David A. Landgrebe: Evolution of Digital Remote Sensing and Landsat

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***Abstract*—David Landgrebe, Professor of Electrical Engineering and Director of the Purdue University Laboratory for Applications of Remote Sensing (LARS), was a primary innovator in the field of digital image analysis and remote sensing of the environment. He and his LARS colleagues, along with a selected few other researchers at institutions including the University of Michigan, University of California Berkley, NASA Goddard Space Flight Center, and NASA Johnson Space Center, defined and developed remote sensing technology to monitor the Earth's terrestrial environment. This research led to the Landsat program, which has continued to monitor the Earth's land areas for a half century. These technologies have defined new fields of scientific query in digital image analysis, biophysical remote sensing, as well as remote sensing science and applications. Dr. Landgrebe's contributions to these research areas were substantial and profound. Understanding the early evolution of work is critical to understanding how this technology is still advancing today. The authors hope that current and future students of these fields will benefit from understanding how this all began.**

***Index Terms*—Agricultural remote sensing, clustering, digital image display, digital image processing, digital remote sensing, Earth system science, feature selection, field studies, multispectral sensor, multitemporal data, pattern recognition, radiative transfer (RT) model, remote sensing science, spectral vegetation indices (SVI).**

NOMENCLATURE

ABI	NOAA GOES Advanced Baseline Imager.
AgRISTARS	Agriculture and Resources Inventory Through Aerospace Remote Sensing.
APAR	Absorbed photosynthetically active radiation.
ARS	USDA Agricultural Research Service.
ASTER	Advanced Spaceborne Thermal Emissions and Reflection Radiometer.
AVHRR	NOAA Advanced Very High Resolution Radiometer.
CBWE	Corn Blight Watch Experiment.
CIR	Color infrared.
CITARS	Crop Identification Technology Assessment for Remote Sensing.
CPU	Central processor unit.
DOI	Department of Interior.
ECHO	Extraction and Classification of Homogeneous Objects.
EM	Electromagnetic.
EOS	NASA Earth Observing System.
EREP	Skylab Earth Resources Experimental Package.
ERIM	Environmental Research Institute of Michigan follow-on to WRL.
EROS	DOI–USGS Earth Resources Observations and Science Center.
ERTS	Earth Resources Technology Satellite.
FAS	USDA Foreign Agricultural Service.
FSS	NASA JSC helicopter-mounted Field Spectrometer System.
GOES	NOAA Geostationary Operational Environmental Satellites.
GSFC	NASA Goddard Space Flight Center.
HIRIS	High Resolution Imaging Spectrometer.
ISLSCP	International Satellite Land Surface Climatology Project.
JSC	NASA Johnson Space Center.
LACIE	Large Area Crop Inventory Experiment.
LAI	Leaf area index.
LARS	Purdue University Laboratory for Agricultural Remote Sensing and Laboratory for Applications of Remote Sensing.
LIDQA	NASA Landsat 4 Data Quality Assessment Team.
MMR	LARS Modular Multiband Radiometer field sensor.

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MODIS	NASA Moderate Resolution Imaging Spectrometer.
MPRIA	Mathematical Pattern Recognition and Image Analysis Project.
MSS	Multispectral scanner.
MTPE	Mission to Planet Earth.
NASA	National Aeronautics and Space Administration.
NASS	National Agricultural Statistics Service.
NDVI	Normalized difference vegetation index.
NIR	Near infrared.
NOAA	National Oceanic and Atmospheric Administration.
NRC	National Research Council.
NSLRSDA	DOI USGS National Satellite Land Remote Sensing Data Archive.
OLI	Landsat 8 & 9 Operational Land Imager.
OMB	U.S. Office of Management and Budget.
PC	Personal computers.
PLDS	Pilot Land Data System.
PVI	Perpendicular vegetation index.
RBV	ERTS return beam vidicon camera system.
RT	Radiative transfer model.
S192	Skylab EREP 13 band circular multispectral scanner.
SBRC	Hughes Aircraft Co. Santa Barbara Research Center.
SCLB	Southern corn leaf blight.
SRAEC	Scene Radiation and Atmospheric Characterization.
SVI	Spectral vegetation indices.
SWIR	Shortwave infrared.
TIR	Thermal infrared.
TM	Landsat Thematic Mapper.
TWG	Landsat D technical working group.
USDA	United States Department of Agriculture.
USFS	USDA U.S. Forest Service.
USGS	DOI U.S. Geological Survey.
UV	Ultraviolet.
VIS	Visible.
VNIR	Visible and near infrared.
WRL	University of Michigan Willow Run Laboratories.

I. Prologue

THIS narrative was compiled, at the request of the Landgrebe special issue editors, to discuss Dr. David Landgrebe's contributions to multispectral digital image analysis and the definition, development, and advancement of the NASA/USGS Landsat Program. The authors were strongly influenced by Dave's work in their studies and work at Purdue University, Pennsylvania State University, Indiana State University, University of Maryland, NASA Goddard Institute for Space Studies, NASA Goddard Space Flight Center (GSFC), and NASA Johnson Space Center (JSC).

For more than 50 years, Dr. Landgrebe held many positions of responsibility as well as being a friend and colleague of the authors. Throughout the text, Dr. Landgrebe is referred to in many ways including Dr. Landgrebe, Professor, Director, Dean, David, and finally, Dave, to reflect the many ways that these authors related to Dr. Landgrebe. Hopefully, readers will understand the personal and historical significance of these relations in defining the tone of this narrative.

II. Introduction

Burgeoning scientific research opportunities in the post-World War Two era confronted David Landgrebe as he pursued his electrical engineering studies at Purdue University. He completed his Ph.D. degree at Purdue in 1962 and then spent 3 years on the west coast with the aerospace industry exploring the use of neural networks in medical research [1].

In 1965, he returned to Purdue as a faculty member of the School of Electrical Engineering to focus on teaching and researching signal theory and representation. He attended a seminar by Ralph Shay, then Head of Purdue's Department of Botany and Plant Pathology, who was in the process of developing an interdisciplinary research group to refine agricultural information through the combined use of engineering methods and aerospace technologies.

Dr. Landgrebe and his colleagues, K-S. Fu and R. A. Holmes, were intrigued with the idea of applying pattern recognition techniques to interpret the newly evolving multispectral remote sensing data. As a result of the Shay seminar, he joined the Laboratory for Agricultural Remote Sensing (LARS) research team. Thus, began a professional career that led to the exploitation of rapidly evolving digital computers for image processing and analysis, and ultimately the deployment of satellite-based multispectral imaging systems to monitor and manage the natural resources of the Earth.

This narrative attempts to summarize Dr. Landgrebe's professional career, primarily while he served as a director of LARS from 1969 to 1981. Both his individual and collaborative work laid the groundwork for the rapid evolution of digital multispectral remote sensing. This was not always a straightforward path, given its relation to major federal government science programs. However, his calm demeanor and sound understanding of engineering, multispectral remote sensing, and pattern recognition, permitted him to take in stride the dynamics of these programs while making major contributions to multispectral and hyperspectral analysis methods as well as the design of Landsat systems.

III. Laboratory for Agricultural Remote Sensing Development

A. National Research Council, Committee on Remote Sensing for Agricultural Purposes

In the early 1960s, the National Academy of Sciences, National Research Council (NRC) formed a Committee on Remote Sensing for Agricultural Purposes, chaired by Dr. Ralph Shay. This committee was charged with investigating techniques to assess insect infestations and diseases in crops and forests across the USA. One of the primary people on the committee was

Dr. Robert Colwell of the Forestry Department, University of California, Berkeley, CA, USA. At that time, remote sensing primarily involved aerial photography. Largely because of Bob Colwell's knowledge of aerial photography and in particular, color infrared (CIR) aerial photography, the committee decided that remote sensing would be the best way to assess agricultural and forest conditions over such extensive areas [2].

Another key person on this committee was Dr. Marvin Holter, from the Willow Run Laboratories (WRL) [later to become the Environmental Research Institute of Michigan (ERIM)] in the Institute of Science and Technology, University of Michigan. Dr. Holter was involved in a research project called Project Michigan. It was a classified military project that included the development of an instrument called an "optical-mechanical scanner" that would obtain imagery of the ground in different wavelength bands of the electromagnetic (EM) spectrum. Ralph Shay suggested that the Agronomy Farm at Purdue would have many species of crops, with detailed "ground truth" information available. On June 2, 1964, the WRL scanner was flown for the first time over a target that was not of military interest—the Purdue Agronomy Farm. Five flights were flown over the Agronomy Farm that summer.

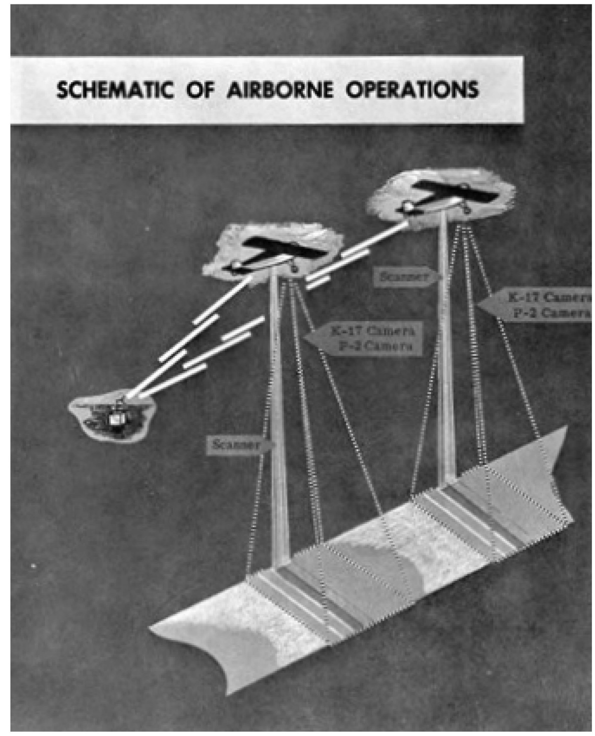

Fig. 1. Flight configuration of the two-aircraft (L-20) each containing a prototype WRL multispectral scanner system. Each pilot used the same visual ground object to maintain the same flight path. Combining the various imaging systems made coregistering of the data problematic [4].

B. Willow Run Laboratories Multispectral Scanner System

In the mid-1960s, the U.S. Military contracted with WRL to advance scanning imaging systems that were originally developed to image the thermal infrared (TIR) portion of the EM spectrum. A prototype WRL multispectral scanner (MSS) system was flown at the Purdue Agronomy Farm in 1964. Two L-20 aircraft were flown in tandem, each containing a double-ended scanner (Fig. 1). One scanner acquired ultraviolet (UV) (0.32–0.38 μm) and TIR (8.2 –14.0 μm) image data. The second scanner acquired four shortwave infrared (SWIR) (1.5–1.7, 2.0–2.6, and 3.0–4.1 μm) images and a second TIR (4.5–5.5 μm) image. Visible and near infrared spectral (VNIR) observations were collected by a nine-lens camera system. In addition, two filtered panchromatic aerial cameras, as well as color and CIR film cameras were included for a total of seventeen varying spectral measurements [3]–[5].

Visual analysis of such a complex mix of spectral images was no simple task. Ignoring the aerial photographs, the 15 spectral dimensions of the imagery, taken three at a time—the dimensionality of most human eyes—produces 2730 permutations to examine for every scene imaged! Not an easy task to undertake.

In 1965, WRL introduced the M5 version of the MSS, which was flown on a DC-3 aircraft rather than the two L-20 airplanes, reducing image acquisition complexity (Fig. 2). In addition, the nine-lens camera was replaced by the 12-band visible-near infrared spectrometer placed in one of the four scanner positions [6] (Fig. 3). This marginally reduced analysis difficulty, but still left a substantial task of coregistering the observations acquired from four optical paths [7], [8].

LARS staff worked with WRL staff to update the MSS to the M7 version, which became available in June 1971 [9] (Fig. 4). The primary advance in this system was that all multispectral observations (up to 19 bands observed and 12 recorded) used the same optical pathway. This supplied coregistered multispectral observations ranging from UV to TIR portions of the EM spectrum, making computer processing much simpler and more accurate.

Fig. 2. WRL DC-3 flew both the M5 and M7 scanners.

The WRL multispectral image data were recorded on analog computer tape for later conversion either to photographic pictures or processing on the WRL analog computers. At LARS, the analog tapes were digitized for analysis using the LARS digital computer software. This also solved another problem: the WRL MSS, developed with U.S. Army funding, made the analog tapes, and any images produced from these analog tapes, subject to

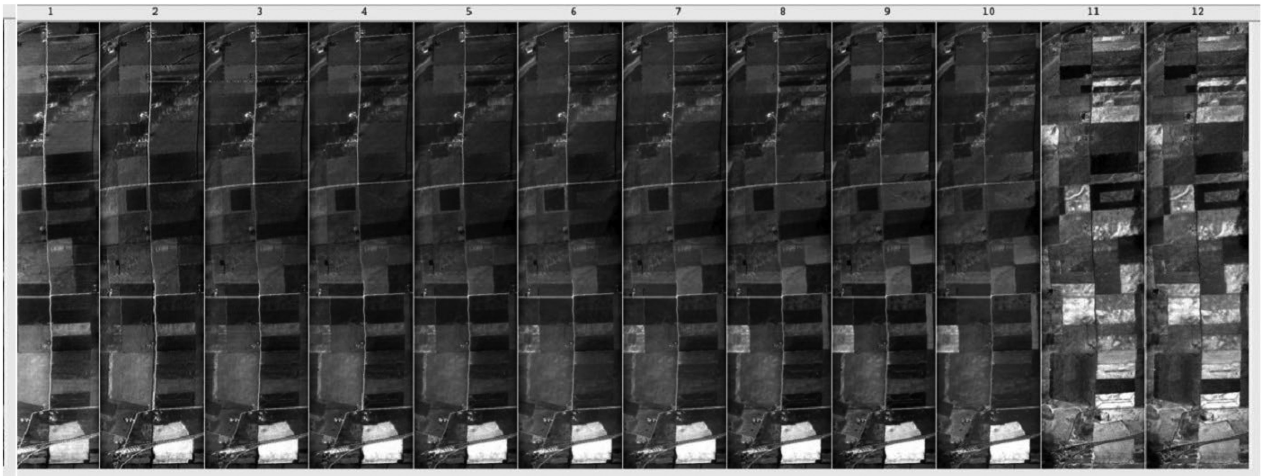

Fig. 3. Example of the M5–M7 12-band spectrometer imagery from flightline C1 acquired for LARS Purdue in June 1966. These data were also the source of the famous "donut hole" analysis shown in Fig. 9. Table I provides the spectral coverage of the bands (L. Biehl, LARS).

TABLE I
M5–M7 12-Band VNIR Spectral Coverage

Band #	Wavelength, µm
1	0.40 - 0.44
2	0.44 - 0.46
3	0.46 - 0.48
4	0.48 - 0.50
5	0.50 - 0.52
6	0.52 - 0.55
7	0.55 - 0.58
8	0.58 - 0.62
9	0.62 - 0.66
10	0.66 - 0.72
11	0.72 - 0.80
12	0.80 - 1.00

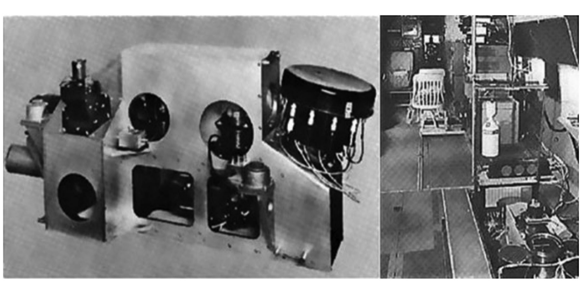

Fig. 4. M7 multispectral scanner (left) with its inspection plates removed and as mounted in the DC-3 fuselage (right). The circular sensor package at the rear of the scanner is the 12-band VNIR spectrometer. M7 installed in the DC-3 took up most of the cabin space (right). Note the "sophisticated" seating! The M7 was a key inspiration for the multispectral scanner instrument flown on early Landsat satellites [9].

security clearance (classified as "confidential"). However, once digitized, these data were no longer subjected to that constraint, and therefore became widely available to LARS-affiliated researchers [10].

C. Founding LARS

In September 1964, Ralph Shay hired Dr. Roger Hoffer to interpret the scanner and photographic imagery from the Purdue Agronomy Farm in the summer of 1964. Roger's task was to visually evaluate whether this imagery could be used to assess damaged or diseased wheat. It soon was evident that the identification of damaged wheat required wheat to be distinguished from other crops, such as corn or soybeans, based solely on reflectance differences in the various spectral bands [3]. Initial results suggested there was a potential to differentiate some crop types, at certain times of the growing season. However, it was also evident that a better, more quantitative data analysis method was needed.

About this time, Roger and Ralph learned that the Electrical Engineering Faculty was working on something called "pattern recognition." A meeting with Roger Holmes, an Electrical Engineering Professor, led to the formation of an interdisciplinary team to apply digital computer pattern recognition techniques to MSS data. Team members submitted proposals to NASA and the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) to develop this research. Both proposals were funded leading to the establishment of LARS in February 1966 [11].

Dr. David Landgrebe, Dr. King-Sun Fu, Dr. Phillip Swain, and Terry Phillips, all from the Department of Electrical Engineering, formed the core of the LARS data processing and analysis team. Robert MacDonald came from IBM to become the LARS Technical Director, and Dr. Marion Baumgardner, Dr. Chris Johannsen, and (later) Dr. Marvin Bauer, all from the Agronomy Department, supplied expertise in that area.

IV. LARS Facilities and Research Foci

From the beginning, LARS was a highly interdisciplinary team. By working together in a single laboratory facility, faculty, professional staff, and graduate students from quite different disciplines were able to learn from each other and contribute

Fig. 5. Because of its interdisciplinary nature, no common space could be found on the Purdue University campus for LARS. However, the newly constructed FlexLab space in the Purdue Research Park, north of campus, was ideally suited for housing LARS. LARS fully occupied FlexLab I and soon nearly filled FlexLab II. Following reduced postagricultural NASA funding, LARS moved on to campus in 1985 (Section IX-A) (L. Biehl, LARS).

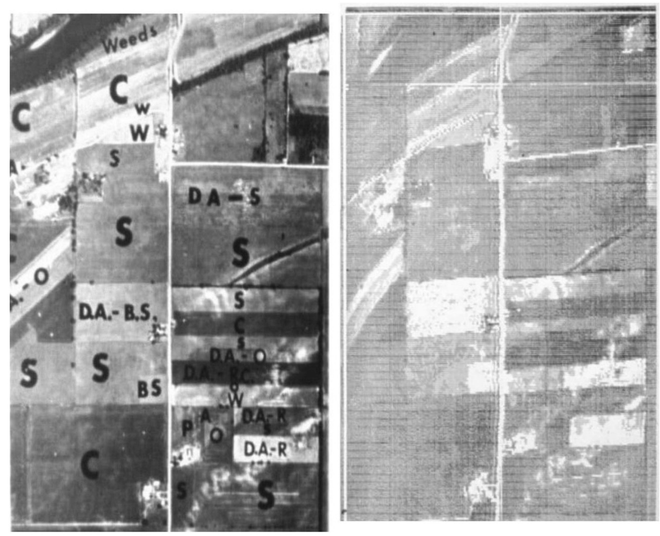

Fig. 6. Aerial photograph (left) compared to a computer line printer map of the red spectral band (right). Letters on the photo indicate different crop species (W–wheat, O–oats, S–soybeans, C–corn, BS–bare soil, H–hay, P–pasture, and DA–diverted acres) (R. Hoffer, S. Goward).

to the common goals (Fig. 5). In 1969, LARS was renamed the "Laboratory for *Application*s of Remote Sensing" to better reflect the broadened research activities of the group for forestry, geology, hydrology, and geography applications, as well as crops and soils.

A. LARS Computing

To implement the pattern recognition technology, in November 1966, LARS obtained an IBM 360 Model 44 mainframe digital computer [12], [13]. This was only the second machine of this model to be installed anywhere in the country. The main central processing unit) was huge, standing about head-high, and was about 10-feet long and 4-feet wide. Data were loaded into it via large seven-track tapes or computer punch cards. It had no monitor or display capability. Therefore, to display the data, a line printer and different alphanumeric symbols were used to represent various levels of reflectance in a particular wavelength band, thus providing a rough gray-scale map of the area. For example, the letter M or W might be used to represent a low reflecting pixel, while –, /, or blank would be used to display high reflecting pixels. From several feet, a person would not see the individual symbols, but only a crude gray-tone map of the area (Fig. 6).

Once this pattern recognition approach was implemented on the digital computer, individual pixel vectors could be interpreted, addressing many of the problems encountered in visually interpreting multispectral imagery [13]. The use of digital technology for analyzing multispectral images was rapidly adopted, particularly after the launch of Earth Resources Technology Satellite (ERTS-1) (Section VI-C).

In 1970, an IBM 360/67 replaced the older LARS computer; this offered timeshare capabilities that permitted the deployment of remote computer terminals of LARSYS (Section IV-B) for sites throughout the USA and internationally (Fig. 7) [11]. To address the image display limitation, in 1971, IBM developed the first-ever computer image display device, with NASA and IBM support, and deployed it on the LARS 360/67 (Fig. 8).

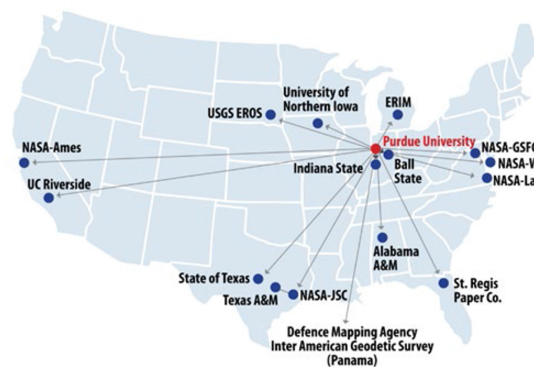

Fig. 7. Remote LARS terminal sites in the USA. Locations as far away as Australia used dial-up capabilities to access LARSYS [11] (L. Rocchio, modified from D. Landgrebe, Purdue University).

B. LARSYS: The LARS Multispectral Analysis System

Led by Dr. Landgrebe, LARS was at the forefront of defining and implementing the processing, classification, and analysis of digital multispectral data. A major goal of the new lab was to develop and apply statistical design theory (pattern recognition) from the signal processing field with emphasis on numerical orientation rather than the pictorial orientation of visual photographic interpretation.

By early 1967, only a year after the organization of LARS, the lab produced a digital classification of crop types in an agricultural area from multispectral image data acquired on June 28, 1966 by the University of Michigan. It included the "donut" field (Fig. 9) that the "ground truth" said was wheat, but in reality, were two fields of wheat and oats that had been

Fig. 8. Purdue University's LARSYS computer system, circa 1971 (left). The world's first digital image display, developed by IBM for LARS, can be seen in the center-left. Using an electronic interface pen, analyst Kay Hunt uses interactive pen technology to locate training pixels on the digital display (right) (L. Biehl, LARS).

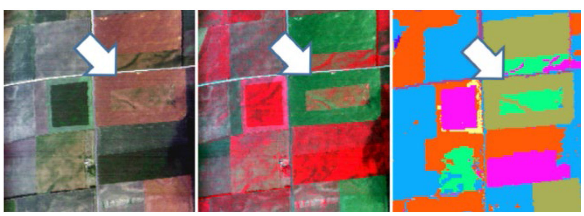

Fig. 9. True color (left), false color (center), and crop classification (right) images of fields in Indiana were created from digital M5 multispectral data, collected in June 1966. The white arrow shows a field planted with wheat on its periphery and oats in the center, the LARSYS software was able to differentiate the two crops, wheat (grey-green), and oats (light green)—the famous "donut" field—as well as three other crops soybeans (blue), corn (red), and clover (magenta) (D. Landgrebe and L. Biehl, Purdue LARS).

correctly classified from the training statistics for wheat and oats [14]. The overall accuracy for the classification of five crop types was 87.5% with average class accuracy of 88.3%. This analysis convinced the Shay NRC committee that flying such a MSS in space made sense for monitoring the Earth's agricultural resources. In addition, scanner data of a 70-mile long flightline were also classified, further showing the potential and effectiveness of this approach for image classification of larger geographic areas [14].

Implicit in Dr. Landgrebe's approach to digital image analysis was the use of methodologies. He recognized early that algorithms were only successful when embedded in an analytical schema which optimizes human involvement and combines relevant techniques. Most notable of these was the hybrid supervised–unsupervised classification approach developed at LARS which showed how effectively and accurately maximum likelihood classification can be deployed when combined with clustering [15].

Over the next several years, the first capability of image display and classification were expanded to LARSYS, a comprehensive system of 18 functions for multispectral and multitemporal data classification including image registration, image editing (for selection of training and test fields), feature (spectral band) selection, class statistics (means and covariance matrices), maximum likelihood, minimum distance, sample classification, and calculation of classification accuracy and area determination. These functions are described in detail in the Swain and Davis [16] and Landgrebe [17] books. Initially developed for aerial scanner data, it was adapted for Landsat MSS and thematic mapper (TM), and other multispectral data (Section VI).

Its implementation on a mainframe computer with timesharing and remote terminal capabilities enabled access by many users to digital image processing and analysis, with the cost advantages of centralized expensive hardware and software maintenance as well as ease of user training. LARSYS was the forerunner of similar systems developed in government laboratories, university research labs, as well as several commercial companies.

C. Maximum Likelihood Approach

In today's terminology, Dr. Landgrebe was a "Bayesianist." That is not surprising given his early career as a signal processing engineer, in which Bayesian estimation formed the basis for reliable signal detection. It was that experience that led him to promote and use Gaussian maximum likelihood classification as the fundamental machine learning tool for the analysis of digital image data.

It was natural to adopt a Gaussian maximum likelihood approach because individual band histograms of specific classes suggested that behavior [18]. The rest is image analysis history—the maximum likelihood rule became the mainstay method for image analysis for decades to come and, importantly, the key classification tools were in place when ERTS-1 data became available for analysis (Section VI-C).

He remained an adherent of maximum likelihood classification throughout his career, recognizing that the move to hyperspectral image datasets presented a challenge in obtaining reliable covariance estimates with limited training data (the so-called Hughes effect). Because of the benefits of the maximum likelihood approach, he met that challenge head-on by establishing a long-standing program of research in dimensionality reduction that culminated in his book *Signal Theory Methods in Multispectral Remote Sensing* [17] which, while acknowledging that other approaches are available, is nevertheless comprehensive in its coverage of maximum likelihood estimation in the hyperspectral environment.

D. LARS Supporting Research

From the beginning, it was clear that effective digital multispectral remote sensing would require substantial advances in not only computer-based pattern recognition and sensor characteristics, but also improved fundamental understanding of how EM energy interacts with terrestrial materials, the atmosphere, and clouds. In the early years, LARS staff borrowed laboratory and field equipment from the military, which resided at WRL at that time [3], [19], [20]. In the mid-1960s, USDA and NASA funded the development by Exotech, Inc. of a field spectroradiometer covering UV to TIR wavelengths [21]. The first instrument (Exotech 20B) was provided to the USDA ARS, Weslaco, Texas, in 1968 and the second (Exotech 20C) went to

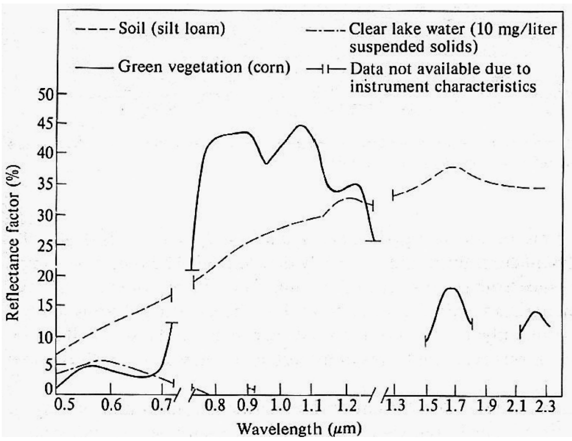

Fig. 10. Spectral reflectance characteristics of green vegetation, soil, and clear water [25].

LARS, in 1971 [22]. Work with the Exotech 20C included field measurements of soils and crops [23], [24].

Early analyses of reflectance spectra revealed that the primary land spectral variations originated from healthy, green vegetation, soils, and water (Fig. 10) [25]. In general, the most information could be derived by using at least one spectral band in each of the primary optical regions of VIS, NIR, SWIR, and TIR wavelengths [26].

While the mean spectral values in each spectral region differed among vegetation, soil, and water classes, the spectral variation within each cover class varied widely. Spectral distributions could overlap depending on extant environmental conditions such as temperature, moisture, solar illumination angle, atmospheric aerosols, and cloud conditions. Thus, began the search for a multivariate combination of spectral reflectance values which would be most sensitive to cover type and least sensitive to variations in environmental conditions.

E. Publishing Remote Sensing Technology and Science Advances

The technical and analytical developments in multispectral remote sensing, originally shrouded in military secrecy, in the 1960s, became a new civilian interdisciplinary scholarly topic. In these early years, apart from grant and contract progress and final reports, there was little information published about this research.

With the support of the military services and the NRC, the University of Michigan WRL began regular symposia on *Remote Sensing of Environment*, in 1962, from which they published nonrefereed proceedings. In 1965, the NRC held a conference in Houston, Texas at the behest of the Office of Naval Research, Division of Earth Sciences [27]. They also held an additional workshop, in Woods Hole, MA, in 1968 at the behest of NASA [28]. Proceedings were published for these conferences as well. In 1973, LARS began a Symposia series entitled *Machine Processing of Remotely Sensed Data* with published proceedings, which continued through 1985 [29].

For nearly a decade, these proceedings were the only source of published papers on this evolving field. Today's new researchers need to be aware almost a decade passed before refereed papers were published in the land remote sensing field.

Finally, in 1969, Dr. David Simonett founded the refereed journal *Remote Sensing of Environment* [30], [31]. In 1975, the American Society of Photogrammetry changed the title of its journal to *Photogrammetric Engineering and Remote Sensing* and added Remote Sensing to the society's name in 1985. In 1979, the IEEE Geoscience Electronics Society became the Geoscience and Remote Sensing Society and its journal the *Transactions on Geoscience and Remote Sensing* and held its first Symposium in 1981.

Various books also began to be published in the 1970s including the Surveillant Science [32], Manual of Remote Sensing [33], Remote Sensing of Environment [34], the LARS textbook Remote Sensing: The Quantitative Approach [16], Remote Sensing and Image Interpretation [35], and Remote Sensing: Optics and Optical Systems [36].

V. Early LARS Large Area Applications

By the late 1960s, LARS staff had conducted a variety of studies, specifically using the University of Michigan WRL scanner data of local fields and the Purdue Agronomy Farm, providing substantial evidence of the potential value of digital multispectral remote sensing for agricultural monitoring [3], [14], [18]. In 1970, nature supplied a demanding situation to test the LARS approach for real.

A. Corn Blight Watch Experiment

In August 1970, a new race of a previously minor fungal disease of corn, southern corn leaf blight (SCLB) was rapidly spreading from southern states to the Midwest Corn Belt. It primarily affected T-cytoplasm varieties which included 80% of the corn acreage. As a result, the 1970 national average corn yield was 15% lower than expected in July. Dr. Archibald Park, Chief, NASA Earth Resources Survey Program, in collaboration with USDA, instructed LARS and WRL to focus their resources on this situation [22].

A preliminary experiment was conducted in western Indiana in 1970 [37]. The NASA RB57F collected CIR photography along a 300-mile flight line and the WRL M5 scanner collected multispectral data for six 10-mile-long intensive study areas within the NASA flight lines in August and September. County extension agents made field estimates of blight severity in sample fields.

Three severity classes were interpreted photographically with 80% accuracy, while five levels of damage were digitally detected in the MSS data with 75% accuracy. Much of the misclassification was to adjacent severity levels; reasonable given observed within-field variations in the images, compared to the overall field condition recorded by county agents.

With SCLB spores expected to survive over the winter, a threat of widespread reoccurrence existed for 1971. USDA and NASA, working with LARS, WRL, the Purdue Agricultural Experiment Station, and regional statewide Extension Services, developed the Corn Blight Watch Experiment (CBWE) to map and monitor the extent and severity of SCLB across seven Midwest Corn Belt

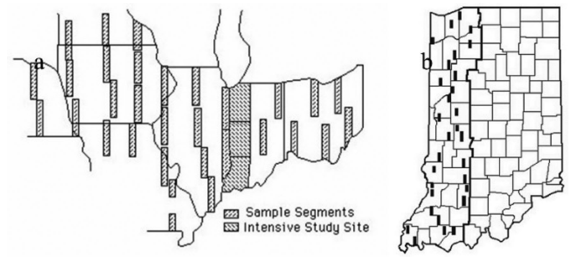

Fig. 11. Sampling scheme for the 1971 CBWE (left). The sample segments were overflown every two weeks throughout the growing season by a high-altitude RB57 aircraft carrying a conventional CIR camera, while the "Intensive Study Site" segments (right) were overflown by the Michigan DC-3 carrying the WRL M-7 multispectral scanner [38].

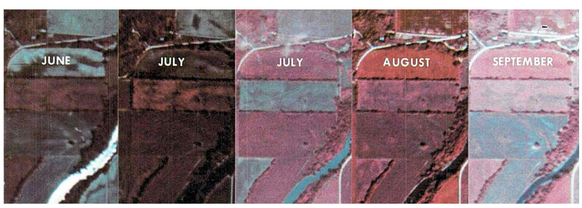

Fig. 12. CIR aerial photographs of a portion of a sample segment. Variations in color and brightness were caused by solar illumination, time of year, atmospheric conditions, as well as corn blight [39]. Analysis of the imagery was shared between LARS, WRL, and Experiment Station staff. The multispectral analyses were better correlated ($r = 0.92$–0.94) with the field observations than the color IR aerial photo interpretation ($r = 0.67$–0.77) (Fig. 13).

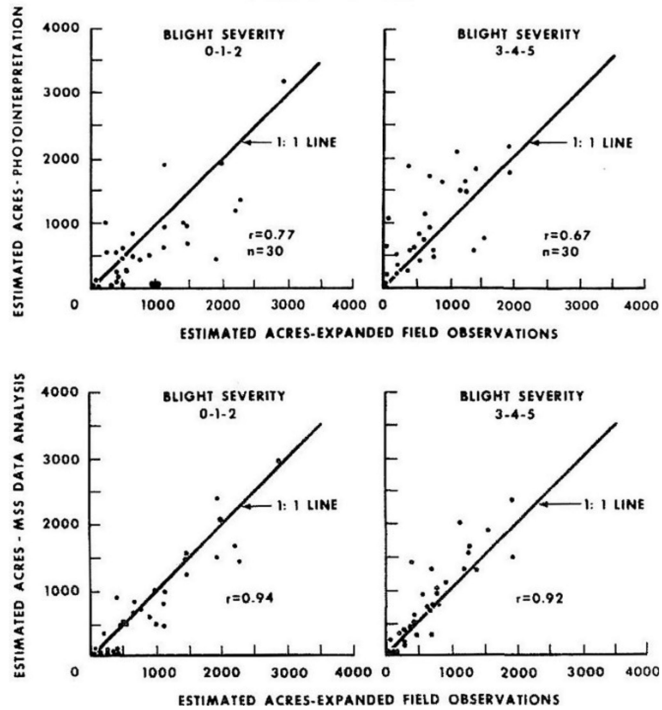

Fig. 13. Correlation of CIR photointerpretation (top) and multispectral scanner data analysis (bottom) with field observation estimates of acreage of relatively healthy (0–1–2) and moderate to severe blight severity (3–4–5) [38], [39].

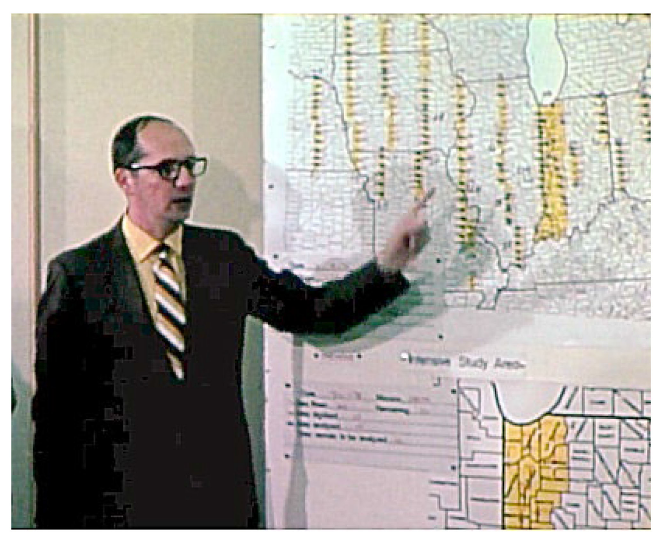

Fig. 14. David Landgrebe briefs NASA and USDA officials on the results from the 1971 Corn Blight Watch Experiment (L. Biehl, LARS).

states to test the potential value of remote sensing in tracking this outbreak [38].

The sampling plan included 30 flight lines (Fig. 11, left) across the seven Corn Belt states, plus an intensive study area in western Indiana Within each flight line, six 1×8 mile sample segments were photo interpreted. The intensive study area, covering 30 counties in western Indiana (Fig. 11, right) added 30 sample segments for a total of 210 segments.

The NASA RB57F acquired color IR photography of the 30 flight lines and the intensive study area every two weeks from mid-June to September (Fig. 12). The newly developed WRL M7 12-band MSS (Section III-B) flew the 30 sample segments in the intensive study area every two weeks. County extension agents recorded blight severity in sample fields in the segments across all seven states.

There were several factors affecting the blight determinations. One is that while the degree of leaf blight is a continuum, the field observations, photo interpretation, and multispectral classifications divided it into discreet classes. As found in the 1970 preliminary study, some of the apparent misclassifications were to adjacent classes. In addition, the field observations used for accuracy assessment assigned entire fields to the class of the sample plots although there was variation within fields.

In addition to leaf blight, several factors caused variations within and among fields, including agronomic differences such as variety, planting date, plant population, soil fertility, and moisture, as well as weather. Further, remote sensing imagery varied, unrelated to the ground scene, because of differences in sun and view angles, atmospheric conditions, and film properties and processing. One of the experiment conclusions was that more research on the causes of variation and relationships to agronomic and other factors would be needed. These issues continue today to be major subjects in remote sensing studies.

The CBWE was the first agricultural remote sensing project that included all the components of a remote-sensing-based information system—remote sensing measurements, sample design, image processing and analysis, area estimation, and information dissemination. It involved 800 people from 14 federal

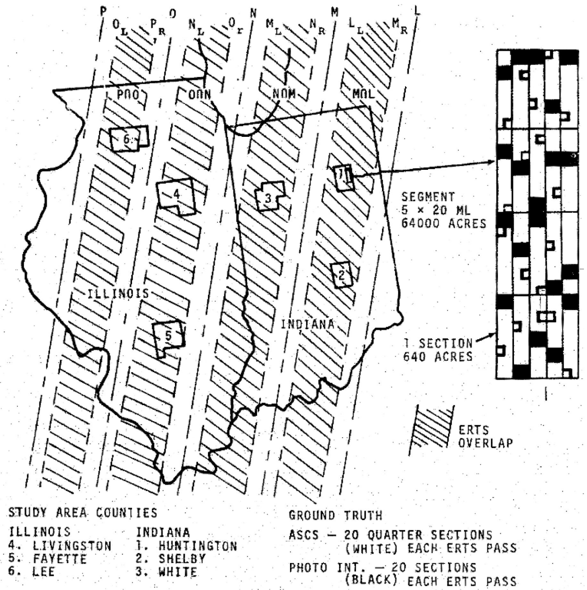

Fig. 15. CITARS study area and sample segment configurations [40].

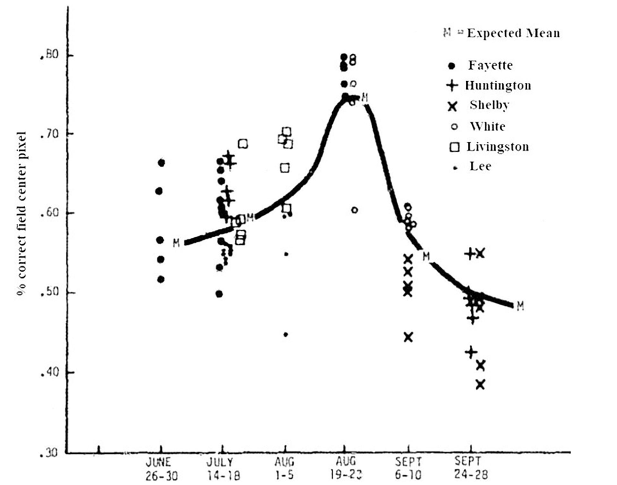

Fig. 16. CITARS crop identification results as a function of the observation date [41].

and state agencies who came together to address a common problem and provided a prototype and guidelines for developing Landsat-based crop inventory projects (Fig. 14), including the crop identification technology assessment for remote sensing (CITARS) (Section V-B), large area crop inventory experiment (LACIE) (Section VII-A), and ultimately, agriculture and resources inventory through aerospace remote sensing (AgRISTARS) (Section VII-B).

B. Crop Identification Technology Assessment for Remote Sensing

In 1973, NASA JSC initiated a 1-year follow-on experiment to the CBWE, the CITARS, to evaluate the newly launched ERTS-1 (Section VI-C) (Earth Resources Technology, aka Landsat) (Section VI) MSS data capacity to identify corn and soybean crops and estimate the areas planted to these crops. This study anticipated that NASA Headquarters would soon support the LACIE project (Section VII-A) [40].

The CITARS study area included portions of Indiana and Illinois (Fig. 15). Landsat data acquired for six periods from June to September for six 5×20 mile segments in Indiana and Illinois were evaluated to assess the accuracy of photo interpretation and the classification algorithms trained with both accurate field information and information from photo interpreters. The impact of field size on the fraction of Landsat pixels that would fall on field boundaries, not be properly classified, and therefore increase crop proportion errors was also evaluated.

The classification accuracies varied by the date of the Landsat acquisition, but were lower than had been reported in the extant literature, ranging between 60% and 70% correct identification (Fig. 16) [41]. Field boundaries, hence field sizes, contributed significantly to misclassification. The use of multidate Landsat acquisitions improved the classification and crop proportion accuracies. While these accuracies were lower than those previously reported for aerial multispectral data in the CBWE, they provided a solid foundation to design the LACIE approach.

The CITARS results also revealed some important limitations and/or considerations of Landsat MSS observations including the following:

Cloud cover: Each 5×20-mile site was located within an overlap zone of ERTS so that coverage was available on two successive days on each 18-day ERTS cycle or 72 potential datasets from late June (26–30) to late September (24–28). However, only 14 (20%) were sufficiently cloud-free for use in the analysis.

Multitemporal analysis: Despite locating segments in the overlap zones to increase the probability of obtaining cloud-free imagery, only one CITARS segment (Fayette) had several clear ERTS overpasses which were spatially registered and then analyzed and processed multitemporally. The use of multitemporal data increased field center classification accuracy from 81% to 89% correct and halved the root mean square error in proportion estimation. New analysis procedures considering the increased complexity of multitemporal scenes will need to be researched and developed [41].

Sensor issues: "Detector-to-detector" differences were found among the mean values obtained from the six detector channels that comprise each spectral band …." This is an interesting early report of issues found with the MSS spectral filters that were more fully explained by Phil Slater in 1979 [42].

Image geometry: The researchers reported that the new MSS sensor data presented multiple challenges by itself. The digital form of the ERTS data (Computer compatible Tape or CCT) contains several geometric distortions. These distortions include scale differential, altitude, and attitude variations, earth rotation skew, orbit velocity change, scan time slew, nonlinear scan sweep, scan angle error, and frame rotation. The major errors are the scale and skew errors. Also, rotation to North orientation is highly desirable (basically, because the midwestern survey system is oriented N-S). [41].

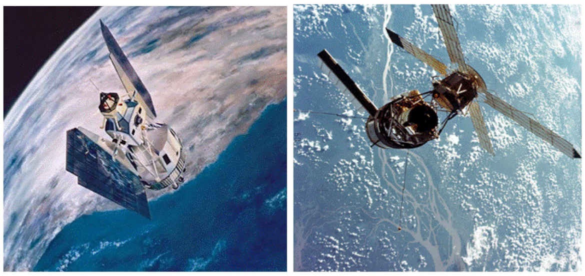

Fig. 17. Artist's rendition of ERTS-1 in orbit (left) and astronaut photo of Skylab over the Amazon Basin, Brazil (right) (NASA).

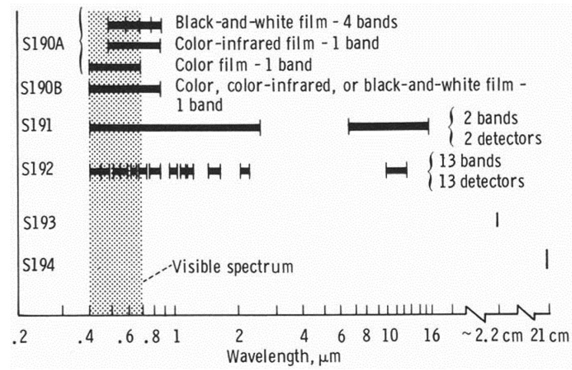

Fig. 18. Wavelengths of Earth-viewing Skylab cameras and sensors (NASA).

Multitemporal registration: Two major potential errors can occur in registration: 1) the pixels from one time are unlikely to have been imaged from the same spot; thus, 2) due to changes in the scene, two images cannot be exactly correlated or matched.

Nevertheless, the CITARS study established the foundation for the LACIE project and pointed the way toward issues that would (and perhaps still) need to be addressed for Landsat and the other earth-observing missions [22].

VI. Beginnings of the NASA Space Earth Observation Programs

NASA's and USDA's continued interest in supporting the cooperative work between Purdue LARS and Michigan WRL to develop multispectral remote sensing hinted at NASA plans for developing space-based observatories to monitor Earth resources.

With the Apollo program ending, initially NASA was seeking new uses for the technology developed under the Apollo program. Their interest was primarily to fly an astronaut-occupied space station, made from Apollo technology, upon which multiple alternate remote sensing technologies could be compared.

However, many U.S. civilian agency staff, including the Department of Interior (DOI)—U.S. Geological Survey (USGS), USDA, and the Department of State, had been attending the ongoing WRL *Remote Sensing of Environment* symposia (Section IV-E). They had become increasingly convinced that a systematic, monitoring satellite system dedicated to the needs of the civilian agencies would be of substantial value to their various resource monitoring responsibilities.

Initially, NASA was more inclined to pursue the space station approach. To counter this inclination, in 1966, DOI Secretary of Interior Stewart Udall, with the support of USGS Director William T. Pecora, announced that DOI would develop and launch its own free-flying satellite [10]. This led NASA to pursue both directions.

A. Space Station vs. Free Flyer: Johnson Space Center and Goddard Space Flight Center

In 1965, the Skylab space station approach was assigned to JSC; and in 1967, the development of the free-flying ERTS was assigned to GSFC (Fig. 17). With this decision, two Earth resources, science and application research initiatives, emerged within NASA. This provided, for the first time, the Earth science community NASA funding opportunities to pursue their research interests.

B. NASA JSC Skylab Space Station and Earth Resources Research Program

In 1971, the JSC Earth Observations Division (EOD) recruited Robert MacDonald, Technical Director of Purdue LARS, to support the development of a global agricultural monitoring system. In anticipation of NASA HQ pursuing such a system, MacDonald, in turn, recruited Forrest Hall in 1972 to develop the CITARS program (Section V-B). This team developed a broad funding program to support the Skylab Earth Resources Experimental Package (EREP) program and more broadly support the JSC EOD Earth resources aircraft program. Researchers from throughout the USA, including LARS staff, were supported under these programs.

The Skylab, launched in 1973, was the first U.S. space station. It was designed to support four astronauts who would carry out a wide range of experiments on human adaptation to space, solar observations, and Earth observations [43]. The Earth observations were carried out with the EREP, consisting of six sensor packages including two camera systems, a VNIR spectrometer, the S-192 13-band multispectral imager, and two microwave sensors [44] (Fig. 18).

The S-192 multispectral sensor data were of particular interest to the LARS scientists. The spectral coverage of S192 was similar to that of aircraft scanners of the time, covering VIS, NIR, SWIR, and TIR portions of the EM spectrum. The spectral coverage of this system met at least some of Dr. Landgrebe's expectations for a spaceborne MSS. However, it employed a novel, filter-wheel, conical scanner technology which created challenges for digital processing and analysis. Nevertheless, several LARS researchers were funded to evaluate the S-192 data [45].

C. NASA GSFC Earth Resources Technology Satellite and Earth Resources Research Program

Goddard engineers developed the fast-track ERTS program mostly from technology previously developed for weather satellites. The platform was from Nimbus [46]. In its day, the Nimbus platform was considered "small" and therefore had limited space for sensors and related equipment. The proposed primary ERTS sensor system was the return beam vidicon (RBV), originally developed for weather satellites and then used on the Ranger missions to locate Apollo moon landing sites [47].

For ERTS, the RBV multispectral consisted of three separate shuttered-video cameras each with its own optical path. In this form, it suffered from coregistration issues like what WRL and LARS analysts experienced with the early versions of the WRL aircraft MSS system.

Dr. Landgrebe and LARS staff, along with WRL researchers, and others requested that NASA also consider including a band-registered MSS. This was explored and a proposal from the Hughes Aircraft Company, led by Virginia Norwood, was funded to develop the MSS. The experimental MSS was space and mass constrained and thus limited to four spectral bands, far less than typical aircraft-based scanners being flown at that time [48]. It was not the MSS system that Dr. Landgrebe had been hoping for but was at least a step in the right direction.

The Goddard Earth Resources research program started with geological activities carried out by staff from the former Apollo lunar geology program [49]. Key hires were also made from Pennsylvania State and Colorado State Universities. This led to setting up the Goddard Earth Resources and Hydrology Branches.

Before the1972 ERTS 1 launch, a call was issued for ERTS science proposals that Goddard would manage. More than 600 proposals were received and over 300 were selected as investigations. The research efforts involved many investigators at universities, private companies, and state and federal agencies. Applications and science topics included agriculture, forestry, hydrology and water resources, geology, and geography [50]. Most analyses, in the beginning, were conducted with visual interpretation, but a few selected studies employed digital image analysis techniques, particularly from LARS.

The ERTS mission ground system configuration was principally designed to convert the electronic image data to photographic products, which could be visually interpreted. However, LARS staff and a few other research labs were more interested in, and demanded, the production of digital image data from ERTS.

Interestingly, the MSS was the first spaceborne mission designed to collect and transmit data to the ground digitally. Once received, these data were converted to analog tapes used to drive photographic production. Conversion of the analog MSS data back to a digital format was not difficult, although this would only be done when requested by those users, such as LARS, interested in using computer pattern recognition algorithms. This led to a serious problem in the 1980s when the Goddard-based Landsat data archive was transferred to USGS Earth Resources Observation and Science Center [51]. Briefly, the early MSS digital archive was almost lost!

D. Defining the Landsat Thematic Mapper

Although the ERTS MSS was only a four-band system, the design for an advanced six-band MSS had been proposed by Hughes Aircraft in 1968 [52]. This design was based on the technical understanding developed from aircraft MSSs such as the WRL M7 system and experience gained in multispectral digital analysis at Purdue LARS. Such an advanced MSS system, entitled Thematic Mapper, was evaluated as sensor for the next generation of the Landsat program (Landsats 4 and 5).

Various expert panels were formed, the Landsat Project Office had many meetings with experts in hardware and software. The Hughes Santa Barbara Research Center ultimately delivered two volumes of research that laid out options for hardware development that could address user requirements and provide a significant improvement over the performance of the MSS on Landsats 1–3.

All of that effort culminated in 1975 with the formation of the Landsat-D Technical Working Group (TWG), which was convened by Dr. Landgrebe in a workshop at Purdue University [53]. Included in this working group was Virginia Norwood, one of the designers of the 1968 Hughes Aircraft six-band advanced MSS system.

The TWG basically supported the original Hughes design, but with an improved 30-m spatial resolution (120-m TIR) and 8-bit digitization to support the finer radiometric resolution. The initial requirements were oriented toward agricultural requirements, but ultimately the geological community prevailed in adding the seventh band in the 2.1 μm region. These technical advances were an improvement from Landgrebe's perspective, but not nearly as advanced as he wanted to see [1].

Interestingly, because the TM sensor produced substantially more data per scene, many users, who were now employing digital analysis techniques, expressed concern that they would be unable to handle the new product and demanded that the original four-band MSS be included on Landsat 4 and 5. This was accommodated on these missions.

Fortunately, these data volume challenges were quickly overcome. At the first Landsat 4 Data Quality Assessment team meeting in 1982, the representative from IBM (Ralph Bernstein) showed he could process a TM image on the new desktop personal computer (PC) he brought to the meeting.

VII. Congressional Redirection: A Decade of Agricultural Applications

From 1970 to 1975, the NASA Earth resources research programs at JSC and GSFC were broadly focused on a wide range of applications from agriculture, forestry, and hydrology to geography and geology. This soon came to an end when the Soviet Union suffered a major wheat crop failure in 1972 [54].

Following atypical weather conditions, wheat crops across large parts of the globe failed in the early 1970s. The USA meanwhile had produced a bumper crop of wheat and had large stockpiles. Before the U.S. commodity market realized there was a global wheat shortage, Soviet traders bought $750 million of U.S. wheat—50 times what they normally purchased (15 million tons vs. 300 000 tons)—at low cost. With U.S. wheat supplies diminished and the global shortage realized, prices rapidly increased. From June 1972 to February 1974, price increases for wheat ranged from 200% to 350%. The U.S. Office of Management and Budget, keen not to have the USA caught

Fig. 19. LACIE project logo, suggesting it's global scope and noting the U.S. federal partners; NASA, NOAA, and USDA (NASA).

flat-footed again, tasked the USDA Foreign Agricultural Service (FAS) to establish a global crop monitoring system [55].

Dr. James Fletcher, then NASA Administrator, proposed to USDA Secretary Earl Butz in 1973 that a large-scale experiment be undertaken to determine the utility of Landsat in estimating the world's wheat production. Worldwide crop monitoring using Landsat's global, repetitive data, would only be possible if automated data processing, which was still in its infancy, could be vastly scaled-up.

As a result, the NASA JSC-directed LACIE was born [22]. The funding for the myriad PI-driven application investigations that had characterized early Landsat and Skylab applications research was largely refocused on the LACIE agriculture effort to tackle global crop monitoring. This brought added funding (and pressure) on LARS and ERIM (recently created from WRL) to rapidly further develop the digital remote sensing analysis methods that they had previously explored in the CBWE and CITARS. This also increased Director Landgrebe's responsibilities to increase LARS staff and research facilities.

A. Large Area Crop Inventory Experiment

LACIE began in 1974 with NASA, USDA, and National Oceanic and Atmospheric Administration (NOAA) (Fig. 19). Robert MacDonald formed the LACIE team at JSC from Apollo veterans and reached out to universities, including LARS, ERIM, and the University of Houston. JSC oversaw the Landsat-focused automated work performed by academic and other key institutions foraying into the nascent field of digital image processing [22].

The remote sensing analysis approach employed 5×6 nautical mile segments (Fig. 20). Selected sample Landsat MSS pixels were interpreted as wheat or not-wheat. The selected wheat pixels were used to train an unsupervised clustering algorithm designed by LARS to locate the remaining wheat pixels in the segment [56]. To meet the goals of the analysis, each analyst had to complete at least one segment per day. Typically, it took analysts 2–3 h to label pixels and the computer clustering took 2–3 min.

The Landsat-derived crop area measurements were combined with NOAA meteorological data and USDA crop models to estimate potential yields, and ultimately the production forecasts. The goal was to meet a 90/90 (10% bias or less with 90% confidence) criteria. The USDA evaluated the use of the experimentally derived production estimates in its crop reports. These reports were made public as a routine service to the domestic and international agriculture community.

In a 1977 quasi-operational test, the LACIE in-season forecast of a 30% shortfall in the 1977 Soviet spring wheat crop came within 10% of official Soviet figures released several months after harvest. In the final year of LACIE, 1978, its global wheat estimates were within 10% of the postharvest estimate, meeting the 90/90 criterion. The LACIE crop production estimates showed well before harvest that the Soviet Union's wheat production would fall short of their expectations.

LACIE demonstrated that remote sensing from earth-orbiting satellites could provide information on foreign crop production with accuracy and timeliness significantly better than those of previous systems.

Unfortunately, the LACIE technology was not adopted by USDA as a result of the commercialization of Landsat, which made the acquisition of Landsat data required for global surveys too expensive (Section IX) [57]. In addition, USDA's existing computer systems were inadequate for LACIE's computer approach that had been implemented on the mainframe IBM computers used for the Apollo space program. Upgrades to computer capabilities and personnel training within USDA would have been difficult to achieve.

In any case, the LACIE success was remarkable considering the limitations of remote sensing technology at that time. Many of the errors resulted from the 80-m spatial resolution of Landsat MSS, large compared to the average field sizes in many of the regions surveyed (Fig. 20). There were no algorithms to correct for aerosol variability and variable solar illumination geometry. Radiative transfer (RT) models were not sufficient to estimate multispectral signatures to be expected for different ground cover classes and their biophysical characteristics, and radiometric calibration was variable (Section VII-C).

B. Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing

In 1979, the Secretary of Agriculture announced a new initiative to develop improved uses of aerospace technology for agricultural purposes—the AgRISTARS. The program was started in 1980 and continued through 1983. Led by the USDA, the program was a cooperative effort with NASA, NOAA, USDA, DOI, and the U.S. Department of State (Fig. 21).

The program goal was to decide the usefulness, cost, and extent to which aerospace remote sensing data could be integrated into existing or future USDA systems to improve the objectivity, reliability, timeliness, and adequacy of information required to conduct USDA missions. AgRISTARS consisted of

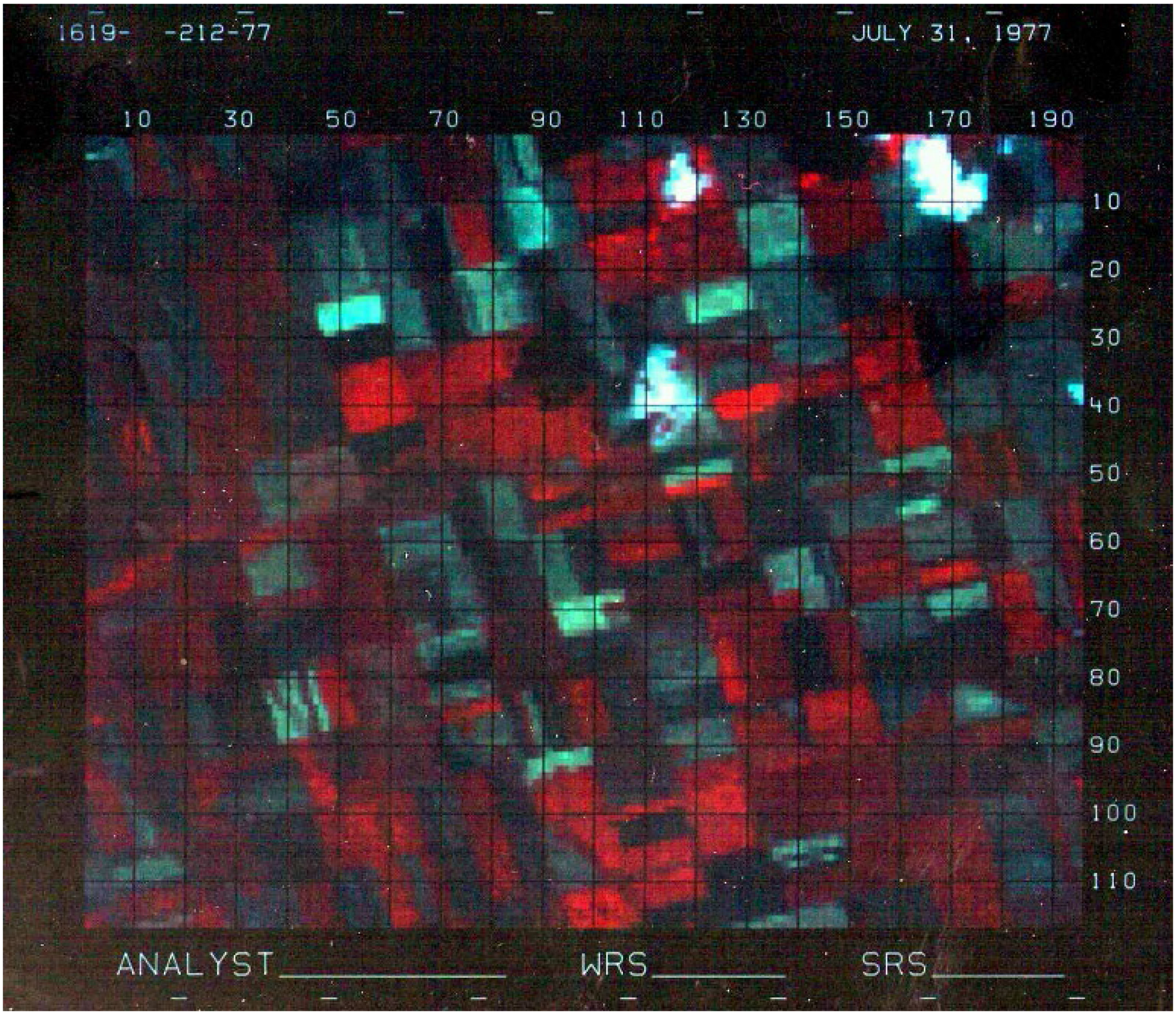

Fig. 20. Example LACIE segment image showing the problem of small field width compared to the 80-m Landsat MSS pixel size and the difficult problem analysts had in locating specific crops. The top and right edge numbers give pixel coordinates within the segment which visual interpreters used to locate specific pixels. White objects are clouds. The winter wheat fields in this late July image are mature and shown here in light green, whereas the still growing spring wheat fields (and other crops) are red (NASA JSC).

eight projects (Fig. 22). Each project addressed specific USDA and other agency research goals in applying remote sensing in agriculture, forestry, land cover, and environmental studies.

In summary, the AgRISTARS Program produced substantial results. Early warning crop conditions assessments developed models for impacts of moisture, flooding, insect damage, winter kill, and hot, dry winds. Crop identification was extended across corn, soybeans, and small grains, and the computer processes for conducting this analysis were advanced in speed and accuracy. The domestic crops and land cover studies produced operational procedures for estimating crop acreages over large areas that were then used to assess major crops in seven states. These estimates were also provided to the USDA Crop Reporting Board for use in their official estimates. Yield modeling research developed new empirical remote sensing-based models for corn, soybeans, wheat, and barley and plant process models for wheat and barley. Forestry studies considered the use of TM data and forest condition assessment in the eastern USA. Conservation/pollution work focused on measuring snowpack water content and modeling snowmelt runoff for U.S. river basins, as well as monitoring high sediment loads in reservoirs and rivers.

In 1986, a special issue of *IEEE Geoscience and Remote Sensing* journal was dedicated to AgRISTARS research, providing example studies from all aspects of the program [60]. The specific outcomes in each project area are detailed in the AgRISTARS annual reports [58], [59], [61], [62].

The AgRISTARS efforts were complicated by the ongoing discussions to commercialize or privatize the Landsat program. Considerable attention was given to the possible use of the NOAA polar-orbiting imagery data as a substitute for Landsat observations. NOAA's update of the advanced very-high-resolution radiometer (AVHRR) sensor to include both VIS

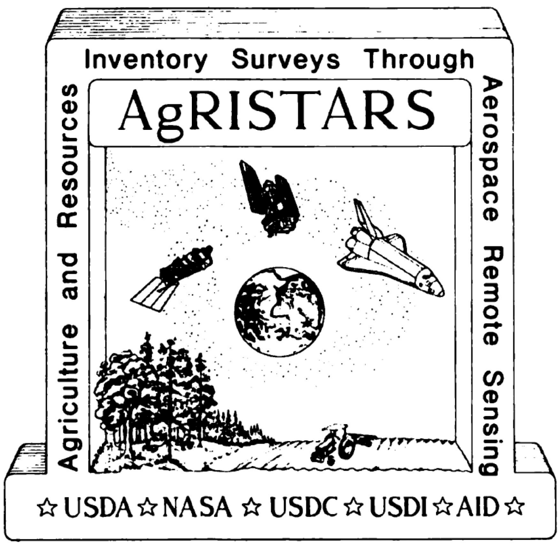

Fig. 21. AgRISTARS logo; this project had more partner agencies than LACIE (NASA).

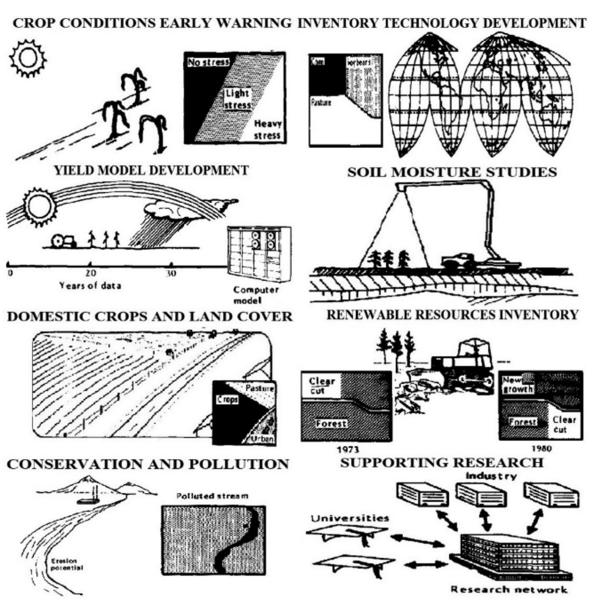

Fig. 22. Icons of the eight AgRISTARS projects, as derived from the Annual Research Reports depicting the outcome goals of each project [58], [59].

and NIR bands made it more attractive for monitoring global vegetation patterns [63], [64]. However, continued attention was also given to the pending Landsat 4 mission which included the advanced TM as well as MSS.

Although AgRISTARS results publications were modest, probably because of early 1980's land remote sensing politics [65], the impact of the program was substantial. In the USDA, remote sensing methods have been widely adopted in the ARS, FAS, National Agricultural Statistics Service (NASS), and the U.S. Forest Service (USFS), as well as the other Federal agencies involved in the program.

C. Supporting Research: Pattern Recognition, Field Studies, and Spectral Vegetation Indices

Under the LACIE and AgRISTARS programs, substantial effort was dedicated to "Supporting Research" as noted in LACIE Symposium Proceedings "The purpose of the Supporting Research program is to provide technology improvements…form the basis for improvements in future applications" [66] (p. 617), continuing the traditions begun when LARS was founded. The number of institutional participants varied over time but typically included over 20 primary players. Topical foci were wide ranging from crop modeling to field research and pattern recognition. LARS was primarily involved in pattern recognition and field research.

1) Pattern Recognition: The primary approach to crop area estimation in LACIE was unsupervised clustering which required substantial analyst-supervised training. Most of the time for the production of LACIE estimates was consumed in the visual (manual) interpretation of hard copy Landsat LACIE segment images (Fig. 20). Throughout the project, substantial efforts were consumed to reduce this time commitment and develop more automated approaches. Six advanced clustering algorithms were explored including the Extraction and Classification of Homogeneous Objects (ECHO) classifier that Robert Kettig and David Landgrebe developed at LARS [67]. In an era of modest computer capacities this approach, although interesting, overwhelmed most mainframe computer resources. However, as computers advanced this early work served as the foundation of other object-based image classification approaches.

One of the most serious problems met in automating crop identification was "signature extension." Because of variations in weather, crop varieties, management practices, and local soil conditions, multispectral signatures extracted in one location rarely worked well in locations beyond a few kilometers away. However, as AgRISTARS supporting research continued to advance researchers found that by employing multitemporal observations, transformed to spectral vegetation indices (SVI) dimensions, consistent, characteristic patterns of crop phenology could be associated with individual crop types (Fig. 23) [68], [69].

One of the problems encountered with multitemporal satellite data was variable atmospheric conditions and cloud cover. A technique known as *compositing*—choosing the maximum SVI values from multidate SVI images—provided a significant advance in minimizing the effects of cloud cover and haze variations [70]. This laid the groundwork for a more generalized use of multitemporal signatures for analysis of continental to global land cover patterns with the AVHRR observations [71], [72].

2) Laboratory and Field Studies: Beginning in 1974, the truck-mounted field spectrometers (Fig. 24), as well as the NASA JSC helicopter-mounted field spectrometer system (Fig. 25), were deployed at multiple research sites to collect measurements in support of the LACIE and then AgRISTARS goals [24], [73]. To further expand field measurement capabilities, LARS staff developed a modular multiband radiometer

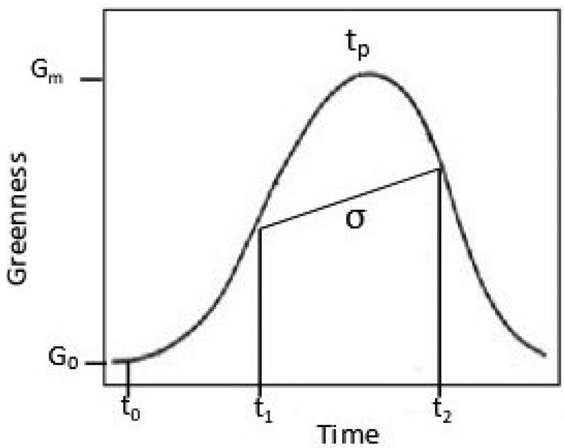

Fig. 23. Temporal profile model of greenness. Key parameters include spectral emergence date (t_0), time of peak greenness (t_p), maximum greenness (G_m), and time between mid-growth and mid-senescence (σ). σ, G_m, and t_p can be used for crop identification and the area under the curve is related to the seasonal accumulation of biomass [24].

(MMR) system covering the Landsat TM spectral bands and an additional 1.15–1.30 μm spectral band [74]. Fifteen copies were distributed to universities, USDA/ARS, and NASA to support wide-ranging field studies [24].

Based on earlier laboratory work on leaf spectral properties [75]–[77], mathematical consideration of plant canopy irradiance was explored [78]. In 1972 Gwynn Suits, University of Michigan developed a more complete RT model [79]. This model analytically captured the fact that healthy leaves are strongly absorptive in VIS wavelengths, but highly reflective and transmissive in the NIR wavelengths. Vegetation canopy multispectral reflectance varies as a function of leaf area index (LAI, as well as background soil/litter reflectance) with visible reflectance decreasing and near infrared reflectance increasing.

3) Spectral Vegetation Indices: With the 1972 launch of Landsat 1, researchers quickly began to show that the four-band MSS sensor fundamentally produced two-dimensional spectral information, with the primary variations in the VNIR wavelengths. Various researchers explored dimensionality reduction through the use of SVI, the earliest of which was the normalized difference vegetation index [80] and the perpendicular vegetation index [81]. In 1976, ERIM investigators Richard Kauth and Gene Thomas [82] outlined these variations as the "tasseled cap" with dimensions including "brightness" (sum of the bands), "greenness" (difference between VIS and NIR bands), "yellowness" (difference between band 3, a red-edge band, and band 4, an NIR band), and "non-such" basically from sources of noise in the instrument and observations. Many additional SVIs were also introduced at about this time [83]. In 1983, Ray Jackson compared many of these alternates in his "Spectral indices in n-Space" paper [84].

As Gwynn Suits and others had shown earlier, all the SVIs are related to canopy LAI and therefore related to various canopy biophysical variables including percent ground cover, green biomass, as well as intercepted and absorbed photosynthetically active radiation [24], [85], [86] (Fig. 26). These biophysical relations with SVI's began a transition from simple cover type

Fig. 24. Larry Biehl explaining the boom truck operations of LARS field spectrometers to participants at the 1982 Eighth International Symposium on Machine Processing of Remotely Sensed Data, held in West Lafayette, Indiana (S. Goward).

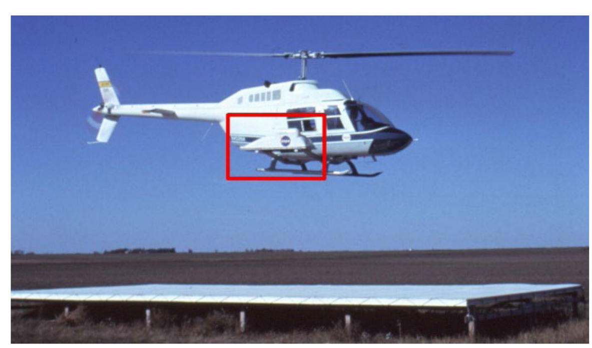

Fig. 25. Field spectrometer system (FSS) is in the pod on the side of the NASA helicopter (inside the red box) [73].

identification to models of plant growth and productivity [87]–[89].

Progress in understanding other aspects of land biophysical characteristics advanced rapidly. As LACIE/AgRISTARS era field research was winding down and NASA was turning its attention to Earth Systems Science, this same field measurement approach was applied to Boreal forests [91]. The study was conducted in the Superior National Forest, including the protected

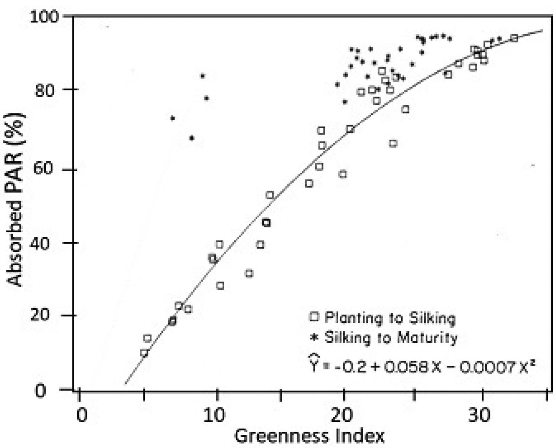

Fig. 26. Relation between APAR and greenness index for growth (planting to silking) and senescing (silking to maturity) periods of corn development. The regression line ($R^2 = 0.96$, RMSE = 5.3%) is for the planting to silking growth stages [24], [90].

wilderness of the Boundary Waters Canoe Area, in northeastern Minnesota [91], [92].

VIII. Gordon Research Conferences: A Time to Reflect

During the LACIE/AgRISTARS era, two Gordon Research Conferences were convened, by Lou Walter (Goddard) and Jack Estes (UC Santa Barbara) in 1979, and Lou Walter (NASA GSFC) with Arch Park (NASA) in 1981. These conferences in many ways celebrated the major progress that had been accomplished in remote sensing science during the first quarter-century of land remote sensing studies. Many of the key figures in the field at the time attended (Fig. 27).

From the top left,

ROW 1: Donald Lowe, John Barker, James Taranick Martin Matthews, A. DeGasparis. Vincent V. Salomonson, David Landgrebe, Philip Swain, David Goodenough, Craig Daughtry.

ROW 2: Russell Moll, Phil Slater, Charles Hutchison, John Lyon, Curtis Woodcock, Howard Hogg, Samuel Goward, W. Murray Strom, Michael Consentio, Vern Vanderbilt.

ROW 3: Don Moore, William Chang. J. Clifford Harlan, Robert Schowengerdt. Charles Goillot, Robert Wrigley, Wayne Mooneyhan, Helene Wilson, Tiny Carey, Pete DeForth, Fred Billingsley, Larry Tiney.

ROW 4: John Park, Donald Lamb, Ida Hoos, Ruth Whitman, Shin Yi-Hsu, Fred Gunther, R. Holmes, R. MacDonald, Stephen Ungar.

FRONT ROW: William Malila, Marvin Bauer, Richard Kiang, Ron Lyon, John Estes, Jim Smith, C. J. Tucker, L. Sam Thompson.

IX. Commercializing Land Remote Sensing

Long-standing debates about Landsat's purpose—experimental vs. operational, public vs. private, or public good vs. market commodity—were met with the economic pressures of the late 1970s, resulting in Jimmy Carter's 1979 Presidential Directive 54, outlining Landsat's management transition to the NOAA as the first step toward commercialization. This action started a process that fundamentally changed the future development of terrestrial remote sensing and the character of Purdue LARS.

The 30-m spatial resolution of the new TM aboard Landsat 4 provided unprecedented detail and encouraged a fast-tracked commercial spin-off. Landsat's practical value had been heavily touted in the late 1960s to get the program funded [93]—now the data were even better and the political ideologies of the Ronald Reagan administration supported an expedited commercialization process.

NOAA was instructed to recover all Landsat operation and maintenance costs through data sales. Full cost recovery prices (~$3000/scene) took effect in October 1982, data sales dropped precipitously, and placed serious constraints on the continuation of AgRISTARS.

It was into that world that EOSAT, the selected commercial operator, entered. The EOSAT business model sharply restricted data distribution and the Land Remote-Sensing Commercialization Act of 1984 limited the company's ability to differentially price data, meaning university scientists paid the same amount as oil companies for an image. This pushed researchers away from Landsat and toward coarser resolution data like AVHRR [63].

Also, competition from the French SPOT satellite and a tight build budget for Landsat 6 were additional pressures for EOSAT. The failed launch of Landsat 6—the first commercially developed Landsat—in 1993 dealt a devastating blow to the company and the commercialization concept. After a decade of frustration for nearly everyone involved, the Land Remote Sensing Policy Act of 1992 returned the Landsat program to government control.

Over this decade of Landsat commercialization, the use of these observations for monitoring Earth resources and land dynamics was seriously impacted: data acquisitions were substantially reduced because of data telemetry costs, and the development of data analysis methodologies as well as scientific applications stagnated [94].

A. Impact on Purdue LARS

Landsat commercialization brought an end to the NASA–USDA-funded agricultural applications. With the decade of large and relatively stable LACIE/AgRISTARS funding terminated, many researchers at LARS, ERIM, JSC, GSFC, and GISS either changed their jobs and/or moved to other universities, NASA centers, USGS, NOAA, and USDA facilities to successfully continue their remote-sensing-based careers.

In 1981, after nearly 15 years of serving as director of LARS, Dr. Landgrebe stepped down to become the Associate Dean of Engineering and Director of the Engineering Experiment Station at Purdue. Marion Baumgardner, a soil scientist in Purdue's Department of Agronomy and a long-time LARS researcher, became the director of LARS.

To reduce the costs of supporting its dedicated computer (mainframe IBM) to run LARSYS, LARS became a remote

Fig. 27. Participants in the 1981 Gordon Conference "Remote Sensing of the Earth's Surface from Space." Many of the key figures in the development of land remote sensing science were present at this conference (S. Goward).

site to a similar computer at NASA JSC. A few years later LARS began using Purdue University's recently installed IBM computer. Essentially all LARS staff left and LARS faculty returned to their departments on the main Purdue University campus, while maintaining their affiliation with LARS. In 1985, LARS left the off-campus LARS FlexLab facilities effectively ending its interdisciplinary (working elbow-to-elbow) nature.

X. Earth Systems Science: A New Beginning for Land Remote Sensing Research

In 1981, NASA convened a series of workshops, many of which Dr. Landgrebe participated in, to consider basic research needs to support future applications of satellite land remote sensing data [95]. From these working groups, the NASA Fundamental Remote Sensing Science Research Program established two funded research elements: 1) Scene Radiation and Atmospheric Characterization (SRAEC) [96] and 2) Mathematical Pattern Recognition and Image Analysis Project (MPRIA) [97].

The SRAEC project focused on modeling the fundamental relationship of energy interactions between the sensor and the surface target, including the effect of the atmosphere. The MPRIA project was concerned with developing models of both the spectral and spatial properties of a remote sensing image. A remote sensing scene was modeled as a spatial arrangement of fields of distinct ground cover types, each with relatively homogenous, distinct spectral properties. In 1982, approximately 35 investigations were funded. The fundamental research program ended in 1984 when research focus shifted from research and development to applying the technology to show its utility in various applications, primarily ecology and climate.

A. Earth Systems Science

In the 1980s, NASA's land science research turned to the terrestrial biosphere in the Earth system using the heritage of research explored during the agricultural era [98]. The restricted commercial access to Landsat observations was sorely felt, but the newly available NOAA AVHRR observations served as a useful alternative [71], [99], [100]. An international program, the *International Satellite Land Surface Climatology Project* (ISLSCP), dedicated to the use of land remote sensing data was also developed [101]. This led to a series of field experiments dedicated to relating these satellite observations to ground measurements (Table II).

Over the next two decades, NASA earth sciences activities evolved sporadically from Global Habitability (1982) [109], [110], Earth Systems Science (1985) [111], Mission to Planet Earth (1992) [112], and Earth Science Enterprise (1998) [113].

TABLE II
FIELD STUDIES IN THE LARS SUPPORTING RESEARCH TRADITION

Project Name	reference	Years	Location	Ecotype	Study Size
Superior National Forest	[102]	1983-1985	Northern Minnesota U.S.	Boreal forest	2500 sq. km
HAPEX-Mobilhy	[103]	1986	Southwest France	Agriculture	1000 sq km
FIFE	[104]	1987-1989	Central Kansas U.S.	Grasslands	225 sq km
HAPEX-Sahel	[105]	1991-1992	Central Africa	Deserts	1^0 x 1
BOREAS	[106]	1994	Central Canada	Boreal forest	10^6sq km
OTTER	[107]	1989-1991	Western Oregon	Coastal Forests	300km transect
LBA	[108]	1998-2000	Amazonia	Tropical Forests	0.5^6 sq km

B. NASA Earth Observing System

These science directions supported the development of a large-scale earth observation program originally discussed as "System Z" and ultimately named the Earth Observing System (EOS). The working documents dated from 1984, with the first funding authorization in 1988 for a start in 1990. Originally funded at nearly $20 billion, the EOS funding levels were revised (downward) multiple times over the next decade and the mission was redesigned as often. A full EOS history (to 2008) is contained in a special issue of the NASA Earth Explorer [114].

One of the proposed early EOS sensors was the high-resolution imaging spectrometer (HIRIS). Purdue professors Christian Johannsen and David Landgrebe were selected as principal investigators and awarded a 10-year grant to pursue this research [115]. This research was ideally suited to Landgrebe's research interests at this time. Unfortunately, when the EOS mission was reorganized to reduce costs, the HIRIS instrument and related activities were canceled, bringing this activity to an end.

The first EOS platform AM-1 included the highly sophisticated Moderate (sic) Resolution Imaging Spectrometer, a highly advanced AVHRR-type sensor, and the Advanced Spaceborne Thermal Emissions and Reflection Radiometer similar to Landsat, but not Landsat [116]. Darrel Williams tried to have a TM sensor placed on EOS AM-1 but did not succeed [114].

C. Salvation of Landsat

In 1992, starting with Landsat 7, Landsat returned to government operations, originally under joint NASA and DOD management, then NASA, NOAA, and USGS, and finally joint NASA and USGS management which continues to this day. Landsat 7 was the first sensor to be designed, launched, and managed under this partnership. Also, with this change, Landsat 7 became one of the EOS satellites and, for the first time, a science team to support this new Landsat science role was selected [51].

There were several working groups convened to evaluate Landsat's new role as a science mission and Dr. Landgrebe participated in most of these committees. The changes realized the vision that he and his colleagues had for the Landsat program for years.

This led NASA to fund the Pilot Land Data System, which supported three project areas to explore the use of Landsat observations in Earth Systems Science: Humid Tropical Deforestation, North America Landscape Characterization, and Global Land Cover Test Sites. In all these studies, Landsat data were acquired and managed by NASA to provide team access to the observations.

Landsat was also given a major boost from the Shuttle Radar Topography Mission in February 2000 [117]. It supplied global data that could be used to orthorectify Landsat data to planimetric maps and high-quality GIS information. A second major step forward for Landsat grew out of the 1992 Land Remote Sensing Act., which directed DOI to develop a National Satellite Land Remote Sensing Data Archive (NSLRSDA) to preserve a Landsat and related observations historical archive [118].

So after a decade that looked as though land remote sensing might be brought to an end, a phoenix-like rebirth occurred. Further, one of the biggest changes for Landsat occurred, in 2008, when USGS decided to make the data freely available to the user community [119]. This led to almost unimaginable scientific advances and uses of Landsat data for research and applications. Finally, the Landsat images became readily available and easily processed and analyzed on digital computers, a dream Landgrebe had held for years.

XI. LOOK TO THE FUTURE

Dr. Landgrebe was a far-sighted engineer. At LARS in the late 1970s, he mentioned to John Richards that he could foresee the day when we would be able to purchase remote sensing imagery over the telephone network and by selected geographic regions. That was well before the internet and email and was when we bought data on 2400 ft magnetic tapes. Geocoding and GIS were new concepts and one had to be an optimist then to think that enough bandwidth would be available to support prompt network delivery.

A. LARSYS to MultiSpec

When IBM's Bernstein first demonstrated use of a PC for processing Landsat TM data in 1982 (Section VI-D), Dr. Landgrebe was intrigued. By 1988, PCs were becoming powerful enough to handle image processing operations. David Landgrebe became interested with implementing LARSYS on these simple machines [120]. He imagined that this might help student classroom learning as well as graduate student research. Larry Biehl undertook the implementation of this vision [121]. The LARSYS Fortran and assembly code were converted to C for a Macintosh version. In addition, the command-line user interface was revised to a graphical user interface. Initially, images could only be displayed as single band B&W images using a 3×3 dot

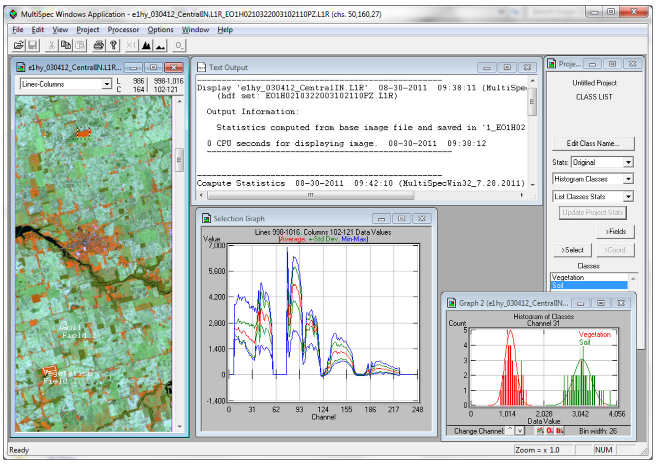

Fig. 28. Illustration of windows in the MultiSpec application including here a display of a Hyperion image, text window, project window, selection graph window, and a histogram graph window (L. Biehl, LARS).

pattern. Soon the Macintosh II computer permitted color images to be displayed. The first operations included display, histogram, and unsupervised classification (cluster) methods. The prototype was found to be student-friendly and more approaches, such as supervised classification, were added.

Since Professor Landgrebe's research focused on hyperspectral data, MultiSpec was written from the beginning to handle images with hundreds of bands. The hyperspectral algorithms, developed by his graduate students, were incorporated into MultiSpec during the 1990s including feature extraction, statistics enhancement, projection pursuit, and others (Fig. 28).

The Purdue Research Foundation copyrighted MultiSpec in 1991 but it was made freely available to requestors on the web in 1995 [121]. Also, at about this time, the K-12 GLOBE Program (www.globe.gov) expressed interest in using MultiSpec as a freeware GLOBE application. It also supported the development of a simple Windows OS version. MultiSpec continues today as both a macOS and Window OS application and, beginning in 2015, as a web-enabled application [122], [123]. In 2020, the source code for MultiSpec was also made available on GitHub [122].

The original vision of using PCs for remote sensing image analysis which Professor Landgrebe put forward in 1988 continues to be fulfilled today. More than 10,000 copies of the MultiSpec applications and tutorials have been downloaded during the past year from more than 100 countries. Moreover, the current PCs are far more powerful than the IBM mainframes (360/370) for which LARSYS was originally developed.

B. *Future of Multispectral Image Analysis*

From the start, Landgrebe considered the use of neural networks for image understanding [13], but rejected that approach because of the then-perceived inefficient methods for training; instead, he took the sensible decision to base image interpretation on maximum likelihood estimation. While it is likely he meant layered "Perceptrons" [124] since the term neural network was not commonly used at the time, he nevertheless could see that the body of knowledge built up around extensive piecewise linear classifier networks would provide a good approach to classification if training could be improved.

It is testimony to his foresight that one of the most popular contemporary methods we now use for image interpretation is deep learning based on convolutional neural networks. While his initial work focused largely on the spectral domain, he always foresaw that interpretation would be improved if scene spatial properties, and the time dependence of the spectral response, are taken into account [12]. That is exactly what we now have in our deep learning tools. Convolutional neural nets [125]–[127] and their recurrent counterparts [7] provide us with very powerful techniques for understanding land cover based on the full integration of spectral, spatial, and temporal properties, and look to do so for some time to come.

C. *Landsat's Future*

Over the past several years, NASA and the USGS have engaged in extensive fact-finding for what the instrumentation and platforms for future Landsat missions should be [128]. Landsat Next, the current nomenclature for the mission after Landsat 9, is likely to be a significant departure from past configurations as nothing was held sacred when considering how to acquire Earth imagery other than being able to derive "continuity of data attributes" with the existing archive of Landsat imagery.

A traditional, single platform observatory, as well as constellations of smaller observatories are being considered. USGS Director now retired James Reilly, a former NASA astronaut, has said "A revolution in space is underway and we'll want to capitalize on that as much as we possibly can. The critical piece … is looking at how we combine all that information and how we calibrate and validate it".

A proposed "super spectral" coverage, consisting of up to 25 spectral bands, is being considered at spatial resolutions ranging from 10-m VNIR, 20-m SWIR and narrow VNIR bands, as well as 60-m atmospheric and TIR bands (Fig. 29, Table III).

Sharing Earth observation imagery obtained by other U.S. and international government agencies is also under consideration. For example, working with the National Geospatial Intelligence Agency to obtain data that "*can be used by the whole government in the future*," or with international allies like the European Space Agency's Sentinel land imaging program to dramatically enhance temporal repeat coverage.

D. *The Future of Terrestrial Remote Sensing*

The early Landsat MSS sensor (four spectral bands) captured the major VNIR contrast between healthy vegetation and background material that CIR films recorded. To Dave Landgrebe, this spectral coverage seemed entirely inadequate. LARS research experience working with 12-24 spectral band aircraft multispectral sensors, as well as the 13-band Skylab S190 instrument, pointed to the need for considerably expanded spectral coverage.

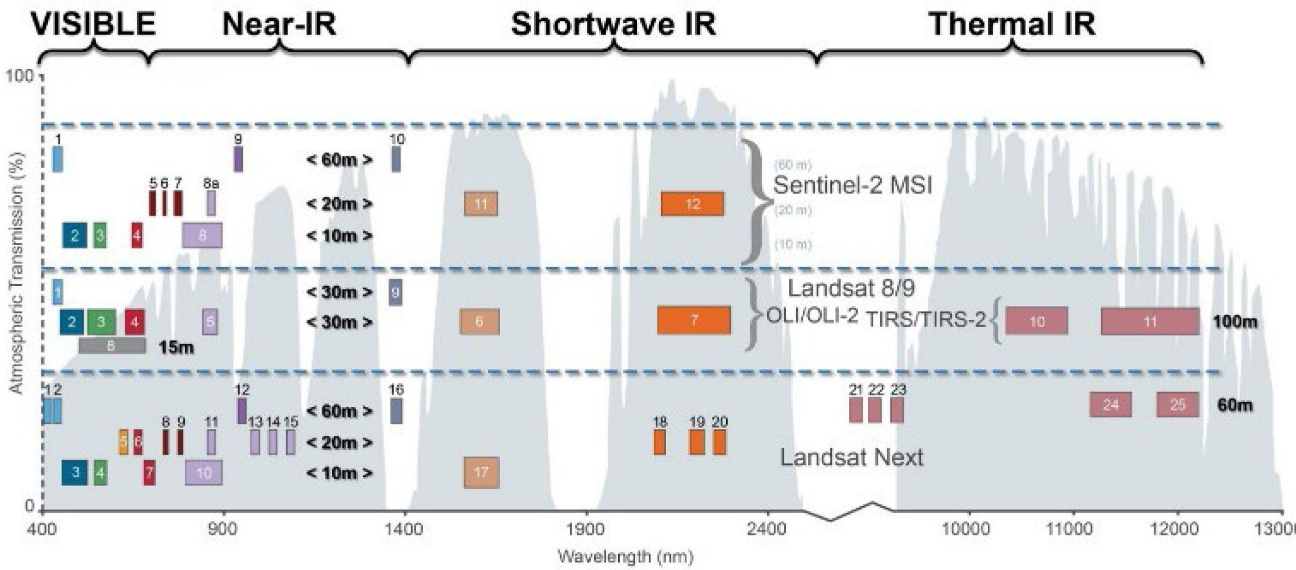

Fig. 29. Comparison of spectral coverage for Sentinel 2, Landsats 8 and 9, and proposed Landsat Next. Note that the proposed Landsat Next configuration meets or exceeds the type of coverage Landgrebe postulated would be needed in 1985. The proposed digital precision for Landsat Next is 14 bits, like Landsat 9 (NASA).

TABLE III
THE FUNCTIONAL PROPERTIES OF THE PROPOSED LANDSAT NEXT SPECTRAL CONFIGURATION (S. GOWARD, MODIFIED FROM NASA WORKING DOCUMENTS)

Landsat 9 continuity	Sentinel 2	New Applications

	Band Name	Ground Sample Distance (m)	Center Wavelength (nm)	Band Width (nm)	Rationale
1	Violet	60	410	20	Improved aerosol retrieval CDOM from inland/coastal water
2	Blue 1	20	443	20	Coastal & Aerosols
3	Blue	10	490	65	Plant pigments
4	Green	10	560	35	> Pigments
5	Orange	20	620	20	Phycocyanin detection
6	Red 1	20	650	20	Phycocyanin, chlorophyll
7	Red 2	10	665	30	Plant pigments, 10m NDVI
8	Red Edge 1	20	705	15	LAI, Chlorophyll, plant stress
9	Red Edge 2	20	740	15	LAI, Chlorophyll, plant stress
10	NIR Broad	10	842	115	10m NDVI
11	NIR1	20	865	20	Landsat continuity (narrower than L8)
12	NIR2	60	945	20	Water vapor, surface temperature, & reflectance
13	NIR 3	20	985	20	Liquid water, water surface state
14	Snow/Ice 1	20	1035	20	Snow grain size (water resources)
15	Snow/Ice 2	20	1090	20	Ice absorption, snow grain size
16	Cirrus	60	1375	30	Cirrus clouds
17	SWIR 1	10	1610	90	Plant leaf water
18	SWIR 2a	20	2100	30	Cellulose/crop residue discrimination
19	SWIR 2b	20	2210	40	Cellulose/crop residue discrimination
20	SWIR 2c	20	2260	40	Cellulose/crop residue discrimination
21	TIR 1	60	8300	250	T/E (Temperature/emissivity separation) M/S (mineral & surface composition)
22	TIR 2	60	8600	350	TE & M/S, volcanic emissions (SO_2)
23	TIR 3	60	9100	350	TE & M/S
24	TIR 4	60	11300	550	TE & M/S, clouds, water vapor, carbonates
25	TIR 5	60	12000	550	TE, clouds, water vapor, snow grain

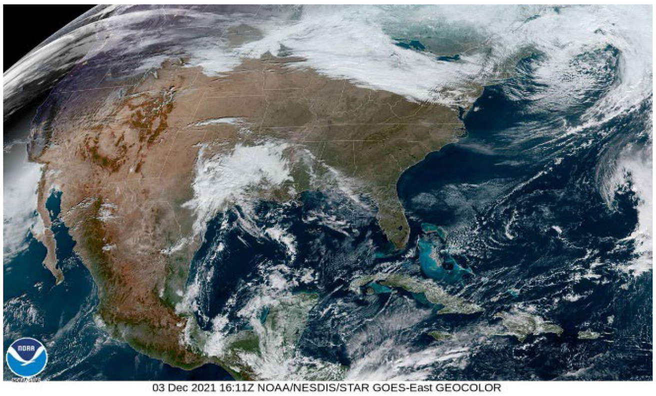

Fig. 30. An example GOES 17 image, collected on December 3, 2021, at 1:11 pm EST. The daytime color composite is formed from blue, red, and NIR bands (1,2, 3) [129]. (NOAA).

The Landsat TM instrument, expanded to seven spectral bands, covered not only the visible spectrum but also the shortwave and TIR regions. This was still not good enough for Dave. Even as the Landsat 8 Operational Land Imager (OLI) instrument began to explore bands that considered atmospheric conditions such as water vapor and ice crystals and the Sentinel 2 expanded this atmospheric coverage, Dr. Landgrebe would not have been satisfied.

Dr. Landgrebe, in reviewing the evolution of multispectral remote sensing in 2005 [1], made the following prescient comments:

> To achieve the potential for the field, the need is for a fleet of perhaps **20 identical satellites** in orbit at any given time. They would need to have sensors with a spatial resolution that is appropriate for a broad class of uses, and **spectral bands that cover the optical range from the blue through the TIR**, **divided into at least 20 and perhaps many more bands**, and with a **S/N adequate to justify at least 10-bit (1024 levels) data**. (**Bold added**)

With the proposed specifications for Landsat Next, this program is just now beginning to meet his expectation. However, many of the spectral bands being considered for Landsat Next are also designed to improve our understanding of atmospheric conditions and clouds within Landsat scenes (Table III).

The community is beginning to fully recognize that space-based multispectral Earth-imaging measurements which include not only land surface phenomena, but also intervening atmospheric variations, will substantially enhance terrestrial monitoring and may be quite useful in more accurately monitoring surface conditions, but also measuring near-surface atmospheric conditions that affect land surface life forms.

A complementary satellite system, which has yet to be considered as a complement to the NextGen Landsat, is the recent version of the NOAA Geostationary Operational Environmental Satellites (GOES) [129] (Fig. 30). Its new Advanced Baseline Imager (ABI) includes 16 spectral bands which are mostly intended to enhance atmospheric characterization and cloud identifications in addition to limited surface measurements. The real advantage of the GOES systems is that the observations are updated approximately every 20 minutes. This daily, multitemporal information when combined with Landsat-type detailed surface information may be used to diagnose the daily changes in environmental conditions which determine the seasonal and annual evolution of biospheric productivity which sustains the life of Earth. These data would certainly be a challenge to merge with Landsat observations, but not more than has been previously addressed in this digital world.

XII. Epilog

Dr. Landgrebe's intuitive understanding of digital, multispectral data was strong. He may not have fully anticipated the integrated systems view of terrestrial remote sensing that is emerging today, but he certainly had the insight to know that the Landsat observatory needed to become far more advanced before it would achieve its full potential.

Dr. David Landgrebe, Department of Electrical Engineering, Purdue University, and long-standing LARS Director was truly one of the pioneers of digital remote sensing. Clearly, the use of MSS data for many applications throughout the world would not be as effective as it is today if it had not been for the dedication and work of Dr. David Landgrebe over more than 50 years. ***Thank you, Dave!!***

Acknowledgment

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References

[1] D. A. Landgrebe, "Multispectral land sensing: Where from, where to?," *IEEE Trans. Geosci. Remote Sens.*, vol. 43, no. 3, pp. 1–10, Mar. 2005, doi: 10.1109/TGRS.2004.837327.

[2] "Remote sensing: With special reference to agriculture and forestry," National Research Council: Committee on Remote Sensing for Agricultural Purposes, National Academy of Sciences, Washington, DC, USA, Rep. 309-01723-8, 1970. [Online]. Available: https://www.nap.edu/catalog/20260/remote-sensing-with-special-reference-to-agriculture-and-forestry

[3] R. M. Hoffer, "Interpretation of remote multispectral imagery of agricultural crops," 1967. [Online]. Available: https://www.lars.purdue.edu/home/references/bulletin_no_831.pdf

[4] D. S. Lowe, F. C. Polcyn, and J. R. Shay, "Multispectral data collection program," in *Proc. 3rd Symp. Remote Sens. Environ.*, 1965, pp. 667–780.

[5] R. M. Hoffer, "Computer-aided analysis of multispectral scanner data - The beginnings," *Photogramm. Eng. Remote Sens.*, vol. 80, no. 6, pp. 482–492, 2014. [Online]. Available: https://www.asprs.org/a/publications/pers/2014journals/June_2014_Flipping/HTML/files/assets/basic-html/index.html#475

[6] P. G. Hasell Jr. *et al.*, "Collation of earth resources data collected by ERIM airborne sensors," Environmental Research Institute Michigan, Ann Arbor, MI, USA, Sep. 1975. [Online]. Available: https://archive.org/details/NASA_NTRS_Archive_19760003468

[7] P. E. Anuta, "Spatial registration of multispectral and multitemporal digital imagery using fast Fourier transform techniques," *IEEE Trans. Geosci. Electron.*, vol. GE-8, no. 4, pp. 353–368, Oct. 1970. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_052270.pdf

[8] P. E. Anuta, "Aircraft scanner data overlay project," 1968. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_103068.pdf

[9] P. G. Hasell Jr., R. Legault, L. R. Larsen, L. A. Levereault, S. R. Stewart, and R. E. Marshall, "Michigan experimental multispectral mapping system: A description of the m7 airborne sensor and its performance," Environmental Research Institute of Michigan, Ann Arbor, MI, USA, Jan. 1974. [Online]. Available: https://ntrs.nasa.gov/api/citations/19740007950/downloads/19740007950.pdf

[10] S. N. Goward *et al.*, "Earth rising," in *Landsat's Enduring Legacy: Pioneering Global Land Observations from Space*. Bethesda, MD, USA: American Society of Photogrammetry and Remote Sensing, 2017, pp. 1–46.

[11] D. A. Landgrebe, "A brief history of the laboratory for applications of remote sensing (LARS)," 1988. [Online]. Available: https://www.lars.purdue.edu/home/LARSHistory.html

[12] D. A. Landgrebe, "Machine processing of remotely acquired data," in *Remote Sensing of Environment*. Reading, MA, USA: Addison-Wesley, 1976. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_031573.pdf

[13] D. A. Landgrebe, "The evolution of landsat data analysis," *Photogramm. Eng. Remote Sens.*, vol. 63, no. 7, pp. 859–867, 1997, doi: 0099-1112/97/6307-859$3.00/0.

[14] D. A. Landgrebe *et al.*, "Automatic identification and classification of wheat by remote sensing," 1967. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_021567.pdf

[15] M. D. Fleming, J. S. Berksebile, and R. M. Hoffer, "Computer-aided analysis of landsat 1 MSS data: A comparison of three approaches including a modified clustering approach," 1975. [Online]. Available: https://docs.lib.purdue.edu/larstech/96/

[16] P. H. Swain and S. M. Davis, Eds. *Remote Sensing: The Quantitative Approach*. New York, NY, USA: McGraw-Hill, 1978.

[17] D. A. Landgrebe, *Signal Theory Methods in Multispectral Remote Sensing*. Hoboken, NJ, USA: Wiley, 2003.

[18] D. A. Landgrebe, P. J. Min, P. H. Swain, and K.-S. Fu, "The application of pattern recognition techniques to a remote sensing problem," 1968. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_080568.pdf

[19] "Remote sensing in agriculture," LARS Staff, Sep. 1968. [Online]. Available: https://www.lars.purdue.edu/home/references/Research_Bulletin_no_844.pdf

[20] "Remote multispectral sensing in agriculture," Laboratory of Agricultural Remote Sensing, West Lafayette, IN, USA, 1967. [Online]. Available: https://www.lars.purdue.edu/home/references/Research_Bulletin_no_832.pdf

[21] L. Silva, R. M. Hoffer, and J. Cipra, "Extended wavelength field spectrometer," in *Proc. 7th Int. Symp. Remote Sens. Environ.*, 1971, pp. 1509–1518. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_052771.pdf

[22] R. B. MacDonald, "A summary of the history or the development of automated remote sensing for agricultural applications," *IEEE Trans. Geosci. Remote Sens.,* vol. GE-22, no. 6, pp. 373–482, Nov. 1984, doi: 10.1109/TGRS.1984.6499157.

[23] J. E. Cipra, M. F. Baumgardner, E. R. Stoner, and R. B. MacDonald, "Measuring radiance characteristics of soil with a field radiometer," *Soil Sci. Soc. Amer. Proc.*, vol. 35, pp. 1014–1017, Nov. 1971, doi: 10.2136/sssaj1971.03615995003500060043x.

[24] M. E. Bauer, C. S. T. Daughtry, L. L. Biehl, E. T. Kanemasu, and F. G. Hall, "Field spectroscopy of agricultural crops," *IEEE Geosci. Remote Sens.*, vol. GE-24, no. 1, pp. 65–76, Jan. 1986, doi: 10.1109/TGRS.1986.289589.

[25] R. M. Hoffer, "Biological and physical considerations in applying computer-aided analysis techniques to remote sensing data," in *Remote Sensing: The Quantitative Approach*, P. H. Swain and A. W. Davis, Eds. New York, NY, USA: McGraw-Hill, 1978, pp. 227–289.

[26] R. Kumar and L. F. Silva, "Separability of agricultural cover types by remote sensing in the visible and infrared wavelength regions," *IEEE Trans. Geosci. Electron.*, vol. 15, no. 1, pp. 42–49, Jan. 1977, doi: 10.1109/TGE.1977.294512.

[27] "Spacecraft in geographic research," in *Use of Orbiting Spacecraft in Geographic Research Manned Spacecraft Center, Houston, Texas*, L. A. Gosling, Ed. Washington, DC, USA: National Academy of Sciences, National Research Council, 1966.

[28] *Useful Applications of Earth-Oriented Satellites: Summer Study on Space Applications*. Washington, DC, USA: National Academy of Sciences, National Research Council, 1969.

[29] L. L. Biehl, "LARS publications," 1995. Accessed: Aug. 9, 2021. [Online]. Available: https://www.lars.purdue.edu/home/References.html

[30] D. S. Simonett, "Editor's preface," *Remote Sens. Environ.*, vol. 1, no. 1, p. v, Mar. 1969.

[31] M. E. Bauer, "Remote sensing of environment: History, philosophy, approach and contributions, 1969–2019," *Remote Sens. Environ.*, vol. 237, pp. 1–7, 2020, doi: 10.1016/j.rse.2019.111522.

[32] R. K. Holz, Ed. *The Surveillant Science: Remote Sensing of the Environment*. Boston. MA, USA: Houghton Mifflin, 1973.

[33] R. G. Reeves, Ed. *Manual of Remote Sensing*. Falls Church, VA, USA: American Society of Photogrammetry, 1975, Art. no. 2123.

[34] J. L. Lintz and D. S. Simonett, Eds. *Remote Sensing of Environment*. Reading, MA, USA: Addison-Wesley, 1976.

[35] T. M. Lillesand and R. W. Kiefer, *Remote Sensing and Image Interpretation*, 1st ed. New York, NY, USA: Wiley, 1979.

[36] P. N. Slater, *Remote Sensing: Optics and Optical Systems* (Advanced Remote Sensing Text Series). Reading, MA, USA: Addison-Wesley, 1980.

[37] M. E. Bauer, P. H. Swain, R. F. Mroczynski, R. P. Anuta, and R. B. MacDonald, "Detection of southern corn leaf blight by remote sensing techniques," May 1971. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_051371.pdf

[38] R. B. MacDonald, M. E. Bauer, R. D. Allen, J. W. Clifton, J. D. Erickson, and D. A. Landgrebe, "Results of the 1971 corn blight watch experiment," in *Proc. 8th Int. Symp. Remote Sens. Environ.*, 1972, pp. 157–189. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_100272.pdf

[39] "Corn blight watch experiment," Earth Resources Program staff Johnson Space Center, 1974. [Online]. Available: https://www.lars.purdue.edu/home/references/other_documents/1974_Corn_Blight_Watch_Summary.pdf

[40] F. G. Hall, M. E. Bauer, and W. A. Malila, "First results from the crop identification technology assessment for remote sensing (CITARS)," in *Proc. 9th Int. Symp. Remote Sens. Environ.*, 1974, pp. 1171–1192. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_041874.pdf

[41] R. M. R. M. Bizzell *et al.*, "Crop identification technology assessment for remote sensing (CITARS): Interpretation of results," Johnson Space Center, Houston, TX, USA, Dec. 1975. [Online]. Available: https://www.lars.purdue.edu/home/references/CITARS_X_1275.pdf

[42] P. N. Slater, "A re-examination of the landsat MSS," *Photogramm. Eng. Remote Sens.*, vol. 45, pp. 1479–1495, 1979. [Online]. Available: https://www.asprs.org/wp-content/uploads/pers/1979journal/nov/1979_nov_1479-1485.pdf

[43] L. F. Belew, Ed. *Skylab, Our First Space Station (NASA SP 400*. Washington D.C, USA: National Aeronautics and Space Administration, 1977. [Online]. Available: https://history.nasa.gov/SP-400/contents.htm

[44] "Skylab EREP investigations summary," NASA, 1978. [Online]. Available: https://www.history.nasa.gov/SP-399/sp399.htm

[45] R. M. Hoffer *et al.*, "Computer-aided analysis of skylab multispectral scanner data in mountainous terrain for landuse, forestry, water resources, and geologic applications," LARS Purdue Univ., West Lafayette, IN, USA, Dec. 1975. [Online]. Available: https://ntrs.nasa.gov/citations/19760012421

[46] S. N. Goward *et al.*, *Landsat's Enduring Legacy: Pioneering Global Land Observations From Space*. Bethesda, MD, USA: American Society of Photogrammetry and Remote Sensing, 2017.

[47] C. Hall, *Lunar Impact: A History of Project Ranger (NASA History Series, No. NASA SP-4210)*. Washington, DC, USA: National Aeronautics and Space Administration, 1977.

[48] V. T. Norwood, L. R. Fermelia, and G. A. Tadler, "Multispectral scanner system for ERTS, four band scanner system: Final report, volume I, system description and performance," Space and Communications Group, Hughes Aircraft Company, Santa Barbara, CA, USA, 1972.

[49] P. D. Lowman, Jr., "Landsat and apollo: The forgotten legacy," *Photogramm. Eng. Remote Sens.*, vol. 65, no. 10, pp. 1143–1147, 1999.

[50] "Symposium on significant results obtained from earth resources technology satellite-1," in *ERTS-1 Symposium*, S. C. Freden, E. O. Mercanti, and M. A. Becker, Eds. Washington, DC, USA: NASA, 1973.

[51] S. N. Goward *et al.*, "Light on the horizon (1992–1999)," in *Landsat's Enduring Legacy: Pioneering Global Land Observations From Space*. Bethesda, MD, USA: American Society of Photogrammetry and Remote Sensing, 2017.

[52] V. Norwood and J. C. Lansing Jr, *Final Report: Multispectral Point Scanner Study and Final Report: Multispectral Scanning Point Scanner Camera System*. El Segundo, CA, USA: NASA, 1970.

[53] W. Hovis, J. Nichols, A. Potter, F. Thomson, J. Harnage, and D. Landgrebe, "Landsat-D thematic mapper technical working group final report," National Aeronautics and Space Administration, Johnson Space Center, Houston, TX, USA, Rep. JSC-09797, 1975. [Online]. Available: https://www.lars.purdue.edu/home/references/other_reports/pinkreport.pdf

[54] C. B. Luttrell, "The Russian wheat deal—Hindsight vs. foresight," Federal Reserve Bank of St. Louis, St. Lous, MO, USA, Oct. 1973. [Online]. Available: https://files.stlouisfed.org/files/htdocs/publications/review/73/10/Russian_Oct1973.pdf

[55] "About FAS," U.S. Department of Agriculture, 2021. Accessed: Oct. 11, 2021. [Online]. Available: https://www.fas.usda.gov/about-fas

[56] R. B. MacDonald and F. G. Hall, "Global crop forecasting," *Science*, vol. 208, pp. 670–679, 1980, doi: 10.1126/science.208.4445.670.

[57] P. Folger, "Landsat: Overview and issues for congress," Congressional Research Service, Washington, DC, USA, Rep. R40594, Oct. 1984. [Online]. Available: https://crsreports.congress.gov/product/pdf/R/R40594

[58] "AgRISTARS research report FY 1981," AgRISTARS Program Support Staff, NASA Johnson Space Center, Houston, TX, USA, Rep. AP-J2-04225, Jan. 1982. [Online]. Available: https://www.nass.usda.gov/Education_and_Outreach/Reports,_Presentations_and_Conferences/GIS_Reports/AgRISTARS%20Annual%20Report%20(FY%201981).pdf

[59] "AgRISTARS research report FY 1982," AgRISTARS Program Management Group, NASA Johnson Space Center, Houston, TX, USA, Rep. AP-J2-0393, Jan. 1983. [Online]. Available: https://ntrs.nasa.gov/api/citations/19840011894/downloads/19840011894.pdf

[60] H. Hogg, "Agriculture and resource inventory survey through aerospace remote sensing (AgRISTARS), special issue," *IEEE Trans. Geosci. Remote Sens.*, vol. GE-24, no. 1, pp. 3–4, Jan. 1986. [Online]. Available: https://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=4072408&punumber=36

[61] "AgRISTARS research report FY 1980," AgRISTARS Program Support Staff, NASA, Johnson Space Center Houston, Houston, TX, USA, Rep. AP-J0-0411, 1981. [Online]. Available: https://ntrs.nasa.gov/citations/19820015733

[62] "AgRISTARS research report FY 1983," AgRISTARS Program Management Group, NASA, Johnson Space Center, Houston, TX, USA, Rep. JSC-18920, Jun. 1984. [Online]. Available: https://www.nass.usda.gov/Education_and_Outreach/Reports_Presentations_and_Conferences/GIS_Reports/AgRISTARS%20Annual%20Report%20(FY%201983)%20(Pages%201-100).pdf

[63] J. R. G. Townshend and C. J. Tucker, "Utility of AVHRR NOAA-6 and NOAA-7 for vegetation mapping," in *Matching Remote Sensing Technologies and Applications*. London, U.K.: Remote Sensing Society, 1981, pp. 97–107.

[64] G. O. Boatwright and V. S. Whitehead, "Early warning and crop condition assessment research," *IEEE Geosci. Remote Sens.*, vol. 24, no. 1, pp. 54–64, Jan. 1986. [Online]. Available: https://ieeexplore.ieee.org/document/4072419

[65] M. M. Waldrop, "Imaging the earth: The troubled first decade of landsat," *Science*, vol. 215, no. 1, pp. 1600–1603, 1982, doi: 10.1126/science.215.4540.1600.

[66] *The LACIE Symposium: Proceedings of Technical Sessions*. Houston, TX, USA: NASA, 1978. [Online]. Available: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19800007188.pdf

[67] R. L. Kettig and D. A. Landgrebe, "Classification of multispectral image data by extraction and classification of homogeneous objects," *IEEE Trans. Geosci. Electron.*, vol. 14, no. 1, pp. 19–26, Jan. 1976.

[68] G. D. Badhwar, "Automatic corn-soybeans feature extraction and classification," *Remote Sens. Environ.*, vol. 14, pp. 15–29, 1984, doi: 10.1016/0034-4257(84)90004-X.

[69] F. G. Hall and G. D. Badhwar, "Signature-extendable technology: Global space-based crop recognition," *IEEE Trans. Geosci. Remote Sens.*, vol. GE-25, no. 1, pp. 93–103, Jan. 1987, doi: 10.1109/TGRS.1987.289785.

[70] B. N. Holben, "Characteristics of maximum-value composite images from temporal AVHRR data," *Int. J. Remote Sens.*, vol. 7, pp. 1417–1434, 1986, doi: 10.1080/01431168608948945.

[71] C. J. Tucker, J. R. G. Townshend, and T. E. Goff, "African land-cover classification using satellite data," *Science*, vol. 227, pp. 369–375, 1985, doi: 10.1126/science.227.4685.369.

[72] C. J. Tucker and P. J. Sellers, "Satellite remote sensing of primary production," *Int. J. Remote Sens.*, vol. 7, no. 11, pp. 1395–1416, 1986, doi: 10.1080/01431168608948944.

[73] L. L. Biehl, "Purdue university research repository: LARS- vegetation and soils field research data," Purdue Univ., West Lafayette, IN, USA, 1995. Accessed: Nov. 2021. [Online]. Available: https://purr.purdue.edu/lars-veg-soils

[74] B. F. Robinson, M. E. Bauer, D. P. DeWitt, L. F. Silva, and V. C. Vanderbilt, "Multiband radiometer for field research," in *Proc. 23rd Annu. Tech. Symp.*, 1979, pp. 8–15, doi: 10.1117/12.957951.

[75] D. M. Gates, H. J. Keegan, J. C. Schleter, and V. R. Weidner, "Spectral properties of plants," *Appl. Opt.*, vol. 4, pp. 11–20, 1965. [Online]. Available: https://forestwatch.sr.unh.edu/pdfs/Gatesetal_1965.pdf

[76] W. A. Allen and A. J. Richardson, "Interaction of light with a plant canopy," *J. Opt. Soc. Amer.*, vol. 58, no. 8, pp. 1023–1028, 1968, doi: 10.1364/JOSA.58.001023.

[77] W. A. Allen, H. W. Gausman, A. J. Richardson, and J. R. Thomas, "Interaction of isotropic light with compact leaves," *J. Opt. Soc. Amer.*, vol. 59, no. 10, pp. 1376–1379, 1969, doi: 10.1364/JOSA.59.001376.

[78] W. A. Allen, T. V. Gayle, and A. J. Richardson, "Plant-canopy irradiance specified by the duntley equations," *J. Opt. Soc. Amer.*, vol. 60, pp. 372–376, 1970, doi: 10.1364/JOSA.60.000372.

[79] G. Suits, "The calculation of the directional reflectance of a vegetative canopy," *Remote Sens. Environ.*, vol. 2, no. 1971–1973, pp. 117–125, 1972, doi: 10.1016/0034-4257(71)90085-X.

[80] D. W. Deering, J. J. W. Rouse, R. H. Haas, and J. S. Schell, "Measuring forage production of grazing units from landsat MSS data," in *Proc. 10th Int. Symp. Remote Sens. Environ.*, 1975, pp. 1169–1178.

[81] A. J. Richardson and C. L. Wiegand, "Distinguishing vegetation from soil background information," *Photogramm. Eng. Remote Sens.*, vol. 43, pp. 1541–1552, 1977. [Online]. Available: https://www.asprs.org/wp-content/uploads/pers/1977journal/dec/1977_dec_1541-1552.pdf

[82] R. J. Kauth and G. S. Thomas, "The tasseled cap—A graphic description of the spectral-temporal development of agricultural crops as seen by landsat," in *Proc. 3rd Symp. Mach. Process. Remotely Sensed Data*, 1976, pp. 41–51. [Online]. Available: https://www.lars.purdue.edu/home/references/sym_1976/1976_4B-41.pdf

[83] C. J. Tucker, "Red and photographic infrared linear combinations for monitoring vegetation," *Remote Sens. Environ.*, vol. 8, no. 2, pp. 127–150, 1979, doi: 10.1016/0034-4257(79)90013-0.

[84] R. D. Jackson, "Spectral indices in n-space," *Remote Sens. Environ.*, vol. 13, pp. 1401–1429, 1983, doi: 10.1016/0034-4257(83)90010-X.

[85] B. N. Holben, C. J. Tucker, and C. J. Fan, "Spectral assessment of soybean leaf area and leaf biomass," *Photogramm. Eng. Remote Sens.*, vol. 46, no. 5, pp. 651–656, 1980. [Online]. Available: https://www.asprs.org/wp-content/uploads/pers/1980journal/may/1980_may_651-656.pdf

[86] G. Asrar, M. Fuchs, E. T. Kanemasu, and J. L. Hatfield, "Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat," *Agronomy J.*, vol. 76, pp. 300–306, 1984.

[87] M. Kumar and J. L. Monteith, "Remote sensing of plant growth," in *Plants and the Daylight Spectrum*, H. Smith, Ed. London, U.K.: Academic Press, 1982, pp. 133–133–144.

[88] S. N. Goward, C. J. Tucker, and D. G. Dye, "North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer," *Vegetation*, vol. 64, pp. 3–14, 1985, doi: 10.1007/BF00033449.

[89] C. J. Tucker, B. N. Holben, J. H. Elgin Jr, and J. E. McMurtrey, "Remote sensing of total dry-matter accumulation in winter wheat," *Remote Sens. Environ.*, vol. 11, pp. 171–189, 1981, doi: 10.1016/0034-4257(81)90018-3.

[90] K. P. Gallo, C. S. T. Daughtry, and M. E. Bauer, "Spectral estimation of absorbed photosynthetically active radiation in corn canopies," *Remote Sens. Environ.*, vol. 17, pp. 221–221–232, 1985, doi: 10.1016/0034-4257(85)90096-3.

[91] F. G. Hall, K. F. Huemmrich, D. E. Strebel, S. J. Goetz, J. E. Nickerson, and K. E. Woods, "Biophysical, morphological, canopy optical property, and productivity data from the superior national forest," NASA Goddard, Greenbelt, MD, USA, Rep. 104568, Jul. 1992. [Online]. Available: https://ntrs.nasa.gov/citations/19920020967

[92] F. G. Hall, D. B. Botkin, D. E. Strebel, K. D. Woods, and S. J. Goetz, "Large scale patterns of forest succession as determined by remote sensing," *Ecology*, vol. 72, no. 2, pp. 628–640, 1991, doi: 10.2307/2937203.

[93] "Useful applications of earth-oriented satellites: Report of the central review committee," Summer Study on Space Applications, National Academy of Sciences, National Research Council, Washington, DC, USA, 1969.

[94] S. N. Goward *et al.*, "Landsat in transition: Privatization in the 1980s," in *Landsat's Enduring Legacy: Pioneering Global Land Observations From Space*. Bethesda, MD, USA: American Society of Photogrammetry and Remote Sensing, 2017, pp. 131–232.

[95] J. E. Estes and L. Eisgruber, "National aeronautics and space administration fundamental research program: Information utilization and evaluation: Final report," U. C. Santa Barbara, Santa Barbara, CA, USA, Jun. 1981. [Online]. Available: https://ntrs.nasa.gov/search?q=19820016259

[96] R. E. Murphy, "Special issue on scene radiation and atmospheric effects characterization (SRAEC)," *IEEE Trans. Geosci. Remote Sens.*, vol. GE-23, no. 5, pp. 616–775, Sep. 1985.

[97] L. F. Gausman, Jr., Ed. *Proceedings of the NASA Symposium on Mathematical Pattern Recognition and Image Analysis*. Houston TX, USA: NASA, 1983. [Online]. Available: https://ntrs.nasa.gov/search?q=Proceedings%20of%20the%20NASA%20Symposium%20on%20Mathematical%20Pattern%20Recognition%20and%20Image%20Analysis

[98] W. Steffen *et al.*, "The emergence and evolution of earth system science," *Nature Rev. Earth Environ.*, vol. 1, no. 1, pp. 54–63, 2020, doi: 10.1038/s43017-019-0005-6.

[99] G. M. Woodwell, R. A. Houghton, T. A. Stone, R. F. Nelson, and W. Kovalick, "Deforestation in the tropics: New measurements in the amazon basin using landsat and NOAA advanced very high resolution radiometer imagery," *J. Geophys. Res.*, vol. 92, no. 2, pp. 2157–2163, 1987, doi: 10.1029/JD092iD02p02157.

[100] C. J. Tucker, I. Y. Fung, C. D. Keeling, and R. H. Gammon, "Relationship between atmospheric CO_2 variation and a satellite-derived vegetation index," *Nature*, vol. 319, pp. 195–199, 1986.

[101] S. I. Rasool and H. J. Bolle, "ISLSCP: International satellite land-surface climatology project," *Bull. Amer. Meteorol. Soc.*, vol. 65, pp. 143–144, Feb. 1984, doi: 10.1175/1520-0477-65.2.143.

[102] F. G. Hall, Y. E. Shimabukuor, and K. F. Huemmrich, "Remote sensing of forest biophysical structure using mixture decomposition and geometric reflectance models," *Ecol. Appl.*, vol. 5, no. 4, pp. 993–1013, 1995, doi: 10.2307/2269350.

[103] J.-C. Andre, J.-P. Goutorbe, and A. Perrier, "HAPEX-MOBILHY: A hydrologic atmospheric experiment for the study of water budget and evaporation flux at the climatic scale," *Bull. Amer. Meteorol. Soc.*, vol. 67, pp. 138–144, 1986.

[104] P. J. Sellers, F. G. Hall, G. Asrar, D. E. Strebel, and R. E. Murphy, "An overview of the first international satellite land surface climatology project (ISLSCP) field experiment (FIFE)," *J. Geophys. Res.*, vol. 97, pp. 345–371, 1992, doi: 10.1029/92JD02111.

[105] J.-P. Goutorbe *et al.*, "HAPEX-Sahel: A large-scale study of land-atmosphere interactions in the semi-arid tropics," *Annales Geophysicae*, vol. 12, pp. 53–53–64, 1994, doi: 10.1007/s00585-994-0053-0.

[106] P. J. Sellers *et al.*, "BOREAS in 1997: Experiment overview, scientific results, and future directions," *J. Geophys. Res.*, vol. 102, no. D24, pp. 28731–28769, 1997.

[107] R. H. Waring and D. L. Peterson, "The oregon transect ecosystems research (OTTER): Summary and overview," *Ecol. Appl.*, vol. 4, no. 2, pp. 211–225, 1994.

[108] D. Roberts, "Large-scale biosphere atmosphere experiment in amazonia (special issue)," *Remote Sens. Environ.*, vol. 87, no. 4, pp. 277–562, Nov. 2003.

[109] "Global change: Impacts on habitability, a scientific basis for assessment: Report from woods hole workshop," JPL Caltech, Pasadena, CA, USA, Rep. JPL D-95, 1982. [Online]. Available: https://ntrs.nasa.gov/citations/19820025024

[110] "Land-related global habitability science issues," NASA Office of Space Sciences and Applications, Washington, DC, USA, Rep. 85841, 1983. [Online]. Available: https://ntrs.nasa.gov/citations/19830021473

[111] *Earth System Science: Overview: A Program for Global Change*. Washington, DC, USA: National Research Council, National Academies Press, 1986. [Online]. Available: https://www.nap.edu/catalog/19210/earth-system-science-overview-a-program-for-global-change

[112] S. G. Tilford, G. Asner, and P. W. Backland, "Mission to planet earth," *Adv. Space Res.*, vol. 14, no. 1, pp. 5–9, 1993, doi: 10.17226/19210.

[113] "Earth science enterprise," NASA, 1998. Accessed: Dec. 2021. [Online]. Available: https://www.hq.nasa.gov/office/codez/plans/99nsp/12.html

[114] "Perspectives on EOS special edition," NASA, Earth Observer, vol. 20, pp. 1–73, 2008. [Online]. Available: https://eospso.nasa.gov/sites/default/files/eo_pdfs/Perspectives_EOS.pdf

[115] C. J. Johannsen and D. A. Landgrebe, "Earth observational research using multistage EOS-like data," Purdue Univ., West Lafayette, IN, USA, 1994. [Online]. Available: https://ntrs.nasa.gov/api/citations/19940028513/downloads/19940028513.pdf, https://www.lars.purdue.edu/home/references/LTR_053194.pdf

[116] Y. J. Kaufman, D. D. Herring, J. Ranson, and G. J. Collatz, "Earth observing system AM1 mission to earth," *IEEE Geosci. Remote Sens.*, vol. 36, no. 4, pp. 1045–1055, Jul. 1998, doi: 10.1109/36.700989.

[117] "Shuttle radar topography mission," NASA JPL, 2009. Accessed: Dec. 2021. [Online]. Available: https://www2.jpl.nasa.gov/srtm/mission.htm

[118] "National satellite land remote sensing data archive," USGS EROS, 2021. Accessed: Dec. 2021. [Online]. Available: https://www.usgs.gov/centers/eros/science/national-satellite-land-remote-sensing-data-archive?qt-science_center_objects=0#qt-science_center_objects

[119] C. E. Woodcock *et al.*, "Free access to landsat imagery," *Science*, vol. 320, 2008, Art. no. 1011, doi: 10.1126/science.320.5879.1011a.

[120] J. C. Lindenlaub, "Guide to multispectral data analysis using LARSYS," LARS Purdue Univ., West Lafayette, IN, USA, Rep. 062874, 1974. [Online]. Available: https://www.lars.purdue.edu/home/references/LTR_062874_2.pdf

[121] L. L. Biehl and D. A. Landgrebe, "MultiSpec—A tool for multispectral-hyperspectral image data analysis," *Comput. Geosc.*, vol. 28, no. 10, pp. 1153–1153–1159, Dec. 2002, doi: 10.1016/S0098-3004(02)00033-X.

[122] L. L. Biehl, "MultiSpec," 1995. Accessed: Aug. 2021. [Online]. Available: https://github.com/larrybiehl/MultiSpec

[123] L. L. Biehl, A. R. Maud, W.-K. Hsu, and T. T. Yeh, "MultiSpec," 2021. Accessed: Aug. 2021. [Online]. Available: https://mygeohub.org/tools/multispec

[124] N. J. Nilsson, *Learning Machines: Foundations of Trainable Pattern-Classifying Systems*. New York, NY, USA: McGraw-Hill, 1965.

[125] I. Goodfellow, Y. Bengio, and A. Courville, *Deep Learning*. Cambridge, MA, USA: MIT Press, 2016.

[126] X. Zhu *et al.*, "Deep learning in remote sensing," *IEEE Geosci. Remote Sens. Mag.*, vol. 5, no. 4, pp. 8–36, Dec. 2017, doi: 10.1109/MGRS.2017.2762307.

[127] Y. Chen, Z. Lin, X. Zhao, G. Wang, and Y. Gu, "Deep learning-based classification of hyperspectral data," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 7, no. 6, pp. 2094–2107, Jun. 2014, doi: 10.1109/JSTARS.2014.2329330.

[128] A. E. Normand, "Landsat 9 and the future of the sustainable land imaging program," Congressional Research Service, Washington, DC, USA, Rep. R46560, Nov. 2021. [Online]. Available: https://crsreports.congress.gov/product/pdf/R/R46560

[129] "ABI bands quick information guides," NOAA & NASA, 2021. Accessed: Dec. 2021. [Online]. Available: https://www.goes-r.gov/

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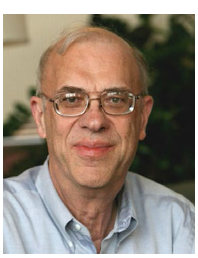
He spent some quality time with the U.S. Army Air Defense, in the early 1970s. He served as Acting Director of the ISU Remote Sensing Laboratory in 1977. From 1978 to 1982, he was a Research Associate in Geography with the Columbia University, and the NASA Goddard Institute for Space Studies, New York, NY, USA, where he primarily worked on LACIE/AgRISTARS. In 1982, he moved to Geography University of Maryland (UMD), College Park, MD, USA, and the NASA GSFC, Greenbelt, MD, USA, as a Research Scientist. He worked with the GIMMS, MLA, and other activities. In 1985–1986, as an IPA, he was a Program Manager with the NASA HQ Remote Sensing Science and Hydrology Programs. In 1986, he became a UMD Geography Faculty. He was tenured in 1989 and promoted to the rank of Professor in 1992. From 1995 to 2001, he served as the Department Chair as well as holding a joint appointment with the UMD Institute for Advanced Computer Studies. In 2015, he retired as a Professor Emeritus. His research interests include NASA, but also USGS, USDA, NSF, Resource21, Northrup Grumman, and Global Science and Technology Inc. In 1992, he was selected as the Landsat Science Team Leader, which continued until 2001, when this team was disbanded. In 2006, he and Darrel Williams, with colleagues, began the compilation of Landsat technical history with NASA History Office funding. The project compiled unpublished documents and conducted stakeholder interviews. The results were published as *Landsat's Enduring Legacy: Pioneering Global Land Observations from Space* (ASPRS, 2017).

Dr. Goward is an emeritus member AAG, AGU, and ASPRS. He has been recognized for his work by the AAG remote sensing specialty group (1998), NASA Goddard *LPSO* (1999)**,** NASA *JACIE* (2004), NASA/USGS *William T. Pecora Award* (1999–Landsat, 2008–personal), USGS *John Wesley Powell Award* (2006) ASPRS *SAIC Estes Memorial Teaching Award* (2008) UMD BSOS College *Dean's Medal* (2013), and ISU Graduate School *Outstanding Alumni Award (2017)*.



Marvin E. Bauer received the B.S. degree in agriculture and the M.S. degree in agronomy from Purdue University, West Lafayette, IN, USA, in 1965 and 1967, respectively, and the Ph.D. degree in agronomy (crop ecology) from the University of Illinois, Champaign, IL, USA, in 1970.

He was a Research Agronomist (1970–1983) with the Laboratory for Applications of Remote Sensing, Purdue University, where he had key roles in the 1971 Corn Blight Watch Experiment, Large Area Crop Inventory Experiment, and AgRISTARS projects. As a Professor (1983–2015) and Professor Emeritus (2015–present) with the University of Minnesota, Minneapolis, MN, USA, his research interests include development of quantitative satellite remote sensing for crop and forest inventory, monitoring lake water quality, impervious surface mapping, and land cover change detection and analysis.

Dr. Bauer was the Editor-in-Chief of *Remote Sensing of Environment* from 1980 to 2014 and is a Fellow of the American Society of Photogrammetry and Remote Sensing, and recipient of the USGS/NASA *William T. Pecora Award*, NASA *Distinguished Public Service Medal*, ASPRS *SAIC Estes Memorial Teaching Award*, and *Minnesota GIS/LIS Consortium Lifetime Achievement Award.*

Larry L. Biehl (Member, IEEE) received the B.S. degree in electrical engineering and the M.S. degree in engineering from the Purdue University, West Lafayette, IN, USA, in 1973 and 1974, respectively.

He was a Research Engineer with the Purdue University's Laboratory for Application of Remote Sensing, from 1974 to 1985 and 1988 to 2004. He participated in Skylab, Landsat MSS, and Landsat Thematic Mapper research, and had major responsibilities in NASA-sponsored field research programs including field spectral data acquisition and calibration procedures, data preprocessing, and software development. He managed the antenna, computers, and image data for the Purdue Terrestrial Observatory from 2004 to his retirement in 2020. He helped to initiate the IndianaView consortium (www.indianaview.org), with Dr. Gilbert Rochon and was the Director of IndianaView until his retirement. He has been very involved with the parent consortium, AmeriaView as a member of the Board of Directors and was the chair of the Education Committee. His professional contributions include the development of a software program, titled MultiSpec, which is used for remote sensing analyses using pattern recognition techniques by undergraduates, graduate students, government, commercial institutions, and K-12 on personal computers running the Mac OS or Windows operating systems and more recently also as a web-enabled application on mygeohub.org as part of NSF funded project.

Mr. Biehl is a member of ASPRS.

Forrest G. Hall received the B.S. degree in Mechanical Engineering from the University of Texas, Auston, TX, USA, in 1963, and the M.S. and Ph.D. degrees in physics from the University of Houston, Houston, TX, USA, in 1968 and 1970 respectively.

In 1963, he was hired by the Johnson Space Center, Houston, TX, USA, to work with a design group, designing such things as docking mechanisms for the Gemini and Apollo missions and landing gear for the Lunar Excursion Module that landed astronauts safely on the lunar surface. A realization of love for physics led him to the University of Houston. When he returned to NASA, analyzing data from scientific experiments placed on the Lunar Surface by the Apollo astronauts, and, when NASA's moon program ended in the late 1960s, this Texan scientist, continued to work on the design of a brand-new concept within NASA: remote sensing. He worked on the Skylab program, putting remote sensing instruments aboard an S-IVB booster, once used to send Apollo missions into space. In the mid-1970s, he was named a Project Scientist on a new NASA remote sensing project, the Large Area Crop Inventory Experiment, to estimate Soviet wheat production from space. This was designed and implemented following a disastrous failure of the Soviet wheat crop in 1972. They created a successful monitoring system using Landsat data. After LACIE, he joined GSFC in 1985 and continued his remote sensing work, using it to aid in the study of the Earth's climate and the effects humans are having on it. He also has held key roles in programs such as AgRISTARS, ISLSCP, and associated field campaigns such as FIFE and BOREAS. His work has led to a better understanding of North America's carbon, water, and energy cycles.

Dr. Hall was the recipient of the NASA/USGS *William T. Pecora Award.*

Roger M. Hoffer was born in Michigan, in 1937. He received the B.S. degree in forestry from the Michigan State University, East Lansing, MI, USA, in 1959, and the M.S. and Ph.D. degrees in watershed management from the Colorado State University, Ft. Collins, CO, USA, in 1960 and 1962, respectively.

After 2 years in the Infantry, U.S. Army (Platoon Leader, Battalion Adjutant, Company Commander; Korea and California), he taught and conducted remote sensing research with the Purdue University, West Lafayette, IN, USA, from 1964 to 1988. From 1988 to 2002, when he retired, he was an Educator and a Researcher with the Colorado State University. He was the academic advisor for 67 M.S. and Ph.D. graduate students, the Principal Investigator or Co-Principal Investigator on 61 research grants totaling more than $4 300 000, and has authored or coauthored 295 research papers and publications. He has conducted research and given scientific presentations (many of which were invited presentations) in 21 countries around the world (he has visited many countries, especially in Europe, Asia, and South America, multiple times). His research interests include computer-aided analysis of multispectral scanner and radar data, and on the spectral characteristics of Earth surface materials, especially agricultural crops and forest cover.

Dr. Hoffer was the National President of the American Society for Photogrammetry and Remote Sensing (ASPRS), from 1989 to 1990, and the recipient of many awards from ASPRS and the Society of American Foresters, including the ASPRS highest award—the Lifetime Achievement Award (no more than 25 living recipients, worldwide, at any time).

John A. Richards (Life Fellow, IEEE) received the B.E. and Ph.D. degrees in electrical engineering from the University of New South Wales, Sydney, NSW, Australia, in 1968 and 1972.

He was the Founding Director of the Centre for Remote Sensing, University of New South Wales, in the 1980s, before moving to the Chair of electrical engineering with the UNSW Canberra, Australian Defence Force Academy. Before retiring, he held the positions of Dean of the College of Engineering and Computer Science, and Deputy Vice-Chancellor and Vice-President, of the Australian National University. He has authored two texts on remote sensing: *Remote Sensing Digital Image Analysis*, 5th ed., Springer, Berlin, 2013 and *Remote Sensing with Imaging Radar*, Springer, Berlin, 2009. His research interests include image analysis and imaging radar.

Dr. Richards is a Fellow of the Australian Academy of Technological Sciences and Engineering.

Laura E. P. Rocchio received the B.S. and M.A. degrees in geography from the University of Maryland, College Park, MD, USA, in 1997 and 2000, respectively, and the M.A. degree in publication design from the University of Baltimore, Baltimore, MD, USA, in 2009.

From 1998 to 2000, she was a Graduate Research Assistant with the Vegetation Canopy Lidar Project. Since 2000, she has been a Science Communicator with the Landsat Program, NASA's Goddard Space Flight Center, Greenbelt, MD, USA (via Science Systems Applications, Inc.). She is currently a Senior Outreach Coordinator with the Landsat team there. She has coauthored the book *Landsat's Enduring Legacy: Pioneering Global Land Observations from Space* and has written scores of Landsat-focused feature stories. Her research interests include the technical history of Landsat, remote sensing applications, and visual communication.

Ms. Rocchio is a member of the American Geophysical Union, and for 5 years conducted a Q&A series based on Landsat-related research presented at the AGU Fall Meetings. She is also a member of the American Association of Geographers.

Vincent V. Salomonson (Fellow, IEEE) received the B.S. degree in agricultural engineering from the Colorado State University, Fort Collins, CO, USA, in 1959, the B.S. degree in meteorology from the University of Utah, Salt Lake City, UT, USA, in 1960, the M.S. degree in agricultural engineering from the Cornell University, Ithaca, NY, USA, in 1964, and the Ph.D. degree in atmospheric science from the Colorado State University, in 1968.

He is currently a Research Professor (Emeritus) with the University of Utah. He has served as a Research Professor with joint appointments with the Departments of Atmospheric Sciences and Geography, University of Utah, from 2005 to 2020. He is also a Senior Scientist (Emeritus) in the Earth Sciences Division with the Goddard Space Flight Center of NASA. Prior to being a Senior Scientist, he was the Director of the Earth Sciences Directorate with the Goddard Space Flight Center, NASA, from 1990 to 2000. He has served with the Goddard as the Deputy Director for Earth Sciences in the Space and Earth Sciences Directorate (1988–1990), the Chief of the Laboratory for Terrestrial Physics (1980–1988), the Head of the Hydrospheric Sciences Branch (1973–1980), and as a Research Meteorologist (1968–1973). From 1988 to 2009, he has served as the Science Team Leader for the NASA Earth Observing System MODIS instrument and Project Scientist for Landsat 4 and 5 (1977–1989). Before coming to Goddard, he spent 3 years as a Weather Officer with the United States Air Force (1959–1962). He has authored/coauthored more than 130 publications in scientific journals, books, conference proceedings, and NASA reports (more than 80 are refereed/peer-reviewed publications).

Dr. Salomonson is a Fellow and Honorary Member of the American Society for Photogrammetry and Remote Sensing, and a member of the American Meteorological Society and the American Geophysical Union.

Darrel L. Williams was born in Punxsutawney, PA, USA, in 1951. He received the B.S. and M.S. degrees in forest science from the Pennsylvania State University, University Park, PA, USA, in 1973 and 1974, respectively, and the Ph.D. degree in physical geography from the University of Maryland, College Park, MD, USA, in 1989.

From 1975 to1991, he was a Physical Scientist with the Biospheric Sciences Branch, NASA's Goddard Space Flight Center, Greenbelt, MD, USA. He then served as the Head of that Branch from 1991 to 2001. From 2001 until his retirement from NASA in 2010, he served in progressively more authoritative positions with the Hydrospheric and Biospheric Sciences (HBS) Laboratory, ending his NASA career as an Acting Chief with the HBS. He also served as an Assistant Project Scientist for Landsat 4 and 5, and as a Project Scientist for Landsat 7. Since 2010, he has been a Chief Scientist for Global Sciences the Technology, Inc, Greenbelt, MD, USA. His research interests include remote sensing research, with a special focus on developing enhanced techniques for assessing forest ecosystems worldwide.

Dr. Williams was the recipient of the NASA Medals for *Outstanding Leadership* and *Exceptional Service*, the *Aviation Week and Space Technology 1999 Laurels Award* for outstanding achievement in the field of Space in recognition of his scientific leadership role for the highly successful Landsat 7 mission, and an *Outstanding Alumni Award* from the School of Forest Resources at the Pennsylvania State University (2006) where his involvement with Landsat began in 1973. He was also the recipient of the *William T Pecora Award* (2017) for his individual contributions as a catalyst behind many innovations for the Landsat program and for outstanding contributions to understanding the Earth through remote sensing.