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2. A STUDY TO IDENTIFY RESEARCH ISSUES
IN THE AREA OF
ELECTROMAGNETIC MEASUREMENTS AND
SIGNAL HANDLING OF REMOTELY SENSED DATA

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SUMMARY AND CONCLUSIONS

A 'Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data' was carried out in two working group meetings and four workshops. Members of the working group are listed at the end of this summary. Seven areas are addressed in the conclusions which follow: platform/sensor system position and velocity, platform and sensor attitudes and attitude rates, optics and antennas, detectors and associated electronics, sensor calibration, signal handling, and system design.

Available or pending (Global Positioning System) subsystems for remote sensing platform/sensor position and velocity selection, estimation, and control cover desirable ranges of those variables. No fundamental research support is recommended, as an ample data base and technology exists for system design.

Strong support of experimental fundamental research in minimization of vibrational and thermal sensitivity of instantaneous sensor boresight axes will pay off downstream in the data flow in easier registration and rectification. The entire platform and sensor complex should be dealt with as a complete and coupled remote sensing subsystem in this research on sensor attitude.

Experimental fundamental research in wide field large aperture optics point spread function analysis and measurement, particularly with respect to static or dynamic misalignment, figures and coatings, and mechanical support structure and manufacturability should be supported; it is needed for multispectral linear or area array sensors. Study efforts in active microwave antenna and radar electronics hardware should be supported to help in the development of multifrequency, multipolarization systems which are required for understanding of radar signal-scene interaction.

Strong support of experimental fundamental research in the detector array characterization area, incuding optical, mechanical, and thermal aspects, will pay off in uniformity and stability of the arrays. This research should emphasize, but not be limited to, the infrared spectrum beyond one micrometer. Material and array fabrication work should be funded from prototype sensor development funds.

Strong fundamental research efforts are needed in radiometric calibration at all wavelength ranges for both precision and accuracy. Success here, coupled with on-board radiometric correction, would reduce ground data processing loads at NASA, NOAA, and users' facilities.

Fundamental research in active and passive microwave signal handling and processing is recommended with concentration on information extraction, registration to other data, and close coupling to the fundamental research in understanding scene-signal interaction. Payoff is in knowing what the radar data alone or with other sensor data reveals about the scene.

A critical review of the system philosophy in ground data processing is recommended, including image formation, geometric correction, radiometric correction, and delivery of various products to users. Optimal placement (on-board, central facility, users' facilities) of processing steps against criteria of cost, timeliness, accuracy, and technology availability should be studied and argued, whether or not it is fundamental research.

Strong support of fundamental research in total system design and simulation is recommended, starting at the electromagnetic measurements and signal handling subsystems, and growing outward to the full span of remote sensing systems from scene radiation characteristics to information utilization and evaluation. System simulation capability pays off in analysis and demonstration of cost and performance sensitivities to user requirements (wavelength, resolution, coverage, data delivery speed, ...), whether the user is oriented towards applications or research.

Working group members were:

Fred C. Billingsley - Jet Propulsion Laboratory

Lloyd M. Candell - Santa Barbara Research Center

Robert H. Dye - Environmental Research Institute of Michigan

Charles Elachi - Jet Propulsion Laboratory

Daniel Held - Jet Propulsion Laboratory

Roger A. Holmes - General Motors Institute (group chairman)

Donald S. Lowe - Environmental Research Institute of Michigan

Robert B. MacDonald - NASA/Johnson Space Center

Marvin S. Maxwell - NASA/Goddard Space Flight Center

Robert F. Pelzmann - Lockheed Missiles and Space Company

Robert S. Powers - Environmental Research Institute of Michigan

Section 1

INTRODUCTION

1.1 Identity, Objective, and Definitions

This is the final report of 'A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data'. The report describes all work performed under contract NAS-9-16390 and covers the time period from July, 1981, through July, 1982.

The primary objective of this work is aptly described in the title of the study. Current status of the area is summarized and discussed in Section 2. Recommendations of specific areas of pursuit of fundamental research in electromagnetic measurements and signal handling are made in Section 3. Applied research and development in system design and modeling supportive of other areas of fundamental research in remote sensing is also presented in Section 3.

The definitions of terms employed in this study are those expressed in NASA Applications Notice AN:OSTA:81-B:

> Fundamental research: Activities intended to increase basic knowledge or understanding of a subject.
>
> Applied research: Activities that utilize existing knowledge and understanding in attempts to meet identified needs.
>
> Development: Activities associated with the design, and engineering demonstration of new devices, systems or methods.

Fundamental research is assumed herein to include both theoretical and experimental endeavors.

1.2 Methodology

Current status and fundamental research issues of electromagnetic measurements and signal handling were determined in two working group meetings and four workshops:

1. Working Group Organizational Meeting at ERIM, Ann Arbor, Michigan, August 6 and 7, 1981. General discussion on issues, format of pending workshops.

2. Workshop I, THE REMOTE SENSING SYSTEM: DATA SOURCES, FLOWS, AND USES, at the Lunar and Planetary Sciences Institute at NASA/JSC, Clear Lake City, Texas, October 14-16, 1981. Briefings from other study team leaders on fundamental research issues in scene radiation and atmospheric effects, mathematical pattern recognition and image analysis, and information utilization and evaluation. Current efforts in the GE-NASA/GSFC-EROS Data Center data source and flow system were presented and discussed as were the multispectral linear array instrument definition studies.

3. Workshop II, NASA REGISTRATION AND RECTIFICATION WORKSHOP, at the Xerox Training Center in Leesburg, Virginia, November 17-19, 1981, followed by an afternoon and morning meeting of the working group on November 19 and 20, 1981. Presentations on a broad range of registration and rectification issues followed by panel discussion and recommendations. The working group identified and discussed research issues in registration and rectification.

4. Workshop III, VISUAL, IR, AND PASSIVE MICROWAVE SENSORS, at NASA/GSFC, Greenbelt, Maryland, January 11 and 12, 1982. Presentations and discussions on atmospheric effects, LIDAR, calibration of sensors, MLA systems, detector arrays, passive microwave systems in soil moisture measurements, detector cooling systems, military systems.

5. Workshop IV, FUNDAMENTAL RESEARCH IN ACTIVE MICROWAVE REMOTE SENSING, at JPL, Pasadena, California, February 1 and 2, 1982. Presentations and discussions on scattering theories applied to imaging radars and scatterometers, imaging radar polarimetry, radiometry, performance metrics, elevation effects and stereo, synthetic aperture radar processing, and synthetic aperture radar data combination with multispectral data after geometric correction and mosaicing.

6. Working Group Recommendations Meeting, at Lockheed Missiles and Space Company, Palo Alto, California, April 12-14, 1982. Final discussions on recommendations of fundamental research work in electromagnetic measurements and signal handling.

Minutes of these workshops and meetings are included under separate cover.

1.3 Relation to Other Fundamental Research Studies

This study was one of four undertaken on the remote sensing system. Study areas are shown in Figure 1.1; the electromagnetic measurements and signal handling area of study is circumscribed.

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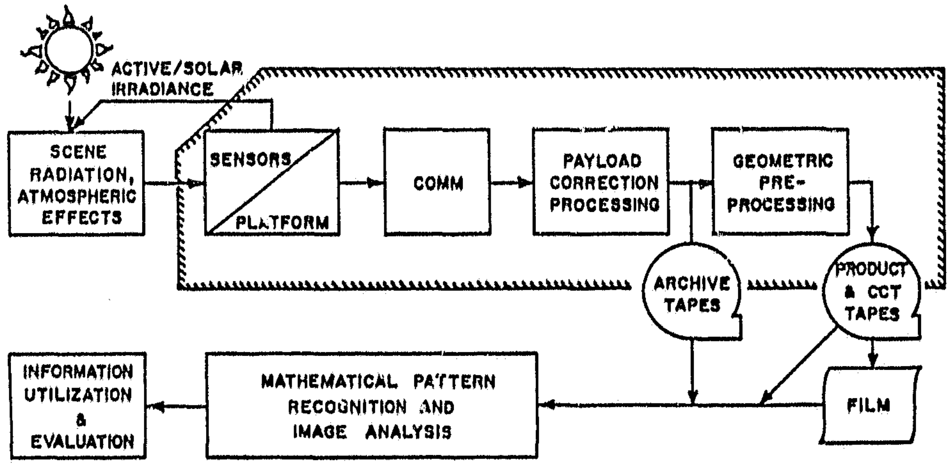

Figure 1.1 The Remote Sensing System

The four study areas are not as neatly separable and mutually exclusive as the diagram would imply.

Thus, the study on Mathematical Pattern Recognition and Image Analysis discusses geometric preprocessing including reference coordinate systems, registration and rectification sequence and methodology, resampling, accuracy measures, sensor and platform modeling, and topographic considerations. These items clearly relate to platform position, attitude, and structural rigidity, sensor geometric design and performance, and on-board and ground station signal processing. That same report discusses radiometric preprocessing including haze distortion, terrain relief effects, and view angle/sun angle effects. These items clearly relate to the sensor radiometric measurement integrity. The finite point spread function of the sensor mixes radiometric and geometric effects, further confounding subsequent image analysis.

The study on Scene Radiation and Atmospheric Effects Characterization discusses research necessary to understand the absorption and scattering of irradiating energy and consequent scene radiance, and atmospheric interaction with the scene radiance resulting in sensor irradiance. Atmospheric path radiance, scene radiance spatial distribution, adjacency effects (atmospheric point spread function), and atmospheric backscatter cross-irradiance influence the radiometric and geometric aspects of sensor measurements and so become influencing factors in preprocessing.

The study on Information Utilization and Evaluation recognizes that an ill-defined user community often unfamiliar with technology capabilities is asked to provide the requirements placed on other portions of the remote sensing system, particularly upon sensors and mission plans. Future system designs can evolve from actual information needs and desires expressed by potential users, from perceived markets envisioned by information system design venturers, or a combination of these forces.

Section 2

CURRENT STATUS OF ELECTROMAGNETIC MEASUREMENTS AND SIGNAL HANDLING OF REMOTELY SENSED DATA

In each subsection of this section current status in the area is summarized in italics; discussion supporting the summarization follows.

2.1 Platform/Sensor System Position and Velocity

Earth remote sensing satellites can be tracked over short arcs to an accuracy of less than a meter to tens of meters depending on the complexity of the tracking system. Orbit prediction models employed over a period of 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 100 meters, and velocity accuracy of one to 10 centimeters per second. LIDAR tracking can yield accuracy of one-tenth to one meter over arcs within tracking view. Orbit adjustment after tracking is accomplished by well-developed thruster technology and is limited mainly by the orbit estimation capability. Real time orbit control is limited by thruster fuel capacity and real time orbit estimation capability. Aircraft position and velocity determination can be done to similar accuracies but control to within meters is difficult due to atmospheric effects.

The platform/sensor system center of mass position and velocity components form an important part of the system state description. Current practice calls for a selection of a desired orbit or flight line, estimation of the actual orbit or flight line, and control or, at least, annotation of the actual orbit or flight line in an appropriate coordinate system.

Most Earth resources sensing orbits to date have been designed to be nearly circular at 700 to 950 kilometers altitude and sun synchronous. Sun synchrony achieved through orbital precession due to Earth oblateness sets the inclination at approximately 98°. While the second order associated Legendre polynomial term in the expansion of the gravitational potential of Earth dominates the orbit perturbation, higher order terms of the gravitational potential expansion, drag, solar radiation pressure, and perturbations from sun, moon, and planetary gravitational fields cause further deviations from the nominal circular orbit (1). Drag-compensated satellites, controlled by sensing motion of a proof mass and compensating by thrusters, can eliminate all but gravitational effects; such satellites are not currently used in remote sensing.

Analysis modules exist with Earth gravitational field expansions carried out to high degree and rank in spherical harmonics and atmosphere and solar effects appropriately modeled. Predictions over a period of days following accurate orbit determination have position uncertainty growth of a few hundred meters per day along track, about 50 meters per day cross-track, and a few tens of meters per day radially at typical resources sensing altitudes. The orbit itself will vary in altitude by over 40 kilometers around the globe, about 20 kilometers over a given latitude, and approximately 5 to 10 kilometers cross-track. The French SPOT satellite uncertainty is expected to be 500 meters in altitude and cross-track, and 1,000 meters along track (2).

Shuttle orbits and geosynchronous orbits for resources sensing are less familiar to the remote sensing community at this time. A considerable literature exists, however, on station-keeping and orbit determination for these orbits. The study cited (1) considers Earth applications orbit analysis for a shuttle-mounted multispectral mapper at a nominal 265 kilometers altitude initially circular sun-synchronous orbit. It shows initial altitude variations of 8 kilometers growing to 25 kilometers after 16 days, and orbital inclination pertubations of about 0.015° peak, translating into a cross-track swing of over a kilometer.

It appears, then, that satellite Earth orbits appropriate to remote sensing will have nearly periodic and monotonic drift deviations from orbit tracking updates that grow at rates of tens to hundreds of meters per day. Orbit selection is nominal at best; orbit determination requires frequent position and velocity measurement and orbit prediction with valid models propagating an epoch state.

Aircraft nominal flight line selection is commonplace. However, deviations from nominal due to winds, turbulence, and pilot action pose the problem of accurate state vector determination, particularly in such applications as active altimeter (laser, radar) profiling of the surface below.

Orbit or flight line estimation is accomplished by direct ground tracking from one or more stations, possibly with laser or radar ranging, Doppler ranging by trilateration from known-orbit navigational satellite constellations (3), and various combinations of multiple ground stations and known-orbit satellite comparisons. A study developing the Earth's gravitational field to eighteenth degree and geocentric coordinates for over one hundred satellite tracking stations from both satellite and terrestrial data (4) is informative of the considerations to be made in the coupled problem of accurate determination of both satellite orbits and tracking station coordinates. Satellite position determinations of 5 to 10 meters accuracy from stations located to 2 to 5 meters accuracy are quoted with optical tracking at 5 to 20 microradians directional accuracy after correction for precession, nutation, aberration and parallactic refraction; laser range data are assumed accurate to about 2 meters after correction. Since this 1973 work precision tracking is able to determine an orbit within tighter bounds; a meter or two has been assumed to be the know accuracy of the Seasat orbit over short arcs.

Predictions on the Global Positioning System state that in Phase I, 5 to 70 meters resolution in position and 0.01 to 0.13 meters/second resolution in velocity is expected. In Phase II position resolution increases to 2 to 15 meters and velocity resolution bounds improve to 0.01 to 0.05 meters/second. The GPS system will also be of value in remote sensing aircraft flight line estimation to similar accuracies (5). This near real time capability will thus give better opportunities for active small area scene acquisition and geodetic correction procedures.

In both satellite and aircraft resource sensing systems it is most desirable to relate the position and velocity vectors of the platform center of mass to an Earth-based datum rather than to a geocentric inertial reference frame. This places the burden for corrections for rotation, general precession, and nutation on the tracking or navigational systems for satellite platforms and aircraft navigating by satellite constellations. This is currently accomplished in the Landsat program, is included in the concept of the World Reference System, and is part of the geodetic error determinator subsystem for Landsat 4. At the present time estimates of the ephemeris state vector are coupled with estimates of attitude and instrument optical axis state vectors and checked against ground control point locations in a recursive distortion estimator process.

Orbit adjustments from nominal values are accomplished by conventional thruster systems for both manned and unmanned satellites. Real time orbit control or orbit transfer maneuvering calls for real time estimation of position and velocity either through tracking, inertial navigation with updates, or a Global Positioning System capability. Aircraft control to a selected flightline within meters is quite difficult; the controls are pitch, roll, and yaw rate actuators and cannot easily control against rapid atmospheric flow and density upsets to aircraft position.

2.2 Platform and Sensor Attitudes and Attitude Rates

Earth remote sensing satellite platform attitude angles have been measured by horizon sensing and controlled to tenths of a degree. Landsat 4 is designed for attitude measurement and control by star tracking, Kalman filter gyro drift estimation and reaction wheels to ±175 microradians error bounds. The High Energy Astronomy Observatory-2 attitude was controlled to within ±10 to 25 microradians and estimated to better than ±10 microradians. The Space Telescope is designed for ±35 nanoradians (rms) pointing error. These inertialy stabilized astronomy systems are noted to emphasize potential capabilities for Earth remote sensing platform attitude control. Platform attitude angular rates are limited by thruster torques and platform dynamics in Landsat 1-3, while in Landsat 4 the design limit is 10^{-6} degree/second. These angle and angular rate specifications apply to low frequency platform attitude control; the estimation subsystem bandwidth is typically a few Hertz or less, and the control system bandwidth is on the order of 0.02 Hertz.

Vibration and thermal warping effects offset the sensor boresight attitude with respect to the platform attitude. Thermal effects are low frequency, large (50 to 100 microradians 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 4 design and called for a triaxial angular displacement sensor with a bandwidth from 2 to 125 Hertz, 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. Landsat 4 expectations have been modeled and verified in actual flight data, and range from 5 to 50 microradians depending on frequency. French SPOT expectations are given in attitude rates of less than 3.5 microradians /second in roll and yaw and less than 7 microradians/second in pitch at frequencies in excess of 2 Hz.

The three angles which describe the instantaneous orientation of a set of platform body-fixed axes with respect to a geocentric inertial frame (say, equinox and equator of a particular epoch) and their rates of change or angular velocities constitute an additional six state variables. If the platform and sensory system can be assumed to approximate a rigid body to within some allowed error budget of, say, fractions of a microradian at all frequencies plus some calibrated, fixed offset, then knowledge of these six state variables plus the center of mass position and velocity state variables would suffice for a dynamic description of the platform/sensor system. However, this is not the present state of affairs. Larson, et.al.(6) noted that applications of modern control theory to nonrigid spacecraft were just beginning to emerge in 1977. The literature concerning flexible spacecraft attitude control has increased since then (see, for example, the Journal of Guidance and Control). One recent paper by Kaplow and Velman (7) addresses the issues of vibrating equipment on optical alignments of large space telescopes and instabilities that may result from flexible coupling between attitude sensors and actuators. A report on control system performance for the High Energy Astronomy Observatory on-orbit (8) addresses thermal bending distortions accounting for up to 92 microradians of misalignment and notes that a jitter specification of less than 5 microradians/second appears to be amply met.

Body attitude selection for most Earth sensing satellite systems has customarily called for maintenance of a nominal nadir pointing of one of the body axes. This is true for the Landsat series and Seasat, and appears to be the plan for the French SPOT and pending Japanese and Canadian satellite systems. Shuttle attitude is clearly commandable.

Estimation and control of platform attitude for remote sensing and other systems has been well-developed through the 1970's based on concepts that were well-understood by the mid-1960's. Roberson (9) reviewed the status of the field in early 1979. White, et.al.(10) dealt with Landsat missions presuming star tracker and landmark measurements in an extended Kalman filter estimation of attitude, orbital ephemeris, and gyro bias drifts. Attitude uncertainties of about 10 microradians in roll and pitch and about 50 microradians in yaw were found in that simulation and sensitivities with respect to star tracker and landmark update frequencies, landmark position error, star tracker angular error, and gyro random drift were graphed. The Seasat A attitude control system is described in considerable detail by Weiss, et.al.(11) to maintain 0.3 degree pitch and roll and 0.75 degree yaw stabilization. Sorenson, et.al.(12) describe digital algorithms for precision attitude estimation and control of attitude to better than ±0.01 degree from nominal for use in Landsat 4. The algorithms assume two precision star trackers making discrete attitude measurements and three rate-integrating gyros for an attitude estimation between star updates. Pointing errors lie well within the ±175 microradians allowed bounds, appearing to have peak-to-peak values of 75 microradians. The control system natural frequency is assumed to be 0.1 radians/second or a bandwidth of about 0.016 Hertz. Star tracker 1-σ noise nominal value was 50 microradians; it is noted the pointing errors are directly proportional to star tracker measurement noise and relatively immune to variations of typical gyro errors about nominal values. Star tracker nominal time between updates is one minute. Dougherty, et.al.(13) describe a preliminary design approach to a strapdown attitude reference system; root sum square error of three single-axis estimates ranges from about 48 to 165 microradians for three example systems. The High Energy Astronomy Observatory-2 system was successfully pointed to 10 to 25 microradians and attitude measurements to better than 10 microradians were evidenced (7). The French SPOT satellite is to be controlled to a low frequency attitude rate of less than 7 microradians/second at frequencies of less than 0.05 Hertz (2).

An electromagnetic sensor mounted on a sensing platform has a boresight axis; the optical axis of a telescope/pointing mirror arrangement or the main lobe axis of an antenna and appropriate orthogonal axes are typical choices. Commandable pointing by mirrors is called for in the French SPOT and the NASA Multispectral Linear Array sensor. The French SPOT sensors call for the ability to pushbroom-scan at up to ±27° off-nadir cross-track. The multispectral linear array design studies recently completed respond to a specification for ±30° roll off-nadir cross-track and ±26° off-nadir along-track for stereo capability. At least one of these studies (Eastman Kodak Company) has been reported in the open literature (14). Future sensor systems will probably have commandable sensor pointing as a matter of routine.

In addition to the purposeful relation of the sensor boresight axis to the platform axes, there will be a dynamic relation through structural vibrations and flexures excited by platform system actuators, sensor moving parts, or time-varying thermal gradients. Attitude and attitude rates of the sensor boresight axis with respect to platform axes constitute an additional six components of an eighteen component state vector: six in position and velocity of the platform, six in angles and angular rates of the platform, and six in angles and angular rates of the boresight axis. This is the current state vector employed in Landsat 4 and Thematic Mapper system analysis.

The frequency dependence of sensor boresight attitude variations is a critical consideration in high resolution sensor/platform system design. Geometric preprocessing is conventionally done by affine transformations on smaller portions of a large image known as subimages. The size of a subimage that can be fit with linear correction terms to within some error bounds depends on the rate and regularity with which a boresight axis changes dynamically during measurement of the scene. A high frequency large amplitude random jitter will substantially decrease the size of a subimage that can be dealt with by linear transformation, increase the geometric preprocessing difficulties, and call for a higher density of ground control points. In addition, such high frequency jitter can be sufficiently strong to cause complete pixel gaps: a study considering these effects has been reported for Landsat 4 (15).

Pre-launch expectations for low frequency variations for the 42.5 microradian instantaneous field of view of Landsat 4 Thematic Mapper were:

Frequency Range	1σ Error (microradians)	Primary Cause
0-0.01 Hz	175	Attitude Control System
0.01-0.4 Hz	48	TDRSS drive motors
0.4-7 Hz	7.3	TDRSS drive motors

For higher frequencies expectations on roll, pitch, and yaw jitter were:

	Baseline Expected Errors (microradians)	Worst Case
Roll	4.50	9.7
>7Hz Pitch	0.97	10.7
Yaw	1.46	81.5

These specifications assure that jitter gap caused by pitch and yaw will be less than one 30 meter pixel even in the severe case. As an additional low frequency attitude effect, there is a 58 microradian offset per degree Celsius across the Thematic Mapper.

While sensor boresight axis expectations are in the microradian or tens of microradians ranges for the Landsat 4 system, it remains to be seen at this writing how the actual performance measures up to expectations. The Landsat D Image Data Quality Analysis Program announced in AN:GSFC-81-A seeks to quantify the actual Thematic Mapper and Multispectral Scanner performances after the launch which occurred on July 16th, 1982. Preliminary communications from NASA/GSFC indicate the attitude displacement sensor shows 12 microradians peak-to-peak motion with the Thematic Mapper only, and about 15 to 20 microradians peak-to-peak motion with both the Thematic Mapper and the Multispectral Scanner active. Primary frequencies are 7, 63, and 68 Hertz, and amplitude changes with the relative phasing between the Thematic Mapper and the Multispectral Scanner.

The French SPOT, with a 24 microradian instantaneous field of view in the multispectral mode, 12 microradians in the panchromatic mode, calls for ±0.15 degree attitude variation limits. Maximum attitude rates are shown below:

		Frequency Range, Hz <0.05	0.05-2	>2
Slew rate, µrad/s	Roll	7	4.4	3.5
	Pitch	7	10.5	7
	Yaw	7	5.2	3.5

Attenuation of high frequency jitter by design is not well understood. Kaplow and Velman (7) propose separation of spacecraft into vibrationally 'dirty' zones and 'clean' zones with active isolation between zones.. While this may be reasonable for sensors that are not themselves potential vibration sources, Thematic Mapper and Multispectral Scanner in Landsat 4 are vibrational sources, coupled and asynchronous.

Aircraft sensing involves much the same issues in attitude measurement and control. Attitude effects are often much more noticeable in aircraft than in satellite data, particularly for lower altitude flights, and more time consuming in correction algorithms.

The Shuttle, as a large structure subject to complex vibrational modes coupled to maneuvers and strong thermal loads, poses potential problems in sensor boresight attitude estimation and control not well understood at this time.

While knowledge of physical principles of vibrations and thermal gradient warpings may be well in hand, the experimental understanding of the importance and magnitude of these effects on data analysis remains to be developed. This may be an important step to solve registration and rectification problems at their source.

2.3 Optics and Antennas

Telescope optics have customarily been of two-surface conic section reflective design exclusive of pointing and scanning mirrors for both satellite and aircraft remote sensing systems. Multispectral Scanner and Thematic Mapper feature Ritchey-Chretien telescopes: 22.8 centimeter diameter f/3.6 and 41.1 centimeter diameter f/6 respectively. SPOT, however, employs a Matsukov (refractive corrector) telescope.

Wide field large aperture designs are necessary for multispectral pushbroom 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 such systems. Commercial aircraft mounted multispectral linear array pushbroom sensors with refractive optics are available.

Rotating or oscillating scan mirrors typically scan cross-track, with scan line advancement achieved by platform motion. The Thematic Mapper employs two phase-locked oscillating mirrors to achieve active scan on both forward and reverse main mirror sweep for an efficiency of 85%. The Multispectral Scanner uses one oscillating mirror with active scan every other mirror sweep for an efficiency of 44%. Rotating mirror scanners customarily have scan efficiencies in the 10 to 50% range. Good scan mirror position estimation and control is a key issue in high resolution sensors.

Wavelength discrimination is done by interference filter overlays on detectors or fiber optics or dispersion after a field stop in a grating or prism spectrometer. Some multispectral linear array designs propose a system of dichroic filters in front of as many detector arrays as there are bands. Coverage ranges from the ultraviolet to the thermal infrared in bands which are typically 10 to 100 nanometers wide in the visible range, twenty to a few hundred nanometers wide in the short wave infrared, and a few micrometers wide in the thermal infrared. Certain applications call for narrower bands in various regions. (The following band-wavelength range definitions are employed in this report: ultraviolet - 0.2 to 0.38 micrometers, visible - 0.38 to 0.72 micrometers, near infrared 0.72 to 1.0 micrometers, short wave infrared - 1.0 to 4.5 micrometers, thermal infrared - 4.5 to 15.0 micrometers.)

Seasat and Shuttle synthetic aperture L-band radar sensors feature large array antennas. Passive microwave plans call for large deployable lightweight dish or phased array antenna designs. Apollo Lunar Sounder radar employed a very-high-frequency Yagi and a high-frequency dipole antenna. Typical aircraft mounted radar sensor remote sensing frequency bands are L, C, X, and K bands, with a variety of like and crossed polarizations. Band choice and transmit-receive polarization choices place stringent limitations on antenna design at present; multi-frequency/multipolarization antennas largely remain to be developed.

Polarization sensitivity plays two contrasting roles. In the optical region it is normally avoided as much as possible. Conscious sensing of polarimetric data in the optical regime is in its infancy in remote sensing of Earth resources. In the microwave region it is normally an inherent aspect of the transmitting or receiving system and is considered desirable as a measure of scene information content.

The optical sensor system telescope is irradiated with electromagnetic power expressable as a radiance field or, more completely, a Stokes vector field at the aperture. Power entering within an infinitesimal solid angle about a given direction should fall in a very small point on the focal plane except for aberrations (determined by degrees of freedom available to the optical designer, misalignment, and imperfect surfaces) and diffraction. The actual spreading of the irradiating power in the focal plane is expressed as a point spread function of the telescope (or its Fourier transform, the modulation transfer function). Misalignment and figure contributions to the point spread function can be modeled (16). The diffraction contribution has been calculated for circular or annular apertures (17, 18). The Thematic Mapper telescope point spread function has been modeled as a two dimensional Gaussian with a standard deviation of about 8 microradians at 0.5 micrometers wavelength or an 80^{0}/o radiant power blur circle of about 25 microradians.

The desire for simultaneous measurements over a wide range of wavelengths (0.35 to 13 micrometers typical) has usually led to a choice of all-reflective optics in the telescope. The Multispectral Scanner and Thematic Mapper are Ritchey-Chretien systems (19) (20). All-reflective optics are expected to continue in popularity in multispectral pushbroom array designs, though there are refractive designs extant, some with Mangin correctors, others with multiple telescopes.

The reflective Schmidt optical design by Kodak (14) is typical of efforts to achieve the wide field essential to multispectral linear array sensors. The multispectral linear array design study requirements call for over 12,000 sensors; at a typical linear array pitch of 15 to 25 micrometers per detector an array length of 18 to 30 centimeters is required. The degrees of freedom available to the designer in the Ritchey-Chretien telescope will not accommodate such a wide field (16) (21), so additional degrees of freedom associated with extra or nonconical section optical surfaces are required. SPOT, limited in wavelength coverage to the visible and near infrared spectral range, employs a refractive corrector in what appears in promotional literature to be a Maksutov telescope. Optical design of wide field large aperture telescopes is an active field of research in optics; configuration choice, diffraction analysis, and stray light understanding and minimization are subjects found in the recent literature.

The two basic processes of scene coverage most commonly used in optical remote sensing are:

1. Scanning by cross-track or conical mirror motion with a relatively small number of detectors per wavelength band (typically less than 25) with forward platform motion raster advancement, and

2. Scanning by forward platform motion while staring with a linear or area array of many detectors per band (typically thousands) with an integrate-and-dump sampling along-track.

Multispectral Scanner and Thematic Mapper are cross-track mirror scanners with pixel dwell times of 14 microseconds and 9.6 microseconds respectively. S-192 was a conical image plane scanner. The French SPOT sensor is a multispectral (visible and near infrared) and panchromatic linear array design with 3000 detectors per band and 6000 detectors respectively. It has a pixel dwell time of about 3 milliseconds multispectral, 1.5 milliseconds panchromatic. The Japanese also plan to launch a multispectral visible and near infrared linear array sensor with 2048 detectors per band. A commercially available multispectral linear array camera employing 7500 cross-track elements is built by Itek Optical Systems (22).

Area array scene coverage with other than photographic emulsion sensors has been employed in remote sensing systems; the return-beam vidicon cameras on Landsat 1, 2, and 3 were shuttered storage and readout array sensors. Recent solid state sensor developments in area arrays will probably call for a staring sensor in the future, with tracking or non-tracking optics.

Scan mirror motion estimation and control is critical to efficient registration and rectification, and is one of the trade-offs to be made for the smaller number of detectors required in a scanner system. Two scan mirrors operate in Thematic Mapper: the main cross-track scan mirror has a nearly linear (17.5 microradian total departure) scan over ±67,500 microradians except at the turn-around points and the along-track scan line corrector mirror jumps ahead at each turn-around of the main mirror and linearly backscans. This scheme permits bidirectional main scanning. The Landsat D Image Data Quality Analysis Program will seek to evaluate quantitatively mirror motion integrity, among other parameters (20).

Wavelength sampling in optical systems is typically done in three ways. First, electromagnetic power entering a field stop may be dispersed in a prism or grating spectrometer. A slit field stop can be used to achieve spatial coverage in one dimension and spectral coverage in an orthogonal direction. Such a system, being developed at Jet Propulsion Laboratory and called an 'imaging spectrometer', has been described by Wellman (23) using area arrays in the focal plane. Aircraft scanner data have been acquired using prism and grating specrometers. One experimental system in the late 1960's used the slit design described above with an image dissector tube as the area detector. The Coastal Zone Color Scanner is a grating spectrometer instrument. Second, several detectors may be spatially separated in the focal plane and overlaid with interference filters for the different spectral bands. This is the design of the Multispectral Scanner, the Thematic Mapper, and SPOT, and is also featured in some multispectral linear array proposals. The spectral data from a given pixel is dispersed in time by this method, either by scanning mirror motion or forward platform motion; it is necessary to repack the data stream to have all spectral channels from one pixel available at one time or memory location. Third, a system of beam splitters with dichroic filters, typically just before the focal plane, can be used to dissect the received electromagnetic power by wavelength. This system has an advantage of nearly perfect overlay of spectral bands during focal plane system construction. Such designs have been proposed in some multispectral linear array work.

Wavelength ranges from ultraviolet through the thermal infrared have been available in aircraft scanners; the situation is not nearly as good from satellites. Landsat 1-3 were limited to visible and near infrared bands though a thermal band flew on Landsat 3 that did not operate satisfactorily. Some lower resolution thermal infrared data have been available through the Heat Capacity Mapping Mission. However, Thematic Mapper offers the first availability of high resolution short wave infrared data and relatively high resolution (120m) thermal infrared data. The Coastal Zone Color Scanner covers four relatively narrow (20 nanometer) bands in the visible portion of the spectrum centered at 443, 520, 550, and 670 nanometers, a near infrared band 100 nanometers wide centered at 750 nanometers,and a 10.5-12.5 micrometer thermal infrared band, all at a nominal instantaneous field of view of 865 microradians (24), or a nominal ground instantaneous field of view of 825 meters. Japanese plans for marine and land observational satellites call for a visible and near infrared imaging linear array sensor and a radiometer with visible, water absorption band (6-7 micrometers), and thermal infrared bands. SPOT band choices of 0.52-0.59, 0.63-0.69, and 0.7-0.8 micrometers are clearly designed for a set of bands similar to those on the Multispectral Scanner of Landsats 1-4 without redundancy in the near infrared. Overall, although it appears that band selections are settling down, research remains to be done in the selection of narrower spectral bands to best observe ground spectral features while ameliorating atmospheric effects.

Polarization measurements remain a relatively unexplored area in the optical wavelengths from either aircraft or spacecraft platforms. Indeed, polarization sensitivity is currently viewed as something to be minimized in optical sensor design. Since much of the radiance at the Coastal Zone Color Scanner is atmospherically backscattered sunlight with variable polarization, that sensor was built with less than 2°/o polarization sensitivity (24). Preliminary field work exists that suggests polarization information is present in optical wavelengths from renewable resource scenes (25). Sensor design to purposely measure polarization at data rates common in remote sensing systems would prove challenging, though possibilities have appeared (26).

In microwave systems antennas tend towards specific frequencies and transmit/receive polarization sets. Unlike optical regions of the spectrum where wavelengths are smaller than even the smallest parts of the hardware, the receiver and transmitter hardware (antenna array elements, feed systems, front-end microstrip circuitry, duplexers, and so on) of microwave systems are inherently strongly wavelength-dependent in design. Radar frequencies used in remote sensing span from L-band around 1 gigaHertz to Kμ-band up to 18 gigaHertz; most systems are L, C, or X band, however.

Antenna designs in active microwave systems follow good radar engineering practice. The array antenna may pose difficulties of phasing, power distribution, and geometric integrity at short wavelengths in X-band and Kμ-band. Adaptive wavefront sensing and appropriate phasing can address such issues, as well as offer beam-steering capability. Relatively little attention has been paid to physical resolving power because imaging is accomplished from range and Doppler information in the return signal, typically using a fixed orientation antenna. To date there is satellite system experience in Seasat and Shuttle Imaging Radar, both in L-band and horizontal-horizontal polarization. Spatial resolution of 25 x 25 meters is achieved from typical Earth sensing attitudes; resolution requirements range from 10 x 10 meters to 100 x 100 meters in a broad user community (27). Generally, transmitting and receiving antennas are one and the same, with transmitting properties directly related to receiving properties. A scanning synthetic aperture radar concept has been proposed (28), as have multiple independent beams and single illuminator-multiple receiver beams, referenced in (28).

Passive microwave antennas achieve spatial coverage by forward platform motion, scanning by antenna or image plane receiver motion, antenna array phasing, and double receivers with aperture synthesis based on the van-Cittert-Zernicke theorem (17). Except in the latter case angular resolution in radians is limited to approximately the wavelength divided by the aperture dimension, and typically is on the order of 0.01 to 0.1 radian. An advanced mechanical conical scanning microwave radiometer and L-band electronically scanning microwave radiometer have been proposed for Spacelab (29).

In microwave systems a multifrequency and multipolarization transmitter and receiver capability is desirable, but is usually implemented by the simple expedient of a complete radar system for each frequency (30). Multifrequency/multipolarization microwave systems will require research in system design to achieve the efficiencies of multiple use of common elements or rapidly adaptive elements.

Polarization information appears to be present in active and passive microwave sensed data. Both Seasat and Shuttle Imaging Radar have horizontal-horizontal (send-receive) polarization only, but various aircraft radar systems exist with both single and dual polarization sets in horizontal-horizontal, horizontal-vertical, vertical-horizontal, and vertical-vertical. Even so, much of the multifrequency and multipolarization information content evidence comes from a truck-mounted microwave active spectrometer (29, 31). More complex polarization sensors have been discussed (29) but not implemented. Polarization sensitivity antenna calibration and minimization of antenna cross-talk between polarizations are areas worthy of development.

The optics associated with active systems involve laser optics. Except for early experimentation on remote sensing of flourescence phenomena in natural scenes, there is little active sensing in the optical spectrum going on at this time in renewable resources. USGS is developing an Aerial Profiling of Terrain System (APTS) using laser profilometers and laser tracking, expected to provide 15 centimeter vertical and 70 centimeter horizontal accuracy.

2.4 Detectors and Associated Electronics

In the optical spectrum a scene image is passed over detector arrays by forward platform motion and scanning mirrors in electromechanical scanning sensors and by forward platform motion alone in pushbroom array sensors. Area array sensors sample the image on a two-dimensional detector matrix in a snapshot or tracking mode.

Vacuum photoelectric devices such as photomultiplier tubes have been used in the visible and the near infrared. Silicon, however, is the current material of choice in the visible and near infrared range. Linear silicon charge-coupled device arrays of a few thousand detectors are available, as are 800 x 800 area arrays.

Detector array technology is currently under development in the short wave infrared and the thermal infrared portions of the optical spectrum. Material preparation and uniformity, charge transfer efficiency, and connections to conventional silicon electronics are areas of concern. Current technology in short-wave infrared and thermal infrared detectors provides about 500 detectors in a linear array and 64 x 64 detectors in an area array. Detector sizes are in the 10 to 25 micrometer range in linear arrays, and in the 40 to 50 micrometer range in area arrays.

Detector array geometric placement accuracy can call for absolute location to within a few micrometers over spans of tens of centimeters. This is a very difficult specification to achieve. Cooling requirements and connection to 200 to 500 leads also call for highly creative design efforts.

Front ends of microwave receivers draw on a well-developed technology of radio frequency and intermediate frequency amplifiers, stable local oscillators, mixers, limiters, and detectors.

The scanning process passes an image in the focal plane over an array of detectors, either by mirror motion and forward platform motion or forward platform motion alone. In the case of scanning mirrors, a relatively small number (tens to hundreds) of detectors scan the scene cross-track; one spatial dimension in the focal plane is generally devoted to spectral coverage in both Thematic Mapper and Multispectral Scanner.

When scanning is done by forward motion alone the scene is swept by that forward motion across an array of detectors (typically thousands) in the cross-track dimension. Again, the other spatial dimension of the focal plane is devoted to spectral coverage in the ways described in the previous section.

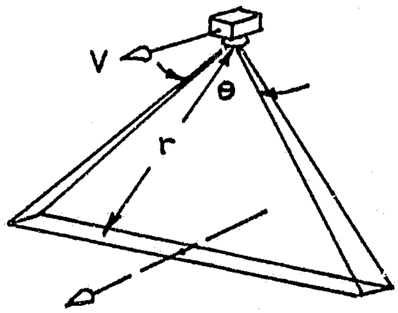

Figure 2.1 Swath Geometry

The rate at which a scene solid angle passes beneath a nontracking sensor is the ground track velocity v times the angular swath width θ divided by the swath-width-averaged slant range r, $v\theta/r$ steradians per second. The geometry is shown in Figure 2.1. In a given wavelength band, n detectors possessing a swath-width-averaged instantaneous field of view solid angle of $\Delta\omega$ sense $n\Delta\omega$ steradians when actually viewing. If the viewing is done some fraction η (scan efficiency) of the available time, the average dwell time on each detector can be defined as

$$\tau_d \cong \eta \frac{n\Delta\omega}{v\theta/r}$$

Generally $\Delta\omega$ is fixed by ground instantaneous field of view specification and the mission flight path or orbit. Slant range r is also determined by flight path or orbit, as is v for satellites. Thus η, n, and θ are the primary determinants of dwell time. Thematic Mapper has a dwell time of 9.6 microseconds; Multispectral Scanner a dwell time of about 14 microseconds; SPOT multispectral mode a dwell time of about 3 milliseconds. The larger the dwell time, the larger will be the number of photoelectrons collected, and the lower the bandwidth on detector electronics, hence improved signal/noise ratio. The desire to increase η (nearly 100°/o in linear arrays) and n while minimizing θ is clearly evident in the SPOT system design.

Area arrays can be used as linear arrays in one dimension, the other dimension being used for spectral coverage as in the Jet Propulsion Laboratory imaging spectrometer linear array design (23). They may also be used as staring or tracking area sensors. Recent solid-state vidicon array sensors have individual spectral coverage elements in a given pixel locale (Hitachi advertisement, Scientific American, May, 1982), and may bear watching as a potential small-area-sensing technology. Dichroic beam splitters could be used in developing multispectral area arrays. At present the primary area sensor experience in land remote sensing centers on the return-beam vidicon cameras in the early Landsats.

At the present time silicon is the detector material of choice in the visible and near infrared spectral range out to the cut-off wavelength of about 1.1 micrometer, even though photomultiplier tubes are being sucessfully used in Multispectral Scanner. The Thematic Mapper array appears to exceed specifications for the four visible and near infrared bands, going down to 0.45 micrometer in the blue region. SPOT employs silicon charge-coupled device arrays. The advanced state of development of silicon technology, including multiplexing registers, preamplifier electronics, and digital control circuitry as well as detector arrays will make this the dominant technology of the visible and near infrared range for the foreseeable future. At present, single chip units of 500 to 2000 detector linear arrays and 800 x 800 detector area arrays are feasible and available. Silicon usually operates without excessive cooling, minimizing focal plane thermomechanical complexity.

The situation is not as well-developed in the short wave infrared and thermal infrared. While there has been support of sensor development in III-V and ternary alloys for surveillance purposes for many years, the commercialization motivations of the silicon marketplace are missing. Moreover, detectors at these wavelengths require cooling to temperatures around 100°K or colder. Mercury cadmium telluride with various portions of mercury and cadium for bandgap selection and indium antimonide appear to attract the most interest in current literature, but other materials such as indium gallium arsenide, platinum silicide, palladium silicide, and various extrinsic IR detector materials have been studied. Thom, et.al.(32) describe the monolithic InSb array technology in an issue of the IEEE Transactions on Electron Devices devoted to infrared detectors. Work by Wong (33) and Sclar (34) indicate that fundamental principles of this technology and their application to detectors are still being explored. Chapman, et.al.(35) describe monolithic HgCdTe infrared imaging array technology. Workshop III minutes contain material from Thom describing the hybrid HgCdTe focal plane array with an intrinsic HgCdTe detector array chip and a silicon multiplexing and readout electronics chip, further described by Lanir and Riley (36). Area hybrid IR arrays have been described by Chow, et.al.(37). Focal plane array technology development and demonstration in the short wave and thermal infrared is currently being pursued by NASA/GSFC. Current technology limits are between 200 and 600 detectors per chip in linear arrays and a 64 x 64 detector area array. Yield, material growth and characterization, uniformity, cross-talk, noise sources, and interconnections are all areas requiring technology development. It is fair to say that fundamental understanding of the full range of knowledge required to achieve successful large-number detector arrays in this wavelength range is still unfolding.

Focal plane geometric placement, detector cooling requirements, and interconnection strategy can demand innovative engineering design even for the relatively small number of detectors in an advanced electromechanical scanner (20). In multispectral linear array sensors these packaging aspects can become very challenging, and constitute alternate costs for the benefits of not having to move mirrors rapidly and accurately. Current day detector fabrication practice provides a linear array detector spacing or pitch of 15 to 25 micrometers. Chip array lengths of, say, 500 detectors would call for 24 chips to make up the 12,000 detector array in each band called for in the recent multispectral linear array study by NASA/GSFC. At 20 micrometers pitch and perfect abutment the array would be 240,000 micrometers or nearly 10 inches long. A placing of all these detectors to 0.1 pixel (called for in the MLA study) calls for roughly 1 part in 10^5 placement accuracy. This proves to be an extremely difficult requirement. In addition, approximately 200 to 500 interconnection leads are typical for such arrays. Cooling requirements in the infrared compound the placement and interconnect packaging problems.

Nevertheless, SPOT will employ 3,000 detectors in each of three multispectral bands and 6,000 detectors in the panchromatic mode. While this area of packaging is one calling for creative design and clever engineering rather than fundamental research, it will be an important aspect of actual system performance.

Electronics at the focal plane consists of preamplifiers, analog charge-coupled device shift registers, and timing and control circuits for appropriate multiplexing and subsequent analog-to-digital conversion. For photodiodes thermal noise generation in feedback and detector resistances, shot noise generation due to leakage currents, and temperature sensitivities of both noise and device parameters are areas requiring careful consideration, but the principles are understood. In charge-coupled devices thermal carrier generation, charge transfer efficiency, noise generation, and coupling of the CCD devices to other CCD devices or conventional MOS or bipolar devices are the comparable areas of consideration.

Microwave receivers are well-developed. It appears that few, if any, fundamental research issues remain in this area, though the infusion of solid state techniques into the higher frequency regimes is still not to a state of maturity.

2.5 Sensor Calibration

Present day optical remote sensor calibration is source-based. Transfer of standards is the primary reason for accuracy limitations of about 5% at best in pre-flight calibration and subsequent 10% accuracy achieved in flight by focal plane calibration. Optical system changes in orbit and focal plane calibration system changes have been deduced from Landsat experience in signal variations of both an abrupt and drift nature.

Sun sensing from orbit for calibration has not been well-developed, though sun sensing is commonly used in field measurement techniques. It appears to offer significant promise when coupled with detector-based calibration concepts and devices.

Detectors designed for nearly 100% quantum efficiency so that nearly all photon events create a known and measurable amount of signal can be viewed as standard receivers of radiance and used in detector-based calibration. Recent work using biased silicon photodiodes and optical trapping to achieve nearly 100% quantum efficiency shows promise for detector-based calibration in the visible and near infrared. Concepts may carry over to longer wavelengths in materials other than silicon. Lambertian known-reflectance surfaces irradiated by a stable but otherwise uncalibrated source in the laboratory or the sun in orbit and viewed by the standardized detector has been proposed as a preflight and in-orbit calibration scheme (38).

Short wave infrared calibration currently employs tungsten lamp focal plane calibration, but could be done by solar radiometry and reflectance panel in orbit.

Thermal infrared calibration employs blackbody sources, typically in the range 260-340°K. Calibration experience with high spatial resolution data is sparse, and understanding of calibration anomalies even at large instantaneous fields of view is still developing (39).

Active microwave remote sensor full system calibration is not developed at this time to the fractional decibel level. Noise equivalent radar cross-section values of -37dB have been quoted, which give a measure of precision, but not accuracy, either absolute or relative.

Passive microwave radiometry designs quote 2° Kelvin absolute (1σ) accuracy, and temperature resolutions in the 0.3 to 1° Kelvin range (29). The large instantaneous field of view and consequent spatial averaging, particularly with integration time smearing, pose difficulties in defining a standard source for calibration purposes.

The precision of a sensor is high if repeated measurements of a given object or scene result in a stable, consistent, and narrowly spread array of measurement values. The accuracy is high if the numbers correctly represent a physical quantity according to some agreed-upon standard. Precision over reasonable spans of time is mandatory for successful relative measurements; accuracy is mandatory for successful absolute measurements.

Current practice in remote sensing in the visible, near infrared, and short wave infrared optical wavelengths is source-based calibration. On the ground the optical system is subjected to nearly 2π steradian irradiance of the telescope aperture from a large integrating sphere with internal quartz-iodine lamps. Because that process itself involves transfer from standard sources to the calibration site it is generally felt that a 5°/o absolute calibration on the ground is quite difficult to achieve and is a best-you-can-do boundary when everything is going right. Further transfer of sources to an in-flight configuration that often irradiates only the focal plane and not the entire sensor results in a generally accepted value of about 10°/o accuracy in orbit. On the other hand, relative detector-to-detector calibration is felt to be better: a few percent. Of course, separate calibrations can be and are performed on the optical surfaces and filter-detector-preamp focal plane assemblies (20). In a multidetector focal plane assembly each detector channel must be separately calibrated for responsivity to spectral irradiance.

It is customary to build calibration sources into both aircraft and spacecraft optical sensor systems. The assumption is usually made that the calibration sources are stable over a period of months or years. However, there are indications in Landsat data that changes in the calibration sources or the detectors can occur abruptly as well as slowly drift due to lamp life (38). The calibration source details for Thematic Mapper have been reported (20). In the visible, near, and shortwave infrared, the on-board source consists of three tungsten filament lamps and a black surface mounted in front of the prime focal plane and a flex pivot resonant shutter phased-locked to the main scan mirror. A blackbody radiance is relayed onto the thermal infrared detectors.

Landsat 1 experiences with in-orbit calibration difficulties have been described by Horan, et.al.(19). The problems were Mylar deposits on a sun calibration mirror during the spacecraft thermal vacuum test transformed by ultraviolet radiation, plus some organic coating of the calibration system and main optics. Sun sensing, which appears to be a nearly ideal way to use an inherently stable source which is also the irradiating source of the scene, has not been well-developed as an in-orbit calibration method. The major problems in solar calibration systems have been deterioration with time of the diffuse reflector surface in the presence of solar irradiance in vacuum and the contamination. Sun spot and solar atmosphere variability effect scene and Earth atmospheric irradiance and hence radiance. As can be seen in Figure 1.1, a solar calibration source would essentially make the remote sensor measurement an Earth scene and atmosphere transfer function measurement, ideally independent of input source variability.

Recent developments in silicon photodetectors as standards of detection due to Geist, et.al.(40-44), provide promise of considerably better than 10o/o radiometric calibration in the visible and near infrared spectral regions. Biasing to achieve either deep depletion regions (long wavelengths) or to remove recombination centers at the Si-SiO interface results in greater than 99o/o internal quantum efficiency from 200 to 980 nanometers. Multiple diode arrangements (Slater shows three (38)) can be used to trap reflected optical power. A reflective panel radiance can be measured at appropriate wavelengths by such a detector. If the panel is irradiated uniformly with a stable though uncalibrated source, the panel itself becomes a detector calibrated radiance source for the remote sensor aperture. The panel can be in a laboratory for ground calibration or on spacecraft for in-orbit calibration (38). The calibration geometry should be such that the radiance fills the sensor aperture over about π steradians typical of Earth radiance at nominal sensing altitudes. The method suffers from being limited to the silicon range at this time.

The importance of relative detector-to-detector calibration is evident in the phenomenon of striping seen in Landsat data. A detector signal output is an integral of a wavelength-dependent aperture irradiance times a wavelength-dependent optical transmission to the detector interior over a filter band wavelength range. Mismatch of, say, filter overlays can cause a striping pattern over one particular spatially uniform target, and a quite different pattern over another spatially uniform but spectrally different target (45).

The thermal infrared spectral region calibration design has been customarily source-based and local, near the focal plane. An exception is the Heat Capacity Mapping Radiometer (39) and the Meteoroligical Radiometers such as the AVHRR which use a large reference blackbody filling the scan mirror. There is little experience in high spatial resolution absolute or relative thermal infrared radiance measurement from space for renewable resources remote sensing, though aircraft data experience is commonplace. Unexplained changes in the system of the Heat Capacity Mapping Radiometer are described by Barnes and Price (39). Price has described the misfortunes of the thermal infrared band on Landsat 3 (46). It appears that outgassing contamination and water vapor collection on cold surfaces are worthy of serious consideration in sensor design throughout the optical spectrum, but particularly where cooled detectors are used such as in the short wave infrared or in the thermal infrared.

An experiment has been proposed for the Landsat D Image Quality Analysis Program, as described by Slater (38), for calibration by a ground area of known spectral radiance. The use of White Sands, New Mexico, as a uniform target of known spectral radiance is combined with atmospheric and ground measurements with an automated spectroradiometer in an effort to establish a direct ground to data output satellite sensor calibration. Other than this proposed experiment, data sets exist from intensive test sites in the Large Area Crop Inventory Experiment and the USDA remote sensing program known as AgRISTARS but they have not been processed for sensor calibration studies and real time atmospheric measurements at overpass moments are sparse in details required for estimation of aerosols.

Active microwave system absolute calibration has not been the focus of much effort, perhaps because little is known about the relation-ship between radar cross section and target attributes. This would naturally lead to more emphasis on relative accuracy and precision (low noise levels, stability, repeatability) and acceptance of good relative values for image contrast essential to spatial pattern recognition. Antennas, receiver front ends, analog amplifiers, demodulators, and so on have been individually analyzed and measured extensively (47, 48), but a system performance test as a synthetic aperture radar to measure absolute cross section from satellite has not been done. While there are standard cross section targets, and cross section analytical techniques are well-developed (48, 49), actual calibration in the presence of nearby ground surface or support structure poses difficulties. Ulaby proposed a concept of a relatively small, active, calibrated repeater in Workshop IV. Polarization sensitivity and cross talk must be considered in active microwave calibration; scene polarization/depolarization effects measurement, if useful, will require this. Absolute calibration to 3 decibels, and relative calibration to 1 decibel are typical requirements (27). The attainment of these requirements has not been demonstrated as of this date.

Passive microwave radiometry results in antenna temperature measurements which are integrals of antenna gain-weighted scene brightness temperatures (50). Polarization can be readily included in the analytical formulation (51). The problem with calibration appears to be lack of a reasonable calibration source. Source microwave radiance may depend largely on the emissivity of the scene rather than the actual temperature, and scene emissivity modeling is not well-developed at microwave frequencies. Perhaps the best that can be expected here is that measurement of the antenna gain function and receiver calibration with reference noise sources may be used to deduce the gain-weighted input power, that is, a detector-based calibration. A water tank target has been used in an experimental test of inversion to brightness temperature (52), using semiempirical modeling of the complex dielectric constant of water.

2.6 Signal Handling

Amplification, analog-to-digital conversion, data compression, modulation, and transmission of remote sensing signals from optical sensors is straightforward. Technical issues exist in dc restoration, dynamic range, gain scheduling, and degree and effects on information content of data compression, but principles are understood.

Reception and storage of the optical sensor data stream, and presentation of raw image data to an output device (CRT console or film scanner) requires a receiving station and associated computer capability. Present day system design is such that reception, storage, and image formation costs call for centralization of facilities, one to several per interested country, and an associated staff of remote sensing data processing specialists.

Active microwave system signal handling up to image formation is considerably more complex and is in an active state of development. Data compression, phase information utilization, information extraction without image formation, and processing-induced distortion minimization are in need of fundamental understanding. The active state of development precludes all but a few highly technical groups of researchers in government, industry, or universities from synthetic aperture radar signal handling and pre-processing experience and image production.

Little experience exists in passive microwave Earth image signal handling, though a good deal of work has been done in atmospheric sounding and oceanographic sensing.

Image formation is followed by preprocessing for radiometric and geometric correction. For the Landsat series this has called for sizeable centralized facilities and large groups of people to staff them. The SPOT program calls for a centralized facility at the Centre Rectification Images Spatiales with data delivery time of a day to a few weeks. Centralized Canadian facilities exist. Such facilities have tended to be major data delivery bottlenecks in the United States. The NASA/GSFC Landsat 4 ground data processing system for Thematic Mapper will evolve over the next few years to a 100 scenes per day potential capacity. The Multispectral Scanner processing will operate at a 133 scenes per day rate. While this will improve matters over the Landsat 1-3 experience, it appears that development of an ancillary data annotation protocol on raw data tapes, and diffusion of preprocessing capability toward the user end of the pipeline is still required to improve actual information utilization rates. The choice of how much preprocessing can or should be *put on-board a platform and how much can or should be put on the ground and where, is worthy of serious system study, regardless of the degree of fundamental research involved. The rapid development of very-large-scale-integrated circuits makes possible compact special-purpose processing systems and adds an additional degree of difficulty and opportunity in such choices.*

High gain analog signal channels are prone to low frequency drifts associated with temperature variations and component temperature sensitivity mismatches, in addition to the higher frequency thermal and shot noises. This drift can be filtered out by high-pass filtering, or compensated by auto-zero techniques after viewing a zero-radiance or known radiance source. Other than this requirement, common to very low signal level detector channels, the remainder of the electronic signal handling hardware and software on-board is conventional technology for A/D conversion, control and timing, delta modulation compression (typically), and transmission. The technology required for very high speed systems (100 to 1000 megabits per second) is very difficult.

Receiving stations for Landsat Multispectral Scanner data are commercially available and have been installed in several global locations (53). Only one receiving station and associated storage capability exists now at NASA/GSFC for Thematic Mapper. Such reception and initial image formation capability is, even for Thematic Mapper, within the state of communications and data recording arts at 85 megabits per second. While attainment of the capability may be demanding in an engineering sense, there do not appear to be fundamental research issues in this initial storage and uncorrected image generation portion of the ground data processing system.

The return signal from an active microwave transmission contains the slant range of a scene scatterer in the time of flight or range gate, the azimuth of a scene scatterer in phase delay history, and the scattering function of the scene in the amplitude, phase, and polarization referred to transmitted values. For spaceborne radar pulse coding is employed so that reasonable power level pulses extended over time can be compressed by filtering and yield fine range resolution. Linear frequency modulation (chirp) is the common coding in synthetic aperture radar systems, though other codes can be used. Several techniques for this pulse or range compression are available utilizing convolution, correlation, or fast Fourier transform - complex matched filter - inverse transform processing. These techniques have been widely studied for many years and are well-developed (54, 55). Seasat A synthetic aperture radar employed an up-chirp coding and a compression ratio of 642:1.

In Seasat's synthetic aperture radar a 19 megaHertz chirp phase modulation of a 1.275 gigaHertz carrier is transmitted to the scene, received after scene scattering, and up-converted to S-band for transmission to Earth. At the Earth receiving station the S-band signal is downconverted to center on about 11 megaHertz, spanning from about 1 megaHertz to 20 megaHertz. The signal phase and amplitude information is preserved in the in-phase and quadrature components of the down-converted signal. The in-phase and quadrature components are then digitized in a 45 megaHertz, five bit A/D conversion process. From that point onward all signal processing is done by computer.

Range compression is done first, followed by azimuth processing. Return from a particular point scatterer will have a particular phase history, depending on the trajectories over time of the sensor and the scatterer. The relative position vector of the scatterer with respect to the sensor can be expanded in a time series about some reference time t_0: a fixed term $\vec{r}(t_0)$ plus a linear term $\dot{\vec{r}}(t_0)(t-t_0)$ plus a quadratic term $(1/2)\ddot{\vec{r}}(t_0)(t-t_0)^2$ plus higher order terms. The return signal to the sensor will be the signal transmitted modified by the scene scattering properties and delayed in time by an amount $\tau_d(t)$ which is the solution of the equation $c\tau_d = 2|\vec{r}(t+\tau_d/2)|$. The phase history can then be predicted and expanded as a nominal phase, a linear term with a Doppler radian frequency coefficient, and a quadratic term with a Doppler rate coefficient (56). In essence, the phase history represents a frequency chirp in azimuth, and the dechirping results in an azimuth compression.

Earth curvature and rotation and spacecraft ephemeris confound the Doppler phase history for satellite sensing in contrast to aircraft radar sensing. In order to coherently sum (multiply by a phase reference function and add, the basic step in azimuth compression) the returns from a particular point scatterer, the relative motion-induced path of the returns through a range-phase memory must be predicted. This path changes as a function of latitude. Image formation beyond the conventional range compression consists of Doppler parameter estimation, range migration compensation, azimuth compression, and image formation by summing the squares of the in-phase and quadrature channel signals. Speckle reduction by filtering of a fully-focused processor image or adding of several lower resolution separate-look processor images completes the image formation process. The separate processing steps have been described by Beckner, et.al.(27).

The processing induced image distortion effects have been described by Curlander (56). Minimization of such effects is important so that attention may be focused on reduction of radar geometry induced distortions, which are severe.

The effects of possible data compression techniques for synthetic aperture radar data on images and image information are essentially unexplored, yet important for a high data rate sensor. This is because the information inherent in synthetic aperture radar return signals is buried in an involved superposition of many range, Doppler, and cross section returns from individual scattering elements in the beam footprint.

There is a feeling among the active microwave sensing community that some information exists in the phase knowledge available in the in-phase and quadrature channels and that it may not be proper to throw it away. The squaring, summing, and square rooting operation yields amplitude information and discards the phase. While rational use of phase information would imply better knowledge of the radar-scene interaction than now exists, empirical use of phase images may be fruitful.

Radar image formation processing is slow, though there are efforts underway at Jet Propulsion Laboratory to make a real time digital processor, and others have proposed such developments. The Seasat processor operated at 1/200th real time circa 1982, though it was felt that technological improvements could increase that processing speed by a factor of two to ten. The issue of the possibility of extracting information from synthetic aperture radar data without the intermediate step of image formation is a high risk, large potential payoff area that is definitely in the fundamental research category. In the foreseeable future, however, images will be formed that are inherently slant range and azimuth (with respect to the platform trajectory) scattering amplitude images. This poses peculiar problems with respect to overlay with optical imagery that will be discussed later.

There are not enough passive microwave Earth sensing data experiences per se to make detailed comment on image formation (29). In that sense, basic passive microwave sensing data analysis may constitute a fundamental research effort in its own right, but will have to await development of data sources. On the other hand, there is considerable experience with passive microwave atmospheric sounding coupled with optical thermal sounding in meteorological satellite sensing.

Geometric and radiometric preprocessing is a major issue and a major bottleneck in the ultimate use of remotely sensed data. The raw data from present day remote sensing systems are not acceptable by, or, indeed, easily available to, users. This situation should change in an evolutionary way as sensor system design improvements come about. However, at present it is necessary to funnel raw data through sizeable, expensive preprocessing systems that appear to delay substantially the availability of good data. Thus, those applications demonstration programs such as the Large Area Crop Inventory Experiment that required timely, registered data delivery have had to make their own special arrangements with the data delivery system.

The primary reason for massive preprocessing is the lack of geometric or geodetic integrity in raw data. In spite of attempts to achieve at least inherent registration and possibly rectification through sensor design and attitude control, registration must still be done through the usual resampling by nearest-neighbor, bilinear, or cubic convolution means (57). Even if sensor and spacecraft were perfect, the spheroidal shape of Earth and terrain variations from that shape would call for resampling to appropriate map projections.

Image registration by various similarity measures has developed rapidly over the last decade. Svedlow, et.al.(58) compared three methods of preprocessing (magnitude of the gradient, thresholding at the median, thresholding the magnitude of the gradient) and three similarity measures (correlation coefficient, correlation function, sum of absolute values of differences). Efficient thresholded correlation coefficient tracking with parallel pipeline architecture has been recently described by Sullivan and Martin (59), and is illustrative of schemes to solve the generally sizeable preprocessing time problem. Haralick (60) has described a second directional derivative operator and compared it with Prewitt's gradient operator and the Marr-Hildreth operator. The effects of misregistration on classification and visual image acceptance are still areas of current study (57), and are confounded in natural scene object sets by the within-object variance and edge pixel effects. NASA/JSC, with extensive experience through the Large Area Crop Inventory Experiment and AgRISTARS in crop classification, has developed a registration processor with a goal of 0.2 pixel registration (61). Sources of misregistration have been discussed by Mikhail and Baker (62), and Prakash and Beyer (15).

Image rectification is required by the specifications for Thematic Mapper of 0.5 pixel geodetic registration 90°/o of the time and 0.3 pixel temporal registration 90°/o of the time. Payload and scan mirror data are transmitted to ground for generation of systematic correction data. This is followed by geodetic correction data computation through a recursive distortion estimator (63). Resampling is a standard part of geodetic rectification to a given map projection, with cubic convolution appearing to be the preferred method if processing capacity is available (57). The body of knowledge of spline theory, of which cubic convolution is a part, is extensive: application of B-splines to image processing has been described by Hoù and Andrews (64). The multiplications and sums inherent in cubic convolution can consume considerable processing time. The ground data processing system at NASA/GSFC contains special purpose processor architecture to enhance general purpose computing capability for Thematic Mapper. One processor, for example, performs an x-axis resampling, scan line extension resampling (into scan gaps), and y-axis resampling at 2.3 microseconds nominal time per output pixel. Special purpose architecture for image processing of high resolution remotely sensed data appears to be a major direction in the solution of the data processing load leading to digital image representation.

It is evident from a study of the Thematic Mapper system and the experience with Multispectral Scanner data to date that there are at least two ways of viewing the preprocessing system design. First, data from archival or product tapes may be made available to users whose basic tools are maps (hence control points) and a reasonable image processing system. Such users have little or no access to an engineering model of or status data from a sensor/platform system. At best the user will be able to process the tape for image formation and radiometric calibration, and then begin the process of registration or rectification by similarity and ground control point image stretching methods without much information as to header interpretation on archival tapes or prior processing steps on product tapes. Second, the user may be knowledgeable about engineering models and data from the sensor/platform system, and wish to establish a preprocessing system on his site, using not only the maps and image processing system of the first case, but also his own methodology consistent with needs perceived by him. This second user might consider rapid delivery of selected raw data to be paramount, and have little interest in any appreciable archiving. Availability of engineering data of ephemeris, attitude, and calibration signals may permit personal design or purchase of preprocessing software and hardware. For example, Dye (65) argues for a resampling scheme based on desired point spread function synthesis, starting with raw data. Further, Welch (66) suggests emphasis on satellite positioning and attitude control rather than reliance solely on dense ground control and costly image processing techniques for mapping purposes.

The present day remote sensing ground data processing and delivery system in the United States is predicated on a massive archiving philosophy followed by precision product processing for the user who wishes to access the archive. Such archiving and production of remote sensing data are currently perceived as best done, and perhaps only done, in large centralized facilities. However, the image processing environment is becoming highly conducive to diffusion of that capability throughout the user community. First, image processing systems of varying degrees of sophistication and speed are far more widespread now than at the opening of the remote sensing satellite era in 1972, and remote sensing is only one relatively small driver on the market demand for such systems. For example, IBM announced its 7350 Image Processing System in mid-April, 1982, and currently has orders for approximately 20 units, largely from exploration-oriented firms (67). Assuming rapid expansion of telecommunications capability and concommittant expansion of rapid data processing capability including image formation, it is not difficult to envision a system of diffuse users commanding data acquisition in a network and satellite protocol, and receiving and processing it on multipurpose installations on their sites.

A decade of remote sensing from satellites has seen signal handling progress from a state of design aimed at image production on film for qualitative analysis to a state of design aimed at digital image production on tape for quantitative analysis. Thematic Mapper has generated a broad awareness that the signal handling subsystem is a major component in overall system design. Choices of wavelength bands, instantaneous fields of view, coverage frequency and overlap, radiometric accuracy, and geometric or geodetic accuracies should not be made without serious consideration of the consequences of those choices on the ground signal handling necessary for digital image formation.

A similar statement can be made regarding active microwave image processing. Once the range compression, Doppler parameter estimation, azimuth correlation, and speckle reduction processing steps have led to active microwave sensed image formation, there is still much to be done to register such imagery with other types of remotely sensed imagery (56). The radar image is a slant range image rather than a ground range image. Foreshortening, layover, and Earth rotation range walk effects arise from the sensor/scene geometric relationships. In addition, Earth rotation causes a complex Doppler response requiring either an adaptive processor or per-frame optimal settings, and sensor parameters are shifted for optimal signal-to-noise ratio and unambiguous pulse repetition frequency. Both these effects induce further geometric distortion. Work is underway at Jet Propulsion Laboratory to locate pixels in latitude and longitude in an unsupervised way using spacecraft ephemeris and sensor data collection system characteristics (68).

On-board processing has been an active research and development area, particularly in military systems with their obvious need for presentation of near real time information for prompt decision-making purposes. The idea of designing a scene-specific on-board multispectral classifier with subsequent transmission of processed image data at reduced rates has existed since the early 1960's in the remote sensing community. Experience has shown, however, that such variabilities as atmospheric effects, crop calendar differences, climatology, soil type and slope, and so on would call for an extremely subtle adaptable classifier. Moreover, change of purpose by another user would call, perhaps, for a different classifier; for N users one might need as many as N classifiers. It appears at this time that on-board processing should be aimed at performing tasks common to all, or most, of a community of diverse users, while ground processing should handle the diverse tasks, generally at the users' sites. Radiometric correction with on-board calibration and associated arithmetic processing appears to be a prime candidate for future development in this area. It would also appear reasonable to provide spacecraft ephemeris and attitude and sensor attitude data in a format appropriate for later use in rectification.

2.7 System Design

In all the areas discussed thus far - platform position and velocity, platform and sensor attitudes, optics and antennas, detectors and electronics, sensor calibration, and signal handling - there are available technologies. These technologies could profit from research and development efforts, to be sure, but there is enough technology available today in each area to serve as a basis for system design and simulation studies to achieve a stated mission. Moreover, technology component models and basic data exist to varying degrees of sophistication, providing the building blocks for system simulation.

Mission statements for past and current systems have been necessarily less than crisp because of the slow development of a diffuse and diverse user community. Landsat 1-2-3 and Skylab Earth resources experiments were general exploratory missions to see what the remote sensing technology could do. Seasat, Landsat 4 Thematic Mapper, Coastal Zone Color Scanner, and the Advanced Very High Resolution Radiometer all have or had allegedly more focused missions but have been or will be used for broader purposes. Remote sensing of Earth appears to be at a juncture of two eras. In the past, missions have been primarily proof-of-technology with attendant awakening and exercising of a potential user community. In the future, operational missions and the attendant system design may be driven more by user requirements for timely data at reasonable cost in the more well-explored portions of the electromagnetic *spectrum. Technology missions may be driven by fundamental research needs in scene radiation characteristics in the less explored portions of the spectrum.*

There is very little comprehension in the operational or research user community of total system design trade-off effects, that is, the cost and performance sensitivities of user requirements on wavelength, resolution, coverage, and so on. Total system models that would permit efficient performance, utility, and cost assessment are not available today though some of the necessary pieces of such models are available. The electromagnetic measurements and signal handling portion of such a total system model appears to be capable of construction now.

Figure 2.2 describes a process of system design that begins with a definition of mission objectives. Scene radiation and atmospheric

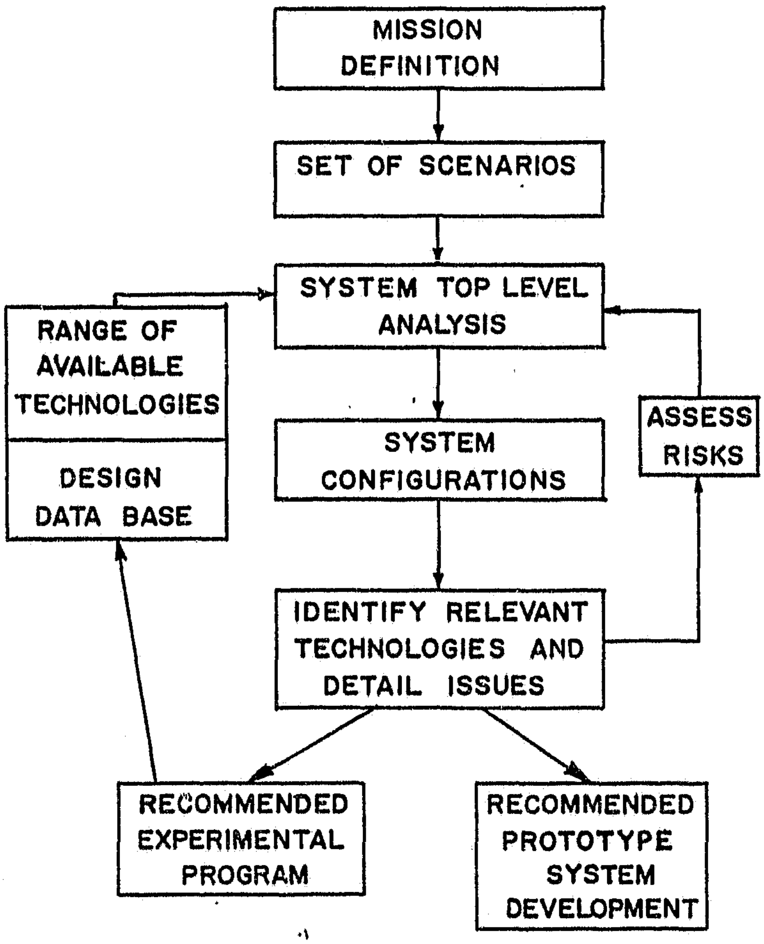

Figure 2.2 A System Design Procedure

effects characterization, electromagnetic measurements and signal handling, mathematical pattern recognition and image analysis, and information evaluation and utilization all play a role in the system design. In each of these areas of the total remote sensing system there are design data bases and ranges of available technologies. These should provide inputs for a top level overall system analysis of a set of scenarios responsive to the mission statement. This leads to system configurations, identification of relevant technologies, and identification of issues and risks. Finally, either a prototype operational system is developed or further experiments are carried out to increase the technology base.

It is clear from the previous subsections that technologies are available in the system components used for electromagnetic measurements and signal handling. One may view the pre-Landsat days as a proof-of-concept era, defining desirable wavelength bands, resolutions, preprocessing schemes, classification schemes, and potential end uses of extracted information. The past decade may be characterized as expanding this proof-of-concept and proof-of-technology to satellites and high resolution sensors. SPOT, the Multispectral Linear Array study program, the Japanese MOS and LOS program plans, and Canadian and German remote sensing satellite plans will seek to expand the technology base, while Landsat 4 Thematic Mapper provides a first look from space at higher resolution responses within and outside of the now-familiar Multispectral Scanner and Return Beam Vidicon wavelength ranges.

The customary specifications of system characteristics have been wavelength bands, instantaneous field of view, swath coverage, and signal-to-noise ratio. Wavelength band choices in the visible and near infrared spectral ranges have settled down to the green leaf reflective region, the red chlorophyll absorption band, and the near infrared high reflectance region for vegetation sensing, and several narrow bands spanning from blue to near infrared for ocean color sensing. Instantaneous field of view desires range from the relatively course AVHRR resolution of over 800 meters to the anticipated 10, 20, and 30 meters from SPOT panchromatic, SPOT multispectral, and Thematic Mapper respectively. While much of the world is now accustomed to data from 185 kilometer swaths, the Russian Meteor spacecraft has 30, 85, 600, 1400, and 2000 kilometer swath widths with 30, 80, 170, 240, and 1000 meter instantaneous fields of view respectively in several instruments. Two French SPOT HRV imagers will cover 60 Kilometers each, a German Shuttle pallet satellite modular optoelectric multispectral scanner will cover 140 kilometers, and the Japanese multispectral electronic self-scanning radiometer will cover 200 kilometers with two 100 kilometer-wide swaths (69). Signal-to-noise ratios have been specified in fractions of a percent to a few percent noise equivalent change in reflectance and fractions of a degree noise equivalent temperature change in the thermal infrared and passive microwave regimes and a noise equivalent scattering cross-section of several tens of decibels down. Such noise levels are generally consistent with six to eight bit quantization of data.

In active microwave sensing the Seasat synthetic aperture radar covered a 100 kilometer swath with 25 meter resolution in L-band with horizontal-horizontal polarization. Shuttle Imaging Radar-A covered a 50 kilometer swath at the same wavelength and polarization as Seasat. Swath widths of 50 to 60 kilometers at L, C, and X band and off-nadir angles of 15° to 60° are planned for future Shuttle Imaging Radar experiments. The knowledge base for active microwave system design choices is likely to come from field and aircraft measurements in the near future; perhaps a decade will pass before sufficient satellite or Shuttle data at several wavelengths, polarizations, and angles will be available. Passive microwave imaging is in a relatively primitive state, though sounding is well-developed.

It is generally understood now that repetitive coverage is essential to renewable resources sensing, that vegetation species have distinctive spectral and temporal growth, maturity, and senescence patterns. Eighteen day revisits appear to be the longest acceptable intervals considering cloud cover probabilities. SPOT offers five day revisits of selected sites if sizeable off-nadir angles are acceptable.

These customary specifications of wavelengths, instantaneous fields of view, swath widths, coverage frequencies, signal-to-noise ratios, polarizations, and so on have been the conventional focal points of system designs from a sensor point of view, being the main items of selection and contention. Ground signal processing, image analysis, and information utilization have sometimes seemed to be a secondary effort left to the interested user and not well-integrated into overall system design a priori, though this appears to be changing in the Landsat 4 and SPOT systems.

Mission definition statements beyond general proof-of-concept have not been commonplace, with some notable exceptions such as the Coastal Zone Color Scanner and the Large Area Crop Inventory Experiment. Most of the remote sensing efforts in electromagnetic measurements and signal handling appear to have been driven primarily as sensor tests with only a loose connection to applications or fundamental research. Sensor tests will continue into the future, but in addition system design driven by applications and fundamental research needs can be expected to increase. The Multispectral Linear Array program is an example of a sensor driven technology test mission, as is SPOT. However, a case can be made that SPOT is primarily an applications-driven mission in well-established wavelength bands of proven applicability and much enhanced spatial resolution to diminish the troublesome mixed pixel effects. Thematic Mapper certainly contains a sizeable sensor test thrust in the image quality assessment program efforts. Yet Thematic Mapper can also be viewed as the sensor portion of a system designed to explore new wavelength ranges and improved resolutions in support of fundamental research in both scene radiation and atmospheric effects and mathematical pattern recognition and image analysis with a vegetation emphasis. The recent active microwave experiments on Seasat and Shuttle Imaging Radar have been oriented towards sensors and signal handling, but field and aircraft programs have been driven by fundamental research essential to the development of applications.

System design driven by applications or fundamental research mission definitions is expected to broaden perspectives. Multiple satellites, coordinated aircraft coverage, different times of day coverage, orbits other than the conventional sun-synchronous orbits, programmable or multiple resolutions and swath widths, programmable pointing and wavelength selection, and direct data delivery to users are just a few of the possible outcomes of such system design. Cost/performance breakpoints will be very significant factors in system design driven by applications.

Remote sensing system components models could be put together in an end-to-end system simulation that would show potential users both the nominal performance expectations and cost impacts of increased or relaxed performance requirements. The efforts at simulation of Thematic Mapper classification improvement are steps in this direction, but they fall short of a total system simulation including cost considerations, particularly in ground data processing costs and performance.

The job of component model integration into an overall simulation is not trivial. First, it is possible to interconnect several system simulation modules, each of which is well-understood, and fail to understand the behavior of the interconnected system due to the complexity of multiple interactions. It has long been a truism of system theory that such an interconnected complex of well-understood parts can behave in strange, counterintuitive ways. Second, with few exceptions (the Large Area Crop Inventory Experiment, the St. Regis forestry project, and AgRISTARS), system costs in money, time, and people typically have not been thought of as germaine to a remote sensing system during the demonstration phase of the technology development; understanding in this area is in a state of active growth. Third, system simulation requires choices of system architecture or topology that can then block evaluation of other possibilities. For example, the architectural choice of an electromechanical scanner, linear array, or area array optical sensor, once made, seriously constrains the system design. Developing several scenarios to achieve a mission is one safeguard against architectural myopia.

There was strong feeling in the working group that total system simulation capability was highly desirable and underdeveloped in United States remote sensing efforts. Pieces of such a capability exist, particularly in the sensor area. The electromagnetic measurements and signal handling area, then, is a reasonable place to start, with expansion to scene radiation and atmospheric effects and mathematical pattern recognition and image analysis. Ultimately, modeling the difficult area of information evaluation and utilization would provide the full span of system simulation.

Section 3

OPPORTUNITIES FOR FUNDAMENTAL RESEARCH IN ELECTROMAGNETIC MEASUREMENTS AND SIGNAL HANDLING

In each portion of this section a synopsis of status is followed by italicized recommendations for fundamental research. Discussion supporting the recommendations follows where appropriate.

3.1 Platform/Sensor System Position and Velocity

Available or pending subsystems for remote sensing platform/sensor position and velocity selection, estimation, and control cover desirable ranges of those variables. The area 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.

We recommend no fundamental research support in this area itself, as an ample technology and data base exists for system design.

3.2 Platform and Sensor Attitudes and Attitude Rates

Low frequency platform attitude control is well-developed; however, the entire platform/sensor system must be viewed as a complete mechanically and thermally coupled system. Attenuation of vibrational effects through design is essential, particularly at higher frequencies. Accurate sensor instantaneous boresight estimation and tight broadband control of the platform/sensor system attitude can profit from fundamental experimental research and a creative engineering design data base.

We recommend fundamental research in minimization of vibrational and thermal sensitivity of instantaneous sensor boresight axes to mechanical and thermal excitations. This research should have a strong experimental component. Results should provide a design data base and technological methods useful in minimizing registration and rectification preprocessing difficulty. Support for this research should be highly selective and aimed at institutions or industries that have considerable experimental capability and experience in the area of flexible structures, including optical systems.

The experience of the Landsat 4 jitter problems point up the need for such effort, and future system designs should be made with data and technological methods that consciously minimize boresight random motion. Physical principles are well-understood, but experimental results on various designs are lacking, and are needed to develop methodologies. The assumption should not be made that multispectral linear array systems will be free of boresight attitude problems due to vibrational and thermal flexure.

For electromechanical scanners research in this area should include mirror motion and flexure as part of the instantaneous boresight problem, even though the mirrors are part of the optics system considered below. The mirrors act as potential vibrational exciters, and are themselves affected in motion by vibrations.

3.3 Optics and Antennas

Wide field large aperture point spread function analysis and measurement is in a state of active development. A variety of scanning schemes have been developed and are limited mainly by mirror dynamics or platform/sensor motion integrity, addressed in the previous section. Wavelength selection by dispersion, dichroic filtering, or interference filter overlay has been developed. Antennas for multifrequency, multipolarization microwave sensing, including multibeam or scanning capability should be developed, though conventional antenna design will suffice for single frequency and fixed polarizations on transmit and receive.

We recommend fundamental research in wide field large aperture optics point spread function analysis and measurement, particularly with respect to static or dynamic misalignment, optical components distortions, figures and coatings, and mechanical support structure. Here, again, support should be highly selective and begin from the base established in the multispectral linear array studies done for NASA/GSFC and the imaging spectrometer work at Jet Propulsion Laboratory.

We recommend further that study efforts in microwave system configurations, with particular regard to antenna hardware, be supported to develop multifrequency, multipolarization systems which are required to understand the radar signal-scene interaction.

Diffraction, misalignment, and stray light effects should be understood for wide area large aperture optical systems being proposed for multispectral linear array sensors. Of equal importance is the behavior of the point spread function under mechanical strain in the support structure. Optical coatings considerations also include the wavelength-selective coatings of dichroic beam splitters and interference filters. The point spread function analysis and measurement is assumed to include dispersion components in the optical system.

Several innovative microwave systems have been proposed on paper. Array antenna techniques have developed rapidly over the last two decades, as have microstripline techniques above one gigaHertz. A continuing effort in this area may be reasonable, but the primary fundamental research area in active microwaves is the understanding of scene backscatter phenomena; detailed major system design efforts should be coordinated with scene backscatter studies.

Passive microwave antenna hardware work at the present time is concentrated in large deployable structures, with emphasis on the structural and electrical properties of such designs. It is valid engineering work.

3.4 Detectors and Associated Electronics

Dwell times of ten microseconds and up provide sufficient signal-to-noise ratios in current scanner systems. Multispectral linear array technology increases dwell times to a few milliseconds or so. Silicon diode and charge-coupled devices technology is well developed for use in the visible and near infrared range of the spectrum. Array detectors for the short wave and thermal infrared are under active development today, with questions ranging from fundamental physics and preparation of specific materials to processing and packaging technique development. Microwave receiver front ends are well-developed.

We recommend continued support for technology development of array detectors, and specifically recommend fundamental experimental research support in the actual development of working detector arrays, particularly in the short wave and thermal infrared regions of the spectrum. This research should include deterministic and statistical array and detector characterizations as data base and technology availability inputs to system design. In addition, the experimental research should characterize the optical, mechanical, and thermal aspects of focal plane arrays, including alignment with integral wavelength selection structures, abutment, and cooling effects. The work should include readout registers or devices and amplification to nominal signal levels for A/D conversion.

It appears that silicon charge-coupled devices visible and near infrared arrays will dominate the conventional Landsat 1-3 wavelength range. Even in this range, with well-developed technology, it is probable that the detector and scene striping evident in Landsat data will continue to be a problem, compounded by sheer numbers in multispectral linear arrays. This calls for good detector-wavelength selector characterization for minimization or, at least, efficient compensation of striping in preprocessing. The situation in short wave and thermal infrared ranges is simple: detector array development in these wavelength ranges is viewed as the number one problem in multispectral linear and area array sensors outside the visible and near infrared range. While there has been extensive effort for many years in detector development in the short wave and thermal infrared ranges outside of NASA auspices, it would appear logical for NASA to support characterization research under a fundamental research thrust, while continuing its recent efforts in technology development at GSFC and JPL.

3.5 Sensor Calibration

Source-based calibration of sensors is about 10°/o absolute, 1 to 2°/o relative in the optical spectrum. Sun sensing for calibration has failed to develop well. Detector-based calibration holds some promise of absolute calibration in the few percent or less range, at least in the visible and near infrared spectral range. Short wave infrared calibration is currently source-based, as is thermal infrared calibration. Irregularities of both a drifting and abrupt nature have occurred in space remote sensing systems to date. Microwave systems usually have component calibrations such as antenna gain, receiver gain, and transmitted power monitoring, but have seldom been calibrated as whole systems against known cross-section targets to better than a few decibels. Passive microwave systems have been calibrated against large water targets as sources of brightness temperature with semiempirical emissivity modeling.

We recommend a strong fundamental research emphasis on radiometric calibration, both experimental and theoretical. The result of such research should be more precise and more accurate radiometric measurement. All regions of the electromagnetic spectrum are appropriate for such research. In particular, first emphasis should be on precision, that is, stability and consistency of measurements. Spaceborne systems exhibit measurement and calibration instabilities that remain objects of conjecture to this day. Efforts to achieve solar-based calibration of spaceborne sensors in conjunction with self-calibrating detectors over the appropriate wavelengths should be pursued. Total microwave system calibration schemes, including polarization phenomena, should be pursued to define absolute and relative cross-section measurement limits.

Slater (70) details the cares and woes of radiometric calibration in the laboratory and transfer of standards to preflight calibration. The changeable nature of spaceborne radiometric calibrations has been noted in the literature (19,39). Imprecision certainly appears typically to exceed the eight and even six bit digitization normally called for by a noise equivalent change in radiance specification. The present hope seems to lie in detector-based calibration, employing either a nearly 100°/o efficient quantum counter or a black pyroelectric detector. Some form of solar calibration would provide the input measurement of the Earth-atmosphere system, while the sensor measures the output radiance of that system. Solar calibration has not been particularly successful in remote sensing systems to date, but warrants further work. In general, then, there is much to be learned about precise and accurate radiance measurements from space and aircraft platforms.

Active microwave calibration to fractional decibel levels is in a similar state of development: not too well along. Standard cross-section targets exist, but not independent of a surrounding, scatterering environment unless placed in air or space well above Earth. Better understanding of the radar signal-scene interaction will require accurate cross-section measurements, hence good calibration of the total radar system. Full polarization or Stokes vector calibration adds a level of calibration complexity not customary to optical system.

3.6 Signal Handling

Sensor signal transmission, reception, and initial storage systems require, for the most part, engineering skills and cost-effective design. An exception exists in the area of unprocessed synthetic aperture radar data compression, where understanding is still growing. Active microwave signal handling and preprocessing of satellite data is in active development, with fruitful avenues for fundamental research. Passive microwave imaging signal handling is relatively undeveloped for Earth scenes. Ground data processing activity has proven to be a major bottleneck in data delivery to users. Diffusion of these processing responsibilities in both directions, toward on-board processing where feasible, and toward the users' site facilities appears warranted.

We recommend fundamental research in active microwave signal handling and processing with emphasis on information extraction with or without image formation. This work should be very closely coupled with efforts to understand signal-scene interaction. In addition, experimental research in automated registration of synthetic aperture radar data to various map projections should continue. Exploratory work in passive microwave imaging system signal handling for overlay with other remote sensing data may warrant support if appropriate data sets are available.

Data compression techniques suitable for on-board use with push-broom (multispectral linear array, imaging spectrometer) sensors are not well established and should be studied.

We further recommend an intense and critical review of the system philosophy in ground data processing including image formation, geometric correction, radiometric correction, and delivery of various products to users. Optimal placement (on-board, central facility, users' facilities) of processing steps against criteria of cost, timeliness, accuracy, and technology availability is worthy of study and argumentation, whether or not it is fundamental research.

The basic information content of the active microwave signal is present in amplitude and phase, arrived at after range and azimuth compression. The relationship of these quantities with scene attributes is a major fundamental research area in active microwave sensing; signal handling and processing of radar data for information extraction should be a parallel effort with signal-scene interaction research. Further, though radar has inherent utility during cloud cover conditions, it is felt that the value of radar data will be enhanced if it can be readily registered to other forms of remote sensing data.

Passive microwave sensor response has been put forth as a potential indicator of soil moisture (29). If so, image formation and overlay with other data will be warranted. Registration of two data sets of grossly different resolutions may be worthy of study.

The processing system from sensor raw data to user product is one component of the total remote sensing system. Several design alternatives exist, depending on the sophistication levels of the spectrum of users, and what prices they are willing to pay in money, learning, and time to extract information they perceive as valuable. The very rapid development of general image processing hardware and software can turn yesterday's truism into today's folly. In such a changing environment it is important to explore alternatives; thus our recommendation.

3.7 System Design

Demonstration of general utility and technological feasibility of remote sensing has been accomplished. New wavelength regions, higher resolutions, various polarizations, and other variations of parameters will fill out the users' charts of what sensor is good for what job. This will cause developmental system design to be driven by fundamental research needs in scene radiation and atmospheric effects seeking to lay the groundwork for further applications. However, operational system design is expected to be driven primarily by applications needs as the user community continues to develop, with cost, availability of data, and ease of use paramount (71, 72). A total system simulation capability, including cost/performance data, does not exist now, though there are component simulations that could be used to begin the assemblage of such a capability. A total system simulation capability would permit quick feedback to the user of the effects of loosening or tightening specifications on cost and performance.

We recommend support in the area of total system simulation starting from a base of sensor and platform modeling that already exists to a degree, and expanding first to the ground data processing system and atmospheric effects in the optical range and signal-scene interaction in the microwave range. Even the partial simulation capability resulting from that effort would be useful, and would form the basis for final expansion into the mathematical pattern recognition and image analysis and information utilization and evaluation areas. We argue that this activity will increase basic knowledge and understanding of total remote sensing system design, and that it is, therefore, fundamental research even though some parts of the system are well-understood.

A considerable quantity of modeling and simulation has been carried out on Thematic Mapper and the platform for Landsat 4 (12, 15, 20, 63). The same is true for the Multispectral Linear Array design studies that have been completed recently for NASA/GSFC. Such work can form the nucleus of an expanded capability. Modeling of the ground data processing system flows and process times in a variety of architectural designs should be carried out. In addition, recent work in atmospheric modeling is well enough along to be a useful expansion to sensor simulations. The same may be said for growing understanding of the phenomena of natural scene-signal interaction in radar remote sensing.

It is possible that a second effort could be started in mathematical pattern recognition and image analysis simulation at the same time, working toward a meeting place at the data products zone of Figure 1.1. The fundamental research issues study by that group showed clearly their desire for useful models of the sensor/platform system, useful in the context of understanding classification inaccuracies stemming from that source.

A genuine user community appears to be developing at last. As applications grow, the appliers will want to know how they can get what they want at a reasonable cost. Translation of what they want into cost estimates and simulated performance demonstrations of alternative system choices will require a system simulation capability that partially exists in scattered components today. It needs to be put together and built upon.

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