots. The x and y scales vary greatly. Note the sand dunes in the shrubland area appear as relatively broad cycles of several meters width in the altimeter data, but are not present at the other sites.

component aggregations. Jornada also has an on-site mechanical shop, laboratory, and an airport within 40 km. Second, the area is relatively flat, allowing researchers to evaluate techniques and products without effects from topography. Third, the clear skies of the desert southwest allow abundant remote sensing data to be acquired in relatively short periods. Fourth, the USDA-owned area has had a rich history of remote sensing and ecological research since 1912. It also serves as a member of the USDA UVB radiation monitoring network (for URL, please see Appendix I), and is one of the 24 initial EOS Land Validation Core Sites (Privette et al., 1999). Thus, there is on-site expertise, and PROVE data could complement ongoing investigations.

Although Jornada was largely covered with grasses prior to livestock grazing, encroaching shrubland has been replacing the grassland in a north-to-south progression since the early 1900s (Humphrey, 1958; Schlesinger et al., 1990). Currently, there are about 8,000 ha of grassland [primarily Black grama (*Bouteloua eriopoda*), Mesa dropseed (*Sporobolus flexuosus*), and Red threeawn (*Aristida purpurea*) interspersed with yucca (*Yucca elata*)], 12,000 ha of transitional land, and 35,000 ha of shrubland. In the shrublands, approximately 70% is dominated by mesquite (*Prosopis glandulosa*), 20% is dominated by creosote bush (*Larrea tridentata*), and 10% is dominated by tarbush (*Flourensia cernua*). The soil consists of well-drained sand. The mesquite-dominated area, the most desertified part of the range, contains areas of sand dunes topped by mesquite

Figure 5. A schematic representation of the size, location, and orientation of transects used during PROVE.



with virtually bare interdunal surfaces (see Fig. 4 and URL in Appendix I).

Site Stratification and Sampling Strategy

The timing and location of measurements for PROVE were largely determined by prior Jornada activities. Since 1995, USDA-ARS has been conducting the Jornada Experiment (JORNEX), a periodic remote sensing assessment designed to evaluate rangeland conditions, climate changes, and scaling effects (Havstad et al., 2000). JORNEX campaigns are conducted twice annually in the periods of minimum (May) and maximum (September) green vegetation. Researchers have concentrated their measurements on plots located in each of the three land-cover variants (grassland, transitional land, and shrubland). Thus, PROVE was also conducted in May at the JORNEX plots. The transitional land-cover plot, hosting the fixed tower, and the grassland plot were given greatest emphasis.

The close proximity of the distinct land-cover variants, each complex and discontinuous, forced PROVE researchers to confront various parameter scaling issues. Three basic ground sampling strategies were employed, including measurements at fixed intervals along transects, measurements at individual shrubs, and randomly located measurements. The transect characteristics varied with location and measurement (see Fig. 5). At the transitional plot, participants outlined eight transects, with each beginning 21 m from the tower and extending 100 m in the cardinal directions, and their diagonals, and were flagged at 5-m intervals. In the same area, two 1-km transects were marked at 10-m intervals in the east–west direction. The lengths and locations of these were based on investigator judgment and in consultation with site personnel.

USDA maintained a 150-m transect, marked at 1-m intervals, extending north–south and beginning about 200 m to the north of the tower. At the grassland site, USDA maintained a second 150-m transect in the east–west direction, and a third (north–south) was maintained at the shrubland site. USDA's shrubland transect was augmented in PROVE by both transect and random sampling of shrub clusters (so-called islands) and bare soils. Transects were then used to estimate shrub cover and larger landscape patterns. Extrapolating transect measurements over larger areas was achieved with satellite data of different resolutions. This technique is likely to be common in EOS validation since ASTER, MISR, and MODIS are on a single platform and in the same orbital track as Landsat-7, which precedes Terra by 30 minutes.

CAMPAIGN EXECUTION

Ground-Based Measurements

More than 40 researchers representing 12 institutions participated in PROVE. The campaign began with cool and moist conditions, including a small rainfall event on day 3

(22 May). Over the 11-day period, conditions became warmer and dryer, reaching maximum temperatures of about 38°C and a relative humidity of about 30% by 30 May (see Fig. 6). Skies were intermittently overcast by thin cirrus clouds. Occasional cumulous clouds were also present. Nevertheless, periods of clear skies allowed investigators to achieve nearly all data collection goals. The most active ground measurement days were 23–26 May.

Three types of data were collected, including: (1) macroscopic parameters of the soil, canopy, and atmosphere, which affect the radiation environment; (2) parameters required to scale point measurements to satellite product resolution; and (3) the radiation environment (e.g., surface irradiance and angular upwelling radiances). The data were collected at various scales, including leaf, land-cover component/endmember (e.g., individual shrubs), plot (e.g., grassland site), and landscape (i.e., Jornada-wide; Privette and Asner, 1999). Key variables measured included:

- canopy-absorbed radiation (or FPAR)
- land-cover component spectra, albedo, and angular reflectance
- landscape roughness (laser altimetry) and bidirectional and hyperspectral reflectance
- surface temperature
- atmospheric spectral/angular transmittance
- shrub and canopy structure
- leaf/stem/plant area index
- leaf/stem angular and spatial distributions
- leaf/stem/litter spectra
- meteorological and atmospheric information

Several other data sets were acquired as part of independent, ongoing investigations. For example, USDA Bowen ratio and UVB stations operated throughout the campaign.

Remote Sensing Measurements

Remote sensing data were collected with sensors on a shoulder-based yoke (Fig. 7), a pivoting monopod (Fig. 8), the truck boom (Fig. 3), and the fixed tower, and instruments held by hand (see Table 2 and Fig. 9).

Three aircraft were used. A Cessna 185 flew along the principal plane of the sun and its perpendicular at several times of day. The plane carried an Exotech 4-band radiometer, mounted to allow off-nadir pointing, as well as a nadir-pointing thermal radiometer. The USDA flew an Aerocommander carrying a one-bounce laser altimeter and a multispectral digital video imager. Finally, the NASA ER-2 aircraft, carrying the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) and a still-frame camera, overflew the Jornada and nearby Sevilleta LTER sites (browse image at URL listed in Appendix I). A Daedalus AADS-1268 Thematic Mapper Simulator (TMS; 4-m and 12-m resolution) was flown over Jornada on 19 June.

Coarser scale remote sensing data were acquired via satellite. The University of Colorado-Boulder collected 137 scenes of day and night NOAA-12 and NOAA-14 AVHRR

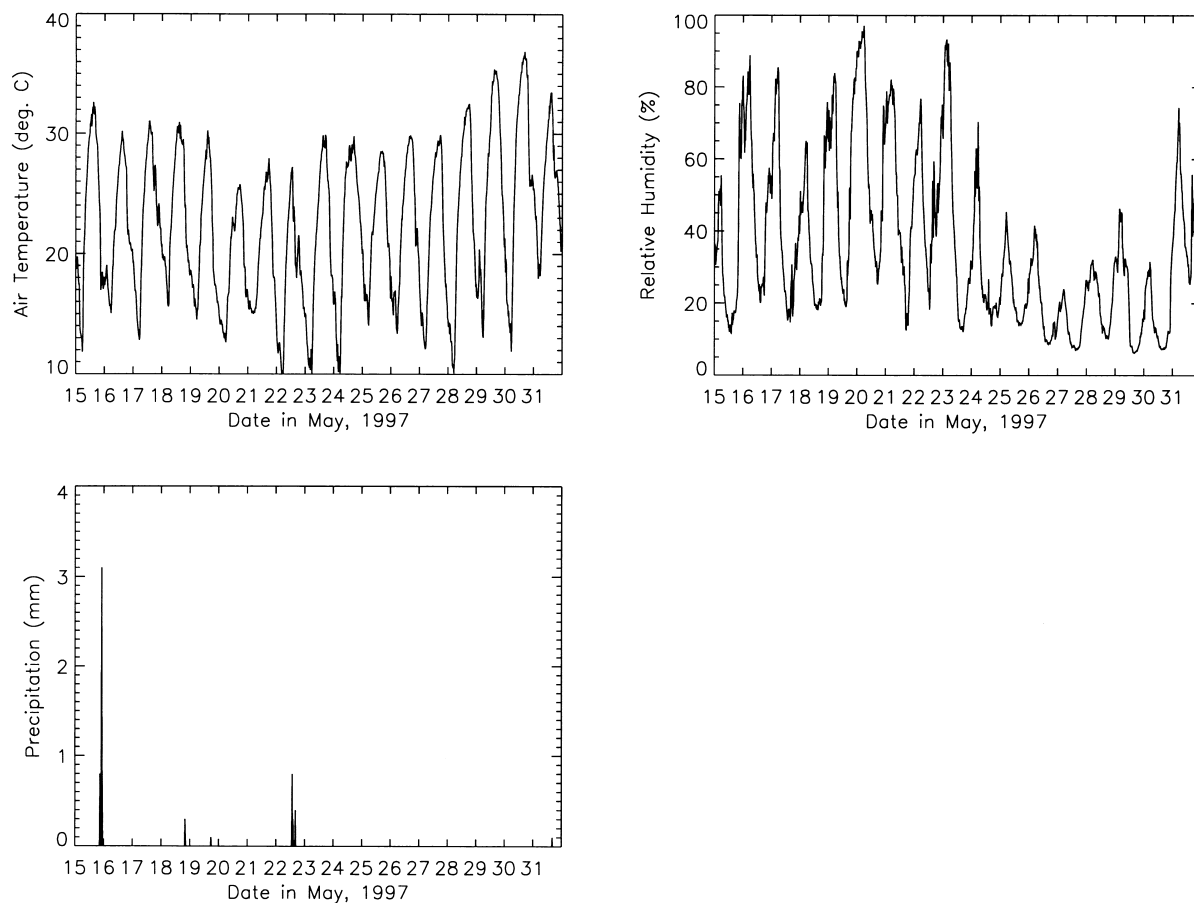


Figure 6. Meteorological conditions at Jornada during PROVE, including (a) air temperature, (b) relative humidity, and (c) precipitation. Note the warming and drying trends through this period.

High-Resolution Picture Transmission (HRPT, 1.1-km resolution) data during the campaign. MODLAND purchased 480 scenes of Geostationary Operational Environmental Satellite (GOES-8) data at 30-minute intervals, which were sent to the ORNL DAAC in near real-time by the commercial provider. Landsat-5 and System pour l'Observation de la Terre (SPOT-2) data were acquired by the Landsat and ASTER teams in conjunction with their simultaneous calibration exercise at White Sands National Monument, approximately 30 km to the east of Jornada. Seven scenes from Polarization and Directionality of Earth's Reflectances (POLDER) were collected and provided by the European Space Agency.

ORGANIZATION AND MANAGEMENT

The lack of a dedicated budget or firm mandate led to a "grassroots" approach to PROVE's planning and operations, requiring (or resulting in) relatively little management. The MODLAND validation group led much of the precampaign coordination. This effort included defining the campaign's scope, reviewing potential field sites, securing agreements, soliciting and coordinating participation

to ensure a coherent measurement suite, procuring and loaning equipment, arranging satellite data acquisition, and disseminating ancillary information. Personnel from Jornada LTER, USDA-ARS, and University of Arizona coordinated the aircraft deployments. Site preparation was largely limited to transect identification.

On-site campaign coordination was primarily conducted via "all-hands" meetings held on evenings prior to days of significant activity. Typically, participants privately organized specific activities, such as coordinated aircraft and ground measurements, and summarized their plans and additional needs (e.g., personnel) at the meetings. The common housing of participants greatly facilitated the meetings, and communication.

DATA MANAGEMENT AND ARCHIVE

On-site meetings were also used to maintain a running record of measurements and metadata (e.g., investigator, instrument, time, place, and problems). The list was useful in planning (e.g., determining data gaps and avoiding excess redundancy) and in facilitating postcampaign data exchange.

Advanced data management and dissemination were



Figure 7. A researcher from the University of Arizona collects multispectral radiometer data over a field transect.

provided by the ORNL DAAC. Specifically, ORNL used PROVE to beta test *Mercury*, a new Web-based metadata search and data retrieval system (see URL in Appendix I). *Mercury* was specifically designed to support the data and information needs of field projects by allowing early exchange of data among investigators, complete control of data visibility by investigators, rapid and economical deployment, and high automation and scalability.

Data exchange via *Mercury* was relatively simple. PROVE participants were encouraged to place their data files on computers accessible by the Internet. To interface with *Mercury*, a metadata file is generated for each data set with the *Metadata Editor* software. Once the metadata files are created and placed in accessible directories, *Mercury* periodically retrieves information from all accessible files and builds an index of World Wide Web links to the associated data files. Data users can then search and find links to the actual data from this single index, located at the central World Wide Web site (ORNL DAAC). By following the links, the data sets can be easily downloaded.

Because the data providers keep the online data files on their home computers, they maintain control over the format, availability, and condition of the data sets.

CONTENTS OF THIS SPECIAL ISSUE

Despite PROVE's goal of validating EOS-like products (e.g., from AVHRR) before Terra's launch, few studies to date directly address that problem. Instead, the initial studies primarily concern the development of new models and algorithms, field measurement techniques, or arid-land research. Below we provide brief overviews of the articles in this issue, beginning with those based on measurements and methods.

Havstad et al. (2000) provide an introduction to the Jornada site, including its history and landscape characteristics, then describe measurement efforts and selected results from JORNEX. Begun in 1995, JORNEX activities concentrated on acquiring remotely sensed data from aircraft and satellite platforms with supporting ground ob-

Figure 8. Researchers from the University of Nebraska measure the multispectral bidirectional reflectance of a shrub. They sampled reflectance at several solar and view zenith angles in the principal and orthogonal planes for most of the landscape endmembers (e.g., sand and grass).

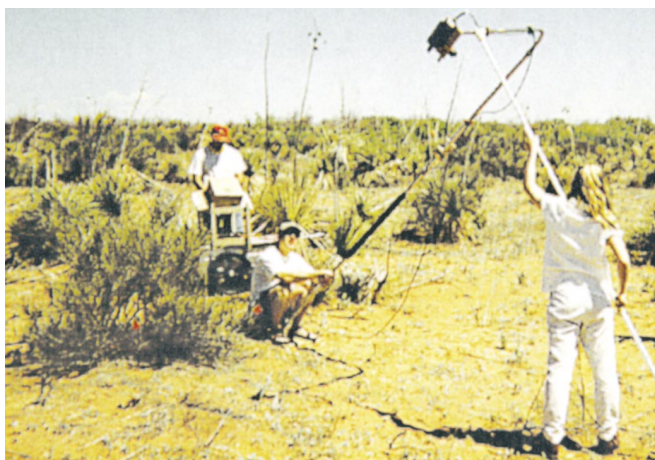


Table 2. Downward-Looking Remote Sensing Instruments Used in PROVE

Sensor	Height (m)	Spatial Resolution (m)	Instantaneous Field-of-view (°)	View Angle Range (°)	Minimum Wavelength ^a (μ m)	Maximum Wavelength ^a (μ)	No. Bands
Exotech	2	0.5	15	0	0.48	0.9	4
SE590	3	0.8	15	± 60	0.4	0.9	100
ASD FR	0.5–1.5	0.1–0.8	18, 25	0	0.35	2.5	215
Cimel	30	0.6	1.2	± 70	0.44	1.0	2
PARABOLA	30	2.6	5	± 70	0.44	11.0	8
Air. Exotech	100	30	15	± 45	0.48	0.9	4
LIDAR	200	0.1	3.4e-2	0	0.9	0.9	1
AVIRIS	2e4	20	5.7e-2	± 15	0.41	2.5	224
Landsat TM	>7e5	30	2.5e-3	± 7.7	0.45	12.5	7
AVHRR	>835	1,100	7.4e-2	± 55	0.58	12.5	5
SPOT HRV	>8e5	20	1.4e-3	± 4	0.55	0.85	4
POLDER	>8e5	7,000	0.93	± 51	0.44	0.91	4
GOES	>3e7	1,000	1.6e-3	fixed	0.52	12.5	5

Note the significant range in spatial resolutions. Upward-looking sensors were also used.

SE590=Spectron Engineering 590 spectrometer; ASD FR=Analytical Spectral Devices Full Range spectrometer; PARABOLA=Portable Apparatus for Rapid Acquisition of Bidirectional Observations of Land and Atmosphere; Air. Exotech=Airborne Exotech radiometer; LIDAR=Airborne LASER altimeter; AVIRIS=Airborne Visible and Infrared Imaging Spectrometer; AVHRR=Advanced Very High Resolution Radiometer; SPOT HRV=System pour l'Observation de la Terre High Resolution Visible; POLDER=Polarization and Directionality of Earth's Reflectances; GOES=Geostationary Operational Environmental Satellite.

^aApproximate Full Width Half Maximum wavelength.

servations. Data sets include long-term observations of climate, vegetation, and soils. During JORNEX field campaigns, the long-term data were supplemented with ground-based measurements of LAI, surface temperature, hyperspectral and multispectral reflectance, and surface energy fluxes. Aircraft data collection included multispectral digital video, multispectral point reflectance measurements, surface temperature, and laser altimetry. Landsat Thematic Mapper data were also acquired. The authors describe how the diverse data sets were used to study evapotranspiration patterns and rangeland conditions, detect and map vegetation change, and examine scaling effects.

Rango et al. (2000) address a critical issue for arid

regions undergoing desertification, namely the encroachment of shrubs and the associated development of sand dunes around these shrubs. The quantification of the size, distribution, and changes of these dunes is critical to the estimation of surface roughness as required for energy balance and hydrological studies. They discuss the application of active scanning laser remote sensing methods, and they show that a coarse scanning laser can be used to measure the morphological characteristics of shrub-coppice dunes with acceptable accuracy and precision for a range of uses. They also show the advantages of “fusing” multispectral optical data with the laser data for increased scientific return.

White et al. (2000) compared various field methods

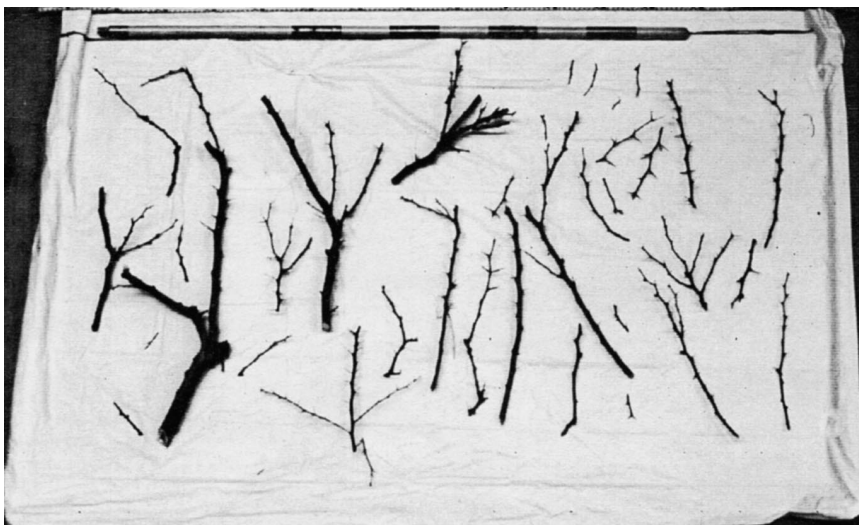


Figure 9. Harvested stems from a prosopis (mesquite) shrub were photographed over a white sheet. The photographs were digitized and processed to determine the stem area index of the sacrificial shrubs. The cutting and denuding of the branches, photography, and area measurements of the small leaves were tedious and time-consuming.

used to estimate structural characteristics of vegetation, including plant area index, LAI, fractional cover, and green fractional cover. They used data collected with a two-band digital camera, Plant Canopy Analyzer (LICOR, Inc.), cep-tometer, and airborne laser altimeter. Various sampling strategies were compared. They conclude that the digital camera is an efficient, accurate, and economical choice to measure desert structure for long-term or large-scale cam-paigns.

Barnsley et al. (2000) compared measurements of albedo with fractions of land-cover components (soil, dry grass, woody/dead material, and green vegetation) as derived from hemispherical photographs at the transitional and grassland plots. By fitting a linear model to the frac-tional component estimates and corresponding albedo val-ues, they were able to estimate the pure component albe-dos. Despite detecting some systematic errors, they found that bare soil has the greatest impact and woody material has the least impact on the mixture albedo. They also found soil moisture and solar zenith angle effects can be strong, but can be corrected with relatively simple empirical for-mulations. They conclude that spatial scaling and charac-terization strategies will be important in validating satellite albedo estimates, given the fairly limited effective views of albedometers mounted just above the canopy.

The vegetation reflectance modeling community showed particular interest in PROVE, in part since PROVE scientists measured nearly all of the land and atmospheric parameters required to validate many of their physically based models [see Privette et al. (1998) for a list]. This popularity may indicate that relatively few complete data sets (simultaneous, colocated land and atmosphere mea-surements in the spectral, and angular and spatial domains) are currently available in the literature.

Asner et al. (2000) used field spectrometry and a can-opy photon transport model to study the relative effects of green foliage, wood, standing litter, and bare soil on canopy and landscape reflectance. They found that foliar properties remained relatively stable among rather signifi-cant land-cover gradients, supporting the hypothesis that resource variation (water and nutrients) is more strongly resolved at canopy level rather than leaf level. Further, the relative impact of tissue, canopy, and landscape factors on pixel-level reflectance changed with plant composition and phenology.

Asner and Lobell (2000) integrated the Jornada in situ spectra into a very large spectral library for arid and semiarid species, then developed a Monte Carlo approach to estimating the aerial fractions of spectral endmembers in mixed hyperspectral pixels. Their linear systems were created by (1) randomly choosing woody and herbaceous species from an extensive database, (2) multiplying the species' spectral reflectances by variables representing the species' aerial fractions, then (3) equating the sum to spec-tra measured by hyperspectral aircraft sensors flying over heterogeneous areas. This process was repeated many

times. They found that the mean of the distribution of retrieved aerial fractions provides a good estimate of the true aerial fractions. They note that this automatic tech-nique for estimating woody and herbaceous fractional cov-ers may significantly improve the accuracy of ecological model simulations of arid areas.

Lucht et al. (2000) inverted kernel-driven BRDF mod-els with data from AVHRR and POLDER to estimate spectral albedo, then integrate spectrally to estimate broad-band albedo. They found that these coarse-scale albedo estimates match well with estimates derived by combining field data with a land-cover classification from aircraft im-agery. They also concluded that albedo in the vicinity of the Jornada tower compares well to coarse-area albedo since the spatial heterogeneity of the two zones is similar.

Ni and Li (2000) coupled a variant of the geometric optical and radiative transfer (GORT) model for discontin-uous canopies with the Jacquemoud et al. (1992) SOIL-SPEC model to produce a new bidirectional reflectance model for semiarid landscapes. This new one-dimensional model compares favorably to POLDER and AVHRR data, and may be useful for inversion studies.

Shabanov et al. (2000) took a more rigorous approach to one-dimensional, bidirectional reflectance modeling by solving a stochastic radiative transfer problem for discon-tinuous canopies by using successive orders of scattering method. A new formula for canopy absorptance is obtained, and the general model is validated with one- and three-dimensional radiative transfer models, as well as Jornada shrubland data.

Qin and Gerstl (2000) developed an L-systems method of modeling discontinuous structural scenes that is amena-ble to radiosity theory and computer graphics techniques. Model results compared very favorably to measured data from ground, tower, and satellite-based sensors in PROVE. They also used the new model to estimate the validity of a linear mixture model for the Jornada landscape and found that the linear model's accuracy increases as pixel size in-creases.

Chopping (2000) developed an AVHRR 1-km pro-cessing chain, including calibration and atmospheric cor-rection components, and inverted several linear kernel-driven bidirectional reflectance models over a $5^\circ \times 5^\circ$ area centered on Jornada. He analyzed the robustness of the inversions given sparse angular sampling (as will be avail-able from MODIS). He determined that the models are effective for describing reflectance anisotropy from arid landscapes and for extracting limited structural infor-mation.

LESSONS LEARNED

Great insight into EOS validation was gained through PROVE. Below, we focus on aircraft options, then discuss the limitations of a small, *ad hoc* campaign relative to a major NASA campaign program (e.g., First ISLSCP Field

Experiment; FIFE, Sellers et al., 1988). Finally, we summarize PROVE's lessons in the context of a global field validation program for EOS.

Aircraft Issues

The staging of the ER-2 from its home base at NASA Ames Research Center (San Francisco, CA) required that we predict afternoon cloudiness about 7 hours before the overflight (decision at 0600 for an overpass at 1300 local time). Because of PROVE's relatively short duration (11 days), we were tempted to approve the ER-2 flight as soon as a cloudiness forecast was reasonably favorable. Although the AVIRIS imagery acquired in PROVE was acceptable, ground observers noted some thin cirrus had developed just before the overpass. In contrast, the light Cessna aircraft was deployed from the Las Cruces Airport, approximately 40 km away. On some days, its flight schedule was quickly adjusted to exploit brief periods of clear skies. Moreover, its occupants maintained in-flight communication with ground researchers. These advantages prompted MODLAND to develop a light aircraft instrument package for future campaigns (Huete et al., 1999).

Limitations of an *Ad Hoc* Field Campaign

Although PROVE took advantage of experience from FIFE and the Boreal Ecosystem-Atmosphere Study (BOREAS; Hall et al., 1993), two differences became apparent. First, FIFE and BOREAS had relatively broad goals related to ecosystem functioning and process modeling. In contrast, the goal of Terra validation was to assess remote sensing products and in some cases their algorithms. Thus, PROVE had a briefer and more focused field period. Its organizers recruited community experts when measurement gaps were identified. These voluntary participants were important to PROVE's success; however, their availability throughout a multiyear validation program is not likely without outside funding and obvious benefit from the collaboration. Thus, a larger burden may need to be borne by campaign organizers.

Second, PROVE was essentially a federated activity of independently funded investigators. This seems to be an evolving trend (e.g., Swap et al., 1998; Havstad et al., 2000). However, such *ad hoc* campaigns lack targeted funding as would be available if they were orchestrated at an agency level (e.g., through a National Research Announcement). Hence, there may be little central organization, few support personnel (i.e., the nonresearcher "staffs" of major campaigns), and no shared/negotiated savings as is possible when large groups pool their efforts.

Challenge of Fast Data Turnaround

It appears the greatest challenge for the EOS Validation Program is to convince scientists to reduce, analyze, and openly release their field data in sufficiently short periods to allow timely improvements to Terra's operational products. The Program acknowledges this basic need by requiring

its investigators to release their data within 6 months of data collection.

In the PROVE experience, however, a 6-month deadline was difficult to meet. Specifically, once investigators were identified and campaign responsibilities were clear, field teams conducted measurements with little support. Following the campaign, PROVE investigators began exchanging data sets relatively quickly, allowing informal processing "pipelines" to develop in which successive investigators provided value-added processing (e.g., atmospheric correction, georegistration, and statistical characterizations), then passed the data on to other investigators. These processing pipelines distributed the burden among multiple participants and were relatively efficient. In recognizing the value of these, Olson et al. (1999) cautioned that participants must document their methods and archive the data for broader application.

However, in practice, most investigators were reluctant to quickly release processed data and its documentation to the general public (e.g., via *Mercury* or ORNL DAAC). In fairness, there may be relatively little incentive to do so. Three concerns are commonly raised: time, costs, and data "rights." As noted above, a dedicated staff was available in other field efforts (e.g., FIFE and BOREAS) to track investigators' progress and assist with data reduction and documentation. The absence of this staff in PROVE put the burden of these tasks on the participants. Without direct funding for PROVE, the missed deadlines were predictable.

Second, quick data release prompts questions of fair use in a competitive research environment, especially when proposals are not funded solely for data collection and release. Still, there is an equally valid question of "fair collection and release," especially when the labors of EOS instrument teams—the Terra products—are released essentially in real-time. Validation programs must confront these controversial issues given the expectedly large group of Terra data users. We encourage funding agencies, program managers, and journal editors (and in some cases, their sponsoring societies) to consider modifications to the research environment that will result in wide validation participation and faster data release. The goal—more accurate EOS products—merits the review.

ORNL DAAC's *Mercury* system should help facilitate the desired data exchange. If PROVE is typical, however, building the community's familiarity with, confidence in, and dutiful use of *Mercury* will take time. Two years after PROVE, some data sets were still not in *Mercury* or the DAAC. Thus, as a start, an on-line inventory of the unreleased data sets that have been collected for EOS validation and their expected release date would be a key step forward.

Site and Project Resources

PROVE also underscored the necessity of adequate facilities at a campaign site. Several experiments were salvaged

or expanded using apparatus repaired or fabricated by Jornada personnel. Their expertise and common interests can accelerate everything from instrument repairs to data and land access. A reasonable alternative is to maintain a mobile laboratory and shop. For example, the MISR team brought two well-equipped vans and was able to repair almost any equipment malfunction in the field. This experience helped support the EOS decision to build a validation program around existing research sites and networks (e.g., LTER and FLUXNET; Running et al., 1999; Privette et al., 1999).

Finally, though it was a contained effort, PROVE largely consumed MODLAND's validation resources in 1997 and part of those in succeeding years. For both labor and budgetary reasons, coordinating and conducting multiple PROVE-like campaigns over a network of sites will be difficult to achieve by a single project or team. International groups such as the Committee on Earth Observation Satellites (CEOS, see URL in Appendix I) may be needed to provide organizational help if validation programs expand.

CONCLUSIONS

PROVE successfully demonstrated that an effective validation campaign could be organized and conducted in short time period, in this case less than 6 months from conception to the final data collection day. Keys to this success included: (1) focusing only on variables that related to actual EOS products or the scene radiation environment, (2) conducting the campaign at site with significant existing infrastructure and with personnel having experience in remote sensing campaigns, (3) enlisting participation from multiple EOS teams and from community experts, (4) including the ORNL DAAC personnel from the onset so that data archiving and documentation issues were immediately addressed, and (5) maintaining a sufficiently small and commonly housed group of participants (in this case about 40) so that coordination was simplified. PROVE also demonstrated some advantages of a light aircraft deployed locally relative to the NASA ER-2 when deployed far from the campaign site.

However, not all PROVE goals have been achieved. Few of the initial PROVE studies concluded with the validation of EOS-like satellite products (albedo and surface reflectance are notable exceptions). Instead, the field data were mostly used in arid-land research and to validate surface reflectance models. This is largely a consequence of conducting PROVE before Terra's launch; however, we believe significant attention should be given to comparing ground- and satellite-based parameter estimates with statistically significant approaches, including compiling error budgets for both. PROVE also revealed the need for faster turnaround of EOS validation studies, including the early and open release of field-collected data. We suggest a fresh review of the research proposal/funding/publishing environment by funding agencies so that field investigators embrace this philosophy.

Still, PROVE provides an excellent data set for a com-

plex, yet spatially extensive, land cover. These data are available for scaling and remote sensing studies and radiation model validation and are available through *Mercury* or the ORNL DAAC. Interested researchers are encouraged to contact the DAAC or authors of this article.

This campaign benefited greatly from the competent staff at the ARS Jornada Experimental Range, who were called upon numerous times to solve field problems. The MISR team, particularly Mark Helmlinger, also helped many teams with various problems. We sincerely thank them. We also thank Dan Baldwin and Bill Emery (CU/CCAR), who provided the AVHRR data; Marc Leroy (CNES/CESBIO), who provided the POLDER data; the Landsat Science Project Office, which provided the Landsat imagery; and J.P. Anderson, who provided the meteorological data. JLP thanks NASA's Terrestrial Ecology Program (D. Wickland, Manager), Nader Abuhassan, and the AERONET team for their support. Finally, we are indebted to Laura Rocchio, Barbara Nolen, and Kris Havstad for their support and efforts. Barbara also provided the land-cover map in Fig. 2. This project was largely funded by the MODLAND, MISR, and ASTER teams.

APPENDIX I. WORLD WIDE WEB ADDRESSES

The following World Wide Web URL addresses were referred to in this article.

1. EOS Land Validation Core Sites (http://modarch.gsfc.nasa.gov/MODIS/LAND/core_site_details.html)
2. Jornada Long-Term Ecological Research (<http://jornada.nmsu.edu/>)
3. USDA UVB Network (http://uvb.nrel.colostate.edu/UVB/uvb_climate_network.html)
4. AVIRIS Browse Scenes (<http://makalu.jpl.nasa.gov/html/view.html>)
5. ORNL DAAC Mercury System (<http://mercury.ornl.gov/servlet/landval>)
6. Committee on Earth Observing Satellites (CEOS) (<http://www.ceos.org>)

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