Reprinted from

Eighth International Symposium

Machine Processing of

Remotely Sensed Data

with special emphasis on

Crop Inventory and Monitoring

July 7-9, 1982

Proceedings

Purdue University
The Laboratory for Applications of Remote Sensing
West Lafayette, Indiana 47907 USA

ADVANCED SENSOR SYSTEMS: THEMATIC MAPPER AND BEYOND

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I. ABSTRACT

Thematic Mapper will be launched on LANDSAT-D in July, 1982, offering new spectral data of 30 m ground IFOV resolution. The French SPOT system is being built for a mid-80's launch and will feature rapid data delivery and a guaranteed ten year service continuity. The Japanese MOS and LOS systems are under development for latter-half of the 80's launches. NASA/GSFC has recently received completed design studies for a multispectral linear array sensor. Results of a study to identify fundamental research issues in electromagnetic sensors and signal handling show that ample technology is available to design systems to meet user needs; the major problem is to get the user to state those needs in a manner that will lead to rational system design.

II. THEMATIC MAPPER

Thematic Mapper has been described in detail by Engel (1). A 41 cm f/6 Ritchey-Chretien telescope with a clear aperture of 1063 cm^2 is preceded by a large main object plane cross-track scanning mirror and followed by a scan line corrector mirror assembly. The scan line corrector assembly jumps forward along-track at each main mirror turn-around and back-scans to provide truly lateral cross-track scanning corrected for forward spacecraft motion. This permits scanning in both sweep directions for an 85% scan efficiency.

A primary focal plane contains detector arrays of 16 each in four spectral bands: 0.45-0.52, 0.52-0.60, 0.63-0.69, and 0.76-0.90 μm respectively. Ground IFOV is 30 x 30m, and noise equivalent reflectance change is 0.5% except for the 0.45-0.52 band where it is 0.8%. Relay optics image a cooled focal plane array of 16 detectors each in the SWIR bands of 1.55-1.75 and 2.08-2.35 μm with a 1% and 2.4% noise equivalent reflectance change respectively, and a 4 detector array at 10.4-12.5 μm with a 0.5^{o}K noise equivalent temperature difference.

The multimission modular spacecraft carrying Thematic Mapper will have a nominal altitude of 705km but will vary from 696 to 741 km with a variation of 19 km over a fixed latitude. Low frequency attitude control will hold the spacecraft body axes to ±175 μrad and drift rates to 18 nrad/s. From 0.01 to 0.4Hz attitude variations are expected to be less than 50 μrad and less than 8 μrad from 0.4 to 7Hz; primary cause for these variations is the TDRSS antenna drive motors. Jitter at frequencies greater than 7Hz are expected to be less than 5μrad in roll and less than 1.5μrad in pitch and yaw. Prakash and Beyer (2) have described the resampling processing to address scan gaps caused by jitter and scan underlap due to altitude variations. Dry rotor inertial reference units estimate body attitude out to 2Hz. An angular displacement sensor mounted on Thematic Mapper estimates optical boresight attitude from 2 to 125Hz.

Users may expect to receive computer compatible archival and product tapes made from high density archival and product tapes at a rate of one scene per day in a research phase. Archival tapes will contain raw data and headers of systematic correction data generated from payload correction data and mirror scan correction data. Raw attitude, scan mirror, and orbit data are not on the archival tapes; rather, these have been processed into a set of correction matrices. Product tapes will contain preprocessed (resampled) data with geodetic and geometric errors removed to the extent possible.

II. SPOT

SPOT is a multispectral and panchromatic linear array sensor to be flown in 1985 in a near-circular 832km sun-synchronous orbit with a 26 day nadir revisit frequency and a 10:30 a.m. equator crossing. Off-nadir viewing will provide approximately 5 or less day viewing intervals, though at angles ranging from near nadir to 27° off-nadir. Two sensors will be mounted side by side on the spacecraft and cover two 60km swaths with 3km overlap for a total 117km swath width.

A plane steerable mirror precedes a Matsukov telescope with an intermediate folding mirror. While I do not have direct data, it would appear from photos to have approximately a 90 mm array length calling for a 1.25m focal length; aperture diameter appears to be about 40 cm for an f/3 system. A 6000 detector array covers 0.51-0.73 μm with a ground IFOV of 10 x 10m. Three multispectral detector arrays cover 0.50-0.59, 0.61-0.68, and 0.79 -0.89 μm in 20 x 20m pixels. Data rates are 25 M bits/sec in both the multispectral and panchromatic modes per sensor.

Position uncertainty in the SPOT orbit will be 500m in altitude, 500m cross-track, and 1000m along-track. Attitude will be controlled to ± 0.15°. Attitude rates will be controlled to be less than 7 μrad/s for less than 0.05Hz, less than 4.4, 10.5, and 5.2 μrad/s in roll, pitch, and yaw respectively for 0.05-2Hz and less than 3.5 μrad/sec in roll and yaw, less than 7 μrad/sec in pitch for frequencies greater than 2Hz.

One can predict that if SPOT performs well the VNIR spectral coverage typical of LANDSAT 1-3 will seldom be done with electromechanical scanners. It should be noted that an aircraft-mounted pushbroom sensor in VNIR is commercially available (3).

A unit called SPOT-IMAGE will market and distribute data products from a Centre des Images Spatiales. Level 1 products contain basic radiometric and Earth motion corrections. Level 1a is radiometric processing to equalize CCD push-broom elements. Level 1b contains a radiometric desmearing due to satellite motion and further corrects for Earth rotation, curvative, and view angle, and constitutes the first resampling. Level 1b is expected to have a geodetic accuracy of 1000m. Level 2 products include rectification via ground control points, but do not include terrain relief; the geodetic accuracy will be 50m. Finally, Level 3 products include digital terrain model correction for parallax effects, resulting in orthophoto-type imagery and an expected geodetic accuracy of 10m. Products will be CCT's or 241 mm film at a scale of 1:400,000, with larger scales also available. 700 scenes/day will be archived, 50 scenes/day is the expected product rate. Level 1a has a one day production time, Level 2 a one week production time. Users will be guaranteed 10 year service continuity. Market distribution expectations circa 1981 are 10% in France, mostly governmental agencies, 20% for French companies with interests in other countries, 30% United States, both governmental and private interests, and 40% the remainder of the countries of the world.

III. JAPANESE PLANS

The Japanese plan to launch a marine observation satellite (MOS) in 1986 with sensors in the visible, thermal infrared, and microwave spectral regions. An MOS 2 and MOS 3 are proposed, as are land observation satellites LOS 1 and LOS 2. Typical sensors include a push-broom VNIR linear array unit with spectral bands at 0.51 -0.59, 0.61-0.69, 0.72-0.80 and 0.80-1.1 μm and a ground IFOV of 50 x 50m from a 909km nominal orbital altitude. Further, a 15 cm aperture radiometer with bands from 0.5-0.7μm, 6-7μm, 10.5-11.5, and 11. 5-12.5μm is included, with a 1mrad IFOV in the visible and a 3mrad IFOV in the infrared. A scanning microwave radiometer is also part of the sensor package with two bands at 23.8 and 31 GHz, 2° and 1.5° beam widths respectively, with an 18 rpm conical scan.

The VNIR sensor will cover a 100km wide swath using a 2048 element CCD with 40 x 40μm detectors, and use an 8 M bits/s data rate. Six bit quantization with AGC is used.

The LOS Spacecraft attitude will be controlled to 0.01°/s roll and pitch, and 0.5°/sec in yaw.

IV. MLA DESIGN STUDY

NASA conducted a design study on a multispectral linear array sensor with the following requirements:

- Thematic Mapper VNIR and SWIR bands
- Operation at 283, 470, and 705 km orbits, 9:30 to 10:30 a.m. equator crossing
- 15 x 15m IFOV in VNIR, 30 x 30m in SWIR
- 0.5% relative, 5% absolute within band radiometric calibration
- 1% relative band-to-band radiometric calibration

- Geometric positioning of 20 IFOV's span in-track, 0.1 IFOV in position cross-track, parallel in separate bands to 0.2 IFOV
- 15° field of view
- Stereo along-track + 26°
- Roll cross-track + 30°
- Two 150 M bits/s links to TDRSS, one 100 M bit

Four companies developed designs: Ball Brothers, Eastman Kodak, Honewell, and Santa Barbara Research Center (Hughes). One has been reported in the open literature by Keene (4) and consists of a reflec-tive Schmidt telescope with interference filters over 15 x 15μm VNIR silicon CCD detectors and over 25 x 25μm HgCdTe detectors in a 30μm pitch array.

Overall, the instrument design study showed that an instrument built to specifications would be complex, difficult, and expensive. There are typically 500 to 1000 leads to the focal plane, cooling is a problem, and the possibility of uniformity of spectral defining filters over tens of centimeters is an unknown. Large aperture wide field optics generally calls for three or more surfaces or non-conic section surfaces. The registration specification of 0.1 IFOV is not reasonable,and 0.2 to 0.3 IFOV doesn't look much better. If the positioning across the entire array is worse then 0.3 IFOV or so then resampling is necessary. Further, radiometric calibration requirements are difficult to meet. The SWIR focal plane array is a major problem requiring technology developments that do not appear easy.

Wellman has reported on technologies for multispectral mapping of Earth resources (5), concentrating on the pushbroom approach. He concludes that the technical problems in order of difficulty (most difficult first) are

1. SWIR detector array development
2. Large aperture wide field optics
3. Cooling
4. Electronics for large data rates

JPL is working on a design based on the wide imaging spectrometer (WISP) concept of the 1960's. A dispersing element (grating or prism) spatially separates different wavelength components in one dimension while a slit field stop determines a cross-track image line in an orthogonal direction. Then an areal array can sample wavelength in one dimension and cross-track location in the other dimension.

V. FUNDAMENTAL RESEARCH IN SENSORS

A study to define fundamental research issues in electromagnetic sensors and signal handling is nearing completion. The area was divided into several categories. The categories and tentative conclusions in each will be discussed in turn below.

A. PLATFORM POSITION AND VELOCITY

Earth remote sensing satellites can be tracked over short arcs to one meter to tens of meters accuracy depending on tracking system complexity. Orbit prediction models employed over a few days after orbit determination by tracking yield position accuracies of hundreds of meters to a kilometer or so. Continuous near real time tracking using the pending Global Positioning System will yield position accuracy of 10 to 100m and velocity accuracy of 1 to 10cm/s. Orbit adjustment is accomplished by well-developed thruster technology and is limited mainly by orbit estimation capability. This category is well-developed in basic knowledge and understanding, models are available for input to system design procedures, and future advancements call for evolutionary engineering improvements.

B. PLATFORM AND SENSOR ATTITUDE AND RATES

Earth remote sensing satellite platform attitude angles have been measured by horizon sensing and controlled to tenths of a degree. LANDSAT-D is designed for attitude measurement and control by star tracking, Kalman filter gyro drift estimation and reaction wheels to ± 175μrad bounds. (High Energy Astronomy Observatory-2 was controlled to ± 10 to 25μrad and estimated to better than 10μrad while Space Telescope is designed to achieve ± 35nrad rms pointing error. These show potential possibilities for Earth sensors.) Typical low frequency platform attitude control is limited to a bandwidth on the order of 0.02 Hz.

Vibration and thermal warping effects offset sensor boresight attitude with respect to platform attitude. Thermal effects are low frequency, large (50 to 100 μrad/°C or more), and could be measured with respect to platform axes on board. High frequency vibrational effects are serious; registration and rectification success depends on their attenuation. The problems of vibrational excitation of high frequency sensor attitude upsets became evident in the LANDSAT-D design and call for a triaxial angular displacement sensor with a bandwidth from 2 to 125Hz, mounted on the Thematic Mapper. General awareness that the remote sensing platform, its subsystems, the sensors, and their subsystems must be viewed as a complete and interactive system for attitude and attitude rate estimation and control is recent. This category of true sensor instantaneous boresight estimation and tight broad-band control of the platform/sensor system can profit from fundamental experimental research and creative engineering design.

C. OPTICS AND ANTENNAS

Telescope optics have been customarily of two-surface conic section reflective design exclusive of pointing and scanning mirrors. Wide field large aperture designs have been proposed for multispectral linear array sensors. These designs tend toward innovative configurations of three or more elements or non-conical section optical surfaces. Stray light and diffraction analysis capabilities are not well-developed for wide field large aperture systems and are candidates for fundamental research topics.

Electromechanical scanning is well-developed. It was customary to correct for scan motion variations from a desired sweep pattern in LANDSAT 1-3. Although Thematic Mapper design went to great pains to achieve a linearity that would avoid cross-track correction, it will still be necessary to do so. Mirror flexure mode effects in large oscillating mirrors need to be considered in system design. Good scan mirror position estimation and control is a key issue in high resolution sensors and calls for design capabilities that border on the realm of fundamental experimental research.

Wavelength discrimination is done by interference filter overlap, dichroic beam splitters, or dispersing elements in a post-field stop spectrometer. In the case of MLA designs the wide field calls for, either uniformity of optical coatings over long spans of many detector chips or a wide field spectrometer optical design, both items of fundamental experimental research. Electromechanical scanning designs of tens to a few hundred detectors tend to minimize the wavelength discrimination problems posed by MLA sensors.

Microwave experimental research opportunities exist in multifrequency, multipolarization systems. Frequency and polarization specifications tend to determine size and orientation of antenna components; some efforts are being pursued in overlayed multiple microstrip antenna array elements and feeds. Electromechanical conical scanning of the focal plane of large dish antennas is common practice for passive microwave sensing; for space systems the main requirement is creative structural design of large, light weight antennas. Adaptive large antennas such as line-of-sight scanners and multibeam systems have been proposed and are valid topics for fundamental experimental research.

Optical designs to measure polarization information in high data rate sensors are nonexistent. The normal rule is to design the system to minimize polarization sensitivity. To the extent that scene radiation studies show polarization information content in scenes, polarization sensor designs will call for fundamental experimental research.

D. DETECTORS AND ASSOCIATED ELECTRONICS

Beyond 1μm wavelength array detector technology is in a state of active development. Indium antimonide, mercury cadmium telluride, indium gallium arsenide, platinum silicide, and palladium silicide are materials being investigated. Indium antimonide at present falls short in charge transfer efficiency. Most hopeful at present is HgCdTe detector arrays coupled by indium bumps to silicon multiplexing chips. Opportunities for fundamental research in detector technology exist but have been well-funded by agencies other than NASA.

Spectral sensitivity, size, and geometric fidelity in multichip arrays are areas for fundamental experimental research. So, too, are areas of spatial and temporal sampling strategies in the focal plane in conjunction with pointing or scanning mirrors such as staring areal arrays sequentially gathering non-contiguous scene samples.

Focal plane packaging, alignment, and interconnection along with cooling requirements call for creative design that may border on fundamental experimental research.

E. SIGNAL PROCESSING AND HANDLING

In optical spectral regions the practice to date has been the return of raw scene signal data, calibration data, and spacecraft and payload data by conventional electronics systems with data compression where necessary. DC restoration in low frequency electronics is felt to still be a problem in achieving absolute calibration accuracy. Beyond that, there is a large question of how much of the ground processing can be put in the on-board data stream, and of that, how much should be ground-programmable. As orbit and attitude control and estimation capabilities improve the temptation to at least annotate data on-board will increase. These are areas for fundamental research inoverall system design.

The microwave area is fruitful ground for fundamental research in signal processing and handling. Direct processing of SAR data without image formation first, processing for squint and spotlight modes, and data compression of raw data are active areas where work is needed. Further, the value of retaining phase information, which disappears in image formation in current processing, is totally unknown and worthy of inquiry.

F. CALIBRATION

This is a very fertile area for fundamental experimental research. Current capability in VNIR is 5% absolute calibration and 1% relative calibration at the very best. Standard sources, stability, spatial uniformity, and sun calibration are areas of concern. In the infrared and microwave portions there is ample room for innovation in calibration of optics, antennas, and detector systems.

G. SYSTEM DESIGN AND MODELING

While several areas of fundamental research opportunities in electromagnetic measurements and signal handling have been stated above, the truth is that there is ample remote sensing technology available today that could be put to effective use if valid system missions statements were available. We have lots of technologies available (with some fundamental issues remaining) but don't know how to string the technologies together to do jobs. We don't have a clear idea of what jobs to do because user needs and proof thereof are vague, perhaps because those who have actual needs are not aware of what the technologies could do to meet those needs. While system design and the models required to carry it out may not be viewed as fundamental research per se, it is an essential supporting effort to fundamental research in scene radiation and atmospheric effects characterization, mathematical pattern recognition and image analysis, and information utilization and evaluation.

A system design flow is shown in Figure 1.

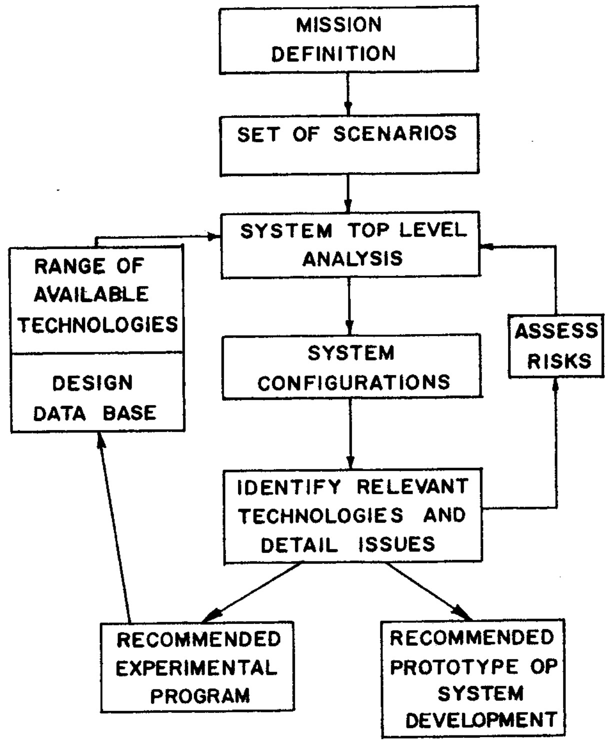

FIGURE I. SYSTEM DESIGN

A mission is stated. Several possibilities might be:

- Provide global VNIR coverage to the existing LANDSAT market at finer resolution with fast data delivery (SPOT).
- Provide global coverage over much of the optical spectral range for fundamental research basic data (Thematic Mapper).
- Sense ocean surface characteristics for inferences on fishing sites (Japanese MOS).
- Determine global crop production on an annual basis for several commercially important crops.
- Monitor forest production for a paper industry.
- Get real-time measurements of soil moisture.

The first three items clearly call for remote sensing capabilities, but it is conceivable that a system design for a certain mission might contain little or no remote sensing component.

Several mission scenarios are selected as candidates; they may or may not include remote sensing. If they do, then scenario choices might consider orbits, coverage frequency, sampling, inexpensive special purpose sensors, distributed data processing for rapid dissemination, long-life highly reliable sensors, and so on. Each scenario is subjected to a system top level analysis with input from a design data base and system technologies models through a simulation capability. Several system configurations are generated and a second, more detailed look is taken at relevant technologies and their issues; risks are assessed and fed back to system analysis. Finally an experimental program or operational system prototype development is recommended, and improved data are put in the design data base. This process should lead to the sort of technology performance/cost curves that show significant breakpoints and thereby allow choice of an efficient system.

The study group felt strongly that this area of system design was the most crucial of missing elements in the U.S. remote sensing efforts. Whether it is labeled fundamental research or not, it ought to be done and should begin with the development of the technology data base, system models, and simulation capability, the generation of prototype missions, and scenario sets to attain mission objectives.

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