Minutes

Working Group Organizational Meeting

A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data

The meeting was held of August 6th and 7th, 1981, at ERIM in Ann Arbor, Michigan. The following people attended:

Fred Billingsley, JPL	Don Lowe, ERIM
Lloyd Candell, SBRC	Bob MacDonald, NASA/JSC
Bob Dye, ERIM	Marvin Maxwell, NASA/GSFC
Dan Held, JPL	Robert Pelzmann, Lockheed
Roger Holmes, GMI	Bob Powers, ERIM

Mike Holter of ERIM welcomed the group. Following a round of self-introductions, Bob MacDonald outlined the organization and need for the four studies to define basic research issues: scene radiation and atmospheric effects, mathematical pattern recognition and image analysis, information evaluation and utilization, and electromagnetic measurements and signal handling. Roger Holmes described and displayed the output documents of two studies already completed and about to result in a NASA Applications Notice, and distributed a sketch of several issues in sensors and signals to stimulate discussion (attached).

Following these introductory events each member of the group was asked to give a first impression of current fundamental research issues in sensors and signals, resulting in this list:

1. Radar (SAR) reflectometry
2. SAR processing speed
3. Registration, including overlay of SAR and optical imagery
4. Entire system radiance calibration
5. Lack of requirements for both sensors and systems
6. Cost-effective system architecture
7. Availability of A-tapes; general data availability
8. Atmospheric effects
9. Non-digital solutions
10. Spatial pattern recognition
11. Performance metric (a general image formation and processing problem)
12. Spectral filter requirements
13. Radar image processing
14. The elevation, parallax, look-angle problem
15. Geoid shape, satellite ephemeris, satellite attitude
16. Storage, transmission, and retrieval of information
17. Systems communications and management problems
18. Simulation

The discussion occurring during the development of this list revealed a consensus that there appears to be a lack of an overall sensor and system philosophy and that workshops to follow should focus on the development of such a philosophy.

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Dan Held and Bob Powers described areas of concern in SAR sensors and systems. Utilization of imagery from SAR is not adequately addressed; work is needed to learn how to use SAR imagery in conjunction with visual and infrared imagery for various tasks. A better understanding of radar beam-scene interaction is necessary in this regard. Comparison of edge location techniques in active microwave imagery and visual/infrared imagery along with the folding in of topographic data is an area of interest as well. Image formation from SAR data at reasonable rates may not be a fundamental research problem except in a computer science sense, but currently fast operations at 1/600th real time could be improved by a factor of 2 to 10. SAR preprocessing, as distinct from image formation, is not routine and will generate fundamental research issues. Current systems do not make use of the full information content potentially available in both the amplitude and phase in the received signal; this may be a fruitful avenue of investigation.

Visual and infrared sensors were discussed with emphasis on geometric and radiometric measurement integrity and the problems anticipated in array sensors. Wide-field high-resolution optics, large uniform filter layers over thousands of detectors, real-time radiance recalibration, destriping, open loop charge transfer electronics calibration, and the degree and irreversibility of on-board calibration processing are all seen as generators of potential array problems, some of which may define fundamental research issues. Current difficulties with large arrays for the short wave and thermal infrared spectral regions seem large in spite of long and well-funded development by agencies other than NASA. The general problems that will arise in attempts to calibrate, register, and rectify data efficiently from 10 to 30 meter instantaneous field of view sensors are expected to influence sensor and platform system architecture. The classical problems of deciding upon spectral sampling strategies (e.g., wavelength bands), IFOV, noise equivalent radiance, and other general system specifications have not advanced a great deal beyond the situation when Thematic Mapper specifications were argued out in 1975. Hence the continuing need for the development of a sensor philosophy and the appropriate simulation models to predict results emanating from choice options within the philosophical framework.

Data preprocessing was a topic considered by the earlier study on mathematical pattern recognition and image analysis. Because of the obvious coupling between sensor radiometric and geometric measurement integrity and preprocessing ease and efficiency, it was discussed as part of this study as well. There is agreement that a key issue is the optimum user transfer points in the preprocessing chain considering allocation of preprocessing costs in time, money, and user frustration. It was felt that preprocessing and data dissemination and communication are intertwined in the whole question of data availability and timeliness.

The work of the group in this meeting culminated in a statement of objectives, formation of a modified schedule of workshops to achieve the objectives, and assignment of participant identification responsiblities for each workshop.

The objectives are:

1. Define specific areas of pursuit (of fundamental research in sensors and signals) that are mission/instrument independent.
2. Define a program which will lead to definition of sensor/systems requirements for various missions.
   - o Identify alternate systems approaches.
   - o Identify sensor/system commonalities.

The workshop plan and assignments are:

1. Workshop 1 - General Sensor and Data Processing Philosophy and Data Handling, Dissemination, and Communication. To be held at NASA/JSC in early to mid October, 1981. Holmes and Lowe to plan program, select participants. To include a presentation and discussion of the first three fundamental research studies from the principal investigators thereof, and working discussions from representatives of the Hughes, GE, GSFC, EROS data acquisition and dissemination chain.
2. Workshop 2 - Geometric Registration and Rectification. To be held in conjunction with a NASA/Headquarters meeting on these topics at the Xerox training center near Washington, D. C., on November 17 or 18 through 20, 1981, tentatively. Billingsley with assists from Dye and MacDonald to coordinate with Headquarters.
3. Workshop 3 - Visual, Infrared, and Passive Microwave Sensors. To be held at NASA/GSFC in January or February, 1982. Maxwell and Pelzmann (possibly Hovis, also) to plan program, select participants.
4. Workshop 4 - Active Microwave Sensors and Image Formation/West Coast Visual, Infrared, and Passive Microwave Input. To be held at JPL in January or February, 1982. Elachi, Candell, and Powers to plan program, select participants.
5. Working Group Meeting - To finalize and edit recommendations for the final report. To be held at Lockheed Missiles and Space Division, Palo Alto, in March, 1982.

The meeting closed with a tour of some of the Applications Division facilities and activities at ERIM, including a presentation of current AgRISTARS work by Bill Malila.

Roger A Holmes

Roger A. Holmes

A SKETCH OF SEVERAL ISSUES

Orbit Ephemerides

It is generally accepted that knowledge of the position and velocity vectors of an Earth observational satellite is essential for fine adjustment of the orbit and efficient reduction of data to geodetic coordinates. Current capabilities appear to locate the satellite to within 100 to 1,000 m or so. French SPOT quotes cross-track, altitude, and down-range specs of several hundred to as much as 2,000 m. GPS Phase I is expected to achieve 5 to 70 m resolution in position and 0.01 to 0.13 m/sec resolution in velocity; Phase II is to achieve 2 to 15 m in position and 0.01 to 0.05 m/sec in velocity. Question is, what accuracy in estimates of $\vec{r}$ and $\dot{\vec{r}}$ is essential, and in terms of ground or on-board preprocessing where, and in what way do these estimates enter the geometric data processing?

Satellite Attitude Estimation & Control

In addition to knowledge of the satellite state in inertial space, $\vec{r}$, and $\dot{\vec{r}}$, complete state description assuming the satellite to be a rigid body requires three angles and angular rates of body-fixed coordinate axes. LANDSAT controlled to within 0.7 degree with respect to local vertical and orbit velocity vectors on three axes and estimated actual attitude to within 0.07 degree. SEASAT called for $\pm$ 0.5^{o} in all axes with estimation of $\pm$ 0.2 degree in pitch, roll, and yaw, with optical sun and horizon sensors. Angular rate limitations of 7μrad/sec or less are quoted for SPOT. A 1975 study by White, et.al., at Draper Lab estimated attitude uncertainties on the order of 20 arc seconds using a combination of landmark updates and star updates in a hypothetical performance study. The same question arises with respect to attitude estimation and control: What accuracy in estimates of angles and angular rates is essential for high resolution observation, and how will these estimates enter the geometric preprocessing data stream?

Satellite and Instrument Vibrational Modes

Serious violations of the assumptions that the spacecraft, its appendages, and its control, communications, power, and sensor components constitute a rigid body cause a more compled state description. Larson, et.al, at JPL conducted a study reported on in 1977 on optimal estimation and attitude control of a solar electric propulsion spacecraft, noting that such modeling was just beginning to reach the open literature. Sampling of attitude on LANDSAT D is planned (if memory serves) at a little above the Nyquist frequency of the TM scan mirror fundamental (7.21HZ) to estimate jitter effects. There are concerns of vibrational mode cross-talk between the TM scan mirror excitation and the MSS scan mirror excitation. Resonant mode excitation in cantilever structures such as antenna booms, solar panels, SAR antennae must be considered when attempting to hold instrument pointing accuracies to 20μrad or less. Structural vibrations with periodic forcing functions may be sufficiently deterministic to void statistical estimation techniques but sufficiently difficult to measure and of a pseudo-random nature to preclude deterministic correction. Question, at what resolution and for what electromechanical scan/spacecraft structure combinations is this a serious problem? Larson, et.al., infer that modeling the non-rigid spacecraft plus control system is not simple and may be counter-intuitive.

Sensor Geometric and Radiometric Calibration

Whether a sensor scans with one or more mirrors (TM is two, MSS one), or, as in SPOT, uses a plane mirror setting to determine the array swath cross-track location, or doesn't mechanically scan at all, the problem of determining the true geometric relation of the centroid of the IFOV of the target and the centroid of the optical detector or the angular position of the antenna (or antenna array) main lobe, even if the spacecraft attitude is perfectly known. Scanning mirror positions would have to be known to within 10μrad on TM across about a 0.1 rad scan to maintain 1/2 pixel integrity, or one part in ten-thousand. Solid-state detector arrays appear to have inherent spatial integrity, and laboratory calibration of the true optical axis and best focus would negate problems associated with mechanical scanners, but at a cost of increased radiometric calibration requirements.

Radiometric calibration periodic updates may pose a problem in large arrays. Moreover, since less than perfect charge transfer efficiencies through several register loads and shifts are an inherent feature of CTD arrays, it may be necessary to calibrate this open-loop portion of the electronics periodically. The status in radiometric calibration of SAR antennae is unknown to me at this time, but five years ago it was considered to be a problem for the finesse required for an attempt at soil moisture estimation.

Array Sensors

This is certainly a hot topic for the 80's. The IEEE Transactions on Electron Devices, Vol. ED27, Jan.80, is a special issue on infrared materials, devices, and applications. Major focus is on HgCdTe and InSb intrinsic arrays in applications. Wellman of JPL pointed to the short wave IR detector array problem as the number one problem in spectral pushbroom scanners at the ERIM symposium in May '81. NIR and visible portions of the spectrum can be done in silicon, with all the advantages of material uniformity and processing technology developed over twenty-five years. Silicon also provides the natural material for adjacent signal conditioning electronics while the development of bipolar and MOS device processing in compound semiconductors is less well-advanced. Readout strategies consistent with charge storage and transfer loss considerations on the radiometric calibration issue may require development. It is probable that the thin-wire problem of array processors is no less a problem in array sensors.

Focal plane cooling of large arrays is considered to pose potential problems of design.

Wide-Field High Resolution Optics

This is considered by Wellman at JPL to be the number two problem of a multispectral array sensor. Keene of Kodak showed an f/2.5 Schwarzschild telescope of 1.06 m focal length at the 81 ERIM symposium; image diameters of 4 to 6μm and an MTF of at least 0.75 is achieved over a 15° field. It would appear that the conventional Cassegrain optics will not do the job for wide field high-resolution array sensors.

Data Preprocessing

Data processing and preprocessing loom as major issues in delivering timely, calibrated, and corrected data sets to users. In SAR the problem is compounded, since significant processing is required compared to optical sensors before one even has the data to a point where images can be made even uncorrected as to received signal strength and geometric integrity.

Prakash and Beyer of GE reported at the Purdue symposium in June, 81, on the scan gap problem expected to be encountered in TM, and its correction through resampling in a simulation study.

The entire issue of preprocessing for radiometric integrity, registration, and rectification of multitemporal, multisensor data sets was discussed by the pattern recognition and image analysis working group. It is noteworthy that that group expressed a strong need for better physical models of the sensors. It is the goal of the TM experiment to provide World Reference System data through a full geometric data correction and system correction program. Throughput is considered to be a problem here, as it is in SAR preprocessing systems.

The SPOT system will provide for data dissemination to users in various levels of preprocessing according to need and willingness to pay costs. That program is considered to be very ambitious, considering the 10 m panchromatic IFOV and the sizeable off-nadir (27°) pointing capabilities.

It is not clear to me at this time what the optimum user transfer point is in the preprocessing chain considering allocation of preprocessor costs in both time and money. Clarification of this issue will be made even more critical with the pending thrust toward commercialization, but with governmental units being 50% of the market for data.

MINUTES

WORKSHOP I

THE REMOTE SENSING SYSTEM: DATA SOURCES, FLOWS, AND USES

Workshop Organizational Philosophy: A NASA program to define fundamental research issues in the remote sensing system, categorized into four interconnected units, began in late 1979. The units are:

1. Scene radiation and atmospheric effects (J. Smith)
2. Mathematical pattern recognition and image analysis (L. Guseman)
3. Information evaluation and utilization (J. Estes/C. Vars)
4. Electromagnetic measurements and signal handling (R. Holmes)

Units 1 and 2 were completed in early 1981 and resulted in NASA Applications Notice AN: OSTA: 81-B, unit 3 is nearing completion in the latter half of 1981, and unit 4 is scheduled for completion in early 1982. This workshop is one component of the study topic of unit 4.

Unit study leaders from units 1, 2, and 3 will present the results of their studies for discussion. By this means we hope to achieve an integration of the issues of the user-oriented parts of the remote sensing system, undersatnd their effects upon sensor and signal system design philosophy, and thus identify specific research needs in sensors and signals.

A critical part of the data acquisition and flow chain, that from sensor to the preprocessed data user/buyer, will be presented for group discussion and commentary from the unit study leaders. Data handling, communication, and dissemination from the satellites to the EROS Data Center is the focus, with emphasis on the amount, annotation, and irreversibility of data preprocessing, timeliness of data availability, and appropriate user hand-off or purchase points.

Schedule

Wednesday, October 14, 1981

8:00 a.m.	Introduction of the Fundamental Research Program	R. MacDonald
8:20 a.m.	Overview of the Workshop Organizational Purpose	R. Holmes
8:30 a.m.	Atmospheric Effects	R. Holmes
9:30 a.m.	Thermatic Mapper and Advanced Linear Arrays) TM and MSS Preprocessing)	J. Baker, M. Maxwell
1:00 p.m.	Ground Data Processing Systems	B. Bachofer
3:30 p.m.	Scene Radiation	J. Smith

Thursday, October 15, 1981

8:00 a.m.	Mathematical Pattern Recognition & Image Analysis	R. Heydorn
10:00 a.m.	Information Evaluation and Utilization	J. Estes, C. Vars
1:00 p.m.	Data Dissemination to the User/Buyer	R. Thompson
4:00 p.m.	Loose Ends	

Friday, October 16, 1981

8:00 a.m.	Total group discussion, identification of fundamental research issues in sensors and signals systems developed in the previous two days.

October 14-15-16, 1981
Meeting Attendees
Workshop I

A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data

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Minutes

Working Group - Workshop I

A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data

The workshop was held at the Lunar and Planetary Sciences Institute at NASA/JSC, Houston, on October 14, 15, and 16, 1981. The workshop structure and participant list is attached.

The meeting opened with a discussion by Fred Billingsley of the registration and rectification workshop to be held by NASA/HQ at the Xerox Training Center in Leesburg, Virginia. The working group plans to stay over on Thursday night, November 19, 1981, and Friday Morning, November 20, 1981, after the three-day workshop to identify research issues evolved during the workshop.

Roger Holmes presented the outcome of the atmospheric effects research issues studies for Jim Smith, who could not arrive until later in the meeting. Major issues are the cross-irradiance and cross-radiance from nearby pixels and the expression of these effects in terms of an atmospheric contribution to the point spread function. The work of Otterman and Fraser is the principal effort to date.

Marvin Maxwell presented extensive material on LANDSAT D and the Thematic Mapper sensor, and the ground processing, communications, and control system. A copy of overheads used is attached, as is a copy of a recent (10/23/81) NASA Applications Notice which contains a reasonably detailed description of TM specifications and components. Considerable discussion ensued on scan gap fill-in, missing detector fill-in, rectification warp, and irreversibility of resampling. The knowledgeable researchers/users, including value-added services people will want archival tape (A-tape) copies, wherein the full set of systematic geometric and radiometric correction data are recorded on a header but the pixel samples are as-received, gaps, missing detectors and all. Once the initial TM product generation results in a product tape (P-tape), a considerable amount of irreversible preprocessing has been performed through fill-ins, rectification warp, and resampling; indeed, spatial and spectral information have been irretrievably mixed by the very nature of resampling, even without scan gaps and missing detectors or samples.

> (Note: The AN attached, on the LANDSAT-D Image Data Quality Analysis Program, can be loosely read as a study of what's really on the A-tape and what happens to it on the way to a P-tape.)

The discussion on fundamental research issues following the LANDSAT-D, TM, and TIPS system presentation returned to the familiar theme of a need for an end-to-end systems study and the effects of sensor and preprocessing systems on image analysis by the pattern recognition community. In particular, expense caused by overspecification without sound system analysis basis for a specification was discussed in connection with error budget analysis.

Following lunch, Marvin Maxwell described the multispectral linear array (MLA) instrument definition studies. A brief and general set of overheads is attached. One member of the group (Candell) missed the presentations since his organization is involved in the competitive study. Four distinct designs were presented. One, the Eastman Kodak design, has been presented in open literature at the 15th ERIM Symposium by George Keene. The issue of SWIR linear array technology was not discussed.

Bruce Bachofer presented further material on error budgets in the LANDSAT-D/TM system. Positional errors are shown in the tables below.

Error Source	1-σ Error, meters	
Ephemeris	100 cross track	500 along track
Time	--	80 "
Attitude	123 "	123 "
Alignment	427* "	855* "
Total RMS	455 "	1001 "

*Offset between optical axis and attitude control system reference; largely removable after launch.

Two days after accurate position determination, the 1-σ error in orbit position and velocity is:

	Position	Velocity
Along Track	500 m	0.163 m/s
Cross Track	100 m	0.065 m/s
Radial	33 m	0.65 m/s

Altitude will vary from nominal, ranging from 696 to 741 km with a variation of 19 km over any fixed latitude. Cross track variation from nominal will be ± 4 km.

Attitude and jitter errors arise from attitude control system error necessary to drive attitude control actuators, TDRSS antenna driver stepper motors, and scanner mirror bounce. Attitude and jitter error 1σ values in arc seconds are shown below.

Frequency Range	1σ Error, arc sec	Primary Cause
0 - 0.01 Hz	36	Attitude control system error
0.01 - 0.4 Hz	10	TDRSS drive
0.4 - 7 Hz	0.3	TDRSS drive

		Baseline expected	Worst case	
	Roll	0.93	20	
>7Hz	Pitch	0.20	2.2	Scanner mirrors
	Yaw	0.30	16.8	

The specifications for greater than 7Hz assure that jitter gap caused by pitch and yaw will be less than one pixel even in the worst case.

An important point was made with regard to error budgets and specifications: If an error has to be estimated and corrected for in any event, don't overdesign the hardware. As an example of this principle, a relatively simple scan mirror system on MSS required straight forward S-curve correction. A more sophisticated scan system on TM to maintain linearity does not remove the need for correction of the data; a simpler MSS-type system might have been less costly and the correction no more complex. Once again discussion on fundamental research issues centered on the need for a full system definition and design study to avoid problems that now crop up on the way to an apriori specified system, requiring algorithmic fixes and patches through software.

Jim Smith presented the results of the research issues study on scene radiation modeling and atmospheric effects. He discussed types of models, ranging from empirical to physical/physiological models. Monte Carlo techniques and radiative transfer techniques have been used on crop canopies and forest canopies. There is a need to address two and three dimensional models. The issue of "what good are models and what do we do with them" led to a lively discussion on how models might be useful in inferring trends in biophysical causes for scene radiance behavior. This led in turn to a discussion of total system simulation so that users might be able to dial up a typical scene for their purposes, sensor configuration, preprocessing scheme, pattern recognition or image analysis scheme, and see how things worked. This leads back once again to end-to-end system definition and design.

The second day of the workshop opened with a presentation by Dick Heydorn of the research issues study in mathematical pattern recognition and image analysis. Two major subsystems were discussed: digital image representation and image analysis. In the digital image representation area issues of coarse and mixed pixels, multitemporal behavior, texture representation, image syntax (primitives to scene), probability density estimation in response space, dynamic behavior in scenes, parallel image processing, and representation of multiple image data were presented. In image analysis issues of clustering, expert systems and convergence of evidence schemes, computer graphics analyst aids, unbiased inventory of entire scenes, increasing of conventional survey efficiencies, and maximal data use (e.g., unbiased estimator with reused data, jackknifing) were discussed. The need for good simulation capability arose once more. The group involved in mathematical pattern recognition and image analysis was attuned to the need for good sensor models and sensitive concern for preprocessing as a prelude to the development of good digital image representation. They were further aware of the output interface of their subsystem on image analysis with the information user community.

Jack Estes and Charles Vars presented the current outcome of the research issues study in information evaluation and utilization. Several major points were made:

- There is no single theory of information value. Indeed, the whole field of placing economic value on information systems is very fuzzy at present.
- Partial information systems can be misread (Bangladesh example) or, how do you improve something you don't understand very well.
- The information user community is very diverse; most members view remotely sensed data as ancillary data.
- Users do not have requirements; they have situations imposed. Several user issues with respect to data systems were discussed, including geographic data bases, standardization, universal communications with details user-transparent, throughput rates, archiving/aggregation/validation/purging of data, the man-machine interface including display esthetics, human factors, and friendliness. The data structures that develop will impact sensors and preprocessing systems.

- In information systems development, follow a seemingly simple rule: study what the user does, help him do it better.
- Much of the technology of information utilization in both hardware and software is going forward independently from the remote sensing systems. Remote sensors should be aware of developments and technology transfer opportunities.

The area of artificial intelligence popularly called "expert systems" was described. Characteristics of such a system include:

- An information data base that is specific to an application.
- An interactive system programmed with user response and behavior patterns in mind.
- Ability to justify performance, i.e., able to explain decisions in terms of a line of reasoning.
- Ability to "learn" quickly.
- An easily modified knowledge base.

Research is needed in areas of discipline concepts, conversational capabilities, explanation capability, data base management systems, and query development.

R. J. Thompson described the history, present state, and future plans for the EROS Data Center digital throughput. From 1972 to 1974 digital data demand was minimal; by 1974 to 1978 there was a fourfold increase in tape demand but photo imagery still accounted for over 90% of the data demand. Prior to 1978 the digital tapes were essentially uncorrected. In the last year and a half processed digital tape has been routinely available, and the value of the LANDSAT tape archive has become apparent. Geometric correction through resampling has been put in only recently. Archival tapes became available in June, 1981, and 161 scenes/day from MSS were being processed in September, 1981. Old format tapes demand is about 9/days, new format demand is 4/day, expected to rise to 15/day. At $300/tape current user demand is 22% federal government, 3% state and local governments, 9% universities, 22% industrial, 7% individual, and 37% foreign users. It takes 40 days to get data after acquisition; a future goal is 10 to 14 days. CCT costs are expected to rise to $1,000/scene, with NOAA forced to charge a TDRSS fee and ground data handling system fee. It is felt that a factor of 10 increase over the $300/tape would effectively kill the program. Concerns were expressed in the working group over the NASA-NOAA-commercial transition status.

Hardware and software specific system issues were discussed. Specialized one-of-a-kind equipment maintenance has proven to be a major difficulty. There is a need to look at mass storage technology. Data volume considerations in storage and retrieval, communications of image data, and compression/reconstitution hardware to solve communications problems are items of current focus. Remote image processing in $20-30K microprocessor-based systems with possible special purpose hardware will develop; prototypes are being developed at EROS Data Center. Standards for integrated data types and overlay in digital data bases need development.

The morning of the third day was spent in presenting and discussing fundamental research issues evolving in the minds of the attendees. A copy of short statements made is attached. The need for a system definition emphasis along with adequate simulation tools including cost and trade-off features is strongly expressed in the statements, either in general terms or on specific system details.

Roger A. Holmes

Attachment

Fundamental Research Issues Synopses

Bruce Bachofer

Areas of Pursuit in Fundamental Research in Sensors and Signal Processing

A significant amount of research (applied research) has been undertaken in the sensor and signal processing areas since the late 1960's. The push in NASA's program in the early 70's came from LANDSATS 1, 2 and 3 and currently encouraged the LANDSAT-D, but limited primarily to the visible near infrared. Sensing and signal processing in the microwave region of the spectrum received some attention through the SEASAT Program, but to a lesser extent over a shorter period in time. Problems associated with use of data from dissimilar sensors using different view angles, scales (or IFOV), etc. have received even less attention. The thrust of the areas of fundamental research, therefore, should be focused in these areas which have not received or likely will not receive the benefit of funding from the major earth observation projects and which are vital to support programs of the late 80's and early 90's.

Some specific areas that should be considered are:

- Image Registration from dissimilar sensors with different resolution and viewing geometry
- Textural Analysis including sub-pixel imaging both as a means to reduce data bandwidth and to improve target recognition.
- IR Detector Array - work needs to be continued

Fred Billingsley

- To determine the sensitivity of loss of analysis utility with non-attainment of desired measurement or errors in the measurement. (And, from this, develop a total information system design methodology.)

  (Modeling, experimenting with better than anticipated data.)
  (Also dissimilar instruments.)

- Develop sufficient knowledge in the knowledgeable user community as to what the design tradeoffs might be, to
  1) allow design (modeling)
  2) provide acceptance
- Continue the atmospheric work.
  - Ancillary Sensors?...
- Keep up with external research and plan the NASA work to supplement this for NASA needs.
- System traffic study
- Convert Algorithms to USLI

Lloyd Candell

1. End-to-End Simulation Model:
   Development of a two dimensional total simulation is proposed that would include atmospheric effects, spacecraft sensor effects, and data processing. Input parameters would include multispectral scene descriptive data and key atmospheric, sensor and data processing parameters. The output data would include hard copy color pictures, CRT display and digital tape data.

2. Life Cycle Cost Model:
   Development of a comprehensive cost model that would include all cost elements through the on-orbit life of the sensor is proposed. This model would allow the first order cost impacts to be evaluated of various system design decisions and system architectural tradeoffs.

Robert H. Dye

1. Need cost-benefit functions for spatial resolution.

2. What p.s.f. should scanner have if subsequent resampling is very likely?

3. Need to be able to relax specs.

Daniel Held

Issues Contained in Tentative Topics List

Workshop on Fundamental Research in
Active Microwave Remote Sensing

Tentative Date: February 2, 3 and 4, 1982
Location: Pasadena, California (at JPL or Cal Tech)
Chairman: Charles Elachi
Co-Chairman: Daniel Held

Tentative Topics:
- Imaging Radar Reflectometry (emphasis on coherent component)
- Imaging Radar Polarimetry
- Combination of SAR and multispectral images. Basic physics behind synergism
- Topography and look-angle problems
- Geometric and radiometric correction/calibration of SAR data
- Development of the performance metrics and the simulation of spaceborne systems. Test patterns.
- Multifrequency array SAR
- SAR processing at high speed

Potential Participants:

J. Benett (MDA, Canada)
A. Blanchard (TAMU)
L. Candell (SBRC)
K. Carver (NASA HQ)
J. Curlander (JPL)
C. Elachi (JPL)
J. Estes (UCSB)
A. Fong (U.of K.)
L. F. Guseman (Texas A & M)
D. Held (JPL)
R. Holmes (GMI)
V. Kaupp (U. of Ark.)
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J. Paris (JSC)
R. Powers (ERIM)
J. Salomon (S. Diego State)
J. Smith (CSU)
F. Ulaby (U. of K.)
W. Waite (U. of Ark.)
T. Walton (NASA HQ)
C. Wu (JPL)

Roger Holmes

1. Develop a sensor irradiance-to-preprocessed data system simulation module that will fit into an overall system simulation. The module should have the following features:

    - Programmable resolution, or better yet, point spread function including electronic transfer function.
    - Selectable wavelength band selection, or better yet, filter response.
    - Selectable altitude, attitude, look angle capability
    - Noise insertion in both radiance and geometric aspects
    - Several resampling schemes plus general spline function capability.
    - Be able to simulate several optical/focal plane system designs.
    - Provide cost and throughput time estimates so the user analyst is aware of the effect of desires for even better performance.

2. Need to provide decent theoretical foundation for a system which may overlap or underlap fuzzy (PSF sense) pixels. Have a spatially noisy and spatially spread out sampling, doesn't fit in with most neat sampling theory. Need also to get a good Fourier 2-D spectrum set over natural scenes in order to do this properly--doubt that such a set exists.

3. Radiometric calibration appears to be sort of a bastard step-child. Need to really do some NBS-type research on what the real status is and how to insure integrity. Sun cal should be mandatory and consistently done according to well-defined standards (shuttle expt's?)

Donald Lowe

1. Are there a set of users whose high resolution requirement can be met with a single high resolution channel and multispectral low resolution? What high to low ratio would be best?

2. Should all data be resampled? How will the various government supplied data formats affect the user/value added service community, i.e., Gov't supplied expands user community, but value added service industries tend to be more creative.

3. With a facility-type sensing system like LANDSAT, how can one assess the relative importance (economic and social) of users for setting system requirements? How can one translate info requirements into system requirements and can these requirements be translated into cost?

4. Can atmospheric effects be treated as a change in point spread function and corrected by deconvolution?

5. What is the optimum point spread function and resampling techniques for a linear array system?

Marvin S. Maxwell

Develop total system models (end-to-end simulation) which can be used to assess the real cost and value or utility of a VIS/NIR/TIR sensing system. The simulation should cover the scene, atmosphere, sensor, on-board processor, communication link, ground processing, information extraction system, and decision making system. The simulation system must have the capability to process large quantities of data to minimize the sampling noise in the assessment of the results.

Robert Pelzmann

Research Topics - Remote Sensing Systems

Preface: Operational Remote Sensing is still an immature concept, yet NASA has converged thru the LANDSAT Series on a single concept for a remote sensing facility. Because it is unlikely that NASA will build and fly several widely different types of systems, a number of analytical and design tools are needed to analyze the "true" operational needs with the goal of identifying hard numbers and ranges for performance and design parameters. A data base for system design must be built as well, thru modeling and simulation, aircraft data, etc..

In order to make system design trades for future remote sensing systems (especially "operational") more quantitative values for critical sensor and system design parameters must be established. Furthermore, the sensitivity to moderate changes in these parameters of the user utility values must be known.

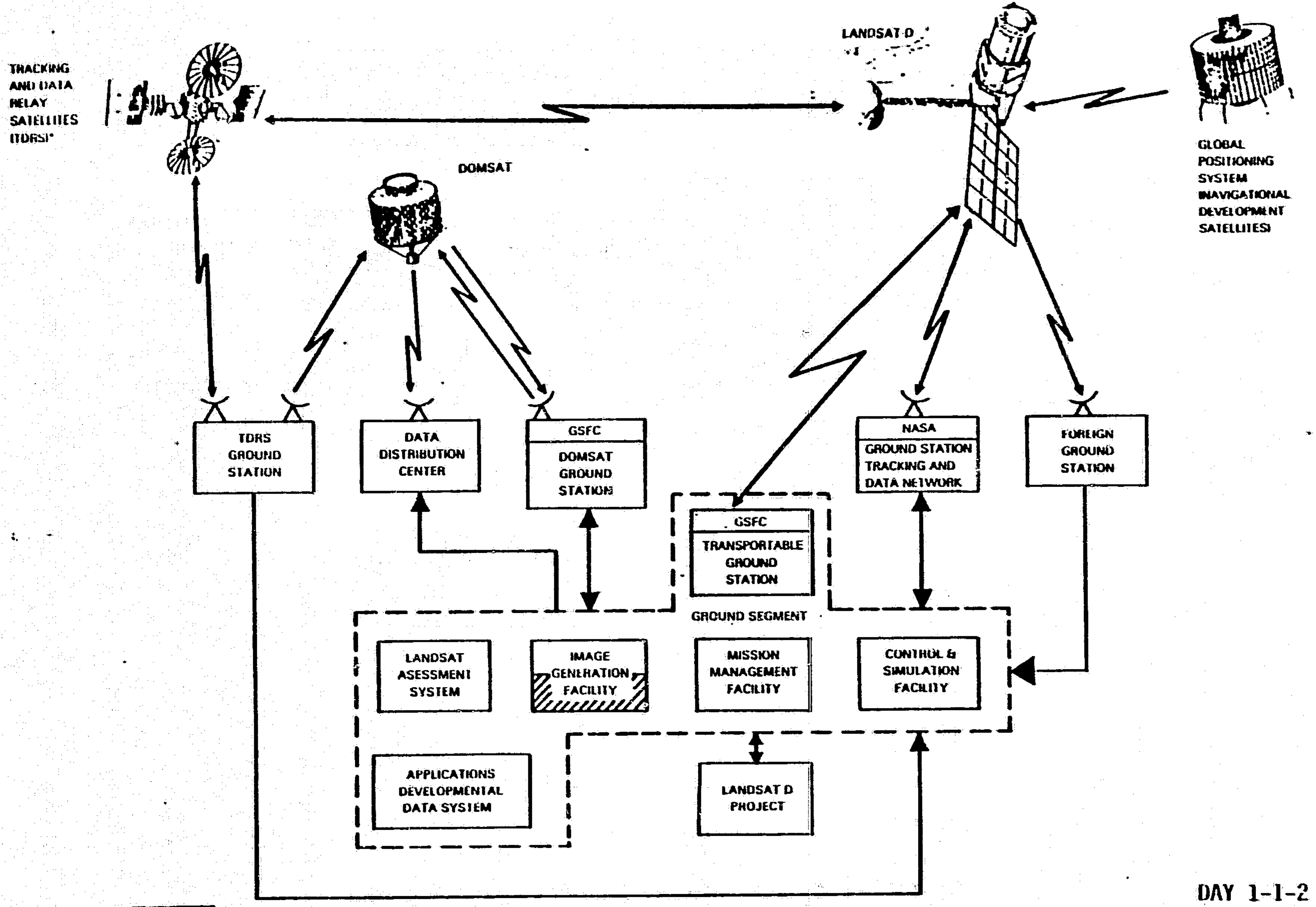
In addition to the above information (which can provide system optimization of an existing baseline design), the utility functions of each of the several (and amorphous) users to major parameters are needed. At least the breakpoints of these utility functions would allow exploration of fundamentally different system concepts which are uniquely suitable for each specific user.

To facilitate user understanding of the system design trades, the cost sensitivities of their requirements must be developed and made available. As with the engineering parameters, both cost sensitivities about a specific design, and system cost alternatives which identify cost breakpoints need to be developed.

In dealing with user "requirements" with an ill-defined user group, it is critical to clearly define assumptions used. Current approaches to remote sensing do not have these assumptions clearly defined.

A key tool needed to be developed for the parameter sensitivity analysis is a functional simulation with variables directly related to the user parameters. Note that such a simulation is dependent on a baseline design and is somewhat facility related. Such a tool may not aid in analyzing widely divergent conceptual designs tuned for specific users.

An Introduction to the Major Elements of the LANDSAT-D System

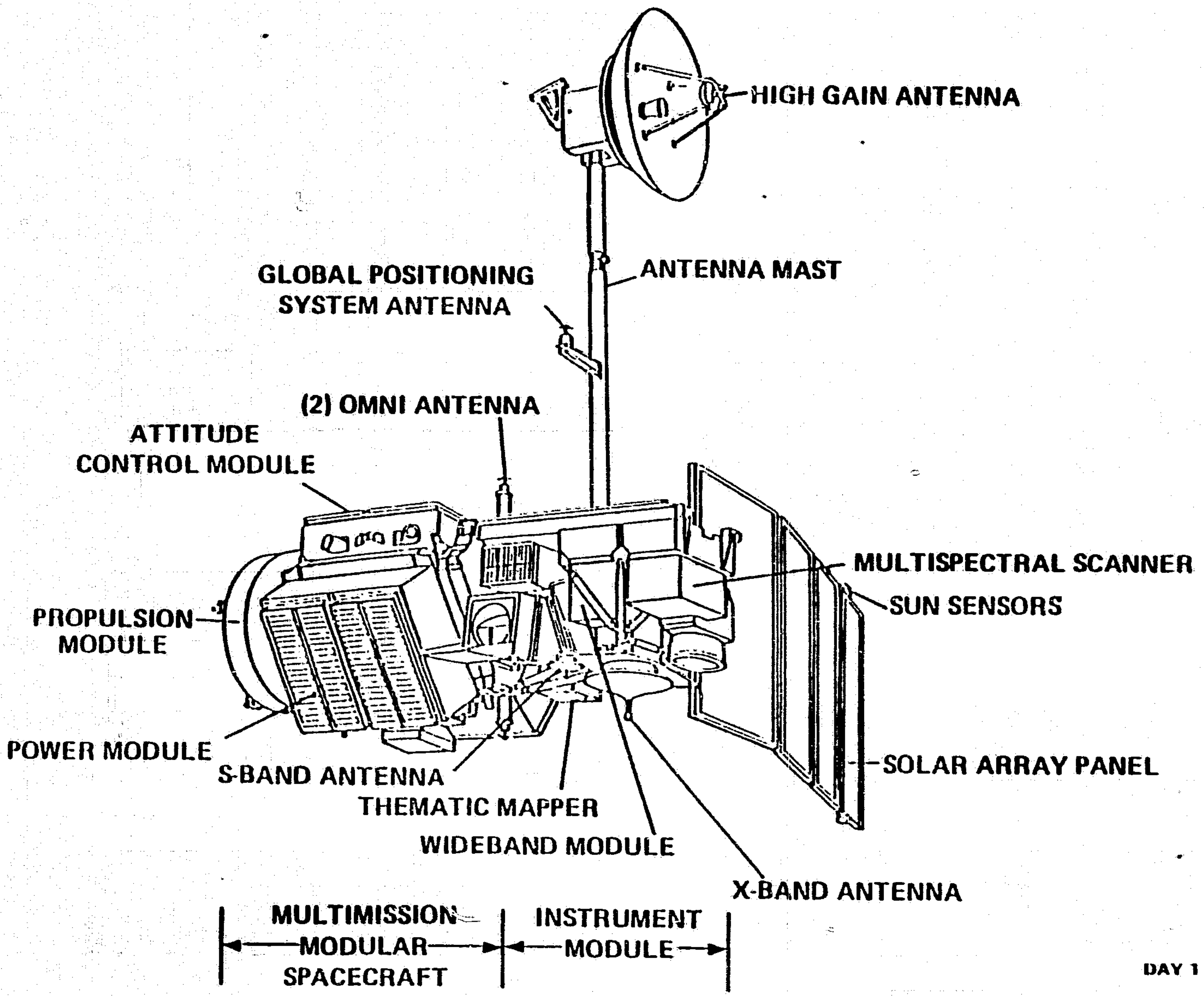


DAY 1-1-2

▨ SUBJECTS OF THE CURRENT REVIEW

- Ground Station Tracking and Data Network will be Utilized until TDRS East Becomes Operational

LANDSAT D FLIGHT SEGMENT



DAY 1 TMSO-2 (S)

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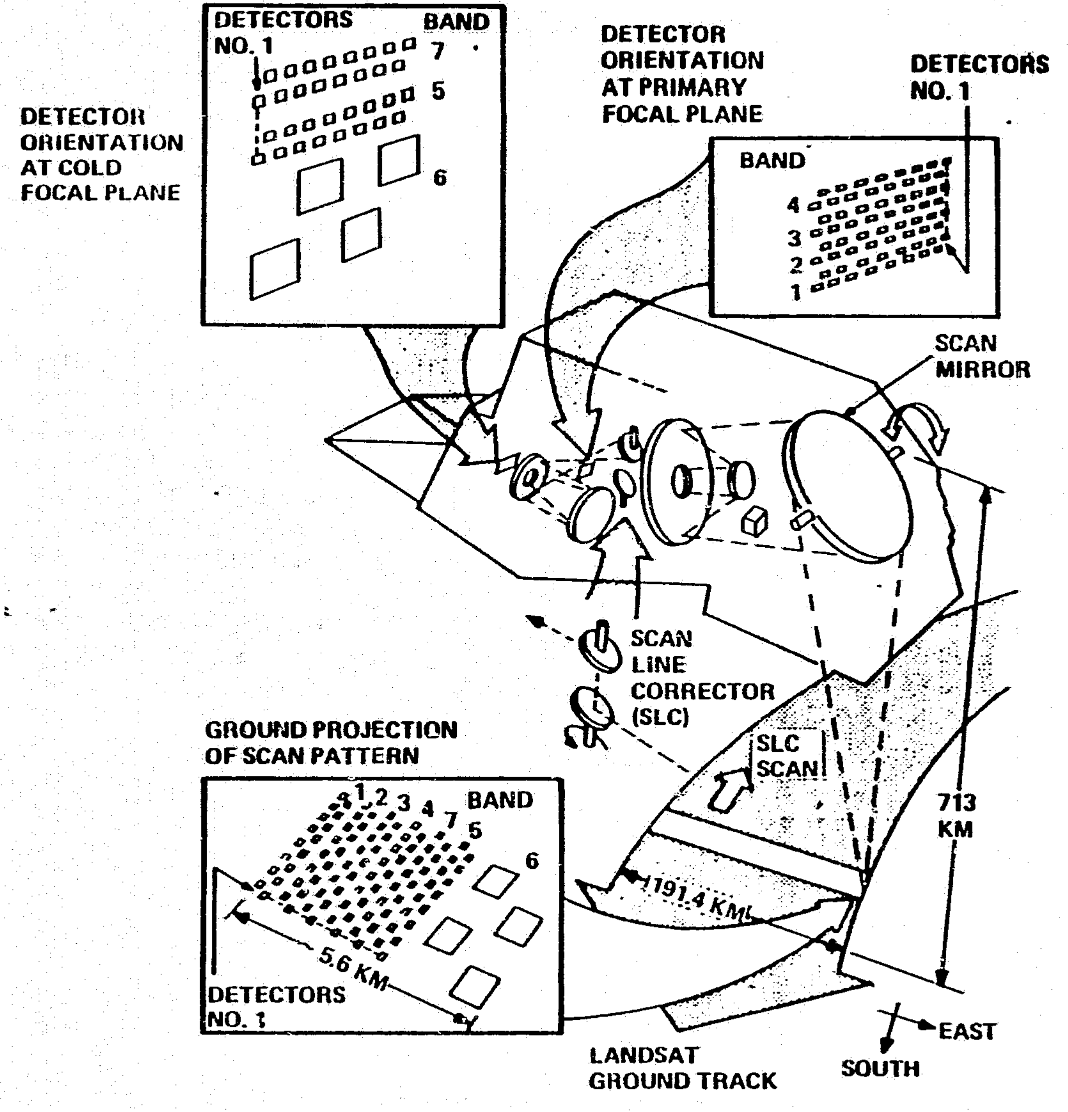
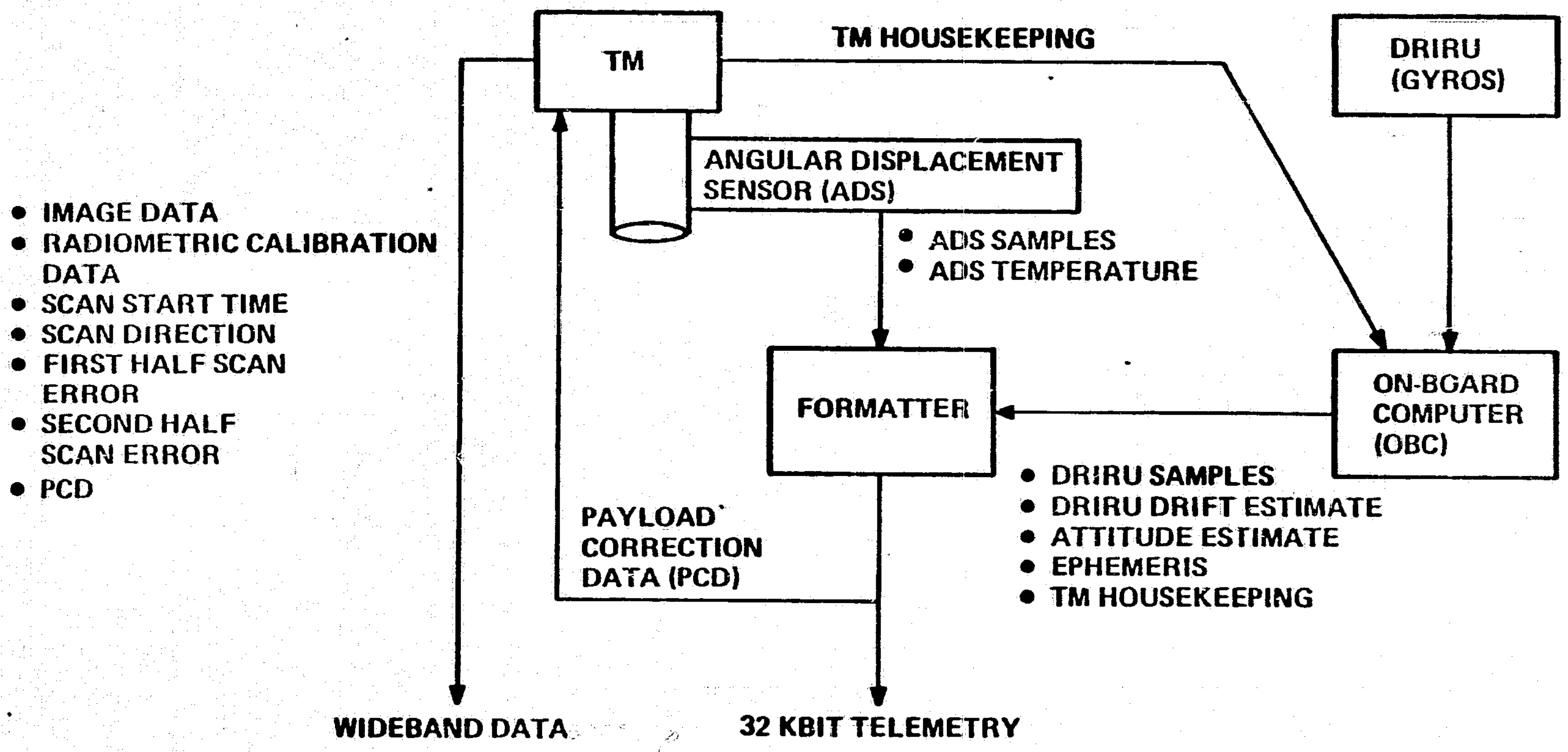
THEMATIC MAPPER



KEY GEOMETRIC FEATURES

- SCAN MIRROR
  - BI-DIRECTIONAL CROSS TRACK SCANNING
  - DATA AVAILABLE TO GROUND:
    - SCAN START TIME
    - SCAN DIRECTION
    - FIRST HALF SCAN TIME ERROR
    - SECOND HALF SCAN TIME ERROR
- SCAN LINE CORRECTOR
  - PROVIDES IN TRACK SCANNING
- TWO FOCAL PLANE ASSEMBLIES
- INSTANTANEOUS FIELD OF VIEW (IFOV)
  - BANDS 1-5, 7: 42.5 μrad (30 METERS)
  - BAND 6: 170 μrad (120 METERS)

SPACECRAFT DATA FOR IMAGE PROCESSING



TM

TM HOUSEKEEPING

DRIRU (GYROS)

ANGULAR DISPLACEMENT SENSOR (ADS)

- ADS SAMPLES
- ADS TEMPERATURE

FORMATTER

ON-BOARD COMPUTER (OBC)

- DRIRU SAMPLES
- DRIRU DRIFT ESTIMATE
- ATTITUDE ESTIMATE
- EPHEMERIS
- TM HOUSEKEEPING

PAYLOAD CORRECTION DATA (PCD)

- IMAGE DATA
- RADIOMETRIC CALIBRATION DATA
- SCAN START TIME
- SCAN DIRECTION
- FIRST HALF SCAN ERROR
- SECOND HALF SCAN ERROR
- PCD

WIDEBAND DATA

32 KBIT TELEMETRY

TIPS PERFORMANCE REQUIREMENTS

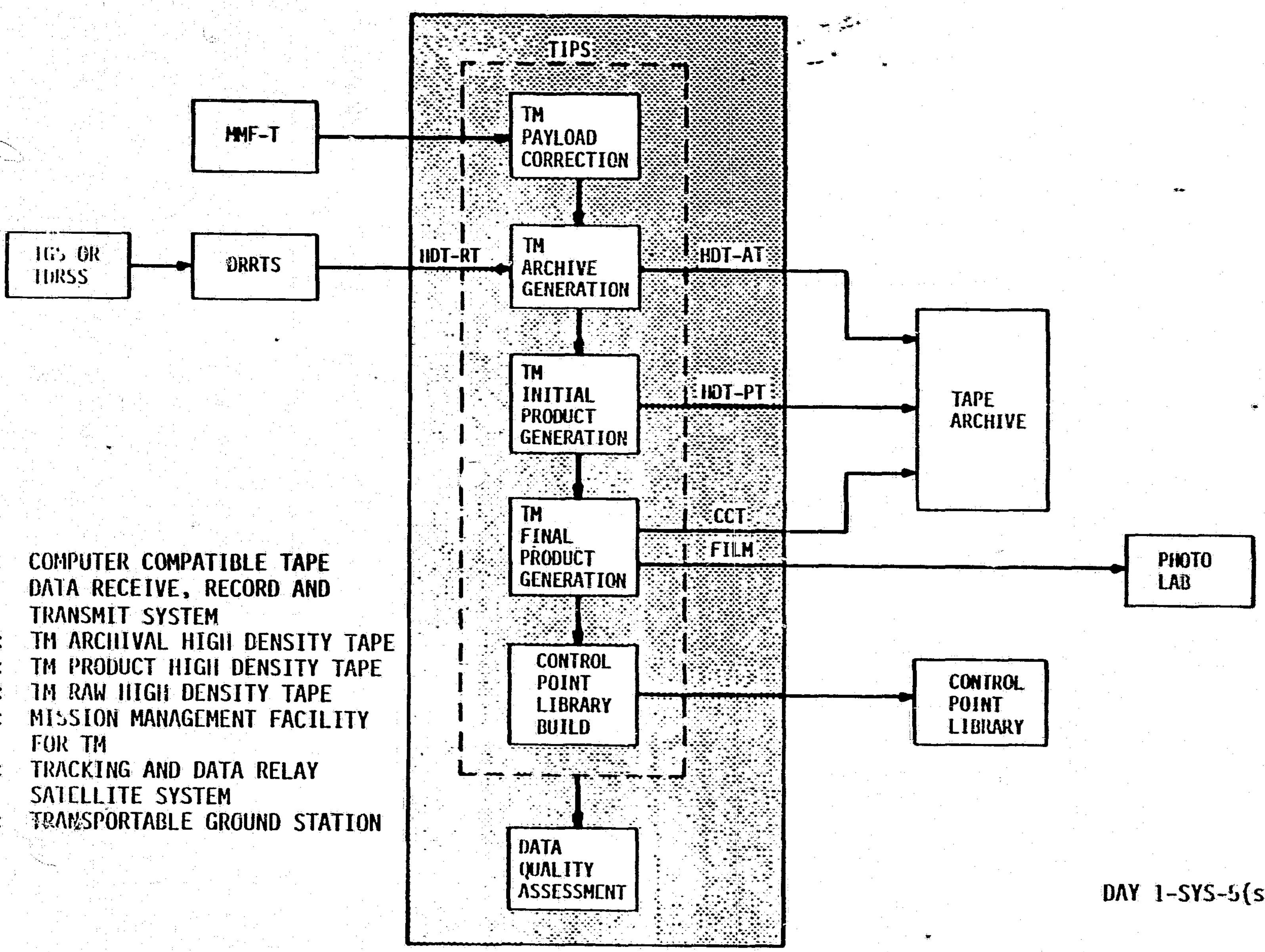
REQUIREMENT	TM R&D SYSTEM JULY 31, 1981	TM BASELINE SYSTEM JANUARY 31, 1985
TURNAROUND TIME	48 HOURS MAXIMUM ● RAW DATA TO - PRODUCT HIGH DENSITY TAPE - PRODUCT FILM - CCT	48 HOURS MAXIMUM ● RAW DATA TO - PRODUCT HIGH DENSITY TAPE - PRODUCT FILM - CCT
MAXIMUM UTILIZATION	85% OF 8 HOUR DAY	85% OF 24 HOUR DAY
RADIOMETRIC ACCURACY	±1 QUANTUM LEVEL	±1 QUANTUM LEVEL
MAP PROJECTIONS	SPACE OBLIQUE MERCATOR UNIVERSAL TRANSVERSE MERCATOR/POLAR STEREOGRAPHIC	SPACE OBLIQUE MERCATOR UNIVERSAL TRANSVERSE MERCATOR/POLAR STEREOGRAPHIC
RESAMPLING ALGORITHMS	CUBIC CONVOLUTION NEAREST NEIGHBOR	CUBIC CONVOLUTION NEAREST NEIGHBOR
GEOMETRIC ACCURACY*		
● TEMPORAL REGISTRATION	0.3 PIXEL ** (90% OF THE TIME)	0.3 PIXEL (90% OF THE TIME)
● GEODETIC	0.5 PIXEL ** (90% OF THE TIME)	0.5 PIXEL (90% OF THE TIME)
	** WITH APRIORI JITTER CORRECTION	

* WITH SUFFICIENT CORRECTABLE GROUND CONTROL POINTS

TIPS PRODUCTION REQUIREMENTS

OUTPUT	NAME	USE	VOLUME (SCENES/DAY)	
			R&D PERIOD JULY 31, 1983	NOAA OPERATIONS JANUARY 31, 1985
HIGH DENSITY TAPE - ARCHIVAL	HDT-AT	ARCHIVAL PRODUCT & LAS	12	100
HIGH DENSITY TAPE - PRODUCT	HDT-PT	INITIAL PRODUCT & LAS	12	50
COMPUTER COMPATIBLE TAPE - ARCHIVAL	CCT-AT	USER PRODUCT, PERFORMANCE EVALUATION & LAS	TOTAL OF 2	TOTAL OF 10
COMPUTER COMPATIBLE TAPE - PRODUCT	CCT-PT	USER PRODUCT, PERFORMANCE EVALUATION & LAS		
241 MM FILM - PRODUCT	F241-PT	USER PRODUCT & PERFORMANCE EVALUATION	12	50
70 MM FILM - ARCHIVAL	F70-AT	PERFORMANCE EVALUATION	12 (IN 2 BANDS)	100 (IN 2 BANDS)
CONTROL POINT LIBRARY	CP CHIPS	GEODETIC CORRECTION	50	100

TM IMAGE PROCESSING FUNCTIONS

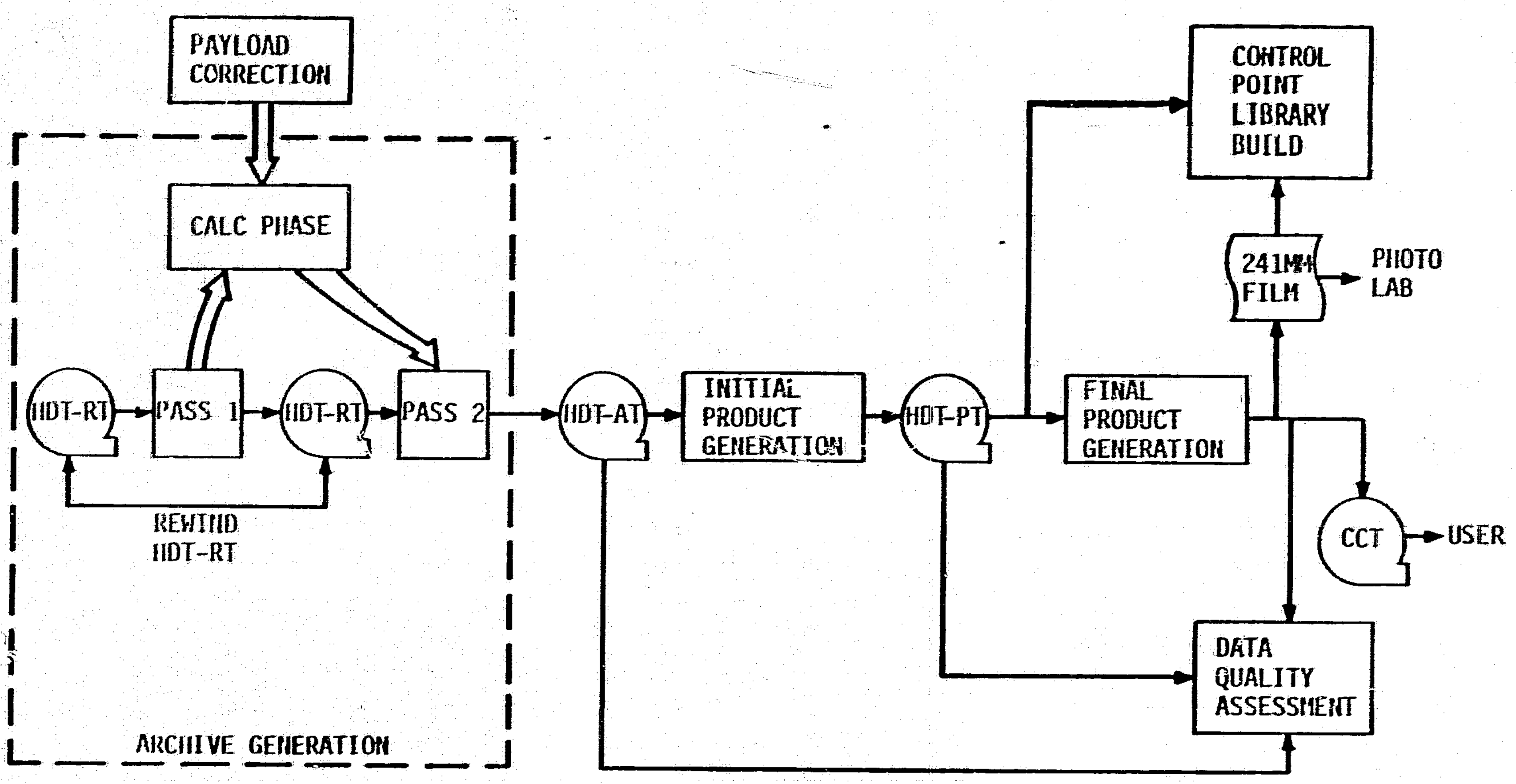


LEGEND:

CCT : COMPUTER COMPATIBLE TAPE
DRRTS : DATA RECEIVE, RECORD AND TRANSMIT SYSTEM
HDT-AT: TM ARCHIVAL HIGH DENSITY TAPE
HDT-PT: TM PRODUCT HIGH DENSITY TAPE
HDT-RT: TM RAW HIGH DENSITY TAPE
MMF-T : MISSION MANAGEMENT FACILITY FOR TM
TDRSS : TRACKING AND DATA RELAY SATELLITE SYSTEM
TGS : TRANSPORTABLE GROUND STATION

TIPS PROCESSING ARCHITECTURE

TIPS PROCESS FLOW

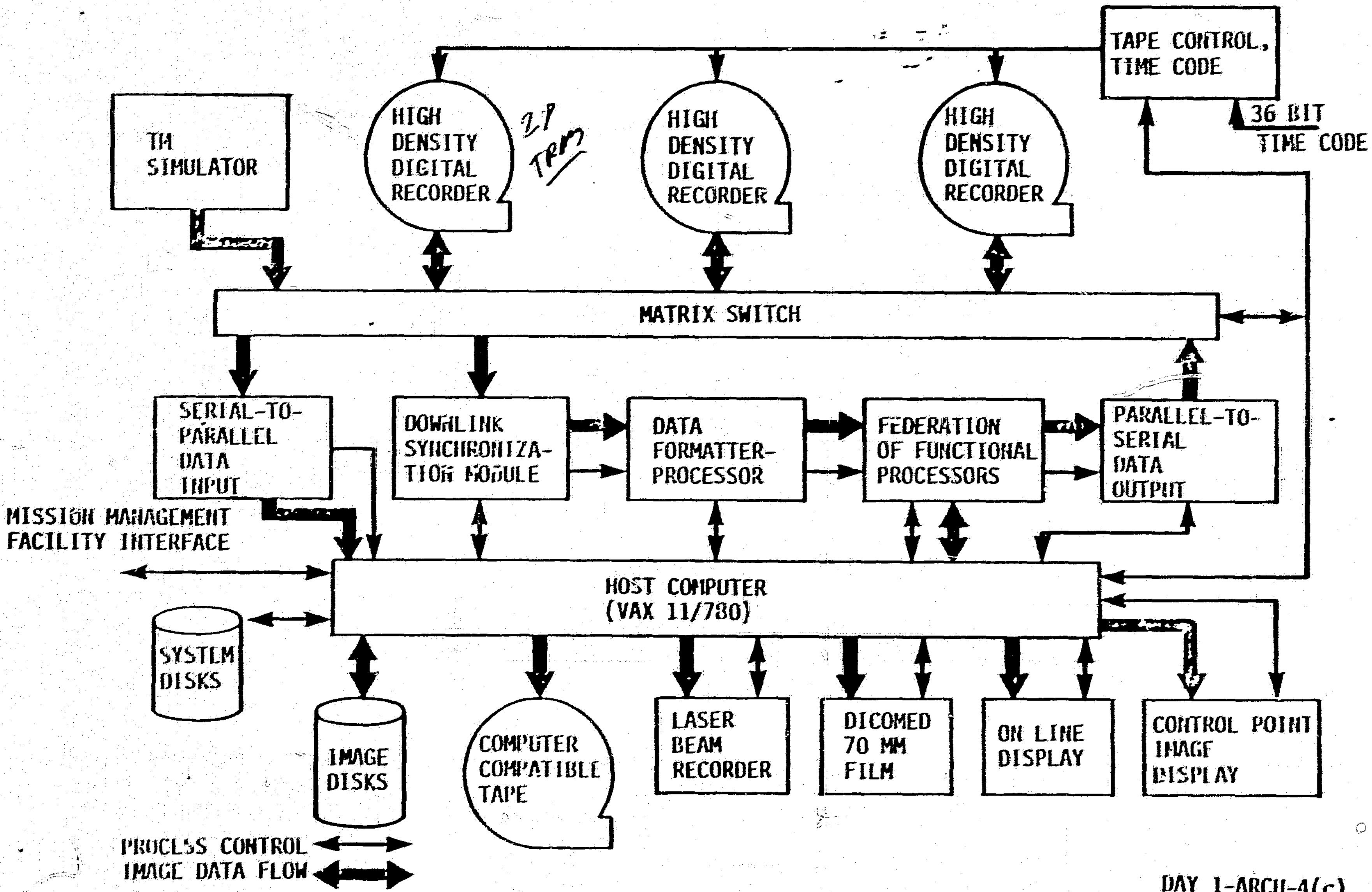


LEGEND:

CCT : COMPUTER COMPATIBLE TAPE
HDT-AT: TM ARCHIVAL HIGH DENSITY TAPE
HDT-PT: TM PRODUCT HIGH DENSITY TAPE
HDT-RT: TM RAW HIGH DENSITY TAPE

TIPS PROCESSING ARCHITECTURE

TIPS HARDWARE ARCHITECTURE

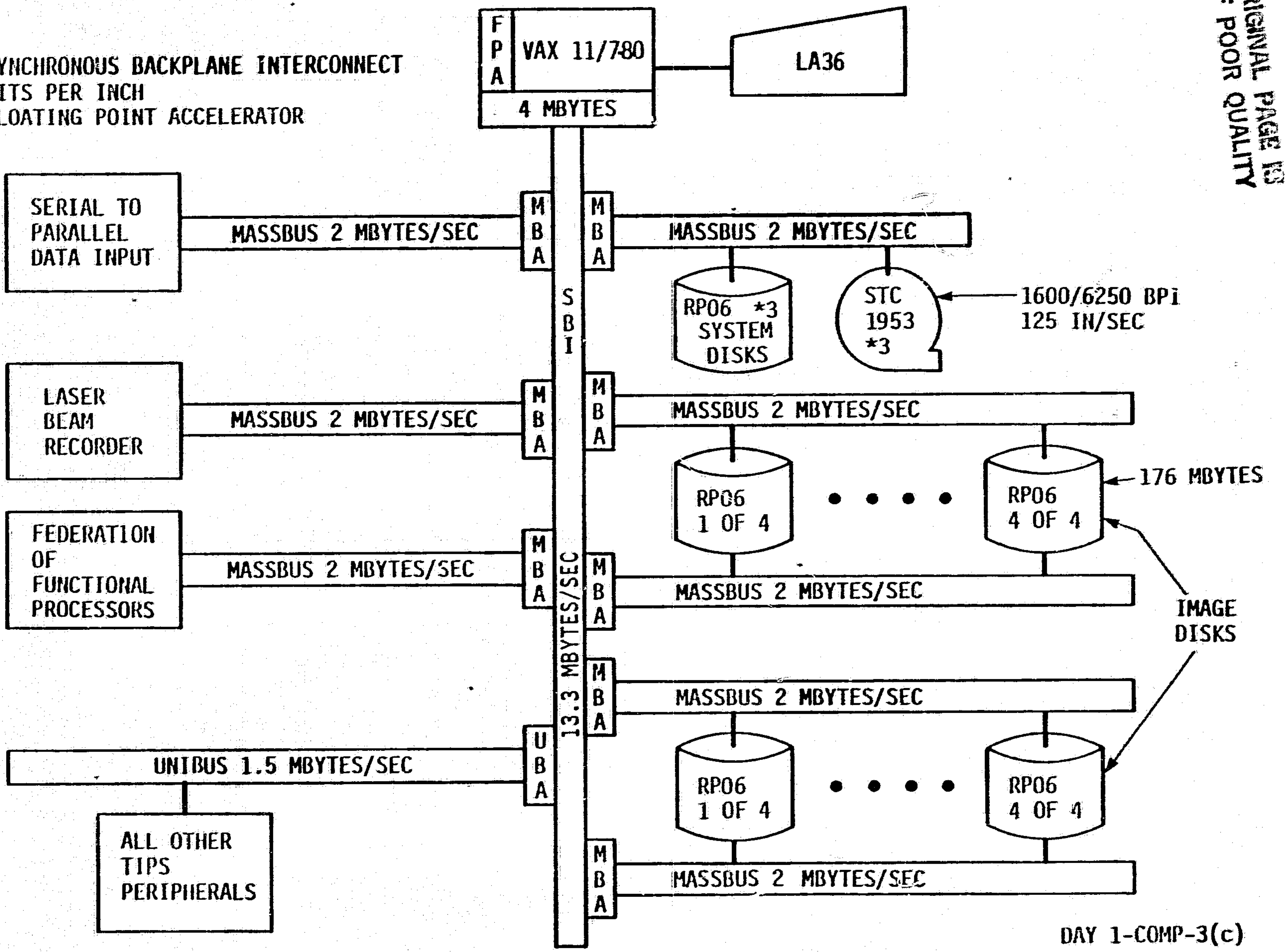


DAY 1-ARCH-4(c)

TIPS VAX 11/780 INTERNAL ARCHITECTURE

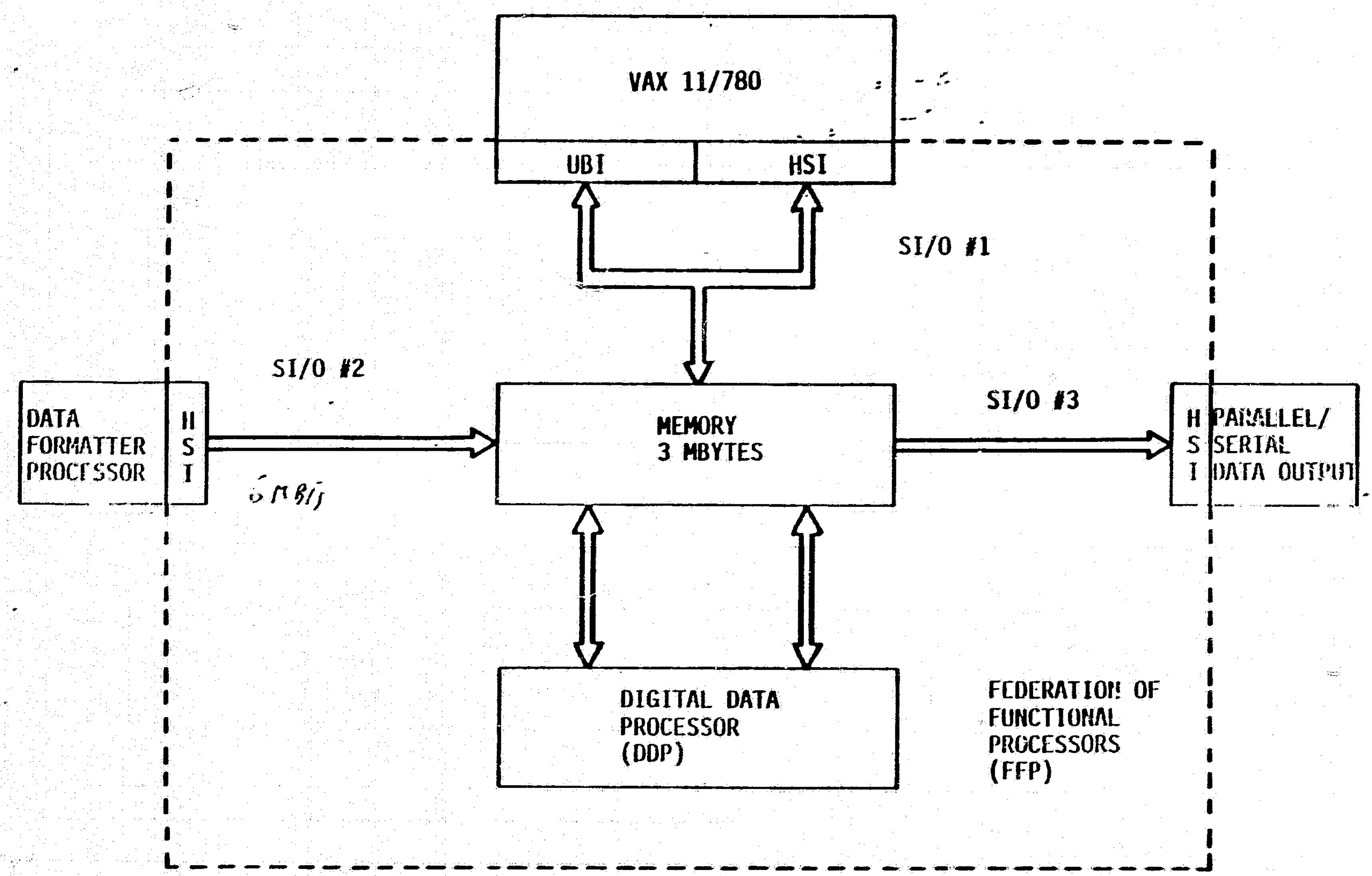
LEGEND:

SBI: SYNCHRONOUS BACKPLANE INTERCONNECT
BPI: BITS PER INCH
FPA: FLOATING POINT ACCELERATOR



DAY 1-COMP-3(c)

TIPS FFP SYSTEM CONFIGURATION



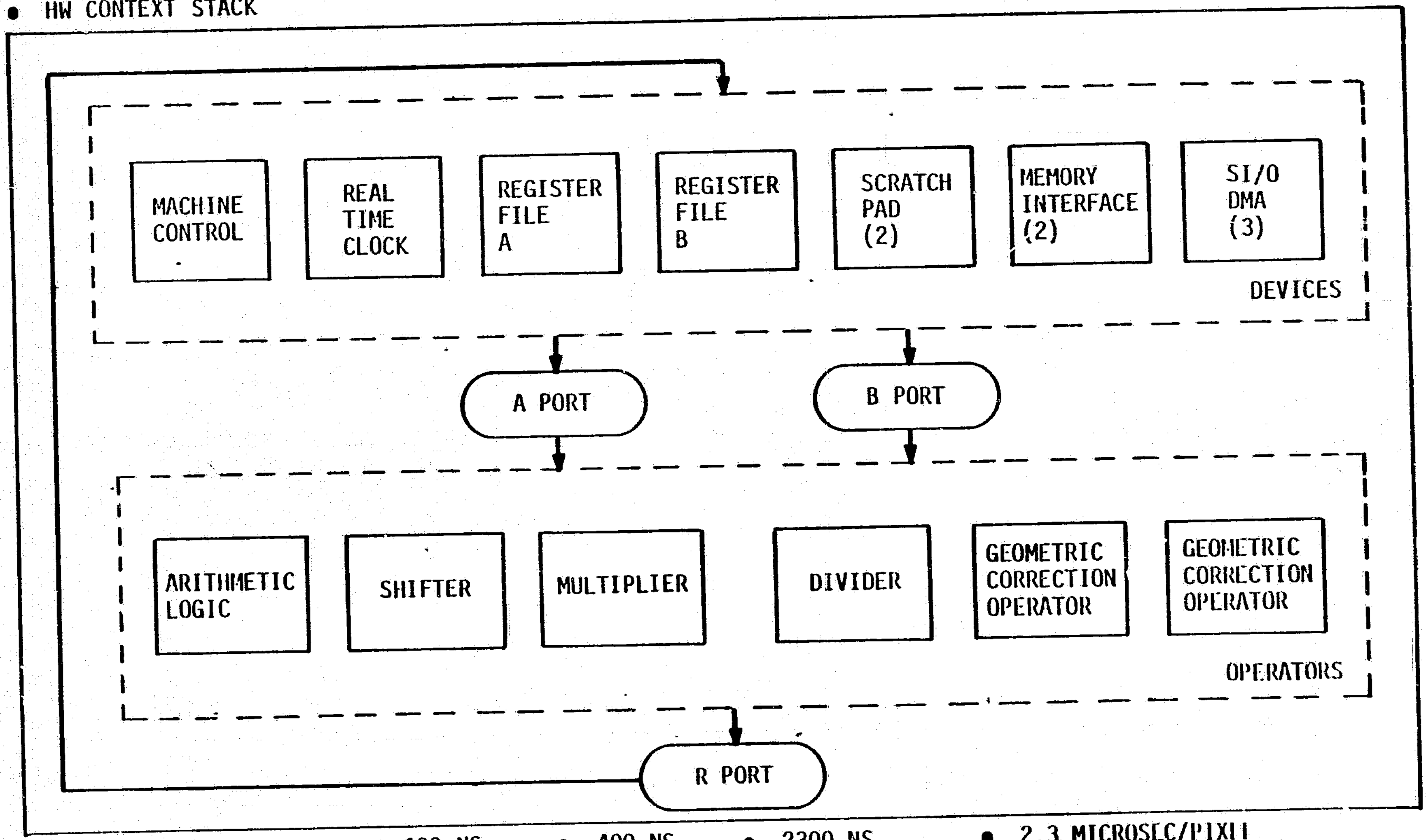
LEGEND:

HSI: HIGH SPEED INTERFACE
UBI: UNIBUS INTERFACE
SI/O: STANDARD I/O BUS

DAY 1-COMP-8(c)

DDP ARCHITECTURE

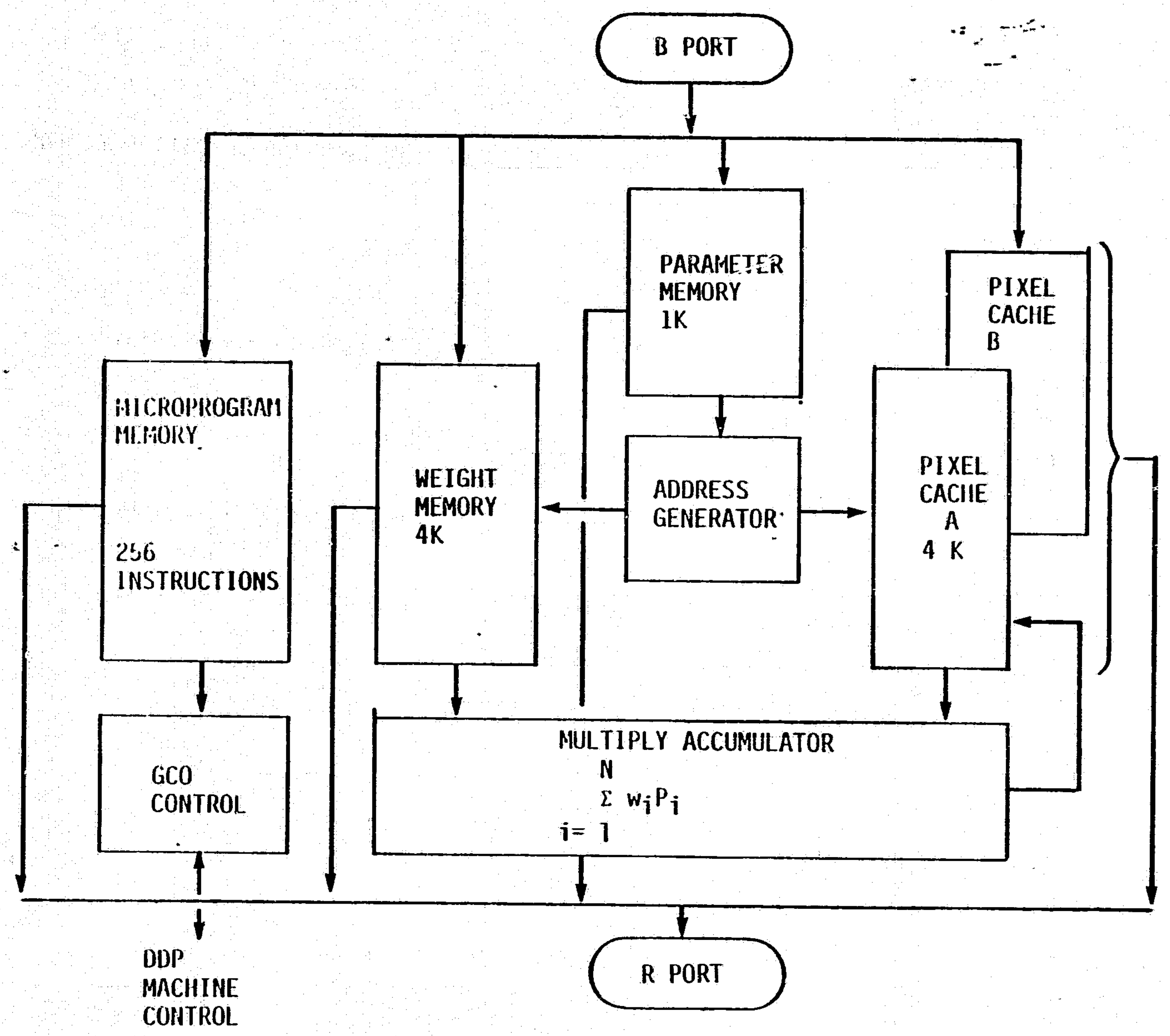
- 16 K WCS
  32-BIT WORD
- 100 NS/INSTR
- HW CONTEXT STACK
- 100 NS
  RESOLUTION
- 16 * 16 REGS
  EACH
- 8 K EACH
  16-BIT WORD
- 4 MBYTE
  ADDRESS SPACE
  EACH
- 6 MBYTE/SEC
  DMA



- 100 NS
  ADD, SUB
  LOGICAL
- 100 NS
  SHIFT
- 400 NS
  MULTIPLY
- 2300 NS
  DIVIDE
- 2.3 MICROSEC/PIXEL
  EACH (NOM)

DAY 1-COMP-11(c)

GEOMETRIC CORRECTION OPERATOR (GCO)
FUNCTIONAL ARCHITECTURE



B PORT

PARAMETER MEMORY 1K

ADDRESS GENERATOR

PIXEL CACHE B

PIXEL CACHE A 4 K

MICROPROGRAM MEMORY 256 INSTRUCTIONS

WEIGHT MEMORY 4K

GCO CONTROL

MULTIPLY ACCUMULATOR $\sum_{i=1}^{N} w_i P_i$

DDP MACHINE CONTROL

R PORT

- SIMULTANEOUS CACHE I/O AND GEOMETRIC CORRECTION
- SIGNIFICANT EVENTS INTERRUPT DDP
- 2.53 μSEC/PIXEL (MAX)
  2.3 μSEC/PIXEL (NOM)
  3-PASS RESAMPLING

UNITS

TM PIXEL = 42.5 μ RAD = 8.77 ARC-SEC → 30 METERS AT 705.3 KM

MSS PIXEL = 117.2 μ RAD = 24.17 ARC-SEC ⇒ 82.7 METERS AT 705.3 KM

1 μ RAD ⇒ .71 METER AT 705.3

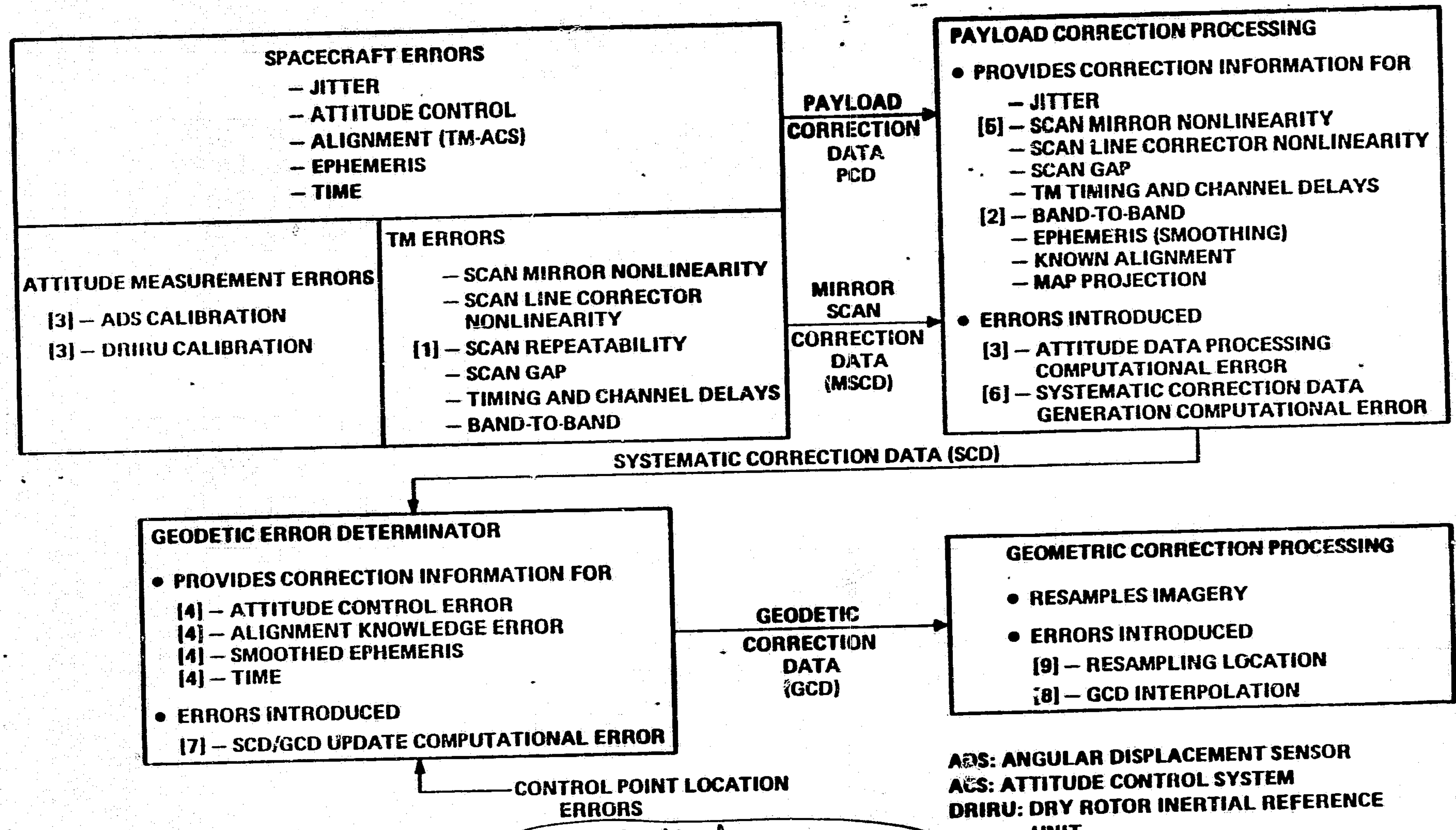
1 ARC-SEC ⇒ 3.4 METER AT 705.3

1 ARC-SEC = 4.85 μ RAD

SINGLE SCENE ACCURACY REQUIREMENT

$$0.3 \text{ PIXEL TEMPORAL } (90\%) \times \frac{42.5 \mu \text{ RAD}}{\text{PIXEL}} \times \frac{(1\sigma)}{1.645(90\%)} \times \frac{\text{SINGLE SCENE}}{\sqrt{2} \text{ TEMPORAL}} = 5.48 \, \mu\text{RAD} = 1.13 \text{ ARC SEC } (1\sigma)$$

TM SYSTEM GEOMETRIC ERRORS



SPACECRAFT ERRORS

- — JITTER
- — ATTITUDE CONTROL
- — ALIGNMENT (TM-ACS)
- — EPHEMERIS
- — TIME

ATTITUDE MEASUREMENT ERRORS

- [3] — ADS CALIBRATION
- [3] — DRIRU CALIBRATION

TM ERRORS

- — SCAN MIRROR NONLINEARITY
- — SCAN LINE CORRECTOR NONLINEARITY
- [1] — SCAN REPEATABILITY
- — SCAN GAP
- — TIMING AND CHANNEL DELAYS
- — BAND-TO-BAND

PAYLOAD CORRECTION DATA PCD

MIRROR SCAN CORRECTION DATA (MSCD)

PAYLOAD CORRECTION PROCESSING

- PROVIDES CORRECTION INFORMATION FOR
  - — JITTER
  - [5] — SCAN MIRROR NONLINEARITY
  - — SCAN LINE CORRECTOR NONLINEARITY
  - — SCAN GAP
  - — TM TIMING AND CHANNEL DELAYS
  - [2] — BAND-TO-BAND
  - — EPHEMERIS (SMOOTHING)
  - — KNOWN ALIGNMENT
  - — MAP PROJECTION
- ERRORS INTRODUCED
  - [3] — ATTITUDE DATA PROCESSING COMPUTATIONAL ERROR
  - [6] — SYSTEMATIC CORRECTION DATA GENERATION COMPUTATIONAL ERROR

SYSTEMATIC CORRECTION DATA (SCD)

GEODETIC ERROR DETERMINATOR

- PROVIDES CORRECTION INFORMATION FOR
  - [4] — ATTITUDE CONTROL ERROR
  - [4] — ALIGNMENT KNOWLEDGE ERROR
  - [4] — SMOOTHED EPHEMERIS
  - [4] — TIME
- ERRORS INTRODUCED
  - [7] — SCD/GCD UPDATE COMPUTATIONAL ERROR

CONTROL POINT LOCATION ERRORS

GEODETIC CORRECTION DATA (GCD)

GEOMETRIC CORRECTION PROCESSING

- RESAMPLES IMAGERY
- ERRORS INTRODUCED
  - [9] — RESAMPLING LOCATION
  - [8] — GCD INTERPOLATION

ADS: ANGULAR DISPLACEMENT SENSOR
ACS: ATTITUDE CONTROL SYSTEM
DRIRU: DRY ROTOR INERTIAL REFERENCE UNIT

[•] ERROR BUDGET ITEMS (NEXT CHART)

Thermal effect
12 arc-sec/°C across TM sensor

3

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DAY 2 TMGE-5 (S)

THEMATIC MAPPER SYSTEM
TEMPORAL REGISTRATION ERROR BUDGET
IN PIXEL (42.5 MICRORAD) 90%

ERROR SOURCE	CROSS TRACK ERROR*	ALONG TRACK ERROR*	ITEM NUMBER (PREVIOUS CHART)
• THEMATIC MAPPER			
— SCAN REPEATABILITY	$.165\sqrt{2}$	$.165\sqrt{2}$	1
— BAND-TO-BAND	$.048\sqrt{2}$	$.039\sqrt{2}$	2
• SPACECRAFT			
— JITTER	$.094\sqrt{2}$	$.094\sqrt{2}$	3
— ATTITUDE, EPHEMERIS, ALIGNMENT, TIME RESIDUAL	.165	.165	4
• GROUND PROCESSING			
— SCAN NONLINEARITY CORRECTION	$.082\sqrt{2}$	0	5
— SYSTEMATIC CORRECTION DATA GENERATION	$.055\sqrt{2}$	$.055\sqrt{2}$	6
— GEODETIC ERROR DETERMINATOR	$.055\sqrt{2}$	$.055\sqrt{2}$	7
— GCD INTERPOLATION	$.055\sqrt{2}$	$.055\sqrt{2}$	8
— RESAMPLING LOCATION	$.014\sqrt{2}$	$.014\sqrt{2}$	9
• TOTAL (ROOT-SUM-SQUARE)	.369	.348	
• SPECIFICATION	.3	.3	

*RESIDUAL ERROR AFTER PROCESSING

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DYNAMIC ALIGNMENT

- SPACECRAFT TEMPERATURE CHANGES CAUSE ALIGNMENT CHANGES
  - EXAMPLE: 1 DEGREE GRADIENT ACROSS THE INSTRUMENT MODULE CAUSES A 12 ARC-SEC ACS TO TM ALIGNMENT CHANGE. (GODDARD ANALYSIS)
- TIME CORRELATION OF DYNAMIC ALIGNMENT CHANGE IS UNKNOWN
- REQUIRE GROUND PROCESSING TO ACCOMMODATE 10 ARC-SEC/MINUTE (1σ) THERMAL ALIGNMENT RATE
- INCORPORATED A FLEXIBLE CORRELATED NOISE MODEL OF ALIGNMENT

[illegible]

SCAN GAP** ERROR

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ALTITUDE VARIATION

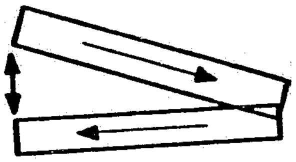
696 — 741 KM FOR 705.3 ORBIT
713 KM TM DESIGN ALTITUDE

JITTER

LESS THAN 1 PIXEL

TM UNDERLAP/OVERLAP

0.2 PIXEL (SPEC)



EARTH LOCATION	WORST CASE END SCAN GAP IN PIXELS*
NORTHERN HEMISPHERE	-0.7 TO 0.8
45°N	-0.4 TO 0.6
EQUATOR	-0.2 TO 0.8
45°S	-0.9 TO 0.1
SOUTHERN HEMISPHERE	-1.6 TO 0.8

WORST CASE GAP RANGE

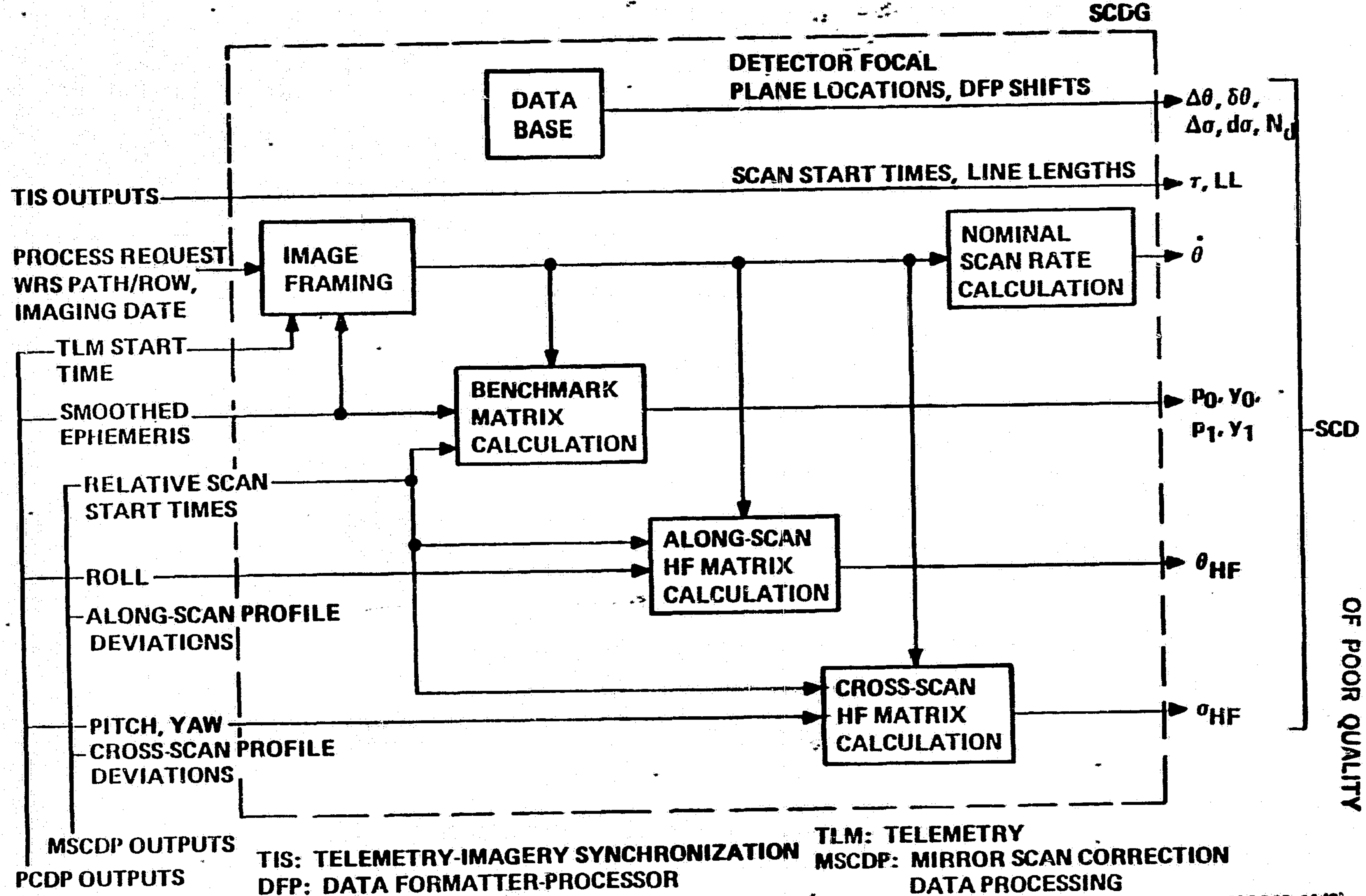
-2.8 TO 2.0

[illegible] Sys can accommodate more than this

*INCLUDES SCAN WIDTH, SCAN LINE CORRECTOR AND BOWTIE EFFECTS

**GAP < 0 : OVERLAP
= 0 : NOMINAL
> 0 : UNDERLAP

SYSTEMATIC CORRECTION DATA GENERATION



TIS: TELEMETRY-IMAGERY SYNCHRONIZATION
DFP: DATA FORMATTER-PROCESSOR
WRS: WORLD REFERENCE SYSTEM
HF: HIGH FREQUENCY

TLM: TELEMETRY
MSCDP: MIRROR SCAN CORRECTION DATA PROCESSING
PCDP: PAYLOAD CORRECTION DATA PROCESSING

DAY 2 PCP-14 (S)

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SCD: OPTICAL AXIS POSITION ON THE OUTPUT COORDINATE SYSTEM

BENCHMARK MATRICES

p_0 (i,j,k), y_0 (i,j,k)

p_1 (i,j,k), y_1 (i,j,k)

i = x coordinate index = 1, . . . ,8

j = sweep index = 1, . . . ,4

k = scan direction index = 1,2

INCLUDES: EPHEMERIS, NOMINAL LINEAR TM ACTIVE SCAN, PERFECT ACS, KNOWN INSTRUMENT ALIGNMENT, MAP PROJECTION

(ONE SET FOR EACH PROJECTION)

ALONG SCAN

HIGH FREQUENCY MATRIX

θ_{HF} (i,j)

i = sample number index = 1, . . . ,35

j = scan number = 1, . . . ,374

INCLUDES: SMA ALONG SCAN PROFILE, SMA LINE LENGTH, S/C ROLL JITTER

MIRROR SCAN START TIMES

τ (j)

j = scan number = 1, . . ., 374

RELATIVE START TIME FOR EACH SCAN

CROSS SCAN

HIGH FREQUENCY MATRIX

σ_{HF} (i,j)

i = sample number index = 1, . . . ,35

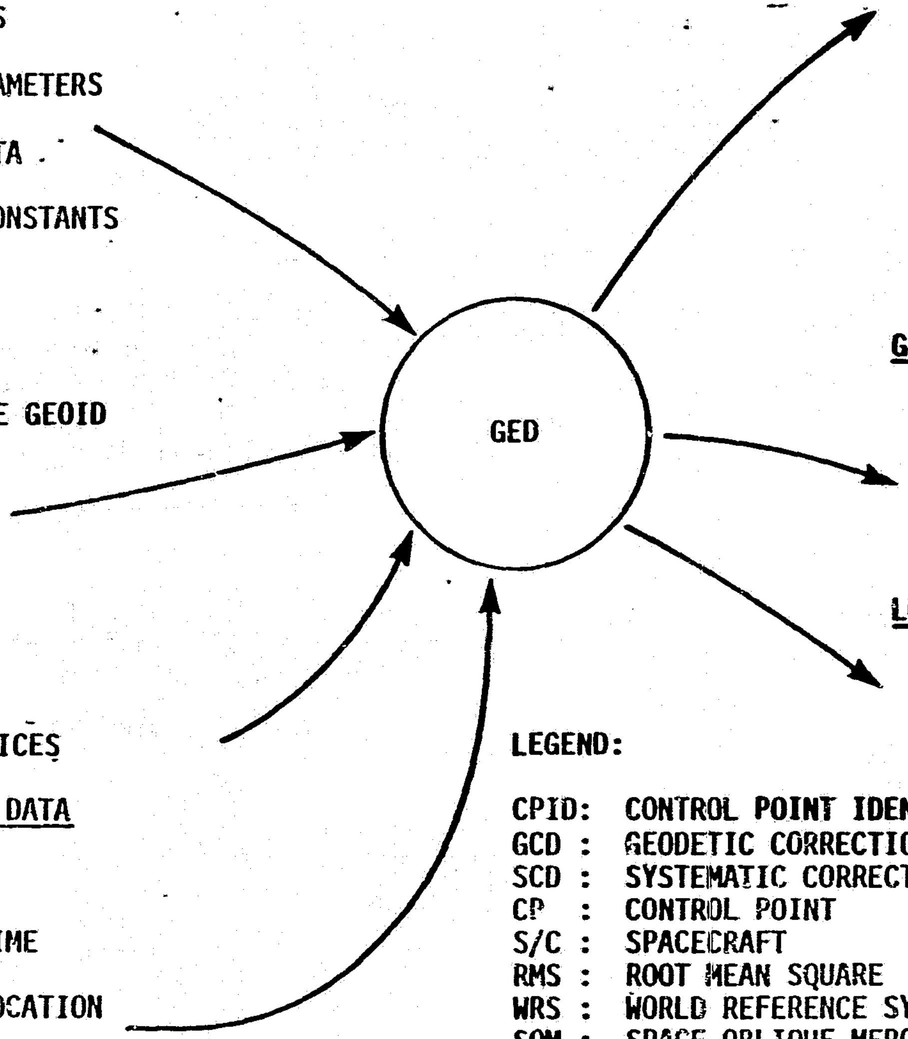
j = scan number = 1, . . . ,374

INCLUDES: SMA CROSS SCAN PROFILE, SMA LINE LENGTH, SLC PROFILE, SLC DELAY, S/C PITCH AND YAW JITTER

SMA: SCAN MIRROR ASSEMBLY
SLC: SCAN LINE CORRECTOR
S/C: SPACECRAFT

GED INPUT/OUTPUT

GEODETIC ERROR DETERMINATION



STATIC DATA

- WRS FRAME PARAMETERS
  - FRAME CENTER ANGLES
  - UNIT VECTORS
- INSTRUMENT PARAMETERS
- STATISTICAL DATA
- MATHEMATICAL CONSTANTS

CONTROL POINT DATA

- CPID
- ELEVATION ABOVE GEOID
- X_{SOM}, X'_{SOM}
- QUALITY DATA
- USAGE FLAG

LOW FREQUENCY SCD

- BENCHMARK MATRICES

PROCESSED EPHEMERIS DATA

SCD SUPPORT DATA

- SCENE CENTER TIME
- SCENE CENTER LOCATION
- WRS OFFSET

QUALITY ASSURANCE DATA

- CP DATA UPDATE (EACH CP)
  - DISLOCATION ($\overline{\Delta X}$)
  - UPDATED USAGE FLAG
  - UPDATED QUALITY
  - CORRELATION STATISTICS
- SCENE DATA (AT CENTER)
  - S/C PARAMETER BIASES
  - COVARIANCE MATRIX
  - CORRECTION QUALITY
  - RMS RESIDUALS

GCD ANNOTATION DATA

- SCENE CENTER TIME
- SCENE CENTER ANGLES
- WRS OFFSET

LOW FREQUENCY GCD

- BENCHMARK MATRICES
  - SOM
  - UTM OR PS

LEGEND:

CPID:	CONTROL POINT IDENTIFICATION
GCD :	GEODETIC CORRECTION DATA
SCD :	SYSTEMATIC CORRECTION DATA
CP :	CONTROL POINT
S/C :	SPACECRAFT
RMS :	ROOT MEAN SQUARE
WRS :	WORLD REFERENCE SYSTEM
SOM :	SPACE OBLIQUE MERCATOR
UTM :	UNIVERSAL TRANSVERSE MERCATOR
PS :	POLAR STEREOGRAPHIC

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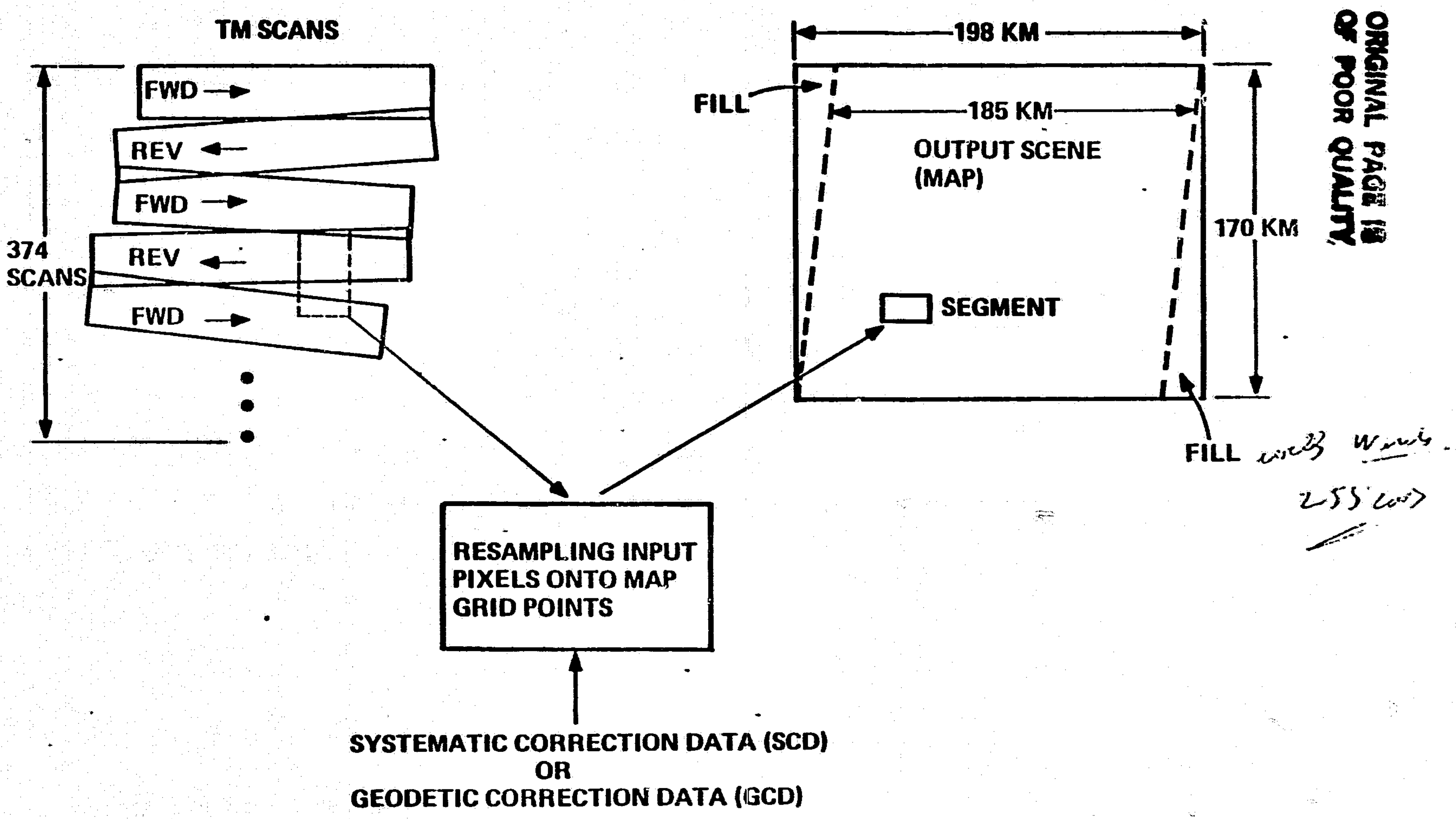
DAY 2-GED-5(c)

RECURSIVE DISTORTION ESTIMATOR

- CORE OF THE GED: ESTIMATES ALL OR SOME SUBSET OF SPACECRAFT PARAMETER BIASES $\vec{\delta}(t)$
- CP MEASUREMENTS USED, ONE AT A TIME, IN A TIME ORDERED SEQUENCE
- UTILIZES A COMBINATION OF
  - PREDICTION, BY MEANS OF DYNAMIC MODELS: $\dot{\vec{\delta}}(t) = \phi(t)\vec{\delta}(t) +$ noise
  - POINTWISE UPDATES OF $\vec{\delta}$ AT CONTROL POINTS (t_k) TO PROVIDE MINIMUM VARIANCE ESTIMATE $\hat{\delta}(t_k)$
- FORWARD PASS THROUGH DATA FOLLOWED BY BACKWARD PASS TO DIFFUSE MEASUREMENT DATA
- ADVANTAGES OVER BATCH PROCESSOR
  - NATURAL EVOLUTION OF TIME BEHAVIOR
  - USES ALL OF OUR KNOWLEDGE OF THE IMAGING SYSTEM
  - MORE FORGIVING OF SYSTEM PARAMETER FLUCTUATIONS
- CRITICAL CHARACTERIZATIONS
  - DYNAMIC MODELS
  - APRIORI STATISTICS OF IMAGING SYSTEM ELEMENTS
  - APRIORI STATISTICS OF IMAGE AND CORRELATION PROCESS

TM GEOMETRIC CORRECTION PROCESS OVERVIEW



GEOMETRIC CORRECTION PROCESS PARAMETERS

- INPUT
  - 7 SPECTRAL BANDS
  - 16 DETECTORS PER HIGH RESOLUTION BAND (BANDS 1, 2, 3, 4, 5, 7)
  - 4 DETECTORS IN THERMAL BAND (BAND 6)
  - HIGH RESOLUTION BAND PIXEL SIZE ≈ 30 METERS SQUARE
  - THERMAL BAND PIXEL SIZE ≈ 120 METERS SQUARE
  - NUMBER OF INPUT PIXELS REQUIRED TO PRODUCE AN OUTPUT SCENE ≈ 250M PIXELS

- OUTPUT
  - OUTPUT PIXEL SIZE = 28.5 METERS SQUARE
  - SCENE HORIZONTAL LINE LENGTH = 6967 PIXELS
  - NUMBER OF HORIZONTAL LINES PER SCENE = 5965
  - NUMBER OF PIXELS PER SCENE = 6967 x 5965 x 7≈290 M PIXELS

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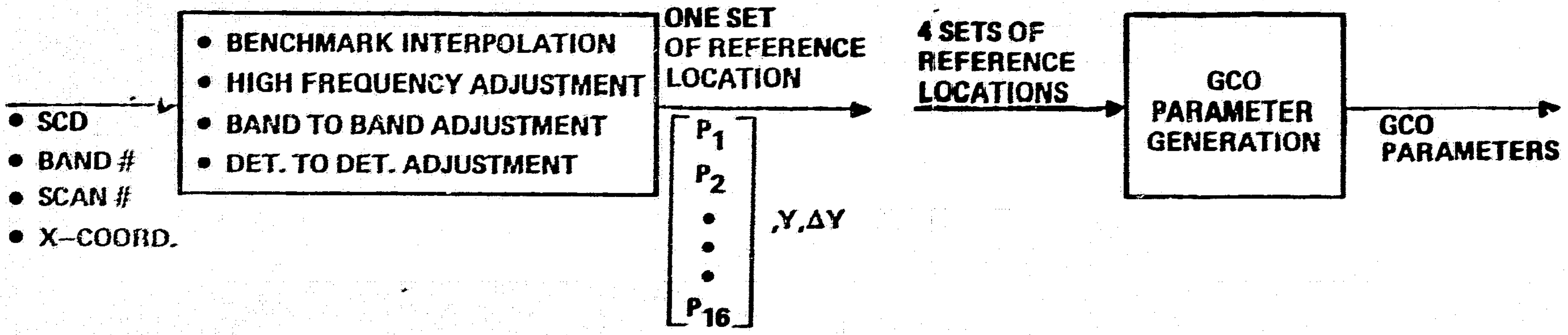
SYSTEMATIC CORRECTION DATA (SCD) UTILIZATION & GCO PARAMETER GENERATION



- SCD
- BAND #
- SCAN #
- X–COORD.

- BENCHMARK INTERPOLATION
- HIGH FREQUENCY ADJUSTMENT
- BAND TO BAND ADJUSTMENT
- DET. TO DET. ADJUSTMENT

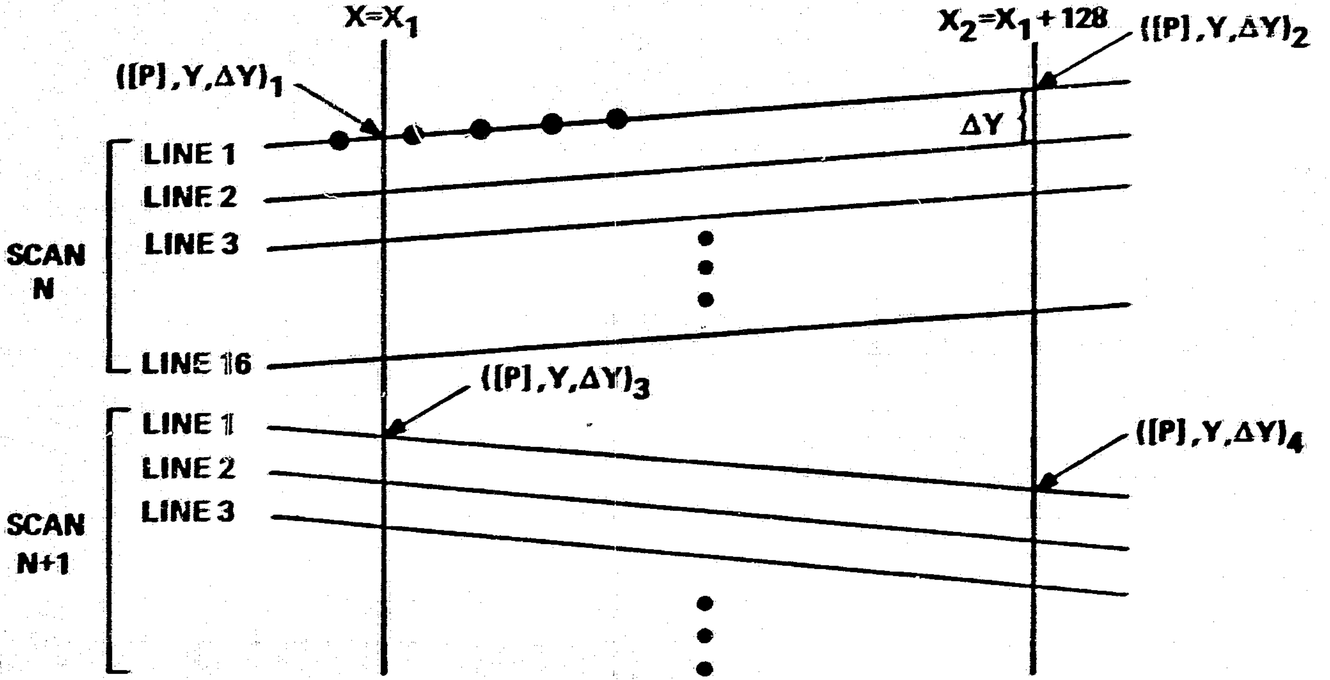
ONE SET OF REFERENCE LOCATION

$\begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{16} \end{bmatrix}, Y, \Delta Y$

4 SETS OF REFERENCE LOCATIONS

GCO PARAMETER GENERATION

GCO PARAMETERS



P: INPUT PIXEL NUMBER
Y: Y-COORDINATE IN OUTPUT SPACE
ΔY: DISTANCE BETWEEN TWO INPUT LINES

GEOMETRIC CORRECTION OPERATOR (GCO)
GAP HANDLING CAPABILITY

	WORST CASE (IN PIXELS)	GCO CAPABILITY (IN PIXELS)
GAP SIZE	–2.8 TO 2.0	–5 TO 3
GAP SKEW OVER 128 OUTPUT PIXELS	–0.42 TO 0.42	–2 TO 2
TM SCAN LINE SKEW OVER 128 OUTPUT PIXELS	–1.0 TO 1.0	–2 TO 2

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TM OUTPUT SCENE SEGMENTATION

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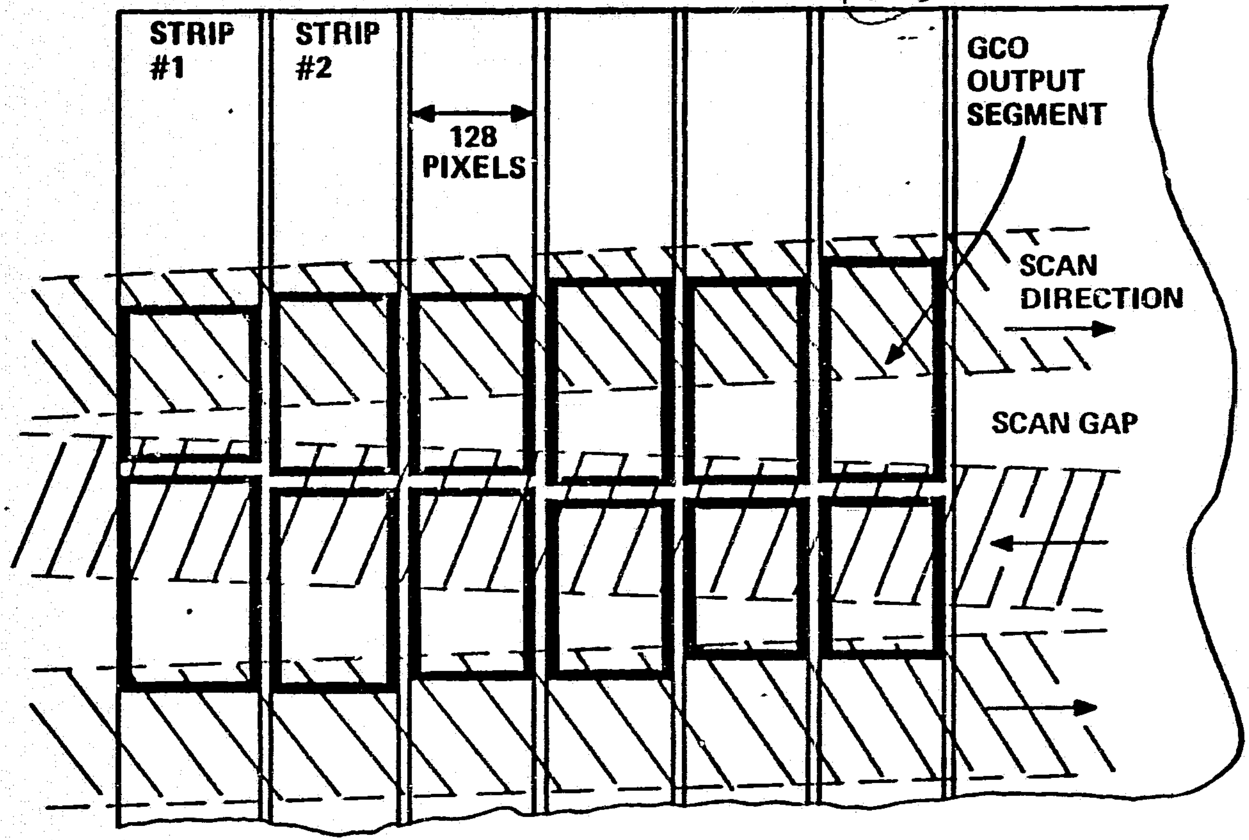
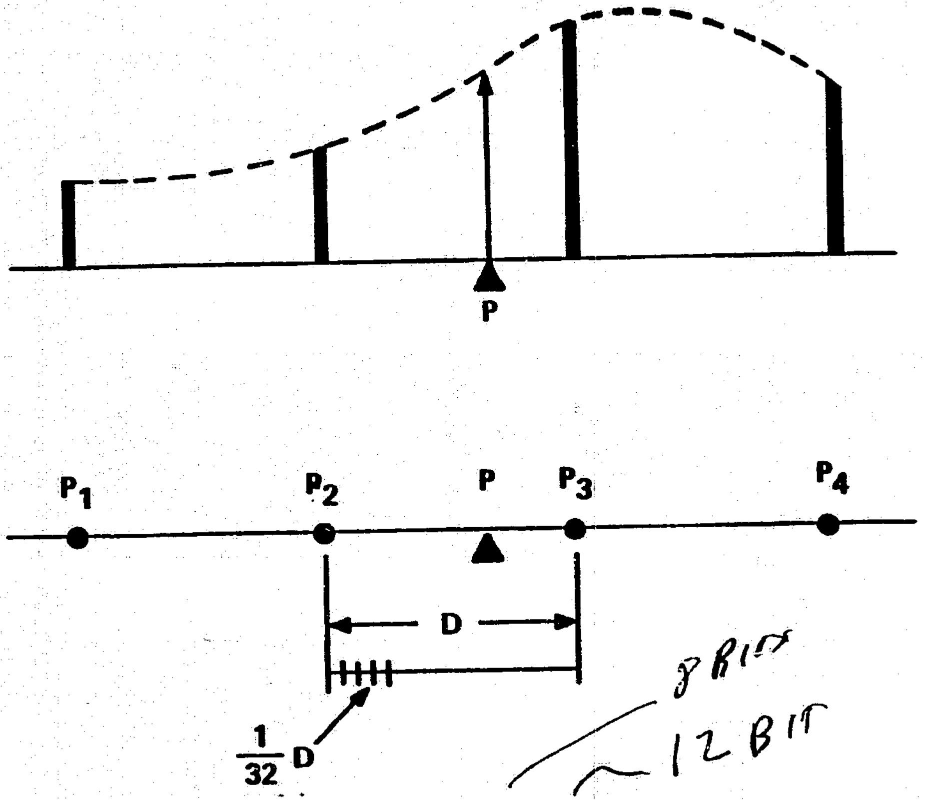


- DIVIDE A FULL SCENE INTO A NUMBER OF 128-PIXEL WIDE VERTICAL STRIPS
- EACH GCO OUTPUT SEGMENT CORRESPONDS TO A TM SCAN AND A STRIP
- GCO OUTPUT SEGMENT HEIGHT VARIES WITH SCAN GAP SIZE
- SCENE SEGMENTATION TECHNIQUE APPLIES TO ALL FOUR RESAMPLING CASES

ONE-DIMENSIONAL CUBIC CONVOLUTION RESAMPLING



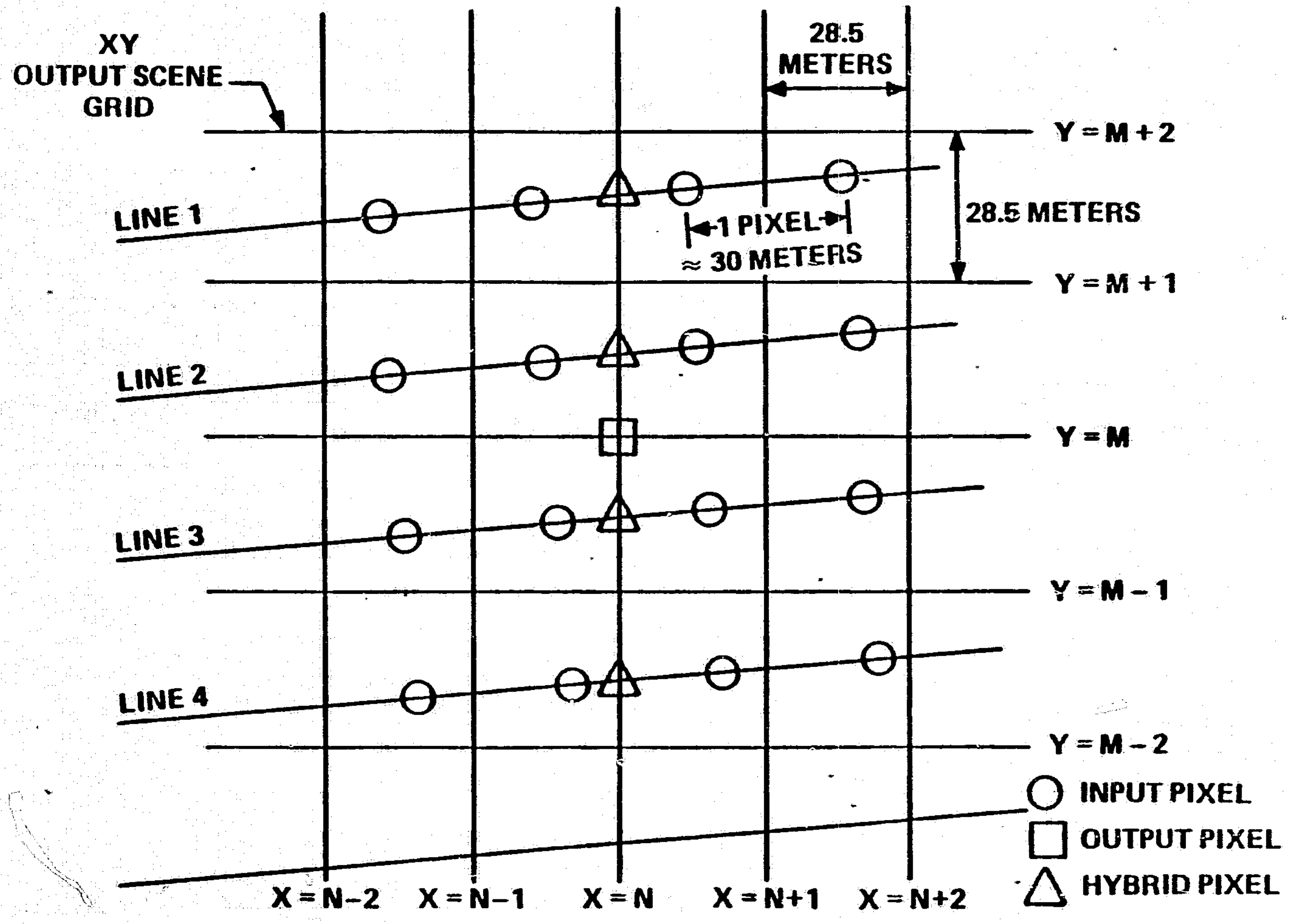
8 BIT

12 BIT

- $P = P_1W_1 + P_2W_2 + P_3W_3 + P_4W_4$
- 32 SETS OF WEIGHTING COEFFICIENTS (W_1, W_2, W_3, W_4) FOR 32 SUB-INTERVALS
- OUTPUT PIXEL LOCATION PRECISION TO (1/64) PIXEL IN RESAMPLING COMPUTATION
- INPUT PIXELS MUST BE EQUALLY SPACED

TWO-DIMENSIONAL CUBIC CONVOLUTION RESAMPLING

- X-RESAMPLING: GENERATE HYBRID PIXELS
- Y-RESAMPLING: GENERATE OUTPUT PIXELS



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THREE – STEP RESAMPLING FOR GAP PROCESSING

X-RESAMPLING

- RESAMPLING ALONG SCAN LINE
- GENERATE PIXELS ON CROSS POINTS OF SCAN LINES AND Y-GRID

E-RESAMPLING

- RESAMPLING ALONG Y-GRID
- GENERATE SCAN EXTENSION LINE PIXELS

Y-RESAMPLING

- RESAMPLING ALONG Y-GRID
- GENERATE PIXELS ON OUTPUT GRID POINTS

B

Require copies -
Refer to [illegible]
of analysis & other matters
& resampling

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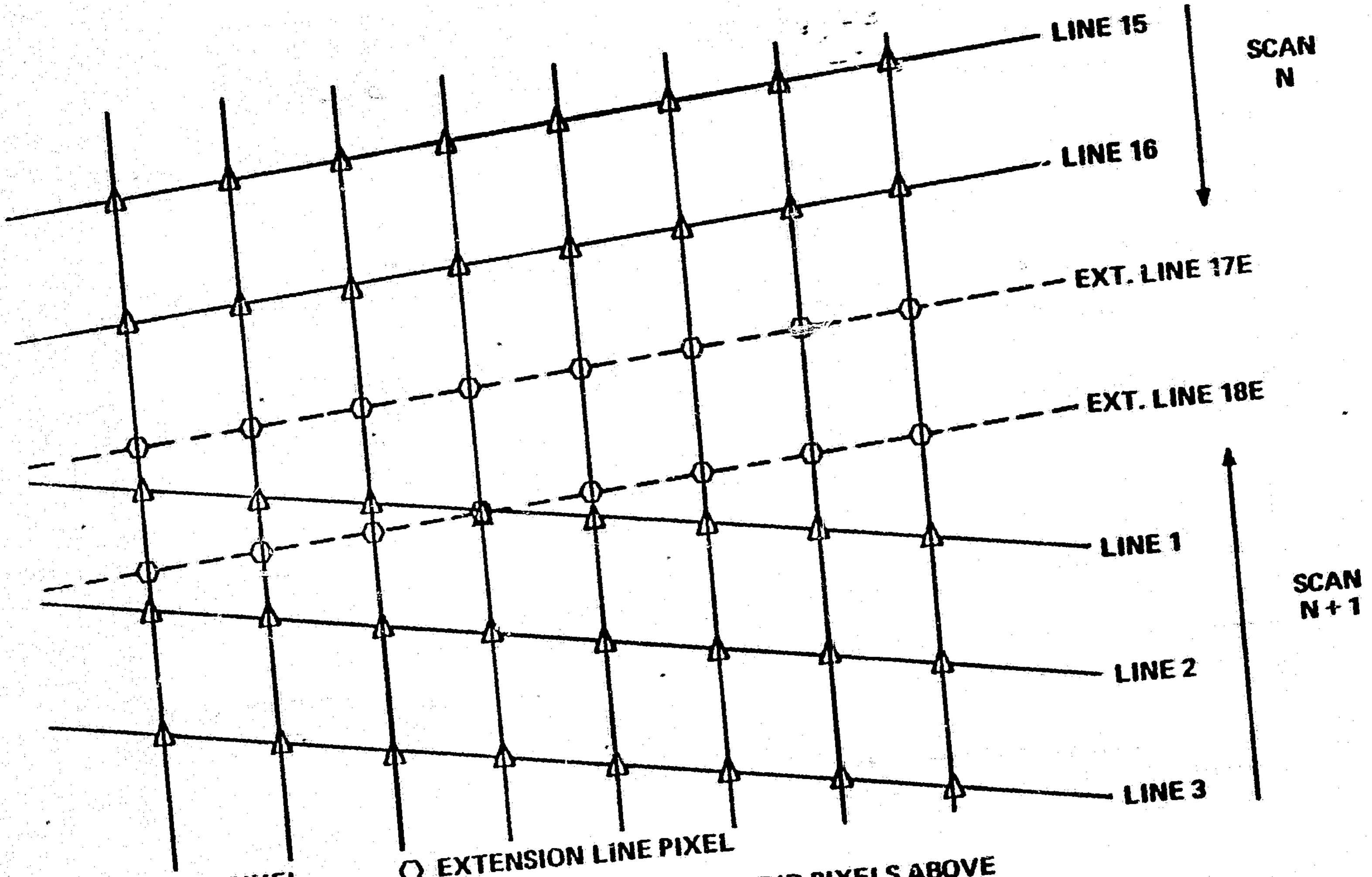
GENERATE SCAN EXTENSION LINE PIXELS



- Δ HYBRID PIXEL ○ EXTENSION LINE PIXEL
- EXTENSION PIXELS ARE GENERATED WITH TWO HYBRID PIXELS ABOVE AND TWO HYBRID PIXELS BELOW
- PIXEL LOCATION PRECISION TO (1/64) PIXEL IN RESAMPLING COMPUTATION

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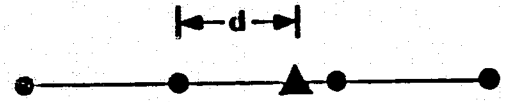
SPLINE INTERPOLATION FORMULA



● INPUT PIXEL LOCATION

▲ DESIRED PIXEL LOCATION

	CUBIC CONVOLUTION WEIGHT FORMULAS	CUBIC SPLINE WEIGHT FORMULAS
W_1	$-d(1-d)^2$	$\frac{2a_1}{ch_1h_2} f_1f_2f_3 - \frac{1}{ch_1} g_1g_2g_3$
W_2	$(1-d)(1+d-d^2)$	$-\frac{1}{ch_1} f_1f_2f_3\left(1+\frac{2a_1}{h_2}+\frac{2a_1}{h_1}\right)+\frac{f_3}{h_2}+\frac{1}{c}g_1g_2g_3\left(\frac{2a_0}{h_2^2}+\frac{1}{h_1}+\frac{1}{h_2}\right)$
W_3	$d(1+d-d^2)$	$\frac{1}{c}f_1f_2f_3\left(\frac{2a_1}{h_2^2}+\frac{1}{h_2}+\frac{1}{h_3}\right)-\frac{1}{ch_2}\left(g_1g_2g_3\right)\left(1+\frac{2a_0}{h_2}+\frac{2a_0}{h_3}\right)+\frac{g_3}{h_2}$
W_4	$-d^2(1-d)$	$-\frac{1}{ch_3} f_1f_2f_3 + \frac{2a_0}{ch_2h_3} g_1g_2g_3$

$f_1 = X_3 - X - h_2$

$f_2 = X_3 - X + h_2$

$f_3 = X_3 - X$

$g_1 = X - X_2 - h_2$

$g_2 = X - X_2 + h_2$

$g_3 = X - X_2$

$h_1 = X_2 - X_1$

$h_2 = X_3 - X_2$

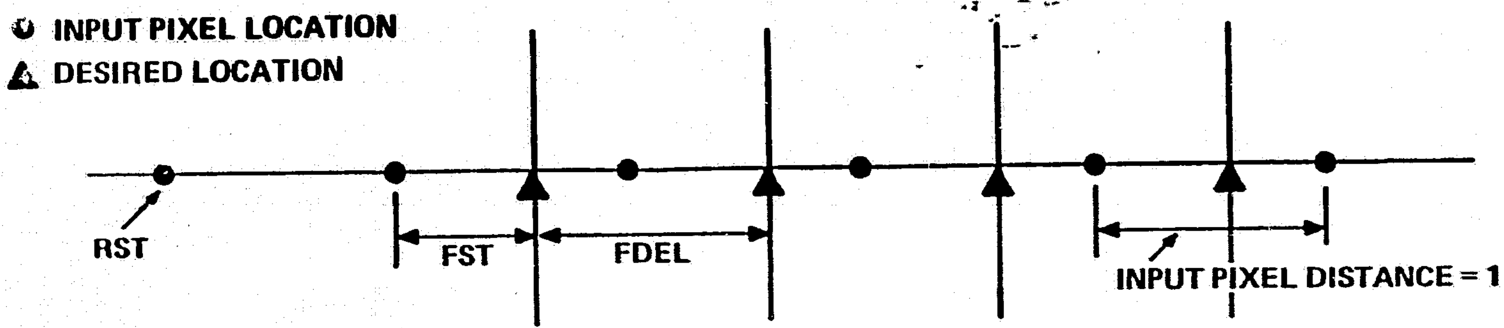
$h_3 = X_4 - X_3$

$a_0 = h_1 + h_2$

$a_1 = h_2 + h_3$

$c = 4a_0a_1 - h_2^2$

GCO X-RESAMPLING AND PARAMETER UTILIZATION ILLUSTRATION



- INPUT PIXELS = 136/LINE
- HYBRID PIXELS = 128/LINE
- RESAMPLING PARAMETERS:
  - RST — GCO CACHE MEMORY READ ADDRESS
  - FST — FRACTIONAL START
  - FDEL — OUTPUT PIXEL DISTANCE
  - WST — GCO CACHE MEMORY WRITE ADDRESS

- PROCESS FLOW

```
COLUMN = 1
FOR COLUMN < 128 LOOP
    USING RST TO EXTRACT 4 INPUT PIXELS     ] MEMORY ACCESS
    USING FST TO EXTRACT 4 WEIGHTS          ]
    $P = \sum_{i=1}^{4} P_i W_i$            ] ARITHMETIC PIPELINE
    PLACE P ON WST OF CACHE MEMORY          ] MEMORY ACCESS
    SUM = FST + FDEL                        ]
    FST = FRACTIONAL PART OF SUM            ] ADDRESS GENERATOR
    RST = RST + INTEGER PART OF SUM         ]
    WST = WST + 1                           ]
    COLUMN = COLUMN + 1
END LOOP
```

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[illegible]
[illegible]

GCO RELATED DATA

- HIGH RESOLUTION BAND
  - NOMINAL GCO INPUT DATA SIZE = 136 PIXELS x 21 LINES
  - NOMINAL GCO OUTPUT DATA SIZE = 128 PIXELS x 17 LINES
- THERMAL BAND
  - NOMINAL GCO INPUT DATA SIZE = 36 PIXELS x 8 LINES
  - NOMINAL GCO OUTPUT DATA SIZE = 128 PIXELS x 17 LINES
- GCO MICROCODE INSTRUCTION TIME = 100 NS
- PERFORM $\sum_{i=1}^{4} P_i \; W_i$ CALCULATION IN 0.8 μs
- TIME TO PRODUCE AN OUTPUT PIXEL IN GCO VARIES WITH SEGMENT HEIGHT
  - HIGH-RESOLUTION BAND CC RESAMPLING = 2.3 μs ±10%
  - HIGH-RESOLUTION BAND NN RESAMPLING = 2.0 μs ±10%
  - THERMAL BAND CC RESAMPLING = 1.8 μs ±10%
  - THERMAL BAND NN RESAMPLING = 1.6 μs ±10%
- REQUIRED THROUGHPUT PER GCO = 2.8 μs/OUTPUT PIXEL

Some ETM pages
Some out of order

MLA INSTRUMENT DEFINITION STUDIES - MID-TERM BRIEFING

MARVIN S. MAXWELL - OCTOBER 1981

TOPICS

PURPOSE OF STUDIES

STATUS

KEY SPECIFICATION REQUIREMENTS

HIGHLIGHTS OF MID-TERM BRIEFING OF SEPTEMBER '81 BY

--EASTMAN KODAK

--BALL AEROSPACE

--SANTA BARBARA RESEARCH CENTER (HAC)

--HONEYWELL RESEARCH CORPORATION

SUMMARY OF STRONG AND WEAK POINTS

CONCLUSIONS

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MLA INSTRUMENT DEFINITION STUDIES

PURPOSE OF STUDIES

- o REFINE INSTRUMENT FEASIBILITY CONCEPTS
- o PROVIDE DESIGN INFORMATION FOR:
    - --REVISING REQUIREMENTS FOR FLIGHT INSTRUMENTATION
    - --GUIDING REQUIRED TECHNOLOGY DEVELOPMENTS
        - o SWIR PROCUREMENTS, ETC.
- o PROVIDE SCHEDULE, WORK BREAKDOWN AND COSTS FOR SENSORS

STATUS

RECEIVED 5 PROPOSALS

AWARDED 3 FULL STUDIES (6 MONTHS DURATION)
BALL, KODAK, HONEYWELL

AWARDED PARTIAL STUDY - OPTICS AND FOCAL PLANE ONLY TO HUGHES
(SBRC DOING FULL STUDY ON IR&D MONEY)

FINAL REPORT DUE DECEMBER 1981
WILL PROVIDE INPUTS TO SUPPORT FY84 NEW START

STUDY REQUIREMENTS

REVISED AT KICK-OFF MEETING TO | - LATER - OK'S OPTION TO STUDY HIGHER RESOLUTION - IF DESIRED

BANDS	λ(μ)	LARGEST IFOV (M)		MIN SNR
1	0.45-0.52	30	15	73
VIS 2	0.52-0.60	30	15	149
3	0.63-0.69	15	15	126
4	0.76-0.90	30	15	168
SWIR 5	1.55-1.75	30	30	54
6	2.08-2.35	30	30	77

- OPERATION AT 283, 470, & 705 KM
- 9:30-10:30 A.M. EQUATOR CROSSING

CALIBRATION - RADIOMETRIC, END-TO-END

- RELATIVE 0.5%, ABSOLUTE 5% ← RELATIVE 1% BAND-TO-BAND
- ON-BOARD CORRECTION
  - GEOMETRIC

	IFOV
SPAN IT	20.0
POSITION	0.1 ←
CUMUL	3.0
PARALLEL	0.2

- 15° FIELD
- STEREO ±26°
- ROLL ±30°
- 85% PROBABILITY 5 YEARS
- DATA LINK - TWO 150 MBPS TO TDRSS
  - ONE 100 MBPS DIRECT
- STS WEIGHT & VOLUME LIMITS

CONCLUSIONS (BY M.S.M.) ON IDS PRESENTATION

- INSTRUMENT IS COMPLEX, DIFFICULT, EXPENSIVE
  - --500, 1000 LEADS TO FOCAL PLANE
  - --COOLING - IF COMBINING SWIR AND VIS/NIR
  - --SPECTRAL DEFINING FILTERS
- REGISTRATION SPEC., 0.1 IFOV NOT REASONABLE
  - --0.2, 0.3 NOT MUCH BETTER

  IF LARGER MUST RESAMPLE ALL DATA
  - --IMPACT OF GAPS WITH REGISTRATION ERROR
  - --GROUND SYSTEM COMPLEXITY AND THROUGHPUT
- DPCM FOR MLA INSTRUMENT NOT OPTIMIZED
- RADIOMETRIC CALIBRATION REQUIREMENTS ARE DIFFICULT TO MEET
  - --TOO TIGHT?
- TEST FACILITIES AND ANALYSES SYSTEM WILL BE VERY COMPLEX

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WORKSHOP ON FUNDAMENTAL RESEARCH IN
ACTIVE MICROWAVE REMOTE SENSING

1st + 2nd

TENTATIVE DATE: Feb ~~2, 3~~ and ~~4,~~ 1982

LOCATION: Pasadena (at JPL or Caltech)

CHAIRMAN: C. Elachi

CO-CHAIRMAN: D. Held

TENTATIVE TOPICS:

1st AM
- Imaging Radar Reflectometry (emphasis on coherent component)
- Imaging Radar Polarimetry

- Combination of SAR and multispectral images. Basic physics behind synergism
- Topography and look-angle problems

1st PM
- Geometric and radiometric correction/calibration of SAR data
- Development of the performance metrics and the simulation of spaceborne systems. Test patterns.

- Multifrequency array SAR

2nd
- SAR processing at high speed

2nd Post processing
Multifrequency

[illegible]

POTENTIAL PARTICIPANTS:

? Spkr → [redacted] Medium
[redacted] Medium
[redacted] Small
K. Carver (NASA HQ)
J. Curlander (JPL)
C. Elachi (JPL)
[redacted] Small
Spkr → [redacted]
[redacted] Medium
Go → D. Held (JPL)
[redacted] Large
Spkr. → [redacted]
F. Li (JPL)
R. Macdonald (JSC)
R. Moore → J. Paris (JSC)
J. Walker → [redacted]
Spkr → [redacted] Small
[redacted] Tomiyasu
Spkr → [redacted] Medium
? → [redacted]
T. Walton (NASA HQ)
C. Wu (JPL)

E. ELACHI:ot
10/12/81

Minutes

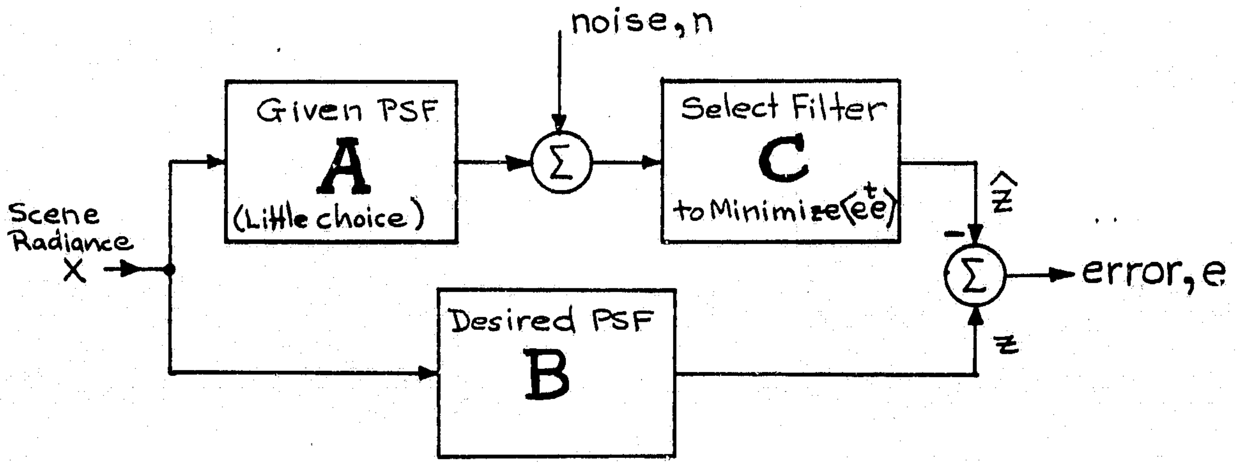
Working Group - Workshop II

A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data.

The working group participated in a workshop on registration and rectification held by NASA Headquarters at the Xerox Training Center in Leesburg, Virginia, on November 17-19, 1981. In addition, the working group stayed over a day to define and discuss research issues gleaned from the three days of presentations and panel discussions. The agenda and attendance list of the Registration and Rectification workshop are attached. ~~A miniaturized set of view graphs from panel discussion reports is attached.~~ The R+R workshop proceedings have been published as JPL Pub 82-23, N.A. Bryant, Editor Some of the workshop material was tutorial for at least a portion of the participants. Two presentations stood out as containing interesting ideas that are not yet fully integrated into the thinking of the remote sensing community at large.

Bob Haralick of Virginia Polytechnic Institute described an edge definition approach based on zero crossings (inflection points) of second directional derivatives in a non-zero gradient direction. Intensity surface derivatives are estimated from discrete orthogonal polynomial tensor product linear combinations.

Bob Dye of ERIM presented a rational scheme to filter a signal from a noisy system so as to approach a desired point spread function in a minimum mean square error sense. In block diagram form with vector signals and matrix blocks the idea is



Members of the working group involved in the post-workshop discussion were Fred Billingsley, Lloyd Candell, John Curlander (for Charles Elachi), Bob Dye, Roger Holmes, Bob MacDonald, Marvin Maxwell, and Robert Pelzmann. The following issues emerged or re-emerged.

- How much distortion should be corrected in the sensor/platform system, and how much should be left to preprocessing?
- To what extent should active sensor pointing control together with scene sampling of small scene elements be employed instead of synoptic coverage?

- Position and attitude -- how well measured, how well-corrected for, and how much of that correction should be on-board, how much on-ground?

- How good does the sensor/platform have to be to get out of GCP or registration problem? Is it achievable?

- System simulation and analytical modeling is still an issue.

- Data compression should not be a concern of our group for conventional schemes, but may be a valid area of inquiry for some SAR data specifics-- burst mode for SAR, range compression, special architectures. Even on conventional schemes, however, we should be concerned with how our signals emerge from a compression process through sensor and scene variabilities.

- To what extent can atmospheric effects be measured by a sensor through soundings? Aerosol optical thickness and distribution are the critical unknowns.

- How much sensitivity should be built into the sensor and is this a matter for fundamental research?

- An associated issue is how much excess signal-to-noise ratio is needed to compensate for later processing disturbances. Don't make the sensor system specifications more demanding than need be if the principal noise sources are in processing.

- What should future system design look like, including the sensor and platform? What is the fundamental research content in such system design?

- What are the ways in which spectral coverage should be sampled? Here there may be a reasonable application of the same filter concept used by Dye in achieving a desired point spread function.

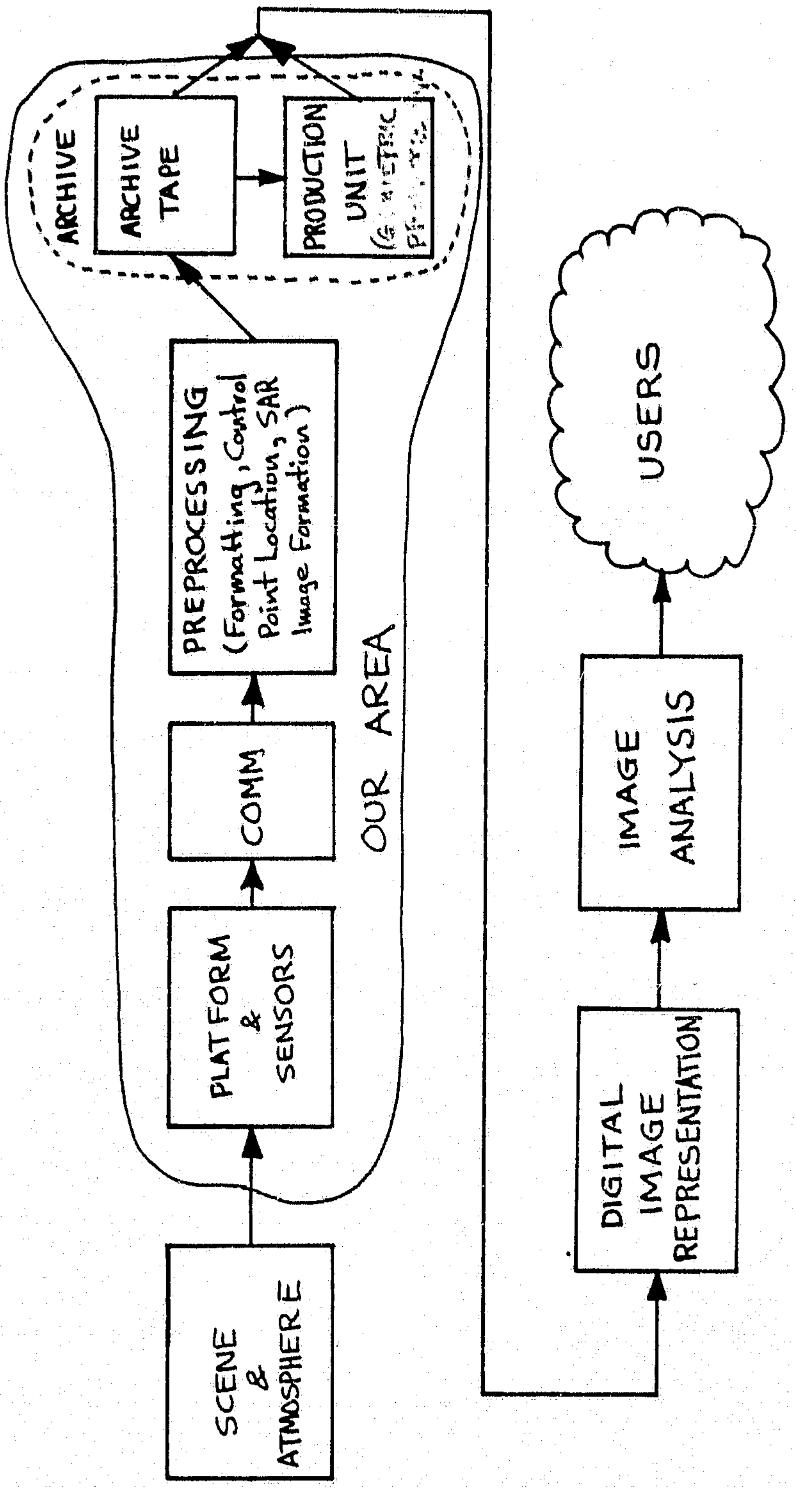
- Smart sensor that can zoom, point, wavelength-tune -- what can be done here?

- Calibration of sensors in general -- what must be done, what's nice to do, degree of difficulty vs. importance.

- Area array with spectral dispersion in one dimension, push-broom spatial coverage in the orthogonal direction -- we haven't discussed this yet, study is by Wellman at JPL.

- Sensors which sort out spectral response by wavelength-dependent penetration. Can be done, may be in experimental phase now.

Overall, the group also spent time discussing our responsibilities in the overall system layout shown on the next page. The boundary between scene and atmosphere and the sensor was readily accepted but opinions varied on the boundary on the output side. It was agreed, finally, that while we may overlap the mathematical pattern recognition and image analysis people in the areas of preprocessing and archive, those areas tie more closely in a technical and system design sense to our interests in sensors and signals.



GMI/NASA PROJECT WORKSHOP

DISCUSSIONS

AT

XEROX TRAINING CENTER

November 19-20.

(Piggyback discussions after NASA Registration and Rectification Workshop attendance at Xerox Training Center in Leesburg, Virginia)

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4. Robert H. Dye
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5. Roger A. Holmes (Principal Investigator)
General Motors Institute
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Palo Alto, California 94304

REGISTRATION AND RECTIFICATION WORKSHOP AGENDA

Tuesday, November 17, 1981

GROUP MEETING TO BE HELD IN ROOM 2464

1.	Introduction (8:00-9:00)	Workshop Chairman: N. Bryant/JPL Workshop Sponsor: A. Villasenor/NASA

2\. Objectives and Format of Workshop (9:00-9:30)

a.	Format	N. Bryant/JPL
b.	Objectives	F. Billingsley/JPL

3\. Presentations on Users Needs (9:30-12:00) (1:00-2:00)

a.	Agriculture/Forestry/Rangeland	R. Allen/USDA
b.	Land Use/Land Cover and Hydrology	L. Gaydos/USGS
c.	Geology	P. Chavez/USGS
d.	Severe Storms	J. Dalton/GSFC
e.	Ocean Processes	D. Nichols/JPL

4\. Presentations on Space Segment Errors (2:00-4:00)

a.	Scanner Imaging Systems, Spaceborne	A. Prakash/GE
b.	Scanner Imaging Systems, Aircraft	S. Unger/GISS
c.	MLA Imaging Systems	K. Ando/NASA
d	SAR Imaging Systems	J. Curlander/JPL
e.	Multi-Mission Spacecraft	H. Heuberger/GSFC
f.	NAVSTAR/Global Positioning System	M. Ananda/Aerospace

5\. Presentations on Ground Segment Errors (4:00-5:00)

a.	Geodetic Control Net Considerations	J. Gergen/NGS
b.	National Map Accuracy Standards	R. Welch/U OF GA
c.	Map Projections	J. Snyder/USGS

6\. Systems Presentations and Discussions (7:00-9:00)

a.	Quantitative Effects of Mis-registration	R. Juday/JSC
b.	Data vs. Information, A System Paradigm	F. Billingsley/JPL
c.	Panel Chairman Overview Discussions	
	- Registration Panel	R. Bernstein/IBM
	- Rectification Panel	A. Tescher/Aerospace
	- Error Analysis Panel	R. Pelzman/Lockheed

TYPING AND COPY SERVICES IN ROOM 3473

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NASA REGISTRATION AND RECTIFICATION WORKSHOP

November 17-19, 1981

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November 17-19, 1981

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NASA REGISTRATION AND RECTIFICATION WORKSHOP

November 17-19, 1981

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NASA REGISTRATION AND RECTIFICATION WORKSHOP

November 17-19, 1981

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NASA REGISTRATION AND RECTIFICATION WORKSHOP

November 17-19, 1981

Attendees

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NASA REGISTRATION AND RECTIFICATION WORKSHOP

November 17-19, 1981

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November 17-19, 1981

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November 17-19, 1981

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NASA REGISTRATION AND RECTIFICATION WORKSHOP

November 17-19, 1981

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November 17-19, 1981

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Minutes

WORKSHOP ON VISUAL, IR, AND PASSIVE MICROWAVE SENSORS - WORKSHOP III

A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data

A workshop on VISUAL, IR, AND PASSIVE MICROWAVE SENSORS was held at NASA/GSFC, Greenbelt, Maryland, on January 11 and 12, 1982. A list of attendees and an agenda is attached.

Bob Fraser described atmospheric effects paying particular attention to the relation between measured nadir radiance at the top of the atmosphere and various sources of that radiance. An example presented showed that for a Lambertian reflectance of 0.1 contributions to nadir radiance were 9% sky backscatter, 6% surface IFOV reflection, and 2% adjacent surface reflection; thus 6/17 or approximately one-third of the received signal is directly related to surface reflectance in the IFOV. Atmospheric errors in radiance resulting from perturbations of a case for 0.1 surface reflectance, 550 nm wavelength, aerosol optical thickness of 0.2, solar zenith angle of 40°, and nadir view showed variations of 1 to 8% from nominal either positive or negative for reasonable variations of the nominal parameters (see attachment), and a pronounced sensitivity to large off-nadir view angles.

MTF degradation by the atmosphere appears to consist of a long and gentle roll-off at low spatial frequencies up to about 3 cycles/km, and a faster roll-off beyond that region. The major issue that evolved from the discussion is that the atmosphere is a major noise source over land, less so over oceans, with many unobservable parameters, and that it may not make much sense to place specs on system components for an order of magnitude or two better S/N ratio than the atmospheric variability warrants. The primary thrusts at GSFC at this time are on measurements of the optical properties of the atmosphere and modeling of the adjacency effect. View graph copies are attached which describe in more detail the adjacency effect and off-nadir viewing variations.

Jim Spinhirn described the LIDAR measurements made at multiple zenith angles, dual wavelengths, and high spectral resolution. He agreed with the work of Dave Pitts that the atmospheric variability is large spatially and temporally and that it will be most difficult to develop algorithms that will suppress atmospheric effects successfully.

Warren Hovis described scanner calibration difficulties due to attempts to transfer from standards, and also described long term drifts and sudden changes in radiance calibration on LANDSAT MSS experiences. General feeling was that 5% absolute radiance calibration was quite difficult to achieve, probably a best-you-can-do boundary when everything is going right. Warren showed some Gulf of Mexico CZCS imagery illustrating significant atmospheric variability from aerosols launched by off-shore winds. He feels that even over oceans, the atmosphere is a real problem.

Aram Mika of SBRC described their approach to a multispectral linear array sensor design. Principal features include telecentric optics with an intermediate image point for calibration sources and a particular dichroic beamsplitter design, with highly parallel electronics. Calibration to 5% absolute, 1% interband, and 0.5% intraband can be done under optimum conditions, with the major difficulty again being transfer from primary to secondary standards. Several recommendations were made by SBRC as to key issues in MLA design (attached). Mechanical housing stability and geometric integrity is viewed as a major risk item. All aspects of the focal plane array are viewed as high priority items including crosstalk, uniformity, yield, and array thermal, mechanical, and interconnection issues in both VNIR and SWIR spectral regions. On the system analysis side resampling/registration analysis and simulation and radiometric accuracy requirements are viewed as high priority tasks. In the system discussion Aram presented a concept of scene entropy (homogeneity or lack thereof) and trade-offs of data compression ratio and classification error as functions of scene entropy.

Mike Calabrese from NASA/Headquarters discussed the new emphasis on fundamental research at Headquarters, with a diminished or subdued interest in applications per se.

Rich Thom of SBRC gave a presentation of the current state of the art in focal plane array technology. Copies of his view graphs are appended. Hybrid mercury-cadmium telluride arrays featuring indium bumps for flip-chip interconnects to Si multiplexing chips were described. A 64 x 64 SWIR array is the current capability while Texas Instruments has an 800 x 800 Si VNIR array capability. At present, liquid phase epit xy mercury cadmium telluride is the material of choice for 1 to greater than 10 micrometers wavelength. Indium antimonide, indium gallium antimonide, and indium arsenic antimonide have been looked at.

Indium antimonide has charge transfer efficiency problems. Silicon Schottky barrier and extrinsic silicon CCD's have been tried but suffer from low temperature requirements and poor quantum efficiency. Monolithic mercury cadmium telluride may be the ultimate focal plane array technology but requires significant technology development. Close-butting of array elements pose problems that need to be addressed. Future research areas in advanced IR focal plane arrays are described in the closing view graph. There was a recognition among the group that DoD had been a strong and motivated funding source for the development of focal plane array technology, that NASA could remain aware of developments, but that NASA would be unable to provide meaningful amounts of support comparable to DoD's effort.

Tom Dod and Dave Le Vign presented material on GSFC efforts in passive microwave sensors. A circular conical scan system with 15 m aperture and 15 m focal length was described. Prime technical issue is design of lightweight high geometric integrity structure. Resolution of the off-axis system would range from 25km to 10km depending on wavelength. A multiple feed array permits dual polarization measurements. Frequencies are 1.4, 2.3, and 4.3 GHz for passive sensing and 5.1 and 11 GHz for active scatterometer sensing. Problems exist in reflector mesh geometry and multiple feeds design. Also described were study efforts for an electronically scanned phased array to scan cross-track through nadir plus or minus 45° with 10km ground resolution from 400km. A waveguide array (heavy, one polarization), strip line array (no orthogonal polarization), and a strip line-fed dipole array were considered. Passive microwave resolutions compatible with rain cell size are sought, plus rapid coverage of wide areas. A passive microwave aperture synthesis scheme based on the Van Cittert-Zernike theorem was described that requires simultaneous measurement of the response from an Earth scene at two locations. The degree of coherence thus measured determines the size of the effective source of radiation. There was some discussion over the long-standing issue of microwave brightness temperature being a valid soil moisture measurement when faced with confusion factors of soil structure and canopy influences.

Bill Barnes of NASA/GSFC described several GSFC efforts including the MLA program, the supporting SWIR hybrid and SWIR monolithic technology programs, optics and beamsplitter design studies, and a passive cooler design study. The details are amply described in the attached view graph set.

On Tuesday Al Sherman of NASA/GSFC described cooler technology. Radiant coolers are most common, handle loads of tens of milliwatts, and achieve temperatures around 90 to 100° K,but requiring shielding or orbit and attitude constraints. Solid cryogen coolers are favored over liquid cryogen coolers for a variety of reasons. A status paper by Allan Sherman is appended that includes better packing density, higher heats of sublimation than heats of vaporization, and lack of sloshing. Temperature ranges of 10 to 125° K and loads of hundreds of milliwatts are feasible with solid cryo coolers, but lifetime is limited to less than a year at present, though designs for longer life systems are underway. Stored liquid helium system development is a very active area for temperatures below 4°K and tens of milliwatts loads, but lifetime is under a year. Superfluid helium coolers will go below 2°K at tens of microwatt loads. Mechanical coolers address the lifetime and cooling load limitations of radiant and stored cryogen coolers, but require power and suffer from vibration. Actual lifetimes are limited by current reliability problems to three to fifteen thousand hours; goals are three to five years. A Sterling cycle cooler with magnetic bearings is being developed by North American Phillips Corp. for NASA/GSFC. Absorption and magnetic coolers are being explored. A tour of the LANDSAT-D and the LANDSAT-D Assessment program completed the morning.

Jim Fraser of DoD/DARPA described unclassified aspects of military surveillance satellite system developments. It appears that the character of the military systems are significantly different from renewable resources monitoring, concentrating on quick recognition of movements of objects distinct from the Earth scene background and quick delivery of that information to an action decisionmaker.

January 11-12, 1982
Meeting Attendees
Workshop III
NASA Goddard Space Flight Center

A Study to Identify Research Issues in the Area of Electromagnetic
Measurements and Signal Handling of Remotely Sensed Data

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JANUARY 11-12, 1982

WORKSHOP III

AT

NASA/GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

Meeting Room: Room 200 of Bldg. 26

AGENDA

Monday, January 11, 1982

- Aerosol and Water Vapor Sensing with Lydar
  F. H. Melfi and R. Fraser, J. Spinhirn

- Calibration of Satellite Radiometers
  W. Hovis

- Sensor Technology
  A. Mika

- Focal Plane Technology
  R. Thom

- MLA Development Activities
  W. Barnes

- Passive Microwave for Snow and Soil Moisture
  T. Dod and D. LeVine

- Recent Activities in the Fundamental Research Program
  M. Calabrese

Tuesday, January 12, 1982

- Advance Cooler Technology (Tentative)
  A. Sherman

- Group Tour of LANDSAT D Ground Station Facility

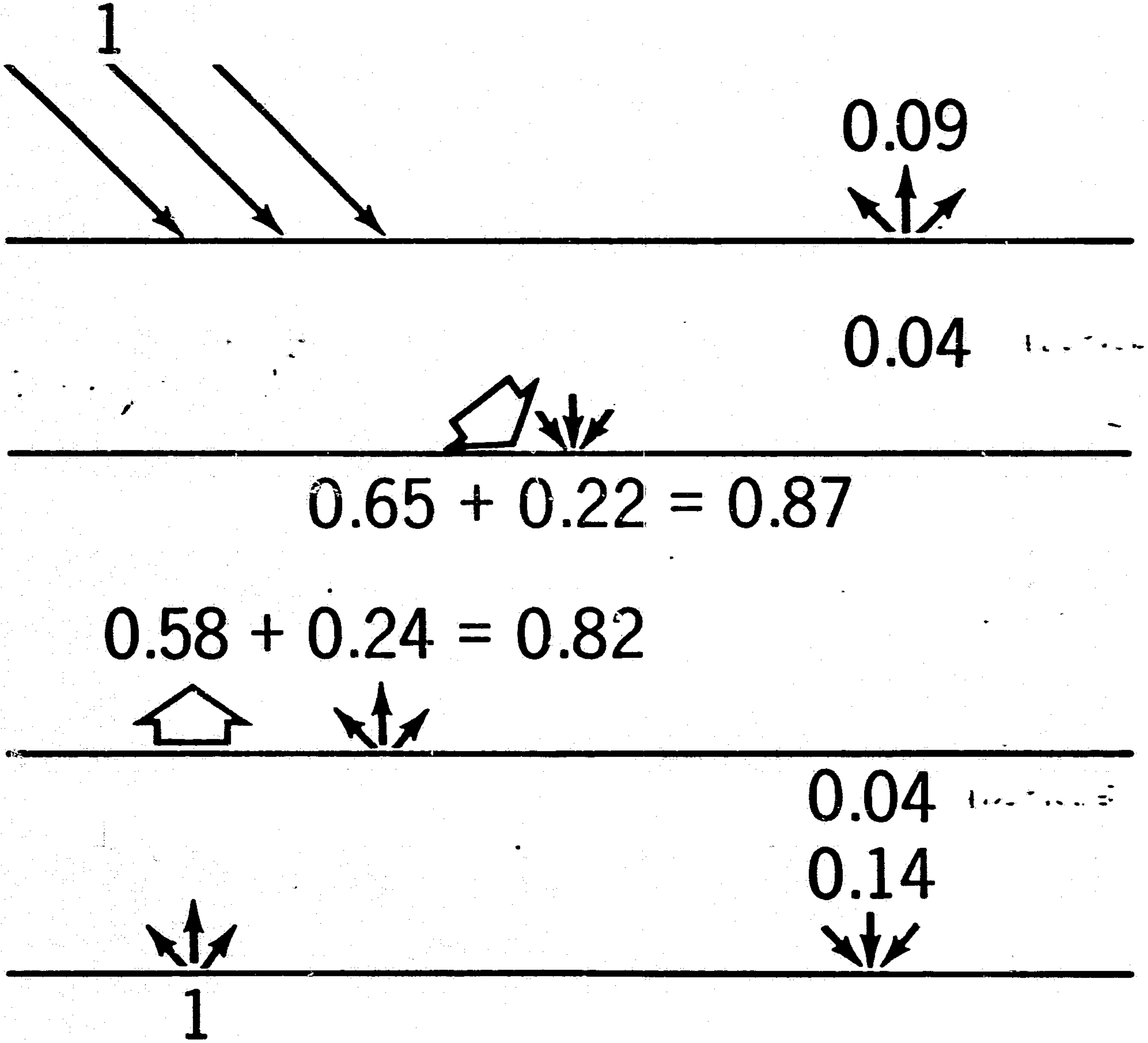
- Group Meeting to conclude workshop activities and draft outline of meeting report

(Revised 1/8/82)

VIEW GRAPHS

Bob Fraser
and
Jim Spinhirn
NASA/Goddard Space Flight Center

ILLUMINATION OF ATMOSPHERE FROM ABOVE



ILLUMINATION FROM BELOW

λ 0.55 μm
$\tau_{.55}$ = ~~.4~~ .33
$\theta_0 = 40°$
$m = 1.5$
$dn/d\ln r$ – r^{-4}

CONTRIBUTION TO
NADIR RADIANCE AT
TOP OF ATMOSPHERE

$R = 0.1$

$$I = I_0 + I_{SURFACE} + I_{ADJACENCY}$$

$I_0 = 9\%$

$I_s = 6$

$I_A = 2$

$I \quad 17$

$$\frac{I_s}{I} = 1/3$$

ATMOSPHERIC ERRORS

UNPERTURBED MODEL

SURFACE REFLECTANCE = 0.1

$\lambda = 550$ nm

AEROSOL OPTICAL THICKNESS = 0.2

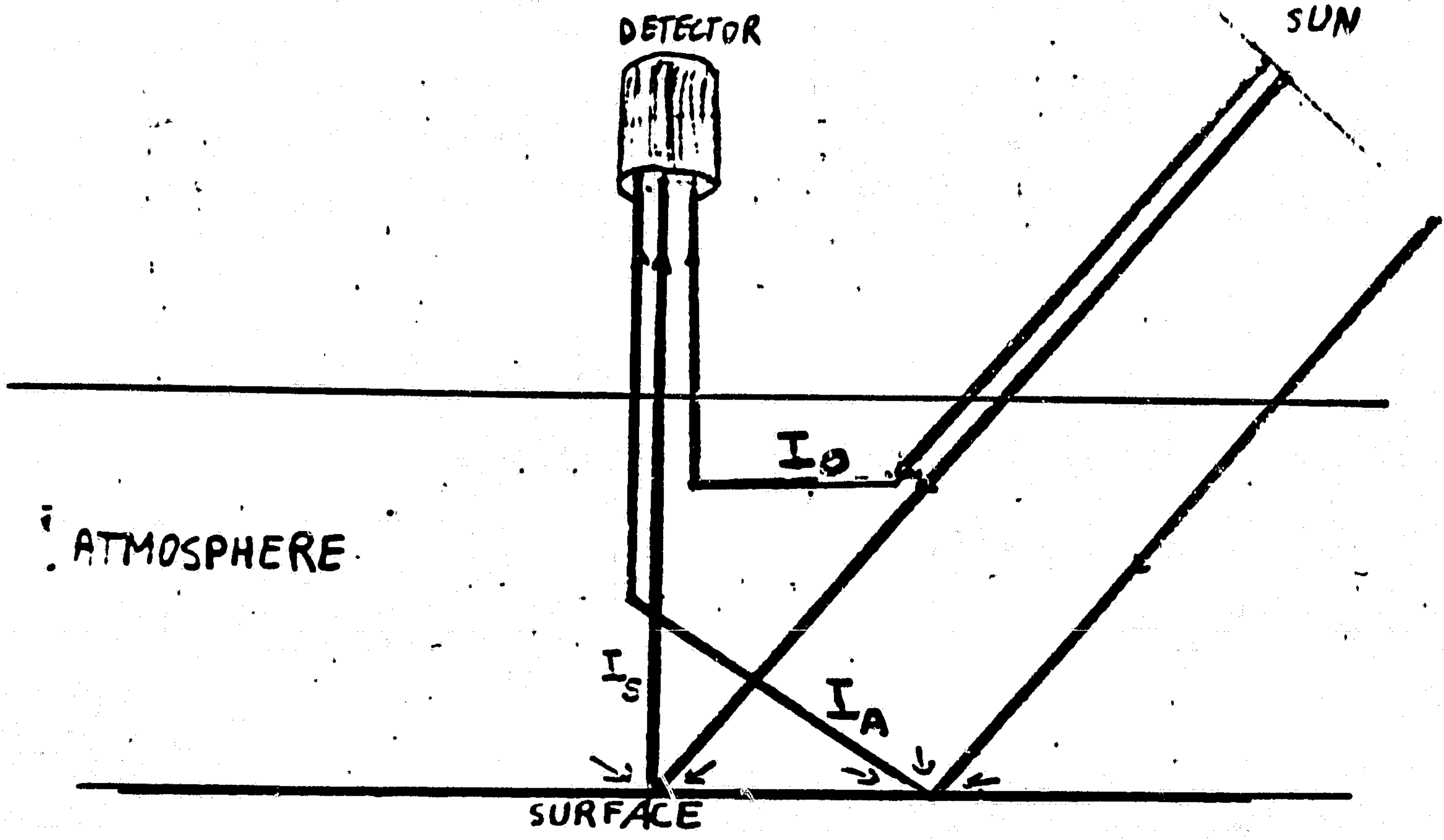
SOLAR ZENITH ANGLE = 40°

NADIR VIEWING

PARAMETER	PERTURBATION	CHANGE IN RADIANCE (%)
SFC. REFLECTION	0.005	3
STD. DEV. FIELDS	0.01	6
OPTICAL THICKNESS	0.1	5
IMAGINARY INDEX	−0.02	−8
NADIR ANGLE	6° 45°	2 38
SOLAR ZENITH ANGLE	1°	−1
PHASE FUNCTION	$\Delta V^{*} = 1$	2
ADJACENCY		

ORIGINAL PAGE IS
OF POOR QUALITY

REMOTE SENSING OVER A NONUNIFORM SURFACE

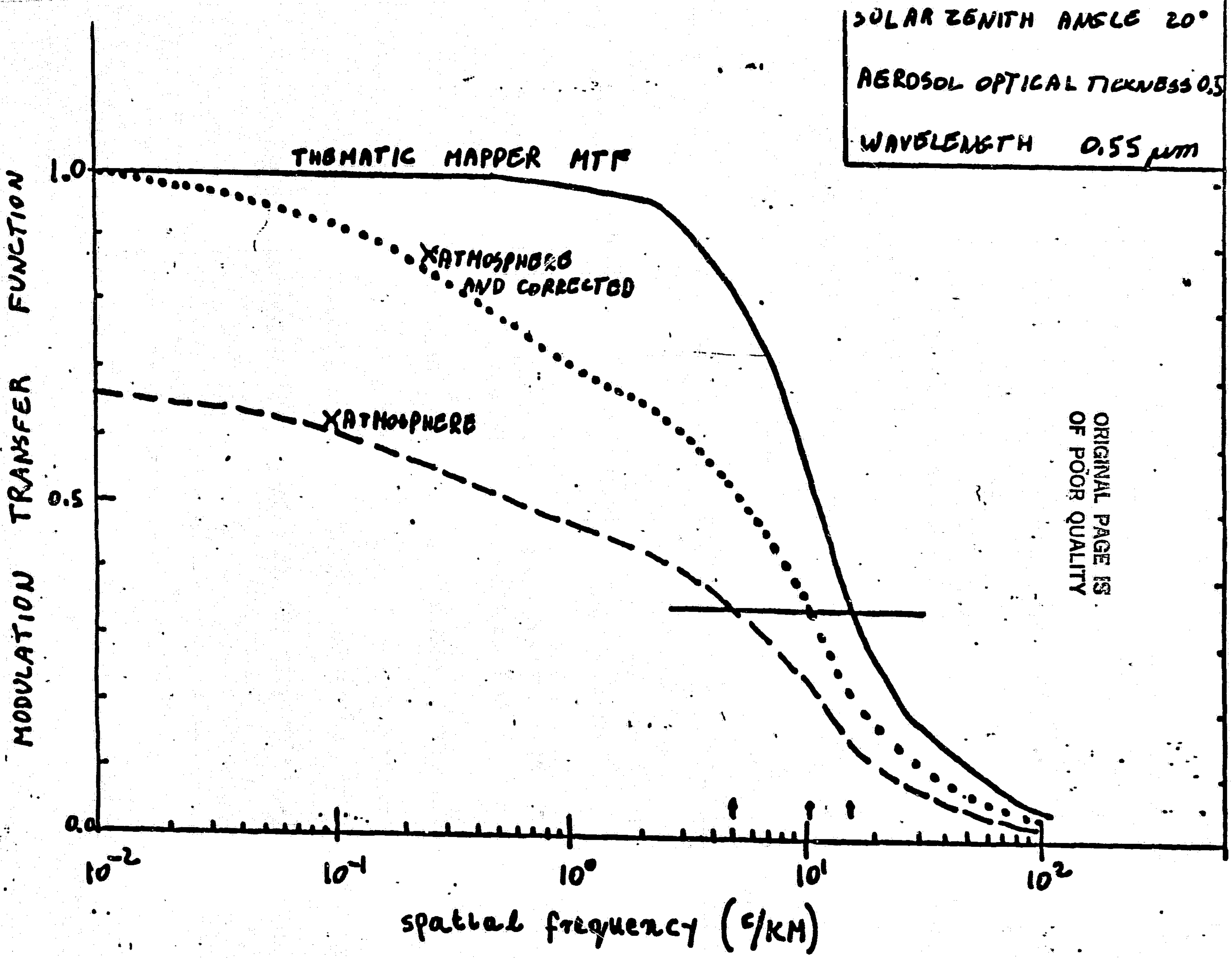


$$I_{DET} = I_0 + I_S + I_A$$

I_0 — ATMOSPHERIC PATH RADIANCE

I_S — THE "SIGNAL" - RADIANCE FROM THE OBJECT ATTENUATED BY THE ATMOSPHERE

I_A — THE DIFFUSE LIGHT SCATTERED FROM BRIGHT AREAS TO THE DARK AREAS (ADJACENCY EFFECT)

SOLAR ZENITH ANGLE 20°
AEROSOL OPTICAL TICKNESS 0.5
WAVELENGTH 0.55 μm
THEMATIC MAPPER MTF
X ATMOSPHERE AND CORRECTED
X ATMOSPHERE
MODULATION TRANSFER FUNCTION
1.0
0.5
0.0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
spatial frequency (c/KM)

KAUFMAN

ATMOSPHERIC CORRECTIONS

1. OCEAN (WEAK SIGNAL)
    a. HOMOGENEOUS SFC, LOW REFLECTANCE
    b. ATMOSPHERIC GRADIENTS WEAK
    c. MEASURE PATH RADIANCE FROM SATELLITE

2. LAND
    a. VARIABLE SFC, MODERATE REFLECTANCE
    b. ATMOSPHERIC GRADIENTS VARIABLE AND UNKNOWN
    c. NO ATMOSPHERIC PARAMETERS OBSERVABLE FROM SATELLITE (EXCEPT H_2O)
    d. NO CORRECTION ALGORITHM

3. PROBLEMS
    a. ATMOSPHERIC OPTICAL PROPERTIES NOT KNOWN
    b. NO METHOD OF MEASURING ATMOSPHERIC PARAMETERS OPERATIONALLY
    c. NO ATMOSPHERIC CORRECTION ALGORITHM

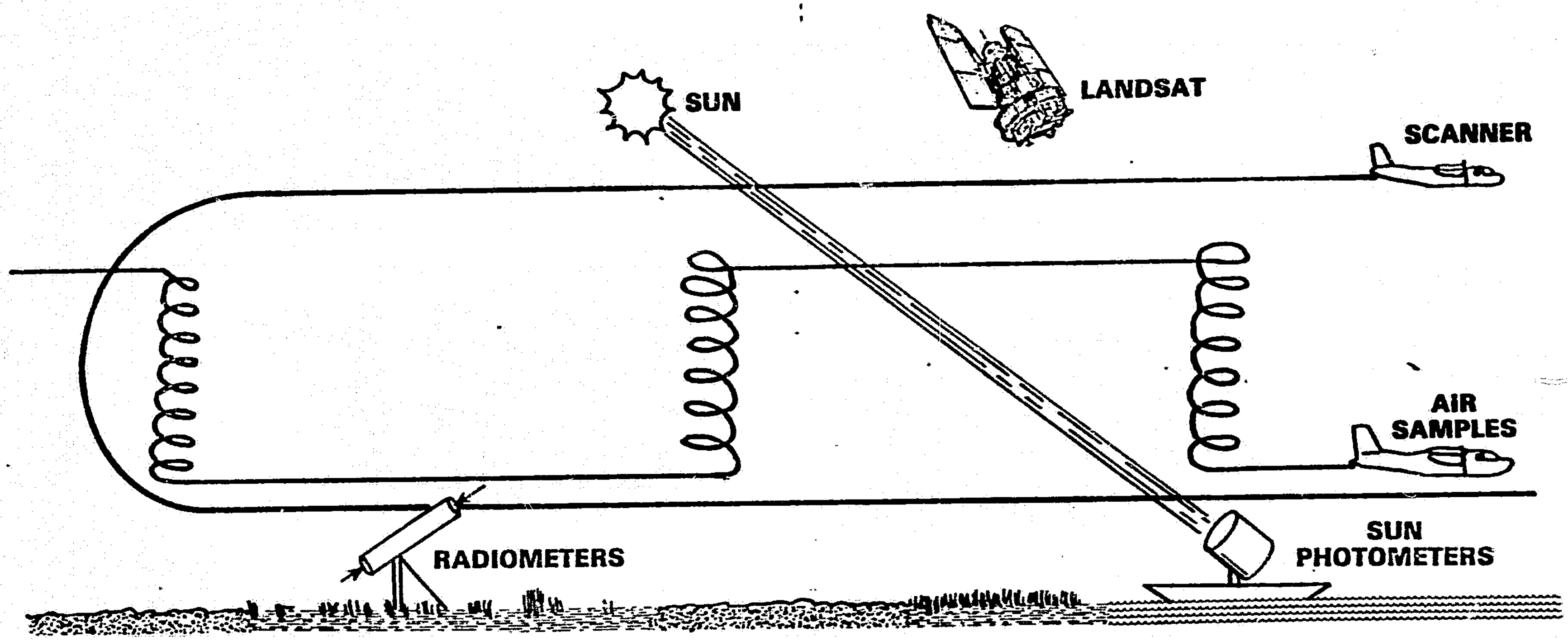
~~LASER~~

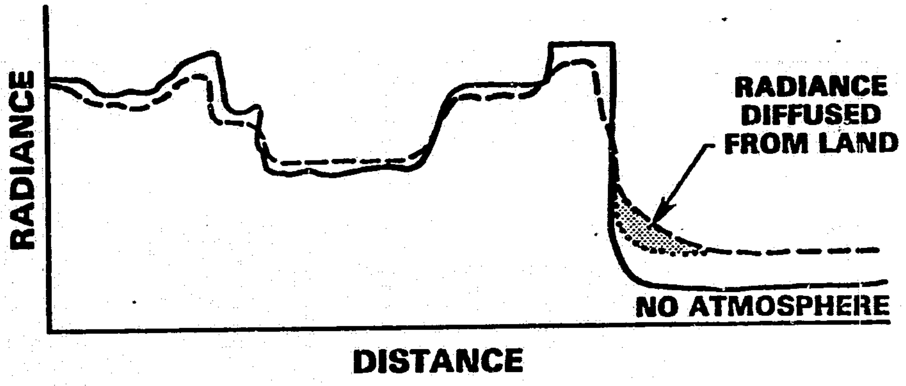
EXPERIMENTS AT GSFC

1. OPTICAL PROPERTIES OF ATMOSPHERE
   - a. COVARIANCE MATRIX OF PATH RADIANCE AND OPTICAL THICKNESS
   - b. AEROSOL ABSORPTION
   - c. AEROSOL SCATTERING PHASE FUNCTION
   - d. AEROSOL SIZE DISTRIBUTION
   - e. DEGREE OF POLARIZATION TO VERIFY MODELS

2. ADJACENCY

COMBINED ATMOSPHERE SURFACE EXPERIMENT





SIMULTANEOUS MEASUREMENT OF:
UPWARD RADIANCE
SURFACE REFLECTANCE
OPTICAL THICKNESS
AEROSOL SPATIAL VARIATIONS
SCATTERING CHARACTERISTICS

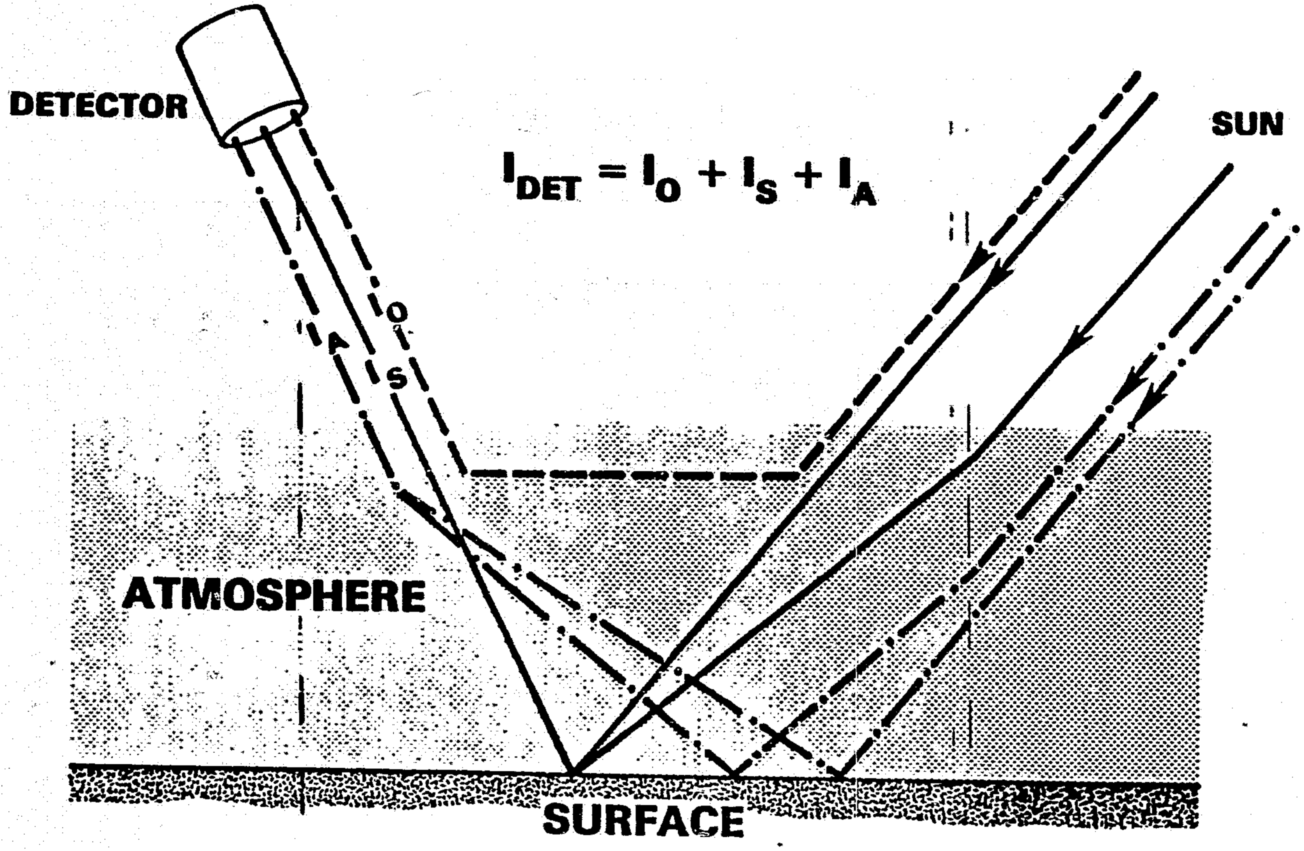
OBJECTIVE: TO OBTAIN A CONTROLLED DATA SETS TO CHECK THEORIES

ATMOSPHERIC EFFECTS
FOR VISIBLE AND NEAR IR SENSORS

- BASIC PHYSICS
- FIRST EXPERIMENT/RESULTS
- ATMOSPHERIC STUDY EFFORT:
  - A) SPATIAL EFFECTS
  - B) SPECTRAL CONSIDERATIONS
  - C) NADIR/OFF-NADIR OBSERVATIONS
  - D) DATA CORRECTIONS (REAL DATA)
  - E) SIGNIFICANCE FOR CLASSIFICATION
  - F) FUTURE EFFORTS

Y. Kaufman
[illegible]

REMOTE SENSING
OVER A NON-UNIFORM SURFACE



$I_{DET} = I_O + I_S + I_A$

$I_{DET} = I_O + I_S + I_A$ FOR AVERAGE CONDITIONS

$100\% = 48\% + 38\% + 14\%$ $\lambda = 0.55\,\mu m$, $A = 0.1$

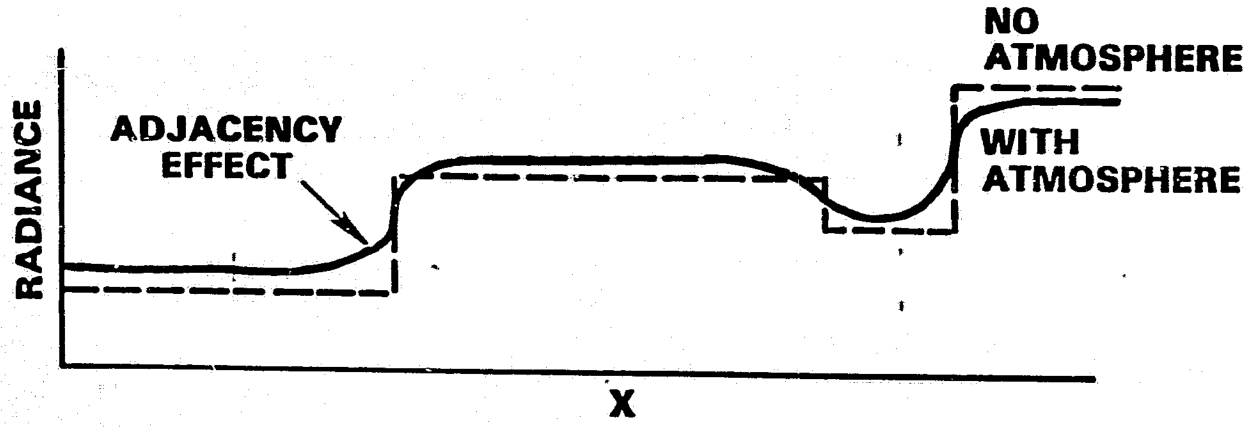
I_O—ATMOSPHERIC RADIANCE SCATTERED FROM THE SOLAR BEAM INTO THE DETECTOR

I_S—THE "SIGNAL"—RADIANCE FROM THE TARGET ATTENUATED BY THE ATMOSPHERE

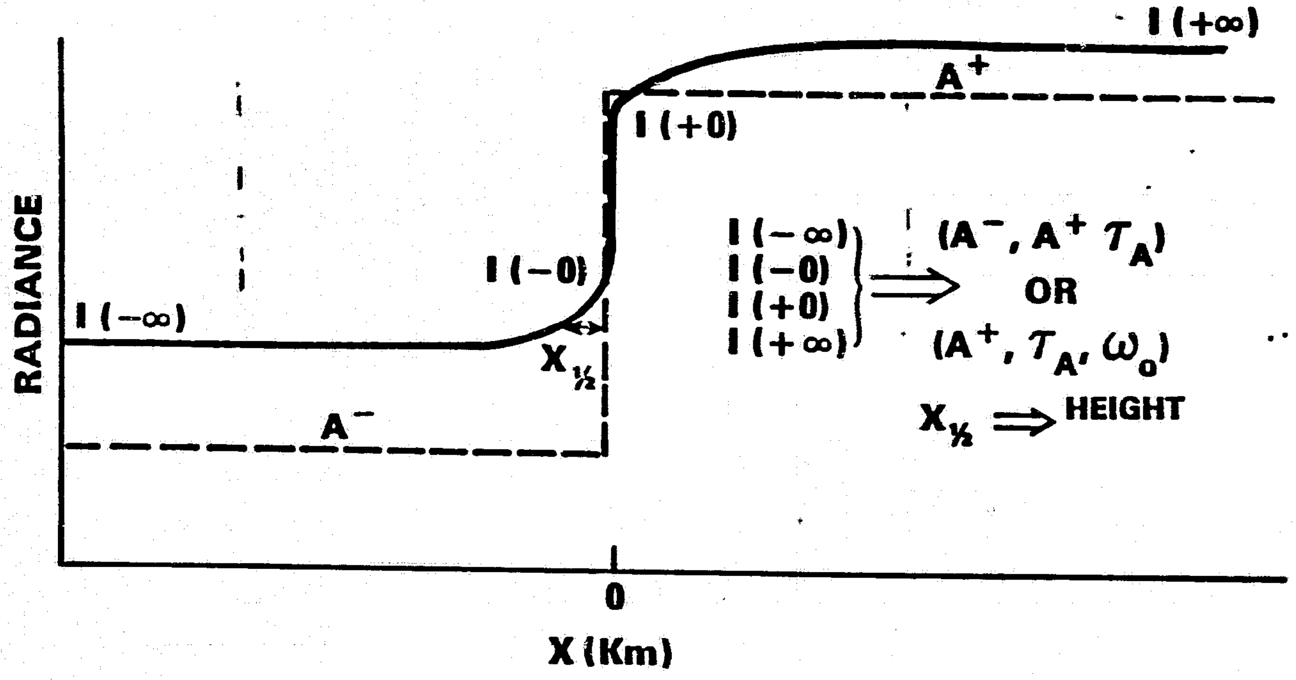
I_A—THE DIFFUSE LIGHT SCATTERED FROM BRIGHT AREAS TO THE DARK AREAS (ADJACENCY EFFECT)

$$A(x, y) \underset{?}{\overset{\text{RADIATIVE TRANSFER}}{\rightleftarrows}} I(x, y)$$

THE ATMOSPHERIC EFFECT ON THE DETECTED RADIANCE



IDEAL CASE



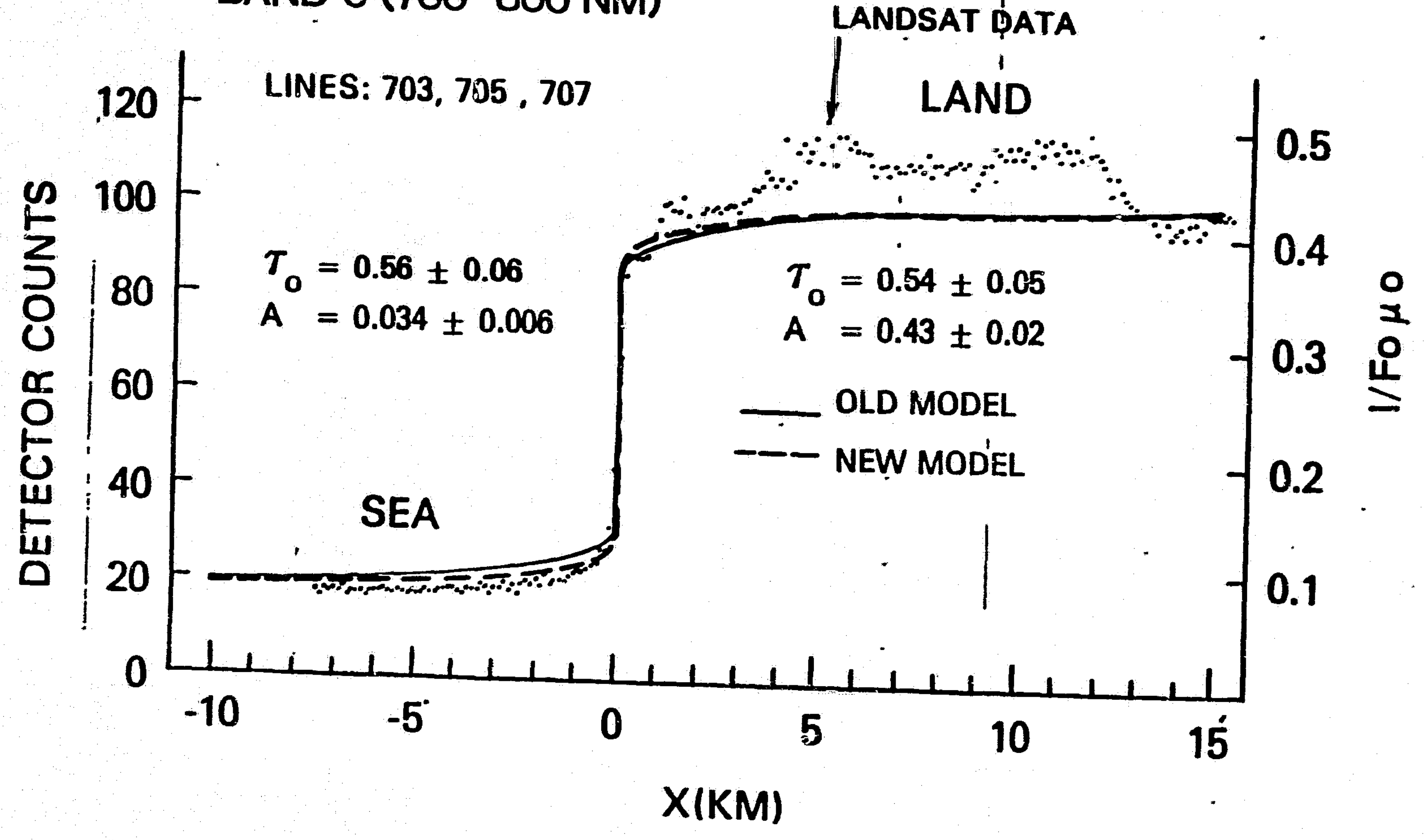
$$\left.\begin{matrix} I(-\infty) \\ I(-0) \\ I(+0) \\ I(+\infty) \end{matrix}\right\} \Longrightarrow \begin{matrix} (A^-, A^+ \tau_A) \\ \text{OR} \\ (A^+, \tau_A, \omega_0) \end{matrix}$$

$X_{1/2} \Longrightarrow$ HEIGHT

SENSING THE ATMOSPHERE

EXAMPLE OF APPLICATION FOR A SEA SHORE

BAND 6 (700-800 NM)

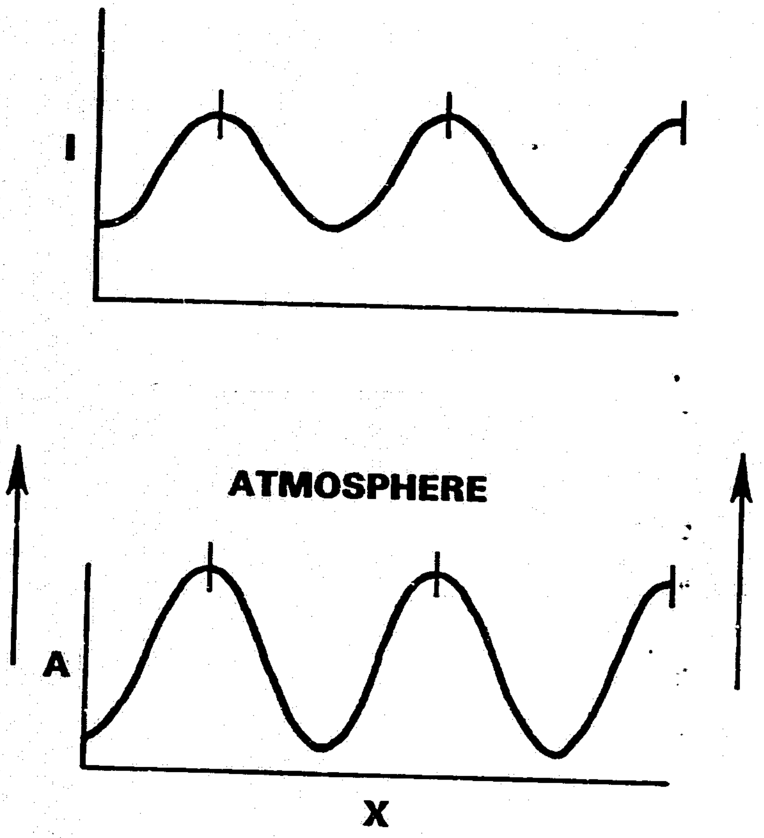


GROUND MEASUREMENTS

$\tau_o = 0.60;\ A_l = 0.027,\ 0.42;\ H = 3$ km

SPATIAL EFFECTS

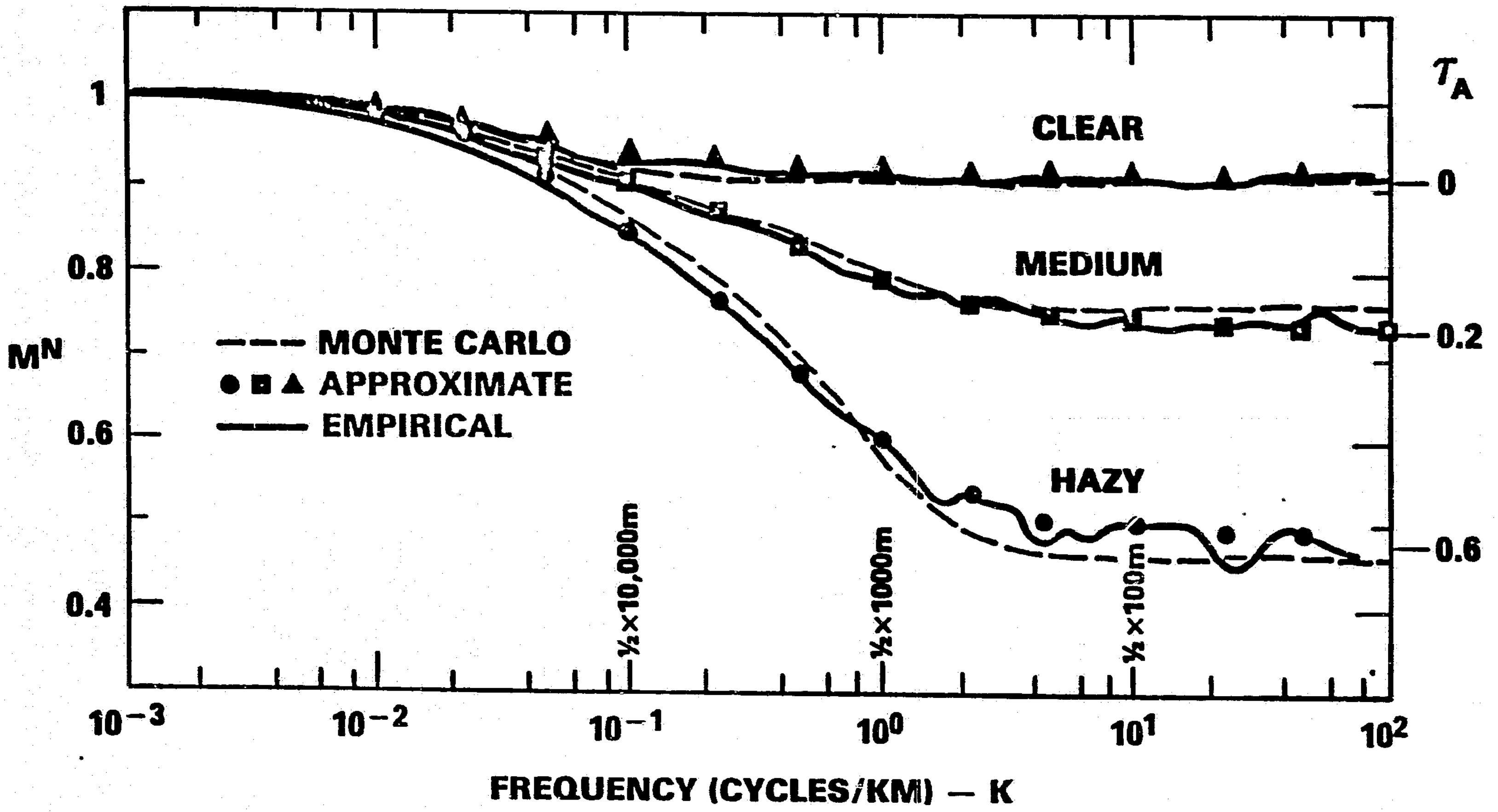
MODULATION TRANSFER FUNCTION



$$M = \frac{I_{MAX} - I_{MIN}}{A_{MAX} - A_{MIN}}$$

MODULATION TRANSFER FUNCTION M, CAN BE USED TO TRANSFER THE SURFACE IMAGE A (X, Y) INTO THE DETECTOR IMAGE I (ξ, η)

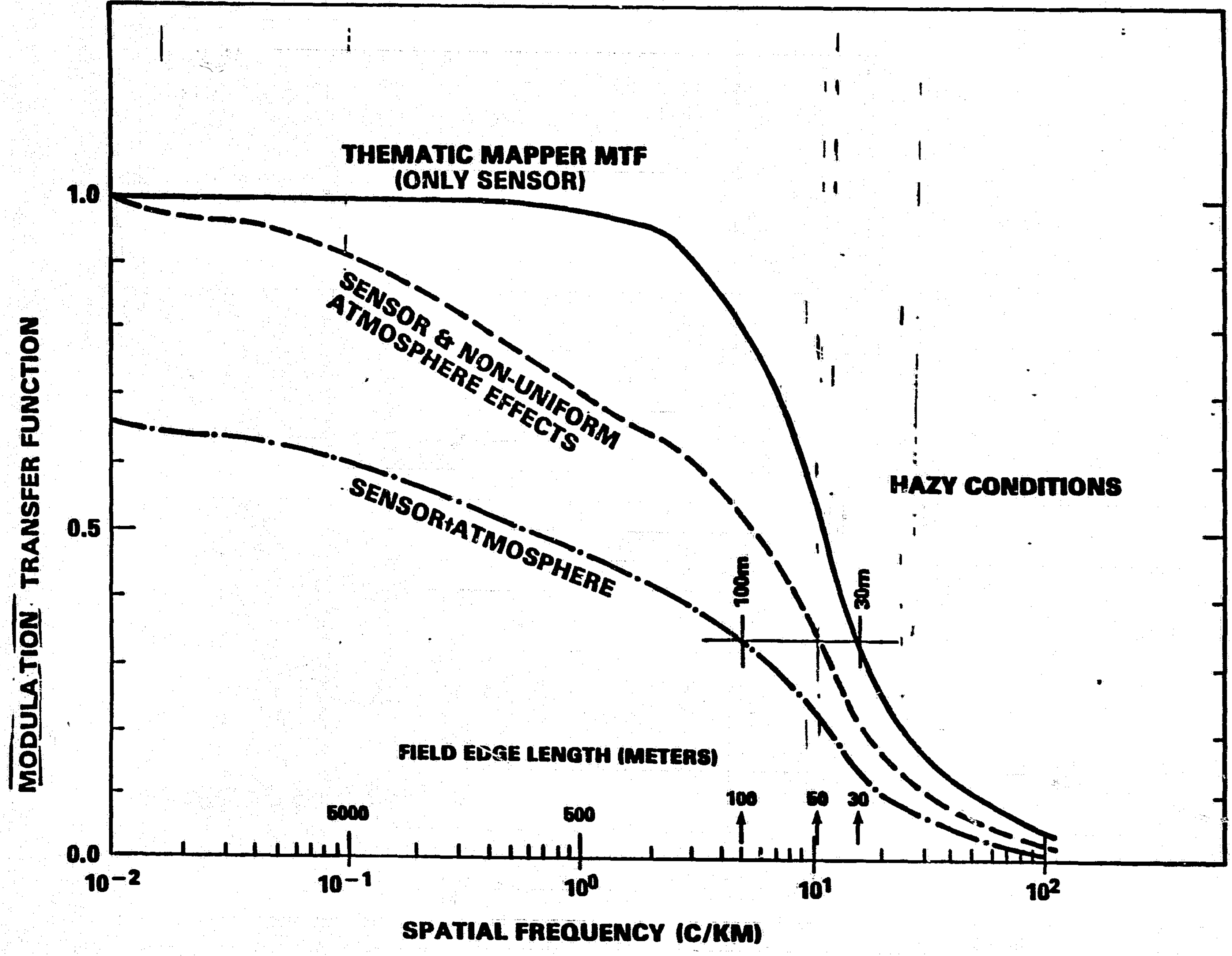
MODULATION TRANSFER FUNCTION



EMPIRICAL FORMULA

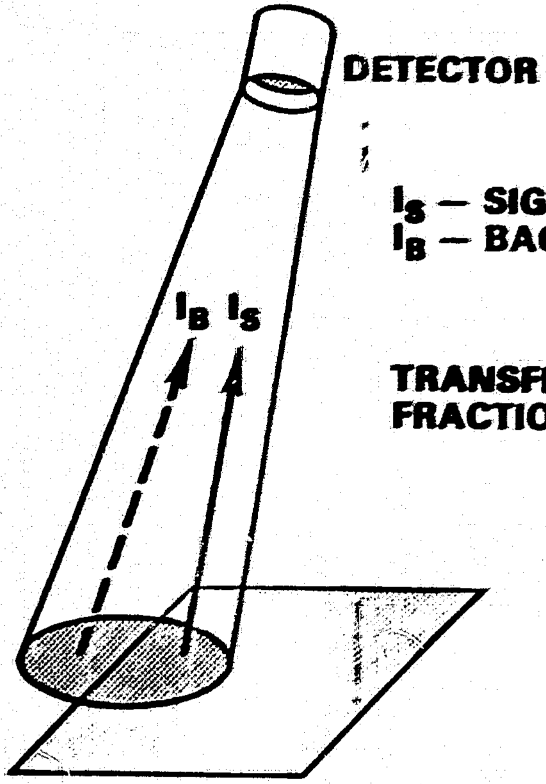
$$M^N(K) = 1 - 0.5\tau_R\,[1 - e^{-20K}] - 0.7\lambda^{0.2}\tau_A\,[1 - e^{-1.3KH}]$$

MODULATION TRANSFER FUNCTION

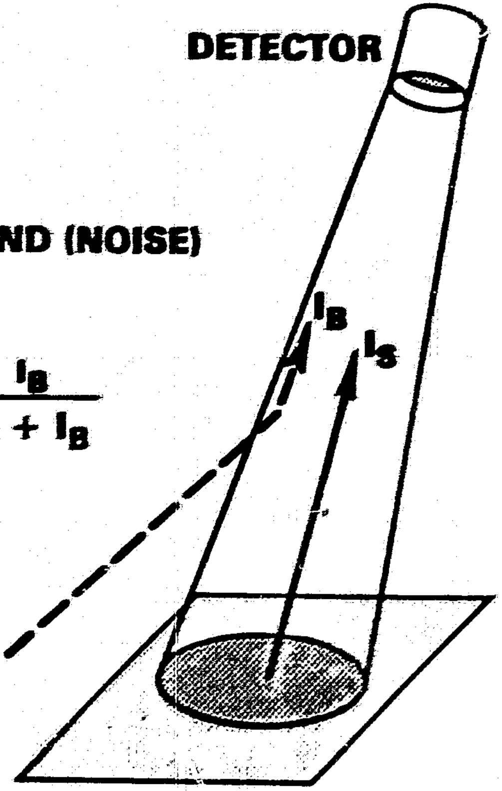


TRANSFER FRACTION

DETECTOR EFFECTS



ATMOSPHERIC EFFECT

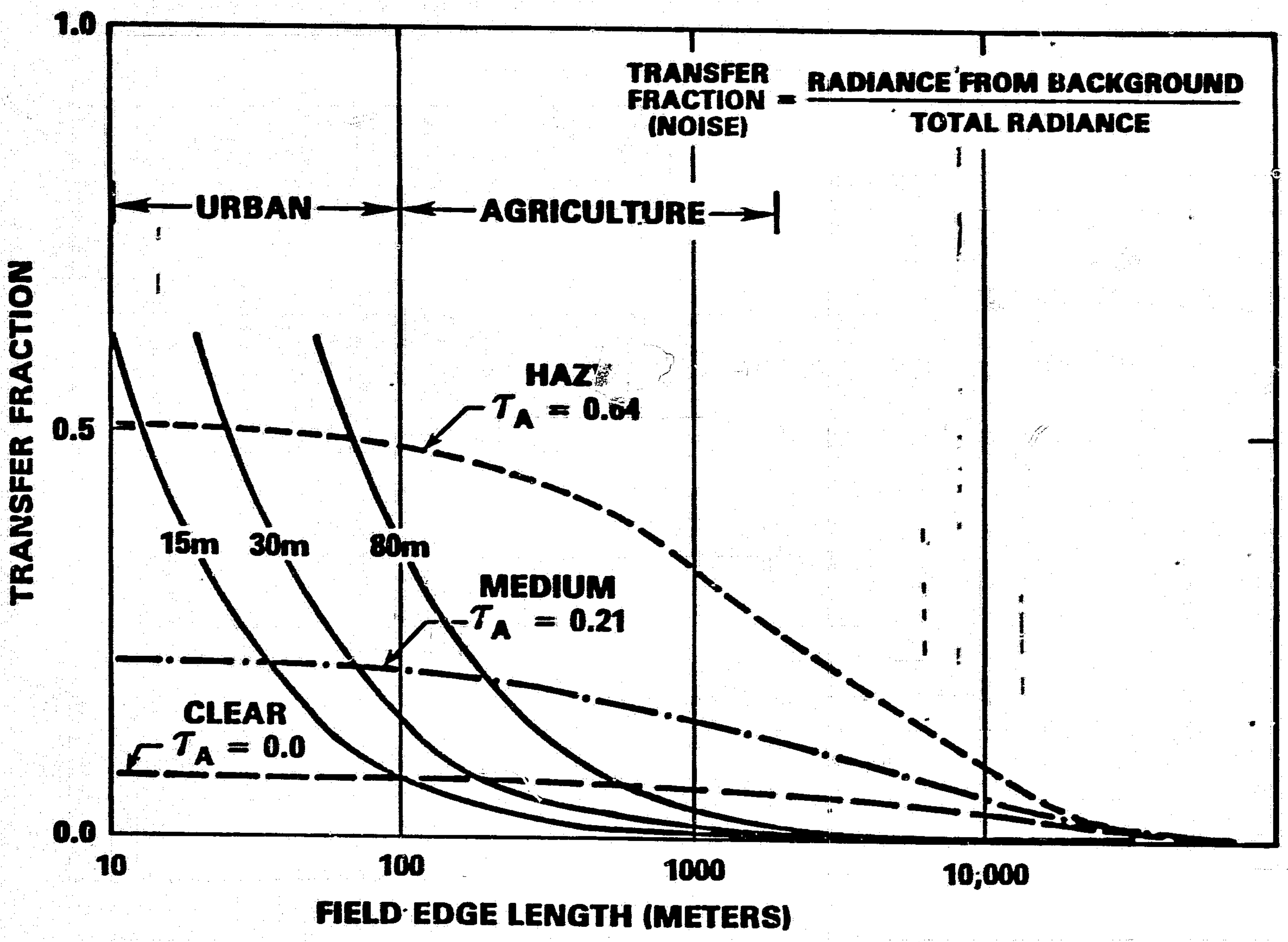


I_S — SIGNAL
I_B — BACKGROUND (NOISE)

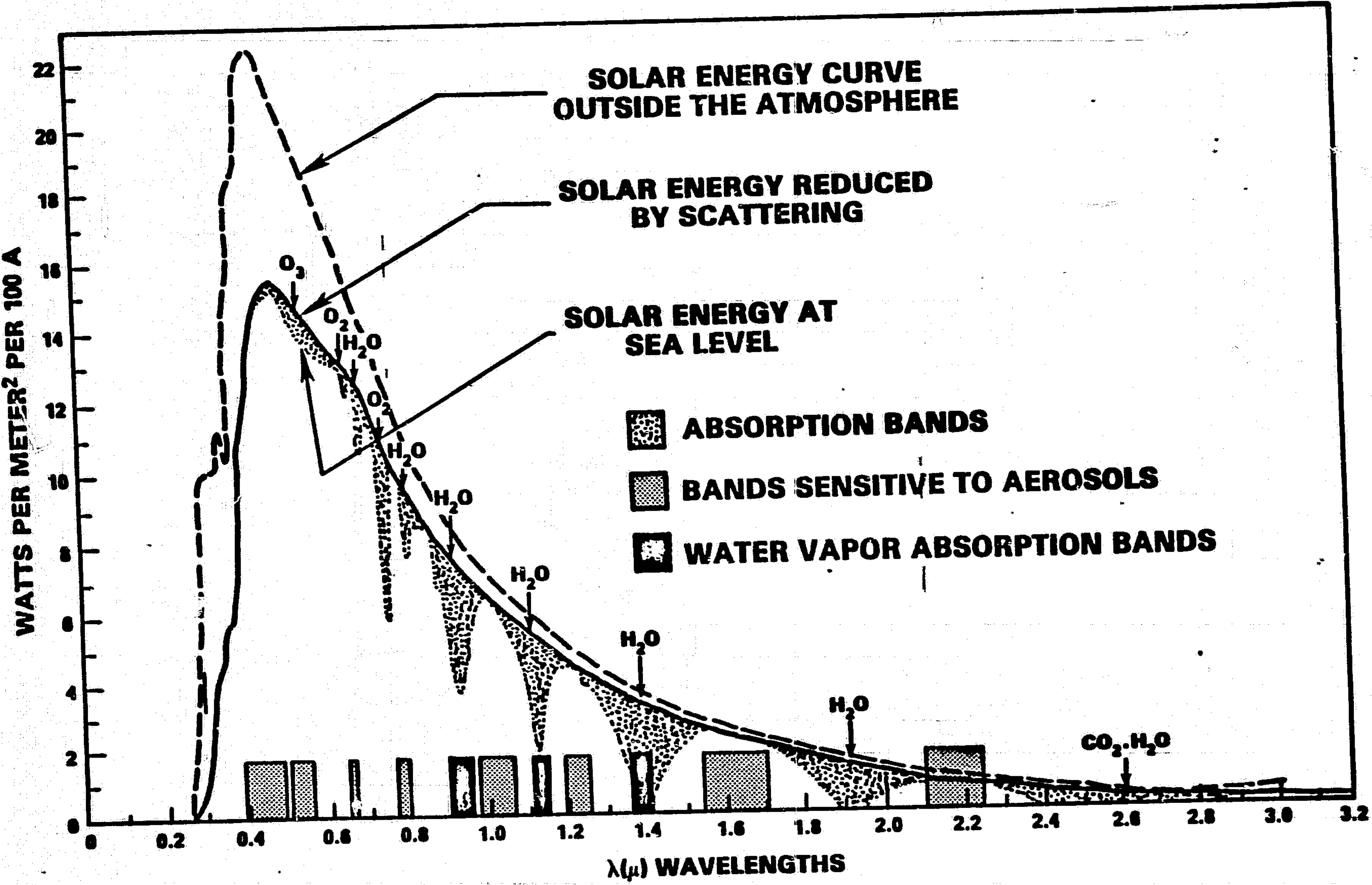
$$\text{TRANSFER FRACTION} = \frac{I_B}{I_S + I_B}$$

THE TWO PHENOMENA HAVE SIMILAR RESULTS: MIXING RADIATION FROM THE FIELD AND ITS BACKGROUND

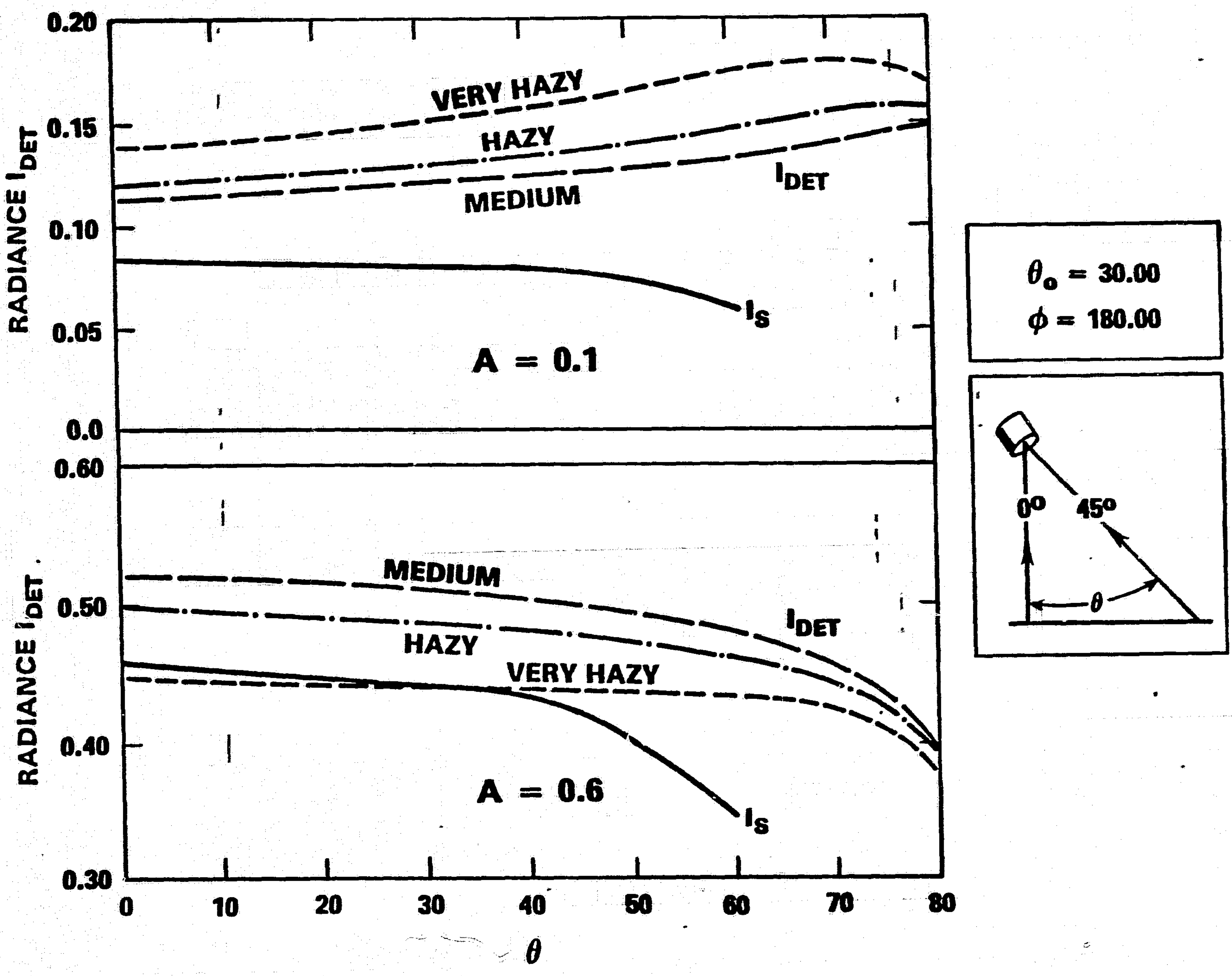
TRANSFER FRACTION



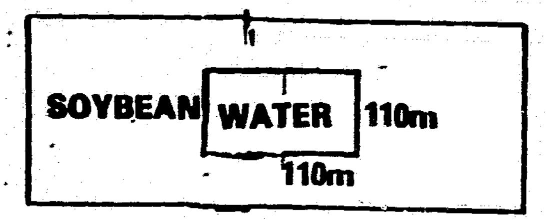
SOLAR SPECTRUM

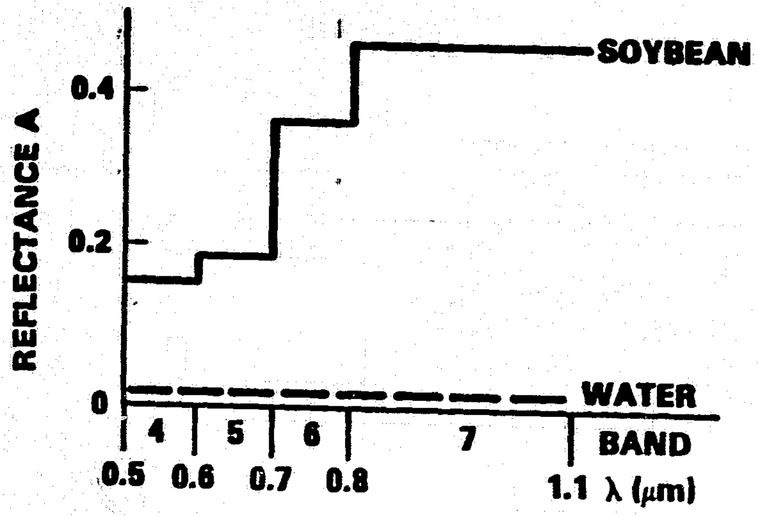


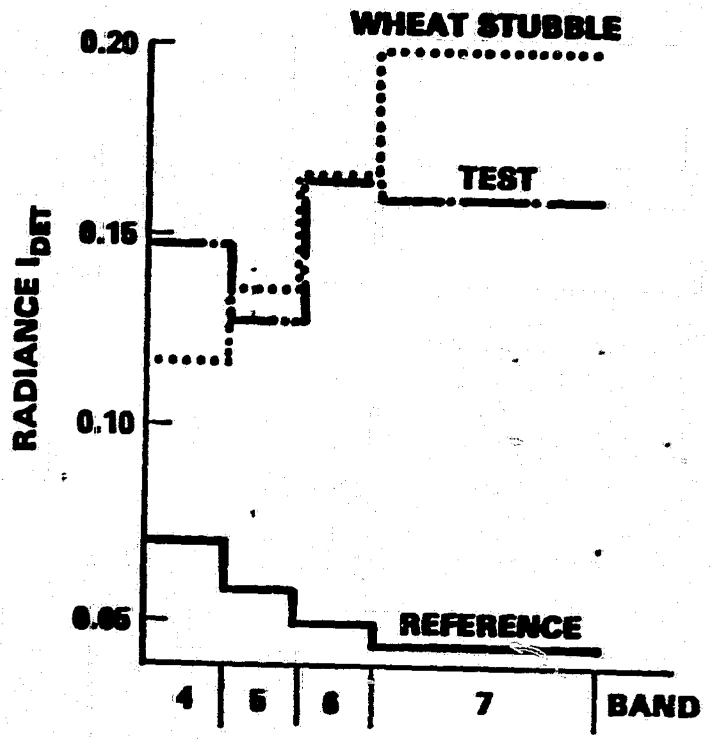
NADIR/OFF-NADIR OBSERVATIONS

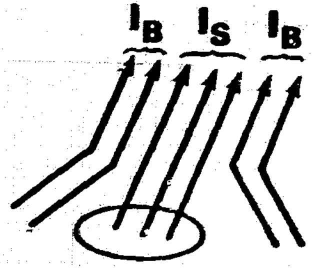


SIGNIFICANCE TO CLASSIFICATION
(ADJACENCY EFFECT)









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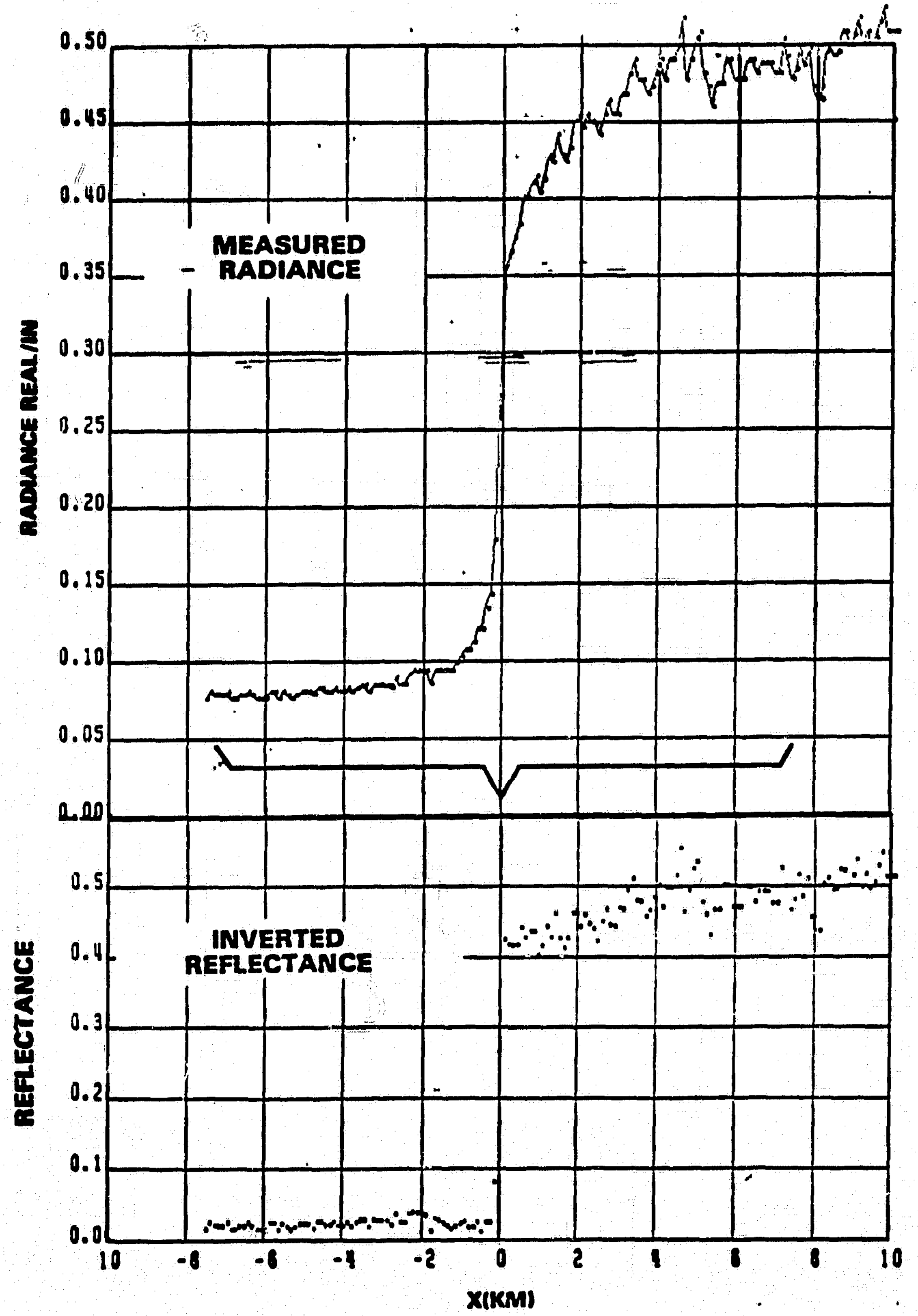
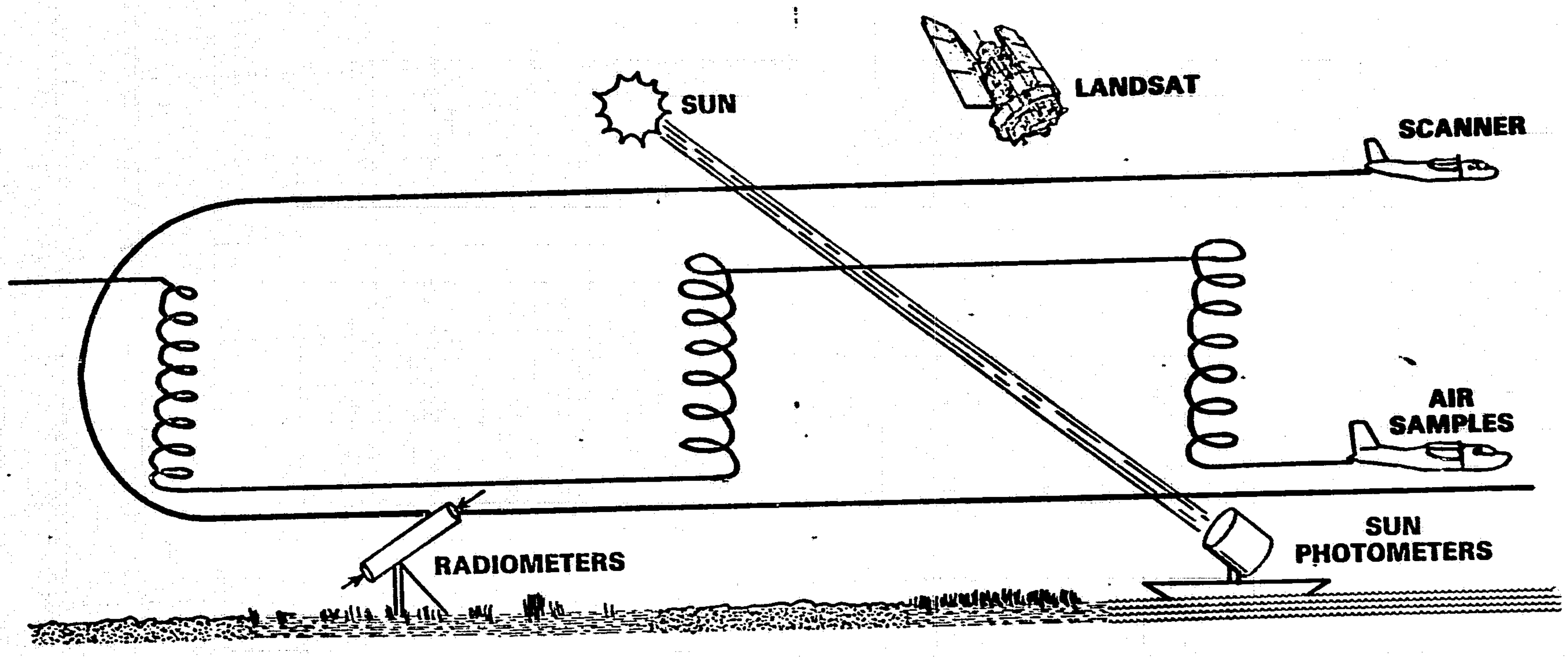
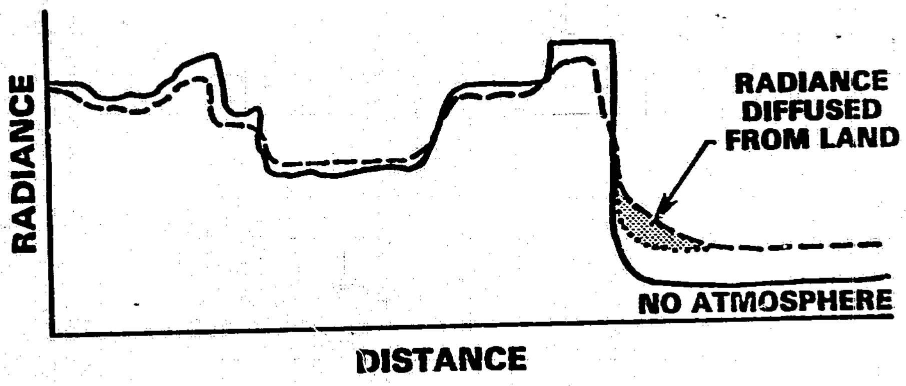
INVERSION OF LANDSAT DATA BAND 6



COMBINED ATMOSPHERE SURFACE EXPERIMENT





SIMULTANEOUS MEASUREMENT OF:
- UPWARD RADIANCE
- SURFACE REFLECTANCE
- OPTICAL THICKNESS
- AEROSOL SPATIAL VARIATIONS
- SCATTERING CHARACTERISTICS

OBJECTIVE: TO OBTAIN A CONTROLLED DATA SETS TO CHECK THEORIES

VIEW GRAPHS

Aram Mika
Santa Barbara Research Center

RECOMMENDATIONS: OPTICS

TASK	PRIORITY	KEY ISSUES
● THIN-FILM COATING DEVELOPMENT ● DESIGN AND ANALYSIS ● FABRICATION AND CHARACTERIZATION	2	● UNIFORMITY OVER LENGTH ● POLARIZATION
● BEAMSPLITTER DEMONSTRATION ● DESIGN, ANALYSIS, ELEMENT PROCUREMENT ● ASSEMBLY, ALIGNMENT, CHARACTERIZATION	3	● REGISTRATION STABILITY ● FABRICATION FEASIBILITY ● HIGH ASPECT-RATIO COMPONENTS ● BONDING DEFORMATION
● TELESCOPE DEMONSTRATION ● DESIGN, ANALYSIS, MIRROR PROCUREMENT ● ASSEMBLY, ALIGNMENT, TEST	4	● FABRICATION FEASIBILITY ● ALIGNMENT FEASIBILITY ● PERFORMANCE VERIFICATION ● HIGH RESOLUTION, WIDE FIELD-OF-VIEW ● POSITION SENSITIVITY

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RECOMMENDATIONS: MECHANICAL/STRUCTURAL

TASK	PRIORITY	KEY ISSUES
● OPTICAL BENCH DEMONSTRATION ● DESIGN AND FABRICATION ● MECHANICAL STABILITY	1	● HOUSING PERCEIVED AS PRINCIPAL MLA RISK ITEM ● DEMONSTRATION TO CERTIFY PERFORMANCE
● SELECT OPTIMUM MIRROR MOUNT TECHNIQUE ● DETAIL DESIGN ● VENDOR COORDINATION	4	● OPTICS VENDORS MUST INTEGRATE MOUNT CONCEPT INTO MIRROR DESIGN ● DIMENSIONAL STABILITY OF MOUNTS
● HEAT PIPE DEMONSTRATION	4	● MECHANICAL, THERMAL COUPLING, HYSTERESIS
● UPGRADE NASTRAN MODEL	5	● ALTERNATE NODAL DESIGNATIONS ● COMPLETE ANALYTICAL BASE FOR TELESCOPE HOUSING AND OPTICS ● REFINE ERROR BUDGETS

RECOMMENDATIONS: FOCAL-PLANE ARRAY

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TASK	PRIORITY	KEY ISSUES
● VNIR ARRAY DEMONSTRATION ● DESIGN AND ANALYSIS ● FABRICATION AND CHARACTERIZATION	1	● UNIFORMITY, CROSSTALK ● PROCESSING YIELD ● READOUT CIRCUITRY
● SWIR ARRAY DEMONSTRATION ● DESIGN AND ANALYSIS ● FABRICATION AND CHARACTERIZATION	1	● PROCESSING YIELD ● UNIFORMITY, 1/f NOISE ● OPERATING TEMPERATURE ● READOUT CIRCUITRY
● FPA MULTI-BAND PACKAGING	1	● ARRAY PLACEMENT TOOLING ● MOUNTING, BONDING, ALIGNMENT ● POSITION STABILITY - MECHANICAL, THERMAL ● INTERCONNECTION AND CABLING ● REPAIRABILITY

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RECOMMENDATIONS: ELECTRONICS, SIGNAL/DATA PROCESSING

TASK	PRIORITY	KEY ISSUES
● DATA COMPRESSION	2	● SCENE STATISTICS V.S. COMPRESSION RATIO ● DECISION ALGORITHM FOR COMPRESSION - MODE SELECTION
● DETECTOR SIGNAL-PROCESSING DEMONSTRATION	3	● VERIFY SIGNAL PROCESSING: DETECTOR→ CORRECTED DIGITAL VIDEO ● GAIN/OFFSET CORRECTION ● SNR, DYNAMIC RANGE ● DRIFT
● GATE-ARRAY DEMONSTRATION ● DESIGN AND ANALYSIS ● FABRICATION AND TEST	4	● INTEGRATION FEASIBILITY FOR ON-BOARD PROCESSOR ● SPEED, POWER PERFORMANCE

RECOMMENDATIONS: SYSTEM ANALYSIS

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TASK	PRIORITY	KEY ISSUES

● RESAMPLING/REGISTRATION ANALYSIS AND SIMULATION	1	● OBJECT-SPACE REGISTRATION IN SPACE V.S. RESAMPLING ON GROUND
		● PROCESSING COST AND TURNAROUND TIME V.S. DATA QUALITY
		  ● RECTIFICATION ACCURACY
		  ● NOISE
		● EFFECT OF MISREGISTRATION AND MTF ON CLASSIFICATION - VERIFY PREDICTIONS

● RADIOMETRIC ACCURACY REQUIREMENTS	1	● ABSOLUTE AND RELATIVE ACCURACY NEEDS ● ATMOSPHERIC DEGRADATION ● SPACE V.S. GROUND CORRECTION
● STEREO/OFFSET MODE ANALYSIS	2	● MISREGISTRATION, DISTORTION ● CORRECTION TECHNIQUES ● ATMOSPHERIC EFFECTS ● PSYCHOVISUAL CONSIDERATIONS - STEREO MODE
● CALIBRATION TECHNIQUES	3	● PRECISION TRANSFER STANDARDS ● FULL V.S. PARTIAL - FIELD CALIBRATOR ● COST, PERFORMANCE

#1

ADVANCED INFRARED FOCAL PLANE ARRAY TECHNOLOGY AT SBRC

11 JANUARY 1982

R D THOM

SBRC
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OUTLINE

- IR FOCAL PLANE ARRAY OVERVIEW

- HYBRID FOCAL PLANE ARRAY (HFPA) TECHNOLOGY
  - PHOTOVOLTAIC (PV) InSb
  - PV HgCdTe
  - LIQUID-PHASE EPITAXIAL (LPE) HgCdTe
  - PV DETECTOR DESIGNS FOR HFPA's
  - HFPA DETECTOR TECHNOLOGY ISSUES/STATUS
  - MULTIPLEXER TECHNOLOGY

- MULTISPECTRAL LINEAR ARRAY (MLA) TECHNOLOGY
  - SWIR DESIGN FEATURES
  - ELEMENT SIZE
  - MLA DEVELOPMENTAL ARRAYS
  - CLOSE BUTTING TECHNOLOGY

- MONOLITHIC INTRINSIC ARRAY TECHNOLOGY
  - SHORT WAVELENGTH (1-5μm)
  - LONG WAVELENGTH (8-12μm)

- RECOMMENDATIONS FOR FUTURE RESEARCH

FOCAL PLANE DESIGN ALTERNATIVES

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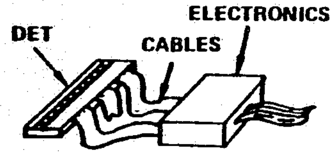
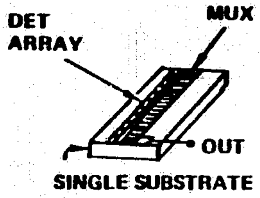
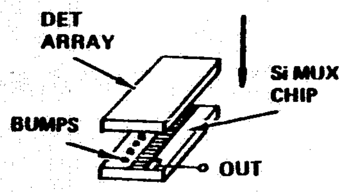
BASIC APPROACH	TYPES/FEATURES	REMARKS
DISCRETE-COMPONENT WIREBONDED ARRAYS  	• ANY DETECTOR MATERIAL OR TYPE OF ELECTRONICS	• CONVENTIONAL APPROACH FOR PRESENT-GENERATION FPAs
	• ONE OR MORE WIREBONDS PER DETECTOR	• LARGE NO. OF WIREBONDS REQUIRED WITH HIGH DENSITY • NOT AMENABLE TO LOWER COST BATCH PROCESSING
FULLY-MONOLITHIC INTEGRATED ARRAYS  	• HgCdTe MONOLITHIC IRCCD	• ULTIMATE SOLUTION FOR FUTURE FPAs • ATTRACTIVE FOR LINEAR ARRAYS AND SWIR • SIGNIFICANT TECHNOLOGY DEVELOPMENT REQ'D
	• InSb MONOLITHIC IRCCD	• LOWER OPERATING TEMPERATURE • STATE-OF-ART CTE TOO LOW
	• Si SCHOTTKY BARRIER IRCCD	• LOW OPERATING TEMP AND QUANTUM EFFIC
	• EXTRINSIC Si (Si:X) IRCCD	• LOW OPERATING TEMP AND QUANTUM EFFIC
	• CHARGE INJECTION DEVICE (CID)	• ADVANTAGEOUS FOR AREA BUT NOT LINEAR ARRAYS
HYBRID INTEGRATED ARRAYS  	• INTRINSIC PV-DETECTOR HYBRIDS (HgCdTe; InSb)	• INDEPENDENTLY-OPTIMIZED DETECTORS AND READOUT ELECTRONICS • COMPONENTS PROCESSED IN PARALLEL AND PRETESTED PRIOR TO ASSEMBLY
	• INDIUM BUMP FLIP-CHIP INTERCONNECTS	• HIGH YIELD, HIGH RELIABILITY BATCH INTERCONNECT TECHNOLOGY
	• EXTRINSIC Si HYBRIDS (SOXS)	• LOW OPERATING TEMPERATURE

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HYBRID FOCAL PLANE ARRAY TECHNOLOGY

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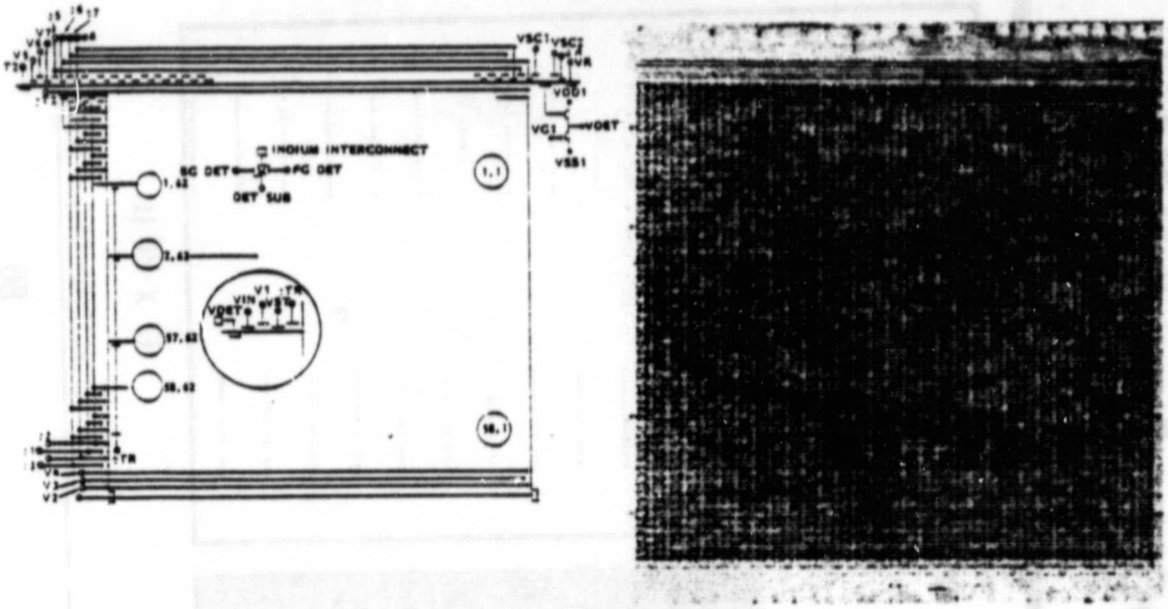
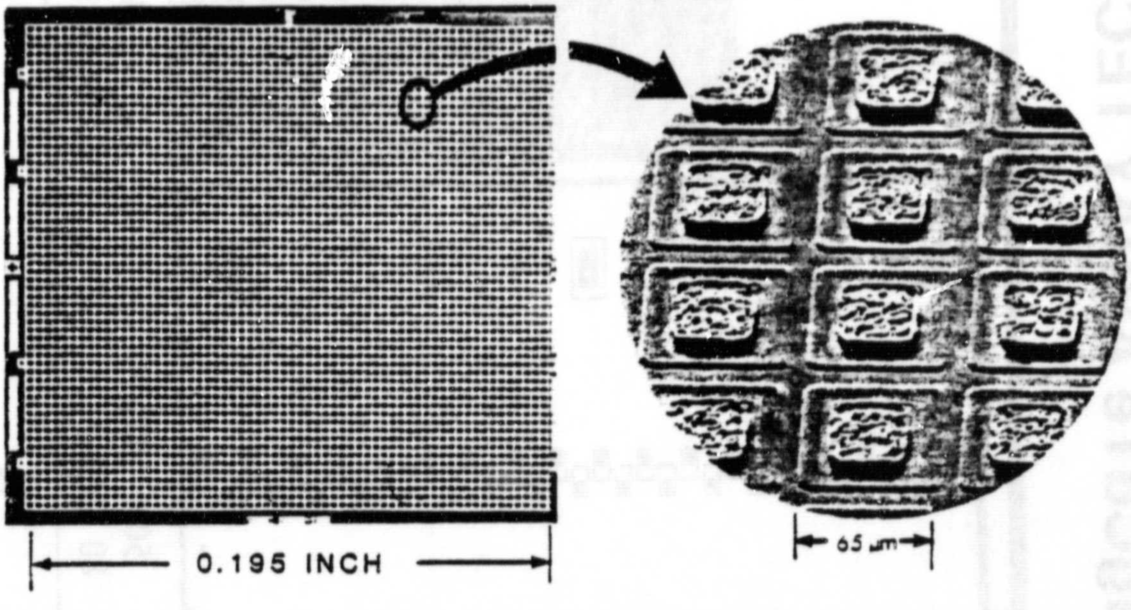


62 x 58 CCD MULTIPLEXER CHIP. SCHEMATIC DIAGRAM AT LEFT AND PHOTOGRAPH OF A CHIP PRIOR TO HYBRIDIZING AT RIGHT



62 x 58 DETECTOR ARRAY. THE INSET IS A HIGH-MAGNIFICATION SEM SHOWING THE 68 um-SQUARE ELEMENTS AND INDIUM BUMP INTERCONNECTS

PV HgCdTe ARRAY TECHNOLOGY

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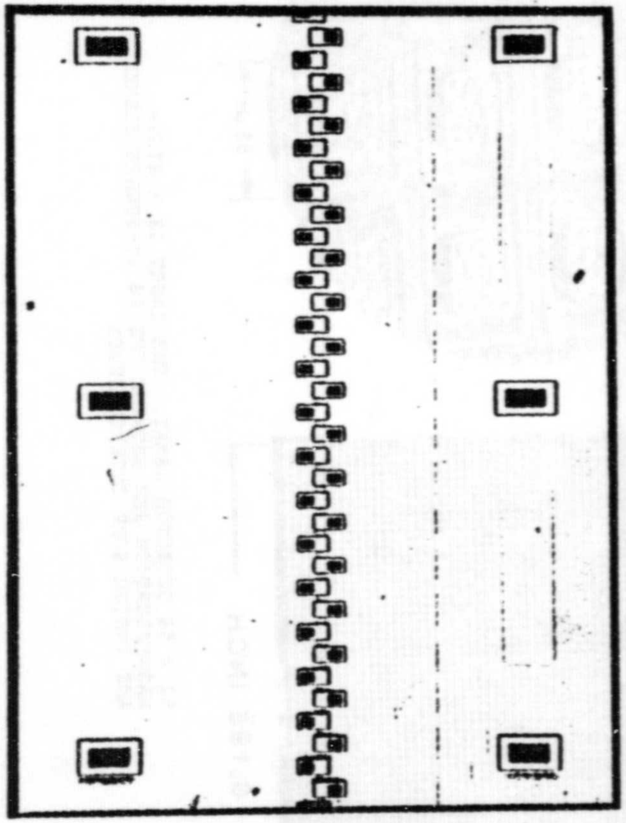
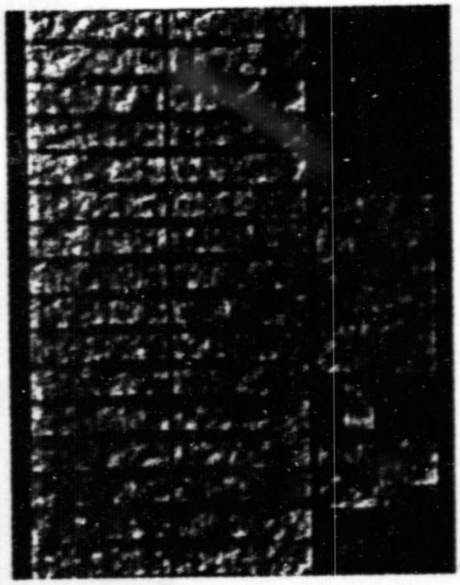
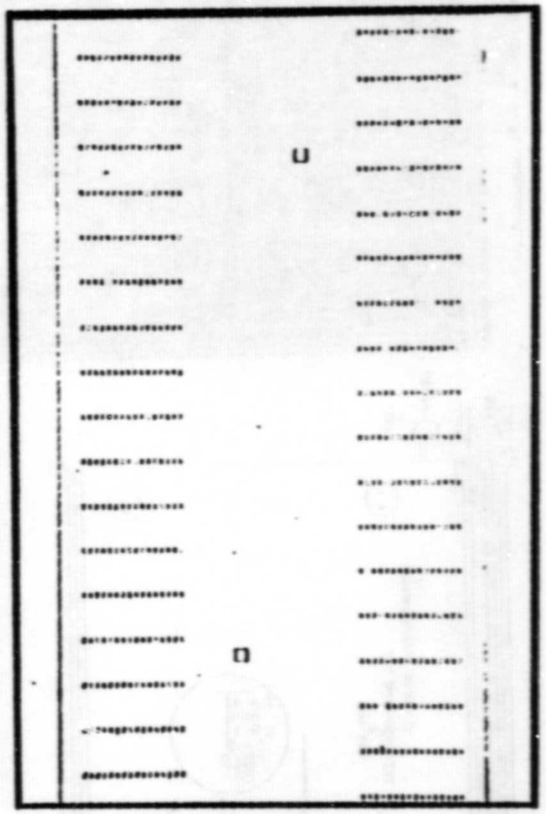


50 x 100 μ
80 ELEMENT



25 x 25 μ
LATERAL DIFFUSION



12 x 20 μ

78 79 80

PV $Hg_{0.7}Cd_{0.3}Te$/N-121 HYBRID ASSEMBLY

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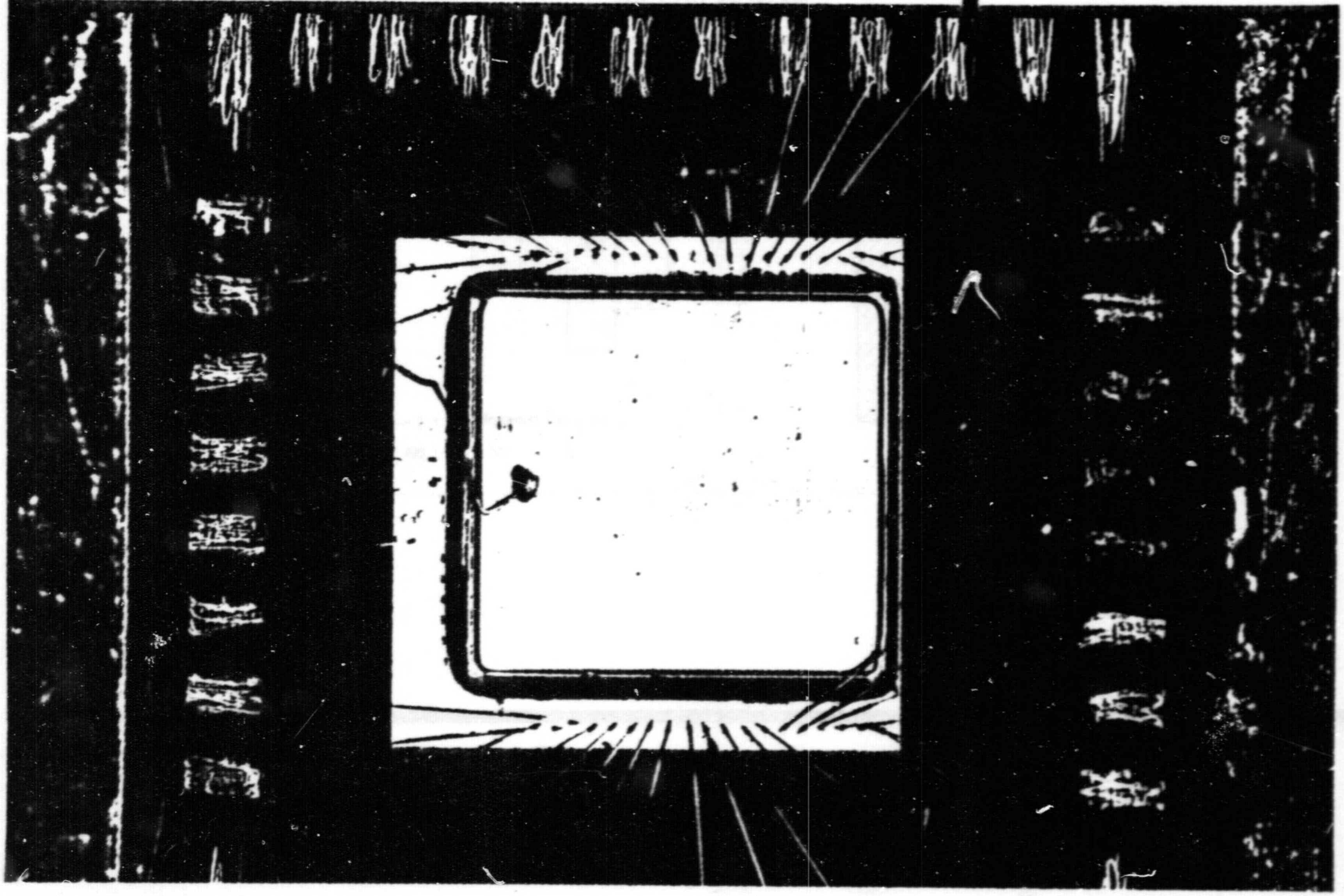

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D* HISTOGRAMS FOR 32 x 32 PV HgCdTe HFPA

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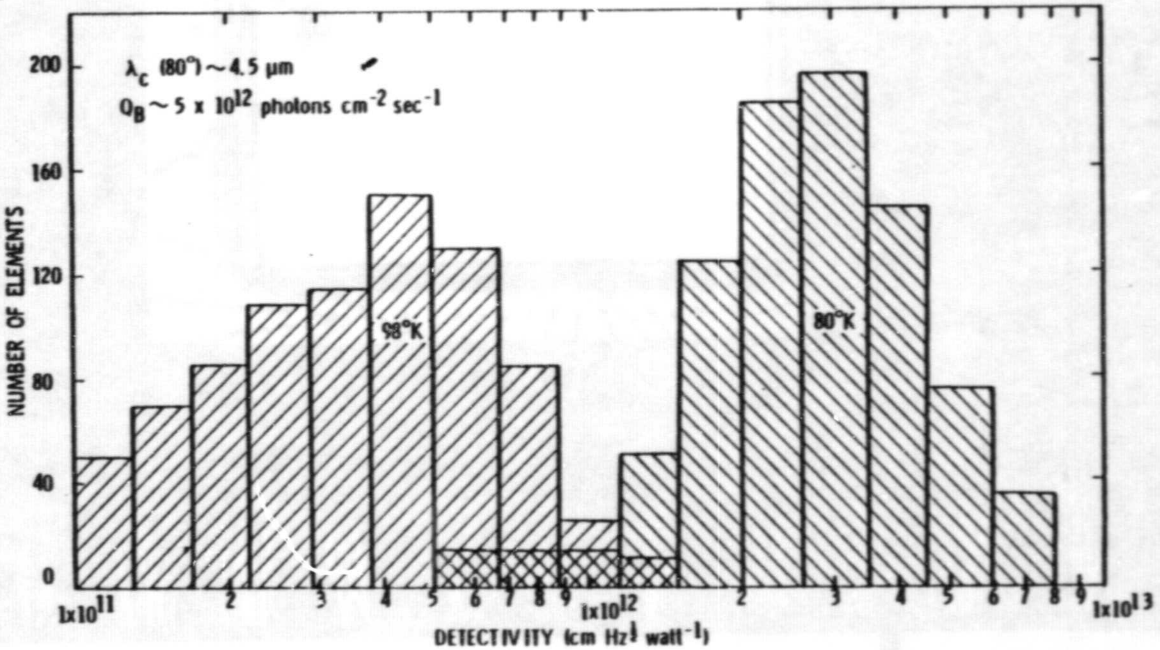

SIZE COMPARISON OF BULK GROWN HgCdTe AND CdTe/HgCdTe LPE

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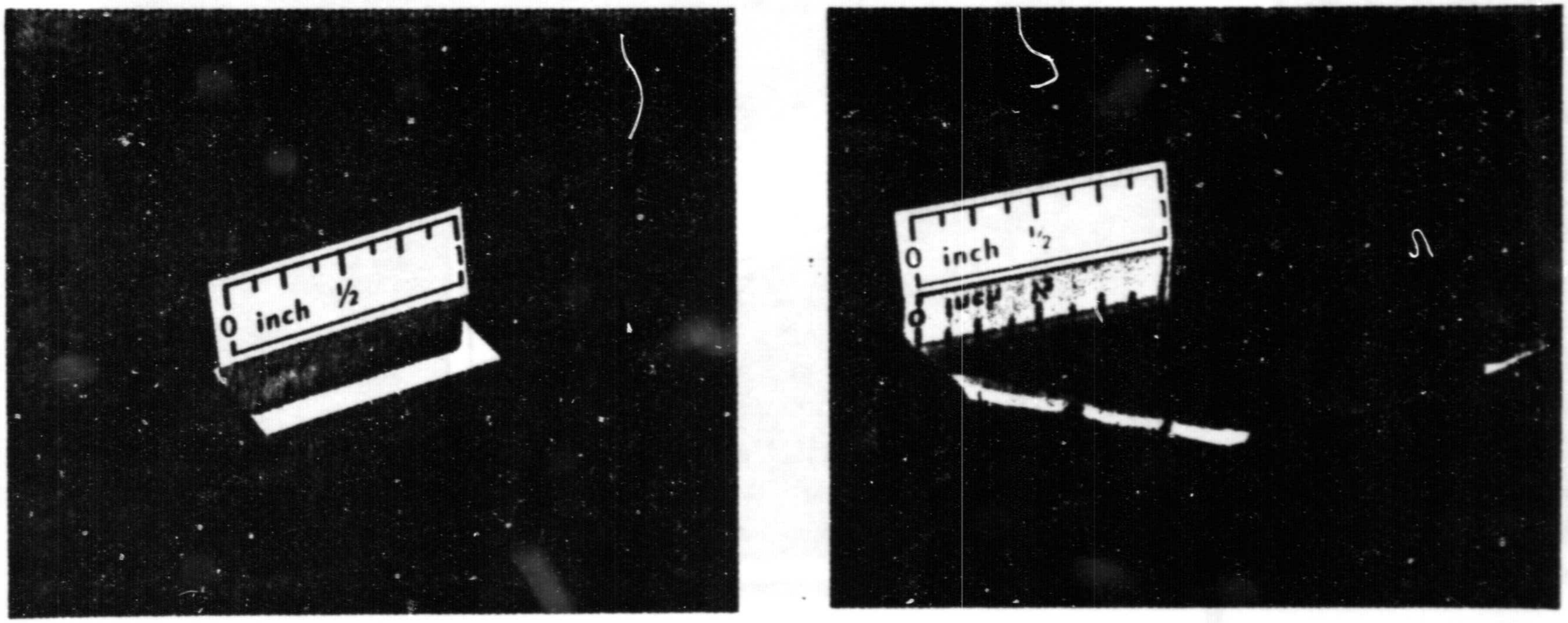
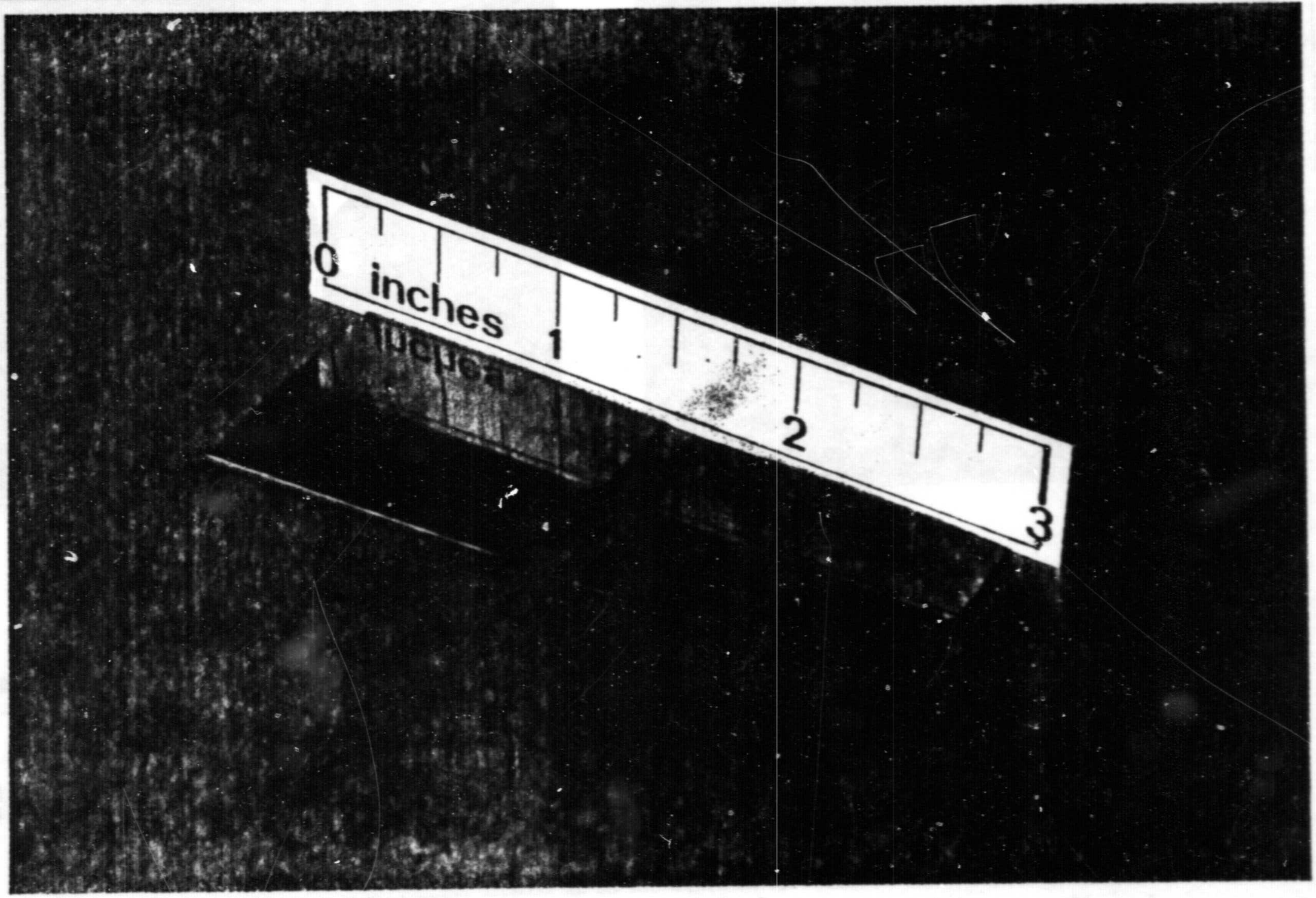


SWIR LPE LAYERS ON $\sim$6 cm^2 CdTe SUBSTRATE



PV DETECTOR DESIGNS FOR HFPA'S

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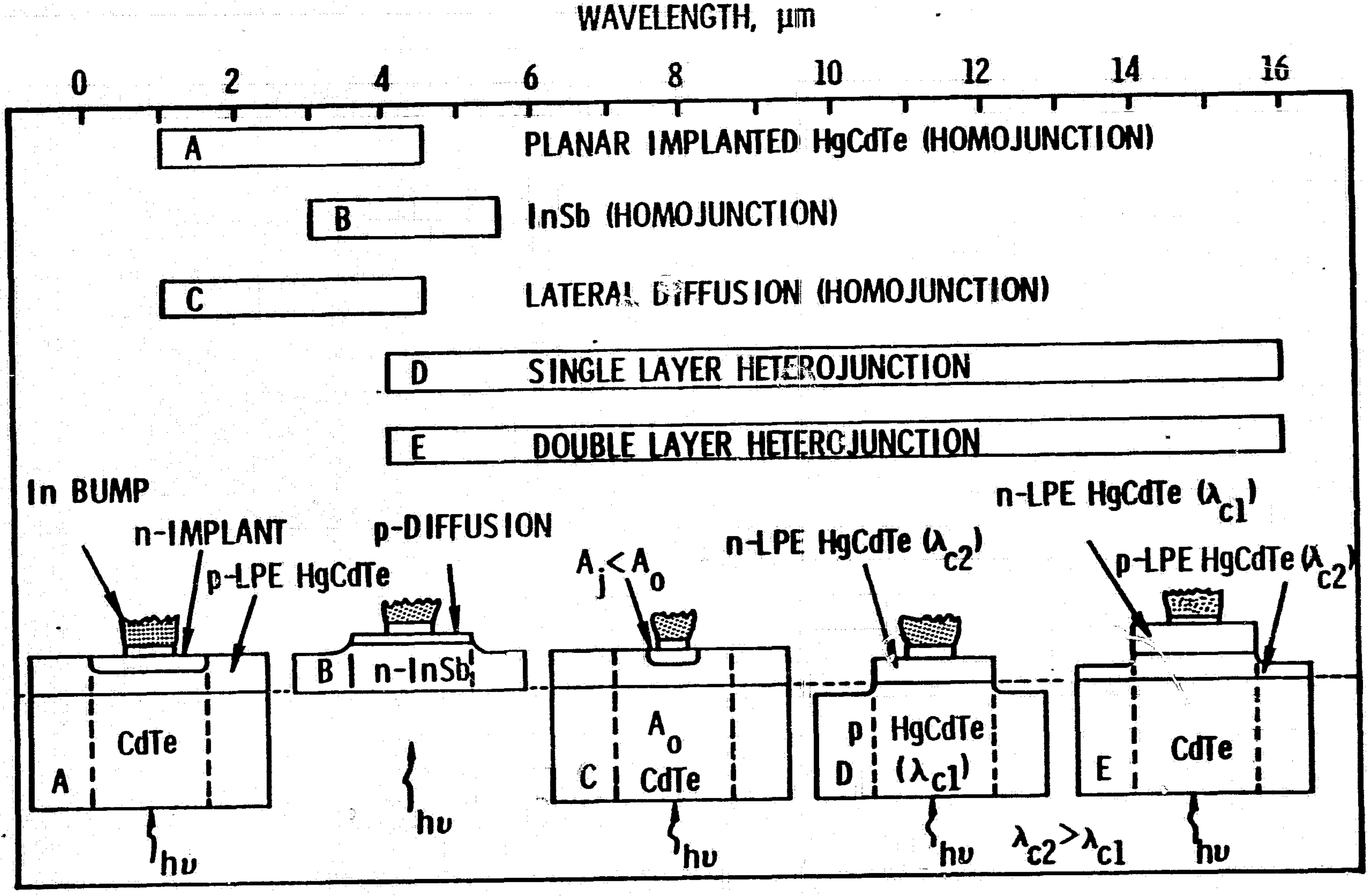
81-5-160



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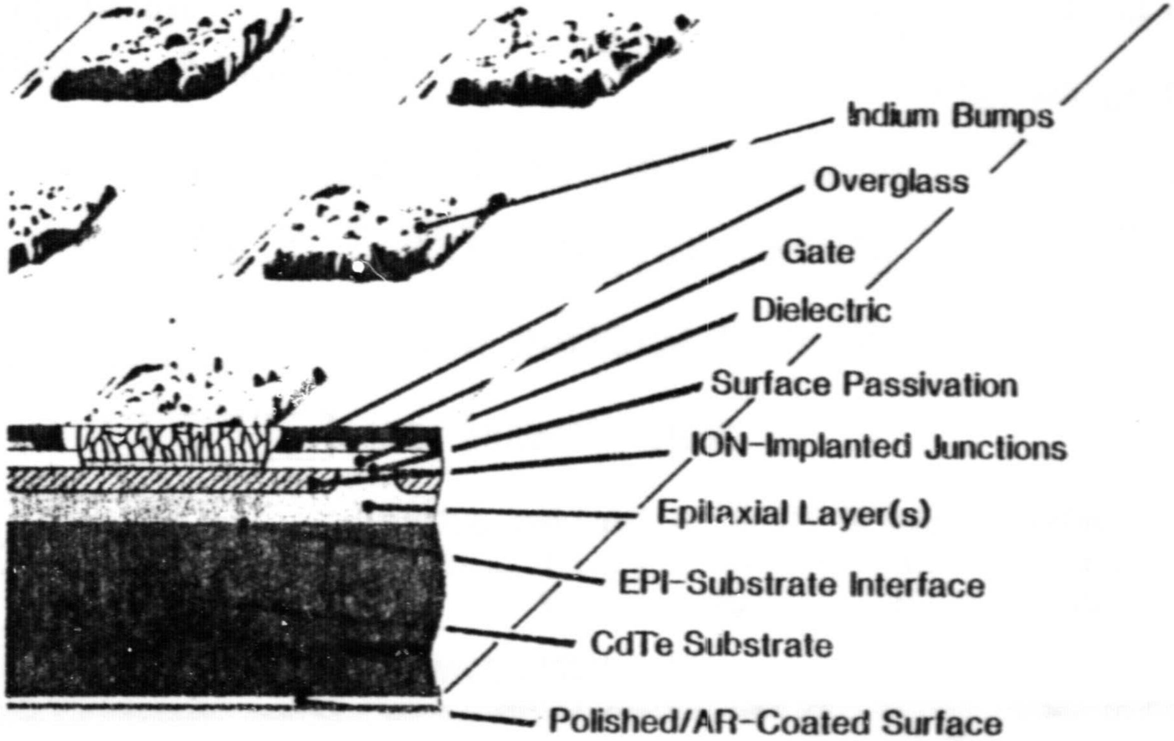
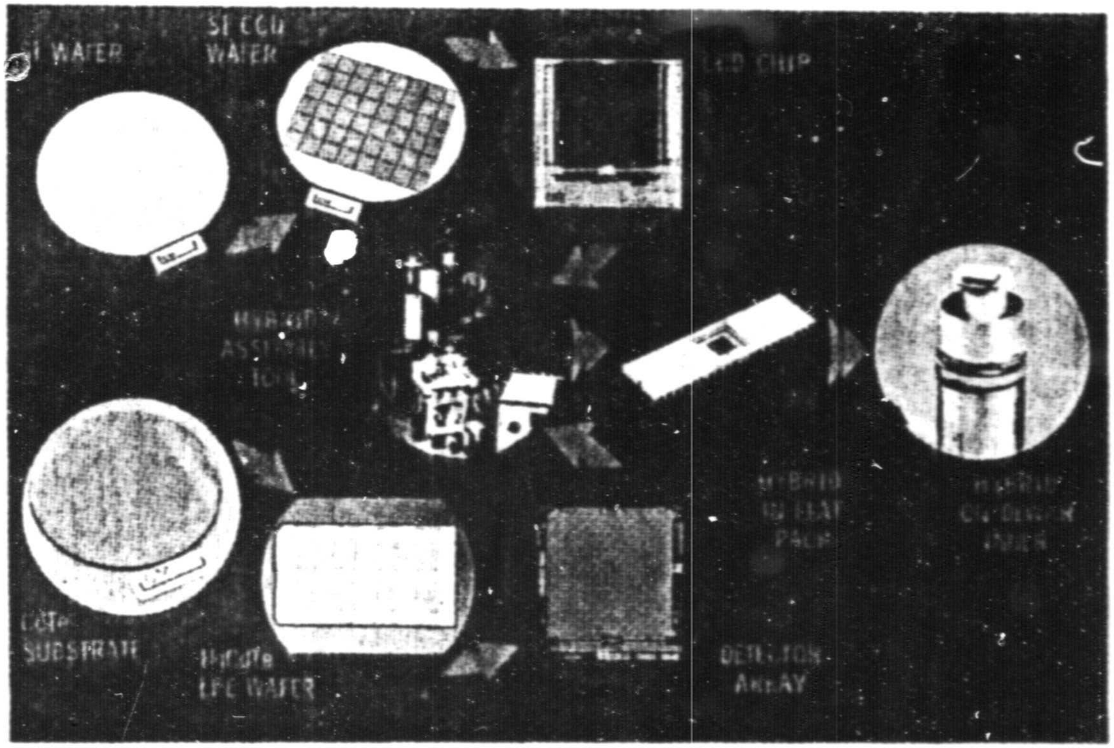
HFPA DETECTOR TECHNOLOGY ISSUES



HYBRID ARRAY PROCESSING SEQUENCE



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KEY PV HgCdTe HFPA TECHNOLOGY ISSUES AND STATUS

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<table>
<tr><th>CdTe SUBSTRATES</th><th>HgCdTe LPE</th><th>SURFACE PASSIVATION</th><th>JUNCTION FORMATION</th><th>DIODE/MUX INTERCONNECTS</th><th>HFPA ASSEMBLY</th></tr>
<tr>
<td>● 6-12 cm^2
● TWIN FREE
● EPD OF 10^2 TO 10^4 cm^2
● BOTH VERTICAL AND HORIZONTAL BRIDGMAN</td>
<td>● N_D AS LOW AS $2x10^{14}$ AS GROWN
● $N_A \approx 10^{15}$
● $\lambda_c \pm 0.02 \mu m$ FOR $x = 0.3$
● THICKNESS OF $10 \mu m \pm 1 \mu m$
● SURFACES SMOOTH TO ±100 Å
● PLANAR WELL DEFINED INTERFACES
● BOTH Hg + Te MELT CAPABILITIES</td>
<td>● $V_{FB} = 0 \pm 0.5v$
● $N_{SS} = 5x10^{10}$
● HYSTERESIS ≤ 0.2v
● $\rho > 10^{14} \Omega$ cm
● STANDARD SiO_2 PROCESSING</td>
<td>● $\eta \sim 0.7$
● B+ IMPLANTS
<table>
<tr><th>λ_c</th><th>T</th><th>R_oA</th></tr>
<tr><td>2.3</td><td>195</td><td>10^4</td></tr>
<tr><td>4.2</td><td>195</td><td>30</td></tr>
<tr><td>5.2</td><td>80</td><td>$>10^6$</td></tr>
</table>
● HETEROJUNCTIONS
<table>
<tr><th>λ_c</th><th>T</th><th>R_oA</th></tr>
<tr><td>9</td><td>80</td><td>500</td></tr>
<tr><td>9</td><td>40</td><td>$>10^6$</td></tr>
<tr><td>12</td><td>80</td><td>4</td></tr>
<tr><td>13</td><td>30</td><td>10^4</td></tr>
</table>
</td>
<td>● > 5K INTERCONNECTS PER CHIP WITH HIGH YIELD
● INTERCONNECTS AS SMALL AS 6 μm DIAMETER
● NO FAILURES IN ENVIRONMENTAL AND FLIGHT TESTS</td>
<td>● ONE-STEP FLIP-CHIP OF PRETESTED COMPONENTS
● HIGHLY PERFECTED THIRD GENERATION ASSEMBLY TOOLING</td>
</tr>
</table>

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GROWTH IN ELEMENTS PER HFPA

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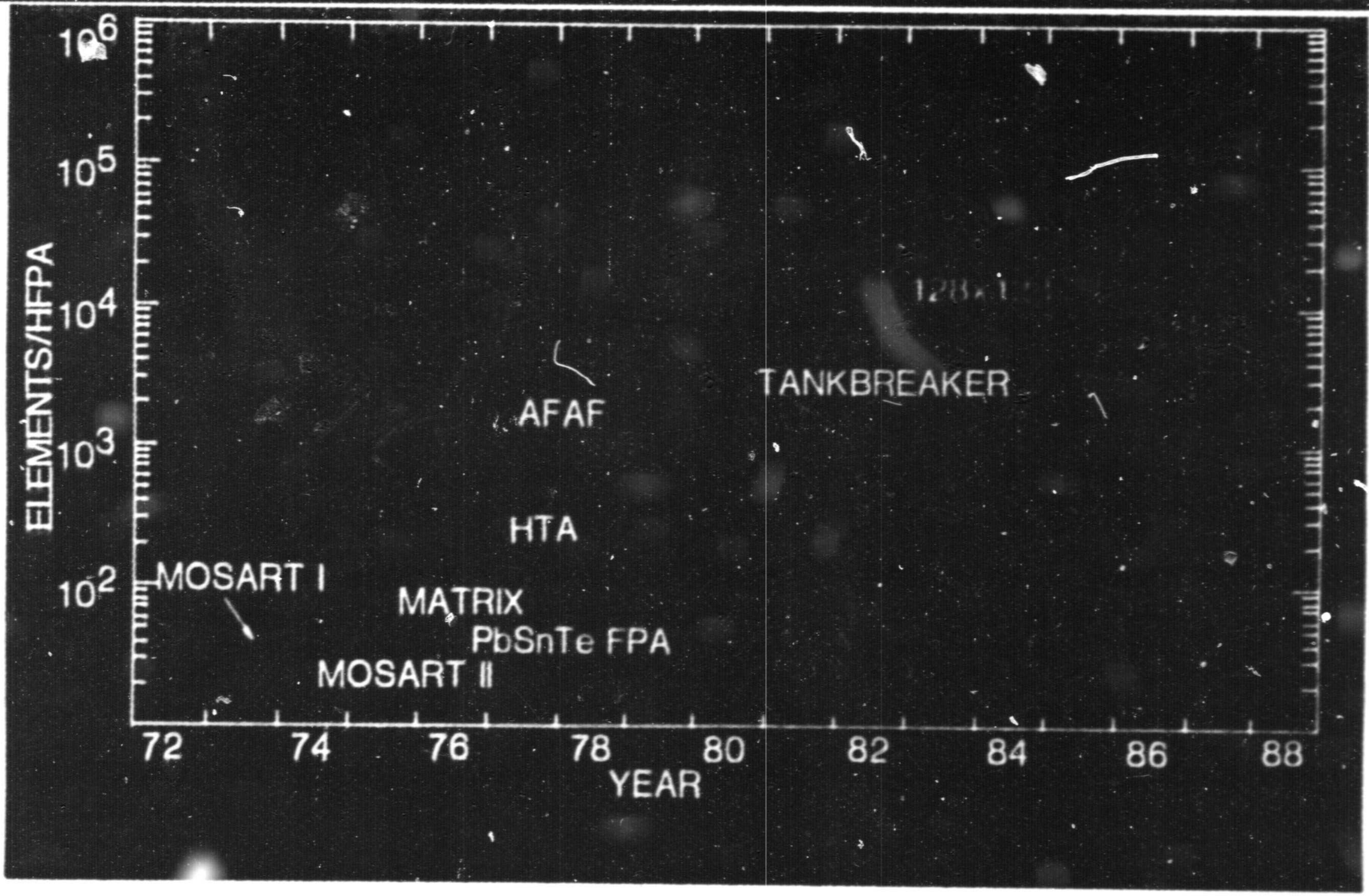

MULTISPECTRAL LINEAR ARRAY TECHNOLOGY

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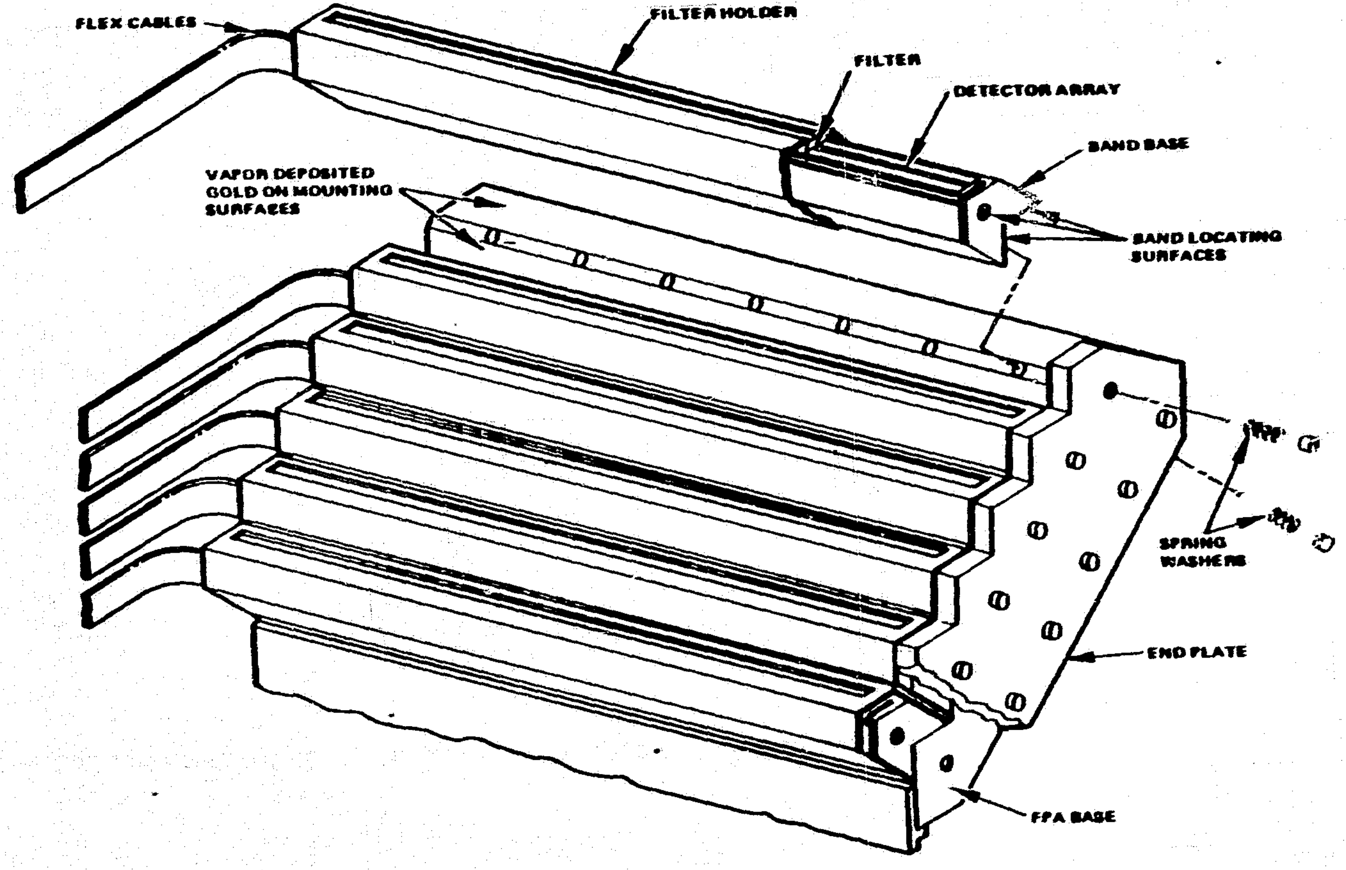
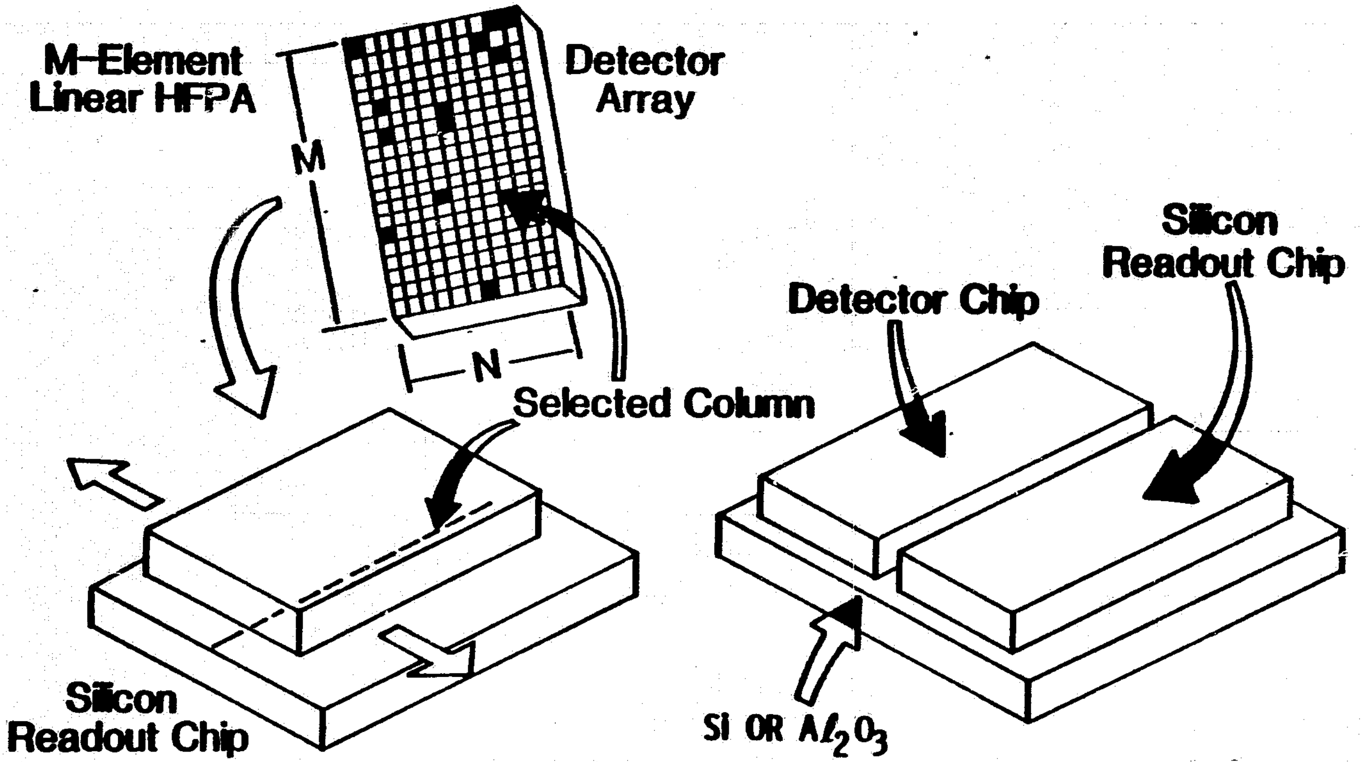
MLA FOCAL PLANE ASSEMBLY



HFPA DESIGNS FOR LINEAR ARRAYS

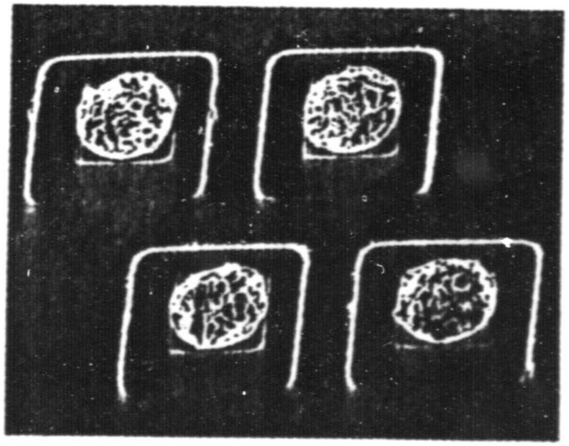


N–Fold Redundancy For Higher Yield

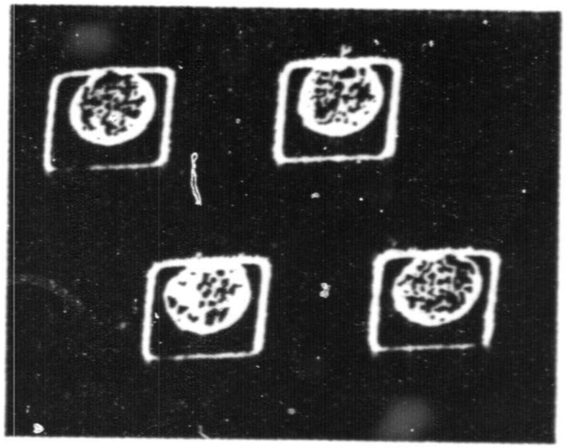
Passive Substrate

HgCdTe HYBRID TEST ARRAY MESA STRUCTURES (SEMs)

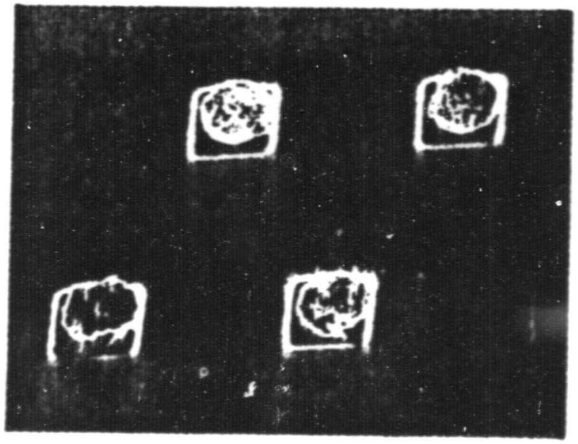
38 µm



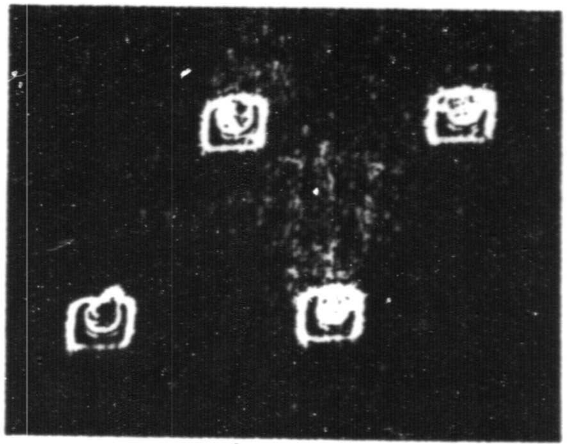
25 µm

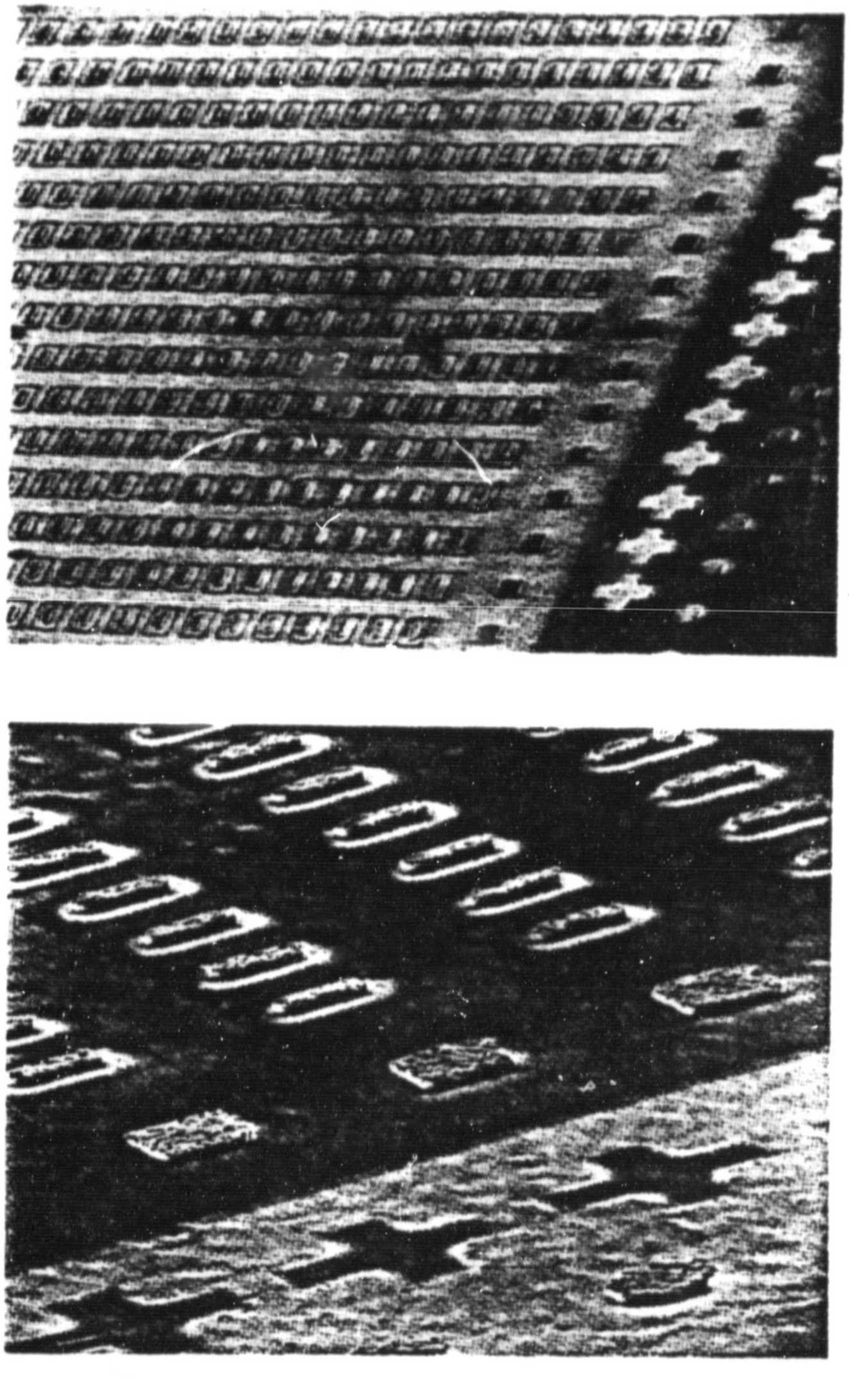


18 µm



13 µm





Scanning Electron Micrographs of MLA
Developmental SWIR Array Fabricated on LPE HgCdTe

RoA HISTOGRAM OF MLA DEVELOPMENTAL SWIR ARRAY SHOWING 100% OPERABILITY OF 256 ELEMENTS

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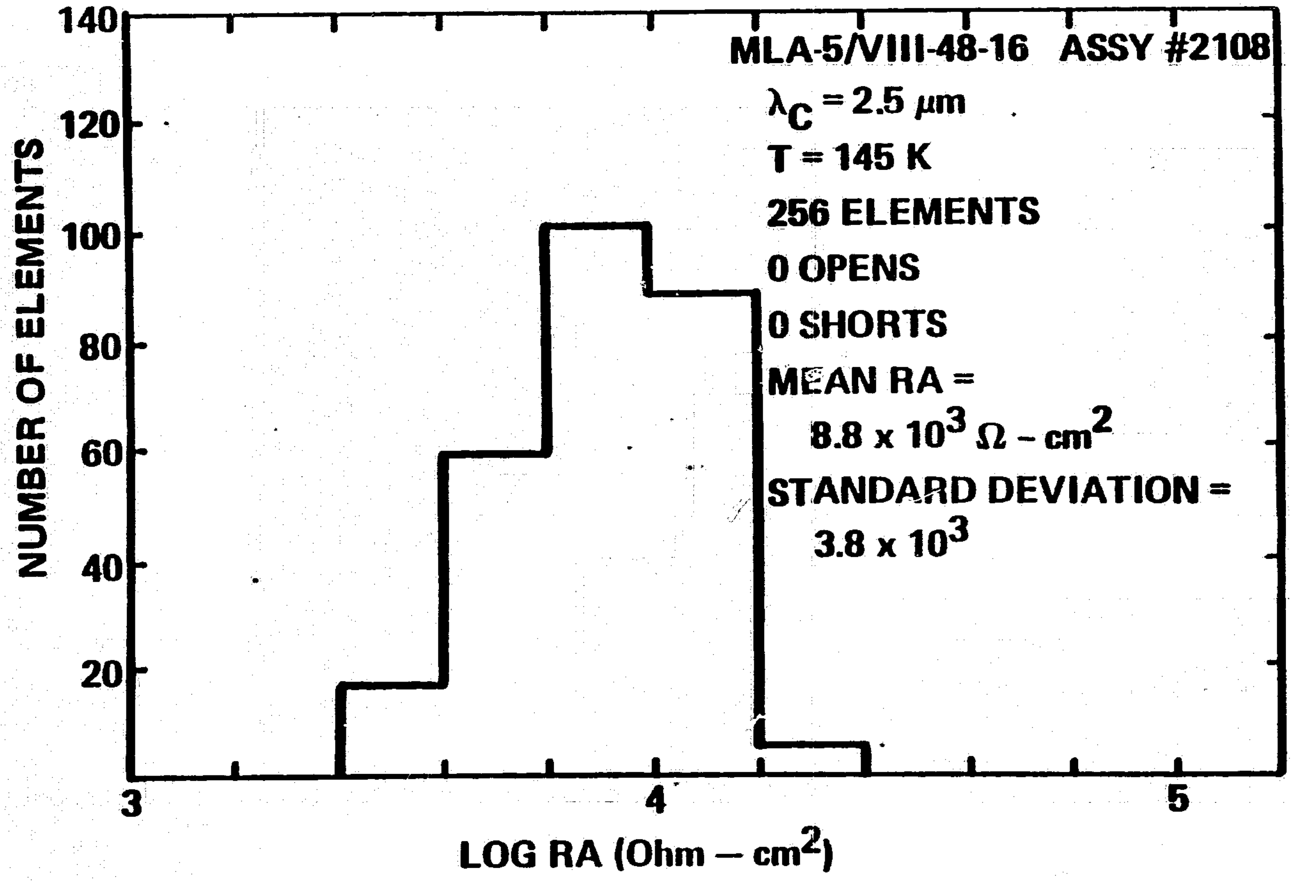
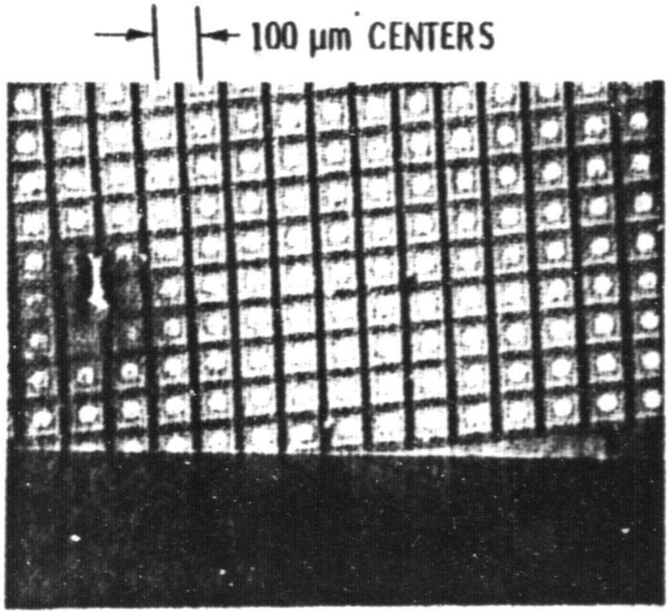


CLOSE BUTTING DEVELOPMENT

SBRC
A SUBSIDIARY OF
HUGHES AIRCRAFT COMPANY

TEST SAMPLE: 32 x 32 HgCdTe ARRAY



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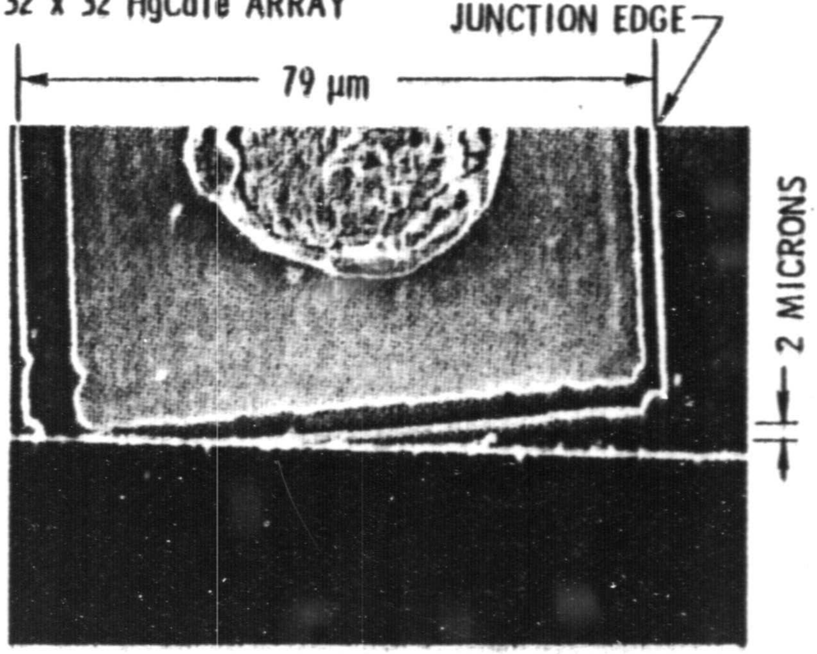


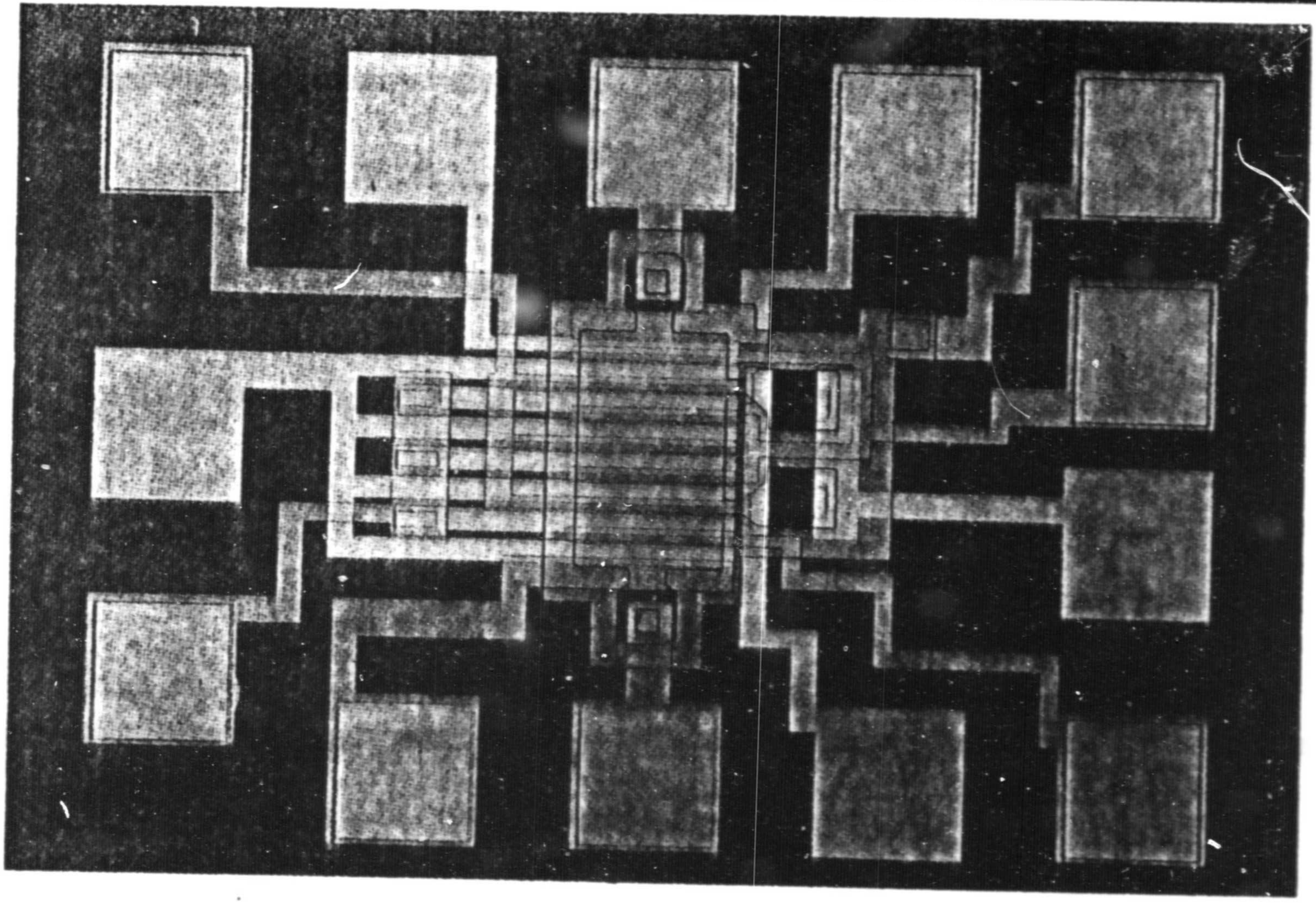
1350X

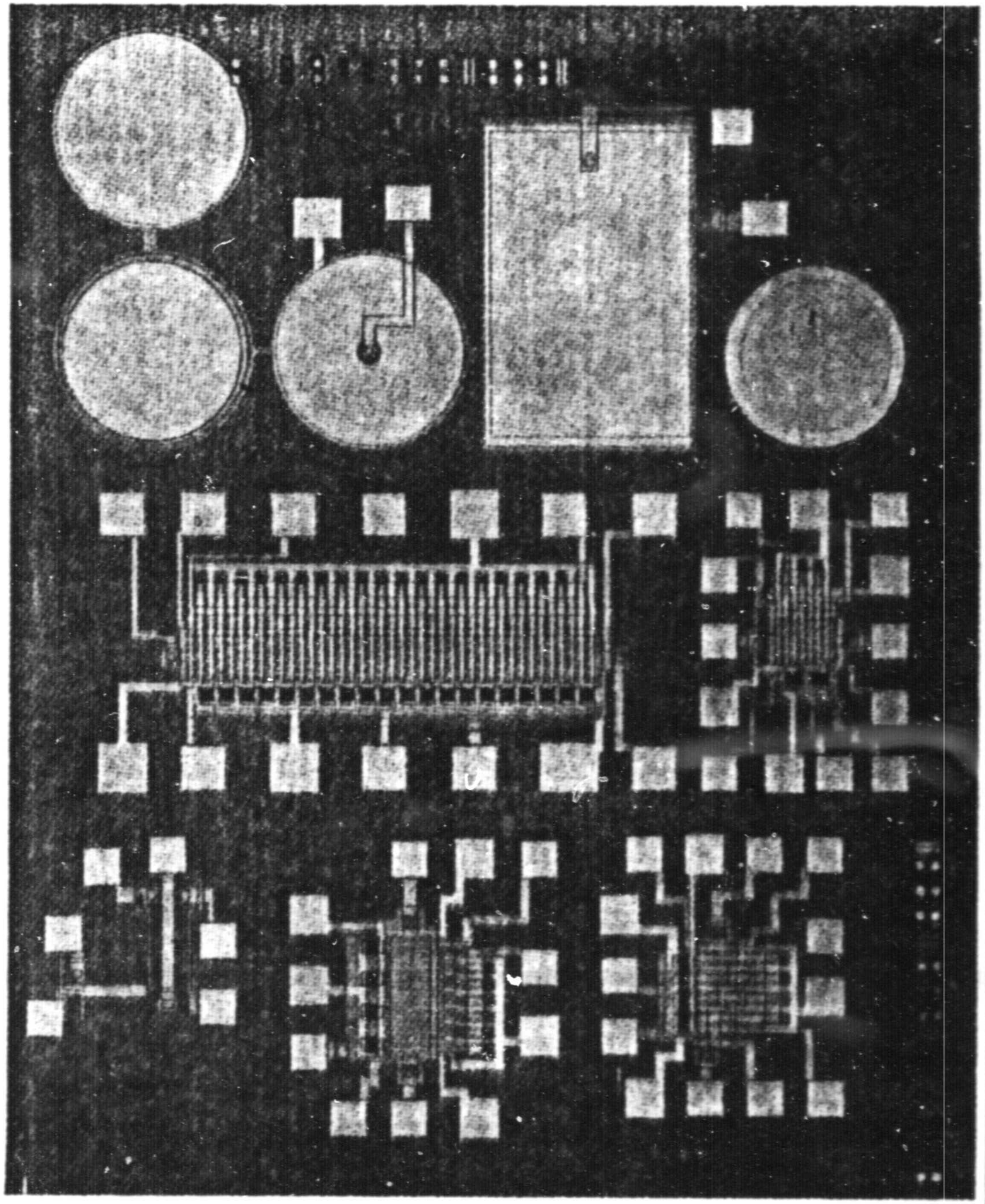
MONOLITHIC INTRINSIC ARRAY TECHNOLOGY

SBRC
A SUBSIDIARY OF HUGHES AIRCRAFT COMPANY

2-ELEMENT LINEAR ARRAY
SBRC 8585 N-CHANNEL HgCdTe CCIRID
(DEVICE: ZH 265-3D–G2)

SBRC
A SUBSIDIARY OF
HUGHES AIRCRAFT COMPANY



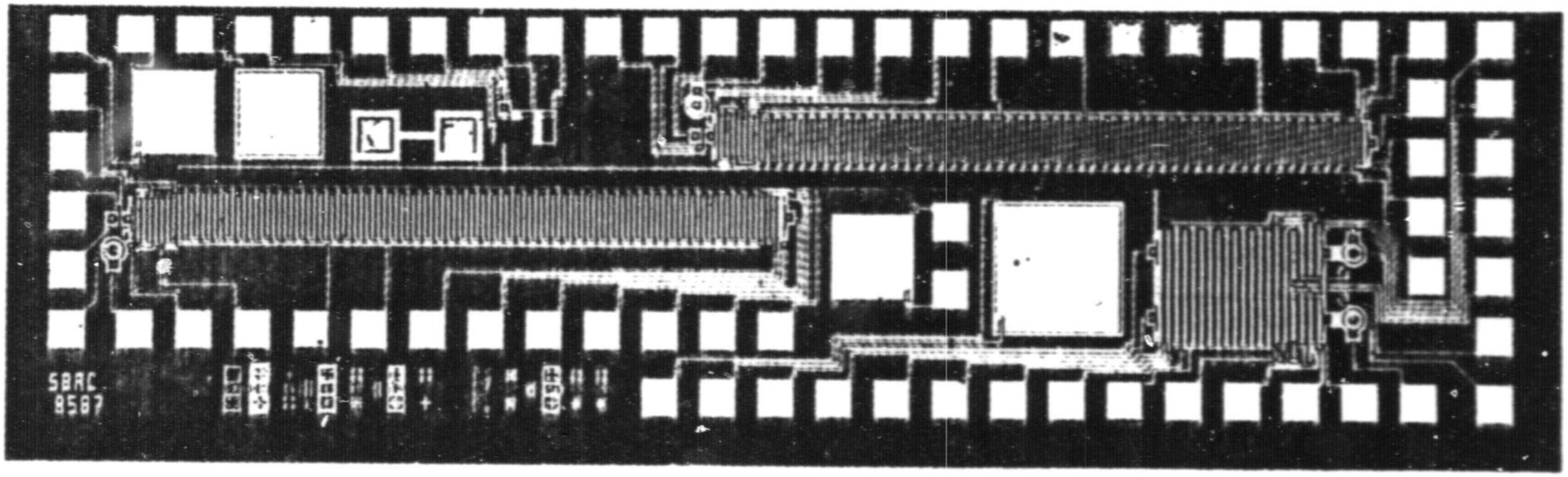


SBRC
A SUBSIDIARY OF HUGHES AIRCRAFT COMPANY

SBRC 8585 CHIP
N-CHANNEL
HgCdTe CCIRIA
(DEVICE: ZH 265-3D-F2)

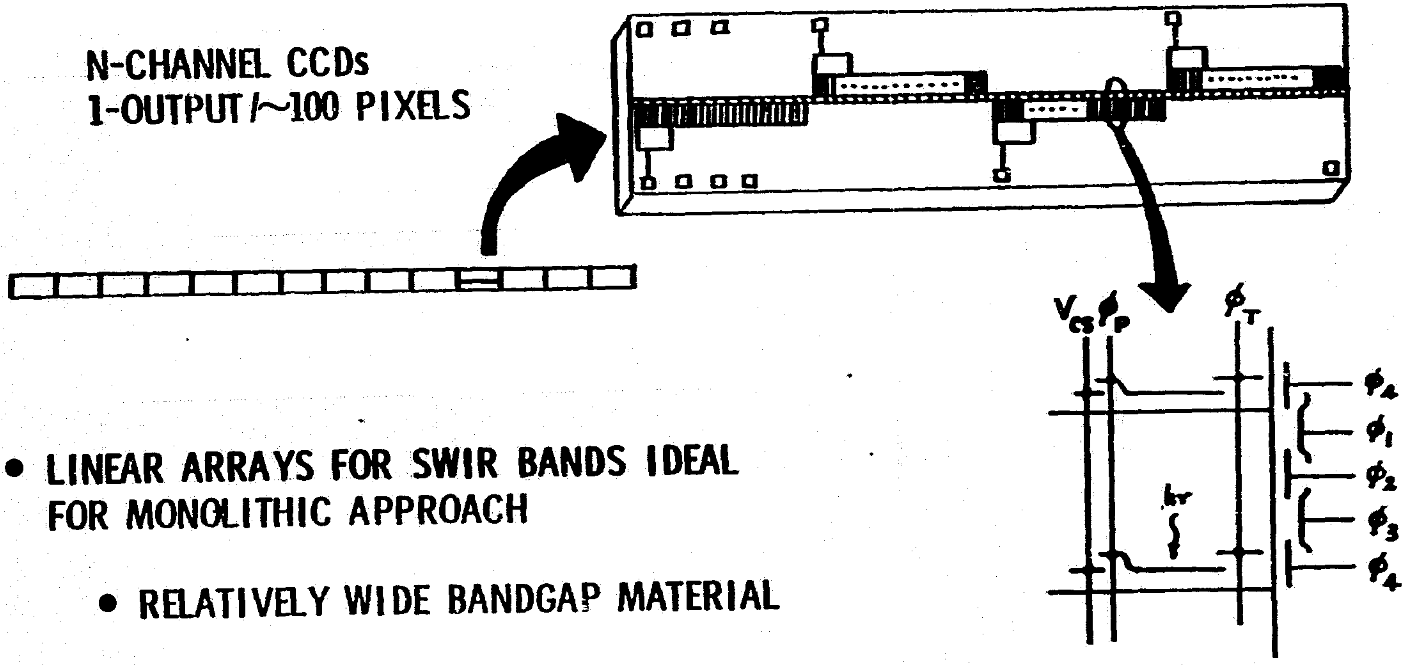
SBRC 8587 100 x 1 LINEAR IMAGING ARRAY

SBRC
A SUBSIDIARY OF
HUGHES AIRCRAFT COMPANY



2.5 μm HCT LINEAR IRCCD FOR MLA

SBRC
A SUBSIDIARY OF
HUGHES AIRCRAFT COMPANY



N-CHANNEL CCDs
1-OUTPUT/~100 PIXELS

- LINEAR ARRAYS FOR SWIR BANDS IDEAL FOR MONOLITHIC APPROACH
  - RELATIVELY WIDE BANDGAP MATERIAL
  - HIGH BREAKDOWN VOLTAGES
  - NO TUNNELLING
  - NO FILL-FACTOR CONCERN ALLOWING SIMPLE FRONTSIDE-ILLUMINATED DEVICES

7/81

NEW TECHNOLOGY DIRECTIONS

SBRC
A SUBSIDIARY OF HUGHES AIRCRAFT COMPANY

RECOMMENDATIONS FOR FUTURE RESEARCH-ADVANCED IR FOCAL PLANE ARRAYS

SBRC
A SUBSIDIARY OF
HUGHES AIRCRAFT COMPANY

TECHNOLOGY AREA	MLA SWIR DEVELOPMENT
MATERIAL AND ARRAY FABRICATION TECHNOLOGY FOR LARGE/LONG ARRAYS	
TECHNIQUES/DESIGNS FOR VERY-HIGH OPERABILITY ARRAYS	●
CLOSE-BUTTING TECHNOLOGY FOR CONTIGUOUS, MULTI-CHIP ARRAYS	●
NOVEL DESIGNS (E.G. OPTICAL SPREADERS) FOR MULTICHIP ARRAYS	
PRECISION DETECTOR ALIGNMENT/PLACEMENT TECHNIQUES	
INTEGRATED INFRARED MULTICOLOR ARRAYS	
SHORT- AND MEDIUM-λ HgCdTe MONOLITHIC ARRAYS	
LONG-λ HgCdTe MONOLITHIC ARRAYS	
NOVEL MULTIPLEXER DESIGNS (NON-CCD)	●
"SMART" FOCAL PLANE/CHIP TECHNOLOGY	
ON-FOCAL-PLANE DRIVE ELECTRONICS	
SURVIVABLE/SELF-REPAIRING FOCAL PLANES	

VIEW GRAPHS

Bill Barnes
NASA/Goddard Space Flight Center

III. MLA CRITICAL SUPPORTING SCIENCE AND TECHNOLOGY

HYBRID SWIR TECHNOLOGY

MONOLITHIC SWIR TECHNOLOGY

VIS/NIR DETECTOR ARRAYS

OPTICS DESIGN AND FABRICATION

PASSIVE COOLER DESIGN

TERRAIN RELIEF COMPENSATION

SENSOR SYSTEM SIMULATION

ASSESSMENT AND CALIBRATION LABORATORY

AIRBORNE MLA SENSORS

MLA SCIENCE SUPPORT

MULTISPECTRAL LINEAR ARRAYS FOR TERRESTRIAL REMOTE SENSING

677-27-01

OBJECTIVES:

- DEMONSTRATE REQUIRED MLA FOCAL PLANE TECHNOLOGY FOR RESOURCE OBSERVATIONS
- DEVELOP A SCIENTIFIC BASIS FOR SYSTEM PERFORMANCE CRITERIA.
- DEVELOP CRITICAL ASSOCIATED TECHNOLOGIES.

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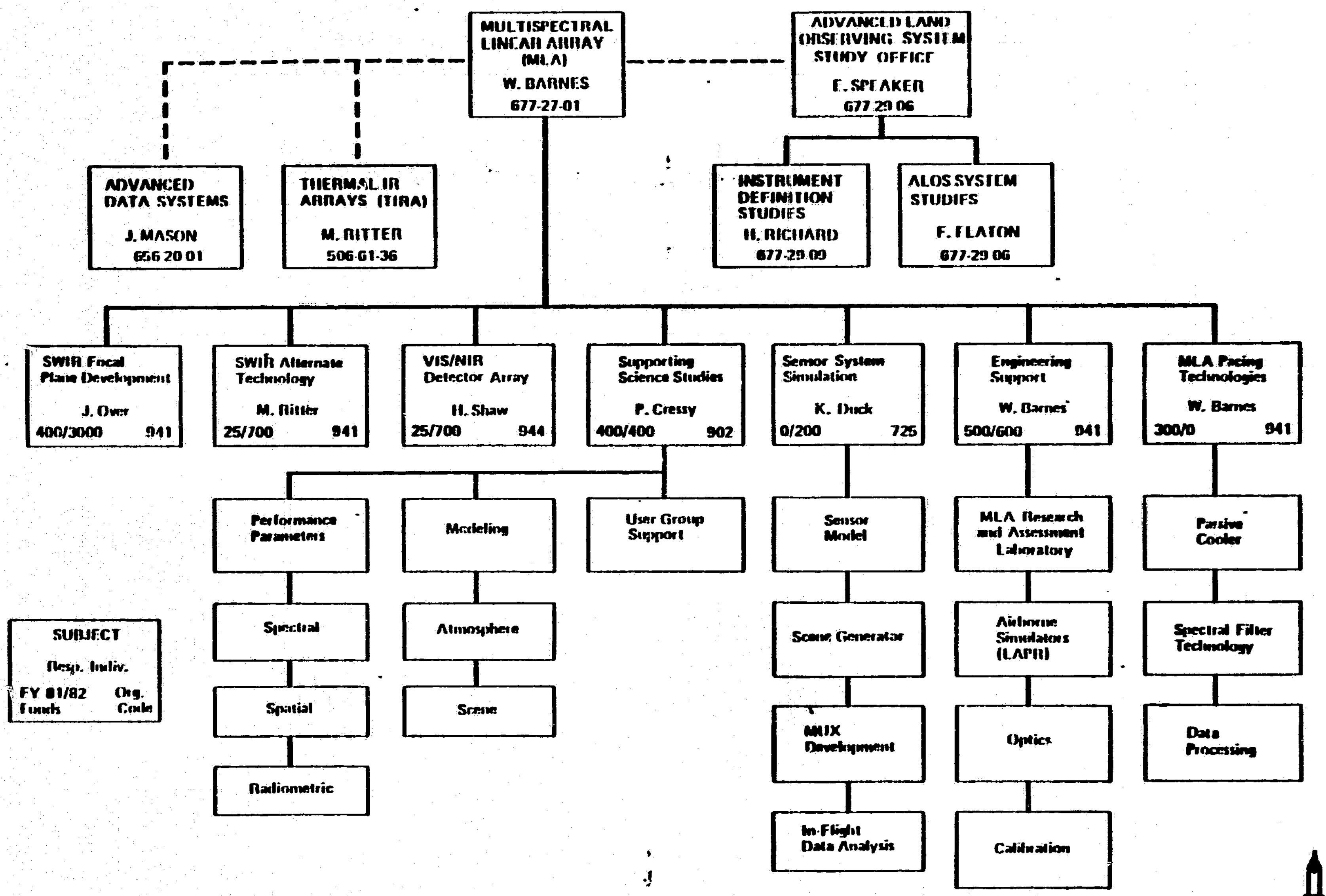
MULTISPECTRAL LINEAR ARRAY PROGRAM



HYBRID SWIR TECHNOLOGY DEVELOPMENT

OBJECTIVE:

TO DEVELOP AND DEMONSTRATE A SWIR FOCAL PLANE DETECTOR/ MULTIPLEXER ARRAY.

APPROACH:

- TWO PARALLEL 42-MONTH CONTRACTS ($4.5M EACH); TO DEVELOP A HYBRID HgCdTe DEVICE.
- PHASE I—DEVELOP 256-ELEMENT MODULE AND 5-MODULE TEST ASSEMBLY.
- PHASE II—DESIGN, FABRICATE AND TEST 6200-ELEMENT FOCAL PLANE ASSEMBLY.

STATUS:

- PROCUREMENT PACKAGE COMPLETE.
- RFP RELEASE .... 2/82.
- CONTRACTS .... 1/83.

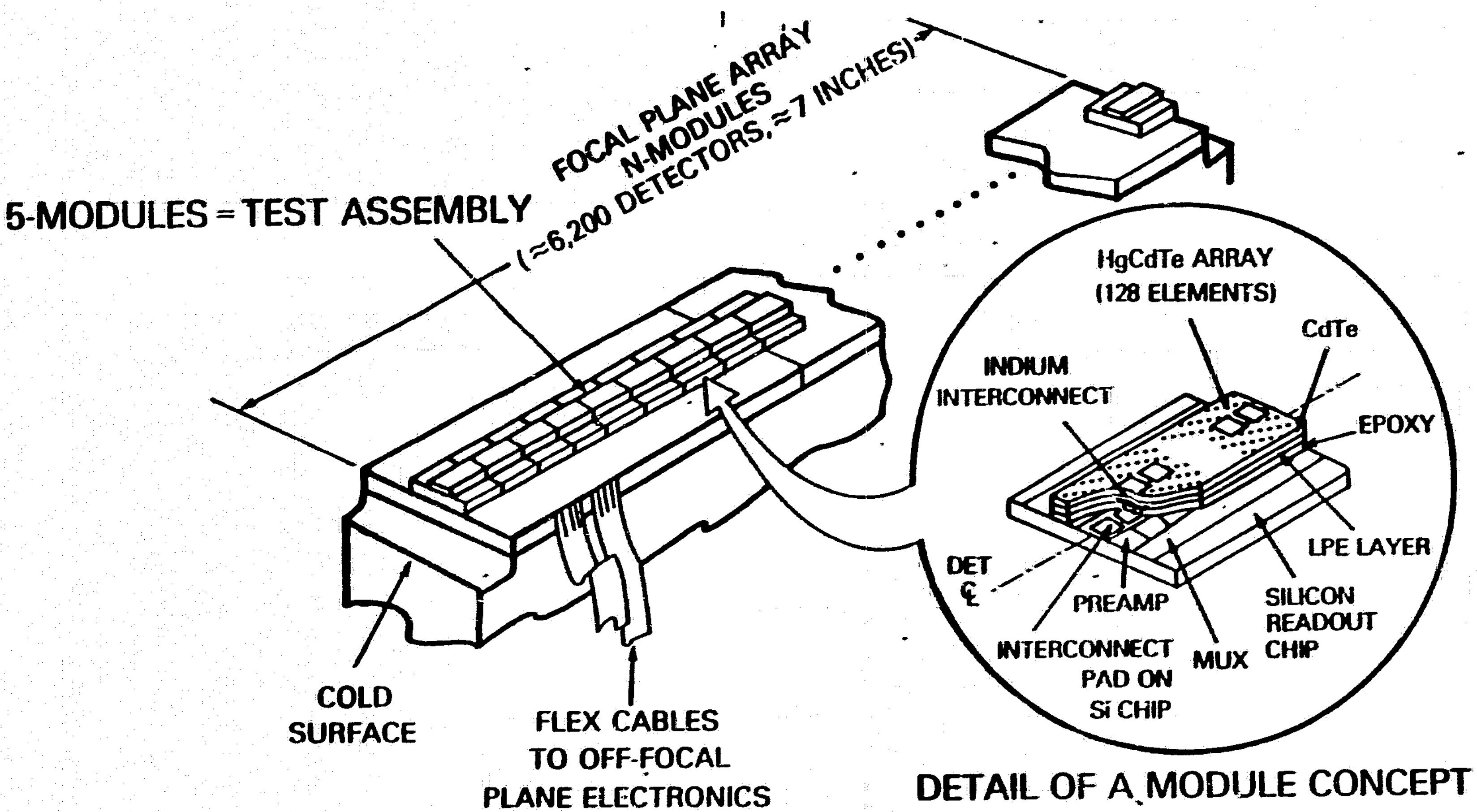
SWIR FPA

KEY CHARACTERISTICS

● SPECTRAL REGION	1.1 TO 2.4 μM
● BANDS	1.2, 1.6, 2.2 μM, <10% BW
● DETECTOR SIZE	30 μM PITCH
● ARRAY	≈6200 DETECTORS
● BLEMISHES	LESS THAN 1%, INCLUDING BUTTS
● SIGNAL-TO-NOISE	100 P-P/RMS AT WORKING LEVEL IRRAD
● STABLE	LESS THAN 1% DRIFT IN 25 SEC
● UNIFORM	LESS THAN 10% STANDARD DEVIATION
● MULTIPLEXING	FIRST LEVEL ON FOCAL PLANE
● OPERATING TEMPERATURE	130K OR WARMER
● HEAT LOAD	40 μW PER DETECTOR

- — RELIABLE
- — TESTABLE
- — REPAIRABLE
- — AFFORDABLE
- — TIMELY

A CONCEPT HYBRID SWIR ARRAY



DETAIL OF A MODULE CONCEPT
(100 TO 500 DETECTORS)

MONOLITHIC SWIR TECHNOLOGY DEVELOPMENT

OBJECTIVE:

TO DEVELOP AND DEMONSTRATE A MONOLITHIC SCHOTTKY BARRIER DETECTOR/MULTIPLEXER MODULE AS A BACK-UP TO THE HgCdTe DEVELOPMENT.

APPROACH:

- 24-MONTH $1M CONTRACT TO DEVELOP AND TEST PdSi/Si MONOLITHIC DEVICE.
- DEVELOP MODULES AND 5-MODULE TEST ASSEMBLY.

STATUS:

- RFP RELEASE .... 11/81.
- PROPOSALS DUE .... 1/18/82.
- CONTRACT AWARD .... 7/82.

GSFC

ALTERNATE SWIR MODULE DEVELOPMENT

PURPOSE:

— BACK-UP TO HgCdTe DEVELOPMENT

LEADING ALTERNATE CANDIDATE:

— SCHOTTKY BARRIER PdSi/Si

ADVANTAGES:

- VERY HIGH UNIFORMITY
- HIGH DETECTOR DENSITIES POSSIBLE
- MONOLITHIC SILICON CONSTRUCTION

DISADVANTAGES:

- LOW QUANTUM EFFICIENCY
- TECHNOLOGY NOT WELL DEVELOPED

KEY CHARCTERISTICS

— SAME AS FOR PRIMARY DEVELOPMENT (EXCEPT ARRAY SIZE AND OPERATING TEMPERATURE)

SCOPE (1 EFFORT):

— DESIGN AND PERFORMANCE TRADES STUDY

— MATERIAL DEVELOPMENT

— CHIP DESIGN

— FABRICATE 5 MODULES (FLAT PLANE)

— PROVIDE SUPPORT ELECTRONICS, BENCH TEST, CALIBRATION AND TARGET SIMULATOR EQUIPMENTS

— VALIDATE MODULE PERFORMANCE

— GENERATE CALIBRATED TEST IMAGERY

VIS/NIR DETECTOR ARRAYS

OBJECTIVE:

DEVELOP A VIS/NIR DETECTOR ARRAY DEVICE THAT WILL SERVE AS THE BASIC UNIT FOR A MLA FOCAL PLANE.

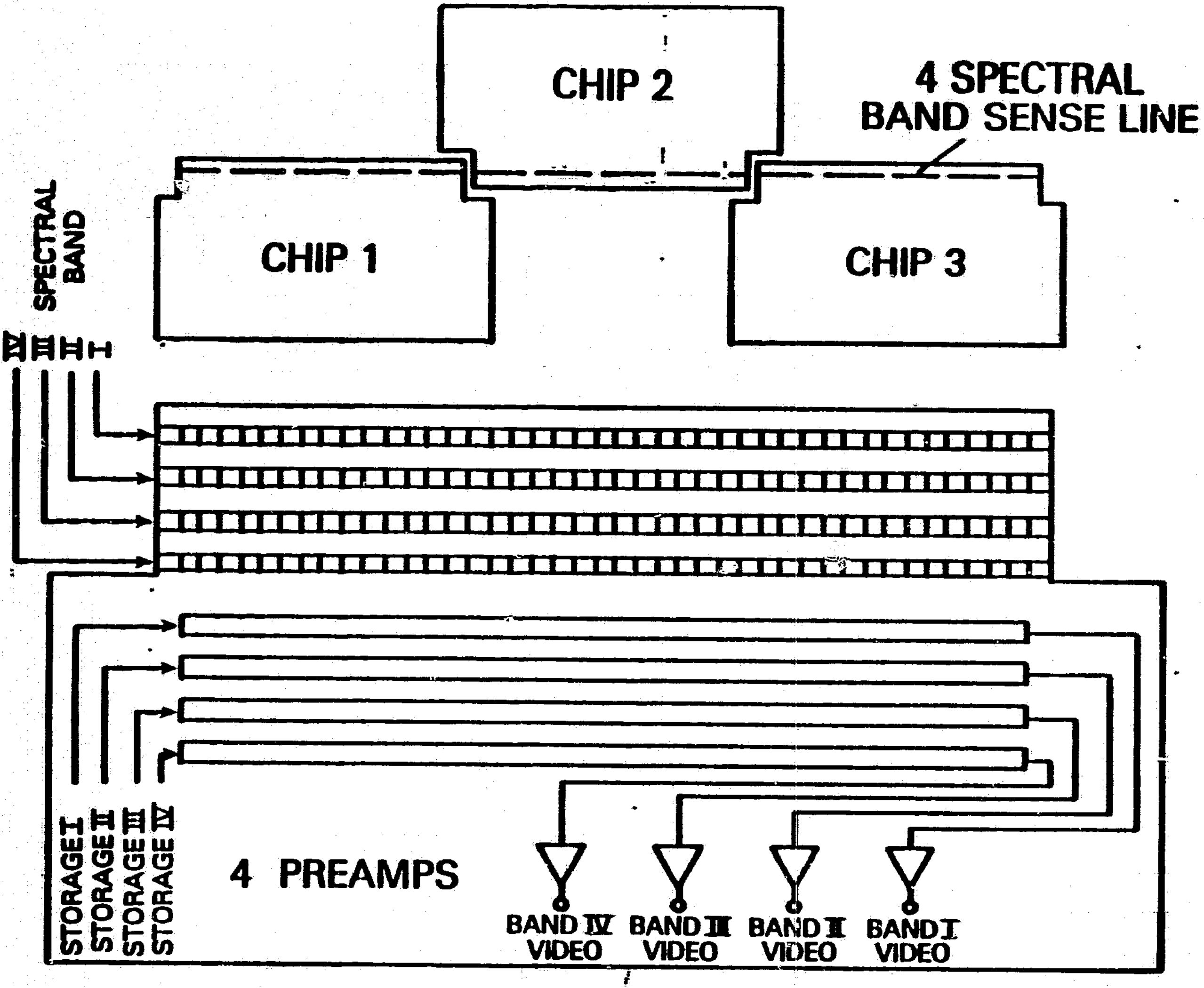
APPROACH:

- 24-MONTH $1M CONTRACT TO DEVELOP A SILICON DETECTOR ARRAY DEVICE.
- EACH CHIP—FOUR 1024-ELEMENT DETECTOR ARRAYS, FOUR SPECTRAL FILTERS AND ASSOCIATED ELECTRONICS.
- DEMONSTRATE BUTTABILITY.

STATUS:

- PROPOSALS DUE 2/8/81
- CONTRACT AWARD 7/82

CONCEPTUAL VIS/NIR DETECTOR ARRAY



4 SPECTRAL BANDS PER CHIP WITH SPECTRAL FILTERS
1024 ELEMENTS PER BAND (NOMINAL)
DETECTOR SPACING 15 μm
< 2 MISSING ELEMENTS/BUTT JOINT

OPTICS DESIGN AND FABRICATION

OBJECTIVE:

DESIGN, FABRICATE AND TEST CRITICAL OPTICAL COMPONENTS REQUIRED FOR MLA SENSOR.

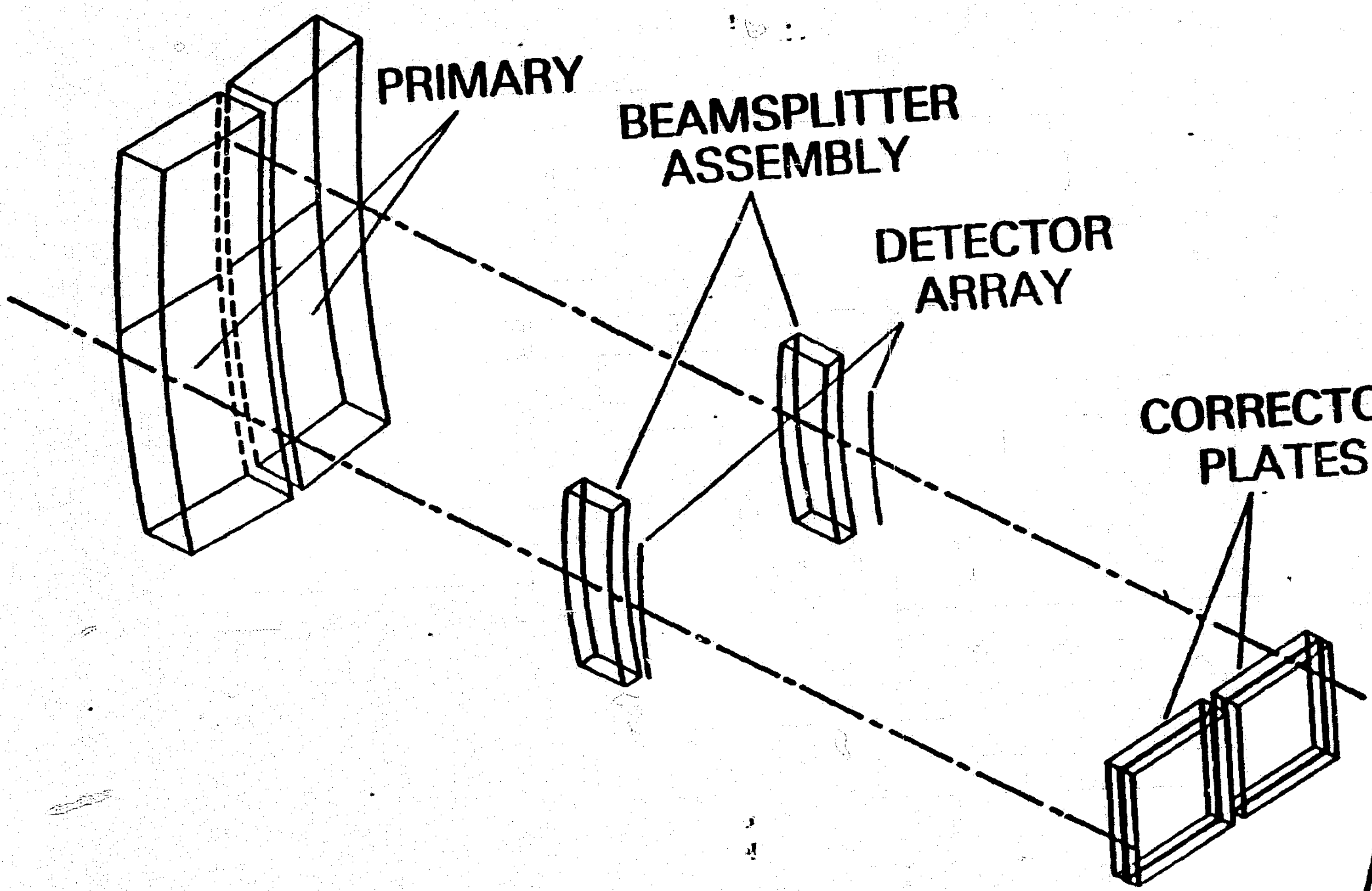
APPROACH:

- NINE-MONTH $100K STRIPED FILTER DEVELOPMENT AND EVALUATION.
- FOUR-MONTH $45K STUDY OF MLA DICHROIC BEAM-SPLITTERS.
- IN-HOUSE ASSESSMENT OF IDS OPTICAL SYSTEM DESIGNS AND DEVELOPMENT OF GSFC DESIGN.

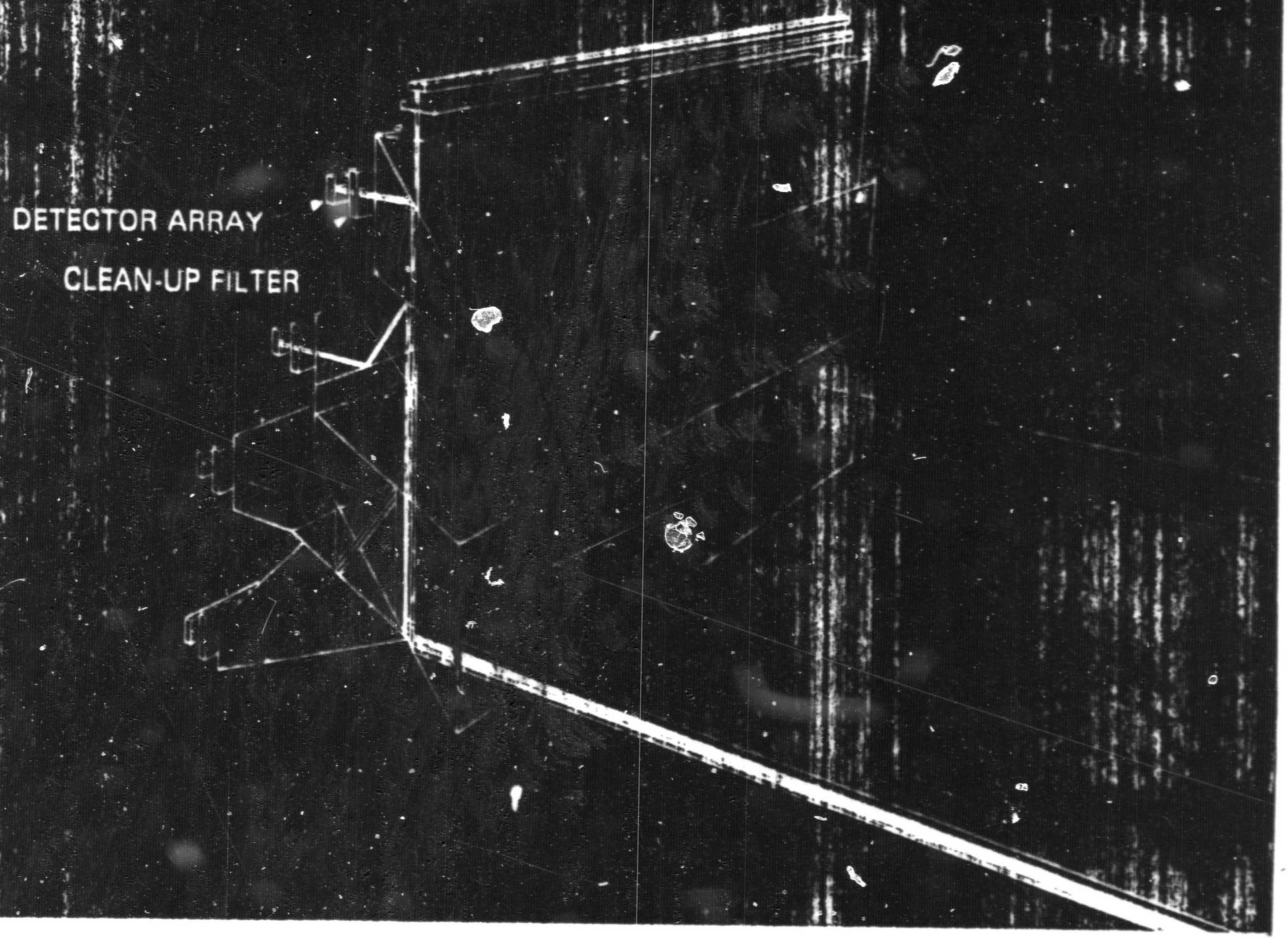
STATUS:

- STRIPED FILTER CONTRACT/WESTINGHOUSE .... COMPLETE 2/82
- DICHROIC FILTER STUDY/PERKIN-ELMER .... COMPLETE 9/81

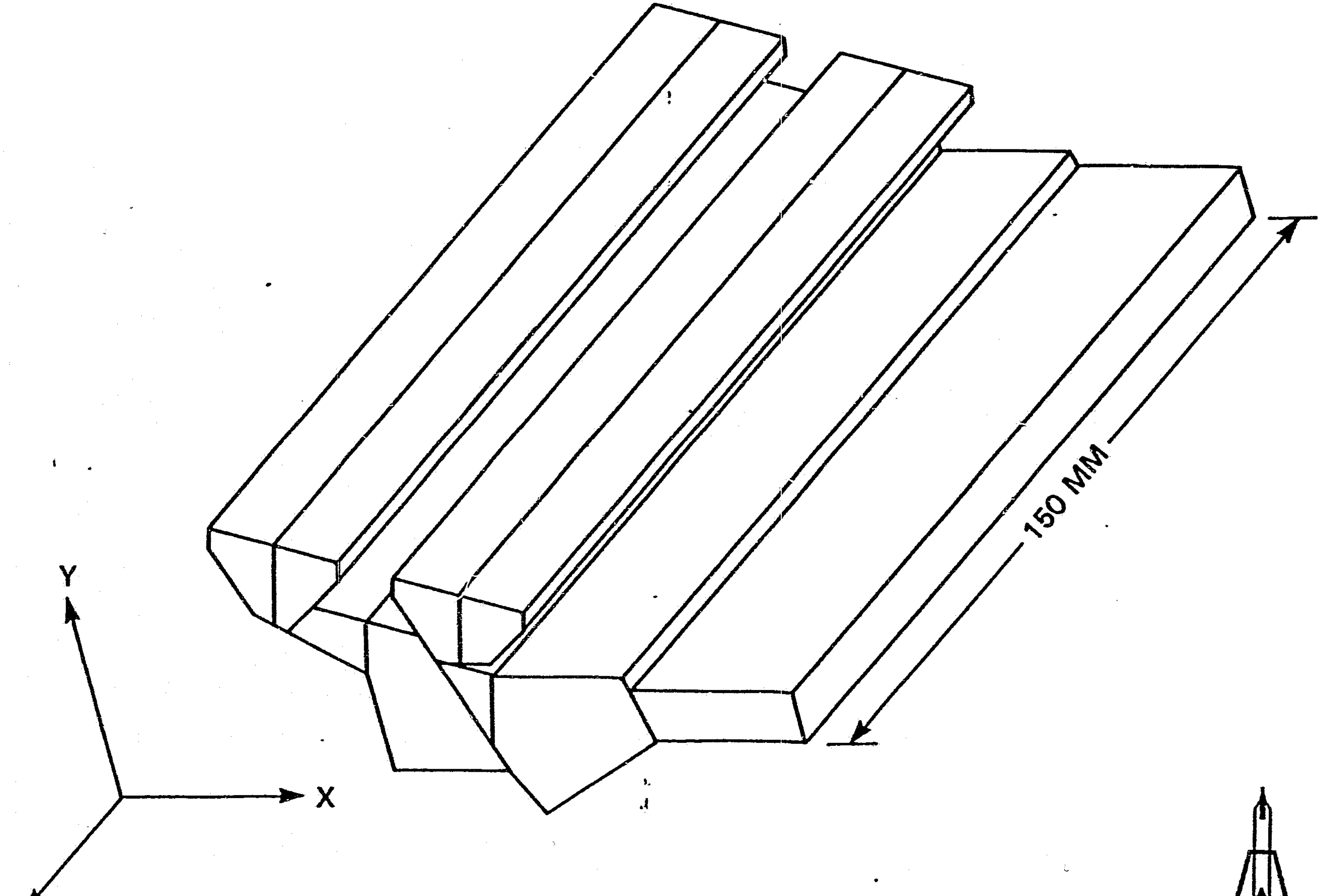
DUAL OFF - AXIS SCHMIDT



SPECTRAL SEPARATION TECHNIQUE
DICHROIC PRISMS



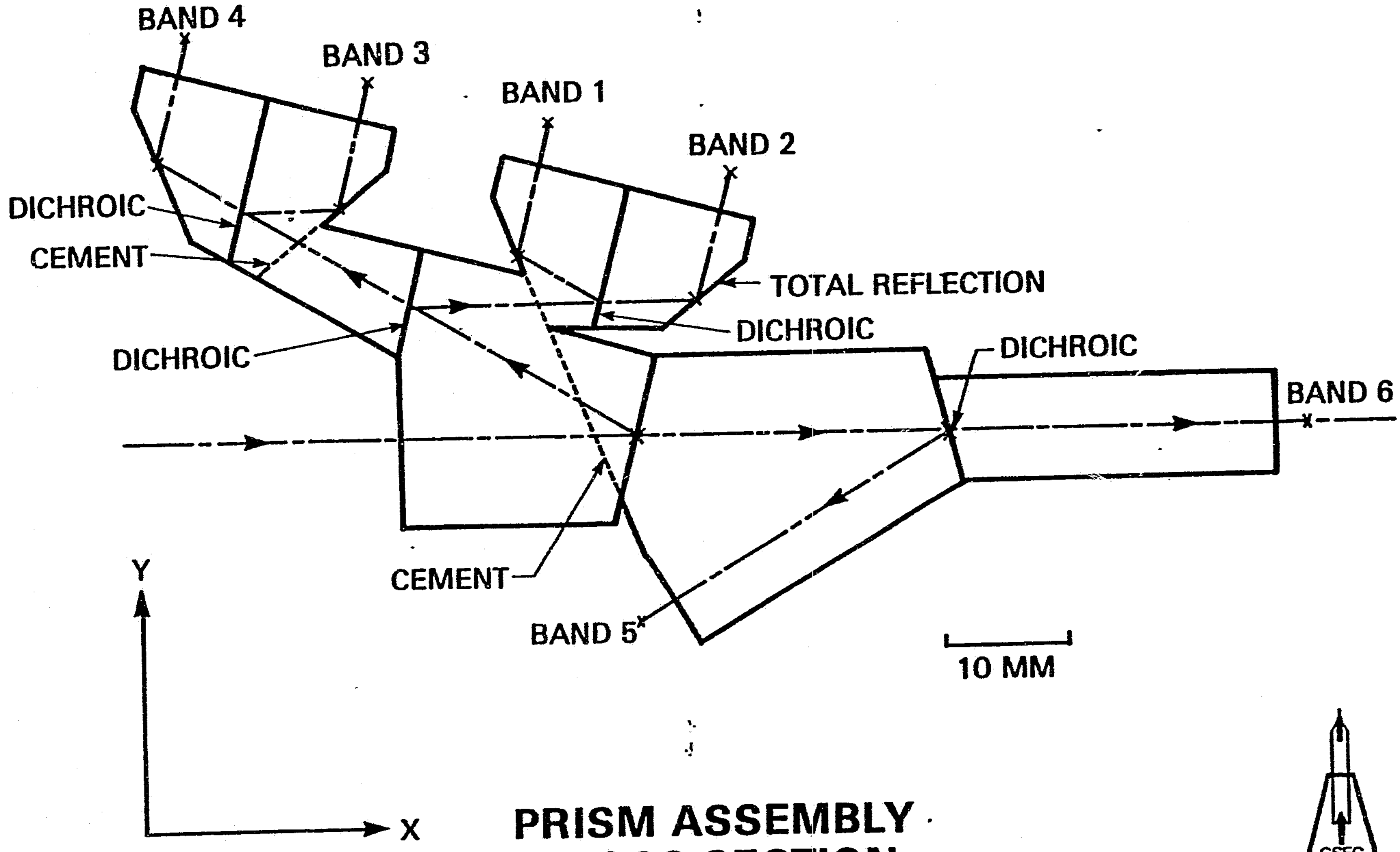
MLA BEAMSPLITTER DESIGN STUDY



PRISM ASSEMBLY

GSFC

MLA BEAMSPLITTER DESIGN STUDY



PRISM ASSEMBLY
CROSS SECTION

MLA BEAMSPLITTER DESIGN STUDY

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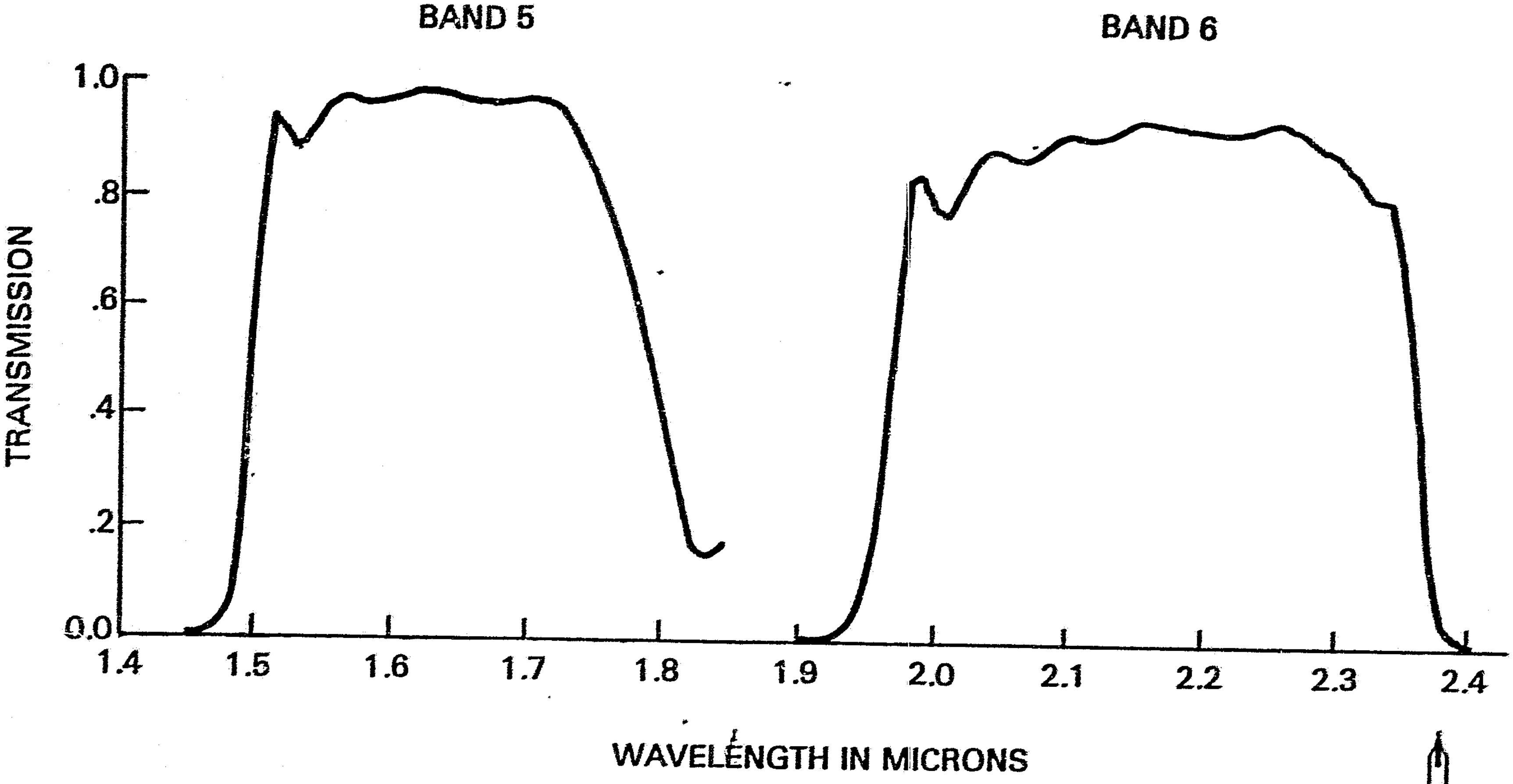
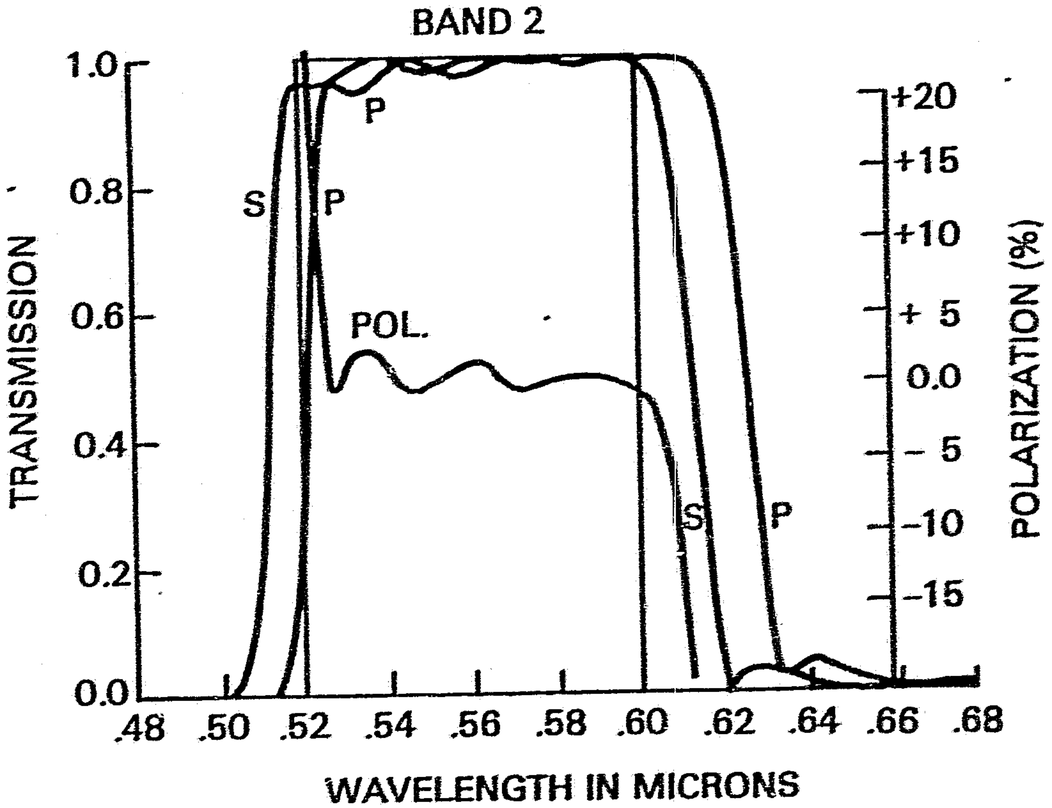


MLA BEAMSPLITTER DESIGN STUDY



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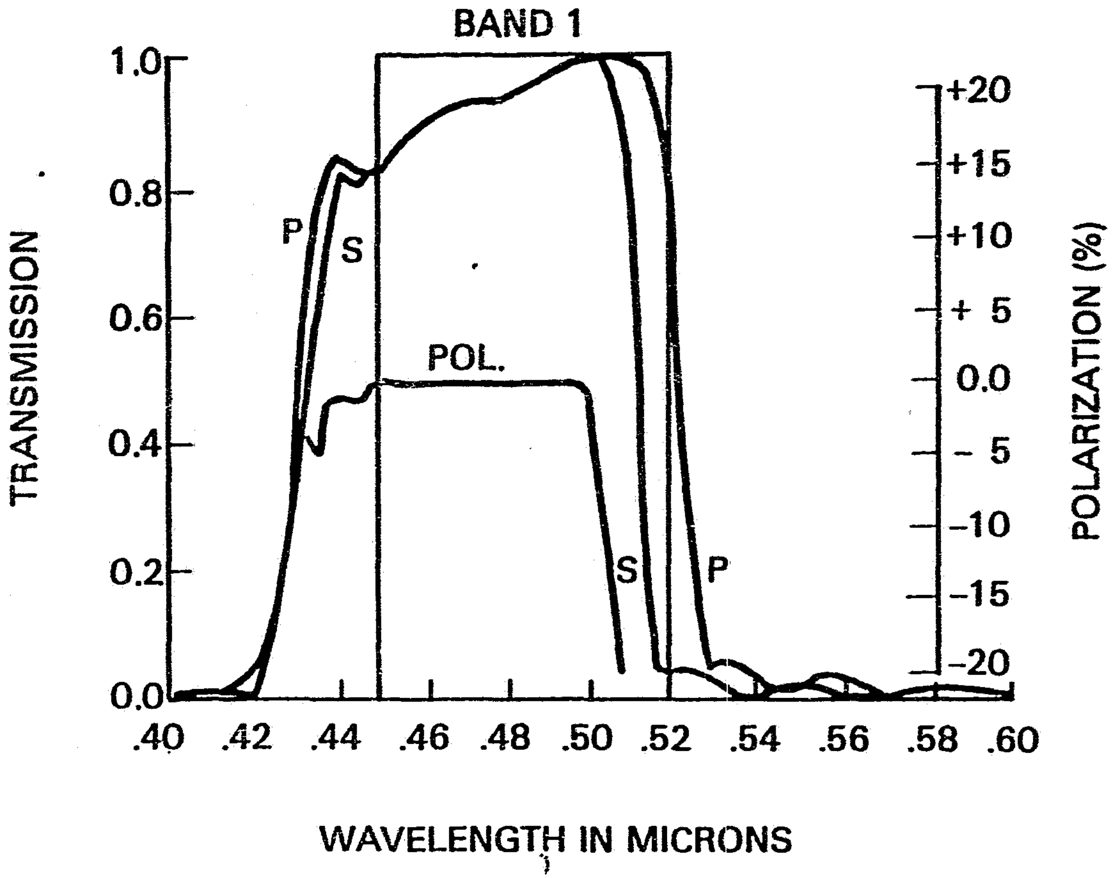
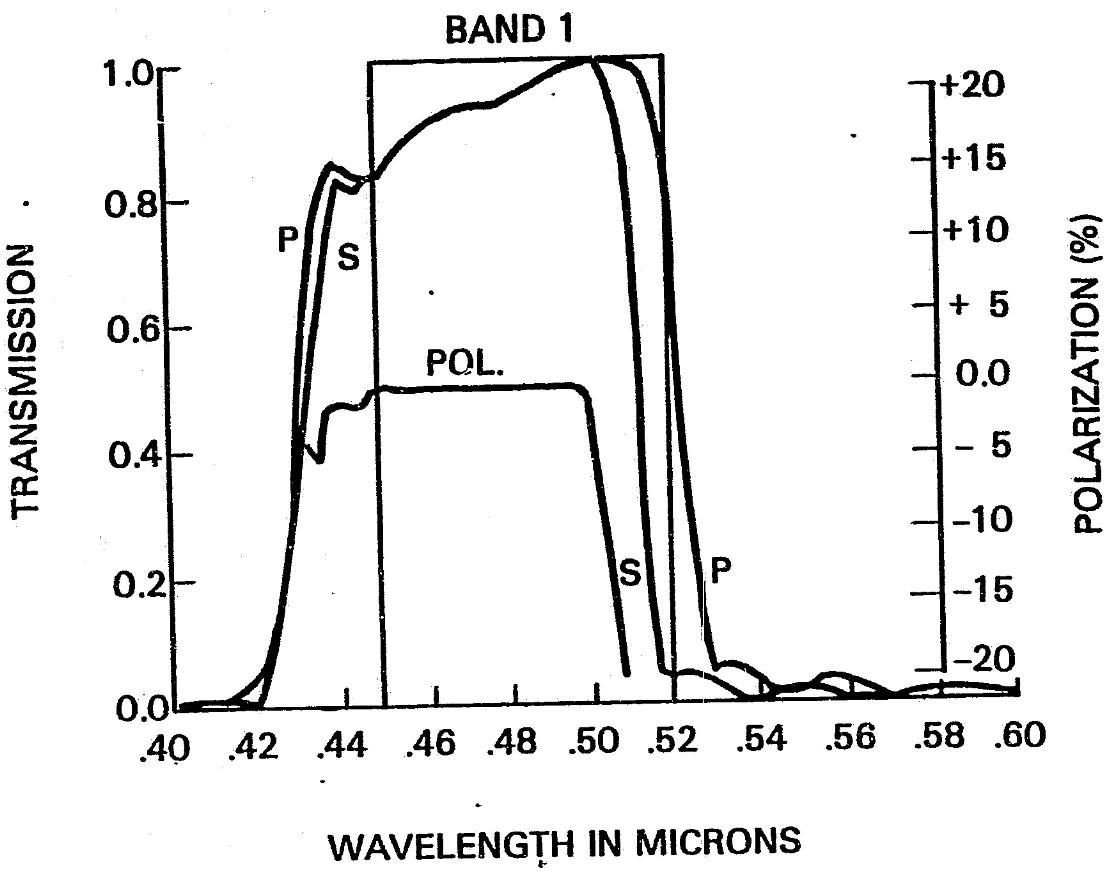
MLA BEAMSPLITTER DESIGN STUDY



MLA BEAMSPLITTER DESIGN STUDY



PASSIVE COOLER DESIGN

OBJECTIVE:

DEVELOP A DETAILED DESIGN FOR A PASSIVE RADIATIVE COOLER
THAT WILL FULFILL THE REQUIREMENTS GENERATED BY A MLA SENSOR.

APPROACH:

$100K CONTRACT FOR RADIATIVE COOLER DESIGN TO MEET IDS REQUIREMENTS

REQUIREMENTS:

1W ELECTRICAL DISSIPATION AT 125K.
400 SIGNAL LEADS.
50 CM HEAT TRANSFER DEVICE.

STATUS:

RFP RELEASE................11/81.
CONTRACT START............. 1/82.

TIRA PROGRAM OBJECTIVE

DEMONSTRATE 5-64 ELEMENT MODULES ARRAY, 10.0-12.0μm, 105K

PHASE I: DESIGN BASELINE MODULE AND ARRAY TO PROVIDE PROPER COUPLING OF PHOTODIODE, CCD'S THROUGH BIPOLAR AMPLIFIERS TO ACHIEVE REQUIRED D^*. ALSO REPLAN AND RECOST PHASE II

PHASE II: FABRICATION AND TEST

A. FABRICATE AND TEST A CHANNEL OF 1 OR 2 DETECTORS FOR GFSC REVIEW 14 MONTHS AFTER START OF PHASE II

B. FABRICATE SAMPLE MODULES

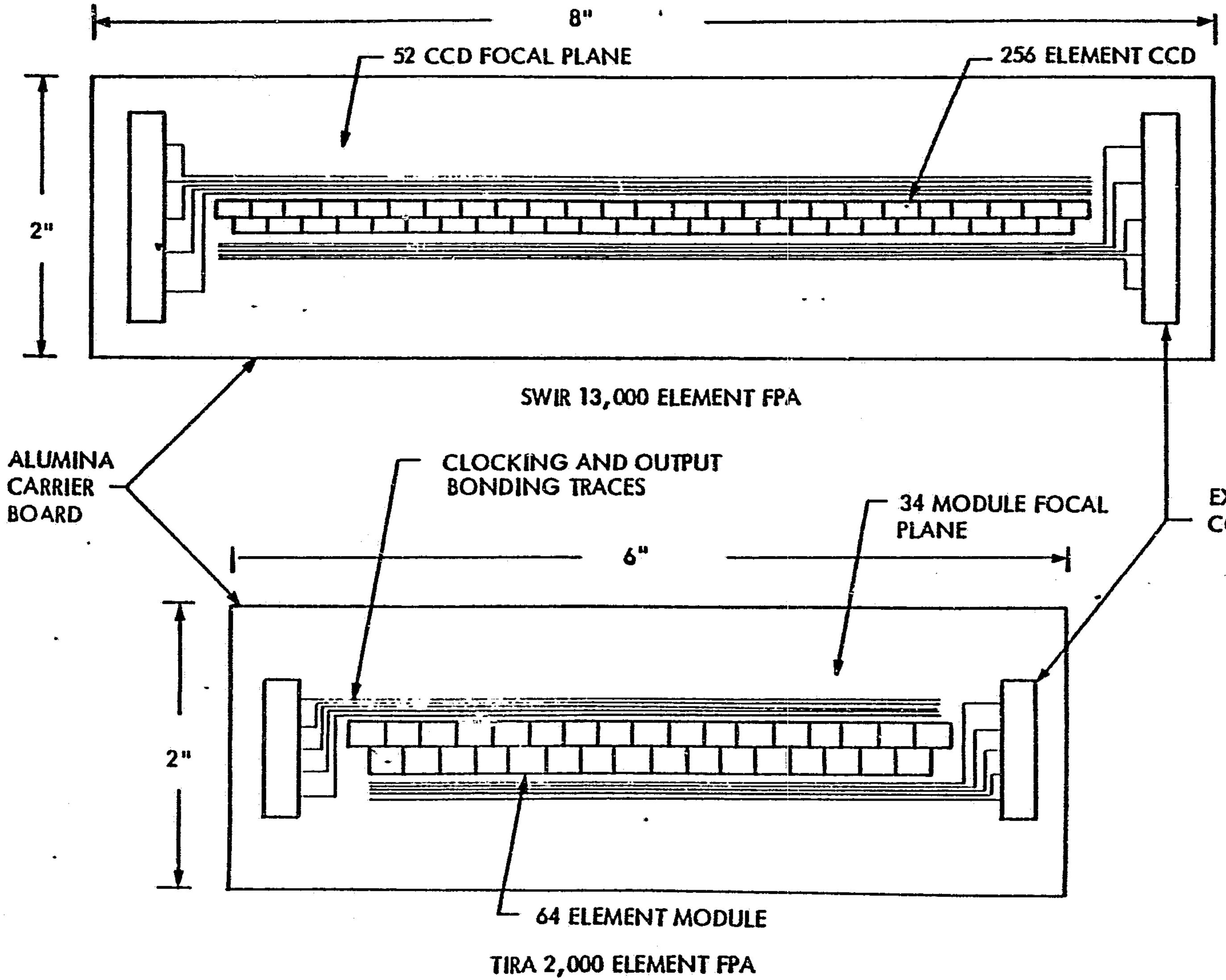
C. FABRICATE A 5 MOUDLE ARRAY

D. DEMONSTRATE ARRAY'S CAPABILITY TO PRODUCE IMAGERY

TIRA TECHNOLOGY DEVELOPMENTS

- TO ACHIEVE IMPROVE PHOTODIODE PERFORMANCE AT 105K;
- TO DESIGN AND FABRICATE A BIPOLAR BUFFER DEVICE WITH THE DESIRED LOW NOISE CHARACTERISTICS AT 105K;
- TO INTEGRATE AND INTERCONNECT THESE TWO DEVICES WITH A CCD IN A 1 x 64 MODULE;
- TO DESIGN AND PROVE A FOCAL PLANE CONFIGURATION WHICH WILL MINIMIZE CHANNEL OUTAGES;
- TO ASSEMBLE A FOCAL PLANE WITH MULTIPLE MODULES; AND
- TO DEMONSTRATE THE SUCCESS OF ALL THE ABOVE TECHNOLOGIES BY PRODUCING IMAGERY WITH THE TIRA TECHNOLOGY

SWIR AND TIRA FOCAL PLANES



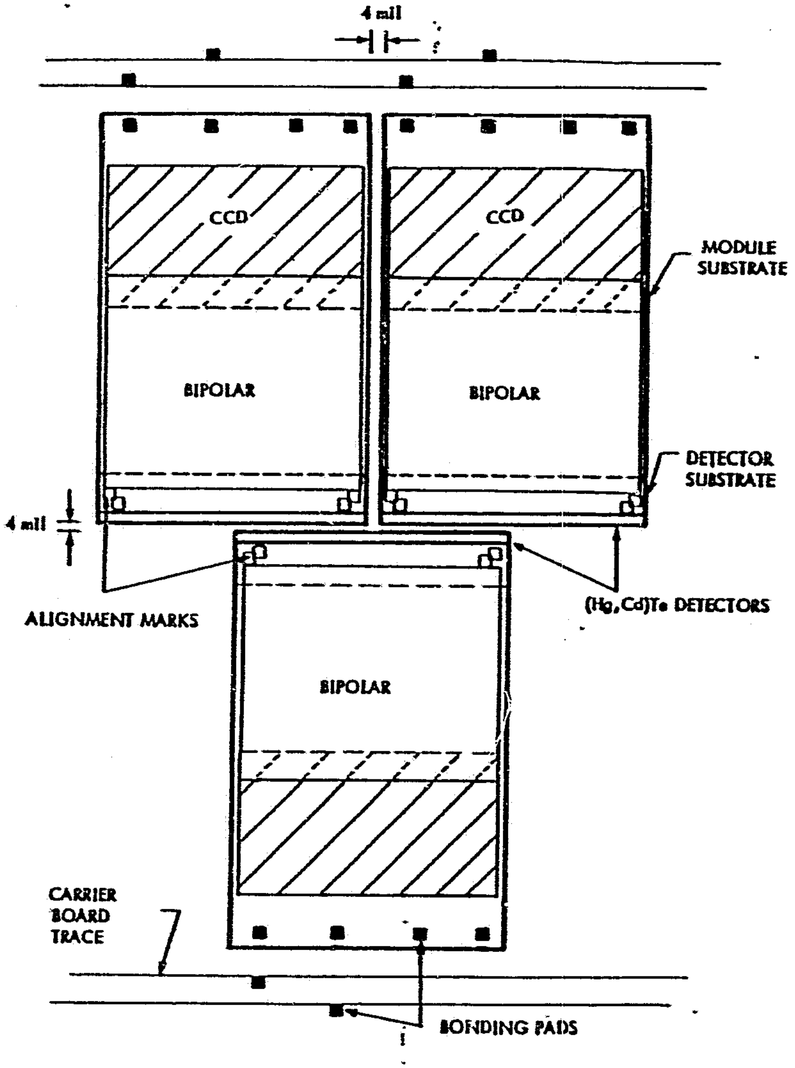
SWIR 13,000 ELEMENT FPA

TIRA 2,000 ELEMENT FPA

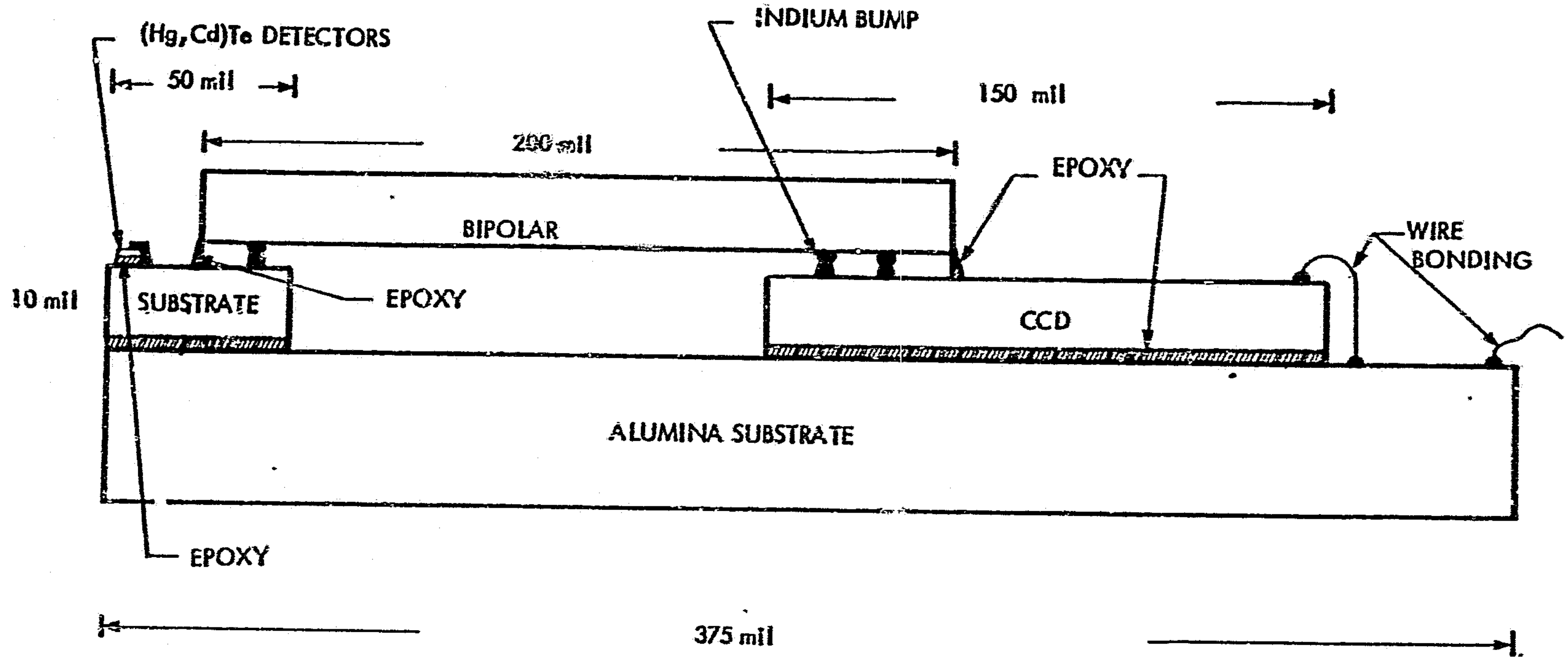
256
52
1512
1280
13,312

64
34
1256
192
2176

TIRA MODULE PLACEMENT



TIRA MODULE CONFIGURATION



HISTORY, STATUS AND FUTURE APPLICATIONS OF SPACEBORNE CRYOGENIC SYSTEMS

Allan Sherman

NASA Goddard Space Flight Center
Greenbelt, Maryland

Presented at the Cryogenic Engineering Conference, August 12, 1981

INTRODUCTION

There are increasing numbers of space instruments that require cryogenic cooling to accomplish their objectives. These include instruments for Earth observation, atmospheric science, gamma-ray and X-ray astronomy, infrared astronomy, space surveillance, and basic research. Potential future space applications for cryogenic cooling include instruments for high energy astronomy, radioastronomy, relativity measurements, and a variety of instruments and systems employing superconducting devices.

The elements of the instruments that may require cooling are the radiation detectors, optical components, baffles, or, in some cases, the whole instrument. Cryogenic cooling is necessary to provide the required detector response, reduce pre-amplifier noise, and/or reduce background radiation.

Table 1 shows an approximate breakdown of the cooling requirements for the various applications mentioned. To provide for these requirements, there are a variety of techniques available or under development. Table 2 lists the cooling techniques with approximate ranges of practical temperatures and refrigeration load.

The development of the spaceborne cryogenic systems presents a considerable engineering challenge. The objective of the discussion herein is to describe the systems' history, status, anticipated technology development and future applications.

RADIANT COOLERS

To date, the most widely used system for obtaining cryogenic temperatures aboard spacecraft have been radiant coolers. These devices were developed for cooling IR (1-25 μm) detectors for NASA Earth-observation instruments and as part of the Defense Meterological Satellite Program.[1]

As shown in Figure 1, a radiant cooler is usually comprised of two stages. The first consists of a cone with a highly reflective, specular inner surface and diffusely coated external radiator. The cone shields the patch (the detector stage) from the spacecraft and Earth or reflects shallow-angle sunlight out of the cooler before it reaches the patch. Mounting the patch to the first stage with low conductive supports further isolates it from the spacecraft. Without a need for shielding from the spacecraft, and with no sun input to the cooler, the first-stage cone can be eliminated (Figure 1 bottom). A deployable (or fixed) door attached to the mouth of the first stage can then block the patch view of the Earth.

A deployable door can also be used with a cone-type cooler to limit Earth input or to warm the cooler (door closed) periodically in orbit. The latter mode of operation would be employed for decontamination.

Typical operating temperatures for today's radiant coolers run about 90-100 K for the patch, and 160 K for the first stage, although a patch temperature of 71 K was attained by a Santa Barbara Research Corporation cooler aboard a meteorological satellite (SMS-1) in a geosynchronous orbit. The patches of radiant coolers have typical radiative capacity on the order of 30 mw, with the sensor heat dissipation but a fraction of the total. An exception is the Thematic Mapper cooler (Hughes Aircraft) that will fly on Landsat-D which has a sensor load of 85 mw. Typical patch and cone mouth-area values are 60 cm^2 and 1000 cm^2, respectively.

Radiant coolers offer a relatively simple, passive, low-weight technique for cooling sensors aboard spacecraft. Unfortunately, thus far they have been severely constrained with respect to temperature (>70 K), cooling load (milliwatts), placement on spacecraft, and spacecraft orbit.

The Air Force has funded a technology program to improve structural materials and assembly techniques with the objective of developing much larger radiant coolers with higher capacity.[2] As part of this program, Rockwell International has fabricated and tested a 9 m^2, two-stage radiant cooler (Figure 2). The cooler employs oxygen heat pipes to transport the energy from the source to the radiator and to isothermalize the second stage radiator plate. Later, a third stage was added to the system, and the cooler was tested again.

A large amount of the data for the advanced radiator has been obtained. As an example, for the two-stage cooler, a second stage temperature of 85 K and a first stage temperature of 148 K were obtained with cooling loads of 10 W and 20 W, respectively. For the three-stage radiator, with zero first stage load, third and second stage temperatures of 41 K and 84 K were obtained for loads of .2 W and 2 W, respectively. These results, however, must be interpreted very carefully. During the testing, there was no simulated Earth, sun or spacecraft loads, while the potential input from these sources are much greater than the measured heat rejection. Thus, to apply the results of this testing to a real situation, one must be sure to include all of the heat loads from the spacecraft and orbital conditions.

There is little doubt that radiant coolers will continue to be widely utilized in the future. However, regardless of the size of the system, the necessity to provide shielding and/or constraints on spacecraft orbit and orientation, in order to limit heat input, will continue to be a problem. From a practical viewpoint, their use will probably be limited to temperatures above 70 K with relatively low heat loads except, perhaps, in rather unique cases.

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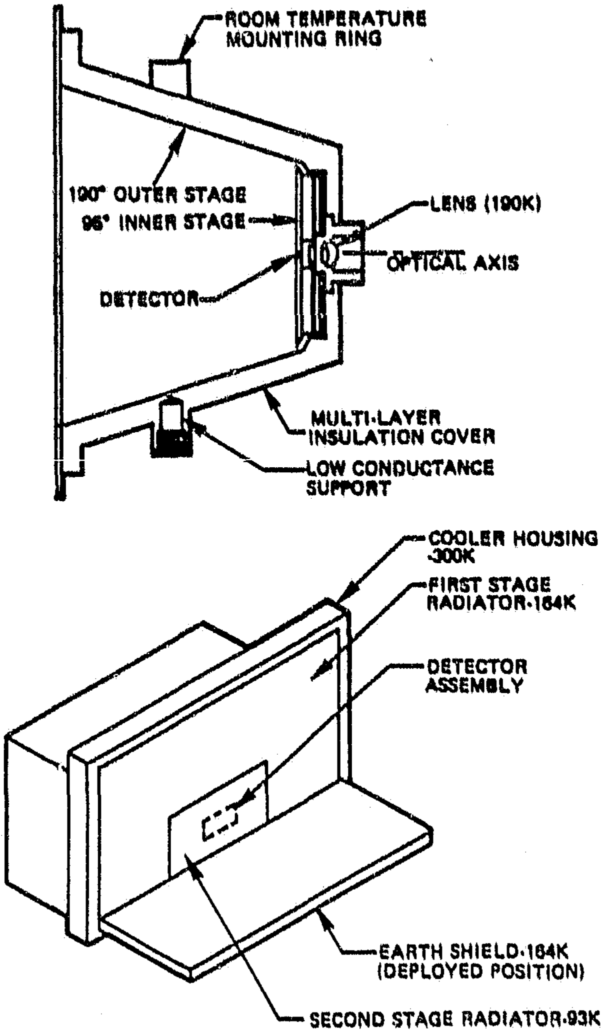

Figure 1. Radiant Coolers: A. D. Little (top), ITT (Bottom)

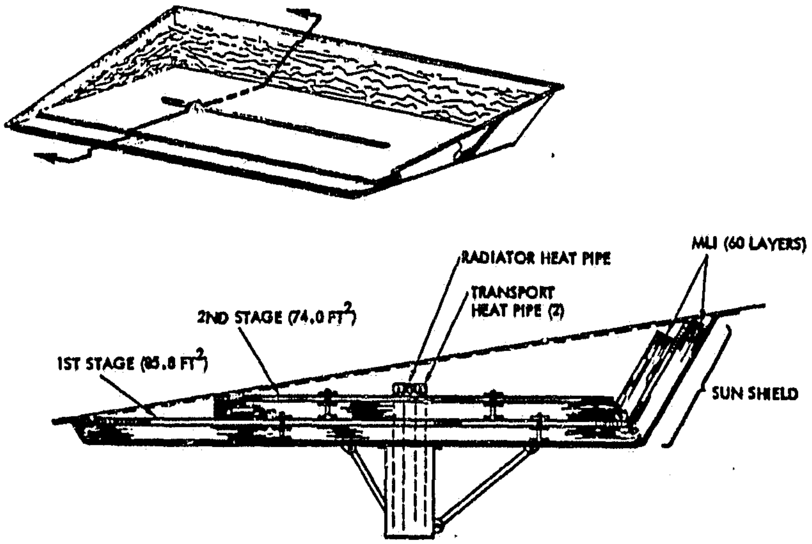

Figure 2. Advanced Radiator Design: Rockwell International

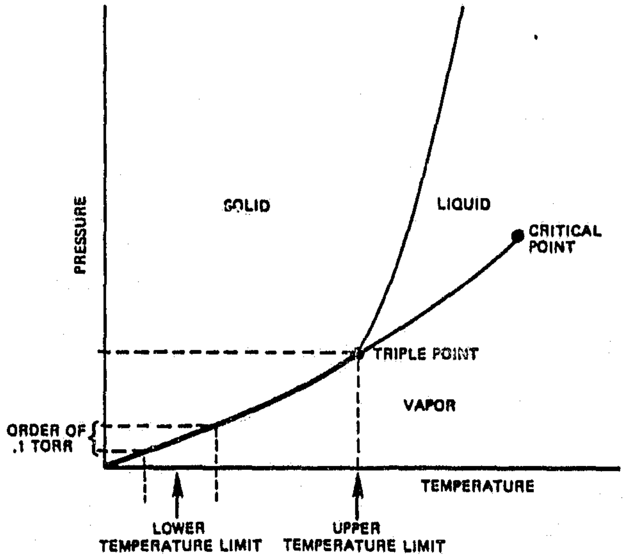

Figure 3. Solid Cryogen Cooler Operating Range

SOLID CRYOGEN COOLERS

Solid cryogen cooler systems utilize the cryogen's heat of sublimation to absorb the cooling load at constant temperature. As shown in Figure 3, the operating point of the cooler must be below the cryogen's triple point. The cooler's lower operating temperature will be limited by the pressure that can be maintained over the solid cryogen while still allowing enough of a potential for venting the effluents. This pressure, around .1 torr, is a function of vent lines and effluent mass flow.

For space applications, stored solid cryogen systems offer distinct advantages over stored liquid systems. Cryogens for this temperature range have heats of sublimation about 10-15 percent higher than their heats of vaporization. Also, the solid cryogen has a density 10-15 percent higher than the liquid, permitting a higher capacity cooler for a given volume. By proper design of fins or other heat exchange surfaces that penetrate and contain the solid cryogen, the phase separation in zero gravity is not a problem. Also, a solid cryogen eliminates possible sloshing problems that could affect the performance of a scanning or fine pointing spacecraft. Advantages of solid cryogen coolers over mechanical refrigerators are that they are vibration-free and require no spacecraft power. The advantages of solid cryogen systems over radiant coolers are that they are generally not limited by orbit, spacecraft orientation, or locations within the spacecraft.

Table 1. General Mission Categories Requiring Cryogenic Cooling in Space
(Values Approximate)

Discipline	Temp. Range, K	Refrigeration Load
Applications Missions (weather, atmospheric science, Earth resources pollution monitoring etc.)	10-100	Milliwatts to 10 W
Gamma-ray and X-ray Astronomy	80-125	Milliwatts to watts
Cosmic Ray Measurements	~4	Milliwatts
Space Surveillance (as published)	12-100	Wide Range
IR Astronomy	.3-5	Microwatts to 100 milliwatts
Relativity Measurements	~2	Microwatts to milliwatts
Superconducting Devices	1-10	Wide Range
Basic Research Experiments	1-10	100 Milliwatts

Table 2. Spacecraft Cryogenic Cooling Techniques

Cooling Technique	Temp. Range,[a] K	Usable Refrigeration Load for One Year Mission[b]
Radiant Coolers	70-100	0-90 mw to date; higher capacity possible in future
Stored Solid Cryogen Coolers	10-125	0-800 mw[b] plus vent gas cooling
Stored Liquid-Helium Coolers	1.5-5.2	0-100 mw[b]
Mechanical Coolers	4-100	0-300 w
He^3 Coolers	.3	0-100 μw
Adiabatic Demagnetization Refrigeration	.001-.3	0-100 μw
Higher Temp. Adsorption and magnetic Systems	not yet defined; possibly wide range.	

[a] These values are not theoretical limits, but are estimates of temperatures and loads based on the designs as they appear to be evolving.

[b] For missions of shorter duration (e.g., 7-30 day Shuttle sortie), higher cooling loads could be accommodated.

Table 3 lists possible cryogens which could be used in solid cryogen coolers. Listed are operating temperature ranges defined by the triple point at the high end and the somewhat arbitrary .1 torr venting limit at the low end. For comparison purposes, the heat of vaporization of helium is also shown. The table shows the advantage of utilizing a two-stage cooler in which a higher temperature cryogen, such as ammonia, cools an intermediate thermal shield guarding a lower temperature cryogen. The advantages of using solid hydrogen as compared to liquid helium for 10 K cooling is also apparent.

An example of a flight cooler design is shown in Figure 4. This two-stage methane/ammonia cooler successfully flew on the High Energy Astronomical Observatory (HEAO-B and HEAO-C) spacecraft. It was developed by the Ball Aerospace Systems Division, had a loaded weight of 75 Kg and measured 76 cm long by 56 m in diameter. The cooler has tubes attached to the cryogen tank walls to flow LN_2 (77 K) during the cryogen fill operation. After the final servicing before flight, the cryogens gradually warm up until the vent seal is opened in orbit. The cryogens then vent to space while drifting down to steady-state temperatures. Heat exchange surfaces are located in both the primary and secondary tanks to promote even heat absorption by the cryogen.

To date, six solid cryogen coolers have been placed in orbit aboard spacecraft, and one will be launched in the near future. A summary of the basic design parameters and performance of the coolers is in Table 4.

Solid cryogen coolers do not have the inherent boundary constraints of radiant coolers, although it is always advantageous to have the outer shell operate as low in temperature as possible. Compared to a mechanical cooler, the solid cryogen system has the advantage of eliminating possible vibration and microphonics problems. The prime disadvantage of a solid cooler is that its weight and volume increase rapidly with cooling load and lifetime requirements. Other disadvantages include the need for bulky ground support equipment and a relatively high cost.

Areas where technology studies could improve performance are in the design of the multilayer insulation and, perhaps, in controlling internal contamination. Thus far, the coolers have not performed as well as originally anticipated. Although little technology development is underway in these areas, an important study on the characteristics of a solid hydrogen cooler has been completed.[3] In this study, the fill and vent of a solid hydrogen cooler was demonstrated and a detailed safety analysis was performed. As an add-on to this effort, a para-to-ortho hydrogen catalytic converter to greatly improve effluent gas cooling is being developed. Solid hydrogen has now been proposed as the cooling system for two instruments for the Upper Atmospheric Research Satellite (UARS).

In the future, there is no doubt that solid cryogen coolers will continue to find widespread use. Efforts to reduce their cost for short-term Shuttle flights are already underway. For free-flyer satellites, the established coolers, as well as solid hydrogen, will be employed. However, for long-duration and/or high cooling load flights, it is clear that a closed cycle cooling system will be required.

Table 3. Candidate Cryogens for Solid Cryogen Coolers

Cryogen	Temperature Range* (°K)	Approximate Volumetric Heat of Sublimation** cal/cc	Approximate Weight Heat of Sublimation** cal/gm
Hydrogen	13.8-8.3	9.7	108
Neon	24.5-13.5	36.4	25.1
Nitrogen	63.1-43.4	59	60.2
Carbon Monoxide	68.1-45.5	75.1	72.2
Argon	83.9-47.8	78.3	48.3
Methane	90.7-59.8	73.5	147
Nitrogen Oxide	110-78.1	174.3	129.1
Ethylene	104-95	123.5	169.2
Carbon Dioxide	217.5-125	246.7	145.1
Ammonia	195.4-150	315.9	432.7
Liquid Helium (For Comparison)	1.5-5.2	.8	5.5

*Lower temperature corresponds to .1 torr
**Values at lower temperature point

Table 4. Flight Solid Cryogen Coolers

Cooler Identification	Cryogens	Total Loaded Weight (Kg)	Length (cm)	Diameter (cm)	Low Temp. (°K)	High Temp. (°K)	Low Temp. Stage Inst. Load (mw)	High Temp. Stage Inst. Load (mw)	Orbit Lifetime
DOD/Lockheed SESP 72-2 (Two launched on same spacecraft in 1972)	carbon dioxide	21.9	35.6	40.6	126	Single Stage Cooler	230	Single Stage Cooler	8 mo. (1 Unit) 7 mo. (second unit)
NASA/Lockheed LRIR Inst. on NIMBUS-F; Launched in 1975	methane/ ammonia	24.1	62.2	33	65	152	52	91	7 mo.
NASA/Lockheed LIMS Inst. on NIMBUS-G; Same cooler as LRIR; Launched in 1978	methane/ ammonia	24.1	62.2	33	65	152	52	91	7 mo.
NASA/Ball HEAO-B launched in 1978	methane/ ammonia	75	81	56	80	150	200*	200	11 mo.
NASA/Ball HEAO-C launched in 1979	methane/ ammonia	75	81	56	80	150	359	367	8 mo.
Teal Ruby to be launched in 1983; performance numbers are estimates	neon/ methane	159	123	80	<16.8	75	38	252	17 mo.**

*Does not include heater cycling for decontamination

**Projected with radiant-cooled 150 K outer shell

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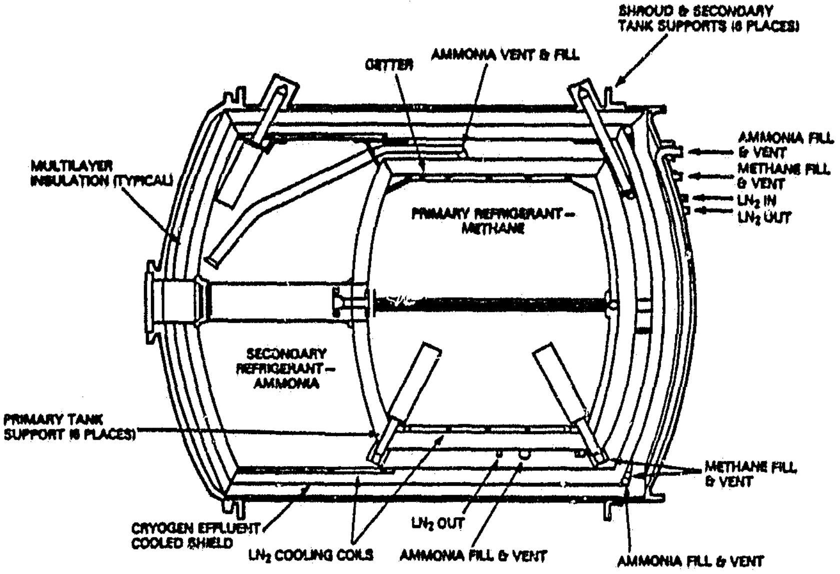

Figure 4. HEAO B and C Solid Cryogen Cooler: Ball Aerospace Systems Division

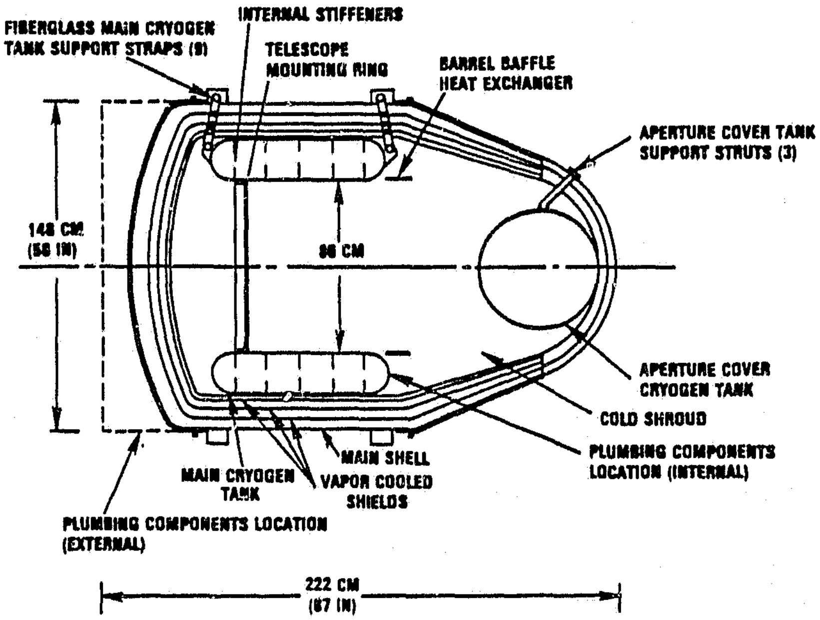

Figure 5. IRAS Dewar System: Ball Aerospace Systems Division

LIQUID HELIUM SYSTEMS

A new adventure in space cryogenic cooling systems is the development of liquid helium systems. These systems, which cover the 1.6 K-4.2 K temperature range, will find wide application.

Thus far, the United States has not orbited a liquid helium system. Reference 4 reports the successful flights of 1.8 liter and 10 liter normal helium cryostats aboard the Soviet "COSMOS" series of spacecraft. The Soviet Union also reports of the successful flight of a helium liquifier aboard Salyut-6.[5]

There are numerous NASA liquid helium space cooling systems under development for flights in the near future. These include long duration, superfluid helium dewars for the Infrared Astronomical Satellite (IRAS)* and NASA's Cosmic Background Explorer (Cobe) missions, and shorter duration systems for the Small Helium-Cooled Infrared Telescope and the Superfluid Properties Experiment.

A schematic of the IRAS cryogenic system (described in detail in Reference 6) is shown in Figure 5. The 1.8 K superfluid helium is contained in a toroidal shaped, 5083 aluminum main cryogen tank. The infrared telescope system fits into the center of the toroid and is mounted to the telescope mounting ring. Structural support is achieved through nine fiberglass/epoxy bands which terminate at the main shell. Additional thermal protection is provided by three vapor-cooled shields and multilayer insulation in the vacuum space. The main shell will operate at 170 K via radiant cooling in orbit to further reduce heat leaks to the main cryogen tank. Liquid-to-vapor phase separation in zero gravity is accomplished by a porous plug located at the main cryogen tank/helium vent line junction. A supercritical helium tank is employed to cool the main dewar cover, which is jettisoned during the initial stages after achieving orbit. From ground test data and mathematical modeling, the operational orbital lifetime for the IRAS dewar is predicted to be 10 months.

The IRAS cryogenic system has completed performance and space qualification testing at the Ball Aerospace Systems Division. It is presently in the Netherlands where it is being integrated with the spacecraft, after which it will be shipped back to the United States. The planned launch date is August 1982.

The Cosmic Background Explorer mission will use the basic IRAS dewar, with some modifications. These include deletion of the aperture cover tank, additional support straps for Shuttle launch (vs Delta for IRAS), and improved valves. The contract for the dewar should be issued to the Ball Aerospace Systems Division in 1982. The launch date for the satellite is in 1987.

A schematic of the Small Infrared Telescope system, which will fly on a 7 day Shuttle mission, is shown in Figure 6. Details of this complex system are in Reference 6. The system is comprised of a 250 liter dewar, a helium transfer assembly, and a cryostat surrounding the telescope. By utilizing a vacuum sealed rotary joint, the telescope can scan in one axis while the dewar remains stationary. The porous plug phase separator is located in the transfer assembly and, thus, only gas is delivered to the cryostat assembly. The helium in the dewar is maintained at 1.6 K while temperature requirements for the cryostat vary from 2.5 K at the detectors to 60 K at the upper telescope sections. During ground hold, a pump located on the Shuttle Pallet will maintain the helium in the superfluid state. The pump will be shut off prior to launch, but will fly with the Shuttle. The dewar and cryostat

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*Joint U.S., Netherlands, U.K. Project.

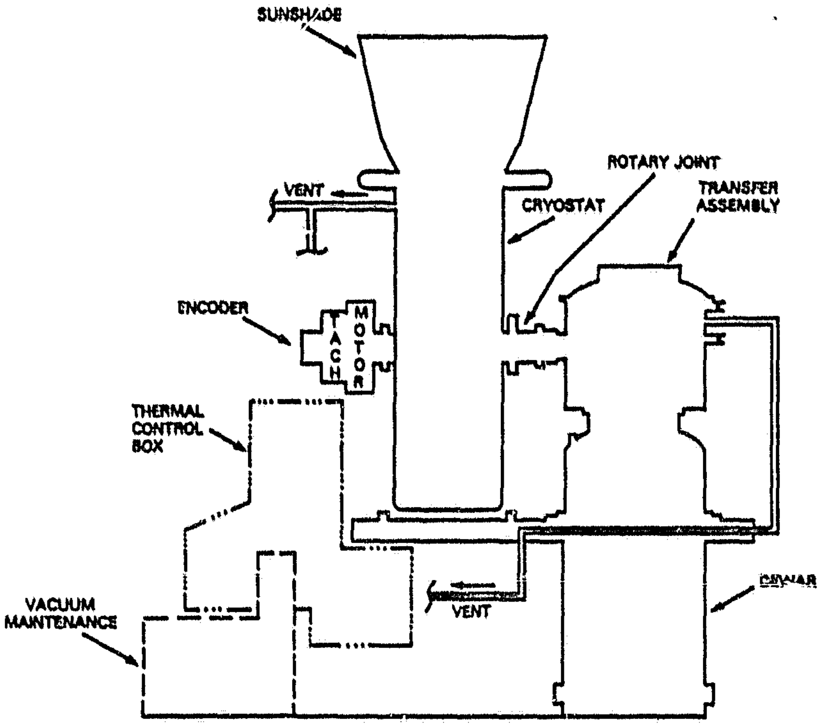

Figure 6. Small Helium-Cooled Infrared Telescope

for the small Infrared Telescope system have been manufactured by Cryogenics Associates, while NASA Marshall Space Flight Center and the University of Alabama are responsible for the helium transfer assembly and subsequent integration.

At the present time, the cryogenic system for the Small Infrared Telescope is being assembled at the Marshall Space Flight Center. Completion of the assembly is expected early in 1982. The Spacelab 2 flight is scheduled for November 1984.

A schematic of the Spacelab 2 Superfluid Helium Properties Experiment mounted on the Shuttle Pallet is shown in Figure 7. Details of the experiment are described in Reference 9. The objectives of the experiment are (1) to measure fluid motion and temperature fluctuations in superfluid helium, and (2) to contribute to the basic understanding of the quantum nature of He II and the interactions between the normal and superfluid components. The dewar, built by Ball Aerospace Systems Division, contains the necessary flight instrumentation. Vapor-cooled shields and multilayer insulation in a guard vacuum are again employed to reduce boil-off, and a porous plug is utilized for phase separation.

At the present time, testing of the dewar for the superfluid Helium Properties Experiment is being completed at Ball Aerospace Systems Division. It will be delivered to the Jet Propulsion Laboratory in September, 1981, at which time the integration period for the instruments will begin. Again, the 7 day Shuttle Spacelab 2 mission is scheduled for launch in November 1984.

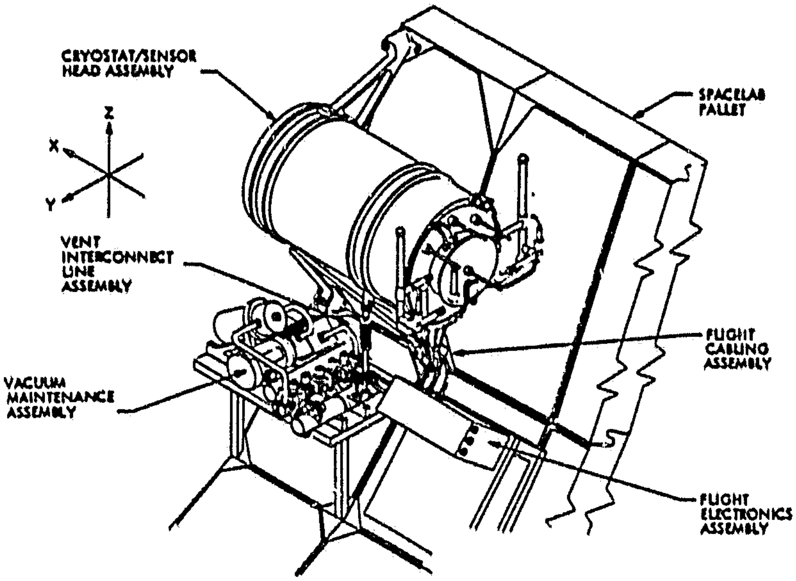

Figure 7. Superfluid Helium Experiment for Spacelab 2

What does the future hold for liquid helium systems? It is clear that liquid helium coolers will be utilized a great deal in the future. Two missions that are in the planning stages[10] include the Shuttle Infrared Telescope Facility (SIRTF) and the Gyro Relativity Satellite. The SIRTF would use a combination of supercritical and superfluid helium cryostats for short duration Shuttle missions, while the Gyro Relativity Satellite would use a dewar similar to IRAS. In addition, in the future, superconducting devices may have wide ranges of applications in space.

Technical improvements in liquid helium systems will occur as future designs evolve. Also, under a recent contract awarded to the Lockheed Palo Alto Research Laboratories from the NASA Ames Research Center, technical improvements and alternatives relative to lifetime extension will be studied.

MECHANICAL COOLERS

As payload refrigeration loads and lifetime requirements are increasing, the need for a closed-cycle mechanical cooler system is becoming more critical. A great deal of effort has been expended in an attempt to develop a long lifetime (3-5 years) mechanical cooler with stable performance. While some progress is being made, much remains to be done. The following is a brief status report on various mechanical cooler development programs and significant recent accomplishments.

Stirling Cycle Cooler Aboard P-78-1 Spacecraft

One of the most significant events in recent years in the development of mechanical cooler technology is the orbiting of four Stirling cycle coolers aboard the DOD P-78-1 satellite.[11] Launched on February 24, 1979, these units have successfully provided cooling for two gamma ray spectrometer detectors.

The coolers were developed by the Philips Laboratories with the Johns Hopkins Applied Physics Laboratory providing the electronics controls and space qualification program. A schematic of the two-stage system is shown in Figure 8. The first stage runs at 140 K with a 1.5w load, while the second stage runs at <75 K with a .3w load. Power consumption at this condition is 30 watts. The weight of each cooler is 7.2 kg, and overall dimensions are 15.4 cm X 18 cm X 30.7 cm. The helium charge pressure is 70 psi.

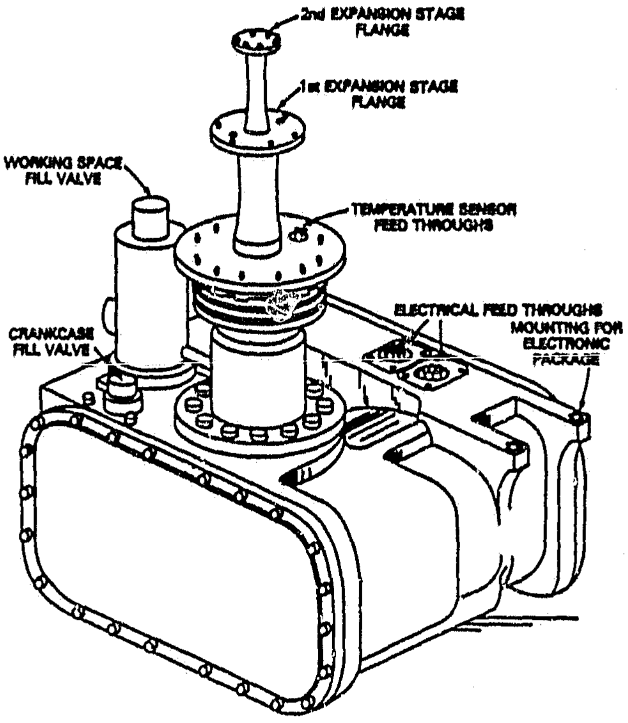

Figure 8. Philips Rhombic Drive Cooler

Two permanent-magnet, brushless dc, counter rotating motors drive the machine at about 1150 rpm. Krytox grease is used in the crankcase for lubrication, while piston and displacer basic seal materials include glass-filled teflon and Roulon. The machine employs the Philips rhombic drive mechanism, which provides for the correct phase relationship between the piston and displacer. The rhombic drive also provides dynamic balance by utilizing counter rotating weights, although the results are not perfect. Ground test data showed some degradation in detector performance caused by machine microphonics, but it was an acceptable amount.

As of July 1980, when the spacecraft had been in orbit for 500 days, the cumulative operating time of each of the four coolers was 2657, 5134, 9542 and 6518 hours. The latest unpublished data shows that one of the machines had surpassed 15,000 hours of run time.

Although the total run time of the refrigerators is impressive, significant degradation in performance occurred. The reasons for this degradation cannot fully be discerned from the data, but it is clear that a significant factor is helium gas leakage. Other factors may be seal wear and internal contamination.

Consequently, after 130 days into the flight, it was necessary to operate two refrigerators per instrument to provide the required cooling, whereas it was planned to operate only one per instrument. Further details on the orbital performance of the machines is in the cited reference.

Notwithstanding the performance degradation of the coolers, the utilization of the Stirling machines to provide instrument cooling over a long period of time in space is indeed a significant accomplishment. Heretofore, no mechanical cooler has operated in space for any significant duration.*

3-5 Year Magnetic Bearing Stirling Cycle Cooler

An innovative approach to the long lifetime mechanical cooler problem is the magnetic bearing Stirling cycle cooler that has been under development for the past 3 years. This cooler is being developed by the North American Philips Corporation under the management of NASA/Goddard Space Flight Center.

The basic design philosophy of the cooler is (1) to have no rubbing surfaces in the machine, (2) to control axial position and piston/displacer phase angles electronically, (3) to utilize a linear drive system, and thus, eliminate mechanical linkages, (4) to reduce the potential for internal contamination by eliminating all organics inside the working gas, and (5) to provide an essentially dynamically balanced machine. A schematic of the machine to accomplish these objectives is shown in Figure 9.

The baseline cooler is a single-stage device which will maintain a cold temperature of 65 K with a 5 watt cooling load. Input power under these conditions will be about 180 watts, as the machine operates at 1700 strokes/minute. The helium charge pressure is 16 atmospheres. The design lifetime is 3-5 years with either continuous operation or 1,000 stop/start cycles. Noncontact between moving and static components can be achieved for startup, steady operation, and shutdown because the bearings can be actuated independent of the linear motor. Piston and displacer seals merely consist of sections with one mil clearances.

The engineering model cooler is due to be delivered to NASA/GSFC in October, 1981, although it is hoped that initial system testing will begin in August at Philips. This model will be quite sophisticated and, except for the electronics, is required to meet the 3-5 year lifetime. A follow-on effort to produce an upgraded prototype model will then follow.

Thus far, the piston motor with associated electronics has been thoroughly tested. Static and dynamic testing of the bearings has also been completed, as have displacer motor static tests. All tests have been highly successful. On the negative side, a series of manufacturing problems, coupled with the need to do more component level tests, have caused schedule slips. A detailed update of the status of the development is in Reference 12.

If the systems level testing of the magnetic bearing machine are successful, a great step forward in the development of reliable mechanical coolers will have been made. Extension of the technology to machines with different load and temperature requirements can then follow.

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*Short-duration operations of mechanical coolers in space include a Stirling cooler on Skylab and a Vuilleumier cooler operated in space in 1973.

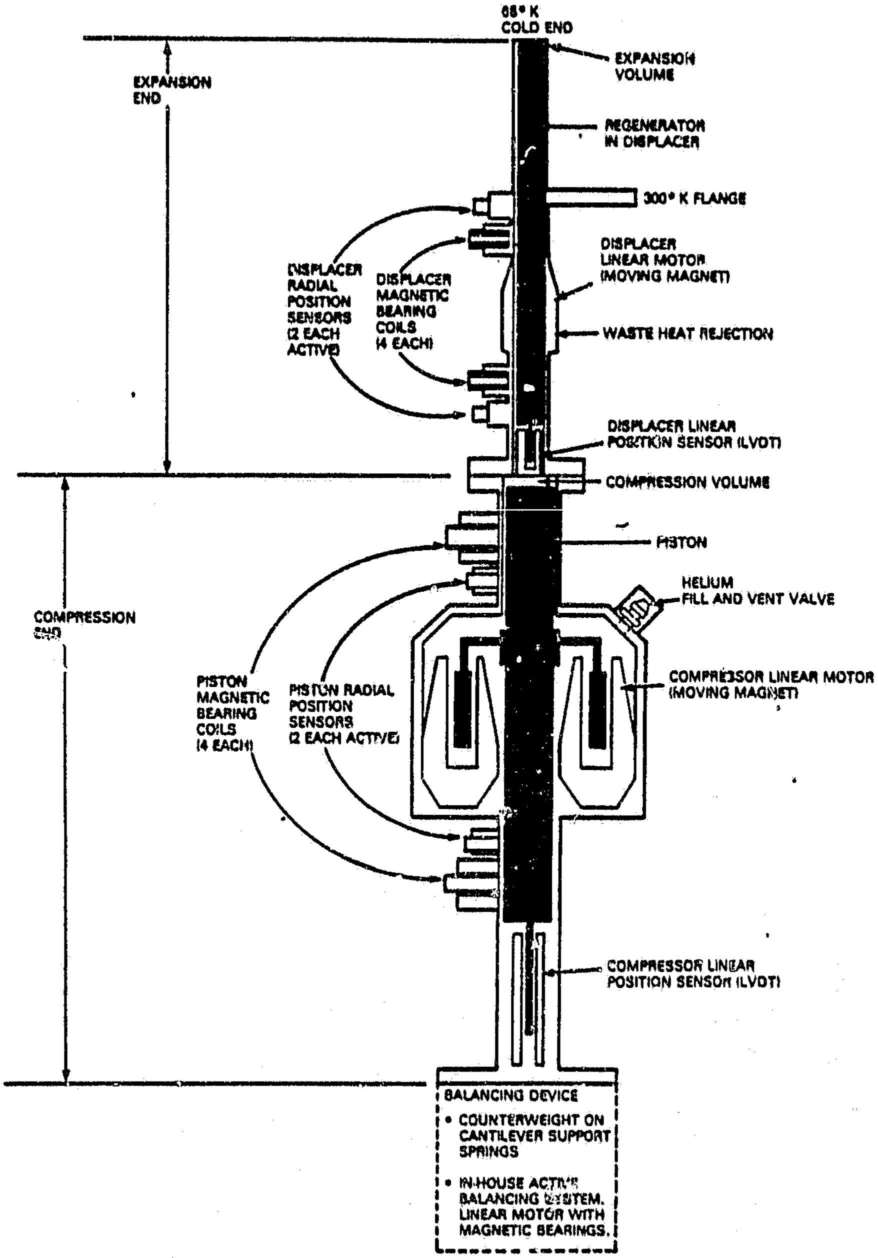

Figure 9. Single Expansion Cryogenic Cooler with Linear Magnetic Suspension: North American Philips Corp.

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Vuilleumier (VM) Coolers

The Air Force has had an extensive Vuilleumier cooler development program over the past decade. At the present time, the major effort is in the development of the Hughes Aircraft Corporation Hi Cap machine (Figure 10). Design requirements for the three-stage cooler are 12w, 10w, and .3w cooling loads at 75 K, 33 K, and 11.50 K, respectively. Long lifetime operation is intended (~20,000 hours) with a maximum input power of 2,700 watts. With the Vuilleumier cycle, most of this input power is in the form of heat.

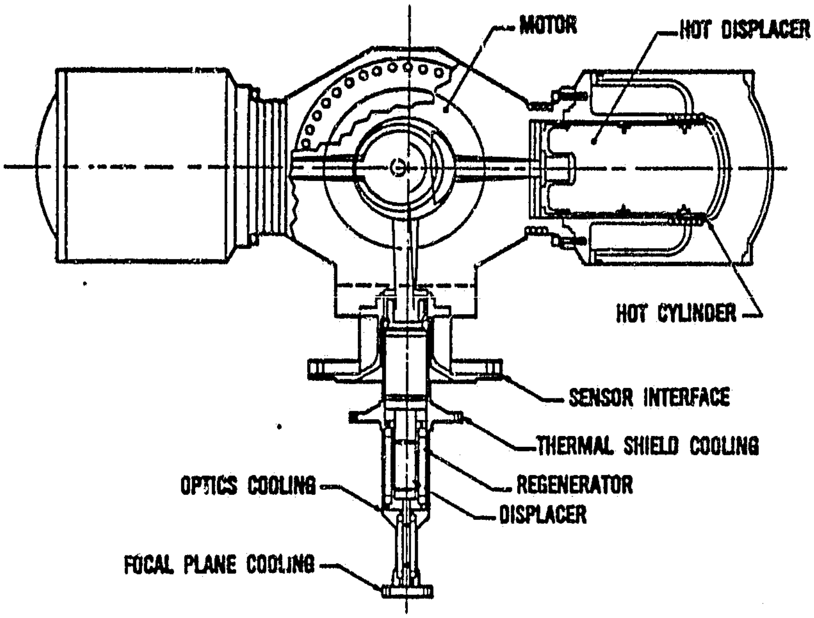

Figure 10. AF Vuilleumier Cooler: Hughes Aircraft Corp.

The Hughes approach uses dry lubricated ball bearings (MOS_2) with a bearing retainer made of Roulon A (filled teflon) with five percent MOS_2. The machine employs rubbing seals on both the hot and cold displacers and flexure pivots at the displacer drive-rod interfaces. Past problems included metal fatigue, internal contamination and seal wear.

A major renewed effort to improve the reliability of the Hi Cap machine is now underway.[13] This effort consists of extensive testing of the three existing coolers to evaluate seals, regenerators, and other components. Several interesting internal-government reports have been written, which give the results of the exhaustive seal materials test program. In addition, the Hi Cap program includes the fabrication of three improved flight coolers. It is expected that the flight coolers will be part of the SIRE (Space Infrared Sensor) experiment, which will fly on short-duration Shuttle flights.

It is difficult, at this point in time, to predict the ultimate success of the Air Force Vuilleumier cooler program. However, much valuable data is presently being collected.

A noteworthy former program in Vuilleumier cooler technology was the NASA Goddard Space Flight Center effort in 1969 and the early seventies. The program resulted in a 5w, 65 K, machine (built by Garrett Airesearch) that had many interesting features, such as solid bearings composed of Boeing 6-84-1 running against flame-sprayed Inconel 718. The machine was tested for about 6000 hours and met all thermodynamic goals, but exhibited some mechanical clearance problems.

Rotary Reciprocating Coolers

The Air Force also has an extensive program in rotary reciprocating cooler development. This effort began in the 1960's. The system utilizes self-actuating, rotary gas bearings in both the compressor and expander sections, and linear motion to achieve the refrigeration. Thus, each moving member is both rotated and reciprocated. The machine also utilizes clearance seals; thus, after startup, there are no rubbing surfaces in the machine. The thermodynamic cycle employed in the current rotary reciprocating cooler is the reverse-Brayton.

To date, all testing has been done on a two-stage cooler with cooling capacities of 1.5 watts at 12 K and 40 watts at 60 K. The effort has been rather long and arduous. At the present time, the most pressing problem is bearing seizure in the first-stage expansion engine.[13] Modifications to the design are planned which will, hopefully, alleviate the problem.

Turborefrigerators

Turbomachinery employing rotary gas bearings offers a high potential for long lifetime operation in space. Consequently, a reverse Brayton turborefrigerator for space was designed under DOD sponsorship in the early seventies. The system goals were cooling loads of 1.5w and 30w at 12 K and 60 K, respectively, 30,000 hour lifetime, and a maximum power consumption of 4 kw. The program resulted in a design of a four-stage turborefrigerator with gas bearings and included some component fabrication and test. The contractor for the work was the General Electric Corporation.

The Defense Advanced Research Project Agency (DARPA) initiated a turborefrigerator program in 1978 with a contract to the Garrett Airesearch Corporation.[13] A system was designed, fabricated and performance tested. The tests exhibited satisfactory operation over a range of conditions and over a time period of hundreds of hours. Full performance testing will continue in 1981 with endurance testing scheduled for 1982. The results of this program to-date are indeed encouraging.

The main problem with turborefrigerators is that their efficiency drops off drastically with gas flow. As a result, they are simply not competitive nor applicable to many of the mission requirements. Reciprocating, or positive displacement, machiens are needed in the low to moderate cooling load regimes.

Other Mechanical Cooler Efforts

Although not specifically applicable to space, the Office of Naval Research has recently initiated a cryogenic cooler program that may have some spin-off. Also, there is a recent effort at Oxford University to develop a .5 watt, 2 year lifetime, Stirling cycle cooler. This machine employs a linear drive and control circuitry similar to the NASA/Goddard effort, but utilizes a spring support system in lieu of magnetic bearings.

ADSORPTION AND MAGNETIC SYSTEMS

Several investigators have developed, or are working in, .3°K, ^{3}He adsorption systems for long wavelength infrared bolometers. Balloon experiments utilizing such systems have already flown,[14] and other flights are planned by NASA. The systems typically use charcoal or zeolite to provide pumping on a container of ^{3}He. A system of this nature, designed and fabricated at the Goddard Space Flight Center for the ground testing of bolometers,[15] is shown in Figure 11. Note the heat switch to permit recycling of the helium.

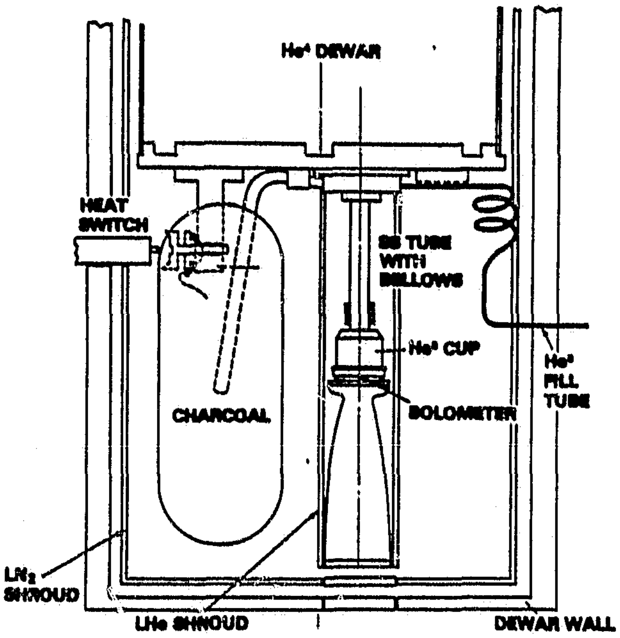

Figure 11. Adsorption ^{3}He Cooler

NASA Ames Research Center is working on a ^{3}He system[16] with a copper sponge type of fluid maintenance device for zero-g operations. Testing of the device with an adverse gravity orientation is planned, but has not yet been accomplished.

The Jet Propulsion Laboratory is working on adsorption, Joule Thompson expansion, refrigerators[17] for possible use on planetary missions. Such systems are generally inefficient. However, the power input is in the form of heat, which could be obtained from an isotope source or a solar collector. To date analytical studies of system designs have been conducted and potential compressor designs are being tested.

Efforts to develop an adiabatic demagnetization refrigerator for space application have been proceeding at the NASA Ames Research Center and Goddard Space Flight Center. The system offers the possibility of cooling infrared bolometers to the .1 K temperature range without any unusual gravity effects. The basic approach differs little from laboratory systems except that the structural design must survive launch loads. Considerable effort has been expended in this area at Goddard and, hopefully, a sound structure has been designed. However, testing of the refrigerator is not yet underway. At Ames, performance demonstration tests of their laboratory system have been completed.

Los Alamos Scientific Laboratory has been exploring the development of magnetic cooling for higher temperature/higher cooling load systems,[18,19] as compared to the described adiabatic demagnetization systems. Under Jet Propulsion finding, Los Alamos has examined their systems for space application. The systems still require a great deal of development in material technology and in the overall design scheme. Another problem is that superconducting magnets are required; thus, the cooling system itself requires very low temperatures with all of the inherent problems for space application.

CONCLUSION

A variety of systems will be used to provide for the increasing demand for spaceborne instrument cryogenic cooling.

Radiant coolers will continue to find widespread application for low cooling-load/high-temperature situations. Advanced radiant coolers will provide larger heat rejection, but will still suffer from spacecraft and orbit constraints.

Solid cryogenic coolers are less sensitive to their environment but, as an open system, are lifetime limited. Future utilization of 10 K solid hydrogen is envisioned.

For very low temperature requirements, liquid helium systems are being developed. The most notable effort is the design, fabrication and test of the nominal one-year lifetime superfluid helium dewar for the Infrared Astronomical Satellite. The same basic dewar will also be used for the Cosmic Background Explorer Satellite.

A long-lifetime closed-cycle, mechanical cooler is one of the most critical space technological needs. Numerous programs are underway to develop these systems.

Other advanced cooler efforts include development work on adsorption and magnetic systems.

The next five years should indeed be very exciting, as many new cryogenic systems will fly and others may exhibit technological breakthroughs. Studies on optimizing system performance by using combinations of the basic cooling systems will also be performed.

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Minutes

WORKSHOP IV - FUNDAMENTAL RESEARCH IN ACTIVE MICROWAVE REMOTE SENSING

A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data.

A workshop on active microwave remote sensing was held on February 1 and 2, 1982, at the Jet Propulsion Laboratory, Pasadena, California. An agenda and attendance list are attached.

Ulaby discussed scene scattering characteristics, commenting on the sparse state of knowledge of complex dielectric constants of scene materials. Water appears to be the primary variable affecting scene response. He commented that in his corn plant experiments 20% of the plant water is in leaves, 80% in stalks. Most of his discussion would call for research in the scene radiation characteristics area. He did note that cross polarization measurements are difficult because of instrumentation problems. Fung followed with a discussion of theoretical modeling, again concentrating on the scene radiation characteristics aspect. He covered surface and volume scattering models, five approaches in each area.

Jerry Solomon presented material on the Stokes vector and Mueller matrix formulation of the scene scattering problem and showed some scatterometer data and radar polarization imagery. Again, the emphasis is on scene characterization. Boerner followed with a discussion of the Poincare sphere presentation of Stokes vector information, and how polarization information could lead to target character inferences. It was clear from these presentations that multifrequency, multipolarization measurements and associated instruments would be required for understanding radar signal-scene interaction.

Dan Held discussed instrumentation aspects of the SEASAT synthetic aperture radar including radiometry. Saturation of electronics causes non-linear signal modifications. Noise sources include data link gain changes when the SAR transmitter is on, leakage effects, and temperature effects. Non-thermal noise signals are present from Earth-bound radars. Ulaby followed with a presentation on the difficulties of calibration of radar systems and put forth an idea of a calibrated receiver-amplifier-transmitter active target. He stated that calibrator cross-section to background cross-section ratio had to greatly exceed 400:1 for half a decibel precision, broad beamwidth is required, and no multiple reflections should occur. There was general agreement that radar system calibration was not easy, had not been done to a level of 3 decibels absolute or 1 decibel relative, and that this was a fruitful area of research in electromagnetic measurements.

Li spoke on performance metrics and their relation to image analysis, emphasizing impulse response, radiometric accuracy, and pixel statistics. Resolution, side lobe structure, range and azimuth ambiguities, relative and absolute radiometry, amplitude transfer function, number of looks, grey levels, and pixel signal-to-noise ratio were considered and a trade-off example was presented.

In closing on Monday afternoon, Kobrick presented the image distortion effects peculiar to radar imagery because it is a slant-range azimuth measurement. Research issues put forth were similar to those discussed by Curlander in the Rectification and Registration Workshop in November, 1981. There is a need to investigate radargrammetry equations analytically, and use simulations extensively.

On Tuesday morning Bicknell discussed synthetic aperture radar processing with emphasis on azimuth compression by FFT convolution in an advanced digital SAR processor. Following this, Curlander and Wang discussed the issues of registration and rectification of radar data. Research issues consist of:

1. Optimal SAR image registration techniques
2. Incorporation of pixel height information into algorithms
3. Parallel processing techniques
4. Automatic feature detection to select registration test areas
5. Feasibility of automatic multisensor registration.

Tuesday closed with presentations by Naraghi and Evans of JPL on applications.

Discussion on several research issues occupied the rest of the meeting. Attendees wrote to Charles Elachi to suggest research topics. A copy of these letters is attached.

Minutes

WORKING GROUP REPORT MEETING

A Study to Identify Research Issues in the Area of Electromagnetic Measurements and Signal Handling of Remotely Sensed Data

A Working Group Report Meeting was held at Lockheed, Palo Alto, California, on April 12, 13, and 14, 1982. A list of attendees is attached.

The meeting began with a critical reading of the outline and partial rough draft report (copy attached). Holmes had taken the position there was little in the way of fundamental research to be done in much of the technology areas of electromagnetic measurements and signal handling. The group voiced its disbelief that this was so and gave examples. Most of the first day was spent in argumentation over fundamental research definition in this highly hardware-oriented area.

On the second day it was decided that we should list the fundamental research needs associated with various categories, and this was done. The list follows:

A. Platform Position, Velocity

Available subsystems cover desirable ranges of 1 to 10m by precision tracking, 10 to 100m by GPS navigational satellites, and 100 to 1000m by orbit prediction following tracking orbit determination. All basic information needed for input to design procedures is available. An exception is precise aircraft position control.

B. Platform and Sensors Altitutde and Attitude Rates

The platform-sensor combination should be viewed as a complete system. This was felt to be a fundamental research item.

At low frequencies, horizon sensing works at the 0.1° control level. Star tracker/gyro systems work at ±180μrad (LANDSAT-D), ±10-25μrad (HEAO-2), and ±35μrad (Space Telescope). Angular rate limits to desirable bounds are not as well demonstrated in either estimation or control, but good lab demonstrations are available. Yaw control is good except in aircraft. 10's of μrad attitude control is available to remote sensing now, and demonstrations to hundreds of nanoradians are in the offering. Not much fundamental research need here.

At high frequencies, the LANDSAT-D attitude displacement sensor is sensitive to about 1μrad. Attentuation of high frequency jitter by design is very necessary and may call for some fundamental experimental research. Accurate instantaneous boresight estimation needs to be done.

C. Antennas and Optics

In the optical area, wide field large aperture optics, including stray light and diffraction analysis and design is an active field of research today. Scanning line-of-sight alignment and precision calls for creative design. Wavelength selection and polarization sensitivity are areas of interest but more closely related to scene radiation studies. Wide field large aperture optics design clearly stood out as the main area for research.

At microwave frequencies, multifrequency and multipolarization antenna design requires good fundamental experimental research. In addition, adaptive large antennas such as line-of-sight scanners and multibeam units may also be appropriate research objects.

On optical active system transmitters, we concluded that this was very well covered by DoD research.

D. Detectors/Preamps

In the optical region cooling is not seen as a fundamental research issue since systems and procedures already exist. Sensitivity, wavelength coverage, size, and geometric fidelity in arrays are seen as areas of potential research. Detector material technology and processing technology are serious limiting factors to electromagnetic sensing but this fundamental research is heavily supported by DoD. Spatial and temporal sampling strategies in the focal plane may be areas of fundamental research closely allied with signal handling at the electronics front-end.

There were perceived to be no problems of fundamental research in detectors and preamps in microwave systems.

E. Signal Processing and Handling

In the optical area low frequency DC restoration is still a problem. Beyond that the question of how much processing should be done on board is viewed as a system design problem. Fundamental research in electronic signal handling is well-advanced and there is a wealth of technology for system designers to draw upon.

In microwave systems there are some significant research areas in information processing and extraction due to the particular character of SAR signals. How to process for squint and spotlight modes is a question. Direct processing of data without image formation could be very useful; no one knows how to do it. The same is true of data compresssion of raw SAR data. The utility of maintaining phase information, which is now lost in image formation is simply not known.

F. Calibration

There is room for innovation and fundamental experimental research in calibration, especially in the infrared and microwave regions. Standard sources, stability, uniformity, accuracy or absolute precision, all are in need of improvement. Current capabilities are no better than 5% absolute, 1-2% relative even in the visible range.

G. System Design

This is the largest single area in terms of work to be done, but the area may not be considered by many to be fundamental research. There are feelings about requirements, such as a just right spatial resolution by situation that should be variable, a definite need to go into the SWIR, TIR, and microwave spectral regions, a need to have coverage flexibility to get the right data at the right times, single or multiple platform choices, and a need for a microwave imaging spectrometer from 1 to 30 GHz with polarimetry capability, but these are seldom justified by a formal system design procedure. Figure 1.1

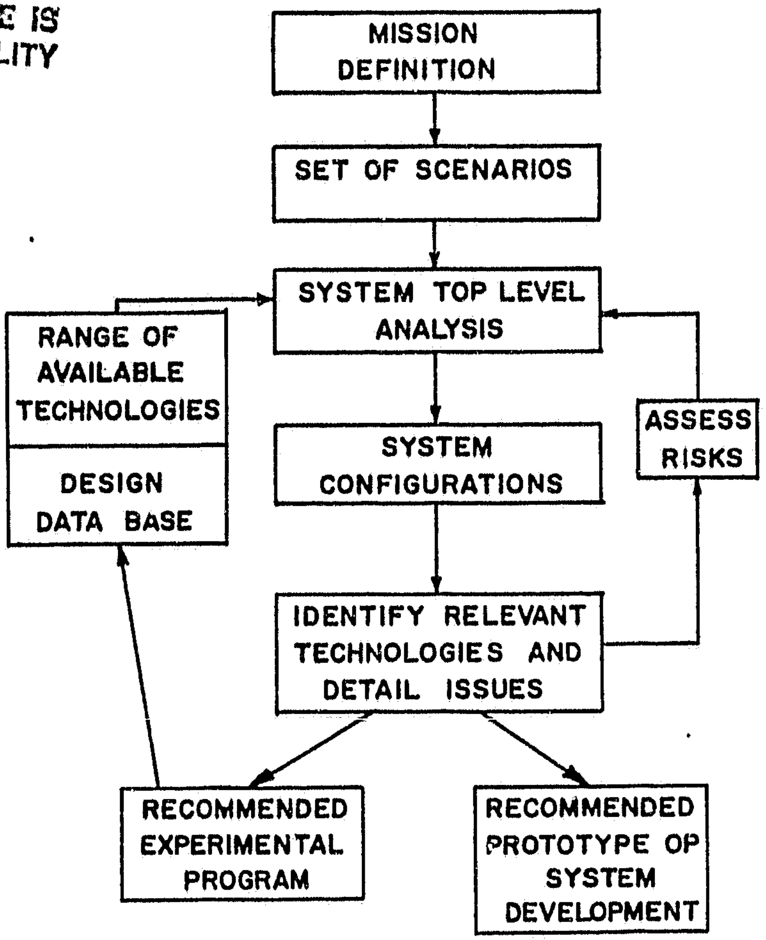

FIGURE I. SYSTEM DESIGN

Figure 1.1

shows a formal system design procedure. It requires reasonable modeling and simulation capability which does not now exist, but could be produced.

The situation appears to be as follows:

1. Actual needs exist, but those who have the needs are unaware of what the technology could do to help them, thus
2. User needs and proof thereof are vague so
3. We don't have a clear idea of what jobs need to be done hence
4. We don't know how to string available technologies together even though
5. There is a lot of technology available, perhaps with some fundamental issues still to be researched.

Following the preceding listing, the group decided that system design was a long-missing activity that in fact would be necessary if for no other reason than to provide support for fundamental research activities in scene radiation and atmospheric effects characterization and mathematical pattern recognition and image analysis. Many different scenarios should be generated, examples given, and it should be done by the electromagnetic measurements and signal handling people .

The afternoon of the second day included a tour of the Lockheed, Palo Alto, research facilities and various project efforts.

Discussion of final report focus and main thrust completed the third day.

A preliminary synopsis of the final report is contained in a paper to be presented at Purdue in July, 1982, attached.

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ATTENDEES

GMI/NASA PROJECT MEETING

April 12-14, 1982

LOCKHEED MISSILES AND SPACE DIVISION
Palo Alto Research Laboratory

1. Fred C. Billingsley
Mail Stop 198-231
Jet Propulsion Lab
4800 Oak Grove Drive
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2. ~~Lloyd M. Candell~~ Couldn't make it
~~Santa Barbara Research Center~~
~~75 Coromar Drive~~
~~Bldg. B-11, Mail Stop 20~~
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~~(Scheduled to attend, but had to cancel due to change of plans)~~

3. Charles Elachi
Jet Propulsion Laboratory
4800 Oak Grove Drive
Mail Stop 183-701
Pasadena, California 91103

4. Daniel N. Held
Jet Propulsion Laboratory
4800 Oak Grove Drive
Mail Stop 183-701
Pasadena, California 91103

5. Roger A. Holmes (Principal Investigator)
General Motors Institute
1700 W. Third Avenue
Flint, Michigan 48504

Couldn't make it.

6. ~~Donald S. Lowe~~
~~Environmental Research Institute of Michigan~~
~~P. O. Box 618~~
~~Ann Arbor, Michigan 48107~~
~~(Scheduled to attend, but had to cancel due to change of plans)~~

7. Robert B. MacDonald
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Mail Code SG
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8. Marvin S. Maxwell
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Lockheed Missiles & Space Div.
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(Rough Draft)

FINAL REPORT OUTLINE

Preface: Summary and Recommendations

Table of Contents

I. Introduction

   A. Objectives of this study, organization of this report.

   B. Format of meetings and workshops (participants lists in Appendix)

   C. Relationship with other fundamental research definition studies

II. Current Status in Electromagnetic Measurements and Signal Handling

   A. Ephemeris selection, estimation, and control

   B. Attitude selection, estimation, and control

      1. Spacecraft or aircraft

      2. Sensory instruments

   C. Electromagnetic power receiver/transmitter (active systems) characteristics

   D. Sampling of received electromagnetic power in space, time, wavelength, phase, and polarization aspects.

   E. Precision and accuracy of measurements at the measurement source

      1. Calibration

      2. Noise sources, characteristics

   F. Handling received electromagnetic power and platform and instrument status signals

      1. Digitization

      2. Communication, compression

      3. Payload correction processing

      4. Geometric preprocessing

   G. System design procedures

III. Opportunities for Fundamental Research in Electromagnetic Measurements and Signal Handling

- A. Creating efficient system design procedures
    - 1. Facility or mission determination of system requirements
    - 2. Simulation tools including costs and breakpoints
- B. Creating accurate deterministic and stochastic models of system components
    - 1. Appropriate degree of model sophistication
    - 2. Experimental verification of models
    - 3. Component limitations - zones of feasibility
- C. Creating signal recovery techniques in the face of calibration difficulties and noise
    - 1. Complex system with many noise sources: system and scene, spatial and temporal in character
    - 2. Mixing and unmixing radiometry and geometry; the resampling issue
- D. Creating objective and subjective performance metrics
    - 1. Human factors in image evaluation
    - 2. Quantitative link with interpretive tasks; by humans, by machines, by both

(Rough Draft - 1/26/82)

Section 1

INTRODUCTION

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 March, 1982.

The primary objective of this work is aptly described in the title of the study. In particular the work defines a program which will lead to the definition of sensor and system requirements for various missions, and defines specific areas of pursuit of fundamental research in electromagnetic measurements and signal handling that are relatively independent of mission and instrument. Current status will be discussed first, followed by opportunities for fundamental research.

Current status of electromagnetic measurements and signal handling of remotely sensed data and opportunities for fundamental research thereon 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 evaluation and utilization. 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 19-20, 1981. Presentations on a broad range of registration and rectification issues followed by panel discussions 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.

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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, SAR processing, and SAR 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, editorial commentary on final report wording.

Minutes of the two working group meetings and the four workshops, including attendance lists, are included in the Appendix of this report.

This study was one of four undertaken on the remote sensing system. The remote sensing system study areas are shown in Figure 1.1 with the portion of interest in electromagnetic measurements and signal handling circumscribed.

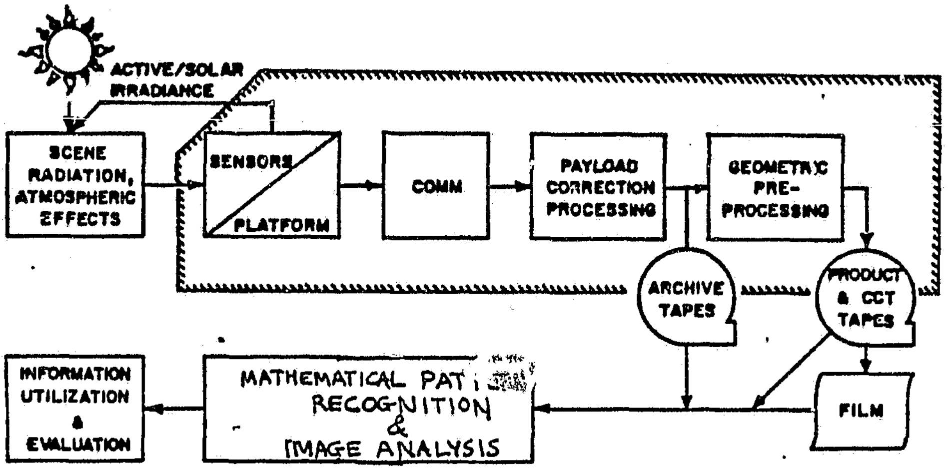

FIGURE 1.1 THE REMOTE SENSING SYSTEM

The four study areas are not as neatly separable and mutually exclusive as the diagram would imply; overlaps of this report with reports from other study areas is inevitable.

Thus, the study on Mathematical Pattern Recognition and Image Analysis discusses the issues of geometric preprocessing including reference coordinate systems, control and correspondence (rectification and registration), resampling, registration-rectification sequence, errors, tolerance, and accuracy measures, sensor/platform modeling, and topographic problems. These clearly relate to issues of satellite ephemeris, attitude, and structural rigidity, sensor geometric design and performance, and on-board and ground station signal processing including SAR image formation. The same report discussed issues of radiometric preprocessing including haze distortion, terrain relief effects, and view angle/sun angle effects. These issues are clearly related to the radiometric measurement integrity of the sensor and the subsequent signal handling system. Further, the mixing of radiometric and geometric effects is inherent in the finite point spread function of a physically realizable sensor even before resampling; resampling causes further confounding of radiometry and geometry.

Issues discussed in the study on Scene Radiation and Atmospheric Effects Characterization include scene and scene parts modeling to develop understanding of the absorption and scattering of irradiating energy to arrive at scene radiance, and atmospheric modeling over non-uniform scenes to understand atmospheric interaction with scene radiance to arrive at sensor irradiance. Atmospheric path radiance, scene radiance spatial distribution, adjacency effects due to atmospheric point spread function contributions, and cross-irradiance through atmospheric backscatter 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 should provide the requirements placed on other portions of the remote sensing system, particularly upon sensor systems and mission plans. While this requirements connection may be ill-defined and vague, it may also be the most important connection to future system designs.

Because of these relationships with the other studies, this report on research issues in electromagnetic measurements and signal handling deals with sensors, platforms, communications, and preprocessing in the context of strong and direct connections to scene radiation and atmospheric effects characterization and mathematical pattern recognition and image analysis as the adjacent components of the system. In a broader sense, the report recognizes that the research issues of sensor, platform, communications, and preprocessing characteristics and mission requirements derive from and are tested against the overall system purpose, which must be stated ultimately by the user of the acquired information, whoever that may be.

Section 2

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

The electromagnetic measurements and signal handling portion of the remote sensing system consists of one or more platforms bearing sensory instruments, on-board signal handling and processing, communications to ground stations, ground signal handling, and preprocessing. A logical organization of current status topics begins with the position and velocity of the mass center of the platform/sensor system in geocentric space. The next topic is the attitude and attitude rates of both the platform and sensory instrument optical or electromagnetic axes. Following this, the basic sensed electromagnetic power receiver (telescope or antenna) characteristics are considered; in the case of active systems the irradiating power transmitter characteristics are included. At this point the sampling strategy (scanning, spatial arrays, range/Doppler schema) of the received electromagnetic power in space, time, wavelength, amplitude, phase, and polarization aspects, resulting in electronic signals, fits in nicely. It is then appropriate to consider the precision and accuracy of the basic measurements at the platform sensor system, with attention on calibration and noise source characteristics. Next to last, the handling of the basic measurement signals from digitization through communication and pay load correction processing to geometric preprocessing is discussed. Current status topics closes with a review of system design procedures, concentrating on current shortcomings.

2.1 PLATFORM AND SENSOR SYSTEM POSITION AND VELOCITY

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 desired satellite ephemeris or aircraft flightline, estimation of the actual orbit or flightline, and control or, at least, annotation of the actual orbit or flightline 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). 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 across 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 across-track.

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 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-to-peak, translating into an across-track swing of over a kilometer.

In general, then, it appears that satellite Earth orbits appropriate to remote sensing will have nearly periodic and monotonic drift deviations from nominal orbits that grow at rates of tens to hundreds of meters per day. Therefore, orbit selection is nominal at best; actual orbit ephemerides require frequent position and velocity measurement or valid perturbation models for epoch state propagation with less frequent measurement.

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 (2), 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 (3) 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 1 to 4 arc seconds directional accuracy after reduction 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 known accuracy of the SEASAT orbit.

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 flightline estimation to similar accuracies (4).

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 D. 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.

Ephemeris control is accomplished by conventional gas thruster systems for both manned and unmanned satellites. A sizeable literature and technology exists in this area. Aircraft control is even more advanced.

In summary, it appears that satellite ephemeris estimation to within a 1-σ error of about 100 meters by tracking is straight-forward, while estimation to within a 1-σ error of about 10 meters is possible with an operational GPS constellation. Thus selection, estimation, and control of platform center of mass position and velocity for remote sensing purposes appears to be well-advanced in fundamental knowledge and understanding and can profit most from evolutionary engineering improvements.

2.2 PLATFORM AND SENSOR ATTITUDE STATE VECTORS

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 an arc second 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.(5) 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 (6) 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 (7) addresses thermal bending distortions accounting for up to 19 arc-seconds of misalignment and notes that a jitter specification of less than 1 arc-second/second appears to be amply met.

An electromagnetic sensor mounted on a sensing platform has a radiometric coordinate system; the instantaneous optical axis of a telescope/mirror arrangement or the main lobe axis of an antenna and appropriate orthogonal axes are typical choices. These sensing axes will be dynamically related to the body-fixed platform axis either purposefully in the case of mechanical scanners, stereo mirrors, and roll joints for side-looking, or inadvertently through structural vibrations and flexures excited by platform system actuators, sensor moving parts, or thermal gradients and transients. Thus it is also necessary to include angles and angular rates of a radiometric sensor coordinate system with respect to, most conveniently, the platform body-fixed coordinate system. Similar considerations hold true for aircraft remote sensing. Thus a complete state vector to describe the pointing of one electromagnetic sensor is typically an eighteen component vector: six in position and velocity of the platform, six in angles and angular rates of a body-fixed coordinate system, and six in angles and angular rates of the sensor radiometric coordinate system. This is the case for LANDSAT D and its Thematic Mapper and Multispectral Scanner sensors.

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 and nominal along-track and across-track pointing of the two remaining 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 plans. For the sensor radiometric coordinate system, there are two aspects of attitude selection with respect to body-fixed axes. First, there may be commandable pointing which calls for a setting of radiometric axes followed by a period of data collection at that setting. The French SPOT sensors call for the ability to pushbroom-scan at up to ±27° off-nadir cross-track. 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 (8). Future sensor systems will probably have commandable sensor radiometric pointing as a matter of routine. Second, electromechanical or electronic scanning is a very rapid time-varying sensor attitude selection, most commonly a linear sweep, though conical schemes have been employed as in the Skylab S-192 sensor.

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 mission presuming star tracker and landmark measurements in an extended Kalman filter estimation of attitude, orbital ephemeris, and gyro bias drifts. Attitude uncertainties of a few arc-seconds in roll and pitch and about 10 arc-seconds 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 D. The algorithms assume two precision startrackers making discrete attitude measurements and three rate-integrating gyros for an attitude estimation between star updates. Pointing errors lie well within the ±36 arc-seconds allowed bounds, appearing to have peak-to-peak values of 15 arc-seconds. The control system natural frequency is assumed to be 0.1 rad/second or a bandwidth of about 0.016 Hz. Star tracker 1-σ noise nominal value was 10 arc-seconds; it is noted the pointing errors are directly propotional 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 9 to 34 arc-seconds for three example systems. The High Energy Astronomy Observatory-2 system was successfully pointed to 2 to 5 arc-seconds and attitude measurements to better than 2 arc-seconds were evidenced (7).

Roberson (9) gives his opinion of attitude control as follows: "...attitude control, at least in many aspects, is about exhausted as a field of research. Much of the field is rapidly becoming an area of development or of conventional engineering practice. Certainly some areas of active research will continue for a time, such as the attitude control of flexible satellites, control under extreme pointing requirements, and certain others." And further, "...the research area of attitude control, notwithstanding a continuing trickle of new work, will have run much of its course in its first quarter-century."

Estimation of the instantaneous radiometric sensor attitude for both intentional causes (scanning, pointing) or unintentional causes (vibrations, thermal flexure) is quite a different problem from the low frequency platform attitude control situation just discussed. Two scan mirrors will operate in Thematic Mapper: the main cross-track scan mirror will have a linear triangle wave motion 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 back-scans to permit bidirectional main scanning. Timing, control, and position estimation of both mirrors is critical to successful ground preprocessing. In LANDSAT D a triaxial angular displacement sensor is mounted on the Thematic Mapper itself to sense vibrational instrument attitude out to frequencies in excess of 100Hz.

The frequency dependence of radiometric attitude variations is critical to high resolution sensors. This is because geometric preprocessing is conventionally done by affine transformations on subimages and the size of the subimage that can be so handled depends on the rate and regularity at which radiometric axes attitudes change; a high frequency large amplitude random jitter would ultimately decrease subimage size to a pixel-by-pixel registration, extraordinarily inefficient. Moreover, the density of ground control points required for a given rectification accuracy increases as high frequency radiometric attitude variations increase. Current expectations on lower frequency attitude errors in LANDSAT D Thematic Mapper are:

Frequency Range	1σ Error, arc-seconds	Primary Cause
0-0.01 Hz	36	Attitude Control System
0.01-0.4 Hz	10	TDRSS drive motors
0.4-7 Hz	0.3	TDRSS drive motors

For higher frequencies specifications on roll, pitch, and yaw jitter are

		Baseline Expected Errors	Worst Case	
>7Hz	Roll	0.93	2.0	All caused by scan mirror motion
	Pitch	0.20	2.2	
	Yaw	0.30	16.8	

These specifications assure that jitter gap caused by pitch and yaw will be less than one 30 meter pixel even in the worst case. As an additional low frequency attitude effect, there is a 12 arc-second offset per degree Celsius across the Thematic Mapper.

While radiometric sensor attitude expectations are in the fractions to ten arc-seconds in design for the LANDSAT D 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 launch planned for the third quarter of 1982. After experience of the last few years, it appears that minimizing unwanted high frequency radiometric attitude variations is mainly a problem of sound structural design and attention to reducing mechanical vibrational sources. Scanning mirror motion integrity and estimation requirements are severe in Thematic Mapper due to a 146 pixel offset between bands due to detector placements in the focal plane.

Kaplow and Velman (6) propose separation of spacecraft into vibrationally "dirty" zones and "clean" zones with active isolation between zones. While this would be reasonable for sensors that are not themselves potential vibration sources, the MSS and TM scanners are vibrational sources.

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

In summary, low frequency attitude selection, estimation, and control is well-advanced in knowledge and understanding. High frequency attitude variations in both the platform and electromagnetic sensor axes with respect to low frequency body attitude sensing instrumentation have appeared as areas of concern in the last three years, with actual system measurements and resulting analysis effects yet to be done experimentally once LANDSAT D goes up. Attitude sensitivities to thermal gradients, vibrations, and scan regimen are areas of current concern. While knowledge of physical principles of vibration, scanning dynamics, and thermal gradient warping may be well in hand, the experimental understanding of the importance and magnitude of these effects on data analysis remains to be developed and may be an important step to solve registration and rectification problems at their source.

2.3 ELECTROMAGNETIC POWER RECEIVERS AND TRANSMITTERS

The two commonplace receivers of electromagnetic energy from remotely sensed objects are telescopes at optical frequencies and either array or disk antennas at microwave frequencies. The Multispectral Scanners and the Thematic Mapper feature Ritchey-Chretien telescopes: 22.8 cm diameter f/3.6 optics and 41.1 cm diameter f/6 optics respectively. SEASAT and Shuttle synthetic aperture radar sensors feature large array antennas. Current plans in passive microwave sensing feature large deployable light weight disk antenna designs. The Apollo Lunar Sounder radar employed a VHF Yagi antenna and an HF dipole antenna.

In the optical sensors the desire for simultaneous measurements over a range from 0.4 to 13 micrometers wavelength has generally meant all-reflective optics. This thrust is expected to continue in multispectral linear array designs with stringent registration requirements, though there are refractive designs extant, some with Mangin correctors, others with multiple telescopes. The reflective Schmidt optical design by Kodak (8) is typical of efforts to achieve the wide field essential to MLA sensors. The MLA design study requirements call for over 12,000 sensors; at a 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 an optical designer in the Ritchey-Chretien configuration will usually not suffice to accommodate such a wide field (14), so additional degrees of freedom associated with extra or non-conical section optical surfaces are required. SPOT employs a Matsukov telescope design.

Optical design technology is well-developed and its principles thoroughly understood. Geometric optics (infinite frequency, zero wavelength approximation of Maxwell's equations) and associated ray tracing design techniques are documented and programmed. Diffraction theory supplies the appropriate finesse to the geometric optics results. Matrix methods and Stokes parameters can be used to address polarization issues, though polarization at optical frequencies has generally been ignored in sensing instrument design.

Microwave antennas also draw upon a well-developed technology. The array antenna may pose difficulties of phasing and power distribution from a practical viewpoint, but principles are established. Because the geometric location of active microwave sensing is related to range and Doppler information, relatively little attention has been paid to physical resolving power. However, polarization has received considerably more attention than it has in the optical frequencies, in part because it is perceived that some information is present in polarization of microwave data. The major questions to be asked in polarization relate to the ability to really develop a polarization measurement capability with minimum cross-talk between polarizations, both sent and received.

Optical transmitters of any reasonable strength involve lasers, with modes and polarizations important. Active optical remote sensing is not commonplace at this time. On the other hand active microwave sensing is the rule. Generally, the transmitting and receiving antennas are one and the same. The transmitting properties of an antenna are usually directly related to its receiving properties. It appears that the technology of energy transmitters is well-understood, and that the main issues involved are engineering issues.

Structural integrity and ease and stability of alignment are considerations for any sound electromagnetic receiver or transmitter system. The principles involved are well-known and engineering practice calls for creative design and for existing good design analysis capability for proposed systems.

The major effect of optical system performance is expressed as a point spread function or modulation transfer function. This is a transfer function approach to optical design, and considers diffraction phenomena, in addition to the geometrical optics approach of the detector as a field stop. At present, the diffraction contribution can be modeled for the typical circular or annular apertures using classical diffraction theory (15) (16). Misalignment and figure contributions to a blur circle can also be modeled (14). Thematic Mapper has been modeled as a Gaussian diffraction point spread function with a standard deviation of about 8 microradians at 0.5 micrometers wavelength or an 80% radiant power blur circle of about 25 microradians, convolved with the 42.5 microradian detector field stop function.

In summary, it appears that the optical and microwave receiver and transmitter areas are advanced in fundamental knowledge and understanding and in need mainly of engineering development for specific systems.

2.4 SAMPLING OF RECEIVED ELECTROMAGNETIC POWER

The electromagnetic power which enters the electromagnetic sensor of a remote sensing system contains information in the Poynting power in the form of amplitude, phase, polarization, wavelength or frequency, and degree of coherence. If the power received is a return from a transmission of known characteristics (an active system) then information is contained in the transformation of these attributes by reflecting scene elements and in time-of-flight in a time-encoded transmission. The received electromagnetic power is sampled in space and in time by detectors and their associated electronics, and by motion of the platform, the pointing or scanning of the electromagnetic receiver axes, Doppler shift, and time-of-flight.

In the optical wavelength region the philosophy in early remote sensing systems (aircraft scanners, MSS, Coastal Zone Color Scanner) has been modest spatial parallelism in order to achieve both spectral separation and slower mirror scans with attendant lower bandwidth and higher signal-to-noise ratio. Beyond that, spatial sampling in such systems is accomplished by platform forward motion and optical axis motion together with sequential time sampling. For example, the Multispectral Scanner has a 24-fold spatial parallelism, 4 units in one direction with interference filters to achieve four different wavelength bands, plus 6 units in an orthogonal direction to reduce the scanning mirror rate and bandwidth (17). In Thematic Mapper 16-fold spatial parallelism per band in the visual, near infrared, and short wave infrared bands reduces bandwidth requirements per detector channel, while a 6-fold spatial parallelism accomodates six spectral bands. In the thermal infrared there is only one band with a 4-fold spatial parallelism (18). The remaining spatial sampling rate capabilities of MSS and TM are accomplished by time sampling at rates roughly comparable to an instantaneous field of view dwell time (MSS$\approx$14 μsec, TM$\approx$9.6 μsec). The tradeoffs with respect to signal-to-noise ratio, scan rate, aperture size, IFOV, and detector type are well understood (14).

In multispectral linear array designs the essential idea is to increase the spatial parallelism to the point that only one time sample per forward pixel movement by the platform is required, quickly dumping charge from thousands of detectors in a cross-track array into a CCD register for sequential readout between along-track samples. The pixel dwell time increases to a few milliseconds, the detector sample rate drops to 500 Hz or so, but the register readout must be clocked in excess of 1 MHz. The appeal of the multispectral linear array is that it does away with the moving mirror and the difficulties of accurate and instantaneous optical axis attitude estimation with moving mirrors; a vibration source is removed and relatively low frequency attitude estimation may suffice. However, putting aside spectral coverage issues for a bit, the gain in system simplicity is not without its costs. There are formidable difficulties in holding dimensions to within a half pixel or so. Current day sensor fabrication practice provides detector-to-detector spacing or pitch of 15 to 25 micrometers. In some spectral ranges current technology limits chip array length about 600 detectors. The MLA design study recently completed called for about 12,000 detectors per band; at 20 micrometers pitch, the array would be 240,000 micrometers or nearly 10 inches long. For some wavelength bands about 50 chips would have to be positioned and abutted to better than one part in 24,000 over that span to achieve 0.5 pixel location accuracy; the MLA study specification called for 0.1 pixel location to avoid resampling - this proved to be an unreasonable specification. The French SPOT system has 3000 sensors in each array in three VNIR bands and 6000 detectors in the panchromatic band array and will be placed in orbit in 1984 or 1985.

Acommercially available multispectral linear array camera is built by Itek Optical Systems (19). It employs 7500 elements across-track in three spectral bands in the VNIR silicon range, and has readout timing defined by the aircraft platform V/h ratio.

Areal array designs for optical wavelengths can be viewed as a collection of close-packed linear arrays. Here the idea is that only a single time sample is needed to capture the entire frame scene with the advantage over photographic emulsion array sensors that the same detectors can be used again immediately after readout. The primary disadvantage of an areal array sensor is that it uses up both spatial dimensions for spatial sampling, leaving no spatial dimension to be used for spectral sampling. Separate areal arrays would have to be used for different spectral bands, creating an inherent registration problem that appears to be much less severe in either scanners or linear arrays. At this time, the areal array technology limits appear to be about 800x800 detectors in the VNIR (silicon) range, and 64x64 detectors in the SWIR (HgCdTe) range.

In all of the sensors above the spatial resolution is limited primarily by detector size and telescope focal length. As stated before, the point spread function of the system from telescope aperture to and including the detector is the detector spatial sensitivity pattern convolved with the telescope optics point spread function. Current practice would indicate that the 86 microradian IFOV of MSS is now viewed as an acceptable worst case, with TM, SPOT, and mapping satellite designs indicating that 10 to 50 microradian IFOV's will be sought in future systems.

Passive microwave spatial sampling schemes include platform motion, scanning by antenna or detector image plane receiver motion, antenna array phasing, and double receivers with data reduction based on the van Cittert-Zernike theorem. 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 an L-band electronically scanning microwave radiometer have been proposed for Spacelab (20).

Spatial sampling in active microwave systems is done by slant range (time-of-flight) and Doppler shift measurements in the received power compared with the transmitted signal. SAR imagery is a slant range and Doppler azimuth history map with respect to platform location and attitude. Range determinations to accuracies of tens of centimeters is possible and accuracies to a few tens of meters is commonplace. Phase and polarization information are usually available in addition to amplitude information because of coherent detection of the received signal and the polarization design of the antenna. To date there is satellite system experience in SEASAT and Shuttle Imaging Radar, both in L-band. Spatial resolution of 25x25 meters from typical Earth sensing altitudes is achieved; this resolution has been accepted by a broad-based user community (21). Indeed, arguments can and have been made for significantly lower resolution to reduce data loads for some applications.

The antenna and detector designs in active microwave systems follow good radar system engineering practice on sensors flown to date. A scanning SAR (SCANSAR) concept has been proposed (22), as have multiple independent beams and single illuminator-multiple receiver beams, referenced in (22). However, in current systems spatial sampling is accomplished by processing return signals from a fixed orientation antenna.

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 has been described by Wellman (23) using areal arrays in the focal plane. Aircraft scanner data have been acquired using prism and grating spectrometers. One experimental system in the late 1960's used the slit design described above with an image dissector tube as the areal 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 MSS, TM, 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 dichroic filters, typically just before the focal plane, can be used to dissect the received electromagnetic power by wavelength. Such designs have been proposed in some multispectral linear array work.

The sensor technology per se is an important consideration in wavelength sampling. Silicon is clearly the material of choice below one micrometer, with a highly developed technology base. Beyond one micrometer mercury cadmium telluride with various mercury and cadmium proportions according to bandgap selection appears to be the long range material of choice, though two SWIR bands in Thematic Mapper are indium antimonide monolithic technology. Indium antimonide, indium gallium arsenide, and platinum silicide, as well as various extrinsic IR detector materials have been studied. Thom, et. al. (24) describe the monolithic InSb array technology in an issue of the IEEE Transactions on Electron Devices devoted to IR detectors. HgCdTe technology development has been heavily supported. Hybrid focal plane array technology with an intrinsic HgCdTe detector array chip and a silicon multiplexing and readout electronics chip is more advanced then fully monolithic array technology. Yield, uniformity, cross-talk, 1/f noise, aterial growth, and interconnection are all areas requiring technology development. Focal plane array technology development and demonstration is currently being pursued by NASA/GSFC. The fundamental principles underlying the technology are well understood. However, much good experimental engineering research remains to be done.

In microwave systems the multifrequency transmitter and receiver capability is desireable but is often implemented by the simple expedient of a complete radar system for each frequency(25). Unlike the optical portion of the spectrum wherein wavelengths are much smaller than even the smallest parts of the hardware, the receiver and transmitter hardware (antenna array elements, feed systems, front-end microstrip circuitry, T-R devices, etc.) of microwave systems are inherently strongly wavelength dependent in design. While multifrequency microwave systems may require creative engineering research and design to achieve efficiencies through multiple use of common elements or rapidly adaptive elements, the fundamental principles are well understood here too; this appears to be an area for technology development.

Polarization information appears to be present in active and passive microwave sensed data. Both SEASAT and Shuttle Imaging Radar have HH polarization only, but various aircraft radar systems exist with both single and dual polarization sets in HH, HV, VH, and VV. Even so, much of the multifrequency and multipolarization information content evidence come from a truck-mounted microwave active spectrometer (26)(20). More complex polarization sensors have been discussed (20) but not implemented.

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. Preliminary field work exists that would indicate polarization information is present in optical wavelengths from renewable resource scenes (27). Sensor design to purposely measure polarization at the data rates common in aircraft and spacecraft systems would challenge optical designers, but again, fundamental principles are understood.

Phase information is captured as a part of the coherent detection in an active microwave system but is normally discarded in developing magnitude information from in-phase and quadrature channels (21). While it may be appropriate to fundamental research in scene radiation characteristics to investigate possible phase information content, at the present time phase information is ignored except in the pre-image formation processing in SAR.

In microwave radiometry and passive optical sensing systems the received electromagnetic power is virtually incoherent. Thus there is no information to be had in phase other than the lack of coherence. There has been one study at NASA/GSFC to employ the van Cittert-Zernike theorem to use partial coherence from an extended source and two radiometers to achieve aperture synthesis for high spatial resolution microwave radiometry.

True time sampling or multitemporal information extraction is accomplished by revisits of the platform sensor system, considering normal change rates in renewable resource scenes. Thus registration of data sets from the same or different sensors separated in time by weeks, months, or years is the general rule in time sampling of natural scenes.

In summary, much of the sampling of received electromagnetic power in space, wavelength, polarization, phase, and time requires technology development and creative engineering design. There will always be choices to be made among several workable schemes for such sampling for a specific sensor design based on desired specifications. However, there is an essential element of fundamental research need in the very complexity of the electromagnetic sensor design choices and tradeoffs. We understand the fundamental principles, design parameter choices, and limits to hardware manifestations of the bits and pieces of a total sensor. It is not clear that we have enough understanding of how all the parts go together in overall system performance, nor do we understand how to arrive at a best system against some cost/performance criteria by other than trial and error.

2.5 PRECISION AND ACCURACY OF ELECTROMAGNETIC POWER MEASUREMENTS

The precision of a sensor measurement is high if it results in stable, consistent numbers on repeated measurement of the same object. The accuracy is high if the numbers correctly represent a physical quantity according to some agreed-upon standard. Precision is mandatory for successful measurements, accuracy is highly desireable.

Current practice in the optical wavelengths is to perform a ground calibration of the optical system with nearly 2π steradian irradiance of the telescope aperture from a large integrating sphere with internal quartz-iodine lamps. Because that system itself involves transfer calibration standards, it is felt that a 5% absolute radiance calibration is quite difficult to achieve and is

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IL

"Advanced Sensor Systems:
Thematic Mapper and Beyond"
Title of R. Holmes' Talk
Sched. for Fri., July 9,'82

I. ABSTRACT

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

II. THEMATIC MAPPER

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

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

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

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

II. SPOT

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

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

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

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

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

III. JAPANESE PLANS

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

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

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

IV. MLA DESIGN STUDY

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

- Thematic Mapper VNIR and SWIR bands
- Operation at 283, 470, and 705 km orbits, 9:30 to 10:30 a.m. equator crossing
- 15 x 15m IFOV in VNIR, 30 x 30m in SWIR
- 0.5% relative, 5% absolute within band radiometric calibration
- 1% relative band-to-band radiometric calibration
- Geometric positioning of 20 IFOV's span in-track, 0.1 IFOV in position cross-track, parallel in separate bands to 0.2 IFOV
- 15° field of view
- Stereo along-track + 26°
- Roll cross-track + 30°
- Two 150 M bits/s links to TDRSS, one 100 M bit

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

Overall, the instrument design study

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

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

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

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

V. FUNDAMENTAL RESEARCH IN SENSORS

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

A. PLATFORM POSITION AND VELOCITY

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

B. PLATFORM AND SENSOR ATTITUDE AND RATES

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

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

C. OPTICS AND ANTENNAS

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

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

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

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

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

D. DETECTORS AND ASSOCIATED ELECTRONICS

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

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

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

E. SIGNAL PROCESSING AND HANDLING

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

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

F. CALIBRATION

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

G. SYSTEM DESIGN AND MODELING

While several areas of fundamental re-

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

A system design flow is shown in Figure 1.

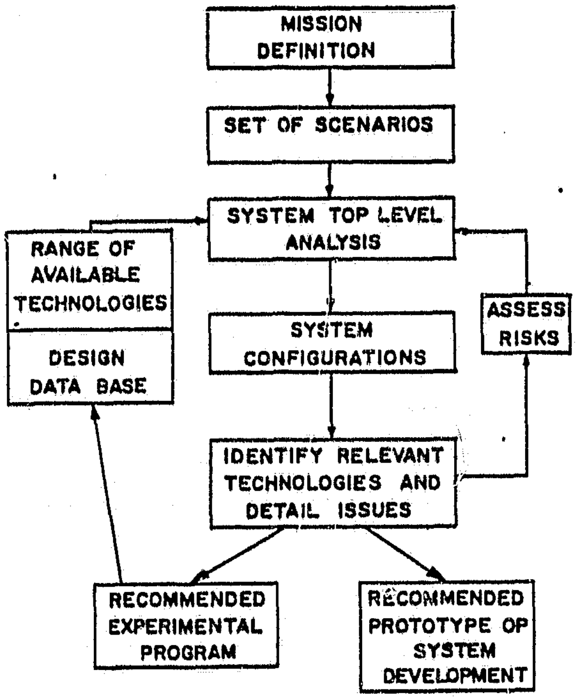

FIGURE 1. SYSTEM DESIGN

A mission is stated. Several possibilities might be:

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

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

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

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

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