NASA-TM-108270

Earth Observing System

Project Science Office, Code 900
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MEMORANDUM

To: EOS Calibration/Validation Panel Members
From: Bruce Guenther BG
Date: May 11, 1992
Subj: Minutes from the fifth Cal/Val Panel Meeting, Boulder

Enclosed please find the minutes and associated documents prepared from presentations and meetings at the Boulder site in April.

Meeting 5 was particularly productive in terms of developing our concepts for data product validation and in raising issues concerning cross-calibration. I think we can look forward to significant progress in this area as we continue to work and refine the issues raised in Boulder.

I would like to call your attention to the list of Action Items included herein. For those of you to whom actions have been assigned please complete your tasks and report to me as soon as possible so that I may notify the group as to the status of those items.

I would also like to solicit your input in regard to facilitating communications between this office and your various groups and teams. Do you feel that existing communications are adequate to the task? If not, what (else) might you like to see implemented? With what frequency? Via what medium? Please send your responses via e-mail to me, and CC: Mitch Hobish (mhobish@nasamail.nasa.gov via the Internet, MHOBISH on NASAmail, or M.HOBISH on OMNET).

Thank you all for your continued support. It is becoming increasingly clear that calibration and data product validation will play a major role in the success of EOS.

(NASA-TM-108270) THE FIFTH
CALIBRATION/DATA PRODUCT VALIDATION
PANEL MEETING (NASA) 485 p

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Earth Observing System

EOS

Agenda

OMIT TO 5-1

Wednesday April 8

2:00 - 3:00	M. Chahine	Introduction to Validation Session - Programmatics, Objectives
3:00 - 4:00	R. Kahn	Validation Issues and Techniques
4:00 - 5:00	P. Bailey	Validation Lessons Learned from UARS

Thursday April 9

9:00 - 10:00	M. Chahine	Role of GEWEX / GVap in Field Campaigns
10:00 - 11:00	J. Bates	NOAA/Pathfinder Data Sets
11:00 - 12:00	All	Discussion
1:00 - 5:00	All	Working Group Meetings

Friday April 10

9:00 - finish	All	Validation Charter

Proposed Subcommittees:

In situ Data Group

Satellite Data Group

Model Data Group

Validation Techniques and Analysis Tools Group

Issues:

Statistical characterization of data sets

Finding statistics that characterize key attributes of the data sets
Defining ways to characterize the comparisons among data sets (Scale issues, statistics,...)

Selection of specific intercomparison exercises

Selecting characteristic spatial and temporal regions for intercomparisons
Impact of validation exercises on the logistics of current and planned field campaigns and model runs

Preparation of data sets for intercomparisons

Characterization of assumptions
Transportable data formats
Labeling data files
Content of data sets
Data storage and distribution (EOSDIS interface)

Attendance List

Carol J. Bruegge	MISR/JPL	(818)354-4956
Kevin F. Carr	Labsphere	(603)927-4266
Shelley B. Petroy	Labsphere	603/927-4266
WILLIAM P. CHU	SAGE III/LaRC	(804)864-2675
William T. Walker	Martin Marietta	(303) 977-8030
Douglas Berkner	Martin Marietta	(303) 971-9204
RONALD HAVERMANN	MARTIN MARIETTA	(303) 971-9691
Richard Heppner	Perkin-Elmer	(714) 593-3581
CARL R. MAAG	SAIC	(818)-335-6888
Ed Washwell	Lockheed	(408)743-0193
BRUCE BARKSTROM	NASA LaRC	(804) 864-5676
Robert B. Lee III	NASA LaRC	(804) 864-5679
D. Ometz	Westinghouse Space Div.	(410) 765-5825
Barbara Grant	RDC/NASA Goddard	(301) 286-2382
Chris Cromer	NIST	(301)975-3216
Peter Jarecke	TRW	(310)813-8756
Hugh Kieffer	USGS, Flagstaff	602-556-7015
Bob Barnes	Chemal, Inc	(804) 824-1637
JIM BUTLER	NASA/GSFC	(301) 286-4606
CATHERINE GAUTIER	UCSB	(805) 893.8095
FRANK EDEN	GE ASTRO	(609) 951 7822

Akira Ono	ASTER/	MITI, NRLM	298-54-4031
PHILIP SLATER	ASTER, MODIS	U of ARIZ.	602 621 4242
STUART F BIGGAR	ASTER MODIS	U of Ariz	602 621-8168
Larry D. Travis	EOSP	NASA GSFC/GISS	212 678-5599

TIR ATTENDANCE

April 7, 1992

Name	Affiliation	Instrument	Phone No.
Peter Abel	NASA/GSFC	MODIS-N	301/286-6829
George Aumann	JPL	AIRS	818/354-6865
George Bailak	Univ. of Toronto	MOPITT	416/978-1297
Robert Casper	Hughes/JPL	TES	310/616-2222
John Gille	NCAR	HIRDLS	303/497-1402
Bruce Guenther	NASA/GSFC		301/286-5205
Richard Heppner	Perkin-Elmer		714/593-3581
Don Hesketh	SpaceTec (NASA/LaRC)		804/865-0900
Mitch Hobish	RDC		301/982-3700
Larry Jacobsen	SPL/USU		801/750-4880
Donald Jennings	STC (NASA/LaRC)	SAFIRE	804/864-7766
Carol Johnson	NIST		301/975-2322
Anne Kahle	JPL	ASTER	818/354-7265
Nick Koepp-Baker	GE		609/951-7512
Robert B. Lee	NASA/LaRC		804/864-5679
William Mankin	NCAR	HIRDLS	303/497-1403
Bob Martin	JPL	Metrology	818/354-3145
Marty Mlynczak	NASA/LaRC	SAFIRE	804/864-5695
Hirokazu Ohmae	Fujitsu Ltd.	ASTER	81-44-754-2087
Frank Palluconi	JPL	ASTER	818/354-8362
Christopher Palmer	Oxford Univ.	HIRDLES	44-865-272890
Cesar Sepulveda	NASA/JPL	TES	818/354-1324
William Walker	Martin Marietta		303/977-8030
Richard Wanner	MMAG	I&T	303/977-2856
Robert Wright	NASA/LaRC		804/864-4743
Yasushi Yamaguchi	Geol. Survey/Japan	ASTER	81-298-54-3737

Jitin — Carol Johnson
Kent Baile

THERMAL INFRARED CALIBRATION WORKING GROUP

BOULDER, COLORADO
~~6~~ 7 APRIL, 1992

9:00 AM INTRODUCTION
Guenther-Present EOS Program, Impact on Calibration
Discussion
Agreement on Agenda

CROSS-CALIBRATION AT THE INSTRUMENT PROVIDERS
9:30 C. Palmer-Limits to Radiometric Accuracy

10:00 BREAK

10:15 H. Ohmai- ASTER Subsystem Calibration

CIRCULATING REFERENCE RADIOMETERS
Status and Development Schedule
10:45 C. Johnson-Role of NIST in TIR Calibration
~~10:45~~ 11:15 Utah State

CROSS-CALIBRATION AT THE S/C INTEGRATOR-OVERVIEW
11:~~4~~5 Present plans at GE
11:30 Utah State-Cross-Calibration Target

12:00 LUNCH

1:00 IN-FLIGHT CROSS-CALIBRATION
Y. Yamaguchi- In-flight Cross-Calibration

1:15 CALIBRATION PEER REVIEW PROCESS AND CONTENT
Discussion

2:15 THERMAL IR CALIBRATION WORKSHOP
- Review of topics
- Utah State Presentation
- Discussion

BREAK AT APPROPRIATE TIME

4:00 CALIBRATION HANDBOOK
Review of function, need, contents
Discussion

MINUTES
EOS CALIBRATION/VALIDATION PANEL
PLENARY SESSION

April 8, 1992
Boulder, CO

Bruce Guenther called the plenary session to order at 8:00am. He introduced Mitch Hobish, of Research and Data Systems Corporation (RDC) as the Cal/Val Panel's Executive Secretary, and distributed minutes from the fourth Cal/Val Panel Meeting, a draft of a cross-calibration plan, and a draft Data Product Validation Policy. He discussed the need for development of data product validation policy over the next 1-2 months, and stated that minutes for the current meeting will be available within two weeks of adjournment.

At 8:15, Bruce Barkstrom presented the report of the Reflected Solar Calibration Working Group (WG A) meeting of April 7, 1992.

Reports from relevant instruments had been delivered, including CERES, MISR, and SAGE III. Five instruments were classed as "hurrying along," four are delayed. Discussed were the philosophy of calibration; calibration equipment list; calibration geometry, including the instrument itself, chambers, and sources; error requirements and error budgets; and calibration traceability diagrams. Also discussed were equations, including instrument data reduction, calibration data reduction, and procedure outlines. The attendees also had generated a list of items to be depended on, which included: preflight and in-flight (crosscalibration) modeling/measurements, coefficient traceability, flight qualification of component characteristics, and mathematical models.

In regard to personnel for calibration reviews at PDR, it was strongly recommended that calibration representatives be on review panels. Schedule, cost, action items are all drivers, and would influence the project. It was suggested that one project member, one science member, and volunteers from the science community should attend reviews and be able to submit action items, to be cleared before adjournment of the review. There was some discussion of length of time necessary for adequate reviews, and the suitability of such reviews for the PDR process. No conclusion was reached concerning length of calibration review, but it was generally concluded that calibration reviews as part of the PDR process would make calibration more visible to project, which in itself was deemed necessary.

With reference to the Calibration Handbook, Barkstrom stated that a more structured outline was being generated. The group would like to make the handbook more "user-friendly" by making it readable and accessible. Electronic distribution of the handbook is the desired route, if possible. The group plans to come to closure on a template/format in 2-3 weeks, and then solicit response from all members of the community. There was some general discussion about the format for submissions, i.e., FrameMaker, TeX, etc. No conclusion was reached, although the need for standardization, especially in regard to e-mail transfers was addressed.

At 8:45 John Gille presented the results of the April 7, 1992 meeting of the Thermal Infrared Calibration Working Group (WG B).

The main item on their agenda was discussion of calibration reviews, with a stated goal of providing in-depth technical review and inputs by experts (peers). The suggested composition of the review panel included team members, calibration WG members, project engineers, NIST and community representatives. The review should be not later than PDR and CDR, although this could be a matter of negotiation between the PI and the Project Scientist. The desired output from such reviews would be a formal report by the peer panel, submitted to the engineering panel. This report could include action items and suggestions. What was found to be needed for refinement of such a plan was charter and a charge, and a method of coming to closure on action items. The group also felt that the contents of any presentations to a review panel should be consistent with mandated calibration plans.

Barkstrom stated that the output of a calibration plan is not necessarily consistent with scientific requirements; plans are usually designed to produce schedule, often contain extraneous material, and do not contain critical science items. ERBE documentation shows this. Gille stated that if such a document were assigned, it would be done. but that it is not on the list of TBDs at this time. Barkstrom wondered who would pay to accomplish action items, and felt that it had to be negotiated with GSFC Project. Guenther stated that is was his job to make sure things get done, and that assignment of an Action Item implies responsibility for payment.

Gille then discussed material that WG B felt should be covered in peer reviews (pre-PDR/CDR) with particular relevance to the AO-mandated activities (see APPENDIX). Their outline was generally congruent with that of WG A.

WG B also suggested that CERES present summary of their PDR presentation at next Panel meeting in September, with preliminary presentations by other instruments. Guenther stated that this must be discussed as no separate TIR meeting as such is planned for the September meeting.

Next was a discussion about calibration peer reviews relative to engineering PDR/CDR. It is deemed necessary to have common review panel members, and not just to have a paper trail. Specifics are still TBD, and Guenther will confer with the GSFC Code 300 representative who runs reviews.

A short report of TIR/WG B activities of the previous day followed, with a generalization of Chris Palmer's presentation/results. The conclusion was that there is no substitute for careful error analysis, and that there is a need for careful planning, and analysis of resultant data, based on the ISAMS experience on UARS. Stray light problems also must be attended to.

Next to be discussed was Ohmai's technique for raising temperature, and the measurements taken during heating and cooling in order to track changes in instrument performance over time in orbit. This brought on a discussion about thermometry, and problems with PRTs. Bob Haskins recommended that this be discussed in and with the larger group. Many present felt that there is already significant data available, including on-orbit data, and that such data should be obtainable from, e.g., NIST, UK, and others. These data indicate some drift, but that the observed changes may not be PRTs, and could be geophysical. This must be ascertained. There was some discussion of Ohmai's mathematical model of ASTER, with a statement from Yamaguchi concerning cross-calibration of ASTER that the instrument doesn't view space, so there's no cold target. He concluded that appropriate views of snow and ice fields might serve this purpose.

At 9:20 Dr. Ono presented his response to an Action Item from the previous Panel meeting. He discussed status of JERS-I (i.e., it is in good shape despite some problems with SAR antenna).

He also discussed the VIS/NIR and SWIR transfer radiometers developed at NRLM for pre- and post-flight calibration, especially in terms of avoiding mistakes, relative consistency, and absolute accuracy. He described two levels of comparison: at instrument manufacturers and at the platform integrator's site with comparison at national labs, and discussed round-robin measurement procedures. General discussion led to a consensus that 1% should be a common goal for all instruments. Ono presented of VIS/NIR and SWIR transfer radiometers constructed for ASTER comparisons, and presented data on long-term stability of these radiometers over 1.5 year span. It varies, but typically within 1% over 1.5 years. One radiometer was examined over 6 years: it, too was typically within 1% spectral radiance. Spectral characteristics appear stable over a 6-year period on a log scale, but on a linear scale there is some shift, which translates to 0.3-0.4nm. Industrial radiometers show larger size-of-source effects. He then showed recent data on round-robin comparisons over 7 sites, compared with a national lab, and his lab. There were small deviations, but well within "allowance level," i.e., <1% of radiance scale. The conclusion from this exercise was that round-robin measurements can demonstrate procedural errors, and indicate ways to improve. He concluded that round-robin measurements must be done more than once, as the first is basically a try-out; the second is required for good data.

General discussion led to agreement that more than one trial is required A question was raised in regard to whether the radiometer lens was cleaned properly, in that dust can make a stray light effect; were procedures in place? Ono stated that these results were not from a clean room. He stated that a detailed calibration manual has been prepared, and that humidity control important.

At 9:55 an Action Item Review from the fourth meeting's Items was presented.

4.01: TBD in peer review process

4.02: open item

4.03: no action

4.04: no action

4.05: closed

4.06: instruments to provide short version in response to item identified Barkstrom's materials.

4.07: open item (??)

4.08: partially closed. Input for mature cross-calibration plan needed in 4-5 weeks to provide input to GE for their planning purposes. A final plan is not needed at that point. There was some discussion re: GE/AM platform specific plan vs. project-level cross-calibration plan with embedded specifics for each platform. A mid-May timeframe would be great for overall plan. The time-sensitive issue is GE-specific; however, a general statement is needed. Guenther will do AM/PM specifics.

4.09+
4.10: (Now combined). The five AM instruments should meet during the week of 6/8(?) at GE for a one-day meeting for accommodation-specific issues, and vacuum chamber needs review. An agenda is to be distributed 4/24, with date selection to be 2 weeks later.

4.11: scheduled/closed.

4.12: open

4.13: open

4.14: open

4.15: open

The group took a break at 10:25, and reconvened at 10:35 with a Project Science Office (Calibration) Report by Bruce Guenther, and a discussion of the relation-ship to CEOS Working Group on Calibration and Validation (WGCV) (see APPENDIX).

NASA will provide terms of reference for passive microwave. So far the Calibration Panel has been relatively unsuccessful in generating critical mass of interest in this topic, although CEOS is interested. A general discussion concluded that ESA is relatively inexperienced with respect to passive microwave calibration. The solution is to have suitable representatives across the EOS program involved in process. The chair of that activity may be US individual, as NASA has the responsibility to make microwave activities happen. Guenther then presented the agenda for the next meeting in Abingdon, UK (May, 1992).

Next to be discussed were cross-comparison issues, such as sources, and radiometers. Guenther stated that there was no need to discuss this in depth, as it had already been discussed during this meeting; however, it has not yet been discussed (publicly) how it will be done, what is the cost, etc. Guenther has asked everyone who wants funding via the PSO to provide a 1-2 page proposal letter--by end of this month--describing the nature of planned of activities, hardware to be built, proposed schedule, and an estimate of how much it will cost. Since the University of Arizona activity is under MODIS and other activities, Guenther is not expecting anything from Phil Slater. The Japanese group is going forward with their own radiometer activities, so again, no letter is expected. He does expect a letter from NIST on concepts for building VIS/NIR and SWIR radiometer hardware, and possibly another supporting TIR radiometer approaches, and still another on VIS/NIR SWIR source (s). Langley should produce one on TIR radiometers and sources, and Utah State University should produce one on TIR sources. All of this should be put the cross-calibration plan, and distributed for comment. Guenther then opened the floor for discussion and comment about cross-calibration issues.

Robert Lee asked who will provide common information on spectral characterization of all filters, and asked if anyone had experience with Fourier transfer interferometers, especially since he was interested in measurements beyond 18ιm to longer wavelengths

Guenther stated that WG A is recommending going to each AM platform instrument team in the process of procuring flight filters for launch and asking some group to seek additional sets of filters (subset of channels, full set) in a common mechanical format, 1" diameter, built to flight specs (or similar). This creates a residual inventory of filters that match the bands of flight instruments, and would be made available on a circulating, 6-month basis for use in labs/field tests as part of the Calibration/Validation program. There is also the possibility of having one or several central locations to make measurements on filters, and make those data available. An open action item is how expensive is it to get extra filters at the time of flight filter production? One issue is that filters that are available are not radiation-hardened. In addition, there are no filters beyond 17ιm. The Action is on each instrument group to find costs for their own filters.

Next to be discussed was the Data Products Validation Policy development process. A draft of a policy statement was provided, primarily to highlight paradox existing in program. As it stands the draft policy is inadequate, but it is seen as a place to start. Guenther stated that details would be presented later during this meeting, with the hope that the group would look at all provided material and begin formulating ideas on what data product validation should be. The goal of this activity is to provide to the SEC or IWG a recommended data product validation policy for EOS. On the basis of this policy as we go through reviews, esp. CDR, we will judge whether people are doing their jobs well or poorly. It may not be this panel's final charge to do this, but we have responsibility to open up issues, and to lay the groundwork. The group is to provide written comments to Bruce Guenther and Mous Chahine as part of a consensus process. It was requested that the members be realistic (financially) based on limited funds, especially with respect to AO statements. It also was requested that members be realistic about the impact/implication of having their (or some other scientist's) name on a data product having gone thorough quality control for the first 6 months, but with no funds available past that. Inputs over course of the next month will go to PSO, for Guenther and Hobish to submit to Chahine, Gille, Barkstrom, and the Program Office at HQ for comments. After one more revision it should be a relatively mature statement, for review by Panel members. If consensus is then reached, it will be taken to the IWG and Program Office for submission as validation policy. Of particular importance is a statement about the right role for the Calibration/Validation Panel and the PSO for development of how data product validation activities will develop.

Discussion followed concerning the timescale for policy development. Guenther stated that it should be ready for the IWG meeting following the one currently scheduled for July. It should get to the SEC by November, and aim for mid-November to finish the process. Gille asked if Calibration and Validation should stay together as a panel, or if a separation was indicated. Guenther said to keep them together.

Guenther and Gille then discussed the possibility of holding evening sessions at future calibration/validation panel meetings.

Bruegge remarked that it appears that MODIS expends more energy in their own, private calibration meetings than they do at these EOS calibration/validation meetings. Other EOS-AM instruments look to MODIS for information on calibration issues. Very little calibration information was presented from MODIS at this meeting. She recommended that WG A meet for one day in conjunction with the MODIS Science Team Meeting.

Labsphere representatives indicated that would be willing to host an autumn calibration/validation meeting in New Hampshire.

At 12:15 the next Panel meeting format, location and date were discussed. It will be the week of September 14 in Logan, UT in conjunction with existing USU/SDL Cryogenic IR Sensor Calibration Conference.

At 12:30 the group was presented with a demonstration of OASIS Software by University of Colorado personnel (see APPENDIX).

The panel broke for lunch at 1:15.

The group reconvened at 2:00 to discuss Data Product Validation (DPV) concepts and processes. This session as chaired by Mous Chahine. The session was organized to help define what we mean by DPV (see APPENDIX).

Chahine proposed that DPV is an error bar with reference to a surface standard. For example, one could compare remote sensing data with in situ data using, e.g., radiosonde, or rawindsonde-derived data. He stated forcefully that we must be careful about what we assume is truth. The operational question, then, is how best to define DPV?

Haskins suggested that validation must take into account long-term and day-by-day measurements, including process studies. This was followed by a discussion of error bar problems. The consensus was that relative statistics along with absolute must be provided. If accuracy can't be met, then an unchanging metric (even with a built-in bias) may be useful anyway.

This raised the question, do all instruments have their own standards, or can we agree on standards? Experience with AIRS shows that even within an instrument there are difficulties between measurements. Standards are necessary, but not sufficient, and that any standard is only a starting point. We must deal with statistical properties of the parameters we wish to measure, i.e., strive for self-consistency of a data set over the time and space we wish to observe. Aumann asked if we were discussing first-principle error bars or heuristic error bars? This led to a discussion of absolute vs. relative validation. Chahine stated that zero-order validation involves looking for and finding an *in situ* measurement. Second-order is to compare your result with trends, climatology, variations, etc. Third-order is how well can one describe--on a 3 - 6h basis--same or related parameters to what you're dealing with? He also stated that validation is parameter-specific and that we must ask, therefore, which parameters can be grouped for validation purposes and by which standards?

It was concluded that data placed on EOSDIS as a standard set must have associated error bars. This is first instrument-dependent, and then parameter- dependent, and that long-term stability of instruments and model(s) must be taken into account. Indeed, we really need two error bars: accuracy, precision. This is likely unnecessary for each measurement, since trends are important here, but the concept must be addressed.

In order to address these issues, Chahine proposed the following subcommittees:

In situ data group: to deal with standard "yardstick" determination (zero-order validation);

Satellite data group;

Model data group: to deal with level II validation/models, 3-6h forecasts, etc.; and

Validation techniques and analysis tools group: to deal with software to allow you to understand how accurate *in situ* data are, look at trends, etc.

The idea here is to create small groups that will meet, and deliberate, and report back to the larger group with conclusions.

Gautier asked for a clear statement of the charge to these subcommittees, what specific data sets should be obtained, and what parameters should be addressed? Chahine said to look for commonality between instruments, i.e., how to validate cloud forcing between AIRS/AMSU, MODIS, CERES, etc. Each group should define a charter. We could then see how they all fit together. There was some discussion as to the size of the subcommittees, which led to a discussion as to the reasonableness of this as an approach, since there are over 200 parameters to be examined. Gille asked to hear from each team their approach to validation, especially since there appears to be little indication that the teams have undertaken this exercise. Slater asked if representation from IDS groups was needed, especially if we are addressing level 3 data.

Chahine stated that letters had been sent, inviting such representation to the Calibration/Validation Panel meeting, but that there was no or little response. A show of hands demonstrated that there were only two attendees out of 25 groups. Chahine opined that at the moment there is too broad a mandate for them to get involved.

Next on the agenda was a presentation by Ralph Kahn on Validation Issues and Techniques, based on the experience of the JPL Exploratory Data Analysis Team at validating HIRS2/MSU cloud parameters (see APPENDIX). Their work was well-received by the Panel, and may provide an excellent paradigm by which the rest of the EOS activities may operate. The main thrust of their approach was to start by establishing program flow control to provide a framework to place assumptions (IF statements). While they started with existing code, Kahn stated that they could do the same kind of analysis based on first principles.

The Panel took a break at 4:00, and reconvened at 4:20 with a presentation by Paul Bailey on Validation Lessons Learned from UARS (see APPENDIX).

Bailey's presentation emphasized the need to get IDS investigators involved early and often, despite their own antipathy and apathy with respect to validation plans, etc. He was most emphatic about the need to learn from the mistakes of others, and that EOS (or any other program) would be remiss if they did not take advantage of the "corporate memory" available from experience with missions such as UARS.

The Panel adjourned at 5:20PM.

Minutes
Reflected Solar Working Group
April 7, 1992

Bruce Guenther presented a review of the restructuring of the EOS program. He stated that 5 or 6 EOS platforms are planned to be flown, with the first platform (the first AM platform) scheduled to be flown in the summer of 1998. The second platform (the first PM) is scheduled for launch two years after the first. The set of all 5 or 6 spacecraft constitutes the EOS mission. The replacement of Jeff Dozier, the EOS Project Scientist, will conducted through open advertisement of his position. The EOS AM Project Manager is Chris Scolese, with Bruce Guenther as EOS AM Project Scientist. The PM Project Manager is Marty Donohoe, with Les Thomson as the PM Project Scientist. In his remarks, Bruce Guenther also requested input from the working group on the what should be covered in the Calibration PDR's.

Bruce Barkstrom gave a presentation on CERES. The calibration chamber for the instrument has been modified, since CERES must be calibrated completely in vacuum. The integrating sphere for CERES calibration will be modified to isolate it thermally from the instrument, reducing interference from long wave ir radiating from the sphere. The accuracy goals for the chamber are 1% in the visible and 0.3% in the long wave ir. The testing of the instrument will begin around April 20, 1992. The PDR for CERES will be held in mid-June 1992. The ERBE instrument had scan dependent offsets in its measurements. Bruce Barkstrom feels that ERBE provided a valuable lesson for CERES and that these problems have been corrected in the CERES design. The thermistor bolometer detectors for CERES have been made by the Servo Corporation. Ed Washwell commented that Lockeed had many years of experience with thermistor bolometers for horizon sensors. Barkstrom said that details on the design and development of the CERES processing system will be made available to interested parties in the future. Barkstrom also presented information on the CERES prototype documentation system and a diagram on the CERES data flow. CERES is working toward providing electronic access for its documentation.

Carole Bruegge spoke about the MISR instrument. MISR has become a project within JPL. The onboard calibration design for MISR has not changed. The instrument will still deploy two diffuser panels, using photodiodes to check the degradation of the panels. Carole circulated copies of the calibration dictionary and of the EOS field-of-view comparison report. MISR will be the driver on the size of the GE integrating sphere. Phil Slater asked what type of radiances are assumed in the MISR reflectance-based measurements. Carole answered that MISR uses top-of-the-atmosphere radiances. Carole also discussed the use of fidelity intervals as a tool to determine the uncertainty of the MISR radiances and as a tool to calculate MISR signal-to-noise ratios. Bruegge presented information of the photodiode calibration facility at JPL and a compendium of information on the properties of diffuser materials. Because of problems with static charge buildup, the proposed baseline diffuser design for MISR has spectralon coated with indium-tin oxide (ITO). However, this type of diffuser must be characterized for space flight. In addition, Carole presented data showing a specular peak in the BRDF for ITO-coated spectralon that was more pronounced at longer wavelengths.

Bill Chu reported that there was nothing new in the calibration of SAGE III. He reported that SAGE III will begin phase CD within the next two years and that the PDR for SAGE III is scheduled for the third quarter of 1995.

Barbara Grant spoke about activities of the MODIS characterization team. She requested input from all interested parties about the MODIS Calibration Plan and Handbook, which are currently being compiled. The handbook will provide results of calibration activities, in addition to supporting information for those who will use MODIS data. The calibration plan will review and integrate all methodologies in the calibration of MODIS. The characterization team is currently working on the selection of homogeneous calibration sites on the Earth.

Larry Travis discussed developments with EOSP. This instrument is scheduled to fly on the second AM platform, and the phase B study for this instrument has been completed. EOSP will not be a driver in the design of the common preflight cross-comparison source. The EOSP project continues to be interested in Carole Bruegge's diffuser studies.

Catherine Gautier spoke on AIRS, which is scheduled for flight on the first PM platform. She works on the visible, short wave portion of AIRS, an instrument that is primarily dedicated to long wave ir measurements. She hopes to apply much of the work from MODIS to her own calibrations. Preflight calibration of AIRS will be performed by LORAL. AIRS will use several inflight calibration methods, coupled with vicarious cross-calibrations with MODIS. Gautier is currently performing a cross-calibration study using data from AVHRR channel 1 and the single visible HIRS channel. The AIRS project is also examining the problem of polarization in the short-wave channels. In addition, the AIRS project is looking for several areas of homogeneity on the Earth's surface for vicarious calibration of the instrument.

Chris Cromer of NIST presented ideas for instruments to be used as transfer standards in the round-robin comparisons. He identified the weak link in these standards as their interference filters and indicated that the radiometers could be tested for polarization effects. Chris Cromer said that NIST was not prepared to build these instruments under low-bid conditions but that NIST would be willing to calibrate the transfer standards.

Hugh Kieffer spoke about the HIRIS project. HIRIS is scheduled to fly in 2005. The project has been put into mothballs, to be resurrected later. There has been a significant migration of HIRIS personnel to the MISR project.

Denny Ometz from Westinghouse spoke on TRMM and the new AVHRR. TRMM is scheduled for launch in 1997, and the instrument is a joint US-Japanese project. AVHRR will carrry inflight calibration devices, including a diffuser that measures solar flux as the instrument passes over the poles. The AVHRR project are looking for 5% absolute accuracy and 2% stability from the instrument during flight. Ometz will be performing studies in parallel with EOS and hopes to share information with those working on the EOS instruments.

Stuart Bigger spoke on radiometers from the University of Arizona that will be used in EOS cross-calibrations. Four instruments have been proposed to make measurements from 0.4 ιm to 14 ιm. They are currently constructing a silicon QED-based instrument that operated from 0.4 to 1 ιm. Other, longer wavelength instruments will be constructed later. The instrument under construction is designed for operation at ambient temperature and pressure. Stuart Bigger needs to know if the radiometer must be designed to operate in a vacuum. In addition, he needs to know the radiances from the sources that he will measure over the wavelength ranges of interest. He also needs to know the schedules for the calibration of the flight instruments. Transmission measurements of the interference filters in the Arizona instruments will be made with a modified CARY spectrometer, using the same beam geometry as used in the travelling radiometers. Stuart would also like to have the efficiency of his trap detectors measured at NIST.

Hugh Kieffer spoke on lunar calibrations. He reported that his project was on schedule for the development of the ground-based instrument. The project has initiated procurement of the detector for visible measurements, and the design of the telescope is near completion. Kieffer anticipates the start of measurements late in the summer of 1993. Three instruments (SeaWiFS, MODIS, and HIRIS) have indicated that they will use lunar measurements as part of their baseline calibration requirement. Kieffer is interested in establishing a set of wavelength bandpasses for his observations. He is estimating measurements in 6 to 20 bands. Hugh has been providing values for lunar radiances to those 3 instruments, so that their gains can be set.

Akira Ono presented a brief discussion of the ASTER calibration. He listed the set of requirements that have been given to the contractors who will build the instrument. Ed Washwell commented that the tight tolerances of those requirements could lead to a very expensive instrument, even by EOS standards.

Bruce Barkstrom presented a list of calibration topics to be covered at the instrument PDR's. Barkstrom also asked for comments from the working group about this list. The PDR topics, as approved by the working group, will be presented as an appendix to these minutes. Hugh Kieffer stated that he would like to know which items can be measured by each instrument post-launch, as opposed to those which must be determined from pre-launch measurements and calculations. Barkstrom then discussed the selection of review panel members for the calibration portions of the PDR's. Barkstrom strongly suggested the inclusion of 1 project member, 1 science member, and volunteers from the science community on the review boards. Carole Bruegge recommended that the complete set of action items from each PDR be assembled before the completion of that review. This practice is generally followed, but the panel strongly endorsed closing the action item list at the end of the review. The panel agreed that the calibration PDR's be handled as a peer review process and that the calibration PDR's be contiguous in time with or included in the engineering PDR.

Bruce Barkstrom led a discussion on the fate of the calibration handbook. It was decided that the handbook remains an important product from the panel. Barkstrom expressed the desire for the project to more actively coordinate its preparation. Bruce Guenther took responsibility for the slow progress of the handbook; he also pointed out that no work is waiting to be done on the handbook at this time. Hugh Kieffer recommended that the handbook include the references (sources) for detailed information from each instrument and include the traceability of the absolute calibration for each instrument. He suggested that the person to coordinate this part of the handbook would be from the EOS project. Carole Bruegge suggested that each instrument present the same information topics in the handbook, that is, that the handbook have a consistent format for each instrument.

Hugh Kieffer proposed a plan to coordinate the bandpass filters for the radiometers in the cross calibration of the EOS instruments. A copy of that proposal is included as an appendix to these minutes. The delivery schedule and cost for these filters remains to be determined. For each selected narrowband filter it was decided that 10, 1-inch diameter filters be produced for cross comparisons. The total number of bands in this set was recommended to be around seven. Bruce Guenther recommended that the information about these filters be coordinated by Carole Bruegge for distribution to the instrument managers.

Minutes
Thermal Infrared Working Group
April 7, 1992

The Thermal Infrared working group was opened by Dr. Gille. The agenda was briefly discussed, with no additional items suggested for inclusion. Gille referred to the recent stressful period in the EOS program resulting from budget cuts imposed by the Congress and by the move towards downsizing the space platforms and renewing emphasis on free flyers, as proposed at the EOS Engineering Review. He showed a table of EOS instruments now recommended for flight in the early 21st century, and invited Dr. Guenther to comment on EOS program restructuring that may result. Guenther responded that "deselection" of certain instruments had reduced the scope of the science that could be done, and that the emphasis was now on measuring and understanding global climate change as the top priority activity. Two large observatories under previous plans would become 6 platforms with lower overall capability, but the change was one of implementation rather than style, The mission remained as Mission to Planet Earth, with unchanged organization, but with some routine personnel changes. Asrar would replace Stan Wilson as Program Scientist at NASA HQ (Wilson is moving to NOAA). Jeff Dozier, Project Scientist at GSFC, will return to UC (Santa Barbara) in the Fall, and the vacancy will be filled through open competition. Chris Scolese is the manager of the AM platform at GSFC, with Guenther as project scientist. Marty Donohoe and Les Thompson perform equivalent roles for the PM platform. Guenther announced that he had appointed Mitch Hobish to take over Guenther's responsibility as Executive Secretary of the Calibration and Data Product Validation Panel, effective immediately, and noted that the Panel's working groups need to consider the topics to be reviewed at upcoming PDRs. These will begin in June, 1992, with the CERES PDR, and will complete the first phase with the AM platform PDR in January or February 1993.

Chris Palmer reviewed limits to in-orbit radiometric calibration accuracy, and illustrated his remarks with references to ISAMS data. The "telemetry equation", relating input radiance to output counts, is usually cast to ignore or underestimate various small effects that are significant at the level of tenths of a percent of full scale. Such effects include nonlinearity, non-additive detector processes, interdependence of telemetry equation parameters such as spectral response and field-of-view, and uniformity of illumination of the entrance aperture. The conclusion is that stray light effects can amount to several tenths of a percent even when careful attention has been paid to their exclusion and characterization, and that stray light effects may be considerably more important in the error budget than more traditional culprits, such as thermometry uncertainties. Radiometric offset measurement is another significant source of uncertainty, particularly at low target radiance levels. Differences between the offsets measured while observing space and in effect while observing the Earth can be significantly different. Palmer noted that polarization effects were found to be insignificant for ISAMS.

H. Ohmai briefly discussed ASTER TIR subsystem calibration. An internal blackbody at 270K is observed for 10 seconds ("short term" calibration) or for 20 minutes while the temperature is continuously raised from 270K to 340K ("long term" calibration). The blackbody takes approximately 100 minutes to cool back to its equilibrium temperature of 270K. ASTER cannot view space. Palmer suggested that higher accuracy may result by observing steady state plateaus rather than steadily rising non-equilibrium temperature distributions in the target.

Carol Johnson reviewed the probable roles of NIST in the EOS program. NIST is not a regulatory agency; therefore, the agency is uncomfortable with the notion that calibration accuracy is "traceable" to NIST standards. NIST's clients are usually government agencies, predominantly DoD. They are provided with technical support and applied research services according to a fixed fee schedule. In recent years NIST's mandate has been expanded to include support to industry in the development and commercialization of new products and processes. The Radiometric Physics Division offers standard reference materials (SRMs, books, radiometric sources, detector packages) and calibration services such as source characterization and calibration, cryogenic ESR detector comparisons, and a LBIR (low background infra red) source. Johnson appealed for more information on requirements for the "round robin" intercomparison program, so that NIST can prepare a suitable proposal, and a discussion ensued. George Aumann said that the first step is to identify the weak points in the error budget for each instrument, then to determine "round robin" requirements. Bob Martin asserted that the first step was to establish that each manufacturer has control of its calibration error budget, while Chris Palmer felt that knowledge of the detailed physics and performance of the instrument was key. Guenther noted that the objective of the "round robin" was to establish commonality of instrument data sets, so that implementation must be a single coordinated community effort. This topic will be further discussed at the Utah State symposium in September.

Larry Jacobsen discussed TIR calibration experience at Utah State. The group has 20 years of activity in sensor calibration, much of it for upper atmosphere rocket experiments to observe the aurora. Three multifunction calibration vacuum chambers (called "MICs") have been constructed to calibrate a variety of TIR sensors. The MICs allow illumination of a sensor entrance aperture under a range of well-controlled conditions, and with selectable sources. Controlled parameters include source radiance, illuminated area, illuminated solid angle, and variable background radiance.

Nick Koeff-Baker discussed activities at G.E. Instrument's calibration will be verified on arrival at G.E., verification being a base calibration with limited resources available. After platform integration, calibration will be available in a T/V chamber with a calibration target that may be supplied by the instrument team, and probably would be the one used for earlier calibration activities at the manufacturer's facility.

Y. Yamaguchi addressed inflight cross-calibration of ASTER/TIR and MODIS-N. This has the potential of improving ASTER calibration at low radiances (brightness temperatures as low as 220K), since ASTER cannot view space as a calibration target. Bands 11 and 14 of ASTER are close spectral matches to MODIS-N bands at 8.55 and 11 microns, but are mismatched in spatial resolution. Yamaguchi suggested that suitable transfer targets could be snow/ice fields in Greenland and Antarctica, or cloud tops, with spectral band models used to correct for differences in atmospheric transmittance. Feasibility calculations, in particular for atmospheric corrections (including clouds), and target selection, are incomplete.

There was a discussion of the Calibration Peer Review process, intended to provide in-depth technical reviews of plans and activities to the PDR and CDR meetings. Several questions remain to be resolved, such as who will select the review team, who is eligible to be a team member, definition of the team charter, the schedule for report delivery, and how to close action items identified by the team. The team should ensure consistency with the closely related information contained in the Calibration Plan.

The draft agenda of the TIR workshop planned for Utah State in September was discussed, and modifications were proposed to emphasize cross-calibration methodology, results from end-to-end calibration studies and in-orbit environment (e.g. South Atlantic anomaly). It was felt that less than the planned emphasis should be given to a discussion of data analysis and archiving. The meeting adjourned with insufficient time to address the last agenda item, a discussion of the format and contents of the Calibration Handbook.

Minutes
AM Observatory Evening Splinter Working Group
April 7, 1992

The first meeting of the EOS AM Observatory Splinter WG was held on the evening of 7 April 1992. All five AM Observatory instruments were represented among the 26 people in attendance. Presentations were provided by Nick Koepp-Baker, General Electric AM Observatory Project, and Carl Maag, SAIC.

Koepp-Baker covered two areas in his presentation. The first area was a description of the current (tentative) instrument accommodation for the AM platform. The now-best observatory design has been improved recently. These designs are implemented against the constraints of a three-foot extended fairing Atlas IIAS-class launch vehicle. The design with the extended fairing is a tight design, which typically allows less than 20 cm between the instruments or an instrument and platform subsystem module. Some instruments are tight to the estimated static envelop for the fairing, and the actual fairing static envelop may be smaller than we are working with in this accommodation. Koepp-Baker also made the point that any instrument stimuli designed to be used with the instrument while that it is housed on the platform must conform closely to that instrument's allotted "footprint".

Acoustic shock testing requirements have been established for the instruments which must be met through testing of the instruments before they are delivered to GE. This (new) requirement has been added in response to our earlier concerns that the instruments were scheduled to see new environments after their final calibrations. This WG recommended that a complete review and reevluation of the rationale for calibrations and testing schedules be accomplished during the Platform and Observatory Preliminary Design Reviews in the coming few months.

Koepp-Baker also presented the current concepts which GE is developing for Integration and Test of the instruments. The schedule for completing all the required testing at GE is tight. Approaches to recover from late instrument delivery are being investigated, and carried as contingencies within these schedules, but these contingencies are not shown explicitly on the schedules. We now have the opportunity to use an instrument specific target when an instrument is attached to the platform. The I & T "flow" indicated that the platform will experience significant handling during its tenure at GE, and also will spend a great deal of time in Bay 8. An instrument will accumulate a certain amount of dust (dirt) on its surfaces if it sits anywhere for a year, even if that location is reasonably clean. Contamination in Bay 8 is likely to be a significant problem for the instruments, and it was suggested to the instrument calibration representatives that they should be planning to bag their instruments and require a clean purge of the bag during as much of the I & T flow as possible.

Two candidate chamber at GE were shown as the location of the cross-calibration. One chamber is a 24 foot diameter chamber which is cryo-pumped and clean for these tests, and a second chamber which is 8 foot diameter, but is an oil-pumped chamber. The larger chamber is used very frequently, and the primary concern for committing to this chamber as the cross-calibration location is the expected difficulty in getting access to the chamber as needed during the EOS AM platform I & T flow. The smaller chamber would require the addition of a large flange to house the cross-calibration targets, change of oil pumps to cryogenic pumps, and replacement of the oil-contaminated shroud inside the chamber.

Funds to use for improvement in the smaller GE chamber to a clean chamber environment for EOS may be difficult to find. The chamber is GE capital equipment and usually improvements to such equipment would be through internal GE funding sources. In the current budget situation, GE may not be able to provide these funds. Resources might be made available by the EOS Project, but that approach also offers significant problems. EOS does not have this improve-ment within its budget, and the use of government funds for the improvement of a company's capital equipment is unusual.

Maag's presentation reviewed the current status of contamination of spacecraft and instruments while they are in shuttle or low earth orbit. The contamination showed that instruments typically undergo modest degradation due to contamination in orbit. The degree of contamination-related reduced performance is significant in comparison to the long-term stability requirements for this mission. The AM Observatory currently does not have any contamination diagnostic equipment contained within its baseline design, and there was significant support expressed by the instrument calibration representatives to seek a change in this status. Each AM Observatory instrument has been asked through their calibration representatives to provide a written set of comments on their present position on this issue. These comments should be provided to the AM Project Scientist within the coming month.

ACTION ITEMS

EOS Calibration/Validation Panel Meeting
April 8, 1992
Boulder, CO

5.1 To Calibration Handbook WG: In next 3 weeks, arrive at a template for the EOS Calibration Handbook.

5.2 To EOS Project: In next 2 weeks, provide meeting attendees with minutes to this meeting and with copies of all handouts.

5.3 To B. Guenther: Must meet with the NASA/GSFC Code 300 representative to discuss content of PDRs.

5.4 To EOS Cal/Val Panel Members: Provide comments to B. Guenther on the draft cross-calibration plan, by 5/8.

5.5 To B. Guenther: put together an agenda of topics to be covered in the visit to GE integration facility and circulate this letter to panel members.

5.6 To EOS Cal/Val Panel Members: two weeks following receipt of the aforementioned letter, provide B. Guenther with a list of dates in which the visit to GE could take place.

5.7 To B. Guenther and C. Bruegge: Work on incorporating input from WG B into the instrument comparison questionnaire.

5.8 To EOS Cal/Val Panel Members: Provide comments to B. Guenther by 5/8 on the distributed version of the data product validation policy with emphasis on defining the role of the Cal/Val panel in this process.

EOS DATA VALIDATION PLAN TEMPLATE
DRAFT 2

1.0 INTRODUCTION

1.1 Experiment Overview

1.2 Validation Criteria

1.3 Validation Approach

- Physical constant standards
- Approach to:
  - identifying internal assumptions
  - test for internal consistency / summary statistics
  - comparisons with other data sets

2.0 DESCRIPTION OF EXPERIMENT PHYSICAL MODEL

2.1 Measurement Concept and Basic Equations

2.2 Forward Radiance Model

- Radiative transfer
- Numerical approximations
  - Range of error values
- Physical constraints (e.g. line parameters summary, plus reference)

2.3 Inversion Approach

- Brief description of basic approach
- Constraint methods
- Numerical approximations
- Use of a priori information

3.0 DESCRIPTION OF INSTRUMENT CHARACTERIZATION AND CALIBRATION

3.1 Accuracy and Stability

- IFC, temperature effects, noise, scale, and bias error stability

3.2 Spectral Response and Registrations

3.3 Spatial Response

- FOV

- Off-axis rejection

3.4 Pointing

3.5 Electronics Response

- Amplitude and phase

- Crosstalk

3.6 Data System Errors

- Gain uncertainties

- Digitization errors

3.7 Summary of Uncertainties with References

4.0 ERROR ANALYSIS

4.1 Sensitivity to Errors in Instrument Model

4.2 Sensitivity to Errors in Forward Radiance Model

4.3 Sensitivity to Inversion Algorithm Errors, Including A Priori Assumptions

4.4 Spacecraft Effects

- Altitude

- Attitude rates

- Ephemeris

4.5 Uncertainties Due to Data Transmission (e.g. altitude Interpolation, True to Earth to IAU)

4.6 Estimate of Total Measurement Error

5.0 PRE-LAUNCH ACTIVITIES

5.1 Instrument Investigator Obligations

5.1.1 Define post-launch instrument verification procedures

5.1.2 Algorithm Test Data Set Creation (Instrument Simulation)

- Test atmosphere creation

- Synthesize radiances with production algorithm and add instrument and other error sources (create Level 1 data)

- Perform retrievals (create Level 2 data)

- Statistical comparison

5.1.3 Define post-launch data product validation procedures

- Documentation / Data Format
  - Characterization of assumptions
  - Transportable data formats
  - Labeling data files
  - Content of data sets
  - Data storage and distribution (EOSDIS interface)

5.2 Validation Software Tools

- Identify and develop tools and methods which will expedite post-launch validation

  - Statistics that characterize key attributes of the data sets

  - Comparisons among data sets (Scale issues, statistics)

- EOSDIS Toolkit interface

5.3 In situ Field Campaign Strategy

- Selection of specific intercomparison exercises

- Selecting characteristic spatial and temporal regions for intercomparisons

- Coordination with other investigations

5.3 IDS P.I. Support

- Specific Contributions by IDS teams that will aid data validation

6.0 POST-LAUNCH ACTIVITIES

6.1 Instrument Investigator Obligations

6.1.1 Implement instrument verification procedure

- Monitor calibration stability (e.g. scale factor, bias)
- Verify spectral registration
- Verify spatial response characteristics
  - Evaluate correlation of instrument signals with orbital events such as (e.g. south Atlantic anomaly, other instrument turn-on events, terminator crossing)

6.1.2 Update error analysis as necessary

6.2 IDS P.I. Support

- Specific Contributions by IDS teams that will aid data validation

6.3 Intercomparisons

6.3.1 Guidelines

- Number of comparisons with correlative measurements, locations, times, coincidence criteria (time, space)

6.3.2 Climatology

6.3.3 Field campaign Data

- Aircraft, balloon, ground-based

6.3.4 Other EOS measurements

6.3.5 Other space-based measurements (e.g. NOAA satellites)

6.3.6 Theory and derived products

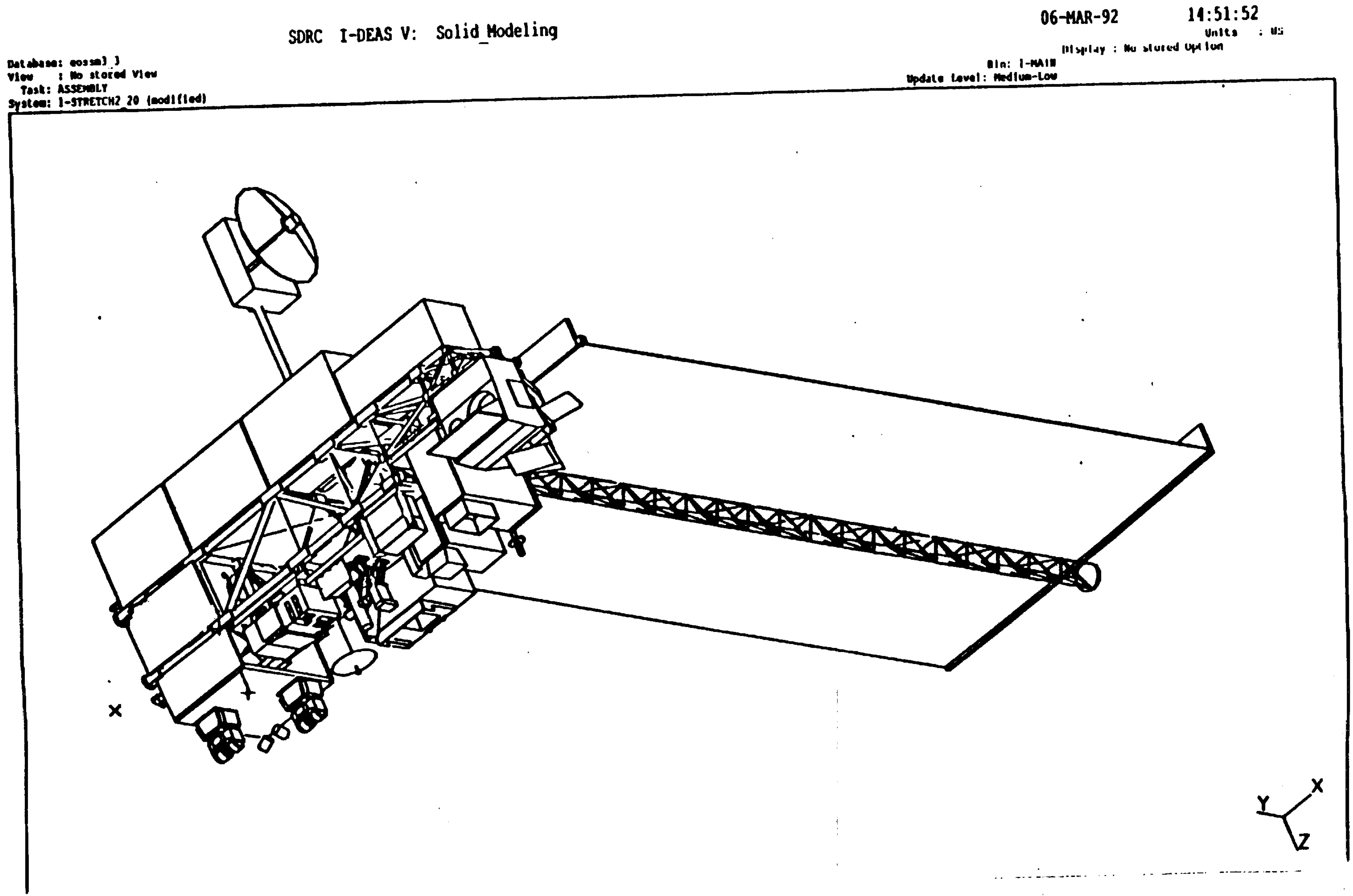
7.0 IMPLEMENTATION

7.1 Detailed Schedule with Milestones

- Completion of on-orbit instrument verification in procedure plan
- Completion of on-orbit instrument verification in procedure plan
- Completion of initial on-orbit instrument verification procedures
- Validation of Level 1 products
- Validation of Level 2 products
- Validation of Level 3 GCM based products

7.2 Resource Requirements

- Personnel and equipment
- Funding
- Other



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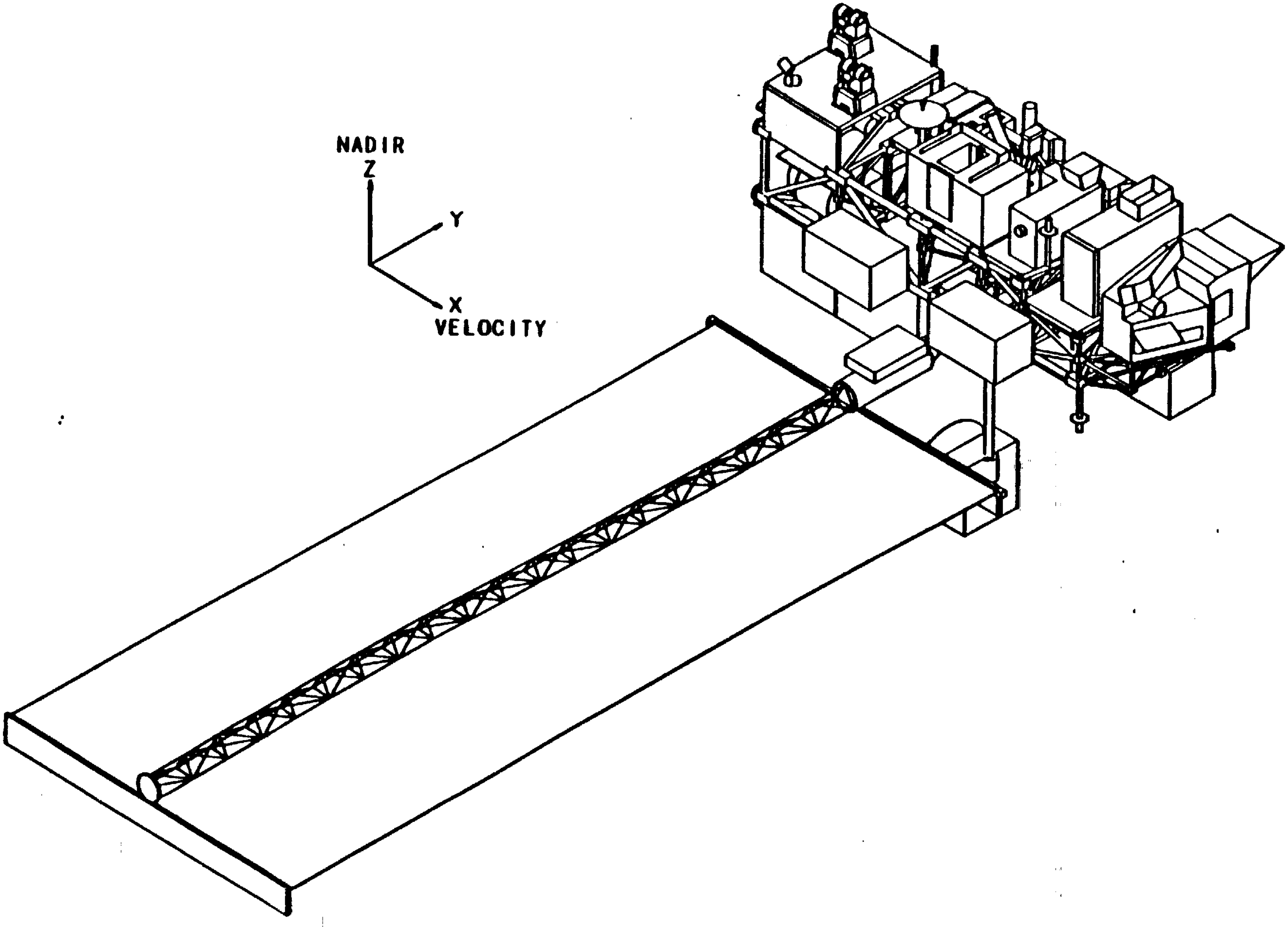
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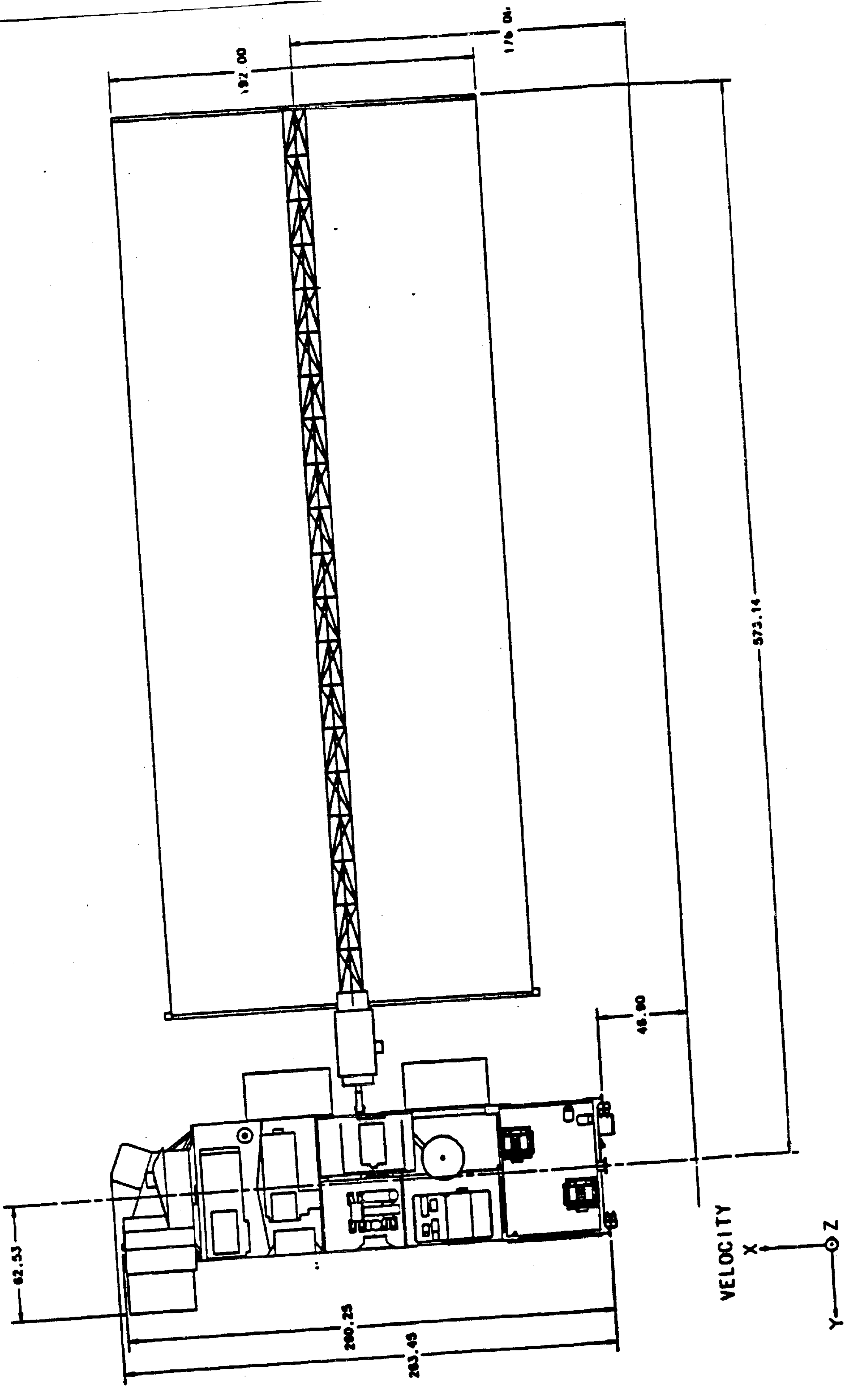
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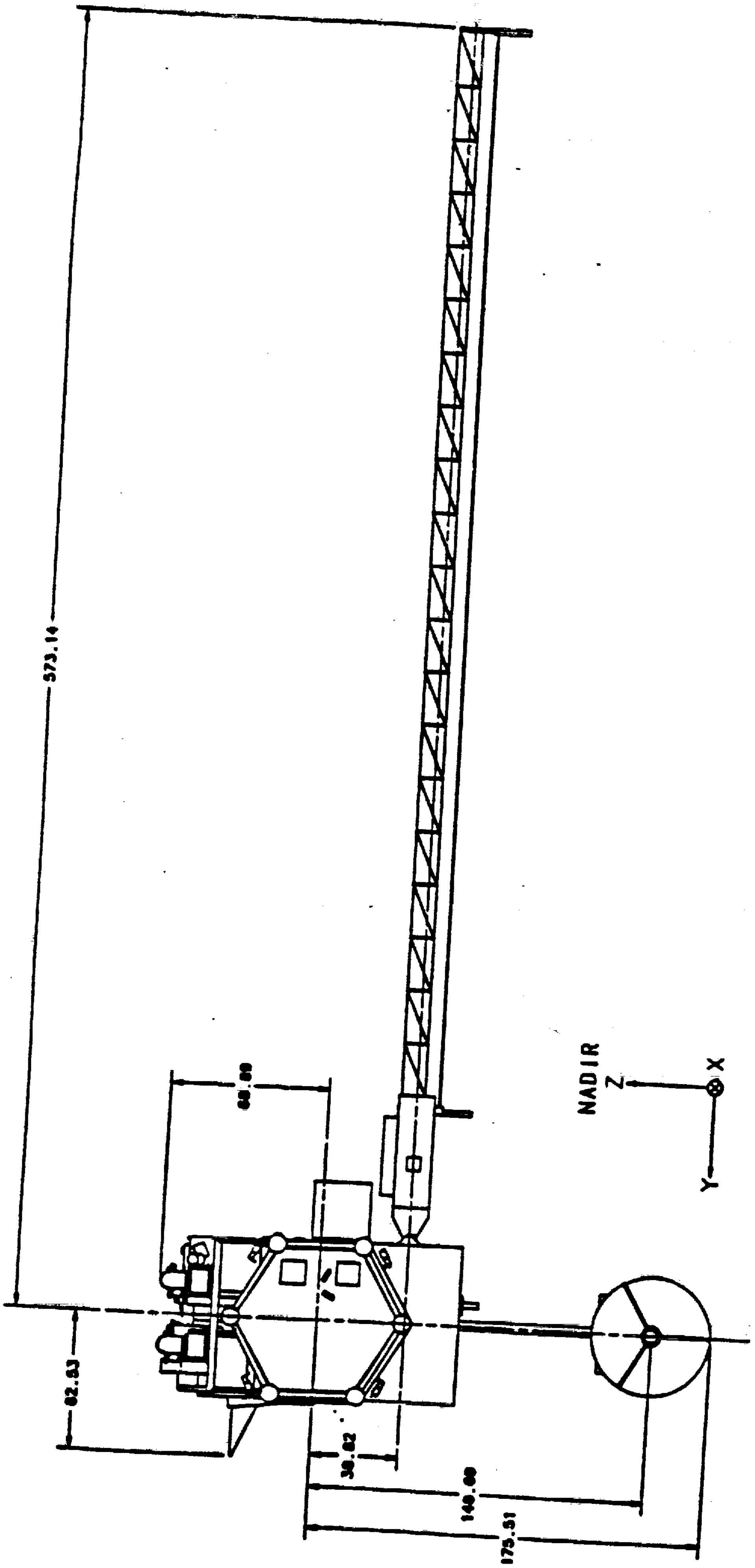
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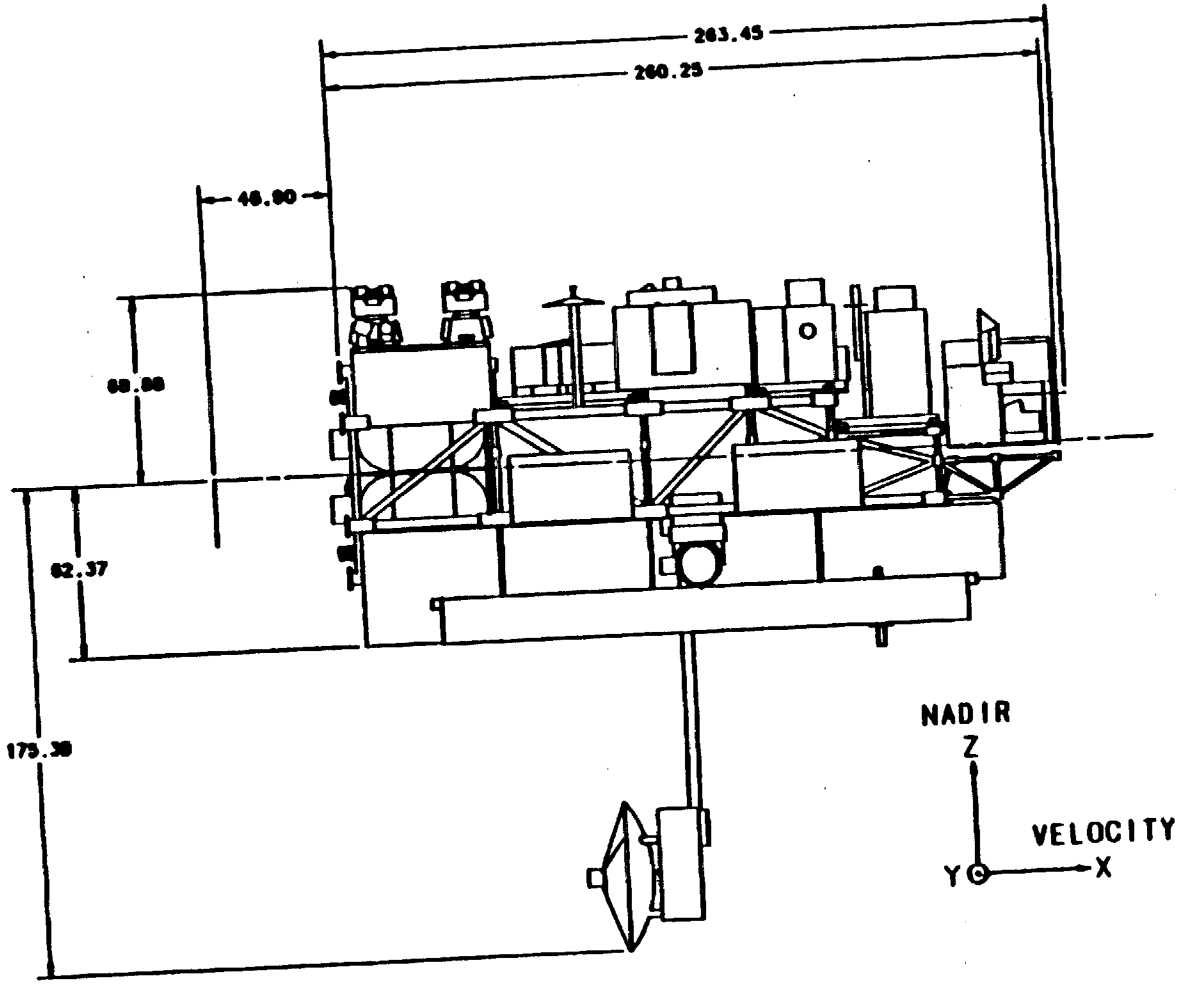
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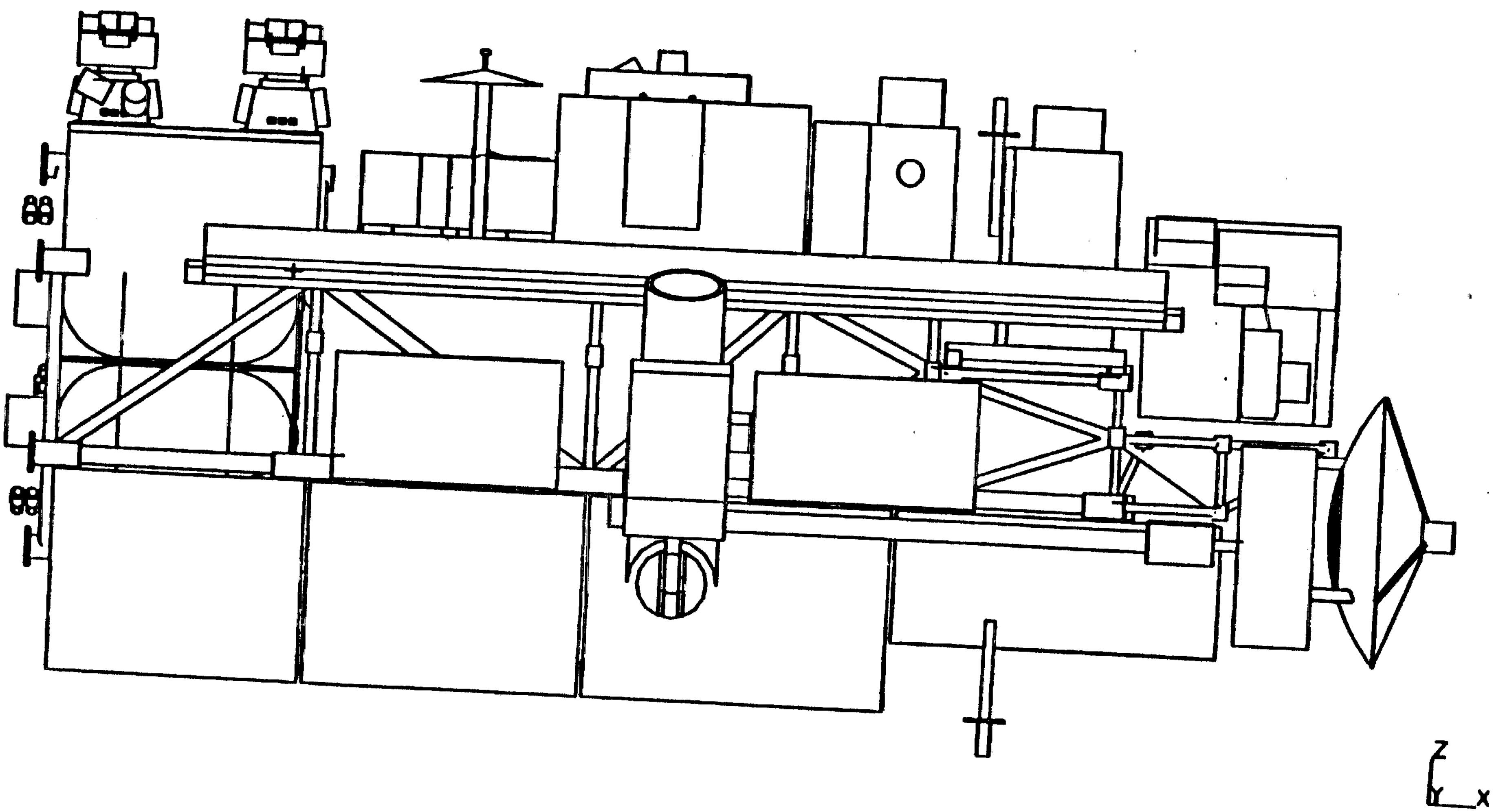

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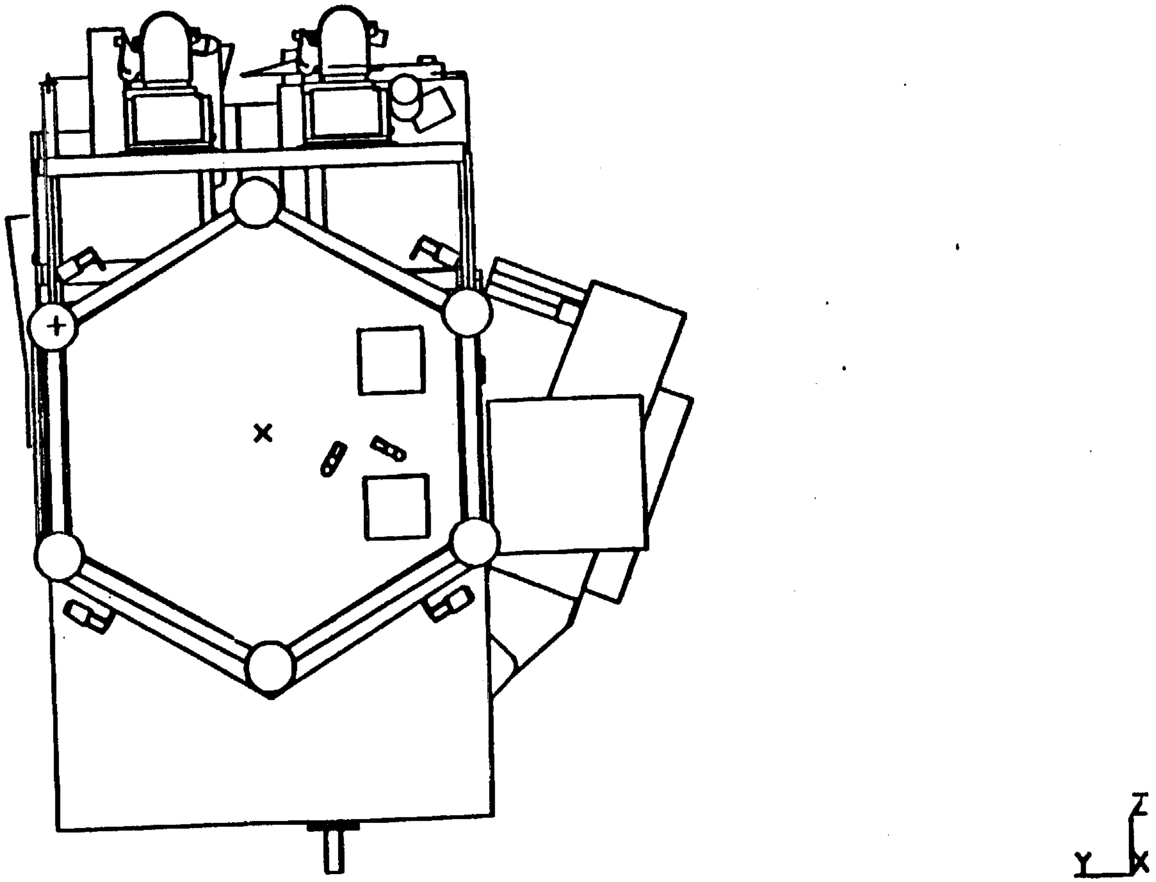

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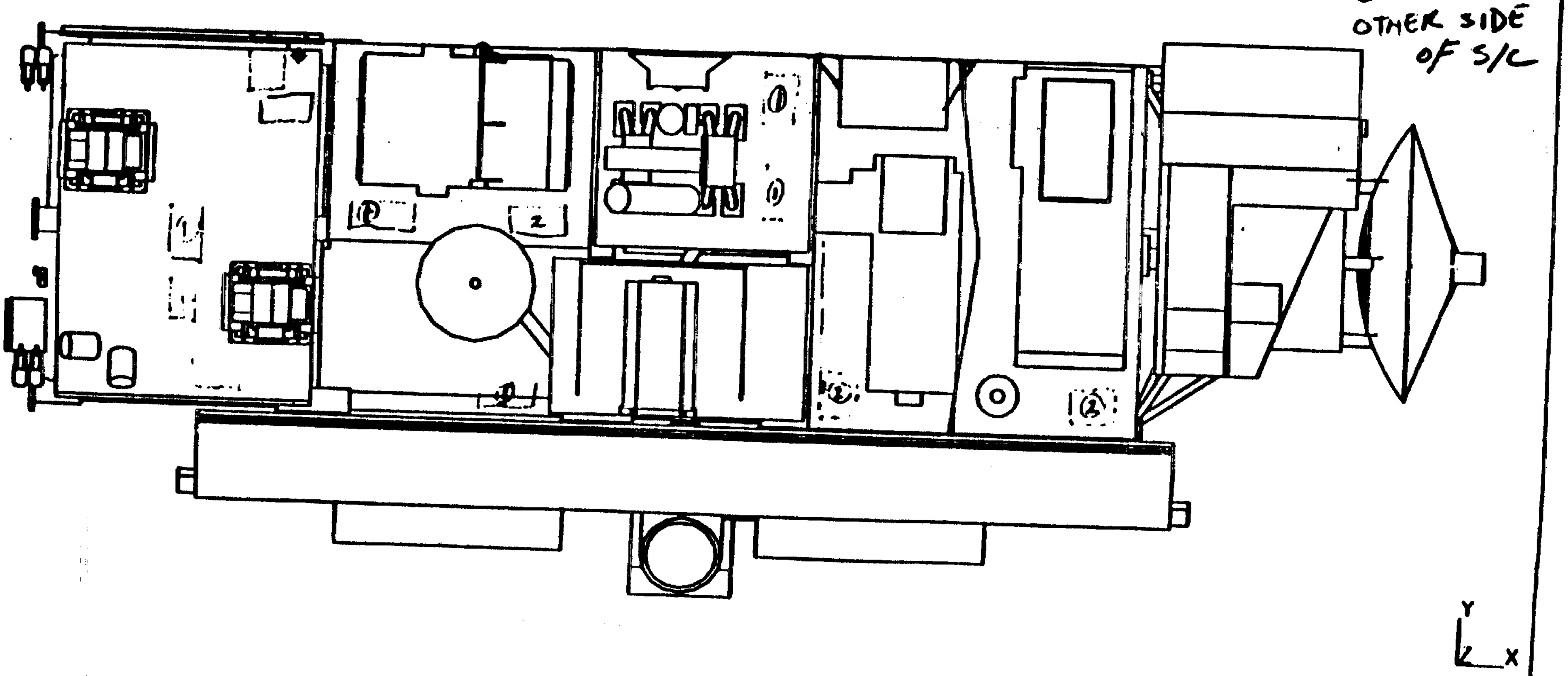

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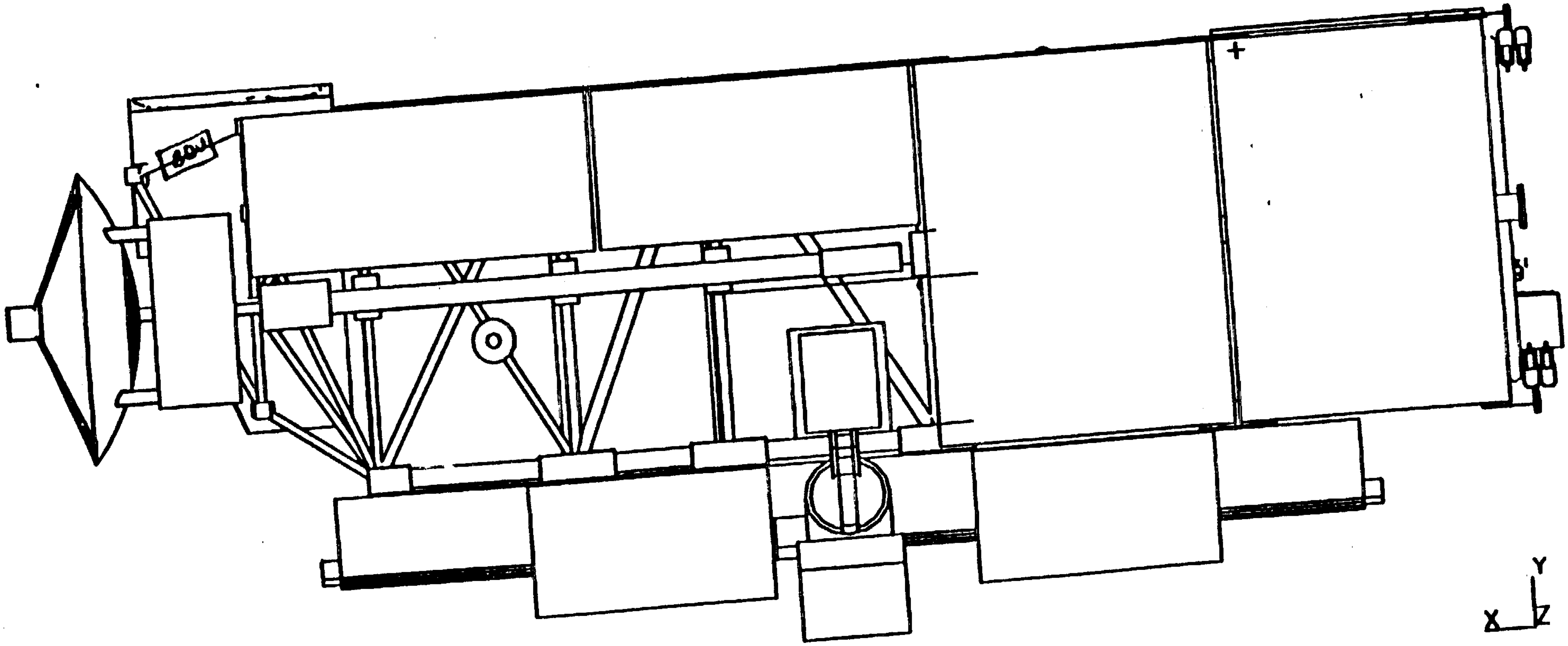

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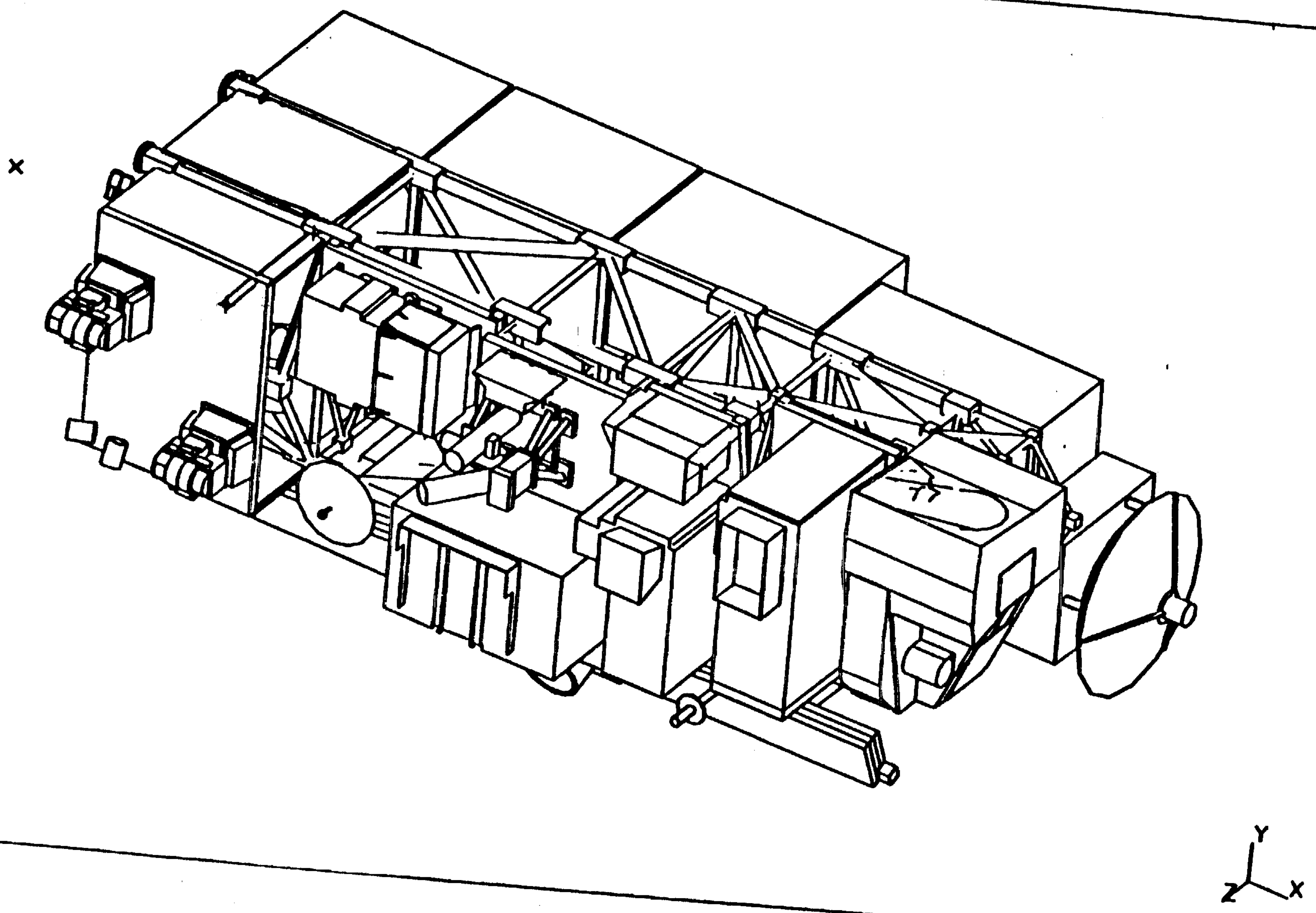

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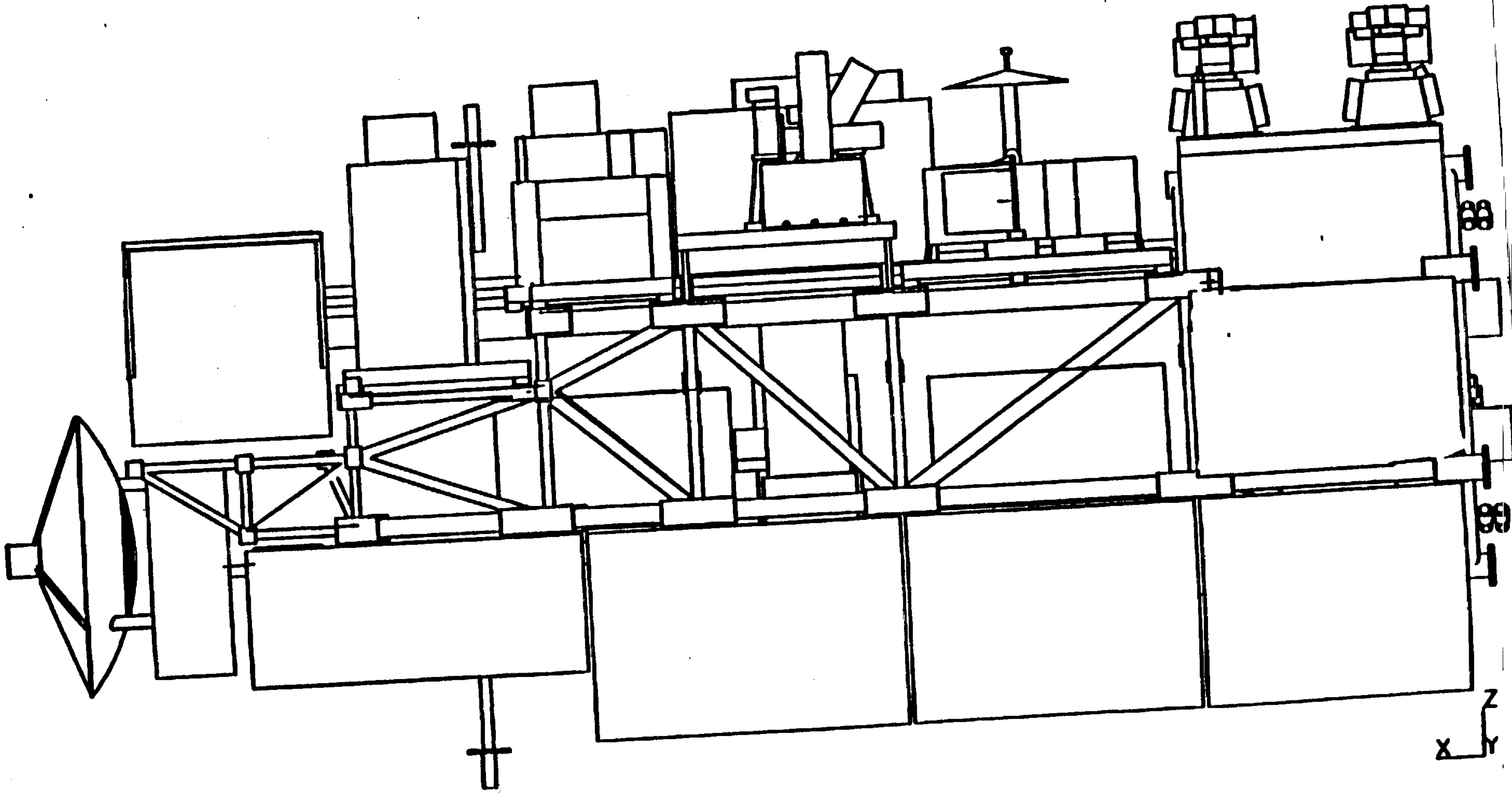

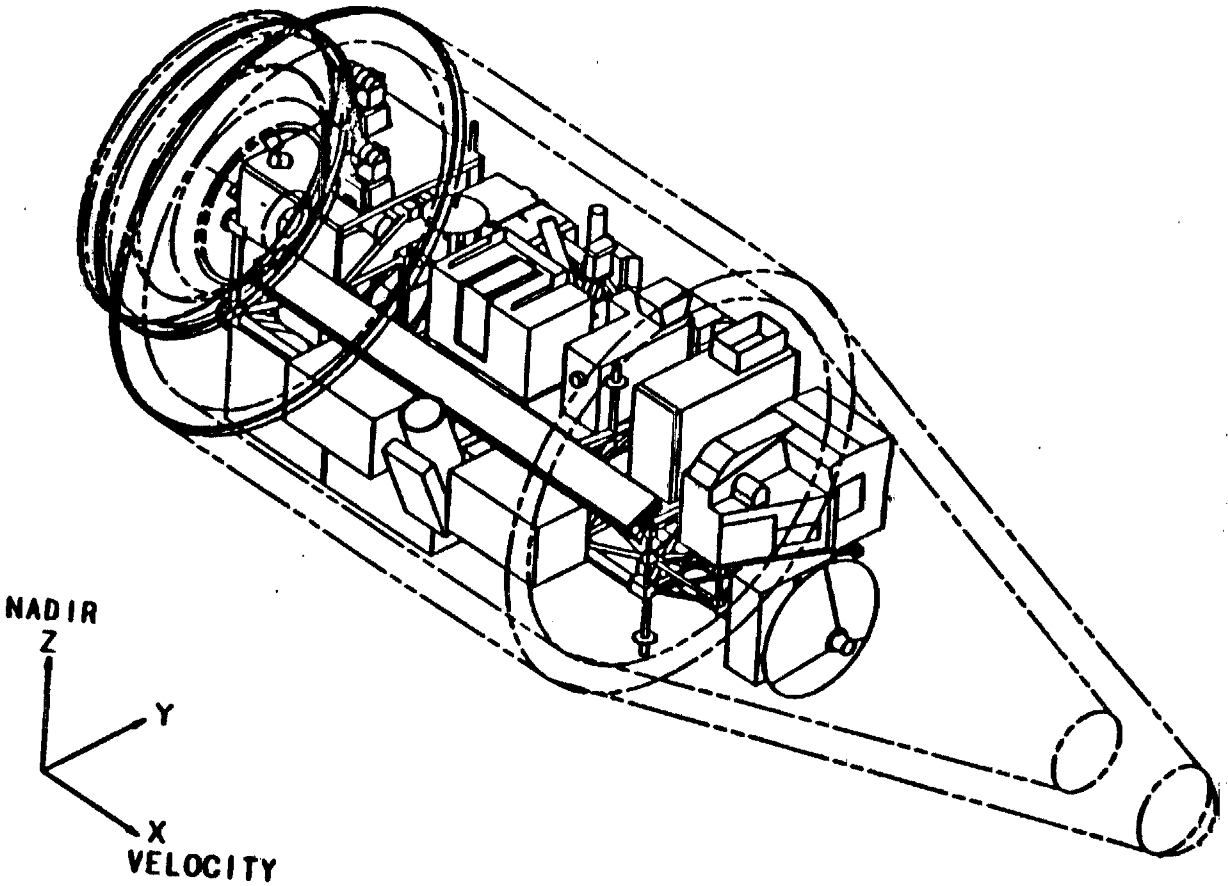
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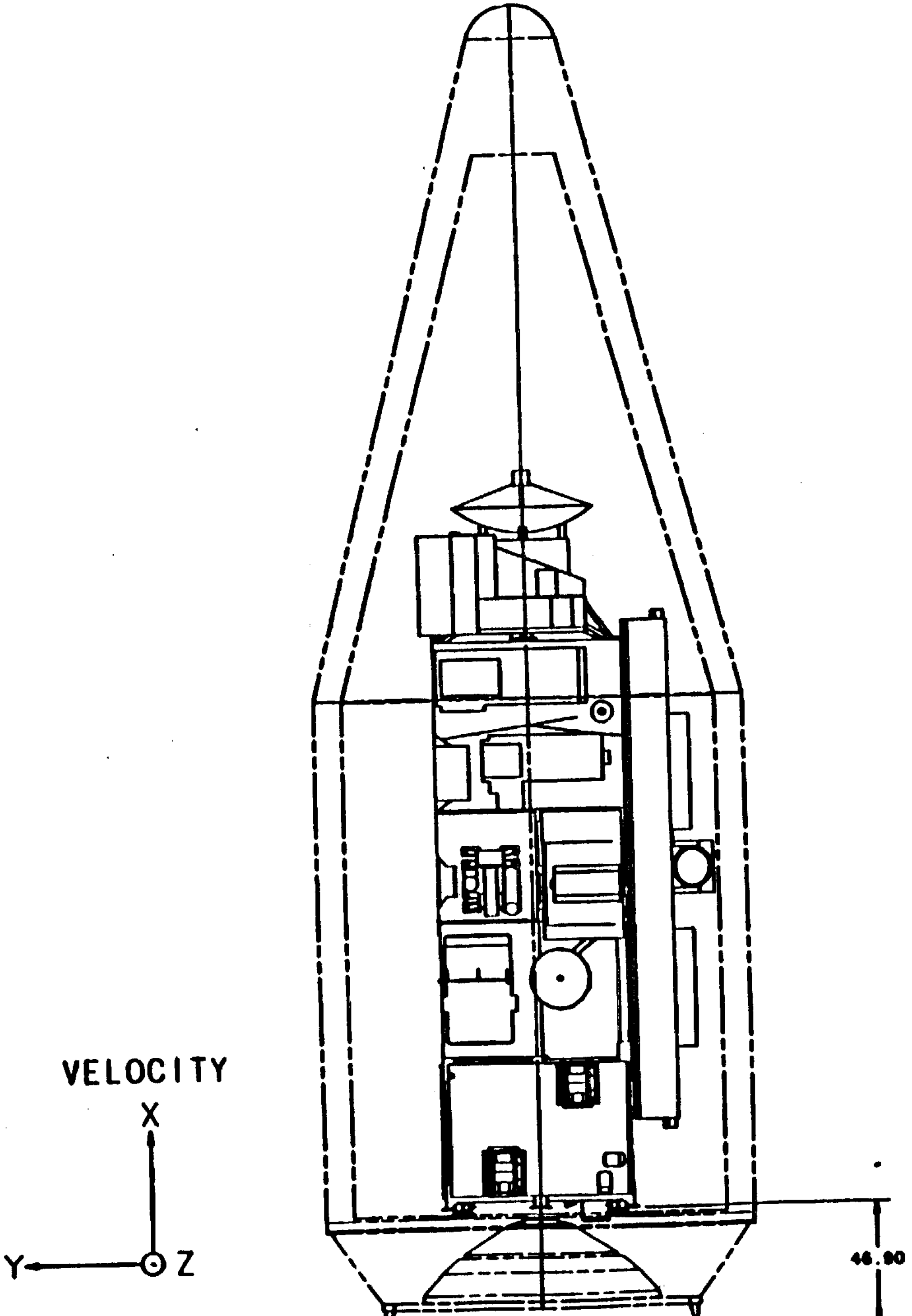
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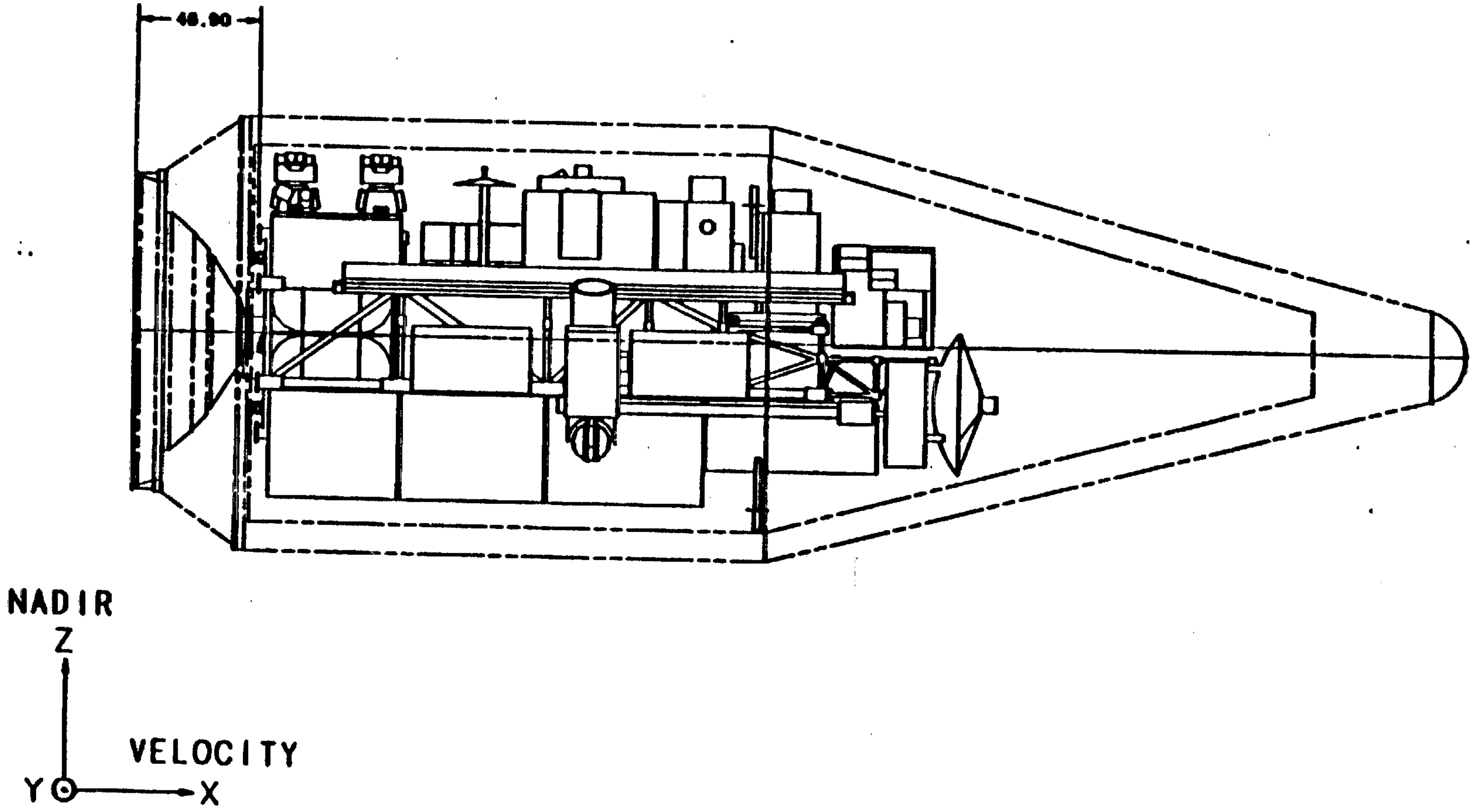
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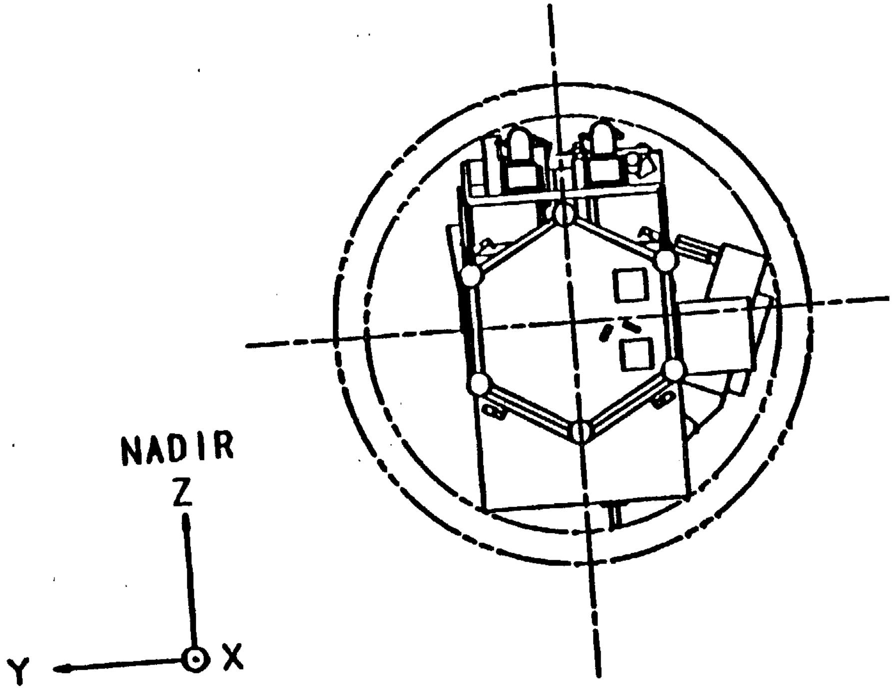
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Integration & Test Flow

G. Keeling
3/5/92

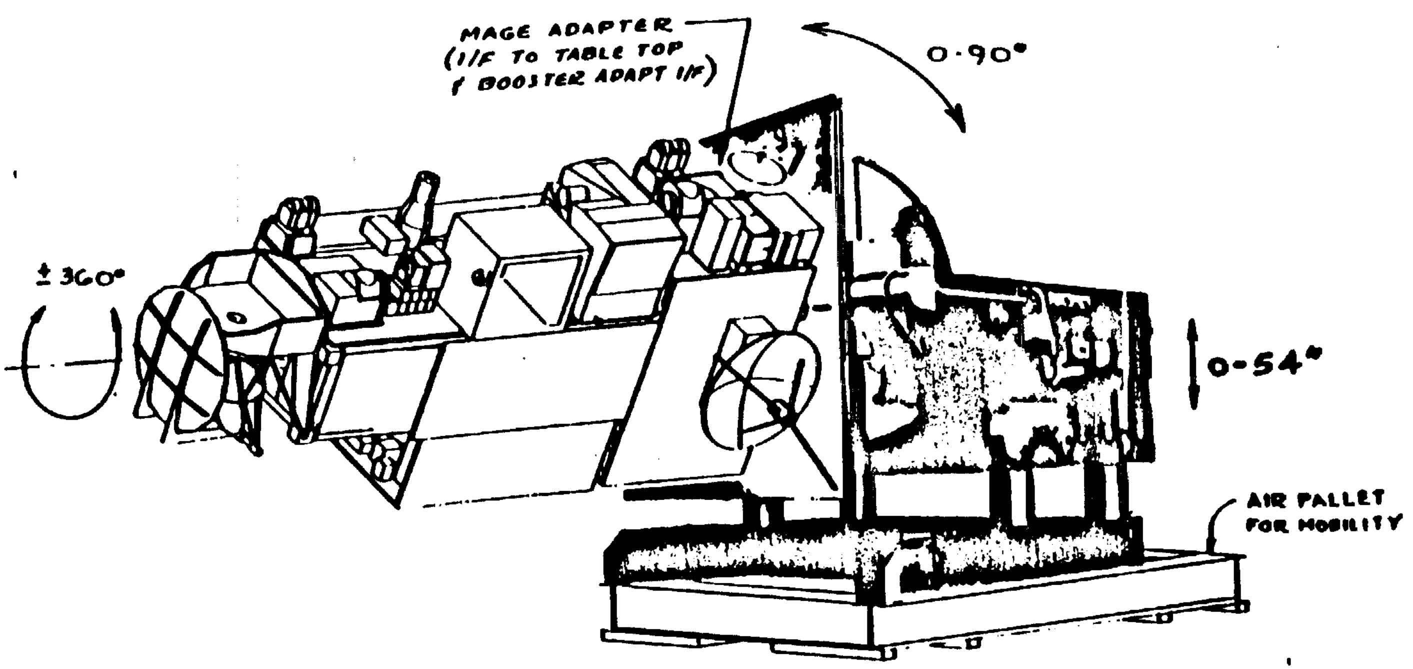


Figure 1, THREE AXIS POSITIONER
w/ RE CONFIGURED EOS

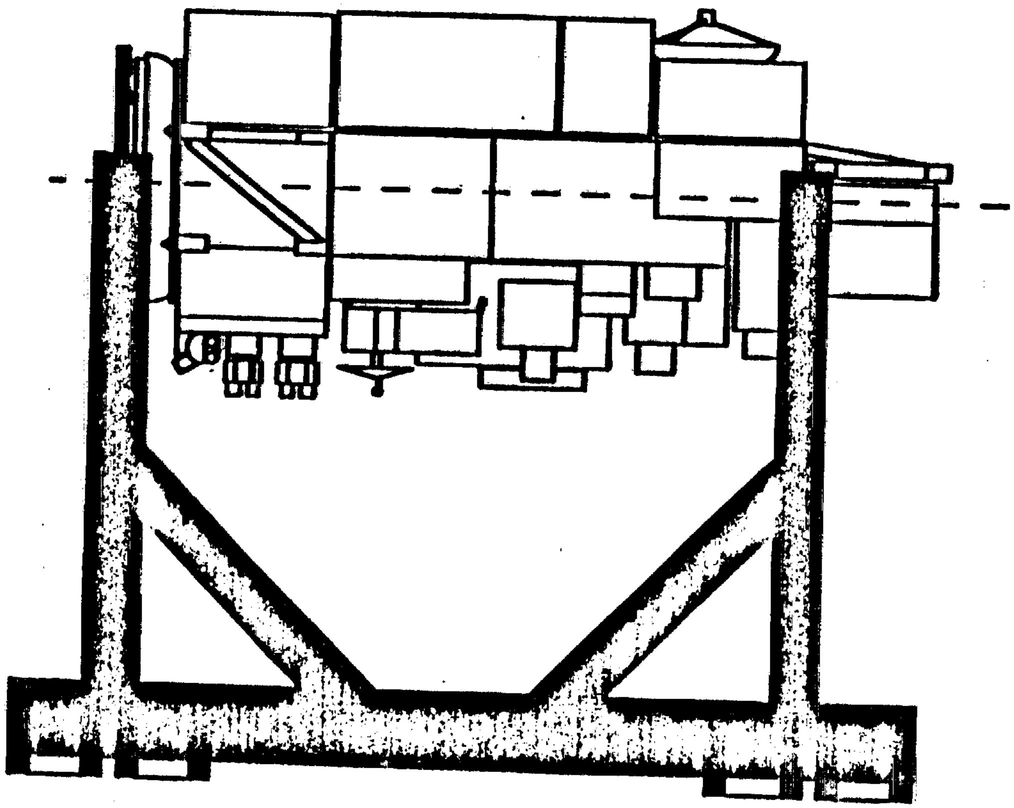
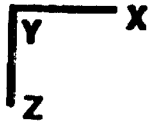


Figure 2, EOS ON HORIZ TEST STAND (METS)

(T/V SETUP)



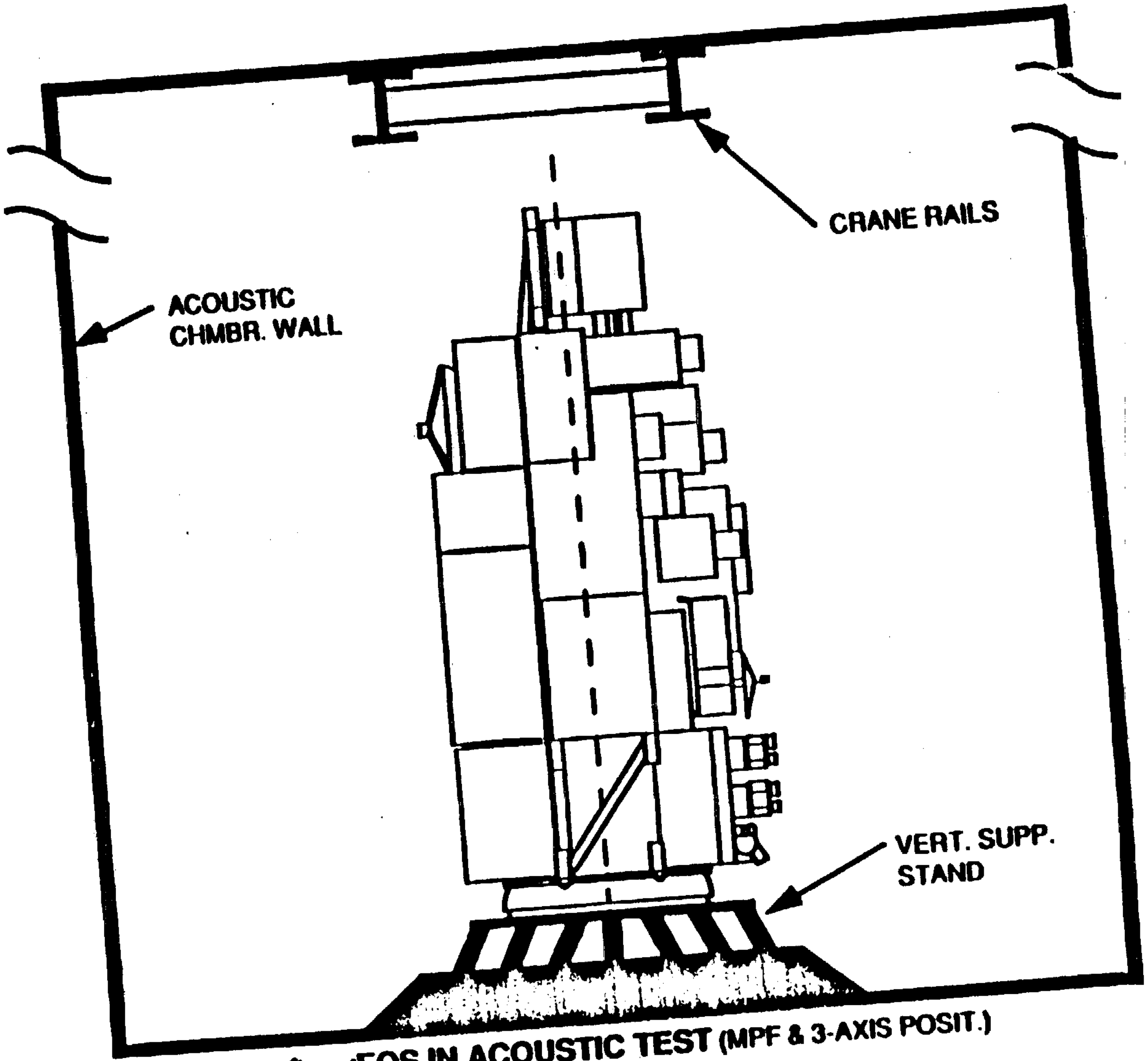
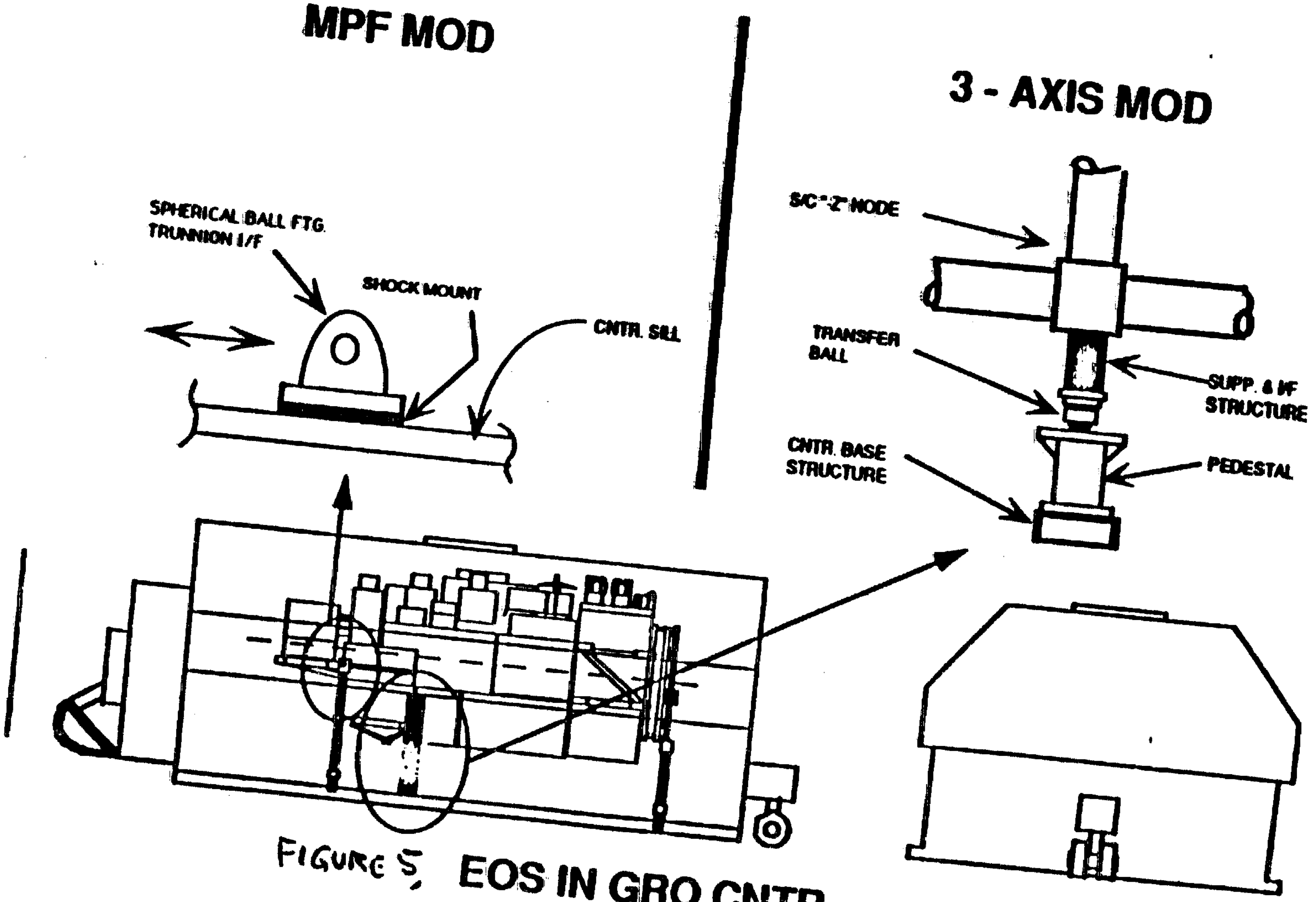


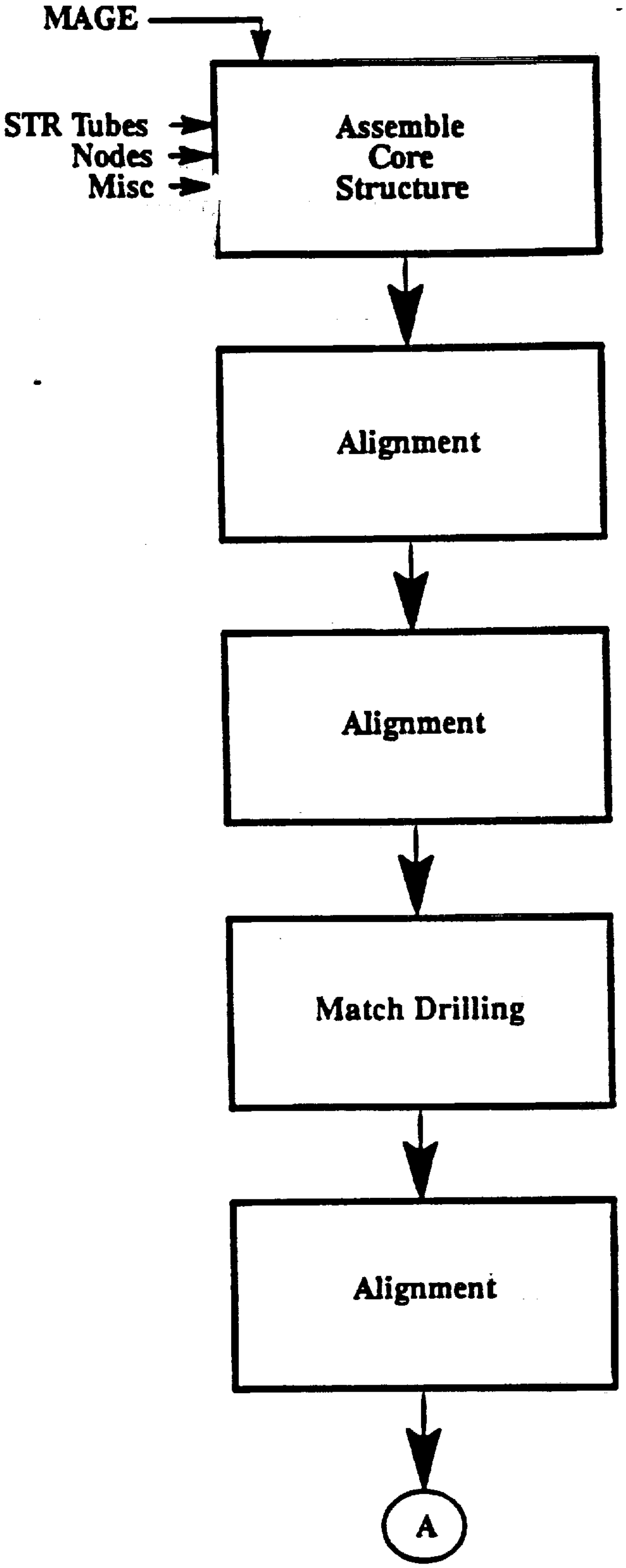
Figure 4, EOS IN ACOUSTIC TEST (MPF & 3-AXIS POSIT.)



MPF MOD

3 - AXIS MOD

FIGURE 5, EOS IN GRO CNTR



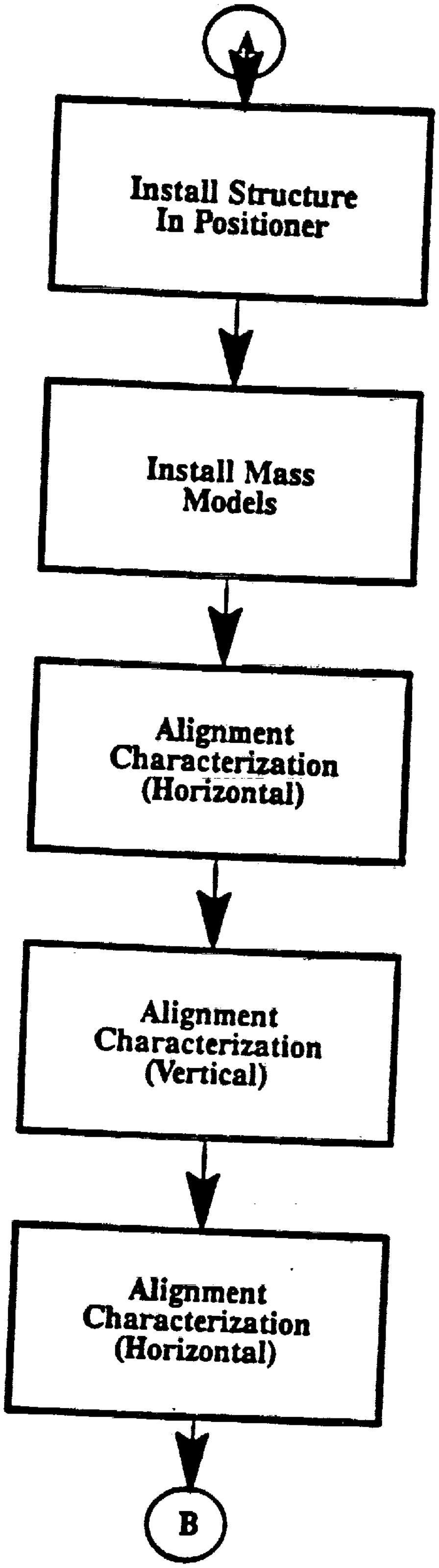
In Static Manufacturing Fixture
Nadir Deck (+Z) Up

In Static Manufacturing Fixture
Nadir Deck (+Z) Up
Structure Clamped Into Fixture
Instrument Drill Templates Clamped
In Place

In Static Manufacturing
Nadir Deck (+Z) Up
Clamps Removed From Structure
Instrument Drill Templates Clamped
In Place

In Static Manufacturing Fixture
Nadir Deck (+Z) Up
Structure Clamped Into Fixture

In Static Manufacturing Fixture
Nadir Deck (+Z) Up
Structure Clamped Into Fixture
Instrument Drill Templates
Temporarily Installed
Remove Drill Templates After
Alignment



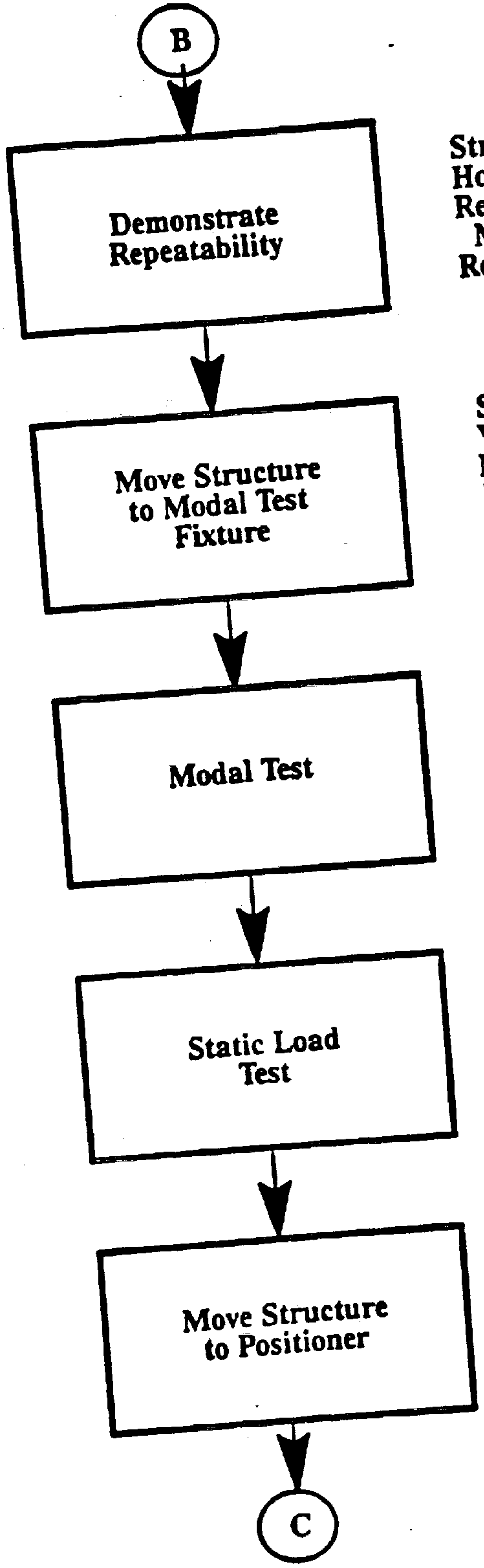
Structure In Manufacturing Fixture
Horizontal Orientation (+Z Up)
MAGE Adaptor Installed
Lift Structure Out of Manufacturing Fixture
Install Structure On Positioner (Horizontally)

Structure In Positioner
Horizontal Orientation (Various)

Structure In Positioner
Horizontal Orientation (+Z Up)
Measure Alignment
Rotate to -Z Up
Measure Alignment

Structure In Positioner
Vertical Orientation
Measure Alignment
Lift Structure Vertically Off Positioner
Re-Install Structure On Positioner
Measure Alignment

Structure In Positioner
Horizontal Orientation (+Z Up)
Measure Alignment
Rotate to -Z Up
Measure Alignment



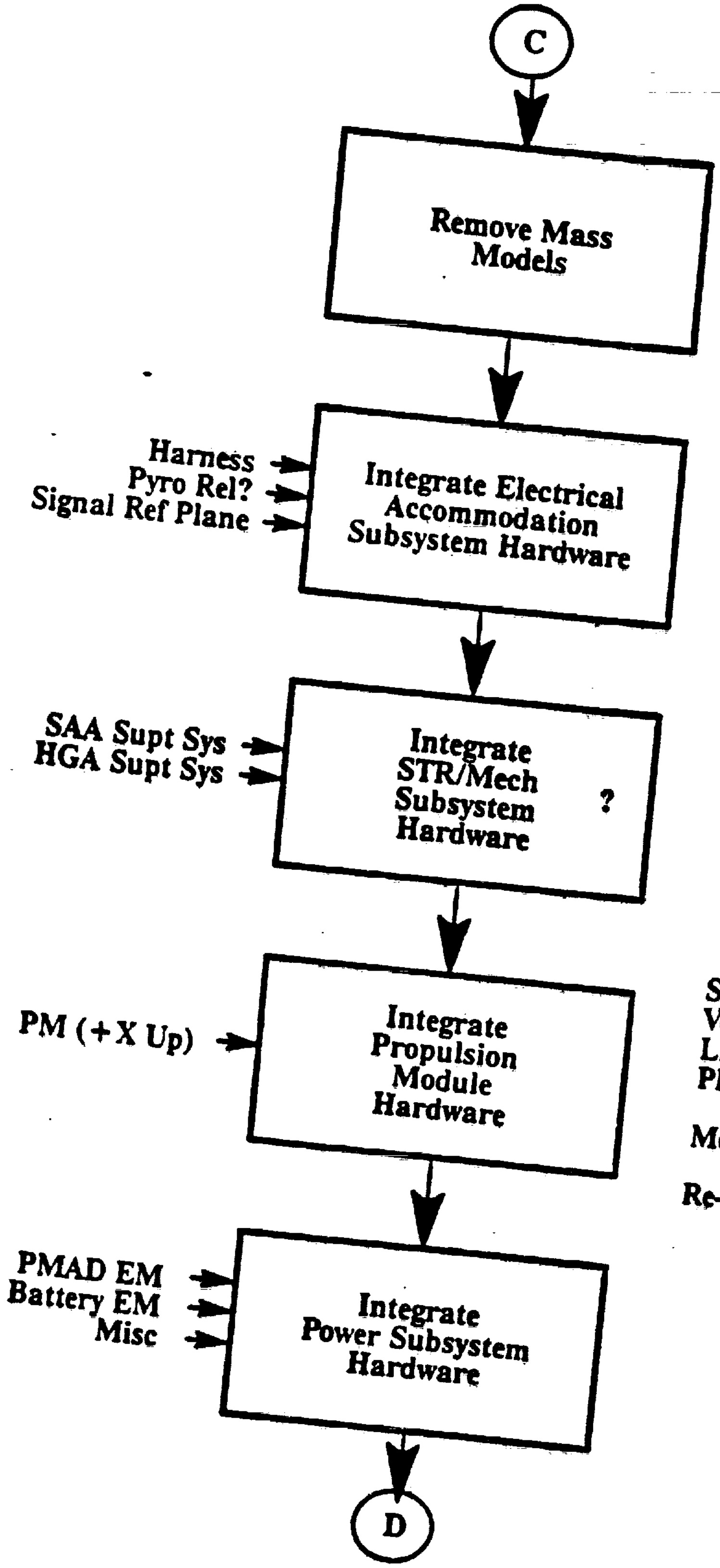
Structure In Positioner
Horizontal Orientation (Various)
Remove and Re-Install Mass Models
Repeat Alignment Measurements

Structure In Positioner
Vertical Orientation
Mass Models Installed
Lift Structure Off of Positioner
Install Structure in Modal Test Fixture

Structure In Modal Test Fixture
Vertical Orientation

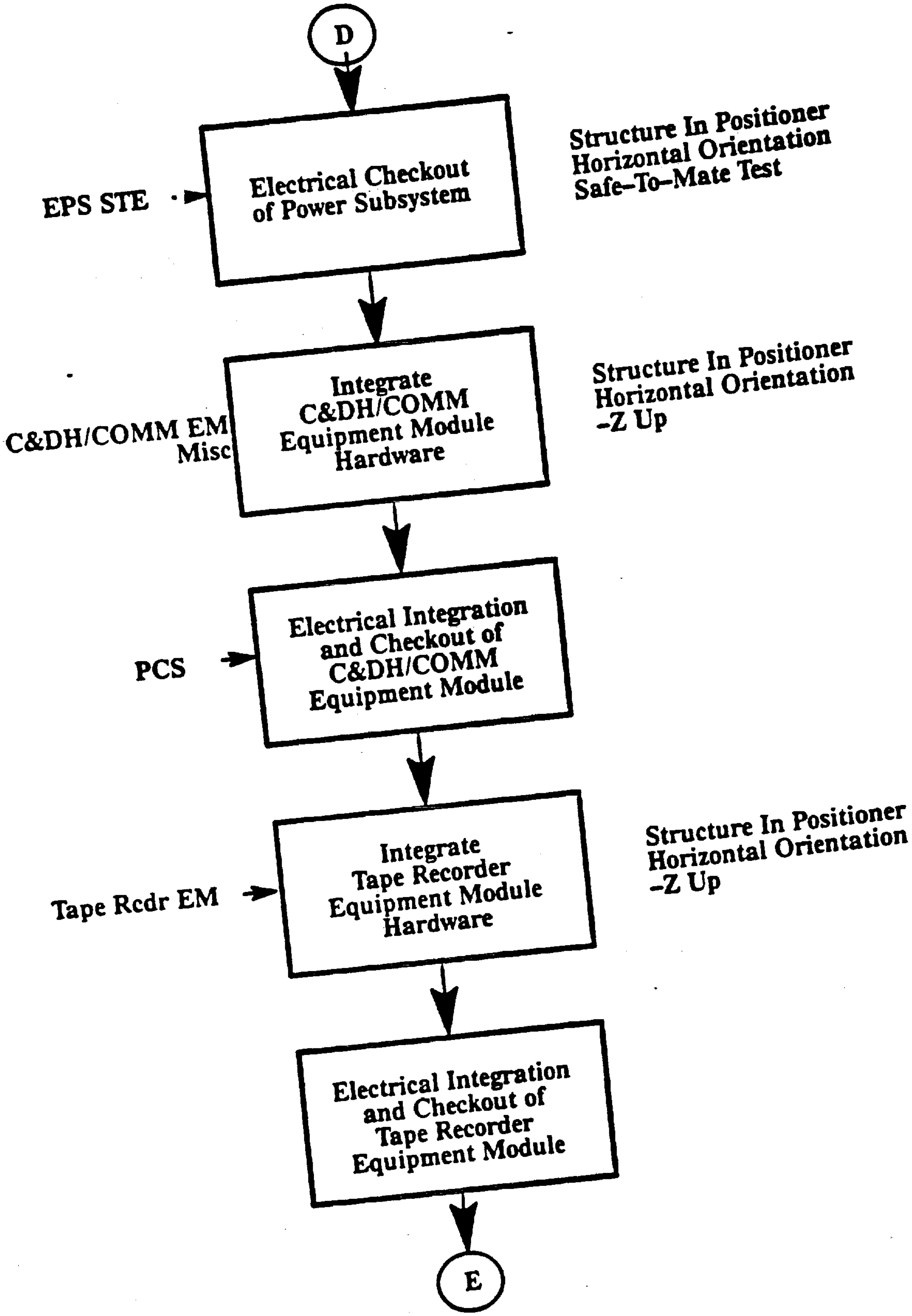
Structure In Modal Test Fixture
Vertical Orientation

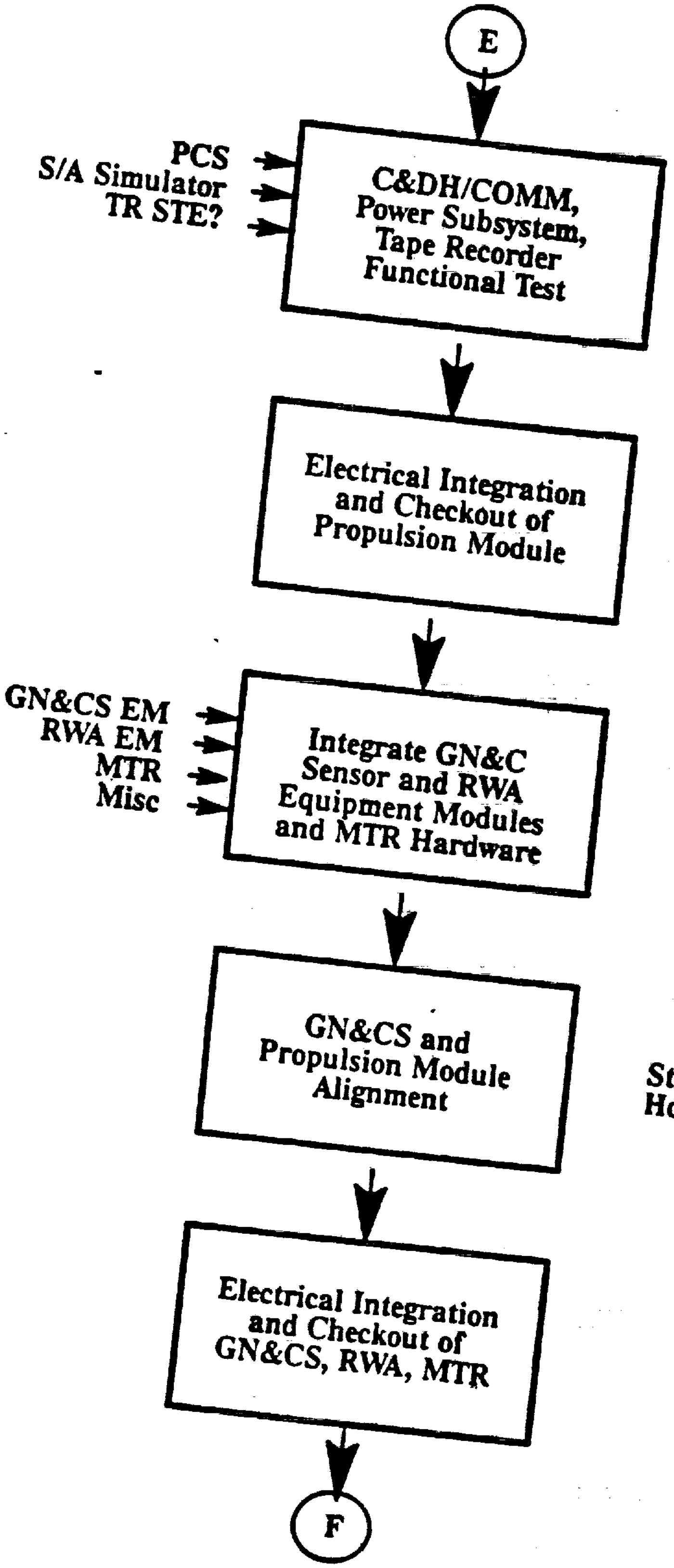
Structure In Modal Test Fixture
Vertical Orientation
Lift Structure Out of Modal Test Fixture
Install Structure On Positioner



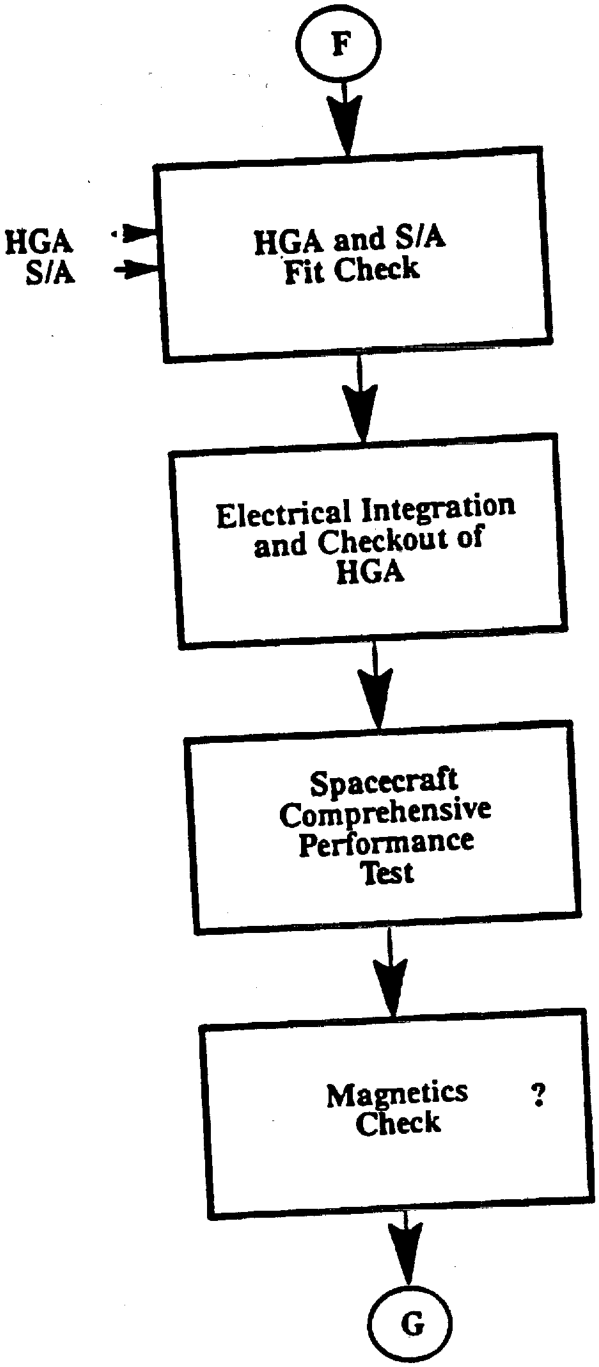
Structure In Positioner
Horizontal Orientation (Various)

Structure In Positioner
Vertical Orientation
Lift Structure Off Positioner
Place Structure Over Propulsion Module
Mechanically Integrate Propulsion Module
Re-Install Structure On Positioner


D
Electrical Checkout of Power Subsystem
EPS STE
Structure In Positioner
Horizontal Orientation
Safe–To–Mate Test
Integrate C&DH/COMM Equipment Module Hardware
C&DH/COMM EM
Misc
Structure In Positioner
Horizontal Orientation
–Z Up
Electrical Integration and Checkout of C&DH/COMM Equipment Module
PCS
Integrate Tape Recorder Equipment Module Hardware
Tape Rcdr EM
Structure In Positioner
Horizontal Orientation
–Z Up
Electrical Integration and Checkout of Tape Recorder Equipment Module
E



Structure In Positioner
Horizontal Orientation

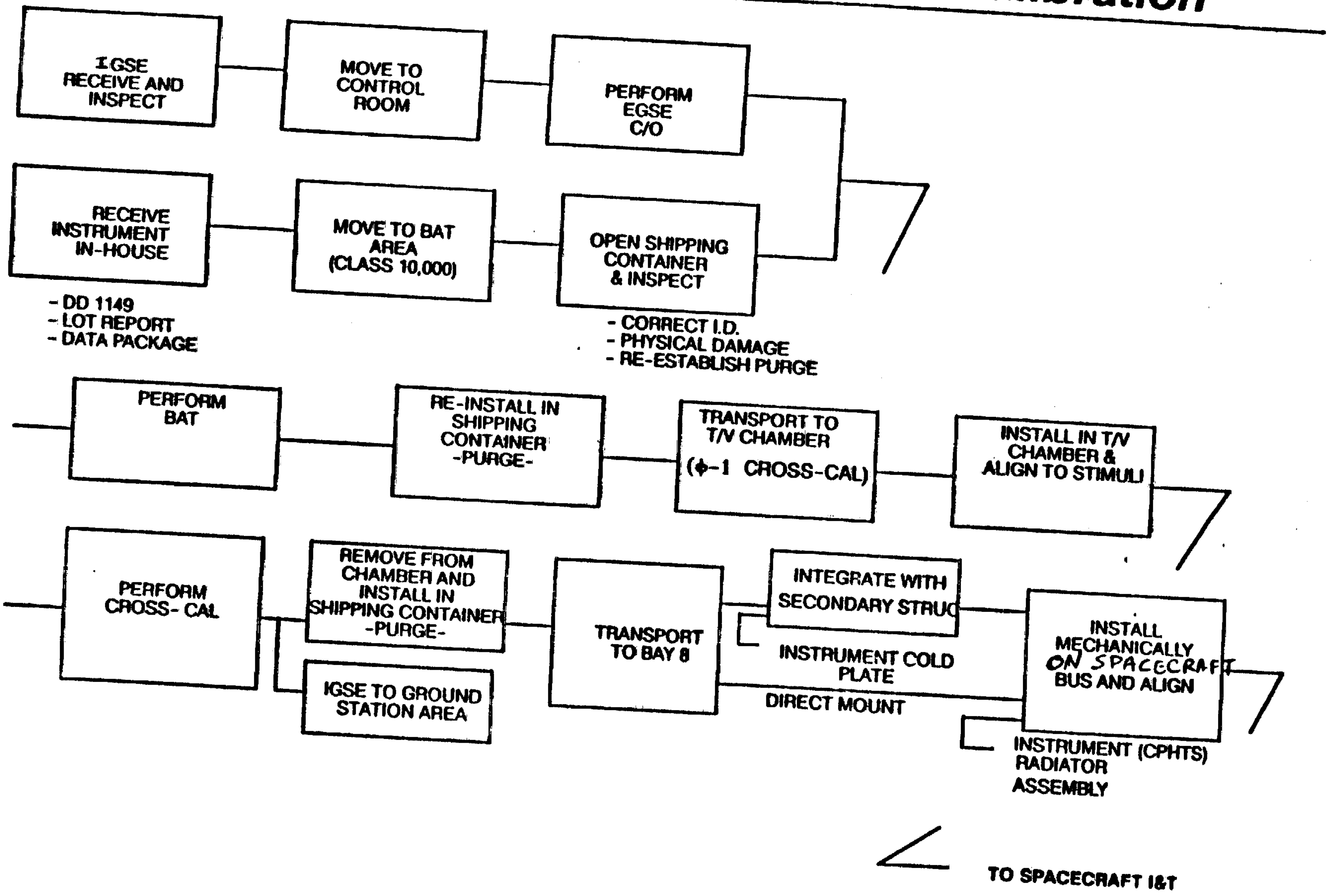


Structure In Positioner
Horizontal Orientation
-Z Up for HGA
-Y Up for S/A
HGA and S/A Removed After Fit Check

Structure In Positioner
Horizontal Orientation
HGA In Dolly

Spacecraft In Positioner
Horizontal Orientation (-Z Up)
Telemetry Data to EOC via NASCOM

Instrument I&T Flow with Cross-Calibration



IGSE RECEIVE AND INSPECT

MOVE TO CONTROL ROOM

PERFORM EGSE C/O

RECEIVE INSTRUMENT IN-HOUSE

- DD 1149
- LOT REPORT
- DATA PACKAGE

MOVE TO BAT AREA (CLASS 10,000)

OPEN SHIPPING CONTAINER & INSPECT

- CORRECT I.D.
- PHYSICAL DAMAGE
- RE-ESTABLISH PURGE

PERFORM BAT

RE-INSTALL IN SHIPPING CONTAINER -PURGE-

TRANSPORT TO T/V CHAMBER (ϕ-1 CROSS-CAL)

INSTALL IN T/V CHAMBER & ALIGN TO STIMULI

PERFORM CROSS- CAL

REMOVE FROM CHAMBER AND INSTALL IN SHIPPING CONTAINER -PURGE-

IGSE TO GROUND STATION AREA

TRANSPORT TO BAY 8

INTEGRATE WITH SECONDARY STRUC

INSTRUMENT COLD PLATE

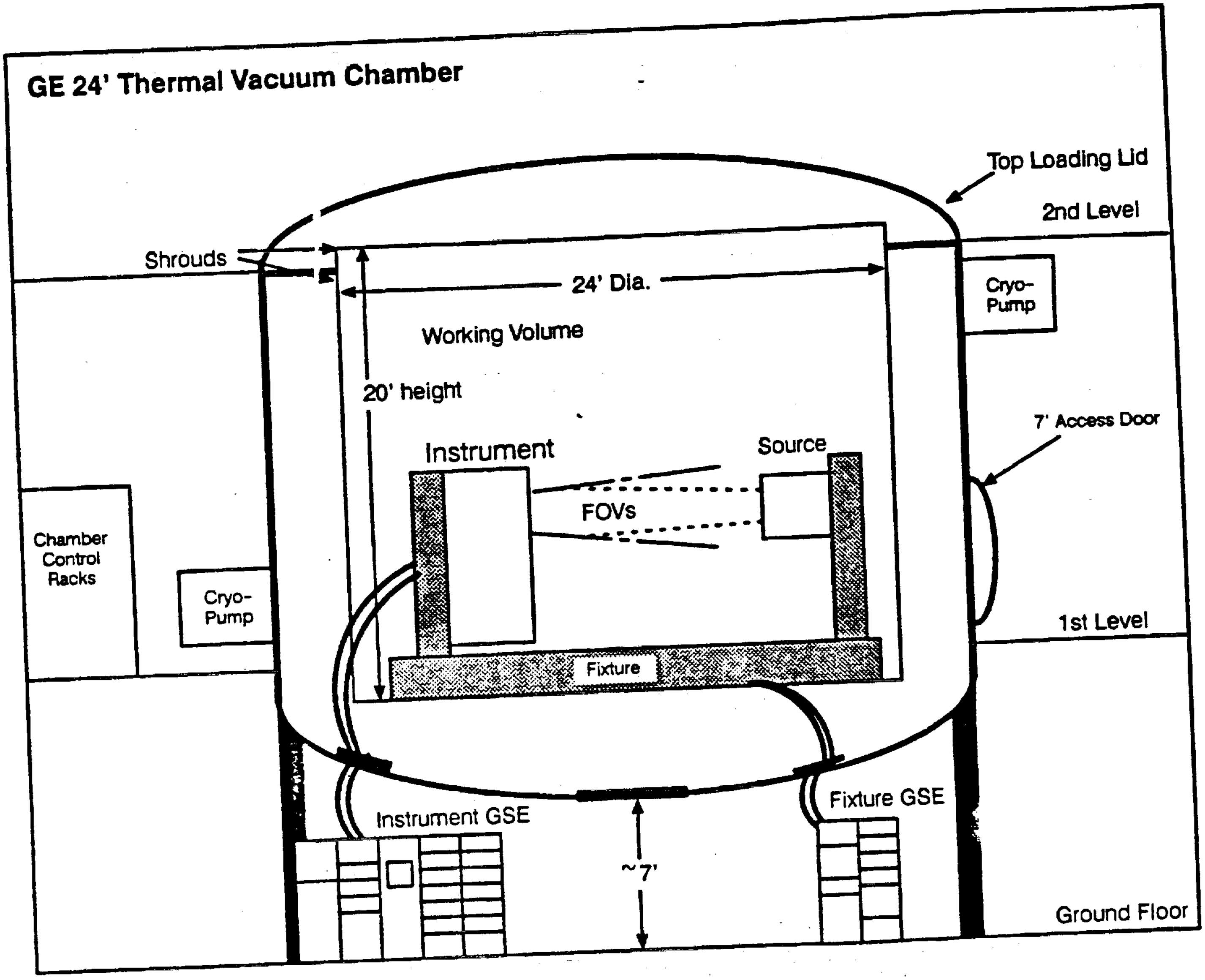
DIRECT MOUNT

INSTALL MECHANICALLY ON SPACECRAFT BUS AND ALIGN

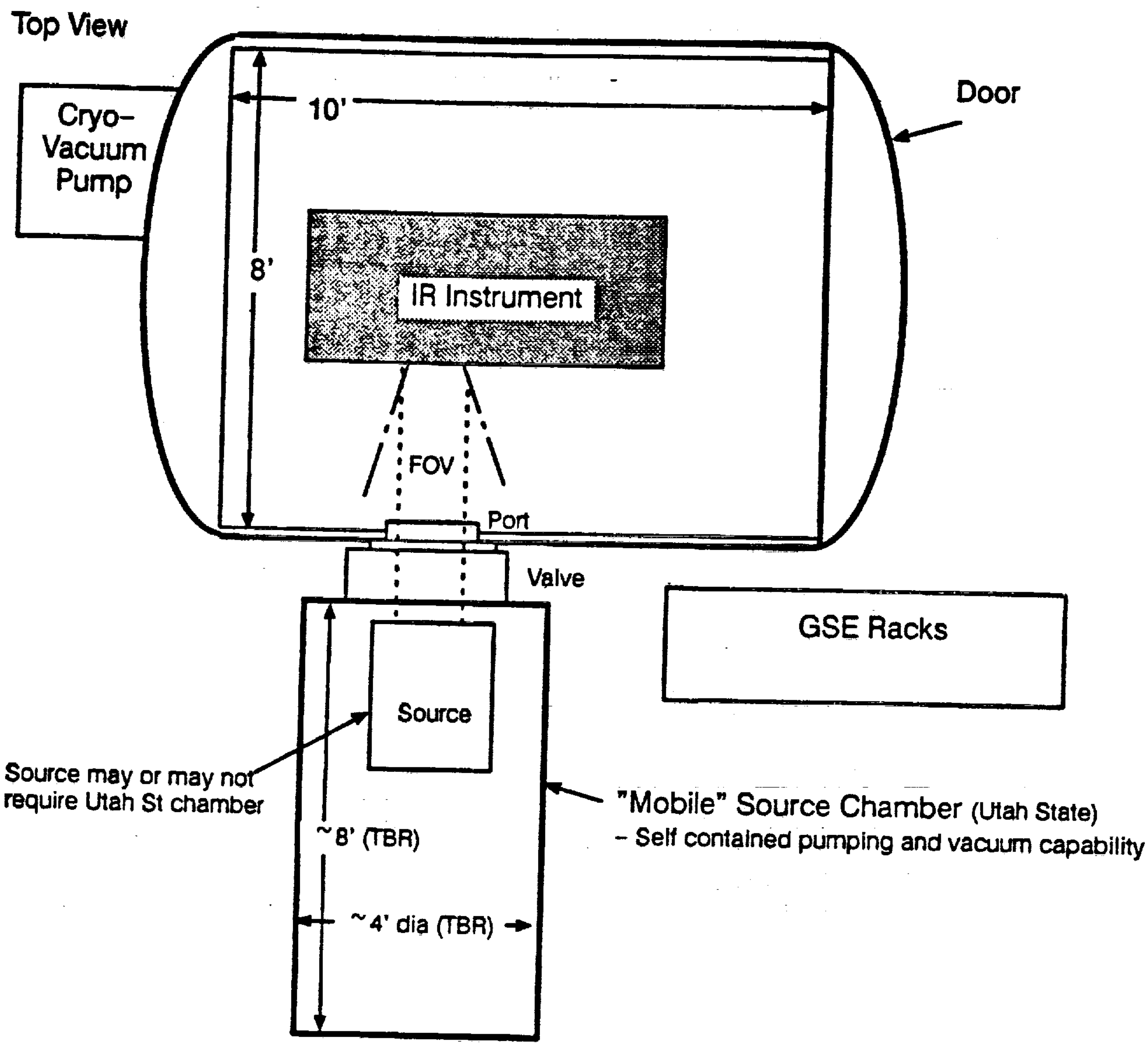
INSTRUMENT (CPHTS) RADIATOR ASSEMBLY

TO SPACECRAFT I&T

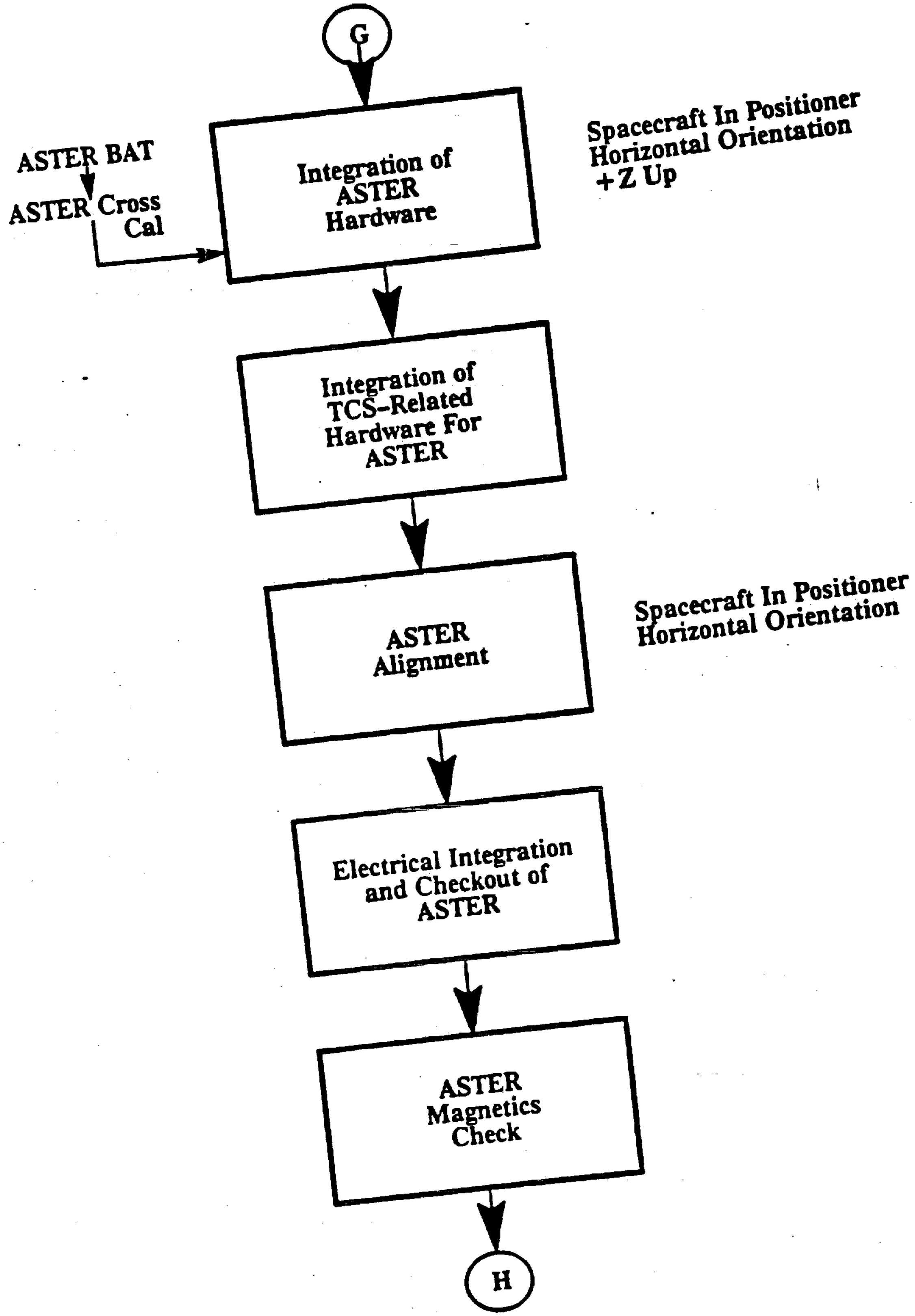
EOS Cross-Comparison: Option 1, 24' Chamber

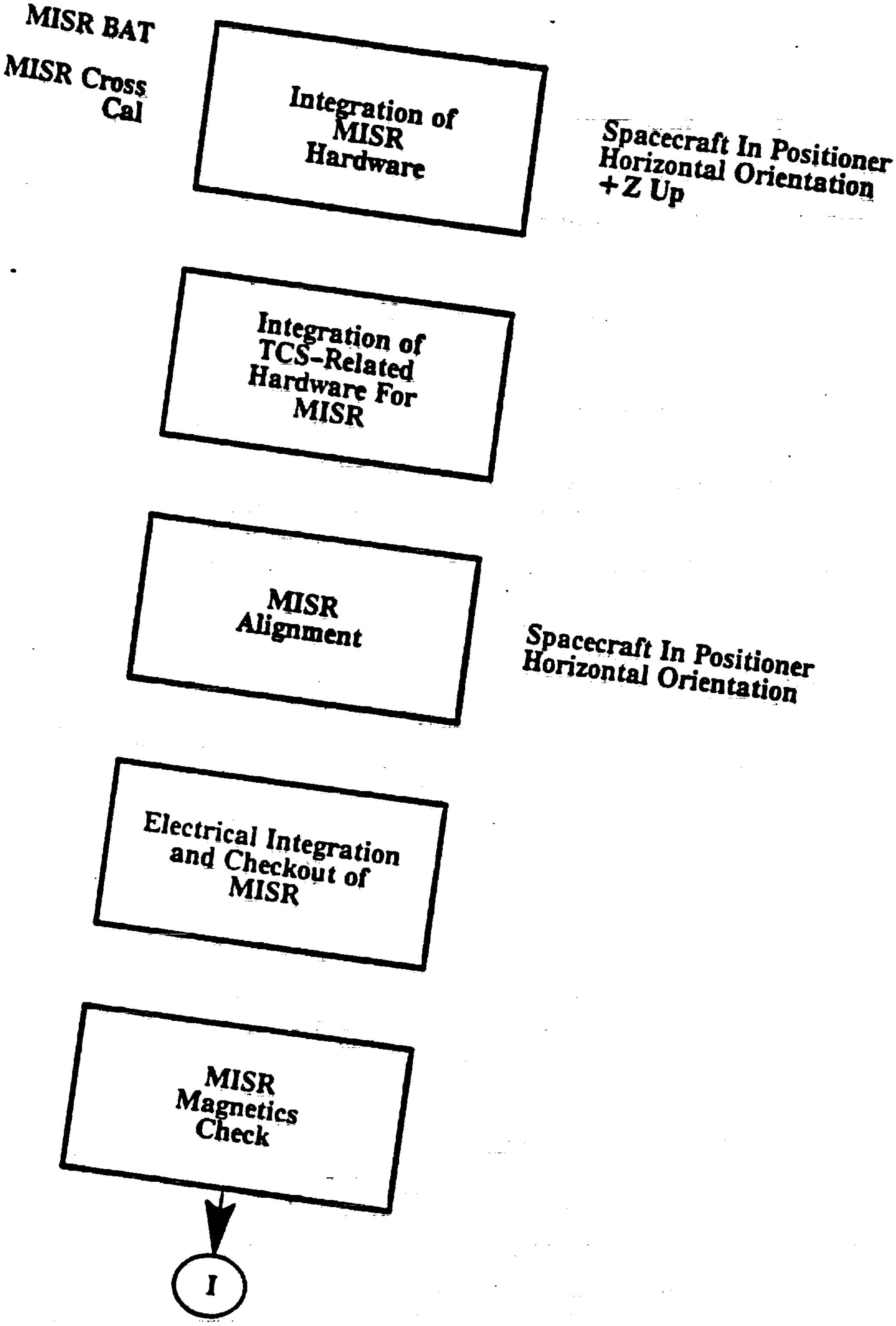


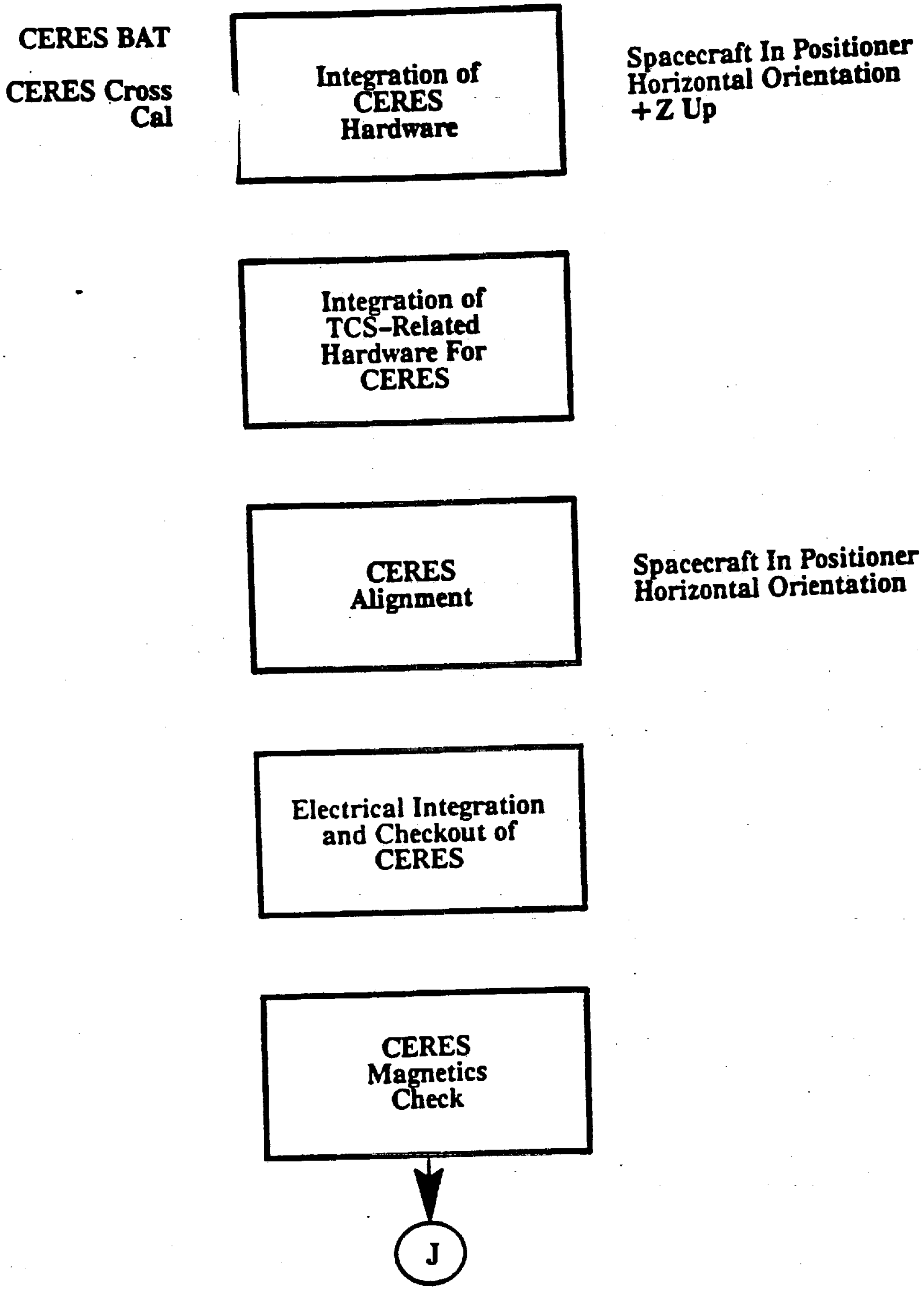
EOS Cross-Comparison: Option 2, 8' Chamber



Modifications:
- Replace diffusion pump with cryo-pump
- Replace shrouds
- Install side viewing port (~14-18" dia.)
- Install gate valve onto access port
- Install new internal equipment support structure (stability requirements)
- New contamination monitoring system (?)


G
ASTER BAT
ASTER Cross Cal
Integration of ASTER Hardware
Spacecraft In Positioner Horizontal Orientation +Z Up
Integration of TCS-Related Hardware For ASTER
ASTER Alignment
Spacecraft In Positioner Horizontal Orientation
Electrical Integration and Checkout of ASTER
ASTER Magnetics Check
H


MISR BAT
MISR Cross Cal
Integration of MISR Hardware
Spacecraft In Positioner Horizontal Orientation +Z Up
Integration of TCS-Related Hardware For MISR
MISR Alignment
Spacecraft In Positioner Horizontal Orientation
Electrical Integration and Checkout of MISR
MISR Magnetics Check
I



CERES BAT

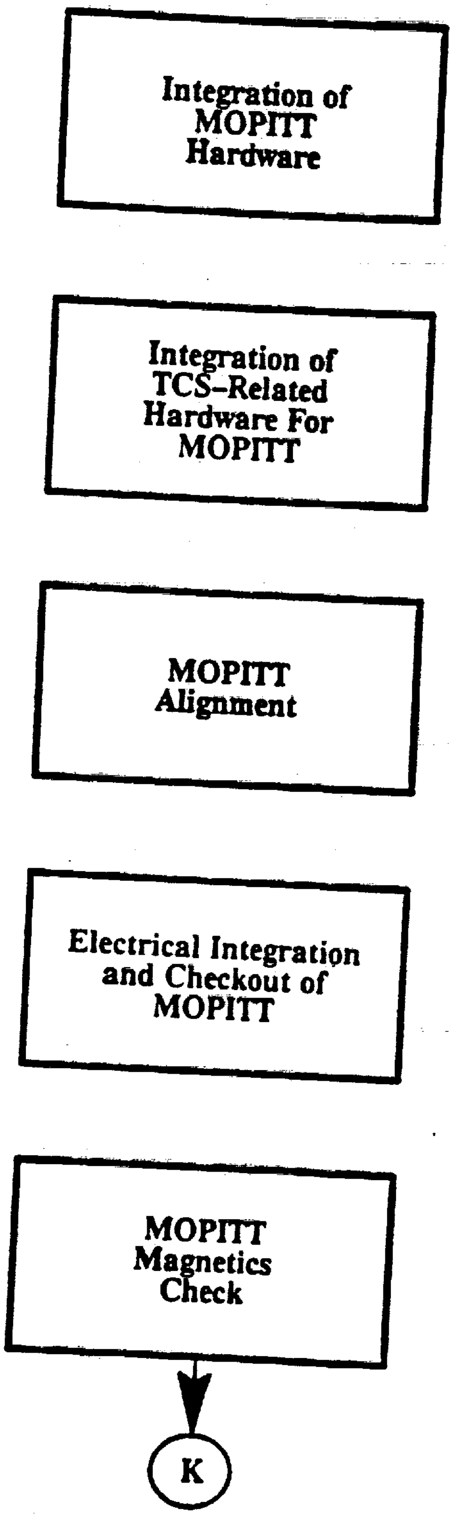
CERES Cross Cal

Spacecraft In Positioner
Horizontal Orientation
+Z Up

Spacecraft In Positioner
Horizontal Orientation

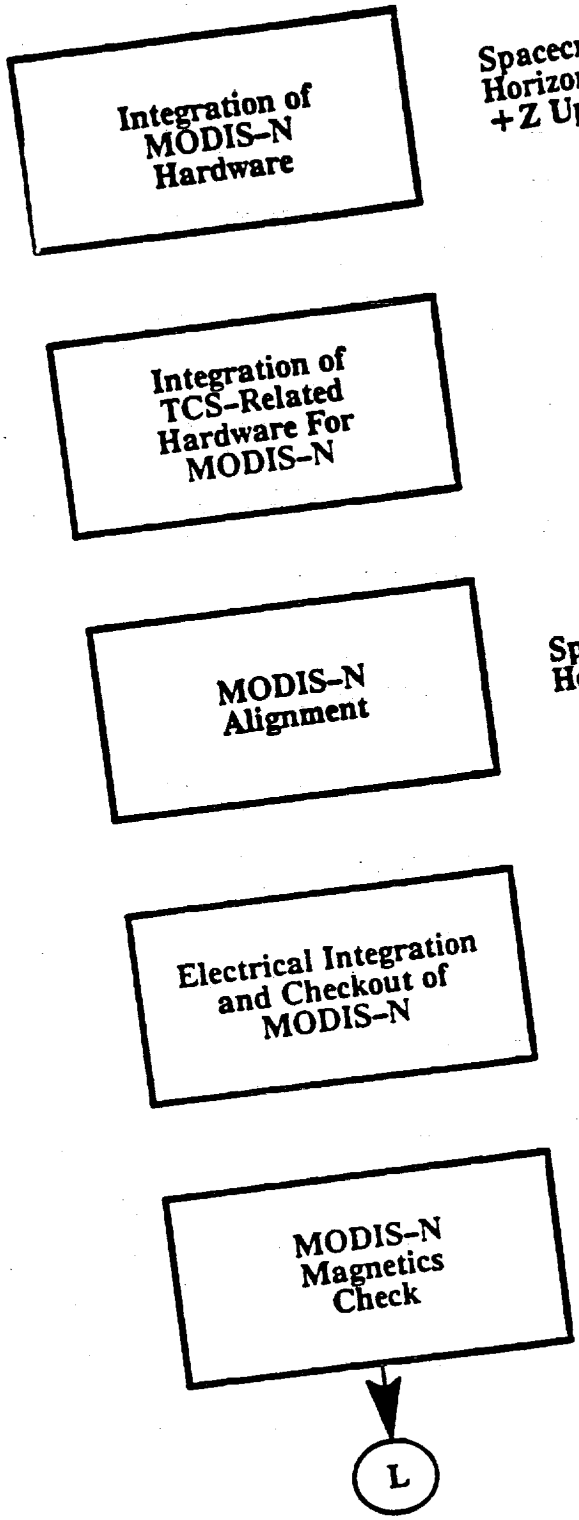
MOPITT BAT

MOPITT Cross Cal



Spacecraft In Positioner
Horizontal Orientation
+Z Up

Spacecraft In Positioner
Horizontal Orientation

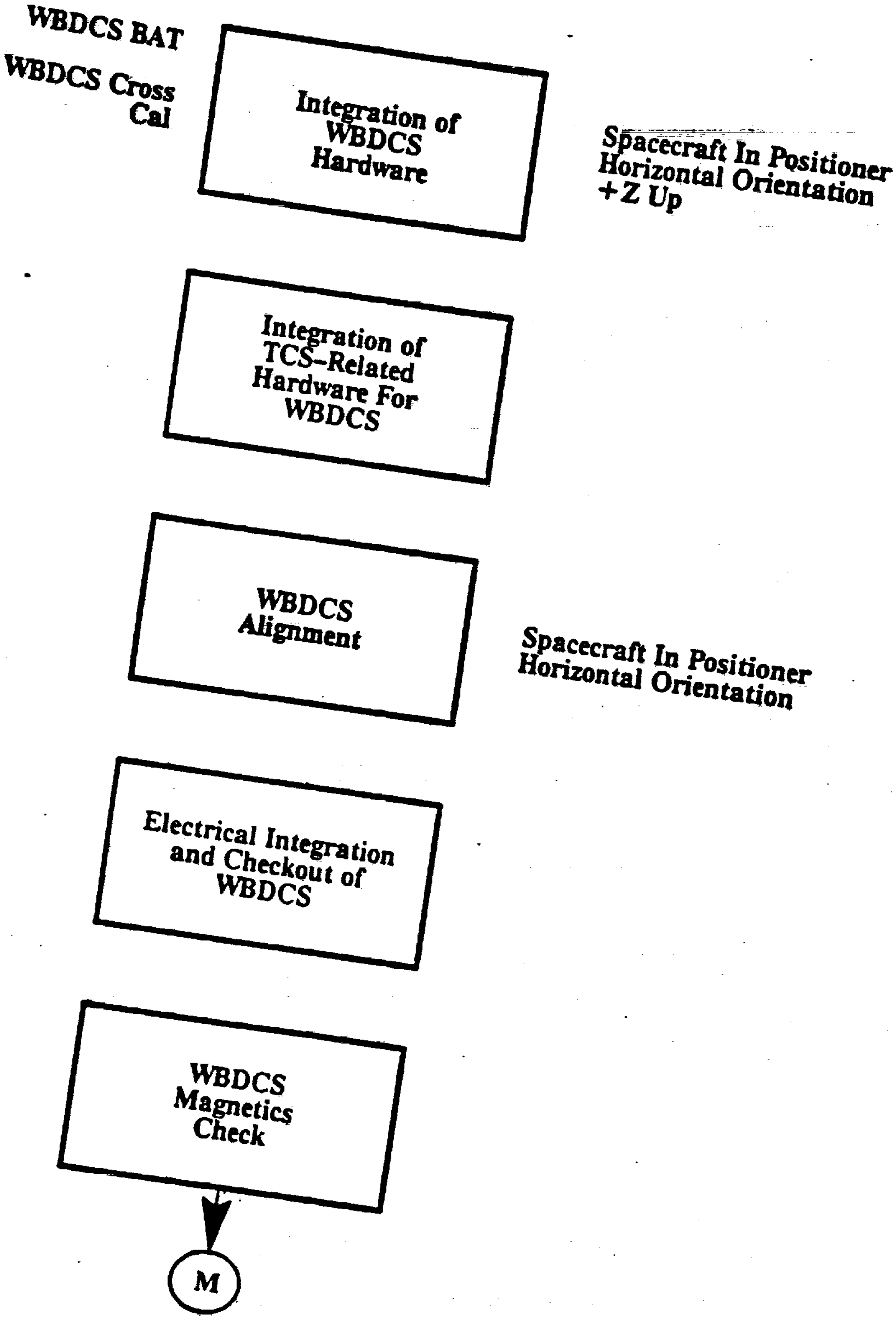


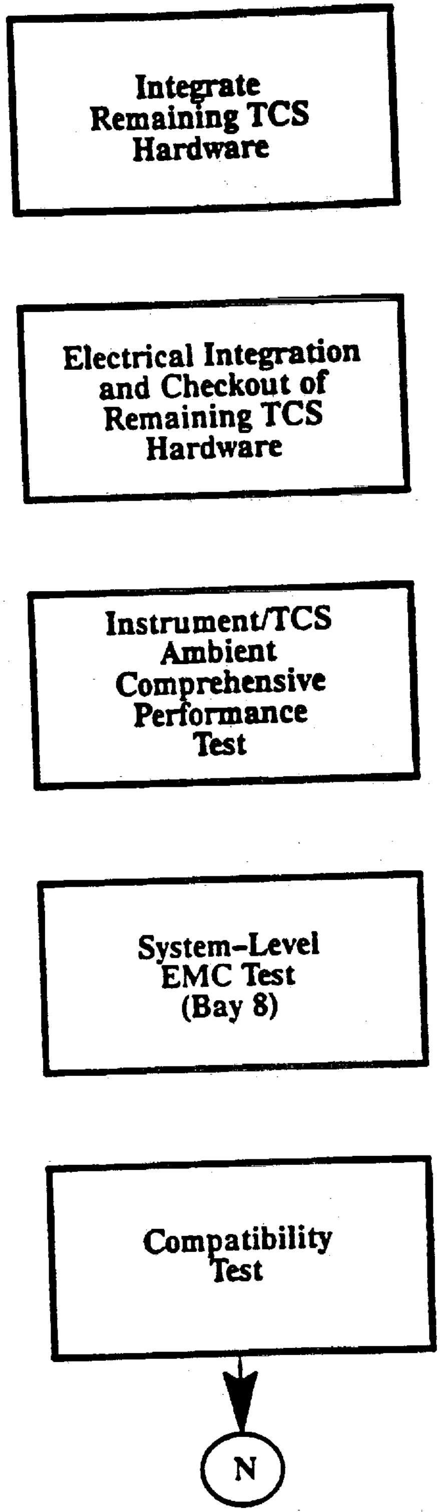
MODIS-N BAT

MODIS-N Cross Cal

Spacecraft In Positioner
Horizontal Orientation
+Z Up

Spacecraft In Positioner
Horizontal Orientation

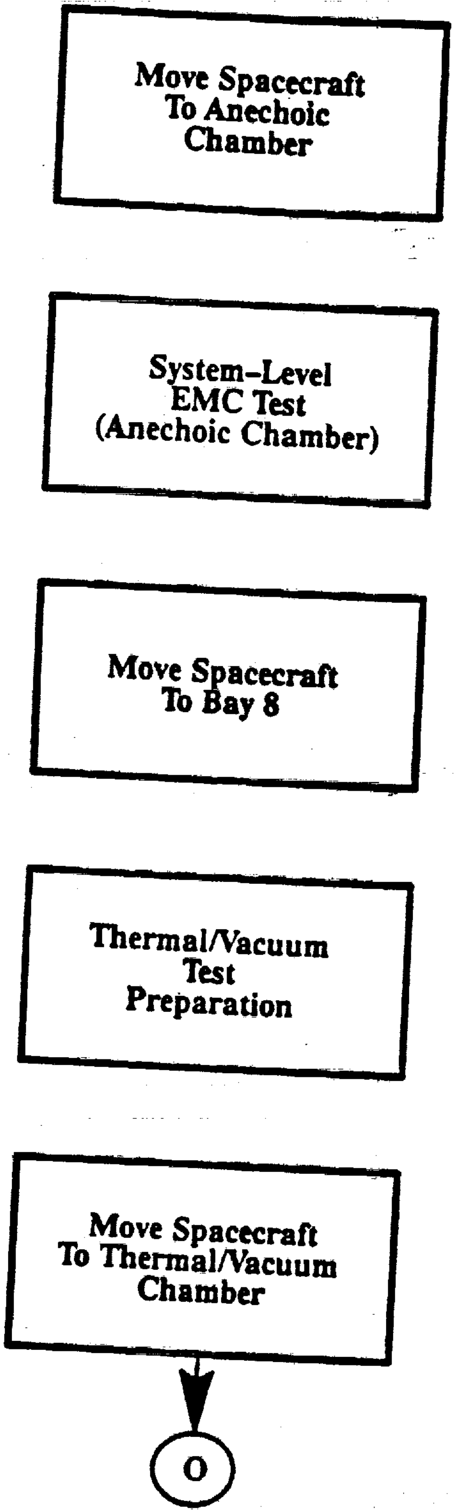

WBDCS BAT
WBDCS Cross Cal
Integration of WBDCS Hardware
Spacecraft In Positioner Horizontal Orientation +Z Up
Integration of TCS–Related Hardware For WBDCS
WBDCS Alignment
Spacecraft In Positioner Horizontal Orientation
Electrical Integration and Checkout of WBDCS
WBDCS Magnetics Check
M



Spacecraft In Positioner
Horizontal Orientation
-Z Up
Telemetry Data to EOS via NASCOM

Spacecraft In Positioner
Horizontal Orientation (-Z Up)
HGA Electrically Mated, Mechanically Demated
Power Profile Test
Transient Tolerance Test
Simulated Orbits
RF Compatibility Test

Spacecraft In Positioner
Horizontal Orientation (-Z Up)
HGA Electrically Mated, Mechanically Demated
TDRSS Compatibility Test
EOC Compatibility Test via NASCOM and TDRSS



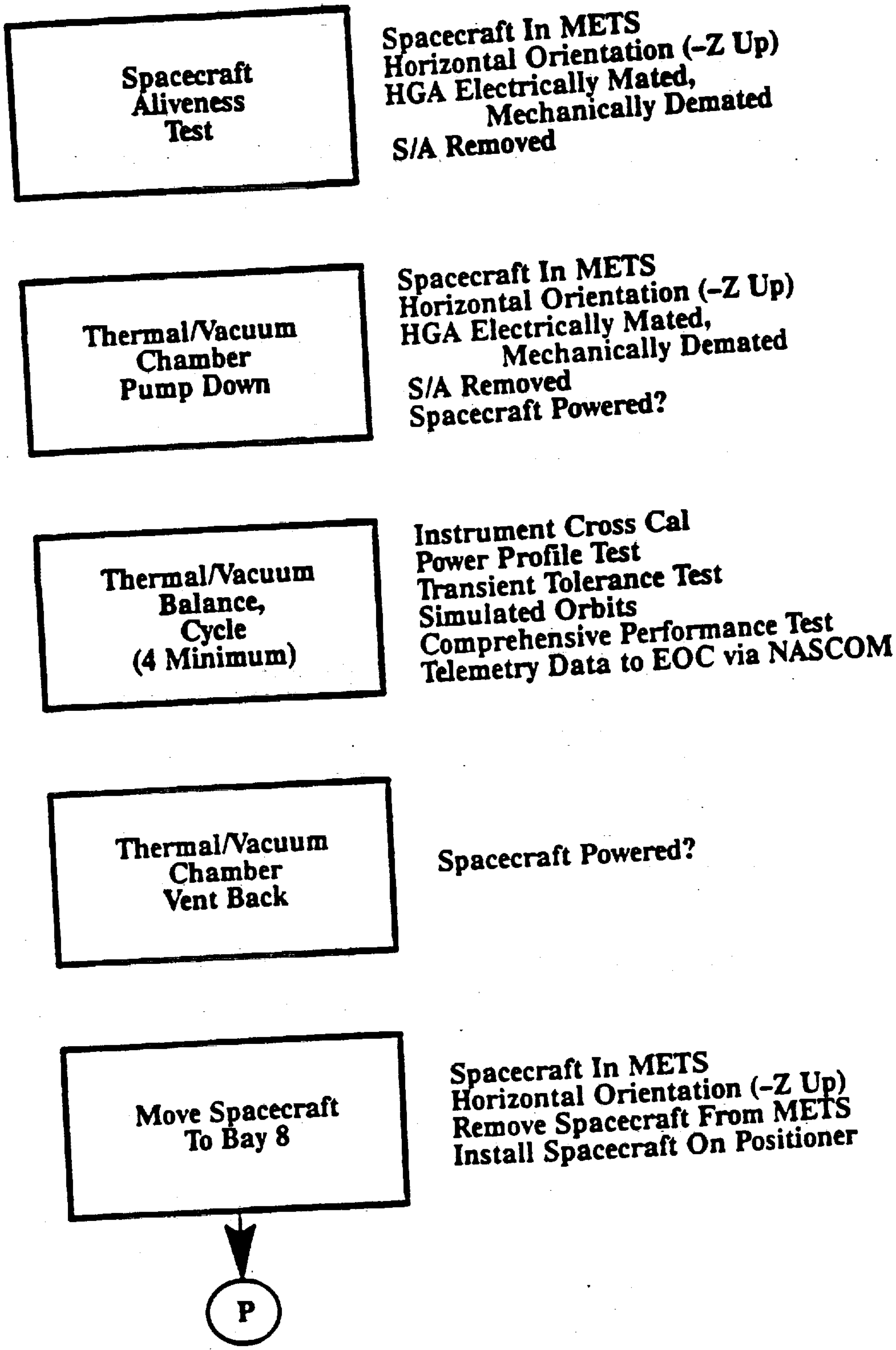
Spacecraft In Positioner
Horizontal Orientation (-Z Up)
Remove Spacecraft From Positioner
Install Spacecraft In METS
Install HGA In Flight Configuration?

Spacecraft In METS
Horizontal Orientation (-Z Up)
Radiated Emissions Measurement?
Radiated Susceptibility Test?
RF Compatibility Test?

Spacecraft In METS
Horizontal Orientation (-Z Up)
HGA Installed In Flight Configuration

Spacecraft In METS
Horizontal Orientation (-Z Up)
Remove HGA
Install Thermocouples
Install Test Heaters
Final Thermal Closeouts

Spacecraft In METS
Horizontal Orientation (-Z Up)



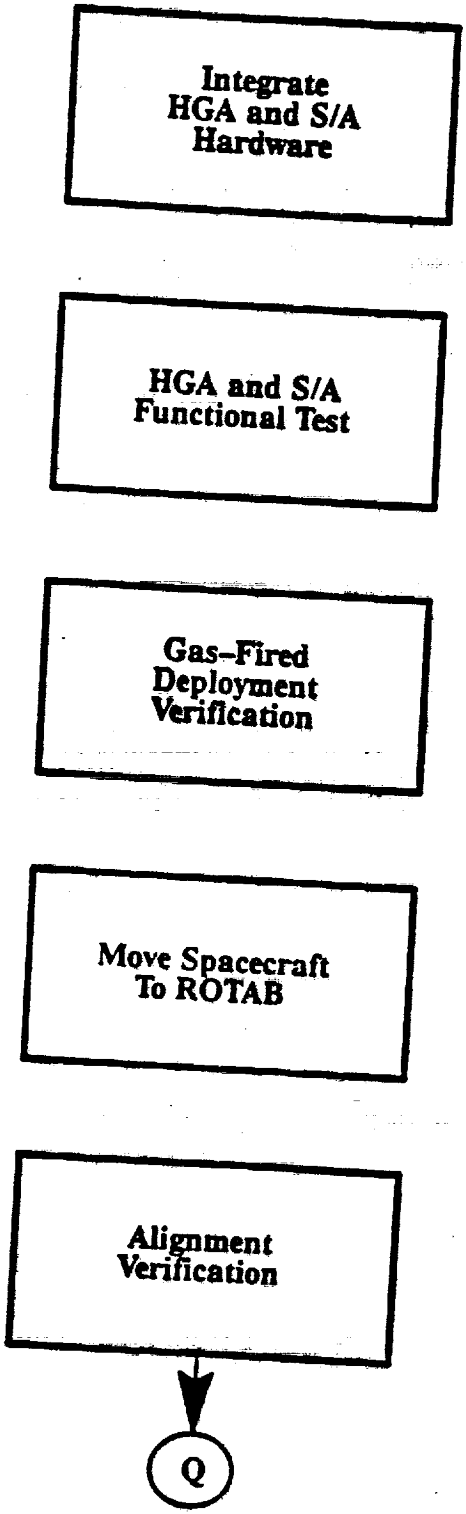
Spacecraft In METS
Horizontal Orientation (-Z Up)
HGA Electrically Mated, Mechanically Demated
S/A Removed

Spacecraft In METS
Horizontal Orientation (-Z Up)
HGA Electrically Mated, Mechanically Demated
S/A Removed
Spacecraft Powered?

Instrument Cross Cal
Power Profile Test
Transient Tolerance Test
Simulated Orbits
Comprehensive Performance Test
Telemetry Data to EOC via NASCOM

Spacecraft Powered?

Spacecraft In METS
Horizontal Orientation (-Z Up)
Remove Spacecraft From METS
Install Spacecraft On Positioner

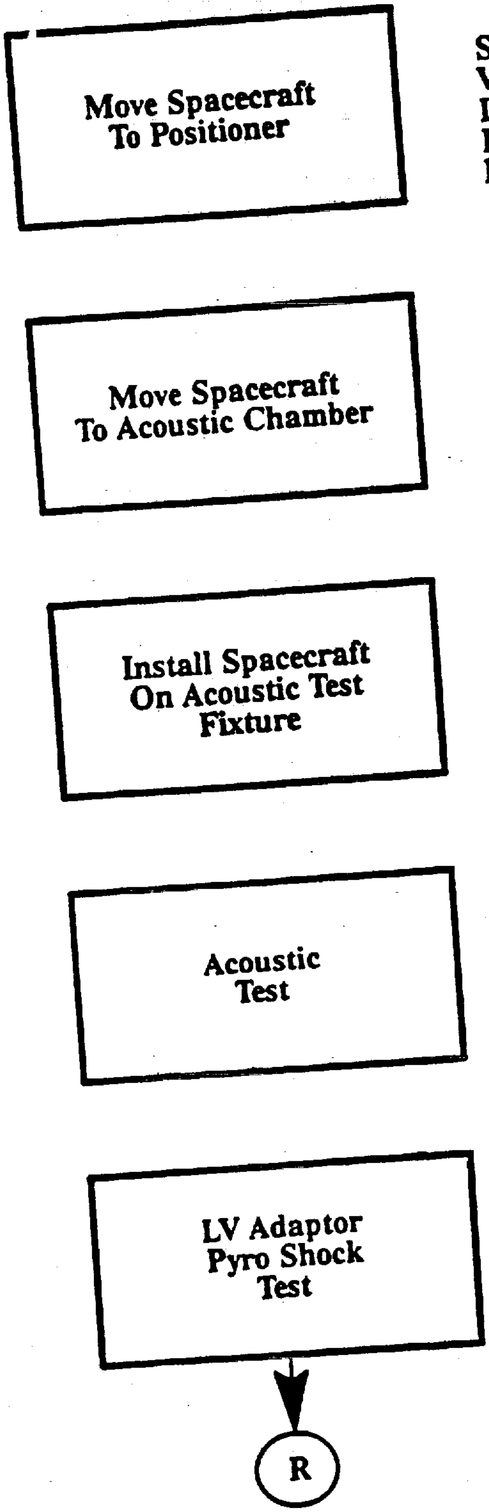


Spacecraft In Positioner
Horizontal Orientation
-Z Up for HGA
-Y Up for S/A

Spacecraft In Positioner
Horizontal Orientation
SAA Blanket Box Pop and Catch
SAA Blanket Box Top Pop and Catch?
HGA Pop and Catch
PM?

Spacecraft In Positioner
Vertical Orientation
Spacecraft Lifted Off Positioner
Spacecraft Installed On ROTAB

Spacecraft On ROTAB
Vertical Orientation



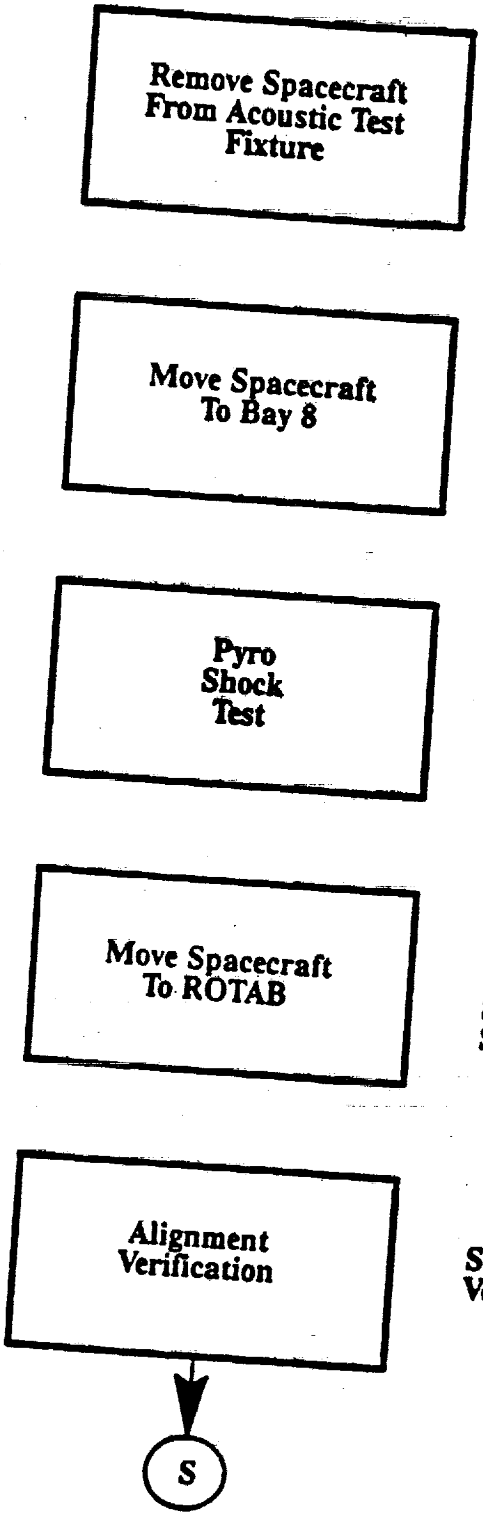
Spacecraft On ROTAB
Vertical Orientation
Lift Spacecraft Off ROTAB
Install Spacecraft On Positioner
Install Instrumentation

Spacecraft In Positioner
Horizontal Orientation

Spacecraft In Positioner
Vertical Orientation
Demate MAGE Adaptor
Lift Spacecraft Off Positioner
Install Spacecraft On Acoustic Test Fixture (with Flight Adaptor)

Spacecraft On Acoustic Test Fixture
Vertical Orientation
Spacecraft Powered On and In Launch Configuration

Spacecraft On Acoustic Test Fixture
Vertical Orientation



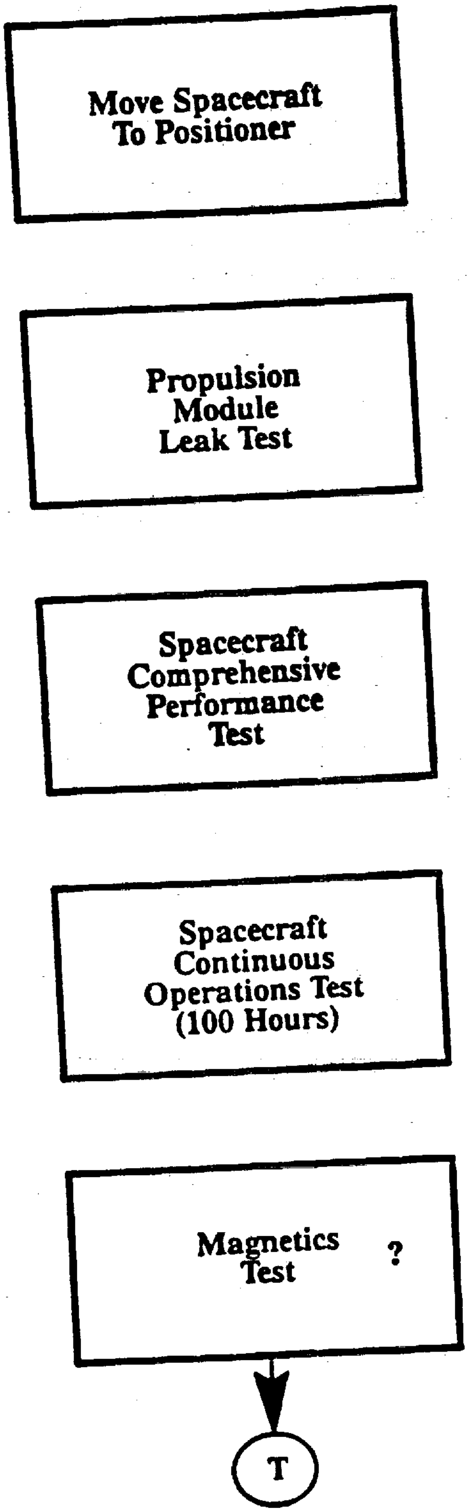
Spacecraft On Acoustic Test Fixture
Vertical Orientation
Demate Flight Adaptor
Lift Spacecraft Off Acoustic Test Fixture
Install Spacecraft On Positioner (with MAGE Adaptor)

Spacecraft In Positioner
Horizontal Orientation

Spacecraft In Positioner
Horizontal Orientation
SAA Blanket Deployment (Full?)
SAA Blanket Box Top Pop and Catch?
HGA Pop and Catch
PM?

Spacecraft In Positioner
Vertical Orientation
Spacecraft Lifted Off Positioner
Spacecraft Installed On ROTAB

Spacecraft On ROTAB
Vertical Orientation

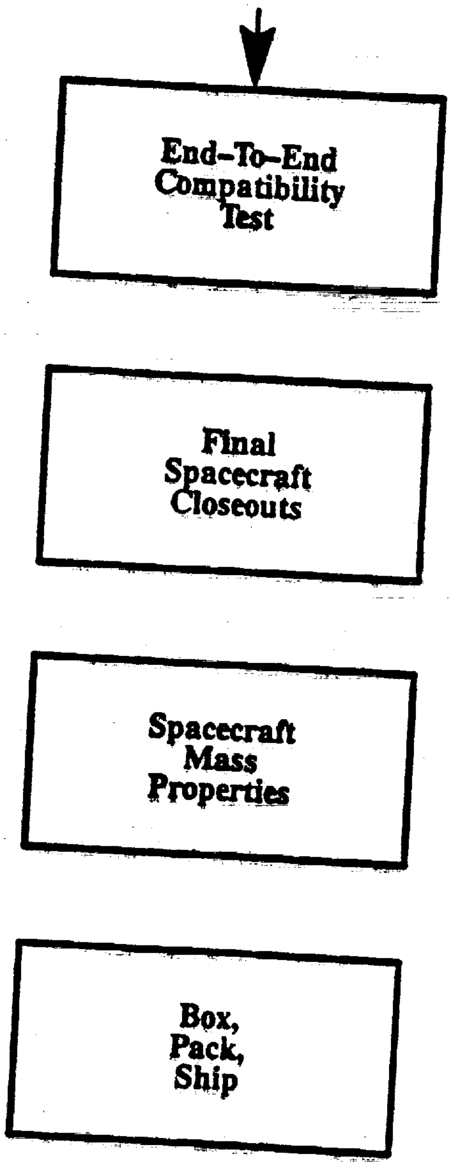


Spacecraft On ROTAB
Vertical Orientation
Lift Spacecraft Off ROTAB
Install Spacecraft On Positioner

Spacecraft In Positioner
Horizontal Orientation ?

Spacecraft In Positioner
Horizontal Orientation (-Z Up)
Telemetry To EOC via NASCOM

Spacecraft In Positioner
Horizontal Orientation (-Z Up)
Telemetry To EOC via NASCOM



Spacecraft In Positioner
Horizontal Orientation (-Z Up)
EOC Compatibility Test via
NASCOM and TDRSS

Spacecraft In Positioner
Horizontal Orientation (Various)

Horizontal Orientation?

Spacecraft In Positioner
Horizontal Orientation
Remove Spacecraft From Positioner
Install Spacecraft In EOS Shipping
Container

N94-23595

51-18

171291

p. 11

THE POSSIBLE EFFECTS OF THE NATURAL AND INDUCED SPACE ENVIRONMENT ON THE OPTICAL AND THERMAL PROPERTIES OF EOS SURFACES

PRESENTED AT

5th EOS Investigator Working Group
Calibration/Data Product Validation Panel Meeting
AM Observatory Splinter Group

07 APRIL 1992

Carl R. Maag
Science Applications International Corp.
Space Technology Division
Glendora, California

Richard A. Heppner
The Perkin-Elmer Corporation
Applied Science Operations
Pomona, California

SAIC
An Employee-Owned Company

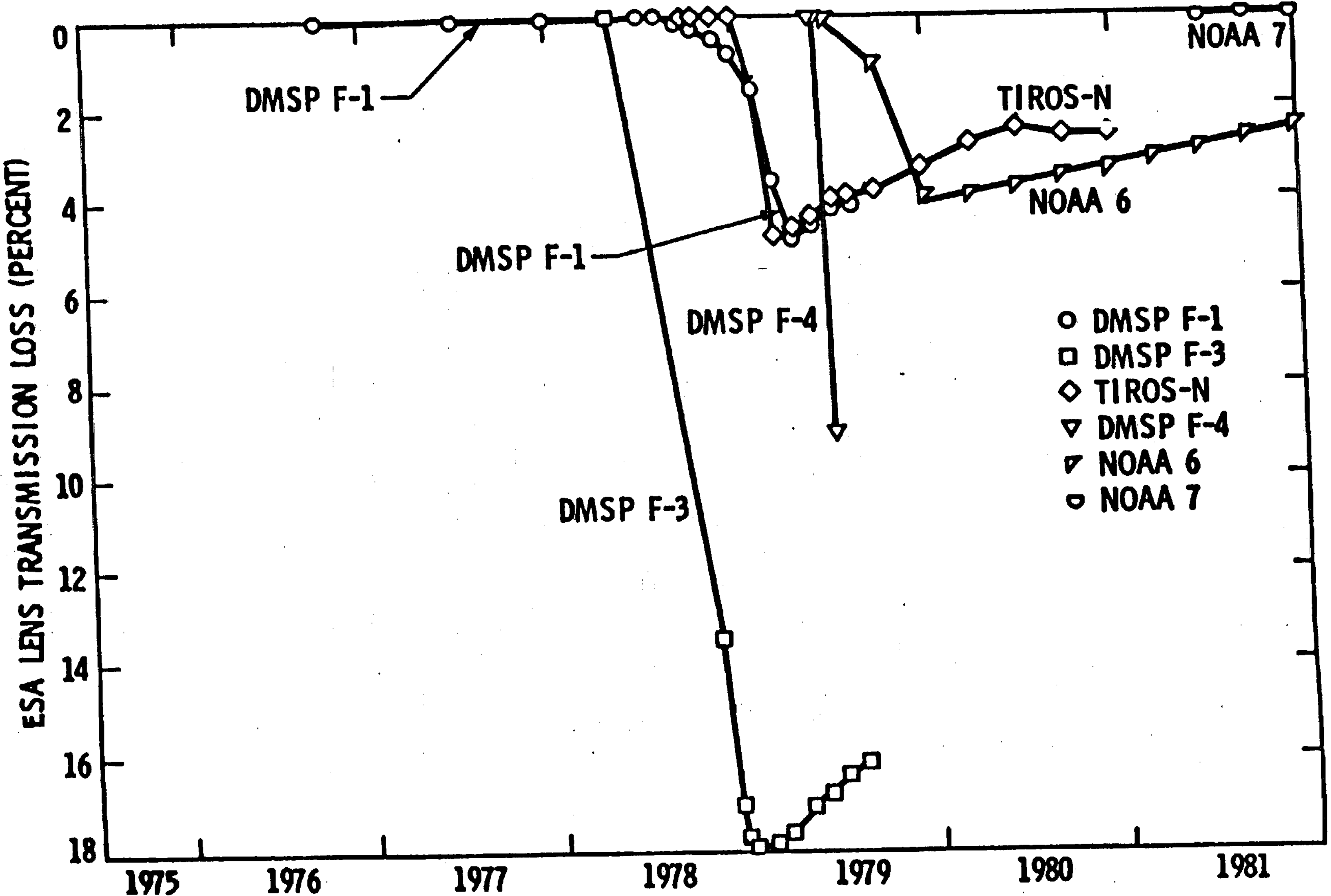
INTRODUCTION

- SPACE MISSIONS, INCLUDING THAT OF EOS, WILL CONTINUE TO BE SUBJECTED TO BOTH THE NATURAL AND INDUCED SPACE ENVIRONMENT. THE CONCERNS ASSOCIATED WITH THIS FACT WILL NOT GO AWAY
- THE NASA AND DOD HAVE RECOGNIZED THE NEED FOR LONG-LIFE STABILITY OF MATERIALS AND STRUCTURES TO THE SPACE ENVIRONMENT
- THE MAJOR AREAS OF INTEREST INCLUDE:
  - THERMAL CYCLING
  - UV DEGRADATION
  - SPACE RADIATION EXPOSURE
  - ORBITAL DEBRIS
  - ATOMIC OXYGEN EROSION
  - CONTAMINATION CONTROL
- HAVING FLOWN A NUMBER OF SPACE ENVIRONMENTAL EFFECTS MONITORS, SAIC HAS DEVELOPED BOTH A DATA BASE TO UNDERSTAND THE MAGNITUDE OF THIS PROBLEM AND MITIGATION TECHNIQUES TO REDUCE THE IMPACT

CONTAMINATION FLIGHT EXPERIENCE

- <u>RETURN FLUX</u>
    - EARTH SCAN ASSEMBLY (ESA) ON TIROS/NOAA/DMSP SHOWED SIGNIFICANT DEGRADATION (UP TO 20%)
    - RADIATIVE COOLER ON DMSP SHOWED SIGNIFICANT DEGRADATION (>400%)
    - CONTAMINATION MONITORS (TQCMs) ON NOAA-7 EXHIBITED HIGH CONTAMINATION ACCRETION (~1300 Å/2 YEARS) IN NADIR DIRECTION
    - CONTAMINATION MONITORS ON STS-3 AND OTHER SHUTTLE MISSIONS EXHIBITED HIGH CONTAMINATION ACCRETION (~15-20%) IN RAM DIRECTION
    - IECM ON STS-3 AND -4 MEASURED HIGH RETURN FLUX RATES

TRANSMISSION LOSS OF THE EXOSPHERIC ATMOSPHERE VIEWING ESA OBJECTIVE LENSES ON DMSP, TIROS-N, NOAA-6, AND NOAA-7 SATELLITES



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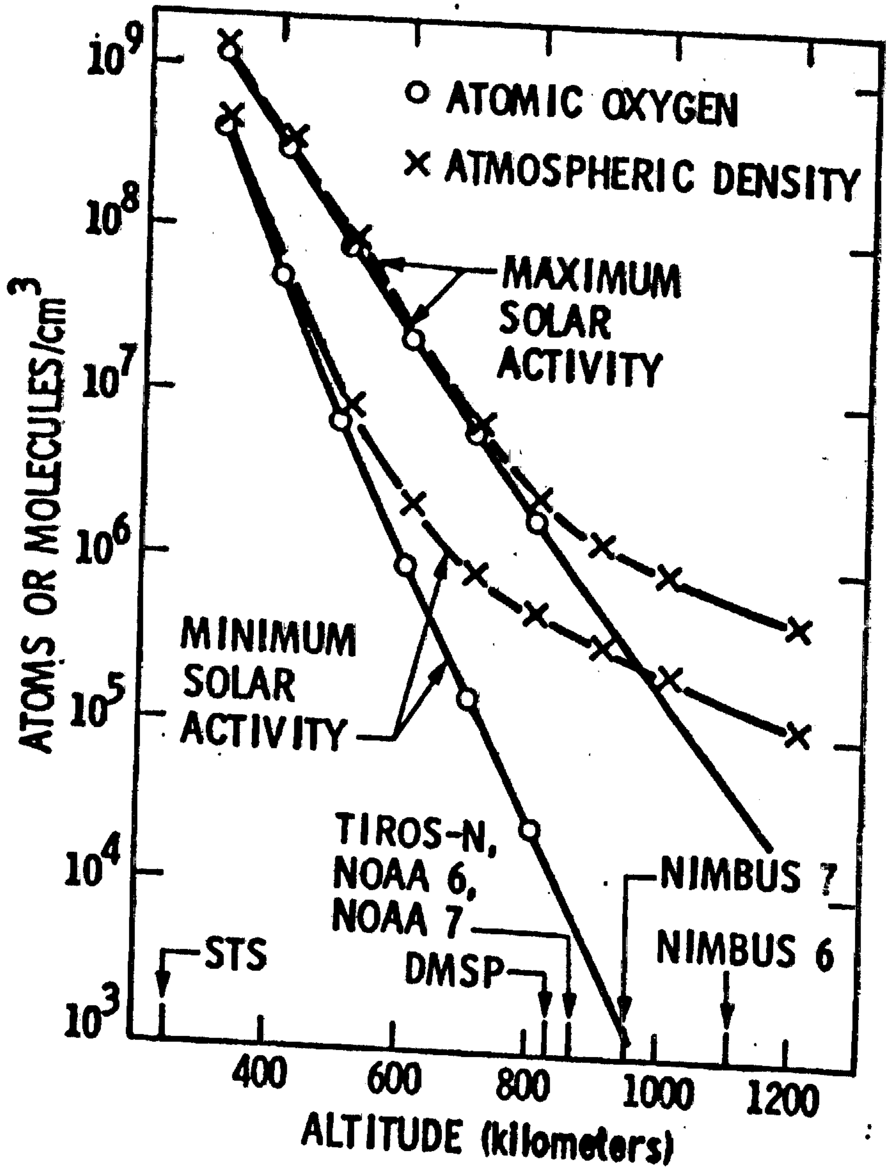
ATOMIC OXYGEN CONCENTRATION AND ATMOSPHERIC DENSITY AS A FUNCTION OF ALTITUDE



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CONTAMINATION FLIGHT EXPERIENCE (CONT)

- **<u>COLUMN DENSITIES</u>**
  - SPACE SHUTTLE MOLECULAR COLUMN DENSITY REQUIREMENTS ESTABLISHED BY NASA WERE EXCEEDED DURING SHUTTLE MISSIONS BY FACTOR OF 100
    - VIOLATED ON MOST MISSIONS
    - OPTICAL INSTRUMENTS WERE IMPACTED

- **<u>PARTICLE RELEASE</u>**
  - SPACE SHUTTLE REQUIREMENTS ESTABLISHED BY CRDG WERE EXCEEDED BY A FACTOR OF OVER 600 PER ORBIT.
    - VIOLATED ON MOST MISSIONS
    - OPTICAL INSTRUMENTS WERE IMPACTED

NOAA/CMI OBJECTIVE AND INSTRUMENTATION

- OBJECTIVE WAS TO MEASURE CONTAMINATION FROM
  - SRM (TE-M-364-15) PLUME BACKFLOW
  - HYDRAZINE RCS THRUSTERS
  - REFLECTION OF SRM OUTGASSING FROM SOLAR ARRAY
  - LONG-TERM SPACE VEHICLE OUTGASSING

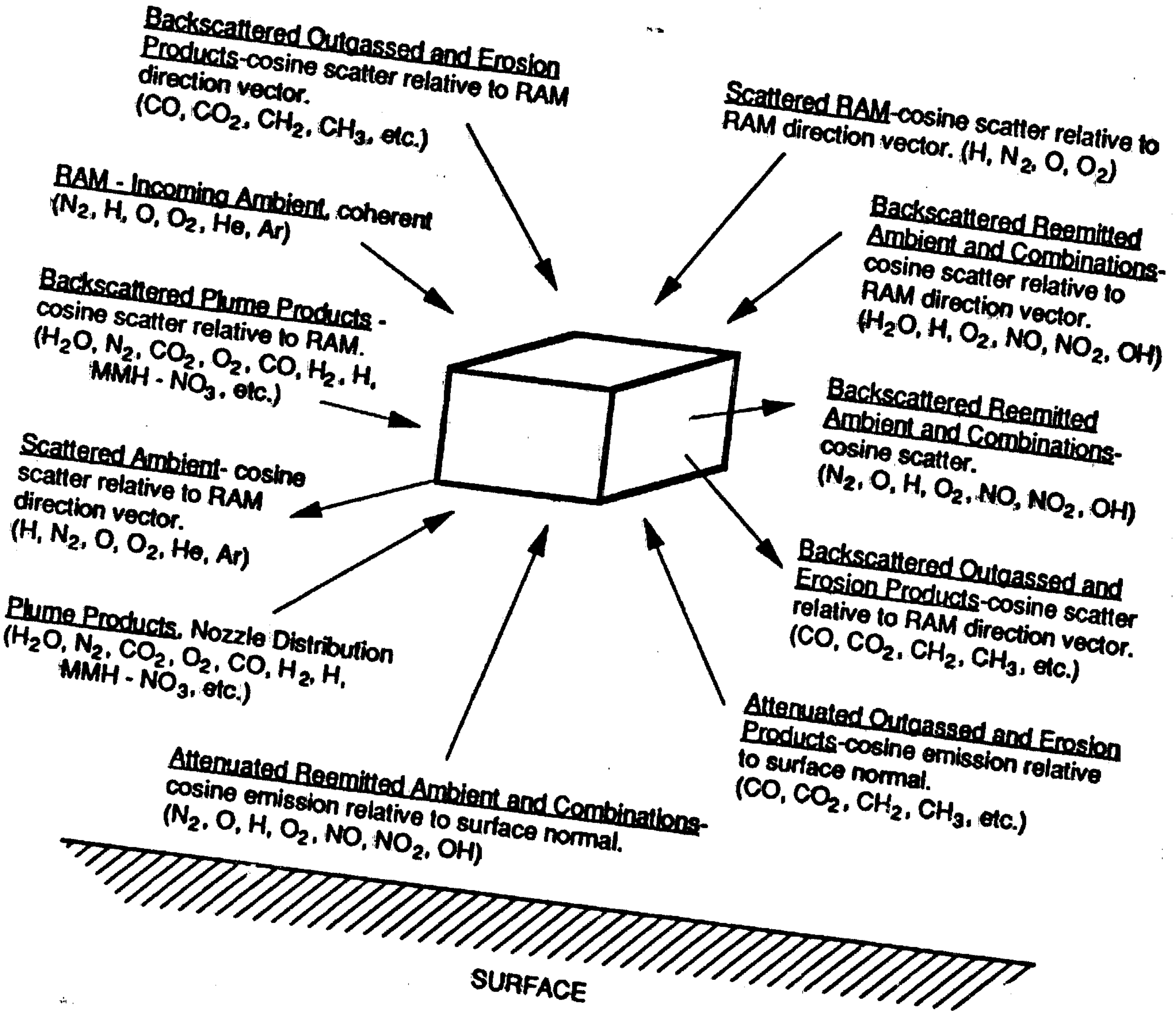
- SENSORS
  - TQCMs
  - UV PHOTODIODE (FILTERED)
  - BLACK CALORIMETERS ($\alpha/\varepsilon = 1.04$)
  - DIELECTRIC MIRROR CALORIMETER
  - DIFFUSE SURFACE CALORIMETER

IOCM OBJECTIVE AND FLIGHT INSTRUMENTATION

- OBJECTIVE WAS TO DETERMINE ANY ADDITIONAL CONTAMINANT FLUX OCCURRING TO PRIMARY PAYLOADS AND INSTRUMENTS FROM PAYLOAD INSERTION THROUGH REMOVAL FROM THE STS ORBITER. IN ADDITION, ORBITAL DEBRIS IMPACTS AND ATOMIC OXYGEN FLUENCE WERE ALSO MEASURED.

- SENSORS
  - TQCMs/QCPMs/AOMs
  - OSR CALORIMETERS
  - PRESSURE GAUGES
  - FLUX SENSORS (UV, VIS)
  - INTACT PARTICLE CAPTURE
  - IMPACT SENSORS (PASSIVE)
  - PASSIVE WITNESS SAMPLES (AO, CONTAMINATION)

NANT INTERACTION WITH THE AMBIENT ATMOSPHERE



Backscattered Outgassed and Erosion Products-cosine scatter relative to RAM direction vector. (CO, CO_2, CH_2, CH_3, etc.)

Scattered RAM-cosine scatter relative to RAM direction vector. (H, N_2, O, O_2)

RAM - Incoming Ambient, coherent (N_2, H, O, O_2, He, Ar)

Backscattered Reemitted Ambient and Combinations-cosine scatter relative to RAM direction vector. (H_2O, H, O_2, NO, NO_2, OH)

Backscattered Plume Products - cosine scatter relative to RAM. (H_2O, N_2, CO_2, O_2, CO, H_2, H, MMH - NO_3, etc.)

Backscattered Reemitted Ambient and Combinations-cosine scatter. (N_2, O, H, O_2, NO, NO_2, OH)

Scattered Ambient- cosine scatter relative to RAM direction vector. (H, N_2, O, O_2, He, Ar)

Backscattered Outgassed and Erosion Products-cosine scatter relative to RAM direction vector. (CO, CO_2, CH_2, CH_3, etc.)

Plume Products, Nozzle Distribution (H_2O, N_2, CO_2, O_2, CO, H_2, H, MMH - NO_3, etc.)

Attenuated Outgassed and Erosion Products-cosine emission relative to surface normal. (CO, CO_2, CH_2, CH_3, etc.)

Attenuated Reemitted Ambient and Combinations-cosine emission relative to surface normal. (N_2, O, H, O_2, NO, NO_2, OH)

IMPLICATIONS AND RECOMMENDATIONS

- THE EOS PLATFORMS WILL BE SUBJECTED TO THE EVER PRESENT "CONTAMINATION CLOUD"
- IF NO MITIGATION TECHNIQUES ARE EMPLOYED, REFRACTIVE/REFLECTIVE OPTICAL ELEMENTS AND THERMAL SURFACES WILL MOST LIKELY BE AFFECTED
- A CONTAMINATION MONITOR PACKAGE, WITH DISTRIBUTED SENSORS, SHOULD BE INCORPORATED WITHIN THE INSTRUMENT COMPLEMENT TO AID IN THE PROTECTION OF THE SENSITIVE SUBSYSTEMS OR INSTRUMENTS

PERFORMANCE OF SUGGESTED EOS SPACE ENVIRONMENTAL EFFECTS SENSORS

MEASUREMENT	SENSOR	TYPICAL OPERATING RANGE	TYPICAL SENSITIVITY
TOTAL PRESSURE	IONIZATION GAUGE	2×10^{-10} to 2×10^{-3} Torr	±0.1 Torr
MOLECULAR DEPOSITION	TQCM	+80°C to -50°C	1.56×10^{-9} g/cm^2/Hz
PARTICULATE DEPOSITION	QCPM	+80°C to -50°C	3.5×10^{-9} g/cm^2/Hz
MOLECULAR SPECIES	MASS SPECTROMETER	8×10^{-11} to 6×10^{-4} Torr For AMU 1-150	± 1 AMU
CHANGE IN SOLAR ABSORPTANCE, α_s	THERMAL COATING CALORIMETER	-40°C to +60°C	± 0.005
CHANGE IN OPTICAL SCATTER, BRDF	SCATTEROMETER	10^{-4} to 10^{0} Sr^{-1}	TBD
DEBRIS IMPACT	IMPACT DETECTOR	0.05 to 1.0 mm	± 0.001 mm

TQCM - TEMPERATURE CONTROLLED QUARTZ CRYSTAL MICROBALANCE
QCPM - QUARTZ CRYSTAL PARTICLE MICROBALANCE
BRDF - BI-DIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION

[redacted]

An Employee-Owned Company

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Information Contents of the SPDB

Investigators:

- Name and Address
- Affiliation
- Phone and Fax Numbers
- E-mail Address
- Associated Team Membership

Instruments:

- Platforms
- Swath and Duty Cycle
- Mass and Power Usage
- Data Rates
- Number of Channels and Spectral Range
- Description

Data Products:

- Investigators
- Platforms and Instruments
- Archive Centers (DAAC's)
- Temporal and Spatial Resolution
- Horizontal and Vertical Coverage
- Accuracies

Retrieval Algorithms:

- Investigators
- Platforms and Instruments
- Input and Output Data
- Description

V0 Datasets:

- Dataset Name
- Parameters
- Temporal and Spatial Coverage
- Platforms and Instruments
- Data Volumes in 1991 and 1994
- Archive Centers
- Data Producers
- Storage Media and Format

What Is the SPDB?

Science Processing Database (SPDB) is an interactive, on-line system that provides updated information about EOS Project, including

- Instruments
- Investigators
- Output Data Products
- Input Requirements
- Retrieval Algorithms
- V0 Datasets archived at DAAC's

What Do You Need?

The SPDB supports VT100 class terminals, VT2xx and VT3xx class terminal set to operate in VT100 mode, and terminal emulator software with VT100 capabilities.

Non-hardwired DEC terminal (VT 100) users need a modem which is Bell 103 or Bell 212A compatible. IBM PC or Macintosh users need communications software capable of VT100 emulation, in addition to the modem. Software that have been successfully tested are:

IBM PC	Crosstalk, Procomm, Pcplot
Macintosh	Versaterm, Versaterm Pro

User Support:

For User's guide and information, please contact:

Yun-Chi Lu
NASA/GSFC, Code 930.9
Greenbelt, MD 20771
(301)286-4093
YLU@GSFCMAIL

For technical problems/comments, please contact:

Chris Lynnes
lynnes@spso.gsfc.nasa.gov
(301)513-1720

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SPDB

SCIENCE PROCESSING DATABASE

Quick Reference Guide

Contents

1. How to Log Into the SPDB
2. How to Navigate through Menus
3. How to Use ESC Keys
4. How to Get Help
5. How to Quit the Program

GSFC/SPSO *February 1992*

How to Log Into the SPDB:

Your equipment determines which connection method to use: dial-up or network. If you have a terminal or PC with a modem and communications software, you can use dial-up access. If your terminal is connected to a computer that is on a national network (e.g., NAN or SPAN), you can use the network access procedures. In the examples given below computer prompts are shown in *Italics* and user entries are shown in **bold text.**

Dial-up:
301-286-9000 (2400 baud)
or
301-286-4000 (9600 baud)
Enter number: **sisc <CR><CR>**
Enter username> **your name**
Local> **c spso**
Login: **spdb**
Password: **spsospdb**

Using Internet::
telnet spso.gsfc.nasa.gov
or
telnet 128.183.112.102
Login: **spdb**
Password: **spsospdb**

Using Span (VAX/VMS):
rlogin spso /username=spdb
Password: **spsospdb**
<SFC-LAN
Using Span (Unix):
rlogin spso -l spdb
Password: **spsospdb**

(Note: If you are using an IBM PC or Macintosh with communications software, make sure that you select the VT100 emulation option.)

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How to Navigate through Menus:

There are three wanys of moving through menus:

1. Move the cursor with cursor keys.
2. Use ESCAPE Keys to scroll.
   (*Caution*: Press ESC and let up, then press and let up the second key)
3. Type the initial letter(s) of an item. *Caution*: if the letters you type uniquely identify that item in the list, the item will also be automatically "chosen" (i.e., executed). To type a new set of initial letter(s), tab to the next item and start typing again.

How to Use Escape Keys:

(*Caution*: Press ESC and let up, then press and let up the second key. Do NOT hold down ESC key)

ESC b	Go to the bottom of the list or menu
ESC c	Clear all fields in the form
ESC d	Page down (scrollable field)
ESC h	Help (field-level) or Valids List
ESC k	Help on keys
ESC q	Quit SPDB
ESC r	Refresh the screen
ESC s	Save comments
ESC t	Go to the top of the list or menu
ESC u	Page up (scrollable field)
ESC x	Delete the current field in the form
ESC ESC	Exit the screen

Valid Lists:

Valid lists are used to fill in a blank from a list of valid values. To pop up a Valid List, type ESC h in the blank you wish to fill. Select the item you want and press <CR>, or type ESC ESC to cancel. Valid Lists are dynamic, i.e., constrained by the blanks already filled in and/or by wildcard strings in the current blank.

Wild Cards:

You can use either SQL or Unix style wildcards in query forms.

Single character:	_ or ?
Multiple character:	% or *

Help:

HELP is available on the following subjects:

- **Screen Help** (help on the current screen)
- **Escape Help** (help on escape keys)
- **User Support** (how to contact SPSO)
- **Help Index** (view any help item)

To get help screen,

1. Post the menu, if not already at the top of the screen, by pressing <CR>
2. Choose **Options** from the menu
3. Choose **Help** from the **Option** submenu

How to Quit the Program:

You can quit the SPDB at any time by typing ESC q, or

1. Post the menu, if not already at the top of the screen, by pressing <CR>
2. Choose **Options** from the menu
3. Choose **Quit Program** from the **Option** submenu (you will be asked for confirmation: type y or <CR> to quit)

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Earth Observing System
Calibration Advisory Panel

Definitions in use by the Visible and Near-Infrared, and Thermal Working Groups

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November 13, 1991

Introduction

The Calibration Advisory Panel (CAP) is composed of calibration experts from each of the Earth Observing System (EOS) instruments, science investigation, and cross-calibration teams. These members come from a variety of institutions and backgrounds. In order to facilitate an exchange of ideas, and assure a common bases for communication, it was desirable to assemble this list of definitions. These definitions were developed for use by the visible and near-infrared working group, and the thermal infrared working group. Where necessary or appropriate, deviations from these for specific instruments or other sensor types are given in the individual calibration plans.

The definitions contained in this document are derived, wherever possible, from definitions accepted by international and national metrological commissions including the United States National Institute of Standards and Technology (NIST), the International Bureau of Weights and Measures (BIPM), the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the International Organization of Legal Metrology (OIML).

Often, the way specific terms are defined can impact procedures, delineate personnel or programmatic responsibilities, and define the time frame in which a given measurement is to be made. It may be sufficient, for example, during *verification* testing, to perform a quick check-out procedure using less accurate sources or testing equipment than that required during a *calibration* test. The *calibration* of an instrument may be conducted by different personnel than the *validation* of an instrument's data products. Thus, the terms used here are updated from those in the literature as needed to reflect the usage of this particular remote sensing community.

In reviewing this document, it is noted that subtle differences often exist between terms. For example, care is used to distinguish between *accuracy, precision, error,* and *uncertainty*. If a measurement system is used to repeatedly measure a constant known source, with some defined variation of environmental conditions, such as the ambient temperature, the population of the measured (reported) values would have the following characteristics:

- one minus the relative standard deviation (standard deviation to mean ratio) of this population is the *precision*,
- the standard deviation plus known systematic error terms compose the *uncertainty*,
- one minus the relative uncertainty is the *accuracy*,
- the difference between any particular measurement and the true value is an *error*.

Where appropriate, therefore, cross-reference is made within the definitions to clarify subtle differences in terms.

Definitions

accuracy. An estimate characterizing the closeness of a measurement to the true measurand. It can be given as one minus the absolute value of relative uncertainty (negative values are set to 0), or as a percentage after multiplication by 100. Note that while *accuracy* assumes reference to a standard or knowledge of error sources, *precision* is a relative measure of the agreement amongst a set of measurements. Also, with *accuracy* higher numbers are better, and with *uncertainty* lower numbers are preferred.

calibration. The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument and the corresponding known values of a standard. For EOS sensors this typically implies the radiometric, spectral, or geometric characterization of an instrument as needed to understand the impact of the instrument performance on the data or the derived data products.

absolute calibration. The determination of calibration factors by comparison with a standard whose output is known in accepted physical (SI) units.

ground calibration. The radiometric calibration of an in-orbit sensor through an *intensive field-campaign*. This calibration is established via a

1) reflectance-based ground calibration in which atmospheric and surface reflectance characteristics are measured and used to compute exo-atmospheric radiances, or

2) radiance-based ground calibration in which helicopter or aircraft sensors are used to map radiances and extrapolate to the required exo-atmospheric radiances.

in-flight calibration. The calibration of an aircraft or satellite-based sensor while in flight. This may be through ground calibration exercises, or through use of an on board calibration system.

preflight calibration. The calibration of a sensor prior to launch.

relative calibration. The determination of the correction by comparison with a standard whose output is not necessarily known in physical units, but which is established in ratio or as a fraction of the value of the standard.

self-calibrating. A *standard* of calibration based upon known physics. These may include

1) self-calibrating photodiodes, also known as quantum efficient detectors, or silicon photodiodes of known or negligible reflectance and known internal quantum efficiency,

2) blackbody radiation simulators operating at a well defined temperature and emittance, and

3) electrical substitution radiometers in which a measured amount of electrical power used to heat a given material is compared to the optical heating of the same material.

calibration curve. The result of a calibration; a term or set of terms by which the instrument values are related to the corresponding known standard values. It may be expressed with calibration coefficients, or with use of a curve. Also referred to as the radiometric transfer curve.

characterization. The measurement of the typical behavior of instrument properties which may affect the accuracy or quality of its response or derived data products. The results of a characterization may or may not be directly used in the calibration of the instrument response, but may be used to determine its performance (the characterized properties may inherently affect the calibration of the instrument.)

confidence interval. An interval about the result of a measurement or computation within which the true value is expected to lie, as determined from an uncertainty analysis with a specified probability.

cross-calibration. The process of assessing the relative accuracy and precision of response of two or more instruments. A cross-calibration would provide the calibration and/ or correction factors necessary to intercompare data from different instruments looking at the same target. Ideally this would be done by simultaneous viewing of the same working standards or target. Any variations in environmental conditions, calibration procedures, or data correction algorithms between the instruments must be accounted for in the assessment.

data product. The final processed data sets associated with the various measured and derived geophysical parameters which are the object of a specified investigation and referred to as a higher level product than the measurement provided by the instrument.

data product validation. The process of assessing, by independent means, the uncertainty of observables or geophysical parameters derived from sensor output. Accurate calibration, data transmission, and processing algorithms are prerequisite to data validation. Data product validation can further be divided into correlative measurements or data product verifications.

correlative measurements. Spatially and temporally coincident measurement of the parameters deduced from a given sensor, made with independent surface, aircraft, or separate in-orbit instrumentation. These activities require coordination with other ground stations, EOS validation teams, concurrent intensive field campaigns, or long-term monitoring stations.

data product verification. Perform product validation analyses by simulation, checks with physical bounds, or self-consistency analyses. Comparisons with routine data products from other in-orbit sensors, or utilization of existing data bases for trend analyses are included.

drift. The slow variation with time of a metrological characteristic of an instrument.

engineering units. A set of defined units commonly used by an engineer in a specific field to express a measurand.

environmental variables. Variable physical properties in the environment of the instrument or target (such as temperature, particulate and electromagnetic radiation, vacuum, and vibration) which may effect the result of a measurement. Note the sensor does not measure an environmental variable; it measures an *observable*.

error. The difference between a reported value and its true value.

relative error. The absolute error of measurement divided by the true value of the measurand.

random error. A component of the error of measurement which, in the course of a number of measurements of the same measurand, varies in an unpredictable way. It is not possible to correct for random error, but its magnitude may be determined by the application of statistical procedures.

systematic error. A component of the error of measurement which, in the course of a number of measurements of the same measurand, remains constant or varies in a systematic predictable way. Systematic errors and their causes may be known or unknown. This error is also referred to as "bias error".

functional test. A test that demonstrates a go/ no go condition with respect to a functional requirement.

geometric calibration. The characterization of the correlation between the actual geometric properties of the observed target and the output of the measuring instrument. Includes such parameters as fields-of-view, registration, and pointing knowledge.

geophysical parameters. Those variables of the Earth's environment, including aspects of the land and water surfaces, atmosphere and space, which are used to describe the environment and geophysical processes. Geophysical parameters may be directly observable or deduced from sensor output as a higher level product.

hysteresis. The property of an instrument whereby its response to a given stimulus depends on the sequence of preceding stimuli. In photodetectors, hysteresis refers to the retention of signal in detectors that have already been read in an amount proportional to the input.

integrator verification tests. *Verification tests* conducted at the integrator facility.

comprehensive test. The full complement of *verification tests* performed at the instrumentor facility at the conclusion of the environmental test phase.

bench acceptance test. A subset of the *comprehensive tests*, performed before and after shipment of instrument to the integrator.

functional test. A subset of the *comprehensive tests*, performed before, during, and after environmental exposure tests to verify that the payload has not degraded. Externally mounted sources and simple targets will be utilized.

operability test. A subset of the *functional tests* used to provide traceability of the instrument performance through PMP (Payload Mounting Plate) integration, observatory integration, and shipment to the launch site. No externally mounted targets will be used.

aliveness test. A subset of the *operability tests* used to monitor the housekeeping command and telemetry data. No science or engineering data are acquired. The test is done before and after shipment to the launch site.

intensive field campaign. A limited period of time in which in-situ measurements are made in support of a remote sensing program. These measurements may be used to provide a sensor calibration, or validate observables or derived data products. An *intensive field campaign* differs from a *long-term monitoring program* in that the latter provides an on-going activity in which instrumentation and personnel are dedicated to the in-situ measurements task. See *ground calibration.*

long-term monitoring program. An on-going in-situ measurements program which is typically at a fixed site using dedicated personnel. These measurements may be used to provide a sensor calibration, or validate observables or derived data products. This contrasts to an *intensive field campaign* in which equipment and personnel are brought to a test site where they remain until the experiment objectives have been accomplished, or until allotted funds or time are depleted.

measurement assurance program (MAP). A program applying specified (quality) principles to a measurement process. A MAP establishes and maintains a system of procedures intended to yield calibrations and measurements with verified limits of uncertainty based on feedback of achieved calibration of measurement results. Achieved results are observed systematically and used to eliminate sources of unacceptable uncertainty.

model.

mathematical model. A mathematical description of a (sensor) system relating inputs to outputs. For EOS, may be implemented in a variety of ways but must be of sufficient detail to provide inputs to system analysis studies such as performance prediction, uncertainty (or error) modeling, and isolation of failure or degradation mechanisms, or environmental limitations.

error model. A mathematical model of the measurement chain in which all potential error sources are identified, quantified, and combined such that a meaningful estimate of measurement uncertainty can be determined.

model validity. Our expectation of the accuracy of assumptions used to develop a mathematical model for a given system.

observables. The fundamental physical quantity or quantities that a sensor can measure, such as temperature which through a process of calibration can be related to a Geophysical parameter. Observables can usually be measured by processes traceable to physical standards.

pointing.

absolute pointing knowledge. The total angle between the actual pointing direction and the reconstructed pointing direction. The reconstructed pointing direction is obtained after the fact by processing "best fit" ephemeris and attitude determination data, sensor data, and instrument image data.

bore-sight angle. The deviation in total angle between the actual pointing direction of an instrument and some reference.

pointing control (absolute placement). The total angle between the actual pointing direction and the desired pointing direction

pointing stability. The variation of the total angle between the actual pointing direction and the desired pointing direction over some time interval.

precision. The consistency of measurements made with the same sensor, as determined through a statistical study. The confidence with which a measurement can be repeated with a given sensor under controlled conditions, or the confidence that two different sensors or techniques can yield a result.

absolute precision. Magnitude of the uncertainty in the result in the same units as the result.

relative precision. Magnitude of the uncertainty in terms of a fraction of the value of the result.

registration. The accurate geometric matching or superposition of two or more measurements of he same object.

repeatability. The ability of an instrument to give under specific conditions of use, closely similar responses for repeated applications of the same stimulus. Measurements are carried out over changing conditions such as:

- The method of measurement,
- The measuring instrument,
- The condition of us,
- The observer,
- The location,
- The time.

Examples are measurements made over long time periods, or where excursions of ambient conditions have occurred. This contrasts to precision where a comparison of measurements is made under constant conditions.

resolution. A quantitative expression of the ability of an instrument to distinguish meaningfully between the smallest detectable values of the input quantity measured. Generally defined by the Rayleigh Criterion in optical systems for angular response. For radiometric observables, this may be set by the digitization size (1 DN).

response time. The time interval in which a sensor increases from 10% to 90% of its final output value, in response to a stimulus which has undergone a specified abrupt change.

rise time. The interval in which a sensor increases to 1-1/e, or 63%, of its final output value.

fall time. The interval in which a sensor decreases to 1/e, or 37%, of its initial output value.

settling time. The time interval it takes an instrument to reach and remain within specified limits of its final value.

responsivity. The change in the response of a measuring instrument divided by the corresponding change in the stimulus. Sometimes referred to as sensitivity.

sampling interval. The size of the samples used to measure something; i.e. in imaging, sampling refers to pixel size. In spectroscopy, sampling refers to the spectral separation between the centers of adjacent samples.

sensor. A device that responds to either the absolute value or change in a physical stimulus (heat, light, sound, magnetism, pressure, or particular motion) and produces a corresponding signal. A sensor can be an entire instrument or the part of it that measures a phenomenon.

spectral calibration.

band-to-band calibration. The determination of variation in radiometric response from one spectral channel relative to another spectral channel.

center wavelength. The wavelength that represents the bandpass of a sensor or sensor channel. It can be defined as the wavelength at the centroid of the instrument's response, the midvalue of the spectral bandpass, or peak value.

spectral sampling interval. The distance in wavelength or wavenumber between the center wavelength/ wavenumber of adjacent spectral channels.

spectral bandwidth. The range of spectral input to which a channel of a sensor produces output at acceptable levels of sensitivity. Can be calculated as the full width at half maximum response for a channel, or by alternative descriptions such as those based on moments analyses.

stability. The ability of an instrument to maintain constant metrological characteristics. Generally a measure of variation in response to a known, stable standard.

short-term stability. Stability as measured over a short time interval. This may be over a period of a shorter than a seconds to one orbital revolution, or may be over a single instrument measurement cycle (single image frame, line time, etc.)

intermediate stability. Stability as measured over an intermediate time interval. This may be on the order of several revolutions to an orbital repeat period (few weeks).

long-term stability. Stability as measured over a long time interval. This may be, for example, from several orbital repeat periods, to the lifetime of an instrument (nominally 5 years).

standard deviation. For a series of n measurements of the same measurand, the parameter σ characterizing the dispersion of the results and given by the formula:

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N} (x_n - \bar{x})^2}{n-1}}$$

standards (physical). An accepted material, instrument, procedure, or system to be used as a reference for establishing a unit for the measurement of a physical quantity.

primary standard. A standard which has the highest metrological qualities in a specified field. It may be realized from first principles, or established by international agreement.

secondary standard. A standard whose value is fixed by comparison with a primary standard

international standard. A standard recognized by an international agreement to serve internationally as the basis for fixing the value of all other standards of the quantity concerned.

national standard. A standard recognized by an official national decision as the basis for fixing the value, in a country, of all other standards of the quantity concerned. The national standard in a country is usually a primary standard. In the United States, National Standards are set by the National Institute of Standards and Technology (NIST). As a working group we recognize that NIST is not the exclusive supplier of standards.

reference standard. A standard, generally of the highest metrological quality available at a given location, from which measurements made at that location are derived.

working standard. A standard which usually calibrated against a reference standard, is used routinely to calibrate or check material measures or measuring instruments.

transfer standard. A standard used as an intermediary to compare standards, material measures or measuring instruments.

travelling standard. A standard, sometimes of special construction, intended for transport between different locations.

traceability. The property of a result of a measurement whereby it can be related to appropriate standards, generally international or national standards, through an unbroken chain of comparisons.

uncertainty. An estimate characterizing the range of values within which the true value of a measurand lies. (As compared to *accuracy*, here smaller numbers are better). Uncertainty comprises, in general, many components. Some of these may be estimated on the basis of the statistical distribution of the results of measurements made under constant and controlled conditions (e.g. the standard deviation). Estimates of other components can only be based on experience or other information. It can also be based upon a set of absolute measurements (made with reference to some standard). Included with uncertainty should be some stated confidence level (3σ, or a 99% confidence level is recommended).

relative uncertainty. Magnitude of the uncertainty in terms of a fraction of the value of the result.

units.

standard (SI) units. The coherent system of units adopted and recommended by the General conference on Weights and Measures (CGPM). The SI is based on the following seven base units:

Entity	Term	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	sec
Electric Current	ampere	A
Thermodynamic Temperature	kelvin	K
Amount of Substance	mole	mol
Luminous Intensity	candela	cd

derived (SI) units. A unit of measurement of a quantity derived from the SI system of base units. Some derived units have special names and symbols:

Entity	Term	Symbol
Capacitance	farad	F
Inductance	henry	H
Electric Charge	coulomb	C
Voltage (emf)	volt	V
Electric Field Strength	volt/meter	E
Resistance	ohm	Ω
Frequency	hertz	Hz
Energy(work,heat)	joule	J
Power	watt	W
Magnetic flux	weber	Wb
Magnetic flux density	tesla	T
Force	newton	N
Pressure	newton per square meter or pascal	N m^{-2} or Pa

derived radiometric units. (Mathematical Symbol in parenthesis)

Entity	Term	Symbol
Radiant Energy (Q)	joule	J
Radiant Flux (Φ)	watt	W
Radiant Flux Density at a surface Radiant Exitance (M) Irradiance (E)	watt per square meter	W m^{-2}
Radiant Intensity (I)	watt per steradian	W sr^{-1}

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Entity	Term	Symbol
Radiance (L)	watt per steradian and square meter	W sr^{-1} m^{-2}
Reflectance = Φ_r/Φ_i = (ρ)	unitless	
Emissivity= $M/M_{blackbody}$ = (ε)	unitless	
Absorptance = Φ_a/Φ_i=(α)	unitless	
Transmittance =Φ_t/Φ_i=(τ)	unitless	

where $\Phi_i, \Phi_r, \Phi_t, \Phi_a$ = incident, reflected, transmitted, and absorbed flux respectively.

SI prefixes. Used as prefixes in combination with the terms and symbols of SI units to form decimal multiples an submultiples of those units.

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	µ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10^{1}	deca	da	10^{-18}	atto	a

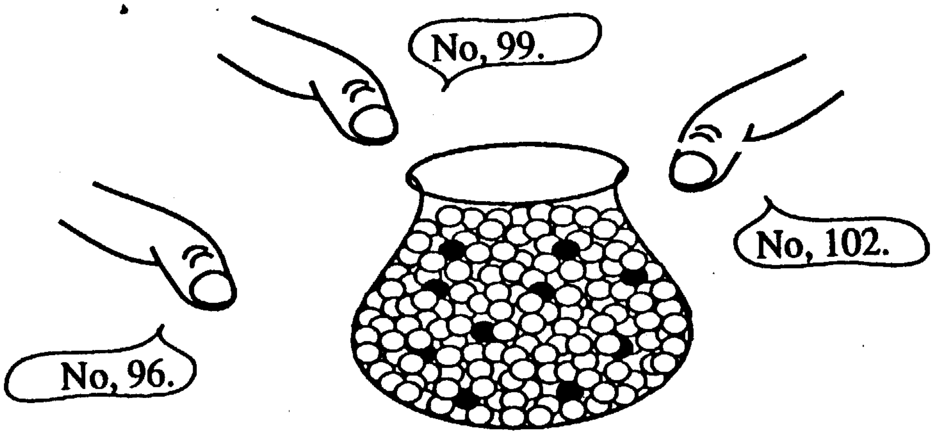
verification. Tests and analyses to be performed during the design, development, assembly, and integration phases of an instrument to assure all instrument functional requirements have been met. Includes all sub-system and system tests done at the functional level. See *integrator verification tests*.

References

Cohen, E. Richard, and Pierre Giacomo (1987). *Symbols, Units, Nomenclature, and Fundamental Constants in Physics*. International Union of Pure and Applied Physics, Document IUPAP-25 (SUNAMCO87-1).

International Organization for Standardization (1982). *Units of Measurement, ISO Standards Handbook 2*. Geneva, Switzerland.

Definitions Example



Problem

Estimate the number of marbles in the jar.

Assumptions

Jar is filled.

Model

Marble diameter, shape; jar volume, computation algorithm.

Systematic error evaluation

- Marbles may be limited to those viewed from outside (other internal material).
- Marble, jar dimensions of estimated uncertainty.
- Algorithm validity

Accuracy specification

Measurement uncertainty: <7% @ 3σ @ full jar
One count relative to another: ±2% @ 3σ @ full jar

confidence level

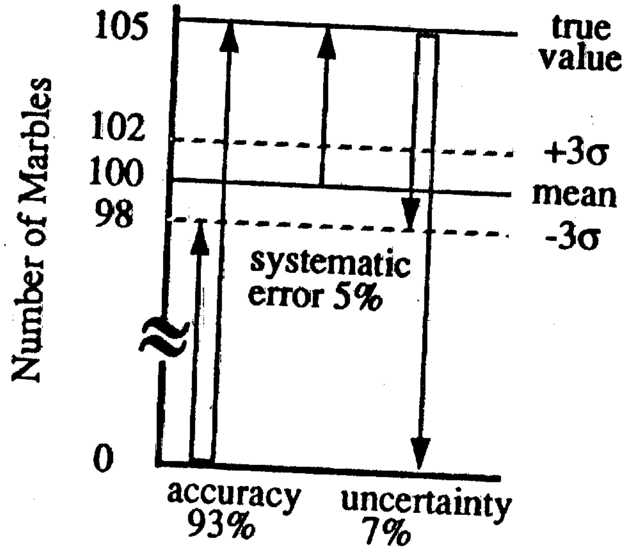
measurement conditions (different specification if only one marble)

Use proper terminology, NOT THIS:
Accuracy: 7%(is uncertainty meant?)
Relative count: 2% (from mean, or full range?)

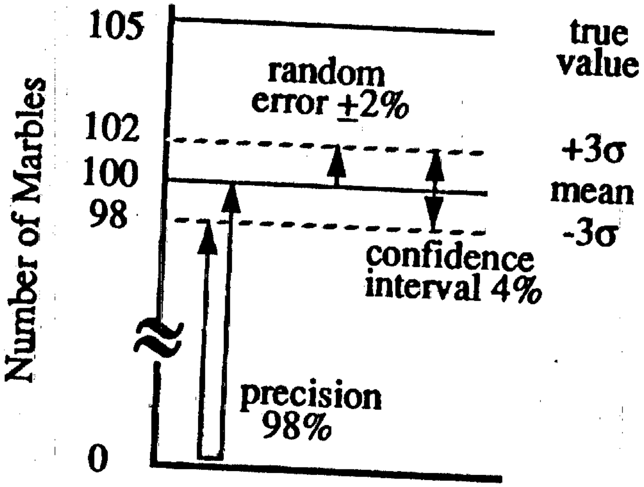
Definitions Example, cont.

CAP

Error analyses



Error parameters computed through model validation and statistics



Error parameters computed through statistical evaluation only

Jet Propulsion Laboratory
California Institute of Technology

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Pasadena, California 91109

(818) 354-4321

JPL

October 11, 1991

N94-23599

171294
p. 10

To: Bruce Guenther
Subject: Cross-calibration survey (VISNIR)

Attached here is a summary of the VISNIR survey I conducted this past summer. Included is 1) a statement of the preferred cross-calibration approach, as endorsed by select members of the VISNIR group, 2) two vugraphs which summarize the wavelength and fields-of-view of the various instruments, and 3) a listing of these same data, as given by the respective calibration representatives in the survey responses. The group would like to wait until payload selection before taking any further actions.

The Cross-Calibration Goal write-up was extracted from a June 6, 1991 memo from Frank Palluconi which expressed the consensus of the U.S. Aster Team members (A. Kahle, H. Kieffer, F. Palluconi, P. Slater, and H. Tsu).

Carol Bruegge

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Cc: Bob Nortrup

Instrumentor Cross-Calibration Goal

The EOS Project is fundamentally commited to the acquisition of data which can be reduced to geophysical data products of high and known accuracy.

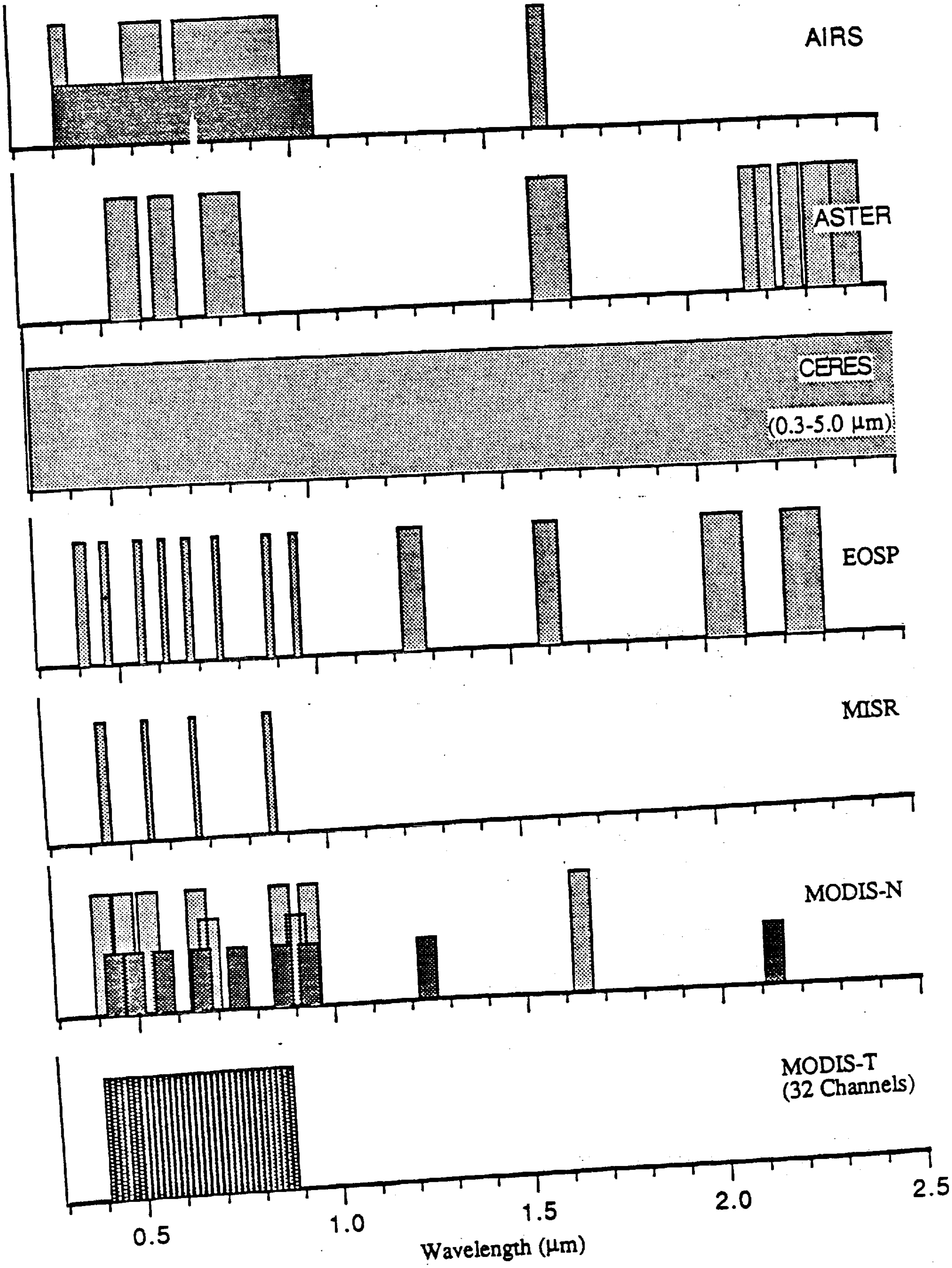
One possible method of insuring the primary data products are of known accuracy is to use the instruments themselves against the same sources to provide an independent check that a common understanding of accuracy exists.

The goal then of the radiometric "Cross-Calibration" at the integrator facility (GE) would be to convincingly establish as late as feasible in the Integration and Test (I&T) cycle that, when stimulated with common sources, the appropriate EOS instrument measurements agree within their previously established accuracy estimates across a useful radiance range, accounting for the additional uncertainty associated with the unique properties of the test set-up itself.

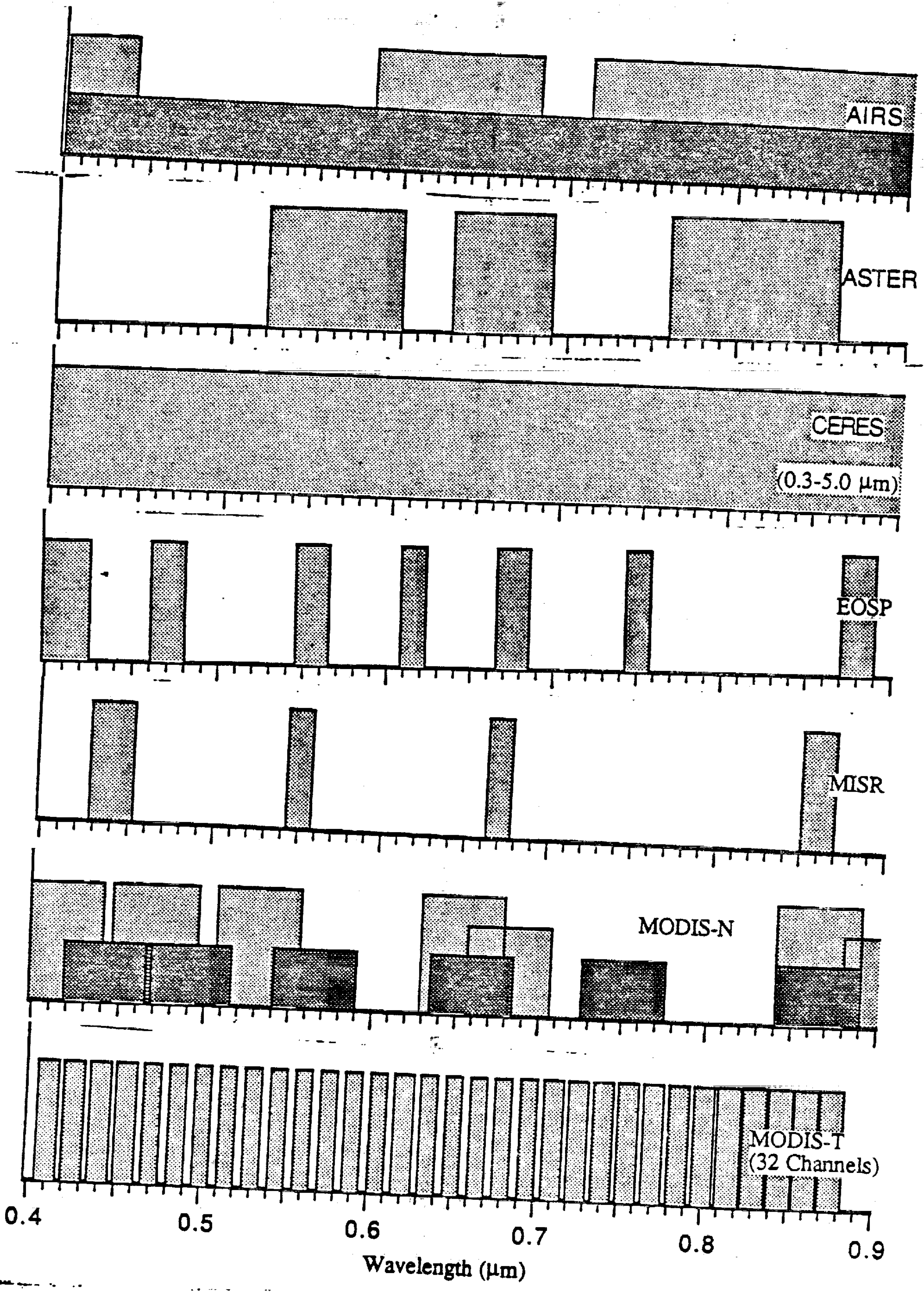
We do not consider that the instrumentor "Cross-Calibration" constitutes a replacement for the radiometric calibration completed at the instrument builders before shipment to GE. If a disagreement is found between instruments, it should be part of the "Cross-Calibration" plan to resolve this disagreement, but should not be the plan's intention that data developed in "Cross-Calibration" at GE replace the previous instrument radiometric calibration.

Likewise, we recognize that instrument to instrument agreement before launch does not insure agreement after launch. It is recommended, therefore, that emphasis be placed upon cross-calibration post launch, since it is the in-flight instrument accuracy which is of primary concern to the data user.

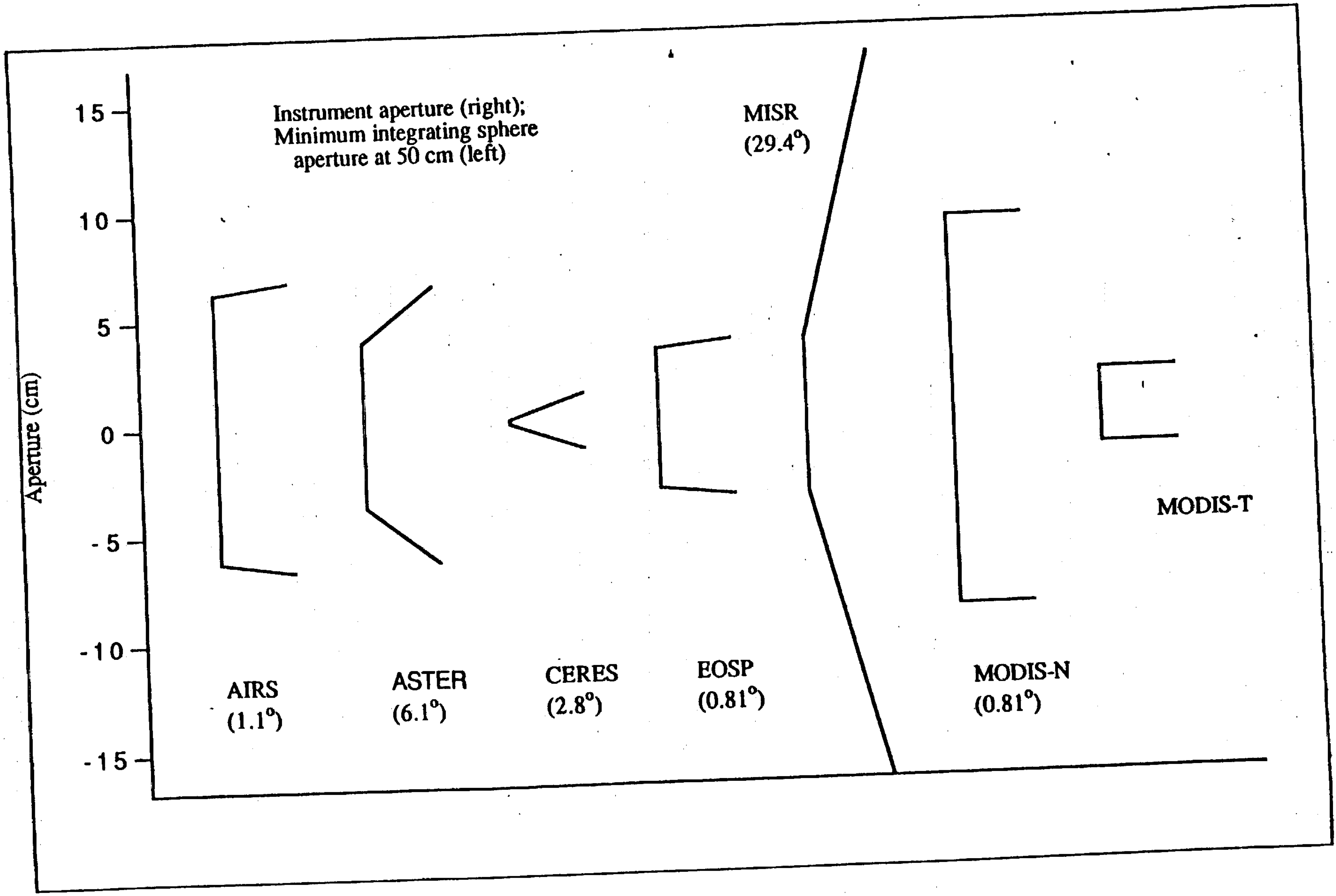
Wavelength Comparison (VISNIR)



Wavelength Comparison
(VIS)



Field-of-view Comparison
(VISNIR)



Survey responses

1. AIRS

Radiometric calibration: 1-2%
Entrance aperture: 12.5 x 12.5 cm
IFOV: 1.1°

Wavelength (µm)	Bandpass (nm)
0.42	40
0.4 to 1.06	
0.63	100
0.85	270
1.64	40

2. ASTER

Radiometric calibration: 4% VNIR & SWIR
Entrance aperture: 7.6 cm VNIR; 17 cm SWIR
IFOV: 6.1° (nadir), 5.2° (forward) with 0.6 aspect ratio; 4.94° SWIR
Notes: At instrumentor only ambient tests are planned

VNIR		SWIR	
Wavelength (µm)	Bandpass (nm)	Wavelength (µm)	Bandpass (nm)
0.56	80	1.65	100
0.66	60	2.16	40
0.81	100	2.20	40
		2.26	50
		2.33	70
		2.40	70

3. CERES

Radiometric calibration: 1% (shortwave); 0.5% (total)
Entrance aperture: <0.15 cm
IFOV: 1.12 x 2.8°
Notes: At instrumentor only ambient tests are planned

Wavelength (μm)
0.3 to 5
0.3 to 200.

4. EOSP

Radiometric calibration: 5%; Goal: 3%
Entrance aperture: 6.5 cm
IFOV: 0.81° (3° needed for calibration as scans)

Wav. (μm)	Bandpass (nm)	Wav. (μm)	Bandpass (nm)
0.410	30	0.880	20
0.470	20	0.950	20
0.555	20	1.250	60
0.615	15	1.600	60
0.675	20	2.050	100
0.750	15	2.250	100

5. MISR

Radiometric calibration: 3%
Entrance aperture: 7 cm
IFOV: 29.4° (A), 23.8° (B), 18.4° (C), 14.4° (D)

Dynamic range can be expressed in term of an equivalent reflectance, $\rho = \pi L/E_0$:

Wavelength (µm)	Bandpass (nm)	ρ_{max}	ρ_{min}
0.440	25	1.0	0.02
0.550	15	1.0	0.02
0.670	15	1.0	0.02
0.860	20	1.0	0.02

(what is ρ_{max}, ρ_{min} for other instruments?)

6. MODIS-N

Radiometric calibration: 5% (relative to NIST)
Entrance aperture: 18. cm
IFOV: 0.081° square

Wav. (µm)	Bandpass (nm)	Wav. (µm)	Bandpass (nm)	Wav. (µm)	Bandpass (nm)
0.415	50	0.653	50	0.905	50
0.443	50	0.659	50	0.936	50
0.470	50	0.681	50	0.940	50
0.490	50	0.750	50	1.24	50
0.531	50	0.865	50	1.64	50
0.565	50	0.865	50	2.13	50

7. MODIS-T

Radiometric calibration: 5% (relative to NIST)
Entrance aperture: 3.4 cm
IFOV: 0.0894°

Wav. (µm)	Bandpass (nm)	Wav. (µm)	Bandpass (nm)	Wav. (µm)	Bandpass (nm)	Wav. (µm)	Bandpass (nm)
0.410	13	0.530	10	0.650	11	0.770	12
0.425	12	0.545	10	0.665	11	0.785	12
0.440	12	0.560	10	0.680	11	0.800	12
0.455	11	0.575	10	0.695	11	0.815	15
0.470	11	0.590	10	0.710	11	0.830	15
0.485	11	0.605	10	0.725	11	0.845	15
0.500	11	0.620	10	0.740	11	0.860	15
0.515	11	0.635	10	0.755	12	0.875	13

GE Integrating Sphere

Assumption

- 40" diameter integrating sphere assumed largest available (60" have been built)
- exit port 1/3 the diameter of sphere (13" ~ 33 cm)
- sphere - instrument working distance is 50 cm
- Fill factor of 2 desirable (largest FOV to accommodate is 6.5" at sphere). Smallest fill factors (bold) are difficult to accommodate

Problem

What is fill factor for various instruments?

Instrument (FOV, °; aperture, cm)	Fill factor	Comments
AIRS (1.1; 12.5)	2.4	
ASTER (6.1; 7.6)	2.6	
CERES (2.8; 0.15)	12.7	
EOSP (3; 6.5)	3.6	3 x FOV required to accommodate scanning
MISR (29.4; 7)	**0.9**	1696 pixels
MISR (29.4/4; 7)	2.5	424 pixels
MODIS-N (0.081,18)	1.8	

Fill = 33 cm/(aperture+2 · 50 cm · tan (FOV/2.))

CERES INSTRUMENT STATUS

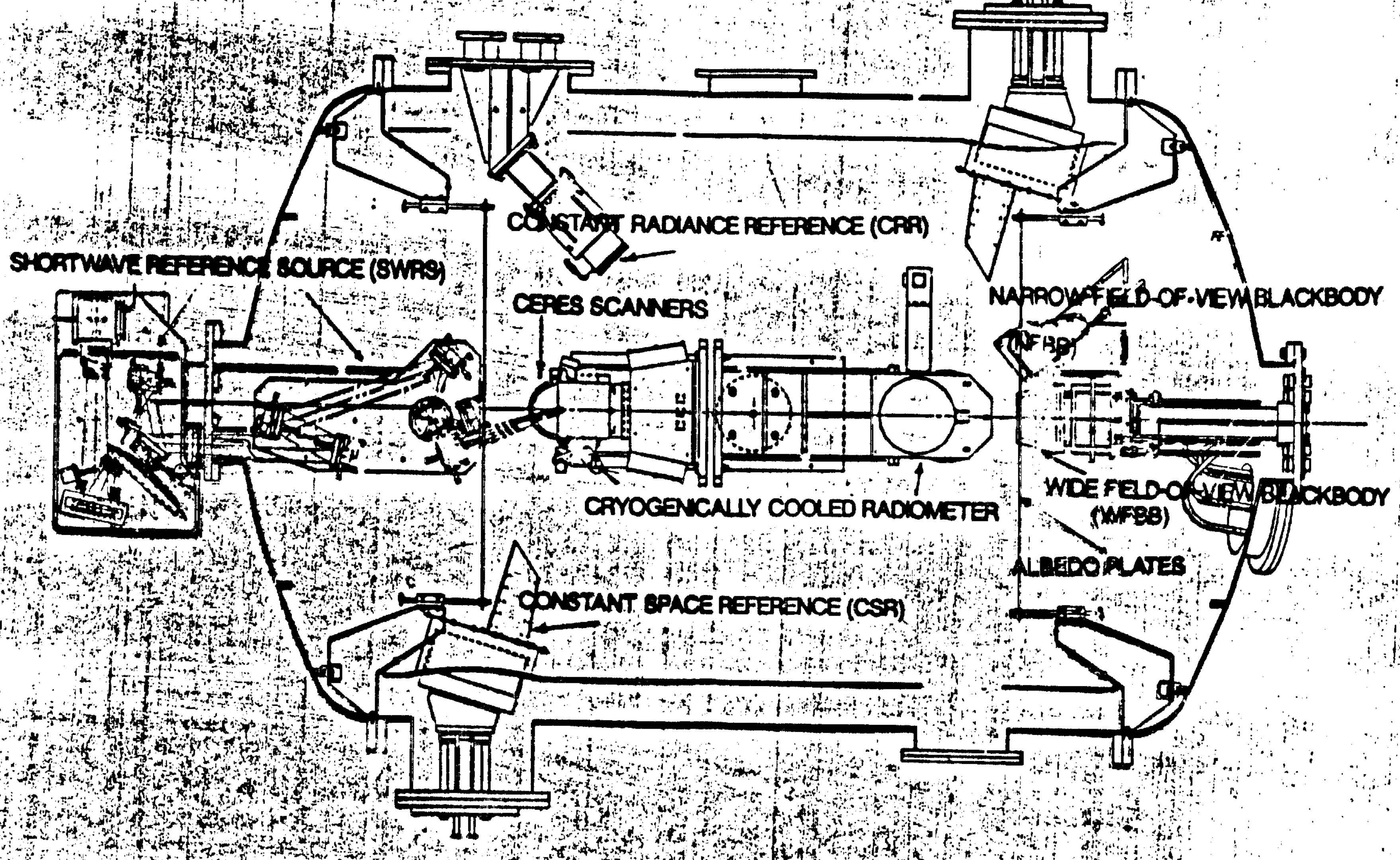
CALIBRATION CHAMBER
- ADDED NARROW FIELD-OF-VIEW BLACKBODY
- CHANGED INTEGRATING SPHERE
- ADDING CRYOGENIC ACTIVE CAVITY RADIOMETER

RADIOMETRIC TEST MODEL
- SINGLE TELESCOPE FUNCTIONAL MODEL
- BEGIN TESTING IN CAL CHAMBER
  - ABOUT APRIL 1

PRELIMINARY DESIGN REVIEW
- EXPECT ABOUT MID-JUNE

OMIT

CERES VACUUM CALIBRATION FACILITY



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CERES PROCESSING SYSTEM
DESIGN & DEVELOPMENT

ELEMENTS OF DESIGN
- DATA FLOW DIAGRAMS
- DATA STRUCTURES
- PROCESS DESCRIPTIONS
  - STANDARD
  - EXCEPTION HANDLING
- OPERATIONS & LOGISTICS
  - NORMAL WITH QUALITY CONTROL
  - VALIDATION AND TROUBLE SHOOTING

PROTOTYPE DOCUMENTATION SYSTEM
- ACCEPT INPUT ALGORITHMS FROM SCIENCE TEAM
- PROVIDE DOCUMENTATION OF ALGORITHM SPECIFICATIO
  - FOR DESIGN AND DATA MANAGEMENT TEAM
- GIVE ELECTRONIC ACCESS OF DESIGN & DOCUMENTATIO

PROTOTYPE DOCUMENTATION SYSTEM

USES TEX AND POSTSCRIPT

3 MAJOR PARTS

- SCIENTIFIC DESCRIPTION
  - DERIVATION & REQUIRED DATA
  - REFERENCES
  - EXCEPTION HANDLING STRATEGY
- DATA MANAGEMENT DESCRIPTION
  - DATA FLOW DIAGRAMS FOR FUNCTIONAL DECOMP
  - DATA STRUCTURES / DATA DICTIONARY
  - PROCESS DESCRIPTION
- OPERATIONS DESCRIPTION
  - SUBSYS. INPUT LIST
  - SUBSYSTEM PROCESSING PRECONDITIONS
  - SUBSYSTEM OUTPUT LIST
  - SUBSYSTEM PROCESSING ACTIVITY LIST

USER ACCESS THROUGH TEMPLATES

SUGGESTED PERSONNEL FOR
CAL REVIEW AT PDR

STRONGLY RECOMMEND PUTTING CAL REPS
ON REVIEW PANELS

SCHEDULE
COST
ACTION ITEM DRIVERS
INFLUENCE ON PROJECT

SUGGEST
1 PROJECT MEMBER ON REVIEW BOARD
1 SCIENCE MEMBER 〃 〃 〃
VOLUNTEERS FROM SCIENCE COMMUNITY
TO ATTEND & PUT IN ACTION ITEMS
ACTION ITEMS TO BE CLEARED
BEFORE ADJOURNMENT

Bruce Barkstrom's Questionaire for
Information to be included
in the Vis/IR
Cal Handbook.

Instrument Description
- Mechanical
  - Size [~~metric~~ m x m x m]
  - Weight [kg]
  - Power [W]
- Spectral Channel Description
  - Number of Channels
  - Channel Description (Center λ, Half Trans. Lower Bound, Half Trans. Upper Bound, Flatness, Out-of-Band Response)
- Earth Sampling Pattern
  - e.g. scan pattern,
    number of pixels per scan
    size of pixel (at satellite, at nadir)
- Operating Modes

Cal Descriptions
- Philosophy
- Ground Cal Equipment List and Cal Geometry
  - Instrument
  - Chamber
  - Sources
- Flight Cal Equipment List and Cal Sources
- Error Requirements and Error Budget
- Calibration Traceability
- Equations
  - Instrument Data Reduction
  - Cal Data Reduction
- Cal Procedure Outline

List of Items

Flight Qual of Component Characteristics

Math Models

Recommended Solar Spectrum

Cross-Calibration Activities
  Philosophies of Ground Cross-Cal
  Ground Cross-Cal Activities
  Philosophies of Flight Cross-Cal
  Flight Cross Cal

Uncertainty Analysis
  Theory
  Instrument Applications and Calculations

Definitions

Goal: Agree upon a modest number of passbands to be used in absolute radiometric calibration comparison between instruments measurements of diffusing materials to be used in orbit, etc.

Justification: Minimize or eliminate errors associated wavelength interpolation; especially where detailed line structure is involved (solar Fraunhofer lines, atmospheric gas lines).

Method:

A. Compare passbands planned for all instruments, select a subset of bands in common, or bands within broader instrument passbands, or bands in SWIR which lie in source spectral plateau.

B. If possible, agree on a common physical size of filters.

C.1. Fabricate filters in a single run, to optimize uniformity.

2. Fabricate as "witness pieces" during flight filter production.

D. Circulate filters (at 6 months intervals) among labs for measuring their characteristics and use in radiance measurements.

C3. Obtain nominally the same filter sets from more than one manufacturer, in order to avoid single systematic errors (such as out-band-leaks).

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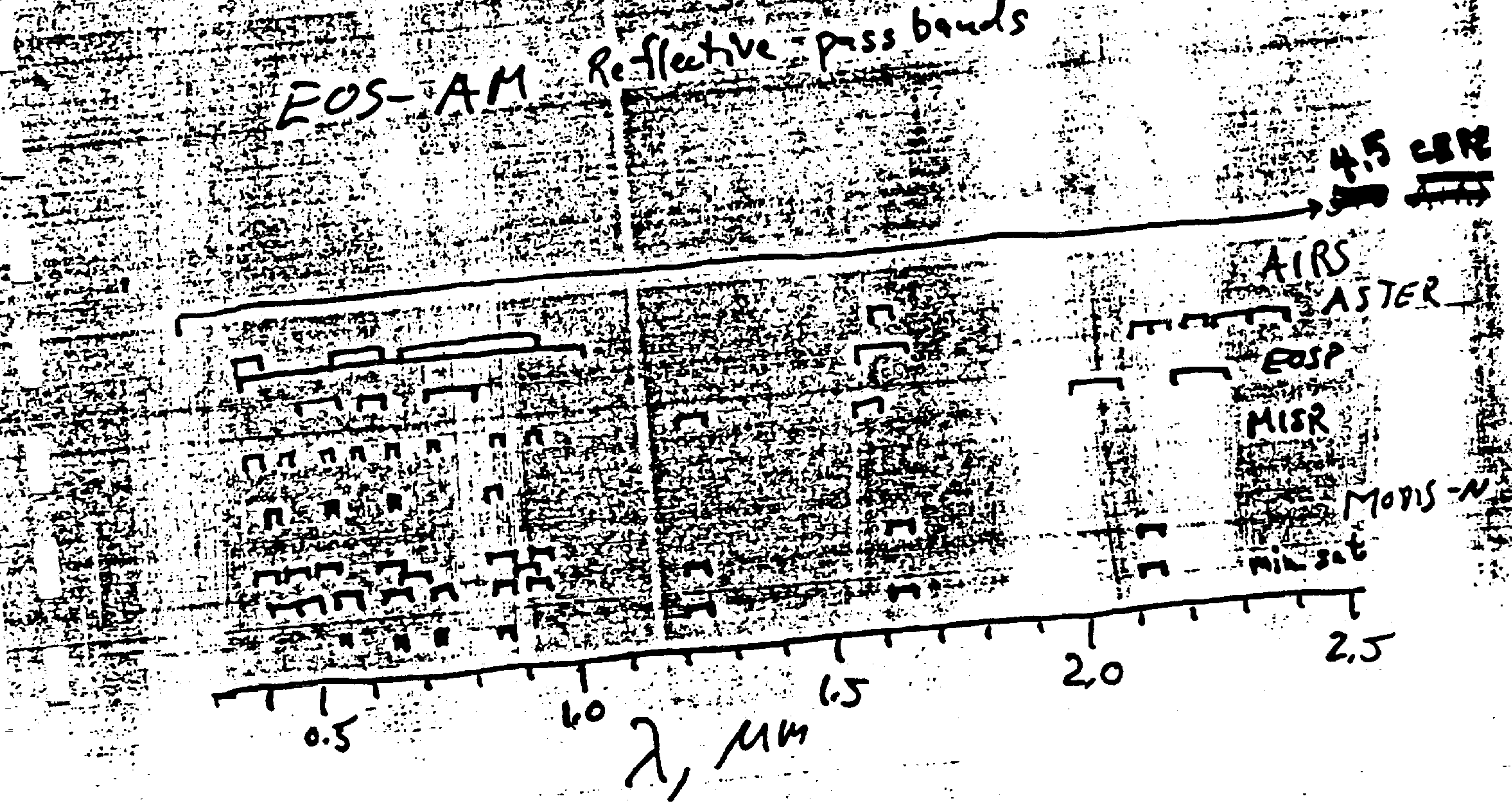
HHK
92 Apr 07


EOS-AM Reflective pass bands
4.5
AIRS
ASTER
EOSP
MISR
MODIS-N
mil sat
0.5
1.0
1.5
2.0
2.5
λ, μm

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55-43
171295
p-32

MODIS Calibration Status Report

to

Reflected Solar Working Group A

at the

5th Meeting

of the

EOS Calibration and Data Product Validation Panel

of the

EOS Investigator Working Group (IWG)

from

MCST (MODIS Characterization Support Team)

John L. Barker, Head
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NASA / Goddard Space Flight Center, Greenbelt, Maryland 20771
FAX: (301) 286-9200

Presented by:
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RDC/7855 Walker Drive, Greenbelt, Maryland 20770
FAX: (301) 286-9200

Tuesday, 7 April 1992

The Broker Inn
Boulder, CO

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Overview
of
MODIS/MCST Calibration Status Report

Calibration Strategy

Calibration Handbook

Calibration Plan

Action Item from 4th EOS Cal/Val Meeting

Agenda for Next Week's MODIS Calibration Working Group

Feedback Sheet

Appendix
    Handbook Table of Contents
    Calibration Plan Table of Contents
    Detailed Agenda for MODIS Calibration Working Group
    Feedback Sheet

MODIS/MCST Calibration Strategy

1. Alternative MODIS Calibration Methodologies

Several alternative calibration methodologies
will be implemented throughout 15-year mission
to provide a robust unique "official" calibration algorithm
and to allow for its validation

2. Time-Scale of Months for Characterizing Precision

Post-launch quantitative characterization and monitoring
of the precision (repeatability) with which MODIS at-satellite radiances
are measured by various methods
will occur within 2 to 6 months

MODIS/MCST Calibration Strategy (continued)

3. Time-Scale of Years for Characterizing Accuracy

Post-launch quantitative characterization and monitoring
of the accuracy with which MODIS at-satellite radiances
are measured by various methods
will occur within 1 to 4 years

4. Time-Scale of 10-20 Years for Validating Math Model

Validation of the components of the math models
for each MODIS instrument
(with an expected life-time of five-six years)
will occur over the 10 to 20 year life-time of EOS mission

MODIS/MCST Calibration Handbook

Objective

Provide results of calibration and sufficient supporting information
to be able to scientifically use and interpret MODIS data.

Approach

Produce a stand-alone scientific user's guide containing all one needs to know
about calibration of MODIS data
throughout the lifetime of the EOS mission
Provide handbook in hard copy and electronic form,
initially from MODIS/MCST Bulletin Board, and
operationally from EOS DADS (Data Archive and Distribution System)
Provide notification of up-dated version
initially to MODIS Science Team members, and
operationally to EOS Science Office Mailing List
Include references to supporting and more detailed publications

Context

Provide an executive summary of results in this handbook
from both external peer reviewed articles on MODIS calibration and
internal NASA readiness review documents

Schedule

Provide up-dated versions at
MODIS Science Team Meetings, and
EOS Calibration/Validation Panel Meetings

MODIS/MCST Calibration Plan

Objective

Provide a comprehensive review and integration of all methodologies
used to calibrate the MODIS instruments

Approach

Integrate calibration plans from all sources and for all phases of the mission:
pre-launch, in-orbit, and on-board
Eventually, provide an on-going structure of the methodologies used
to obtain the results in the MODIS Calibration Handbook
Include references to supporting and more detailed publications

Context

Provide an executive summary of methodologies
from both external peer reviewed articles on MODIS calibration and
internal NASA readiness review documents

Schedule

Provide up-dated versions at
MODIS Science Team Meetings, and
EOS Calibration/Validation Panel Meetings

For E-mail correspondence address GSFCmail:JBarker or BGrant.
For updates on the latest events and available documents, CHECK MCST.BB bulletin board on GSFCmail.

MODIS/MCST Action Item
from 4th EOS Cal/Val Meeting

1. Outline Global Calibration Site Selection Procedure

Objective

Locate potential MODIS calibration targets on the Earth's surface
that are radiometrically homogeneous on a scale of 3 by 3 Km.

Approach

Initially use annual NDVI biweekly datasets of 1 Km AVHRR data
in the continental United States in 1990
to search for radiometrically homogeneous regions
using the standard deviation of a traveling 3X3 pixel area
as a measure of heterogeneity.

Context

Use calibration sites within the MODIS imagery to provide for
1) every-pass calibration potential
using a modified "radiometric rectification" methodology,
2) aircraft under-flight calibration support, and
3) occasional support of ground field calibration experiments

Schedule

Preliminary results for 1990 dataset from EDC (EROS Data Center)
will be reported at the Calibration Working Group sessions
of the April 14th MODIS Science Team Meeting

Calibration Working Group

AGENDA

for

MODIS Calibration Working Group Meetings

before and during the

MODIS Science Team Meeting

NASA/Goddard Space Flight Center, Greenbelt, MD

13-16 April 1992

Monday, April 13, 1992 830-1300

MODIS -Related Status Reports and Plans associated with Calibration and Characterization

Tuesday, April 14, 1992 1515-1715

Cross-Track Calibration Issues

Wednesday, April 15, 1992 800-1200

Instrument-Related Calibration Issues

Thursday, April 16, 1992 800-1130

Cross-Calibration MODIS with other Instruments

MODIS/MCST Feedback Sheet
on MODIS Calibration Handbook and MODIS Characterization/Calibration Plan

Questions ?

Concerns ?

Suggestions ?

Actions for Next Meeting?

Date:

Name:

For E-mail correspondence address GSFCmail:JBarker or BGrant.

For updates on the latest events and available documents, CHECK MCST.BB bulletin board on GSFCmail.

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MODIS Calibration/Characterization Plan

edited by MCST
(MODIS Characterization Support Team)

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Ken Brown (925)/MODIS Airborne Simulator (MAS)
Wayne Esaias (671)MODIS Ocean Discipline Head/SeaWiFS
Bruce Guenther (925)/EOS AM Project Scientist/EOS Calibration Scientist
Forrest Hall (924)/Image-Based Radiometric Rectification Calibration
Joann Harnden (925)/Artificial Intelligence Information
Yoram Kaufman (913)/Atmospheric Corrections
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Otis Brown
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Miami, FL 33149

Hugh Kieffer/Lunar Calibration/HIRIS Cross-Calibration
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University of Arizona
Tucson, AZ 85721

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    1.6 Multiple Parallel Approaches
    1.7 Mathematical Model Development
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    5.1 Objectives/Rationale
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    5.2.1.1 Spectroradiometric Calibration Assembly (SRCA)
    5.2.1.2 Blackbody
    5.2.1.3 Solar Diffuser Panel and Solar Diffuser Stability Monitor (SDSM)
    5.2.2 External Solar
    5.2.3 External Lunar
    5.3 Target-Based Calibration
    5.3.1 Target Related/Ground Reflectance
    5.3.2 Bio-Optical Oceans
    5.4 Image-Related
    5.4.1 External Image-Related Radiometric Rectification
    5.4.2 Class-Specific Scene Equalization

6 In-Orbit Geometric Characterization

7 In-Orbit Spectral Characterization

8 Official MODIS/MCST Calibration Algorithm
- 8.1 Objectives/Rationale
- 8.2 Minimization of Instrument Systematic Noise Sources
- 8.3 MCST Calibration Flow

9 MODIS/MCST Calibration Algorithm Validation and Upgrade
- 9.1 Algorithm Correction for Systematic Errors
- 9.2 Inclusion of In-Orbit Calibration Information
- 9.3 Creation of Calibration Error Images

10 Definitions and References
- 10.1 Data Dictionary/Glossary
- 10.2 Acronyms
- 10.3 Additional References

1 Introduction

1.1 MCST Calibration/Characterization Plan Objectives

MCST will evaluate, integrate, and update calibration plans and related information for pre-launch and in-orbit phases of the MODIS mission. Vendor calibration information will be included by reference in the MCST documentation. These plans will be reviewed by the MODIS calibration review committee, and will be included in the MODIS calibration plans to be delivered to EOSDIS. Updated versions of MCST's Calibration/Characterization Plan will, in general, be available at the times of the MODIS Science Team meetings.

MCST will be the primary source of information on the MODIS instrument for the many science data users who will need instrument characterization and calibration information. This document is intended to provide a thorough discussion of the plans for pre-launch and in-orbit radiometric calibration, spectral characterization, and geometric characterization of the MODIS instrument. References to other published literature are included when possible. A list of helpful acronyms follows the technical sections. Administrative information, including schedule information and related organizations and responsibilities, may be obtained in the MODIS Calibration Management Plan.

1.2 Document Overview

Chapter 1 discusses the MCST Calibration/Characterization Plan Objectives and provides an overview of all chapters.

Chapter 2 describes the pre-launch calibration and characterization methodologies. The MODIS-N Preliminary Calibration Management Plan provided by Hughes Santa Barbara Research Center (SBRC) and dated September 17, 1991, is the primary source of information for this chapter.

Chapter 3 contains information on cross-calibration plans. MODIS instruments will be compared to one another and to other instruments with comparable fields-of-view and spectral coverage. These comparisons will enhance the calibration data base and provide a more thorough understanding of instrument performance. Other sensors whose output will be compared to the MODIS instruments include AIRS, ASTER, EOSP, MISR and SeaWiFS on the EOS Platforms; and the Landsat Thematic Mapper.

Chapter 4 discusses the transfer of calibration and characterization from pre-launch to in-orbit phases using the on-board calibrators. Historically, this transition has been among the least well-understood aspects of the calibration process. The MODIS instrument utilizes a solar diffuser and Spectroradiometric Calibration Assembly (SRCA) to transfer calibrations and characterizations between pre-launch and in-orbit states.

Chapter 5 describes the in-orbit radiometric calibration and characterization methodologies. Discussed here are the instrument-based methods using the calibrators noted in Chapter 4; target-based methods, including the use of ground targets and ocean phenomena to achieve a calibration; and image-related methods including radiometric rectification and class-specific scene equalization techniques.

Chapter 6 contains information on in-orbit geometric characterization.

Chapter 7 describes in-orbit spectral chracterization.

Chapter 8 discusses the official MODIS calibration algorithm.

Chapter 9 provides a strategy for the MODIS calibration algorithm validation and upgrade. In order to provide a reliable model for MODIS behavior, the algorithm must be continually refined as new design and performance information becomes available. In addition, a measure of the quality of the calibration will be provided by error images to be generated as part of this task.

Chapter 10 includes a list of acronyms, definitions, and references appropriate to the topics considered.

1.3 Applicable Documents

Documents pertinent to this one include, but are not limited to:

(1) Earth Observing System (EOS) Project Calibration Plan, 29 July 1989, GSFC 420-03-01;
(2) Earth Observing System (EOS) Project Configuration Management Plan, GSFC 420-02-02;
(3) 1990 Reference Handbook, EOS;
(4) MCST Interface Control Document;
(5) MODIS Calibration Plan;
(6) MODIS Verification Plan;
(7) MODIS Calibration Data Book;
(8) MODIS Calibration Handbook.

1.4 Overview of Instrument Design

MODIS–N is an imaging scanning spectro–radiometer. It views the Earth from an orbit of 705 km. and continually scans through the nadir to ±55°. The instrument measures the at–satellite radiance in 36 bands from 0.408 µm to 14.385 µm. The footprint of the detectors varies from 0.25 km. (2 bands) to 0.5 km. (5 bands) to 1 km. (29 bands).

The spectro–radiometer itself is a 2–mirror off–axis Gregorian design. Radiation from the Earth passes through dichroic beamsplitters which reflect/transmit the light onto four focal planes. Discrete interference filters provide the higher spectral resolution.

1.5 Single Official Calibration Algorithm

It is the responsibility of the MCST, together with review by the MODIS science team, to select a single calibration algorithm which will be used as the official calibration algorithm for producing Level-1B products (radiance images). This algorithm may be selected from various methods, although early versions will depend heavily on the internal instrument methodolgy provided by the vendor. This algorithm will change with time as understanding of the instrument, data characterization, and calibration methods improve.

1.6 Multiple Parallel Approaches

In order to have confidence that the required precision and accuracy have been met, several independent methods will be used in parallel. In addition to the pre-launch calibrations and characterizations, there will be in-orbit (on-board) calibrations using lunar images, as well as in-orbit ground truth calibrations using reflectance and radiance based methods (both on-ground and aircraft). The primary purpose of these multiple pathways is to obtain, through independent means, a "calibration table" which can be used to convert instrument DN's to radiance on a routine basis (the MODIS/MCST calibration algorithm).

1.7 Mathematical Model Development

The contractor (Hughes/SBRC) will develop and maintain a mathematical model of the instrument to allow performance prediction, uncertainty modeling, environmental sensitivity studies, and degradation and failure analyses. The characterization of the MODIS-N subcomponents will be of sufficient accuracy to allow meaningful analyses to be performed with this model, thus this guideline defines the subcomponent calibration specifications. Reports will be produced to document analyses and the impact of the code on instrument characterization.

1.8 Comprehensive Documentation Trail

The contractor (Hughes/SBRC) will provide system-level calibrations (radiometric, geometric, and spectral) which are traceable through documentations of data, procedures, and data analysis techniques, and the contractor will radiometrically calibrate to a set of physical units as expressed in the Systeme International (SI) set of units. In addition, the contractor will adhere to a common set of calibration terminologies, as sanctioned by the EOS Calibration Advisory Panel. These will be supplemented, as needed, for clarification or instrument-specific procedures.

2 Pre-Launch Calibration/Characterization Methodologies

2.1 Objectives/Rationale

Prior to launch, the MODIS instrument shall undergo radiometric, geometric, and spectral calibrations. These pre-flight values will be compared with in-flight and on-orbit results to obtain a measure of performance of the MODIS sensor over time. In addition, the instrument shall be well-characterized before launch for properties including, but not limited to, linearity, signal-to-noise ratio, coherent noise, scan modulation, and band-to-band stability. The Modulation Transfer Function (MTF) will be measured along-track and across-track. Spectral band shapes and out-of-band responses will be measured. The transient response, including rise time and overshoot or undershoot, will be tested. Polarization sensitivity will be measured. The spectral band registration along-track and across-track will be measured. Most of these tests will be performed under both ambient and vacuum conditions. A total of 29 different types of characterization tests are planned.

As part of EOS calibration planning, MODIS and all EOS-A platform instruments will be cross-calibrated using a common known source and/or a traveling standard radiometer. These activities are in the early planning stages now and will be summarized when they become public.

Information in this section comes from two sources. The primary source is the Preliminary Calibration Management Plan for the MODIS instrument provided by Hughes/SBRC, the prime MODIS contractor. It is included in this document prior to review by members of the MCST. Additional information is provided by MCST.

2.2 Radiometric Calibration

MODIS Preliminary Calibration Management Plan,
Hughes Santa Barbara Research Center, September, 1991

Pre-flight radiometric calibration of the MODIS Instrument and the On-Board Calibrators will be performed. For the solar reflective bands of MODIS, an absolute accuracy of 5% is required; for the thermal bands, this requirement is 1%.

2.2.1 Absolute Calibration

Source-based calibration techniques, with sources traceable to NIST primary standards, will be used to perform the pre-flight calibration of MODIS. A spherical integrating source (SIS) will be used for the VIS, NIR, and SWIR bands, and a full-aperture blackbody will be used for the MWIR and LWIR bands. These measurements express digitized output as a function of input radiance. The repeatability in the measurements constitutes their precision, while the deviation of the results from a true value is the calibration accuracy.

2.2.2 Relative Calibration

The preflight absolute calibration of MODIS is the first data point in the MODIS calibration history. Subsequent calibrations will enable assessment of sensor performance as a function of time, allowing a relative calibration history to be documented. Relative comparisons are also performed by ratioing the output of one sensor band to another, or comparing the outputs of different detectors within a band.

2.3 Geometric Characterization

The pointing accuracy of MODIS will be sufficient to locate any pixel on the Earth's surface to within ± 0.5 times the length or width of the pixel. Registration of pixels to 0.1 pixel or better will be made, but a pointing knowledge of 30 arc seconds and alignment changes of 60 arc seconds will reduce the overall pointing knowledge to 0.5 pixels.

2.4 Spectral Characterization

Preflight spectral Characterization of the MODIS instrument will based on relative spectral response measurements made with a grating monochromator coupled to the MODIS calibrator. Accuracy of this test device will be traceable to NIST silicon photodiode reference detectors for the VIS and NIR, and to Naval Ocean Systems Center (NOSC) for reference pyroelectric or thermocouple detectors.

3 Instrument Cross-Calibration

3.1 Pre-Launch Cross-Calibration

3.1.1 Cross-Calibration Among MODIS Instruments

3.1.2 Cross-Calibration Between MODIS and Other Instruments

MODIS shall be inter-compared after integration with all other optical instruments operating in the same spectral regions (e.g. ASTER, MISR, AIRS, SeaWiFS, and also with HIRIS for the C platform) using a single source. A cross-calibration between MODIS sensors and the Landsat Thematic Mapper will also be performed.

3.2 In-Orbit Cross-Calibration

3.2.1 Cross-Sensor/Within Platform

Phil Slater et al., University of Arizona; Doug Hoyt, RDC

Introduction

Several passive remote sensors using visible radiation are planned for the EOS–A platform. Each instrument will be independently calibrated. After corrections for differences in footprint size, spectral resolution, and pointspread functions are made, the radiances measured by the separate should agree to within their stated accuracies. If they do agree, it tells us that any biases, whether the bias is zero or not, are the same. If they do not agree, an opportunity exists to investigate the reasons for the disagreements. The more instruments that agree, the more confidence we can have that correct measurements are being made. Potential comparison instrument include MODIS (am) to MODIS (pm), AIRS, ASTER, EOSP, and MISR. Several of these potential configurations are discussed below.

AIRS (Atmospheric Infrared Sounder) has a 56 km. nadir footprint with five channels in the visible region from 0.4 to 1.1 microns. Inter–comparison to MODIS–N will consist of combining many MODIS pixels, weighted by the AIRS pointspread function, to form an image like a single AIRS pixel. Because MODIS–N also appears to have better spectral resolution in the visible, several appropriately weighted MODIS–N bands will be required to match the AIRS resolution. Comparison of many hundreds of AIRS pixels with MODIS–N simulated AIRS pixels should give a reasonable indication of the amount of agreement.

Both AIRS and MODIS–N also make thermal infrared measurements which allow comparisons to be made. At each thermal wavelength, contributions are coming from all layers of the atmosphere and the surface usually expressed through atmospheric weighting functions. If the two instruments do not have similar bandpasses, the comparison is made difficult since the same layers of the atmosphere are not sampled equally. It is likely that radiances in the thermal bands for these two instruments will not be compared directly, but a derived geophysical parameter such as sea surface temperature will be used for the inter–comparison. The thermal cross–calibration technique for this pair of instruments and for other pairs of instruments is a topic requiring further study.

ASTER (Advanced Spaceborne Thermal Emission and Reflection) has a 30 meter nadir footprint and one near infrared band from 850 to 920 nm. Since MODIS-N has bands centered at 865 and 905 nm an inter-comparison is possible using appropriate weights or filter factors for the two instruments. Spatially the MODIS-N pixel can be simulated by summing up the ASTER pixels using the MODIS-N pointspread function as the weighting function. Inter-comparisons in the thermal infrared are also possible for these two instruments.

EOSP (Earth Observing Scanning Polarimeter) has a 10 km. nadir footprint and several spectral bands in the visible region. MODIS-N radiances can be spatially re-mapped, using the EOSP pointspread function, and spectrally re-mapped, using the EOSP filter transmission functions, to match the EOSP radiance observations.

MISR (Multi-angle Imaging Spectro-radiometer) has four viewing angles which can be duplicated by MODIS-N. Four other MISR viewing angles cannot be matched by MODIS-N. MISR has spectral bands centered at 440 and 860 nm which are closely matched by MODIS-N bands at 443 and 865 nm. The wavelength resolution for MISR is not available, but probably is less than MODIS-N. By spectrally re-mapping MODIS-N and spatially re-mapping MISR, a matching image for the two instruments appears possible which will allow them to be inter-compared.

Approach

One method for the cross-calibration of different instruments on the same platform is identical to that used by the University of Arizona for the calibration of AVHRR with respect to TM. It should be emphasized that cross-calibration of instruments on the same platform eliminates uncertainties associated with different illumination and viewing geometries.

The University of Arizona group plans to make in-orbit calibrations of high spatial resolution EOS sensors such as ASTER (and HIRIS for the C platform) using a reflectance-based method which references a well characterized ground site such as White Sands [1]. MODIS in-orbit calibration with reference to a ground site shall be done with a method similar to its AVHRR work [2].

Results

The University of Arizona group has found that the responsiveness of channels 1 and 2 of the AVHRRs on NOAA-9 and -10 has degraded significantly since launch [2]. The group has refined its reflectance-based method and applied the refinements to its TM calibrations [3]. The group has also developed a refinement to its reflectance-based method which uses measurements of the diffuse and total irradiance at the surface [4].

The University of Arizona group is currently and analyzing channels 1 and 2 of the AVHRR on NOAA-11. Preliminary investigations show degradation of approximately 5 and 15 percent in channels 1 and 2.

The University of Arizona group plans to continue with this type of work with future AVHRR and follow-on sensors and a MODIS simulator if it becomes available. The group plans to refine its methods to include the use of a field SWIR spectrometer, a solar radiometer designed to measure total column water vapor, and an imaging solar radiometer which will be used to study the solar aureole. The aureole is a sensitive indicator of aerosol scattering and the group hopes to improve its knowledge of the scattering phase function with this future instrument.

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3.2.2 Cross-Platform/Among Sensors

The University of Arizona group has investigated the calibration of a low spatial resolution imaging sensor by reference to a higher resolution "calibrated" sensor [1,2]. This work has been funded under a NASA grant and is ongoing. The AVHRR sensors on the NOAA 9, 10, and 11 satellites have been calibrated with reference to the Thematic Mapper (TM) and Systeme Probatoire d'Observation de la Terre (SPOT) HRV cameras. The high resolution sensor is calibrated with reference to a ground site such as White Sands, New Mexico. This calibration is normally done using a ground reflectance-based method. Pixels from a high resolution calibrated image (taken nearly coincident with the low resolution image) are spatially registered and then are aggregated to the spatial resolution of the AVHRR image. Corrections are made for sensor spectral response differences and for the ground target bidirectional reflectance factor (BRF) if the sensor acquisition geometries are significantly different. The ground reflectance is determined from the calibrated high resolution image [3]. Spatially uniform areas on a scale of multiple low resolution pixels are used in a reflectance-based method to determine the calibration of the AVHRR sensor. The atmospheric correction is normally done using spectral optical properties measured from the ground at the target site during the high resolution image acquisition.

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3.2.3 Target related/aircraft

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Introduction

Satellite radiometers observing the Earth in the visible and near infrared (visnir) spectrum (~400 to 1100 nm) have usually suffered significant losses in gain while in orbit. For example, Advanced Very High Resolution Radiometer (AVHRR) visnir channels have shown gain loss rates ranging from 7% per year (NOAA-9) [1] to nearly zero (NOAA-6), and CZCS results for the four years after launch indicate that degradation is more rapid at shorter wavelengths (average degradation rate of 7% per annum for Channel 1 at 443 nm, falling to less than 1% per annum for Channels 3 and 5, at 550 and 670 nm respectively [2]). A primary objective of aircraft studies is therefore to measure the absolute gain of the MODIS visnir channels and their rate of change in orbit. Based on results from other satellite sensors, it would be necessary to collect such measurements at least twice a year (more frequently immediately after launch) to establish the gain to the accuracy required for useful application in global change science.

MODIS will have an onboard radiance calibration system for the visnir channels, but the system represents technology that is unproven in space. A second objective is therefore to provide independent calibration data to validate the performance of the onboard system.

Either MODIS instrument's scan mirror, if contaminated in space, will cause the channel gains to become dependent on scan angle. No measurements of this dependence will be available from the onboard calibration systems, so a third objective is to measure gain as a function of scan angle.

Approach

Figure 3.3.1 illustrates the method, which uses a sunlit, optically stable, highly reflective and cloud-free ground target as a transfer standard between a well-calibrated spectroradiometer on the aircraft and the radiometer on the satellite. The method depends on accurate prediction of the satellite-target viewing geometry, which is necessary to enable the aircraft spectroradiometer to be coaligned with the satellite view vector during satellite overpass. Small corrections must be applied to account for the effects of the atmospheric path between the aircraft and the satellite, and to account for the difference between the footprints of the two instruments on the target. These corrections, and knowledge of the spectral response function of a given channel of the satellite radiometer, allow the calculation of equivalent sets of radiance values (from the aircraft measurements) and count values (from the satellite measurements) that correspond to the altitude of the satellite radiometer and the field-of-view of the aircraft spectroradiometer. These sets are augmented in the case of AVHRR, for example, by the measurement of the count corresponding to the radiance of space, which is assumed to be zero. A least squares fit between the sets gives the gain (i.e. count output divided by radiance input) of the satellite radiometer's channel as the slope of the best-fit line.

The atmospheric correction is minimized by operating the aircraft in the stratosphere, so the necessary corrections are limited to stratospheric aerosol and stratospheric ozone. In this case the atmospheric correction for reasonable observation geometry is calculated to be less that 3% for channel 1 of AVHRR and is smaller for channel 2. The correction may be calculated to adequate accuracy, in the absence of recent additions of aerosols of volcanic origin, by adopting climatological averages for stratospheric composition, and calculating the correction with the LOWTRAN-7 [3] computer code. The aircraft spectroradiometer collects data for a period of approximately 3 minutes over the target. Satellite data encompassing the spatial range of the aircraft data are collected from the satellite radiometer for approximately 3 seconds in the middle of this period, and the method assumes that the two data sets correspond to identical states of scene structure and illumination.

The footprint correction is achieved by making the footprint of the aircraft spectroradiometer much larger that that of the satellite radiometer. The footprint used as the transfer standard is then the footprint of the aircraft spectroradiometer, which is well-characterized compared to that of the satellite radiometer. Initial navigational uncertainties between the aircraft and satellite pointing vectors amount to the equivalent of several footprints of the aircraft spectroradiometer. It is therefore necessary to search the satellite image to find the image displacement from nominal alignment that corresponds to maximum correlation between the set of aircraft radiance measurements and the equivalent set of counts from the satellite radiometer. This approach to fine-tuning of the navigation implies that the correct displacement is that which corresponds to the best (in a least-squares sense) linear relation between radiance and counts, and the approach is therefore unsuited to a determination of the linearity of response of the satellite radiometer. Over effectively uniform targets (such as clear ocean surface) this restriction does not apply.

The method assumes that the spectral response functions of the satellite radiometer channels have not changes since being measured before launch, and all observed changes in response in orbit are attributed to changes in gain. For NOAA-11 AVHRR the preliminary results reported here show that the gain ratio of channel 1 to channel 2 during the period November, 1988, to October, 1990, is constant to within ± 1%. This strongly suggests that neither channel has changes its spectral response during this period.

The spectroradiometer has been radiance and wavelength calibrated on an irregular schedule since the equipment was acquired for NOAA in March, 1988. The system was calibrated in a NASA/GSFC laboratory at Greenbelt, MD, before and after most flights, but the time intervals between flight and calibration usually exceeded 1 month. All calibration data were collected under ambient laboratory conditions and without the aircraft window in place. The window transmittance as a function of incidence angle was measure separately, and included in the calculations as a correction term.

Figure 3.3.2 illustrates the experimental arrangement in the laboratory to radiance-calibrate the 1.22 m diameter hemisphere calibration source. The spectral irradiance spectrum of a secondary standard lamp supplied by Optronic Laboratories, Inc., is transferred to an Optronic model 740A spectroradiometer equipped with a small integrating sphere at its entrance port. The purpose of the integrating sphere is to render the 740A's response to input irradiance effectively independent of the angular (and spatial) distribution of input irradiance elements at the entrance aperture of the 740A system. The (740A) irradiance to (hemisphere) radiance transfer requires accurate measurement of the diameters of the apertures in the sphere and the hemisphere, and of their separation.

The 1.22 m diameter hemisphere source is internally coated with a barium sulfate pigment embedded in a polyvinyl alcohol binder. Twelve 200W coiled-coil tungsten filament lamps are arranged internally along the great circle of the hemisphere adjacent to the flat face. Light from the lamps is baffled by a barium sulfate-coated internal cylindrical section that prevents direct illumination of the exit aperture, and the flat internal face of the hemisphere is painted matt black. The lamps are independently switchable, and are run at a current of 6.500 ± 0.001 amps. Results for the uniformity, accuracy, and stability of the radiance calibration of the hemisphere have been published elsewhere [4]. Uniformity of the radiance field (with all 12 lamps lit) as a function of spatial and angular displacement from a position observing along the axis of the hemisphere was reported to be better than ±0.3%.

The spectroradiometer is mounted on a gimbal in the aircraft that allows its optical axis to be directed to a range of angles to the right and below the aircraft axis. These motions are controlled by an onboard minicomputer through azimuth and elevation drive motors with a positioning accuracy of approximately 1°. The optical axis passes through the center of an uncoated quartz or infrasil window (both have been used) set into the floor of the aircraft.

The silicon detector and preamplifier (EG&G HUV 4000B) is hermetically sealed behind its window. The detector responsivity near 400 nm and especially near 1000 nm is temperature dependent, so the detector temperature is actively controlled at approximately 17 C with a Peltier heat exchanger. Heating pads are wound around the body of the spectroradiometer to minimize internal temperature gradients. Under flight conditions the temperature of the supporting frame measured close to the spectroradiometer is in the range of 0 to 10 C.

The onboard minicomputer also acts to control motion of the second blocking filter and the beam blocking actuator, and supervises the recording of spectral and housekeeping data. Data are recorded with a resolution of 12 bits, and include the spectral data, frame and detector temperatures, power supply voltage, time from a dedicated clock, and gimbal azimuth and elevation. The pitch, roll, heading, and altitude of the aircraft are recorded by the separate aircraft Inertial Navigation System (INS), which has its own dedicated clock.

White Sands, NM, has been the target of choice for recent measurements, but the CZCS was successfully calibrated in 1983 by this method using clear ocean surface as the target. High reflectivity targets, such as snow and stratus cloud fields are attractive candidates for future evaluation as suitable targets.

Results

Figure 3.3.3 show preliminary results [5] obtained for the NOAA-11 AVHRR from 6 ER-2 flights over White Sands, NM, between November 1988 and December 1990.

The method has several major advantages: it is the only absolute method now available (excluding on-board systems), it has high intrinsic accuracy traceable to NIST standards, it requires no field work, and it can be configured for rapid response to a request for calibration information. Figure 3.3.3 also shows the results from Kaufman and Holben, using selected desert areas observed at annual intervals with the same observation and illumination geometry, and the results of Che et al., using White Sands to transfer the calibration of the SPOT Haute Resolution Visible (HRV) channel to AVHRR. These two methods represent, respectively, the more precise relative methods now available, and the methods for cross-calibrating sensors on the same or different platforms. The trend of gain decreasing with time shown by the aircraft results is confirmed by Che et al., and is consistent with the results of Kaufman and Holben, although the aircraft-measured absolute gain is displaced from the other results for channel 2. Figure 3.3.3b gives the results expressed as the ratio of gains for channels 1 and 2. Normalized Difference Vegetation Index (NDVI) is a function of gain ratio, which must be held constant (or measured accurately) to provide useful estimates of NDVI. The aircraft measurements indicate that the gain ratio is within ± 1%, which agrees with the results of Kaufman and Holben for the February/March periods, and disagrees with their results for August/September and with the results of Che et al.

This project is now reducing data collected from the GOES-7 VISSR/VAS and from NOAA-9 AVHRR. Underflights of NOAA and GOES satellite sensors are planned for spring and fall of 1992.

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Kaufman, Y. and B. Holben, personal communication.

4 Transfer of Calibration between Pre-Launch to In-Orbit Using On-Board Calibrators

4.1 Objectives/Rationale

Instrument behavior during the period between pre-flight calibration and the first in-flight calibration is currently not well quantified. On-board calibrators have been designed for the MODIS instrument to aid in bridging the gap between ground and in-flight calibrations. These calibrators, including a solar diffuser and Spectroradiometric Calibration Assembly (SRCA), will transfer the radiometric, geometric and spectral calibrations of MODIS between pre-launch and in-orbit phases of the mission by providing a relationship between calibrator effective radiance and sensor digitized output. **An assumption critical to this process is that the on-board calibrators themselves will not change calibration after insertion into the space environment.**

4.2 Radiometric Calibration

The full-aperture blackbody source for the On-Board Calibrator (OBC) will be calibrated pre-flight with traceability to a NIST temperature standard. Similarly, redundant tungsten lamps will be calibrated with NIST traceability. The solar diffuser for on-orbit reflectance calibration will be calibrated pre-flight and traceable to NIST reflectance standards. BRDF measurements to determine the diffuser's response as a function of wavelength and angle of incidence will also be made.

4.3 Geometric Characterization

4.4 Spectral Characterization

5 In-Orbit Radiometric Calibration /Characterization Methodologies

5.1 Objectives/Rationale

In-orbit calibration of the MODIS instruments is crucial to assessing the performance of the instruments during the lifetime of the mission. In-orbit techniques, combined with pre-flight and ground truth calibrations, provide the necessary redundancy to ensure thorough knowledge of instrument operation.

5.2 Instrument Based Calibration

<u>MODIS Preliminary Calibration Management Plan,</u>
Hughes Santa Barbara Research Center,
September, 1991.

The MODIS sensor includes the capability for in-orbit calibration using instruments specifically designed for this function. Included are the Spectroradiometric Calibration Assembly (SRCA), a solar diffuser and its stability monitor (SDSM), and an on-board blackbody source for calibration of the MODIS thermal bands.

5.2.1 Internal sources/assemblies

5.2.1. Spectroradiometric Calibration Assembly (SRCA)

The SRCA will allow in-orbit capability for radiometric calibration of the VIS, NIR, and SWIR bands; and for spectral calibration of the VIS and NIR bands. It utilizes an incandescent source and internal optics to collimate a beam directed to the MODIS scan mirror for relay into the MODIS instrument.

5.2.1.2 Blackbody

MWIR and LWIR bands use a full-aperture blackbody for in-flight calibration. The blackbody, operated at ambient temperature, will have excellent temperature uniformity across its surface and provision for directing residual reflection toward similar temperature surroundings. The blackbody cavity design is similar to that used for SBRC's ground test, utilizing an aluminum plate with V-grooves cut at 25-degree half-angles.

5.2.1.3 Solar Diffuser Panel and Solar Diffuser Stability Monitor (SDSM)

The solar diffuser is a panel with two BRDF levels for extended dynamic range of operation. The solar diffuser stability monitor periodically compares the reflectance properties of the panel to the sun and measures any changes. The optical system of the SDSM consists of a Czerny-Turner grating spectrograph with a fixed entrance slit, grating, and exit slit detector. The fore-optics can image either the diffuser or the sun, and can provide attenuation allowing the signals to come within two orders of magnitude of one another, where comparisons can be made.

5.2.2 External solar

5.2.3 External lunar

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<u>Introduction</u>

In-flight calibration of imaging instruments is a difficult task. Calibration subsystems themselves are subject to offset and drift, and many do not calibrate the entire optical system, which can be done only by having external, full aperture sources, such as solar diffuser surfaces. Calibration can be done through the use of well characterized ground targets, but this requires near-simultaneous measurements, a substantial ground campaign, and a difficult correction for the atmosphere.

The objective of this work is to provide new radiometric information needed to allow the moon to be used as a well-characterized radiometric source for calibration of earth-orbiting instruments that can view it. In addition to direct use of the radiometric information, such detailed knowledge of the lunar brightness enables better use of the moon for measurement of the MTF and scattered light performance of the instruments.

Background

The moon has several unique properties: it is within the dynamic range of most imaging instruments, it is surrounded by a black field in both reflective and thermal band, and its surface brightness distribution can be better known than that of any other natural object at which most instrument can be safely pointed. Although the moon's photometric properties are thought to be intrinsically constant over long time scales (natural rate of change estimated at 10^{-9} percent per year [1]), the effects due to the variation of illumination conditions and observation geometry must be considered. These in turn are related primarily to the lunar photometric function and the lunar libration

The libration of the moon, the change of the position of the sub-earth point on the moon, results from the axial inclination and the small change in the angular velocity of the moon around the earth due to eccentricity of the lunar orbit (optical libration) and small nonuniformity in the rotation rate of the moon (physical libration). These combine to yield a variation of about ± 7° in both latitude and longitude, both with a period of near one month, but with small differences that require the dual precessional cycle of 18.6 years (accidently approximately the same length as the Saros cycle) to complete.

The variations of albedo over the face of the moon are common knowledge. Quantitatively, at modest spatial resolution the normal albedo (in V band) ranges from 9% to 23%, with a mean value near 12.5% [2]. Albedo variegation extends to scales below the limit of telescopic resolution. The moon appears gray in the visible, but has a general increase in reflectivity into the near infrared [3]. Variation of color between different locations on the moon is small, and those spectral features that do exist are relatively broad [4,5].

The moon does not behave as an ideal diffuse reflector. As the phase angle (sun-moon-observer angle) becomes small, the moon brightens dramatically; this is called the "opposition effect" [6], which increases up to the point that lunar eclipse begins. Current knowledge of the lunar photometric function is limited to a few wavelengths, and to a few small areas or for the spatially-integrated lunar brightness (the phase function) [7,8].

The moon has several additional characteristics that require consideration in treating it as a radiometric standard. Light from the whole moon has small negative polarization at small phase angles, becoming most negative at ~ -1.2% near a phase angle ~ 12°, then increasing through 0 polarization near 24° up to about +8% at phase angles near 90°. Individual areas (appropriate for HIRIS spatial resolution) typically have polarization at phase angles less than 15° of 1.2% or less at 361 nm, and polarization decreases toward longer wavelengths out to at least 1 μm [9]. The degree of polarization is approximately inversely proportional to albedo, begin greatest for dark areas, and least for bright areas [6]. Variations with albedo are small for phase angles less than about 40°. Early work indicated that near full moon, polarization near the limb of the moon was about 0.1-0.2% parallel to the limb [10].

Because the surface of the moon can become as hot as 400 K[11], thermal emission becomes important for longer wavelengths. Thermal emission at 400 K contributes about 0.1% at 1.8 µm, 1% at 2.0 µm, and 10% at 2.3 µm. Thermal models and prior infrared measurements [12] would allow correction for thermal emission to about 1/5 of these levels. Simultaneous measurements of lunar radiance near 3.5 µm would allow correction for thermal emission to better than 0.5%.

Approach

Current knowledge of the radiometry of the moon is limited to attempts to calibrate the absolute spectral reflectance at a few points [13], and measurements of the integrated lunar brightness at a few wavelengths [7]. In order to support the spatial resolution of EOS instruments, especially HIRIS, extensive radiometric observations will be made with spatial (angular) resolution of 4.4 arcsec, twice as fine as HIRIS. The wavelengths of reasonable transparency of the earths' atmosphere between 0.3 and 2.5 µm will be covered. Because the technology to do radiometry with imaging spectrometers has not yet been developed, radiometry will be at a discrete set of passbands by use of interference filters; on the order of 20 wavelengths will be used.

Two filter imagery systems will operate simultaneously, one in the VIS and one in the VNIR. Each will have its own telescope, boresighted and supported on a common mount. No beam splitter or fold mirrors will be involved and each telescope and detector system will be axial, so that the detection systems should be polarization-insensitive.

For wavelengths from 0.3 to 1.0 µm, a conventional astronomical silicon CCD will be used, with 512 x 512 pixels. No "off-the-shelf" photometric arrays are available for wavelengths longer that 1 µm, and this project had planned to use an array produced as part of the HIRIS development. The exact type of infrared array to be used is still under study, but it is assumed that a 256-square array with characteristics similar to HIRIS test arrays will be available.

An in-dome radiometric standard will be observed at least as often as the beginning and end of astronomical observations each night. This standard will utilize a NIST-traceable halogen standard lamp and a nearly ideal diffusing surface large enough to illuminate the full aperture of the telescopes. Our plan is that this facility be part of the circuit for the EOS portable radiometer standard (Phil Slater proposal), and the connection to NIST be established every 6 months.

The telescope system will be highly automated and entirely under computer control. Most of the telescope time will be spent observing standard stars, especially those in a band along the moons' orbit. This both allows quantitative determination of atmospheric extinction (needed to correct to exo-atmospheric radiances) and ties the radiometric system to the existing standard star system. Experiments "trailing" stars at different rates will be done to determine the best radiometric techniques and to determine the high-frequency variation of apparent radiance due to atmospheric lensing (scintillation).

Design and planning for this lunar radiometry facility has begun, and routine observations are scheduled to begin in the fall of 1993. Observations would continue at least 4 1/2 years; observations over at least 1/4 the Saros cycle are required to cover the range of lunar libration.

Observations will be made each month when the moon is at 90° phase or less (the bright two weeks of each lunation) on all photometric nights (at the planned observatory site in Flagstaff, there are approximately 100 photometric nights each year). In order to develop a photometric model for each resolution element on the moon, all observations will be reduced to a special projection that incorporates all areas of the moon visible from the earth over the full range of libration, yet has minimum distortion from the appearance of the moon for a single observation. Observations will be reduced to produce a photometric model of each pixel in this projection for each wavelength band.

Initial error budget analysis that the expected long-term precision is ~0.8% and absolute radiance ~2.3%. The largest contribution to uncertainty of absolute radiometric accuracy is the calibration of the standard lamp.

For the nominal EOS platform orbit, the average angular size of the moon is equivalent to a nadir target of 6.73 km. Instruments of 15 m, 30 m, 250 m, and 1 km resolution would have 425, 212, 25.5 and 6.4 pixels across the moon, respectively.

Because the moon is darker than most terrestrial scenes, spacecraft calibration observations of the moon should be made at small phase angles if possible to avoid being low in the dynamic range of the instrument. Spacecraft observations could be made at any phase angle greater than 1.5°, where lunar eclipse phenomena begin. The moon attains a minimum phase angle of less than about 6° each month, and near zero twice a year.

Expected Results

For any specific spacecraft observation, the precise illumination and observation geometry will be used to calculate a radiometric image of the moon at full model spatial resolution in each wavelength. This radiometric image will then be geometrically transforms to match the resolution and orientation of the spacecraft instrument image. (The spatial uncertainty in resampling to a specific HIRIS observation increases the overall radiometric uncertainty 0.1%, other instruments would be similar for pixels that are fully on the moon). The team for that instrument would produce a radiometric image based on their calibration files. The ratio of the two images represents the factor between the two calibration systems.

Such radiometric images can also be used in reduction of instrumental scans across the moon for study of MTF and scattered light sensitivity [1], although for these purposes the spatial resolution and radiometric precision of this study would rarely be needed.

Preliminary calculations of lunar radiance levels, with about 15% uncertainty, are now available for use in design of instrument gain settings.

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5.3 Target-Based Calibration

5.3.1 Target related/ground reflectance

The reflectance of a ground target large enough to have a stable spectral reflectance over many sensor pixels is carefully measured when the image is taken by the sensor to be calibrated. At the same time, the extinction optical depth of the atmosphere is measured along with certain necessary meteorological parameters. The aerosol particle size distribution is inferred from the spectral optical depths. A radiative transfer code which accounts for multiple scattering and absorption is used to predict the in-band radiance at the entrance pupil of the sensor being calibrated. This radiance is used along with the average digital counts of the pixels corresponding to those measured on the ground to compute the calibration [1, 2]. This same method has been applied to calibrate the AVIRIS sensor in an ER-2 [3] and a Daedalus 1268 operated by EG&G in both a jet aircraft and a helicopter [4]. This method is NOT directly applicable to MODIS as the MODIS pixel size is too large for a ground crew to adequately sample the ground reflectance over multiple pixels. An modified approach, provided by the University of Arizona, is described below.

The University of Arizona group plans to make in-orbit calibrations of high spatial resolution EOS sensors such as ASTER (and HIRIS for the C platform) using a reflectance-based method described above. MODIS in-orbit calibration with reference to a ground site shall be done with a method similar to its AVHRR work [5]. The U of A group plans to continue with this type of work with future AVHRR and follow-on sensors and a MODIS simulator if it becomes available. The group plans to refine its methods to include the use of a field SWIR spectrometer, a solar radiometer designed to measure total column water vapor, and an imaging solar radiometer which will be used to study the solar aureole. The aureole is a sensitive indicator of aerosol scattering and the group hopes to improve its knowledge of the scattering phase function with this future instrument.

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5.3.2 Bio-optical oceans

Water leaving radiances over the many ocean locations at wavelengths greater than about 700 nm are close to zero. The satellite radiance therefore is arising entirely from the path radiance. An accurate radiative transfer model allows the path radiance to be calculated. This path radiance provides a known source which allows MODIS to be calibrated. The technique makes the instrument calibration and the radiative transfer model self-consistent.

Buoy measurements of pigment concentration can be compared with MODIS determined pigment concentrations. A discrepancy between the two may be resolved by altering the calibration of the satellite. This technique can be introduced into the routine processing and is called bio-geochemical normalization.

5.4 Image Related

5.4.1 External image related radiometric rectification

Certain regions on Earth contain areas which are radiometrically stable. For example, exposures of bedrock may have a relatively stable reflectance over long periods of time. These radiometrically stable areas within images can be used to correct other portions of an image so that they are internally self-consistent with the stable portions of the image. The technique is generally applied to high resolution images such as those produced by Landsat or SPOT. The applicability of the technique to MODIS images will be researched and applied.

5.4.2 Class-specific scene equalization

A generalization of the within image radiometric rectification technique in which multiple scenes are used will also be employed for monitoring the MODIS stability.

6 In-Orbit Geometric Characterization

A deployable line ruled recticle will on occasion be placed in the field of view of the instrument. The alignment of the sensor will thus be periodically checked.

7 In-Orbit Spectral Characterization

8 Official MODIS/MCST Calibration Algorithm

8.1 Objectives/Rationale

During routine processing, one calibration algorithm will be used to determine the Level-1B radiances. This "official" algorithm may be one of the techniques described above, but it is more likely to be a combination of methods.

8.2 Minimization of Instrument Systematic Noise Sources

The contractor will work to ensure that sources of systematic noise, which will detract from the absolute instrument performance, are minimized during the design and build phases.

8.3 MCST Calibration Flow

The calibration algorithm produced by MCST shall take into account all instrument components, both optical and electronic, between the radiance input and the digitized output of the sensor. Components in each optical path will be accounted for. In this manner, the propagation of error in the calibration process can be more meaningfully quantified.

9 MODIS/MCST Calibration Algorithm Validation and Upgrade

9.1 Algorithm Correction for Systematic Errors

Systematic error sources that have not been eliminated from the hardware will be processed out by application of the software algorithm. These error sources yield image-related effects including, but not limited to, drifts within scan, "memory effect" which is manifested as pixel-to-pixel aliasing, and the effects of the array's fixed pattern noise.

9.2 Inclusion of In-Flight Calibration Information

Additional information on MODIS performance will be available after the instrument is launched. On-board calibrators and solar calibration will provide data that will be analyzed to further validate and upgrade the software algorithm.

9.3 Creation of Calibration Error Images

A two-dimensional image, representing the error in the calibration on a pixel-by-pixel basis, will be created after each calibration procedure.

10 Definitions and References

10.1 Data Dictionary/Glossary

10.2 Acronyms

A

AIRS	Atmospheric Infrared Sounder
ASTER	Advanced Spaceborne Thermal Emission and Reflectance
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infra-Red Imaging Spectrometer

E

EOS	Earth Observing System
EOSP	Earth Observing Scanning Polarimeter

G

GOES	Geostationary Operational Environmental Satellite

H

HIRIS	High Resolution Imaging Spectrometer

M

MCST	MODIS Characterization Support Team
MERIS	Medium Resolution Imaging Spectrometer
MISR	Multi-angle Imaging Spectro-Radiometer
MODIS	Moderate Resolution Imaging Spectrometer
MTF	Modulation transfer function

N

NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

S

SeaWiFS	Sea Viewing, Wide Field-of-View Sensor
SBRC	Santa Barbara Research Center
SDSM	Solar Diffuser Stability Monitor
SRCA	Spectro-radiometric Calibration Assembly

10.3 Additional References

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MODIS-N CALIBRATION HANDBOOK

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MODIS-N CALIBRATION HANDBOOK

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1. Introduction

1.1 Overview

This document is intended as an introduction to the results of the radiometric, geometric, and spectral calibration/characterization of the MODIS-N instrument scheduled for launch on the EOS-A platform in 1998. Readers of the document are expected to be those in the EOS program who are concerned with calibration, but not concerned primarily with the MODIS-N calibration efforts. This document provides these readers with sufficient information so they will have a clear picture of MODIS-N calibration/characterization plans. Every attempt will be made to make this handbook succinct yet complete. It is the intent to maintain and up-date this document as part of the information mode available to both EOS and non-EOS scientists through the EOSDIS's (EOS Data and Information Systems) DADS (Data Analysis and Distribution System).

MODIS-N is an imaging scanning spectro-radiometer. It views the Earth from an orbit of 705 km. and continually scans through the nadir to ±55°. The instrument measures the at-satellite radiance in 36 bands from 0.408 mm to 14.385 mm. The footprint of the detectors varies from 0.25 km. (2 bands) to 0.5 km. (5 bands) to 1 km. (29 bands). Some properties of the bands are summarized in Section 7.5.

The spectro-radiometer itself is a 2-mirror off-axis Gregorian design. Radiation from the Earth passes through a dichroic beamsplitter which separates the light into four major bands. Discrete interference filters provide the higher spectral resolution.

Calibration sources include views of the Sun through a diffusing plate, the moon, deep space, a blackbody, and a spectro-radiometric calibration assembly which provides a measure of the wavelength stability of the instrument.

1.2 Science Calibration/Characterization Objectives

The MODIS-N specifications call for a radiometric calibration accurate to 5% below 3 mm and 1% above 3 mm. Stray light must be less than 1% and co-registration of different detector elements must be to within 0.1 pixel. Polarization sensitivity must be less than 2% at all wavelengths from 0.43 to 2.2 mm.

1.3 Organizations and Responsibilities

The MODIS Characterization Support Team (MCST) provides the overall planning and coordination of the MODIS-N calibration efforts under the direction of the MODIS Science Team. Hughes/SBRC, the instrument contractor, does the ground calibration and characterization and demonstrates that the specifications are met.

2. Pre-Launch Calibration/Characterization

2.1 Objectives/Rationale

Before launch, tests will be conducted to characterize the properties of MODIS-N. These plans call for the testing of the following radiometric properties: Gain, offset, signal versus radiance, linearity, signal-to-noise ratio, on-board calibrator performance, spectral matching, coherent noise, scan modulation, and band-to-band stability. The Modulation Transfer Function (MTF) will be measured along-track and across-track. Spectral band shapes and out-of-band radiation levels will be measured. The transient response including rise time and overshoot or undershoot will be tested. Polarization sensitivity will be measured. The spectral band registration along-track and crosstrack will be measured. Most of these tests will be made under ambient conditions and under vacuum conditions. A total of 29 different types of characterization tests are planned.

As part of EOS calibration planning, MODIS-N and all EOS-A platform instruments will be cross-calibrated using a common known source and/or using a traveling standard radiometer. These activities are in early planning stages and will be summarized when they become public.

The results summarized in this section come from two sources. The primary input comes from the MODIS-N contractor, Santa Barbara Research Center (SBRC), in Santa Barbara, CA. A parallel calibration and characterization effort has been provided by the MODIS Characterization Support Team (MCST) at NASA's Goddard Space Flight Center in Greenbelt, MD. Initial drafts of this document carry requirements prior to the availability of results.

2.2 Radiometric Calibration

Before launch the MODIS-N Calibrator will be used to provide a series of checks on the instrument. These checks include a radiometric sensitivity check and measurements of band-to-band registration, coherent noise, MTF, IFOV, transient response, optical alignment, scene simulation, and coherent noise.

2.2.1 Absolute Calibration

A minimum absolute radiometric calibration accuracy of ± 5% is required in the visible and near-infrared and ± 1% in the thermal infrared is required.

2.2.2 Relative Calibration

A ± 2% accuracy relative to the Sun is required. Over two weeks, a ± 0.5% stability is required. Section 3 is devoted to in-orbit calibrations.

2.3 Geometric Calibration

The pointing accuracy of MODIS-N will be sufficient to locate any pixel on the Earth's surface to with ± 0.5 times the length or width of the pixel. Registration of pixels to 0.1 pixel or better will be made, but a pointing knowledge of 30 arc seconds and alignment changes of 60 arc seconds will reduce the overall pointing knowledge to 0.5 pixels. Section 4 is devoted to in-orbit geometric calibrations.

2.4 Spectral Calibration

The spectral response of MODIS-N as a function of time must either be stable or measured with sufficient accuracy so that the overall radiometric calibration goals are reached. MODIS-N has a Spectro-radiometric Calibration Assembly (SRCA) which allows the spectral response of the scanning radiometer to monitored over time. Section 5 is devoted to in-orbit spectral calibrations.

3. In-Orbit Radiometric Calibration/Characterization

3.1 Objectives/Rationale

The characterization efforts before launch and the use of known radiation sources in orbit will allow the initial in-orbit calibration to be measured and maintained within specifications during the mission life. Multiple calibration techniques and sources will be used to obtain the necessary calibration accuracy. Sections 3.2 through 3.5 describe different calibration techniques. The approach to synthesizing the multiple approaches into a single official calibration algorithmis discussed in Section 6.

3.2 Instrument-Based Calibration Methods

Radiometric calibration of MODIS-N will be made through the use of known sources to establish the instrument's response. These known sources include the Sun, the [illegible] cold or dark space, a blackbody, and an incandescent source.

3.2.1 Spectro-Radiometric Calibration Assembly (SRCA)

A single blackbody operating at the ambient temperature will be used to calibrate the MODIS-N thermal channels. The blackbody will be viewed once per scan and calibrate channels 20 through 36. The blackbody itself is aluminum with v-groove cuts of 25°. Its effective emissivity is 0.992 or greater.

The Spectro-Radiometric Calibration Assembly (SRCA) can be used for radiometric checks in the visible and near infrared since it has an incandescent source. It can be used at any time during the orbit. The SRCA is also used in spectral calibration and spatial registration studies.

3.2.2 Solar Diffuser Stability Monitor (SDSM)

A solar diffuser plate is part of the MODIS-N design. It can be used to calibrate channels 1 to 7 and 17 to 19 once each orbit. The properties of the diffuser plate are monitored, in turn, by the Solar Diffuser Stability Monitor (SDSM) which alternately views the sun and the diffuser.

This method of calibration is a primary method of calibration since the entire optical path of the instrument is monitored.

3.2.3 External Lunar

MODIS-N can view the moon, once per month in the spring and autumn, when deep space is viewed. For 4 to 6 times per year, for periods lasting about one day, the moon is visible in the deep space scans. The moon is an extremely stable radiation source, which potentially allows it to be used for calibration. The intensity of the lunar disk will vary during the year as the Earth-Sun distance changes and will also vary with the lunar libration angle and phase angle. The MODIS-N design only allows the moon to be observed when it is in a gibbous phase about 22.5° beyond the half-moon phase. Given the precise illumination and observation geometry, a high spatial resolution model of the spectral radiance from the moon will be calculated. This radiometric image will then be transforms to match the resolution and orientation of MODIS-N. Periodically then, MODIS-N will be exposed to a stable radiometric source, allowing the long-term stability of the instrument to be monitored. Hugh Kieffer of the USGS-Flagstaff is the principal investigator for lunar calibration; Dr. Kieffer is a Team Member of both the ASTER and HIRIS Facility Teams.

This method of calibration is a primary method of calibration since the entire optical path of the instrument is monitored.

3.3 Instrument Cross-Comparison Methods

3.3.1 Cross-Sensor/Within Platform

Several passive remote sensors using visible radiation are planned for the EOS-A platform. Each instrument will be independently calibrated. After corrections for differences in footprint size, spectral resolution, and pointspread functions are made, the radiances measured by the separate should agree to within their stated accuracies. If they do agree, it tells us that any biases, whether the bias is zero or not, are the same. The more instruments that agree, the more confidence we can have that correct measurements are being made. Potential comparison instrument include MODIS-N (am) to MODIS-N (pm), MODIS-T, AIRS, ASTER, EOSP, and MISR. Several of these potential configurations are discussed below.

AIRS (Atmospheric Infrared Sounder) has a 13.5 km. nadir footprint with five channels in the visible region from 0.4 to 1.1 microns. Inter-comparison to MODIS-N will consist of combining many MODIS pixels, weighted by the AIRS

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pointspread function, to form an image like a single AIRS pixel. Because MODIS-N also appears to have better spectral resolution in the visible, several appropriately weighted MODIS-N bands will be required to match the AIRS resolution. Repeated comparisons of AIRS pixels with MODIS-N simulated AIRS pixels should give a reasonable indication of the amount of agreement.

Both AIRS and MODIS-N also make thermal infrared measurements which allow comparisons to be made. At each thermal wavelength, contributions are coming from all layers of the atmosphere and the surface usually expressed through atmospheric weighting functions. If the two instruments do not have similar bandpasses, the comparison is made difficult since the same layers of the atmosphere are not sampled equally. It is likely that radiances in the thermal bands for these two instruments will not be compared directly, but a derived geophysical parameter such as sea surface temperature will be used for the inter-comparison. The thermal cross-calibration technique for this pair of instruments and for other pairs of instruments is a topic requiring further study.

ASTER (Advanced Spaceborne Thermal Emission and Reflection) has a 30 meter nadir footprint and one near infrared band from 850 to 920 nm. Since MODIS-N has bands centered at 865 and 905 nm an inter-comparison is possible using appropriate weights or filter factors for the two instruments. Spatially the MODIS-N pixel can be simulated by summing up the ASTER pixels using the MODIS-N pointspread function as the weighting function. Inter-comparisons in the thermal infrared are also possible for these two instruments.

EOSP (Earth Observing Scanning Polarimeter) has a 10 km. nadir footprint and several spectral bands in the visible region. MODIS-N radiances can be spatially re-mapped, using the EOSP pointspread function, and spectrally re-mapped, using the EOSP filter transmission functions, to match the EOSP radiance observations.

MISR (Multi-angle Imaging Spectro-radiometer) has four viewing angles which can be duplicated by MODIS-N. Four other MISR viewing angles cannot be matched by MODIS-N. MISR has spectral bands centered at 440 and 860 nm which are closely matched by MODIS-N bands at 443 and 865 nm. The wavelength resolution for MISR is not available, but probably is less than MODIS-N. By spectrally re-mapping MODIS-N and spatially re-mapping MISR, a matching image for the two instruments appears possible which will allow them to be inter-compared.

The University of Arizona, under the direction of Dr. Philip Slater, plans to perform cross-calibration comparisons of the type described in this section. They have extensive experience with AVHRR-SPOT comparisons and NOAA-9, NOAA-10, and Landsat TM comparisons.

3.3.2 Cross-Platform In-Orbit

Using sensors on other satellites for inter-comparison proceeds much like the inter-comparisons described above. The major difficulty and drawback in comparisons between two satellites is that seldom are both satellites over the same region at the same time so matching satellite and solar geometries can be obtained. Without the geometry and temporal match, the inter-comparison become considerably more involved. Some potential comparison instruments are AVHRR, SPOT, and Landsat as discussed below. Other potential comparisons with MERIS, SeaWiFs, GOES, and other satellites are also possible.

AVHRR (Advanced Very High Resolution Radiometer) has a 1.1 km. nadir footprint, which is close to the 1 km. nadir footprint for some MODIS-N channels. AVHRR has a lower spectral resolution than MODIS-N. AVHRR's channel 1 measures in the range of about 560 to 700 nm and channel 2 covers about 720 to 970 nm. Weighting the MODIS-N bands centered at 531, 565, 653, 681, 750, 865, 905, 936, and 940 nm by the filter transmission of the AVHRR interference filters should allow an AVHRR type scene to be constructed from the MODIS-N observations. The initial pre-flight filter transmissions for AVHRR are known, but because filters of this type change their properties in flight, it is not clear that using the pre-flight transmission functions will give correct results. Another drawback with the AVHRR/MODIS-N inter-comparison is that the AVHRR sensors are not well calibrated. It is also not clear if the present AVHRR design will be flying in the MODIS-N era. Finally comparison between the two sensors will be limited to those times when both are crossing the same scene within as yet to be defined window of time.

SPOT has a 10 meter nadir footprint and several visible bands which offer opportunities for inter-comparison with MODIS-N. SPOT images can be spatially re-mapped and MODIS-N images can be spectrally re-mapped to achieve synthetic images which can be inter-compared.

Landsat has a 30 meter nadir footprint and visible bands covering 450-520, 520-600, 630-690, and 760-900 nm which offer opportunities for inter-comparison with MODIS-N. Landsat images can be spatially re-mapped and MODIS-N images can be spectrally re-mapped to achieve synthetic images which can be inter-compared.

The University of Arizona plans to perform cross-calibration comparisons of the type described in this section. They have extensive experience with AVHRR-SPOT comparisons.

3.3.3 Target Related/Aircraft

MODIS-N radiances will be compared to the radiances measured from high flying aircraft such as NASA's ER-2 aircraft using an Optronic model 740A spectroradiometer. Except for small corrections of the order of less than 5% for the path radiance caused by atmospheric scattering above the aircraft, co-located radiances from these two sensors should be nearly the same. The technique assumes the spectral response of the satellite radiometers remains unchanged over time and measured changes in response are gain changes only. Co-location of the aircraft and satellite observations can be done by fine-tuning the navigation of the satellite such that the maximum correlation between the two sets of measurements is achieved. Since the aircraft radiometer can be re-calibrated in the laboratory with traceability to NIST standards, the technique allows the MODIS-N observations to be maintained to within several percent over the entire 15 years of the EOS experiment. The technique is slightly more complicated to use when significant stratospheric aerosols are present such as those from El Chicon or Mt. Pinatubo.

3.4 Target-Based Calibration Methods

3.4.1 Target Related/Ground Reflectance

In-situ observations of radiance from the ground or from aircraft can be compared to satellite radiance observations by using radiative transfer models. These in-situ radiance measurements, in effect, become known sources suitable for calibration. The following sub-sections describe these techniques. Buoy observations of pigment concentration can also be compared to MODIS-N derived values for the same pigment concentration. A difference in the two determinations can indicate a calibration problem exists, which can be corrected by altering the calibration until the two pigment concentrations exists. This technique may not calibrate the spectrometer so much as tune the spectrometer-radiative transfer-pigment concentration algorithm combination.

MODIS-N radiances can also compared to ground observations provided a good radiative transfer model is available and the composition and vertical structure of the atmosphere are well measured. Co-located ground and satellite measurements then allow the calibration of the satellite sensor to be checked much as is done using high flying aircraft.

Characterizing atmospheric composition requires measurements of total precipitable water, total ozone amount, and aerosol optical depth as a function of wavelength. Atmospheric water vapor can be measured using radiosondes, or total precipitable water vapor meters using either solar or microwave radiation. Dobson spectrometers can provide total ozone amounts. Aerosol properties can be measured using lidar, sunphotometers, aureole meters, combined pyranometers and pyrheliometers giving the diffuse-direct ratio, or pyrheliometers equipped with Schott glass filters. The combination and choice of instruments has not yet been made.

3.4.2 Bio-Optical Oceans

Water leaving radiances over the many ocean locations at wavelengths greater than about 700 nm are thought to be close to zero. An accurate radiative transfer model allows the path radiance to the satellite radiance to be determined. This path radiance therefore provides a known source which allows MODIS-N to be calibrated. This technique makes the instrument calibration and the radiative transfer model self-consistent.

Buoy measurements of pigment concentration can be compared with MODIS-N determined pigment concentrations. A discrepancy between the two may be solved by altering the calibration of the satellite. This technique is called bio-geochemical normalization.

3.5 Image Related

3.5.1 External Image Related Radiometric Rectification

Certain regions on Earth contain areas which are radiometrically stable. For example, exposures of bedrock may have a relative stable reflectance over long periods of time. These radiometrically stable areas within images can be used to correct other portions of an image so that they are internally self-consistent with the stable portions of the image. The technique is referred to as "within image radiometric rectification" and is generally applied to high resolution images such as those produced by Landsat or SPOT. The applicability of the technique to MODIS-N images will be researched and applied.

3.5.2 Class-specific Scene Equalization

A generalization of the within image radiometric rectification technique in which multiple scenes are used will also be employed for monitoring the MODIS-N stability.

4. In-Orbit Geometric Calibration

The SRCA will provide in-orbit spatial registration measurements. The assembly consists of an incandescent lamp source which illuminates a double pass grating spectrometer that provides a light source of known wavelength to the scanning spectro-radiometer. When a recticle pattern is deployed in front of the SRCA exit slit, the alignment of spectro-radiometer can be measured and compared to previous measurements.

5. In-Orbit Spectral Calibration

The SRCA will provide in-orbit spectral calibration. The assembly consists of an incandescent lamp source which illuminates a double pass grating spectrometer that provides a light source of known wavelength to the scanning spectro-radiometer.

6 Official MODIS-N/MCST Calibration Algorithms/Models

6.1 Objectives/Rationale

During routine processing, one calibration algorithm will be used to determined the Level-1B radiances. This official algorithm may be one technique, but it is more likely to be a combination of methods. MCST has the responsibility of supplying this algorithm to convert the raw Level-1A quantized value to Level-1B radiances.

6.2 Algorithm Sensitivity/Simulation Studies

7. Definitions, References, and Tables

7.1 Table of Personnel to Contact for More Information

TOPIC	CONTACT PERSON(S)	TELEPHONE
General	John Barker Phil Slater	301-286-9498 602-621-4242
Ground Calibration of MODIS-N alone	Jim Young	
Cross-calibration prior to flight	Bruce Guenther Phil Slater	301-286-5205 602-621-4242
In-flight Calibration	John Barker	301-286-9498
Cross-calibration in orbit	Phil Slater S. F. Biggar	602-621-4242
Calibration using Ground-Truth Measurements	Phil Slater S. F. Biggar	602-621-4242
Calibration using Aircraft Underflights	Peter Abel Mike King	301-286-6829 301-286-5909
End-of-Flight Tests	John Barker	301-286-9498
Thermal Calibration	Peter Abel	301-286-6829
Visible Calibration	John Barker	301-286-9498
Lunar Calibration	Hugh Kieffer	602-556-7015
EOS Calibration Plans	Bruce Guenther	301-286-5205

7.2 Data Dictionary/Glossary

7.3 Acronyms

A	
AIRS	Atmospheric Infrared Sounder
ASTER	Advanced Spaceborne Thermal Emission and Reflection
AVHRR	Advanced Very High Resolution Radiometer
E	
EOS	Earth Observing System
EOSP	Earth Observing Scanning Polarimeter
G	
GOES	Geostationary Operational Environmental Satellite
I	
IFOV	Instrument field of view
M	

MCST	MODIS Characterization Support Team
MERIS	Medium Resolution Imaging Spectrometer
MISR	Multi-angle Imaging Spectro-radiometer
MODIS-N	Moderate Resolution Imaging Spectrometer - Nadir
MODIS-T	Moderate Resolution Imaging Spectrometer - Tilt
MTF	Modulation transfer function
N	
NASA	National Aeronautics and Space Administration
S	
SeaWiFs	Sea Viewing, Wide-Field-of-View Sensor
SBRC	Santa Barbara Research Center
SDSM	Solar Diffuser Stability Monitor
SRCA	Spectro-radiometric Calibration Assembly
T	
TM	Thematic Mapper

7.4 References

Hughes, Santa Barbara Research Center, 1991. Instrument Design Summary (MODIS-N).

Hughes, Santa Barbara Research Center, 1991. Moderate Resolution Imaging Spectrometer - Nadir (MODIS-N). Phase C/D Proposal. Technical Design Summary.

1990 Reference Handbook. EOS, Earth Observing System.

MCST Presentation at the MST Meeting (9/24/90).

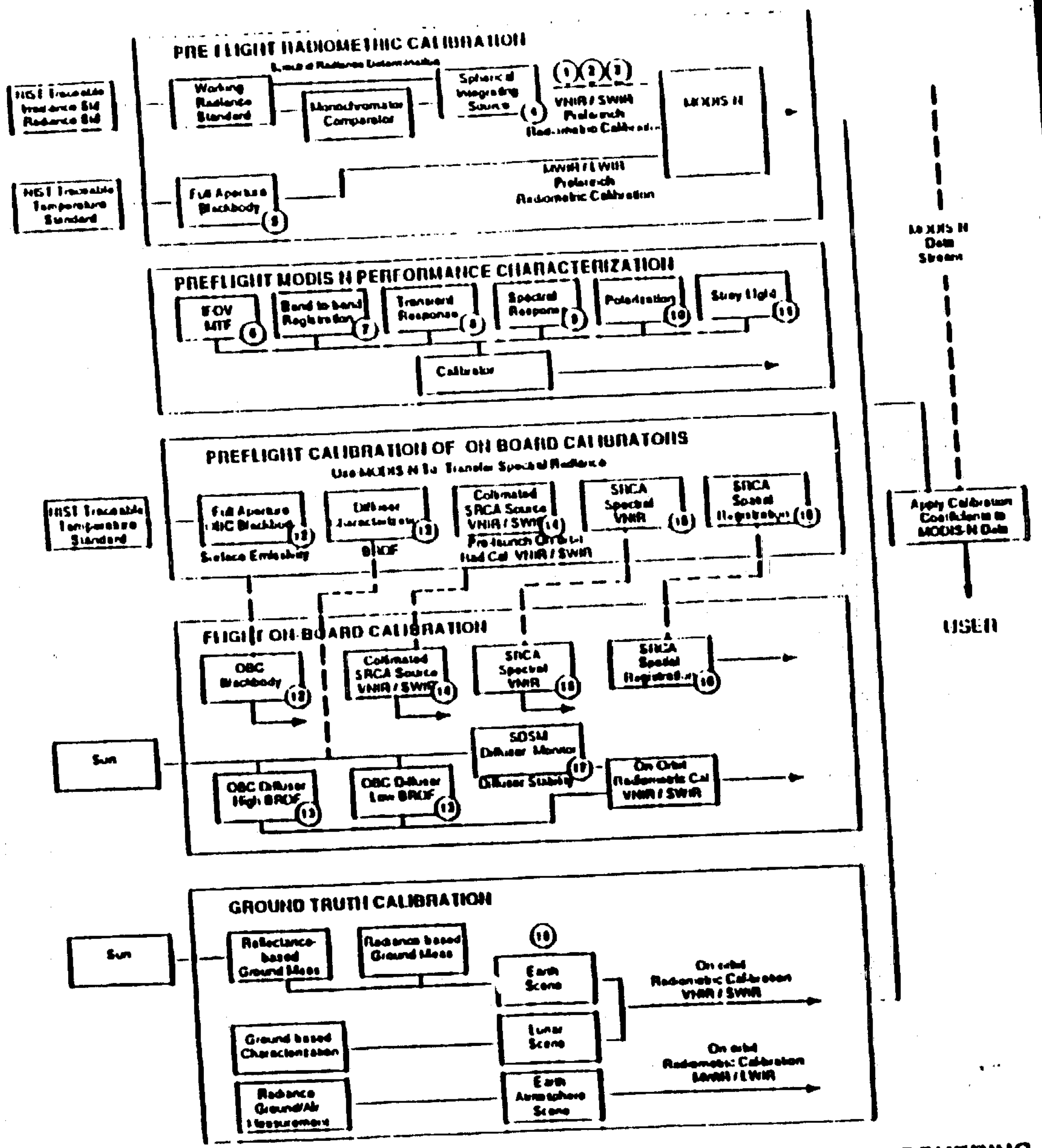
7.5 Tables

MODIS VISIBLE FOCAL PLANE CHANNELS			
Channel Number	Central Wavelength (um)	Bandwidths (microns)	Signal to Noise Ratio
3	0.470	0.020	438
4	0.555	0.020	428
8	0.415	0.015	1284
9	0.443	0.010	1241
10	0.490	0.010	1456
11	0.531	0.010	1452
12	0.565	0.010	1281

MODIS NEAR INFRARED FOCAL PLANE CHANNELS			
Channel Number	Central Wavelength (um)	Bandwidths (microns)	Signal to Noise Ratio
1	0.659	0.050	241
2	0.865	0.040	438
13	0.653	0.015	1630
14	0.681	0.010	1238
15	0.750	0.010	1061
16	0.865	0.015	1053
17	0.905	0.030	463
18	0.936	0.010	119
19	0.940	0.050	643

MODIS SHORT AMD MID-RANGE INFRARED FOCAL PLANE CHANNELS			
Channel Number	Central Wavelength (um)	Bandwidths (microns)	Signal to Noise Ratio
5	1.240	0.020	274
6	1.640	0.020	433
7	2.130	0.050	225
20	3.750	0.180	1098
21	3.750	0.050	12
22	3.959	0.050	649
23	4.050	0.050	746
24	4.465	0.050	161
25	4.515	0.050	510
26	4.565	0.050	499

MODIS THERMAL OR LONG-WAVE INFRARED FOCAL PLANE CHANNELS			
Channel Number	Central Wavelength (um)	Bandwidths (microns)	Signal to Noise Ratio
27	6.715	0.360	272
28	7.325	0.300	498
29	8.550	0.300	1425
30	9.730	0.300	803
31	11.030	0.500	2572
32	12.020	0.500	2085
33	13.335	0.300	431
34	13.635	0.300	340
35	13.935	0.300	295
36	14.235	0.300	201



MODIS-N CALIBRATION MANAGEMENT PLAN BLOCK DIAGRAM COVERING PREFLIGHT AND ON-ORBIT ACTIVITIES INCLUDING MATH MODEL INDEX

HUGHES

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MODIS-N CALIBRATION PLAN

11/91
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Type of Calibration	Source	Mechanism	Aperture	Spectral Bands	Usage Frequency (Max)	Other Comments
Zero Radiance	Space		Full	All	Once per scan line	
Radiometric	Sun	Solar illuminated diffuser	Full	VIS/NIR/SWIR less 8 through 16	Once per orbit	BRDF = 0.18 sr^{-1}
Radiometric	Sun	Solar illuminated diffuser	Full	VIS/NIR/SWIR	Once per orbit	BRDF = 0.018 sr^{-1}
Radiometric & DC Restore	Blackbody	Blackbody	Full	MWIR/LWIR Restore (All)	Once per scan line	
Radiometric	Incandescent source	SRCA spectrally shaped collimator	Partial	VIS/NIR/SWIR	Available any time during orbit	
Spatial Registration	Incandescent source and IR source	SRCA	Partial	VIS/NIR/SWIR MWIR/LWIR	Available any time during orbit	
Spectral (MODIS N)	Incandescent source	SRCA grating monochromator	Partial	VIS/NIR/SWIR	Available any time during orbit	Grating is rotated to produce λ scan
Spectral (monochromator)	Incandescent source	SRCA grating monochromator and filter	Full	0.40 μm ≤ λ ≤ 1.00 μm	Available any time during orbit	Grating is rotated to produce λ scan
Diffuser stability monitor	Sun	SDSM grating spectrograph and fold mirror	Full	0.40 μm ≤ λ ≤ 2.20 μm	Available once per orbit	High BRDF diffuser
Diffuser stability monitor	Sun	SDSM grating spectrograph and fold mirror	Full	0.40 μm ≤ λ ≤ 2.20 μm	Available once per orbit	Low BRDF diffuser

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MODIS-N IN-FLIGHT CALIBRATION CAPABILITY

MODIS-N

11/91
91-0908-807

Appendix
for
MODIS Calibration Status Report
to
Reflected Solar Working Group A
at the
5th Meeting
of the
EOS Calibration and Data Product Validation Panel
of the
EOS Investigator Working Group (IWG)

from
MCST (MODIS Characterization Support Team)

John L. Barker, Head
301/286-9498 or GSFCmail: JBarker
Code 925 - Sensor Development and Characterization Branch
NASA / Goddard Space Flight Center, Greenbelt, Maryland 20771
FAX: (301) 286-9200

Presented by:
Barbara Grant
301/286-2382 or GSFCmail:BGrant
RDC/7855 Walker Drive, Greenbelt, Maryland 20770
FAX: (301) 286-9200

Tuesday, 7 April 1992
The Broker Inn, Boulder, CO

Outline for
MODIS Calibration/ Characterization Plan

1 Introduction
  1.1 MCST Calibration/Characterization Plan Objectives
  1.2 Document Overview
  1.3 Applicable Documents
  1.4 Overview of Instrument Design
  1.5 Single Official Calibration Algorithm
  1.6 Multiple Parallel Approaches
  1.7 Mathematical Model Development
  1.8 Comprehensive Documentation Trail

2 Pre-Launch Calibration/Characterization Methodology
  2.1 Objectives/Rationale
  2.2 Radiometric Calibration
    2.2.1 Absolute Calibration
    2.2.2 Relative Calibration
  2.3 Geometric Characterization
  2.4 Spectral Characterization

3 Instrument Cross-Calibration
  3.1 Pre-Launch Cross-Calibration
    3.1.1 Cross-Calibration Among MODIS Instruments
    3.1.2 Cross-Calibration Between MODIS and Other Instruments
  3.2 In-Orbit Cross-Calibration
    3.2.1 Cross-Sensor/Within Platform
    3.2.2 Cross-Platform/Among Sensors
    3.2.3 Target Related/Aircraft

4 Transfer of Calibration/Characterization from Pre-Launch to In-Orbit using On-Board Calibrators
  4.1 Objectives/Rationale
  4.2 Radiometric Calibration
  4.3 Geometric Characterization
  4.4 Spectral Characterization

5 In-Orbit Radiometric Calibration/Characterization Methodology
  5.1 Objectives/Rationale
  5.2 Instrument-Based Calibration
    5.2.1 Internal Sources/Assemblies
      5.2.1.1 Spectroradiometric Calibration Assembly (SRCA)
      5.2.1.2 Blackbody
      5.2.1.3 Solar Diffuser Panel and Solar Diffuser Stability Monitor (SDSM)
    5.2.2 External Solar
    5.2.3 External Lunar
  5.3 Target-Based Calibration
    5.3.1 Target Related/Ground Reflectance
    5.3.2 Bio-Optical Oceans
  5.4 Image-Related
    5.4.1 External Image-Related Radiometric Rectification
    5.4.2 Class-Specific Scene Equalization

6 In-Orbit Geometric Characterization

7 In-Orbit Spectral Characterization

8 Official MODIS/MCST Calibration Algorithm
  8.1 Objectives/Rationale
  8.2 Minimization of Instrument Systematic Noise Sources
  8.3 MCST Calibration Flow

9 MODIS/MCST Calibration Algorithm Validation and Upgrade
  9.1 Algorithm Correction for Systematic Errors
  9.2 Inclusion of In-Orbit Calibration Information
  9.3 Creation of Calibration Error Images

10 Definitions and References
  10.1 Data Dictionary/Glossary
  10.2 Acronyms
  10.3 Additional References

Outline of MODIS Calibration Handbook

- 1 Introduction
    - 1.1 Overview
    - 1.2 Science Calibration/Characterization Objectives
    - 1.3 Organizations and Responsibilities
    - 1.4 Schedules
- 2 Pre-Launch Calibration/Characterization Methodology
    - 2.1 Objectives/Rationale
    - 2.2 Radiometric Calibration
    - 2.3 Geometric Calibration
    - 2.4 Spectral Calibration
- 3 In-Orbit Radiometric Calibration/Characterization Methodology
    - 3.1 Objectives/Rationale
    - 3.2 Instrument-Based Calibration
    - 3.3 Instrument Cross-Comparison
    - 3.4 Target-Based Calibration
    - 3.5 Image-Related
- 4 In-Orbit Geometric Calibration
- 5 In-Orbit Spectral Calibration
- 6 Offical MODIS /MCST Calibration Algorithm
    - 6.1 Objectives/Rationale
    - 6.2 Algorithm Sensitivity/Simulation Studies
- 7 Definitions and References
    - 7.1 Data Dictionary/Glossary
    - 7.2 Acronyms
    - 7.3 References

Calibration Working Group
MODIS Science Team Meeting
13-16 April 1992

AGENDA

Goddard Space Flight Center
Building 22, Room 365
Monday, April 13, 1992

0830	Phil Slater	Introductions and Introductory Remarks
0845	John Barker	MODIS Characterization Support Team (MCST) Report
0930	Bruce Guenther	MODIS-Related EOS Cal/Val Panel Issues
0945	BREAK	
1000	Jim Young	MODIS-N Instrument Cal/Val Plans Status
1100	John Barker	MODIS Science Calibration Plans
1115	Stuart Biggar	Cross-Calibration Progress, Plans and Concerns
1125	Brian Markham	Simulated MODIS Imagery from TM
1135	Jan-Peter Muller	Modeling of MODIS Sensors
1145	Ken Brown	MODIS Aircraft Simulator (MAS)
1155	Peter Abel	NASA Aircraft-Satellite Instrument Calibration
1205	Bill Barnes	SeaWiFS Instrument Calibration
1215	Phil Slater	Identify Calibration-Related Issues/Action Items
1300	ADJOURN	

AGENDA

MODIS Science Team Calibration Working Group
Goddard Space Flight Center
Building 8, Auditorium
Tuesday, April 14, 1992

1515	Phil Slater	Review Agenda for Meeting
1530	Jim Young	SBRC Proposed Cross-Track Calibrator
1615	Peter Abel	Aircraft/Satellite Cross-Track Calibration
1630	Joann Harnden	Alternatives for Cross-Track Calibration Multi-Year Scene Statistics 90-Degree Observatory Rotation ("MISR" mode)
1645	Phil Slater	Recommendation on Cross-Track Calibration for MODIS Science Team
1715	ADJOURN	

AGENDA

MODIS Science Team **Calibration Working Group**
Goddard Space Flight Center
Building 8, Auditorium
Wednesday, April 15, 1992

0800	Phil Slater	Review Agenda for Meeting Prioritize Calibration Issues
0815	Jim Young	Discussion of Instrument-Related Calib. Issues - Thermal Bands Calibration Accuracy - Lunar Calibration Options - Solar Panel/Door Modification - SRCA Changes and Options - Imbedded Detector Data in Housekeeping Telemetry - Radiometric Math Model - Band-Pass Options
0945	Phil Slater	Identify any Proposed Changes in Requirements
1000	BREAK	
1015	John Barker	Proposed Schedule of Reviews Plans, Instruments, and Calib. Algorithms
1030	Phil Slater	Develop Recomendations for Science Team Proposed MODIS Calibration Peer Review Panel Develop Action Items for MCST, Working Group, etc.
1200	ADJOURN	

AGENDA

MODIS Science Team **Calibration Working Group**
Goddard Space Flight Center
Building 8, Auditorium
Thursday, April 16, 1992

0800 Phil Slater — Review Agenda for Meeting
0810 John Barker — Plans and Options for Cross-Calibration
0820 Stuart Biggar — Pre-Launch Cross-Calibration Options
In-Orbit Ground Validation Experiments
0825 Peter Abel — NASA Aircraft-Satellite Instrument Calibration
0830 Phil Slater — Prioritize Cross-Calibration Issues
0845 Panel Discussion on Cross-Calibration of MODIS with other Sensors

EOSPM/AIRS	Larry Strow	UMBC
EOSAM/ASTER	Hugh Keiffer	USGS
	Akira Ono	JPL
	Phil Slater	U. AZ
NOAA/AVHRR	Phil Slater	U. AZ
SPOT	Phil Slater	U. AZ
CERES	Mike King	GSFC/913
	Bruce Wylicki	LaRC
Landsat TM	Les Thompson	GSFC/925
EOSAM/MISR	Carol Bruegge	JPL

1000 BREAK
1015 Phil Slater — Review Calibration-Related Issues/Action Items
Action Items for MCST and Individuals
Recommendations to MODIS Science Team (MST)
Agenda for Fall Cal Discipline WG Meeting
Input to EOS Cal Meeting October 1992
1130 ADJOURN

MODIS/MCST Feedback Sheet
on MODIS Calibration Handbook and MODIS Characterization/Calibration Plan

Questions ?

Concerns ?

Suggestions ?

Actions for Next Meeting?

Date:

Name:

For E-mail correspondence address GSFCmail:JBarker or BGrant.

For updates on the latest events and available documents, CHECK MCST.BB bulletin board on GSFCmail.

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p. 27

Eos Cross-Calibration Radiometers

Stuart F. Biggar
Remote Sensing Group
Optical Sciences Center
University of Arizona

Presented to:

Calibration/Data Product Validation Panel Meeting
April 7-10, 1992
Boulder, Colorado

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Eos Radiometers

Philosophy

Spectral Coverage

Specific Design

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Philosophy

Portable

Stable

Precise

Accurate

Spectral Coverage

0.4 - 1.0 µm	(Silicon QED)
0.8 - 1.65 µm	(Germanium)
1.5 - 2.5 µm	(cooled Indium Arsenide)
3.5 - 14.5 µm	(cooled Mercury Cadmium Telluride)

Silicon QED

Design Considerations

Fabrication

Data collection/storage

Concerns

Design considerations

- Spectral
  - 0.4 - ~1.0 µm
  - Silicon detectors
    - (3 Hamamatsu S1337-1010BQN)
  - Interference Filter(s)

- Radiometric
  - No optics (other than filter)
  - Precision apertures (2)
  - QED (5 detector surfaces)

- Thermal
  - Temperature control
    - Detector / Amplifier
    - Apertures
    - Filter
  - Material
    - Invar
    - Stainless steel

Fabrication

- Custom built
- Precision tolerances
  - detector alignment
    - position
    - angle
  - aperture
    - centering
    - diameter
    - circularity
    - separation
- Interchangeable detector blocks

Data collection/storage

- Analog outputs
  - Detector voltage
  - Detector temperature
  - Filter temperature
  - "Instrument" temperature

- Digital outputs
  - Filter id number

- Analog/Digital conversion
  - Commercial data logger
    - 17 bit A/D
    - 0.03% accuracy (dcv / 1 year)
    - Rugged, compact (3 kg)
  - Commercial data acquisition hardware
    - 17 bit A/D
    - 0.01% accuracy (dcv / 1 year)
    - Rugged, transportable

- Storage
  - Data logger (and/or)
  - Small MS-DOS computer (RAM card)

Amplifier

- Design
  - Transimpedance configuration
  - low noise FET type OP AMP
  - temperature controlled
    - op amp
    - feedback resistor(s)
  - single or 1 per detector

- Variable gain
  - set by switch
    - or
  - digital io from logger

Concerns

Operating Conditions (vacuum ?)

Radiance levels

Scheduling

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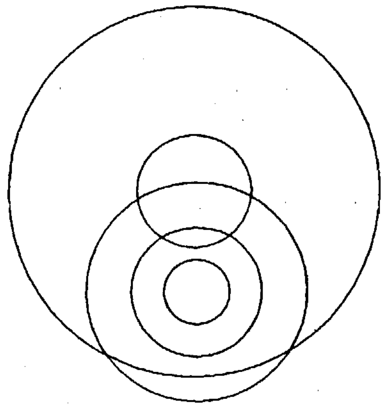
Dimensions are inches



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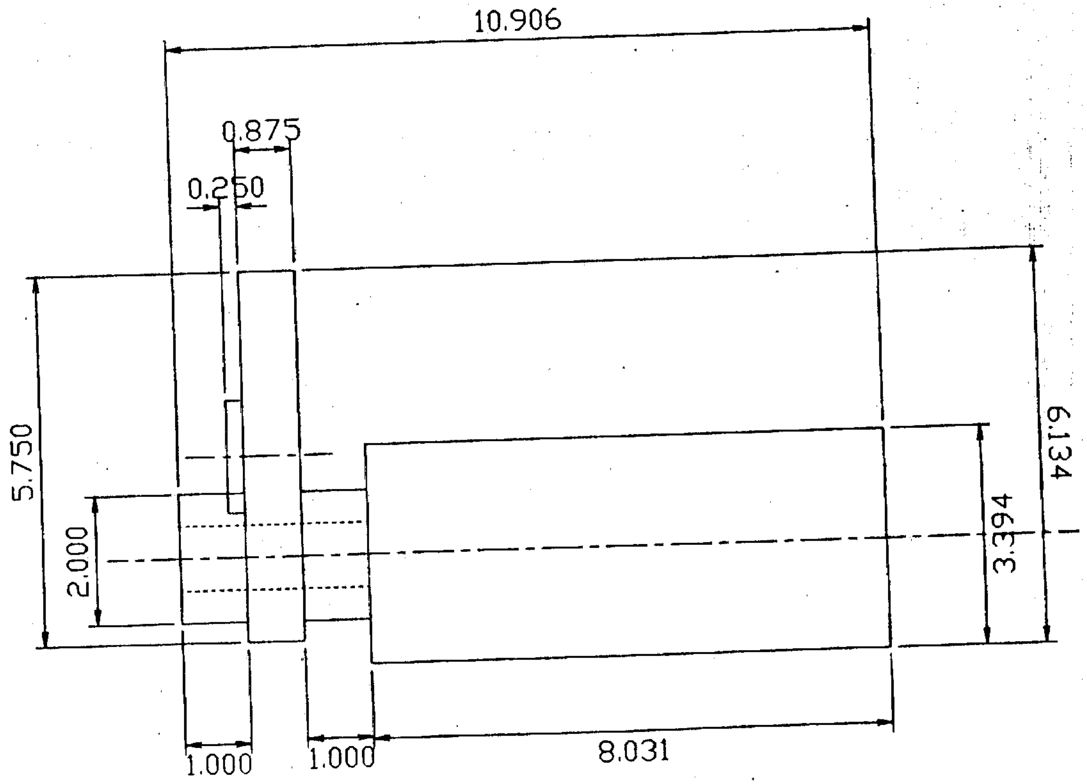


Side

EOS

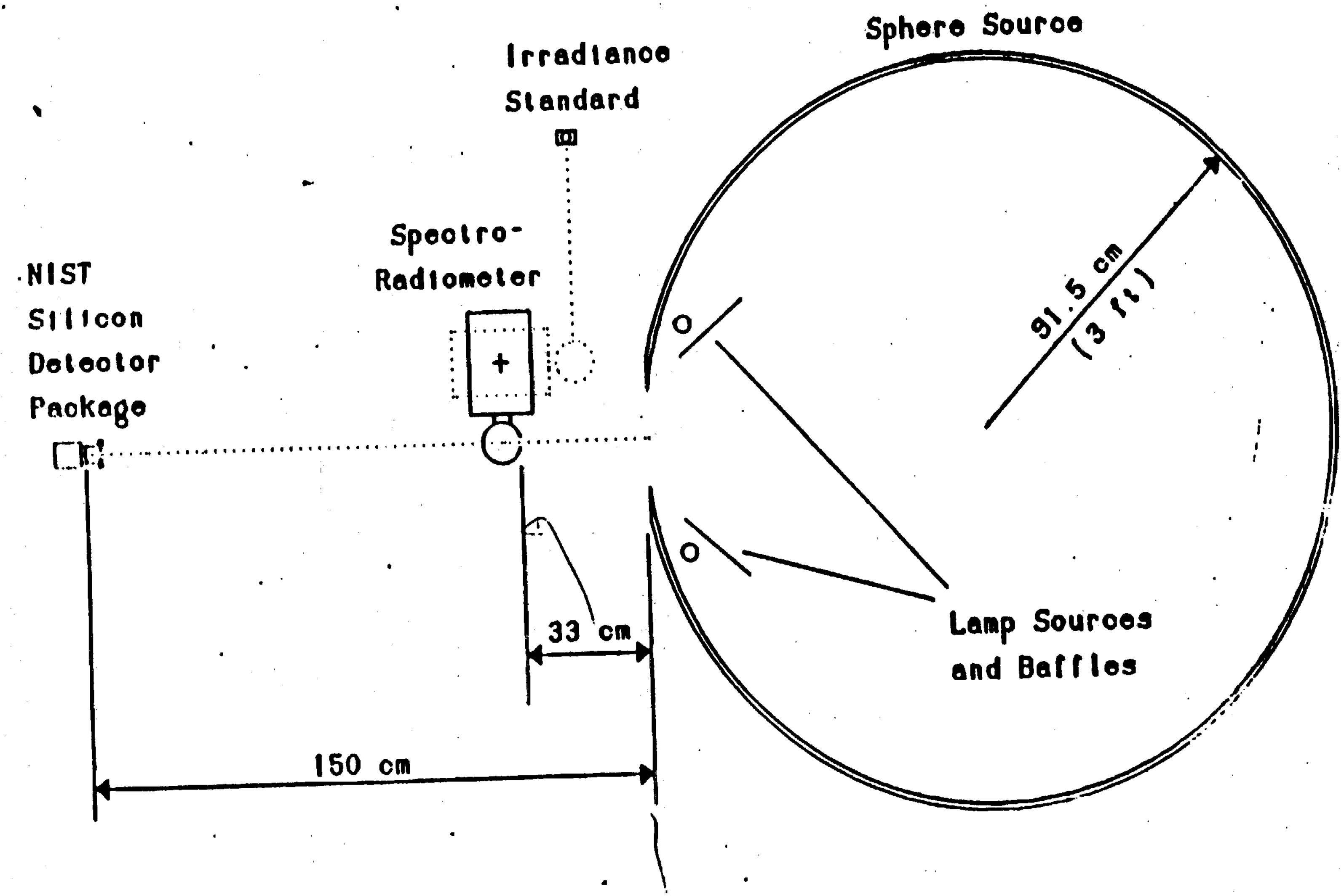
5th Meeting of

Calibration
Data Product Validation
Reflected Solar Group

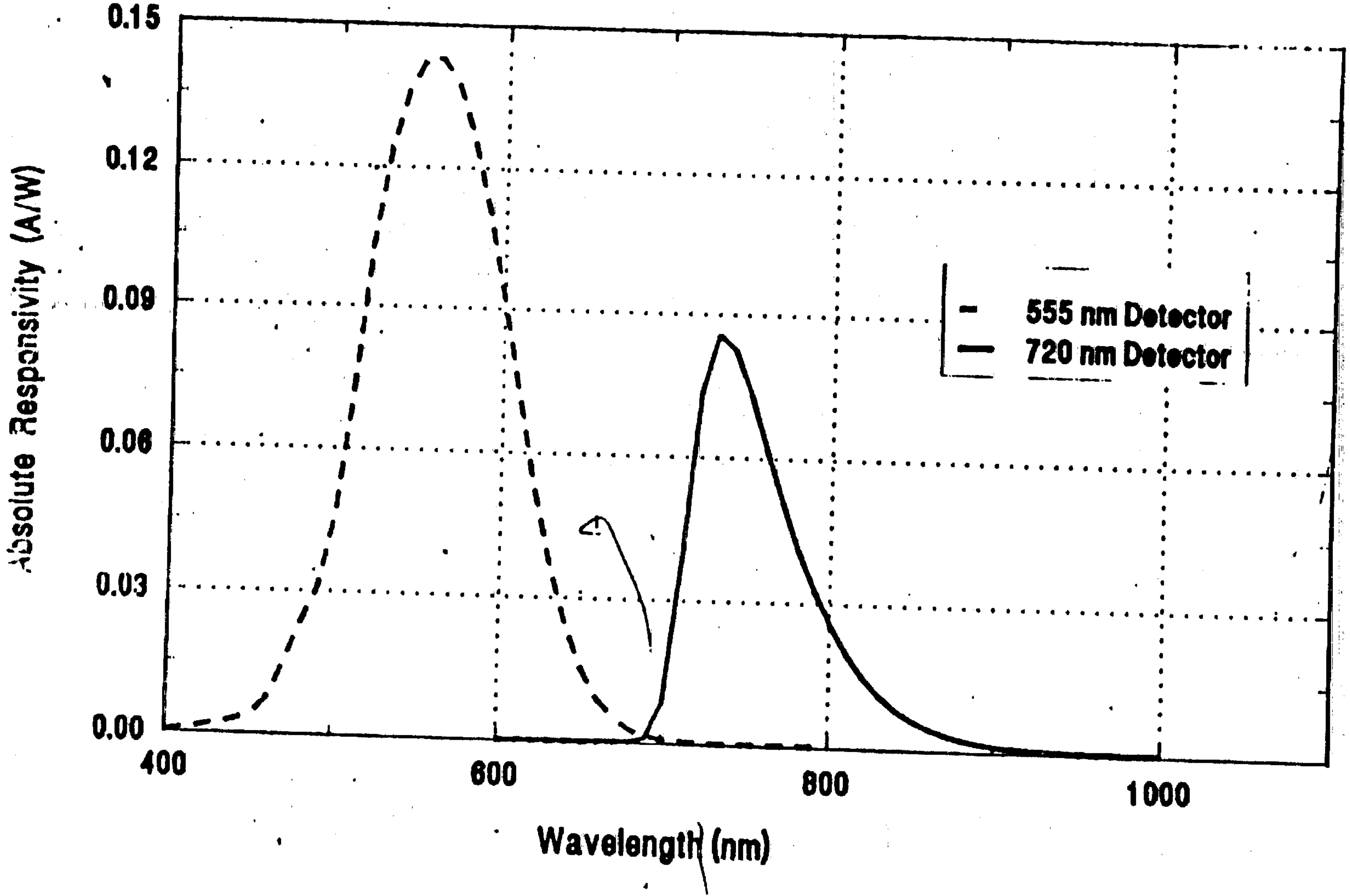
Calibration Source Verification

Dr. Christopher L. Cromer

NASA Goddard Sphere Source Measurement Setup



Spectral Responsivity of Detectors



RESULTS OF NASA SPHERE SOURCE MEASUREMENTS AT NASA

(183 cm diameter sphere with 25.4 cm aperture)

Detector Filter Peak Wavelength (nm)	Source to Detector Distance (cm)	Difference of Predicted Signal from Measured Signal (%)
555	190	-0.2
555	150	-0.1
555	100	-0.1
720	190	-0.4
720	150	-0.2

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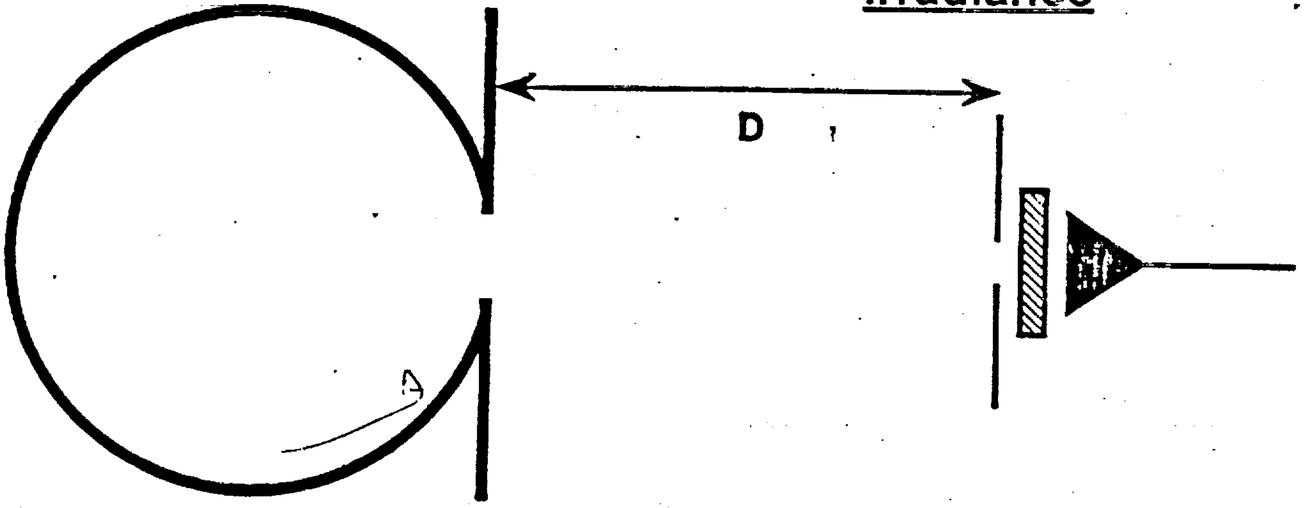
Verification Methods

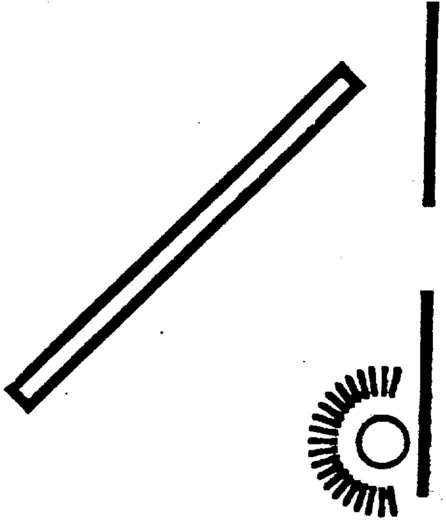
Sources | Radiometers

Sphere Source

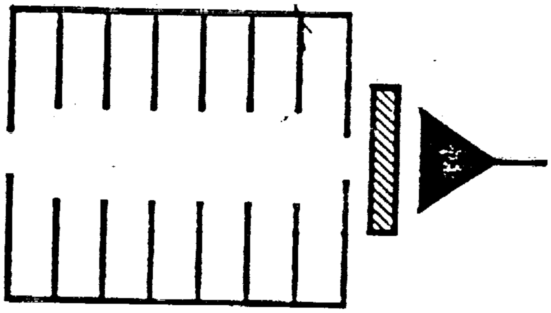
Irradiance



Diffuser Plaque



Radiance



Options

Entrance Optics

- Aperture
- Telescope
- Baffle Tube

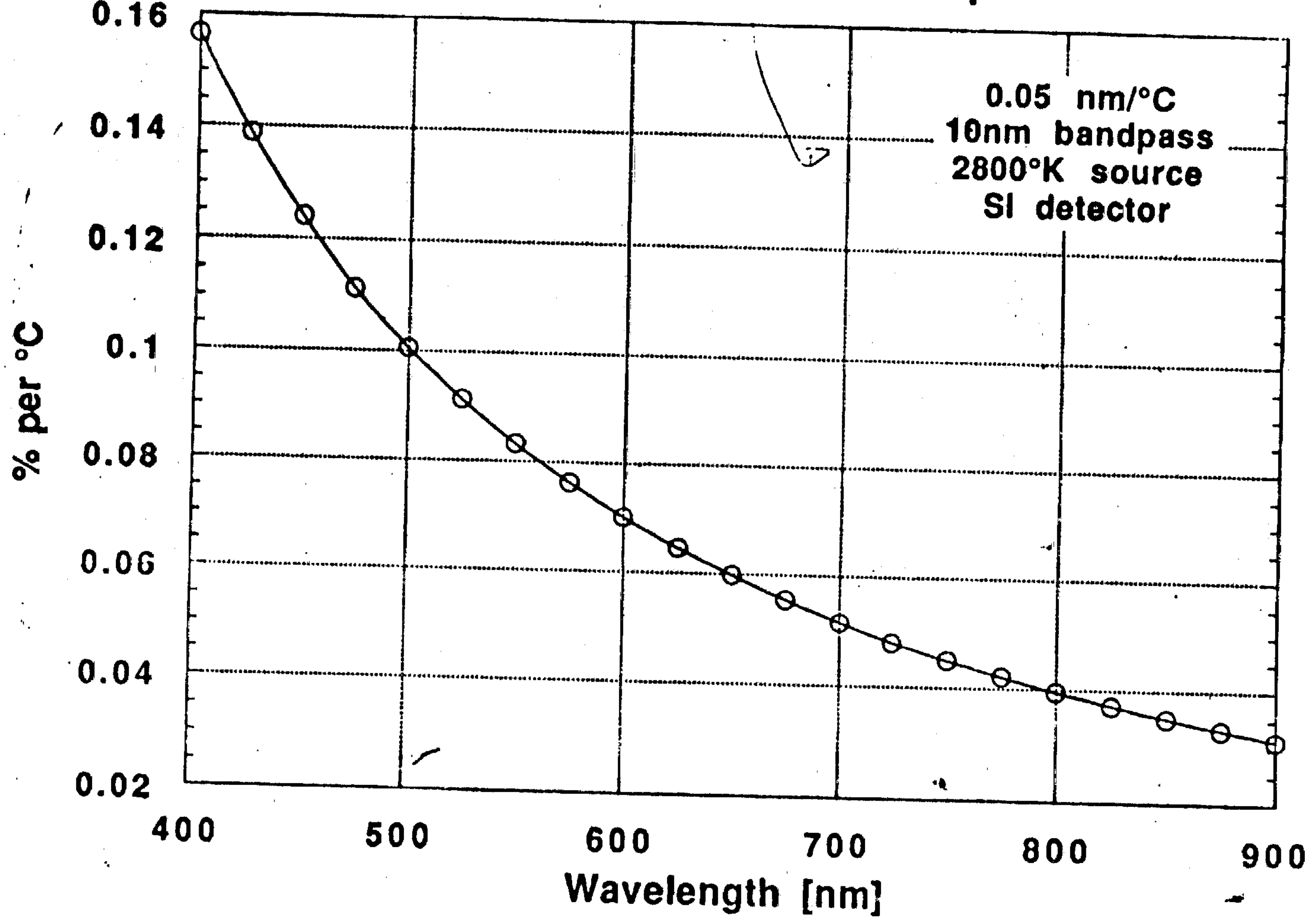
Filters

- Absorbing
- Interference
- Monochromator

Detectors

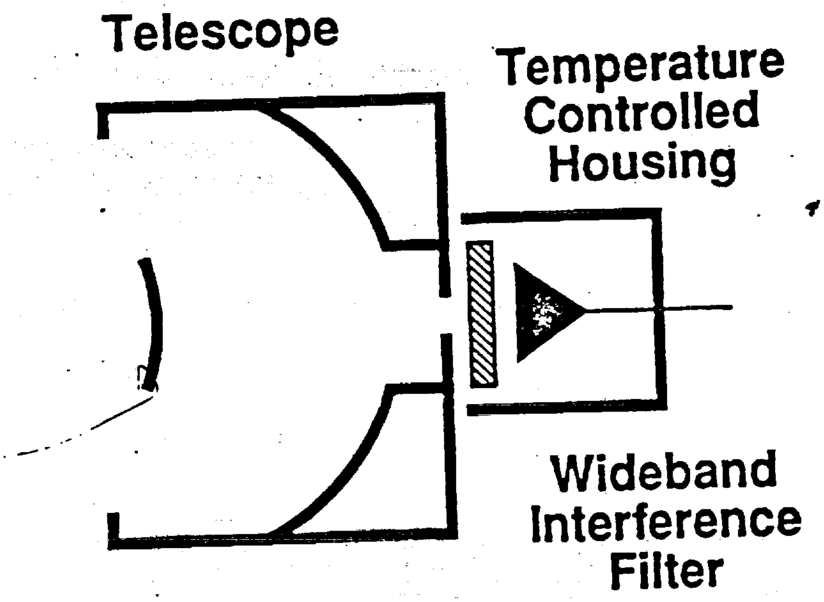
GaP	.2 µm - .5 µm
GaAsP	.2 µm - .7 µm
Si	.2 µm - 1.1 µm
Ge	.9 µm - 1.7 µm
InGaAs	.9 µm - 1.8 µm
PbS	1. µm - 3.3 µm
InAs	1. µm - 3.8 µm
InSb	1. µm - 5.5 µm

% Change in Signal with Temperature

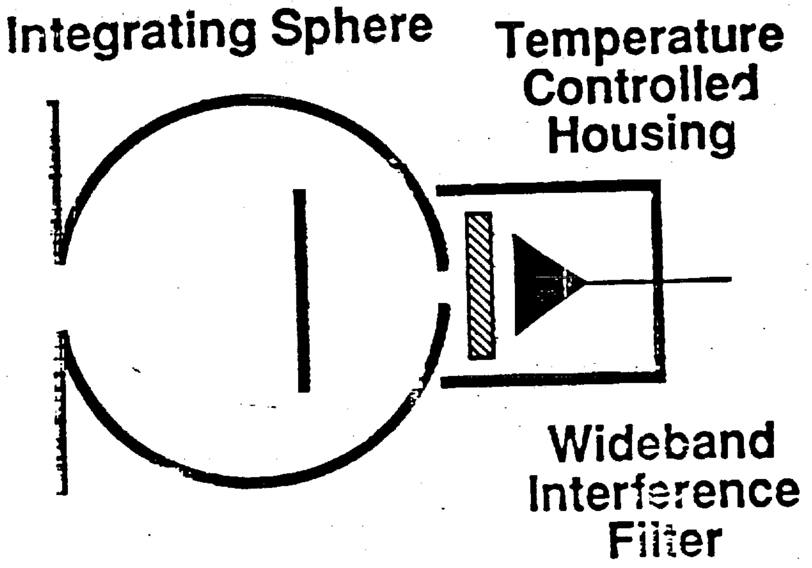


Proposed Geometry

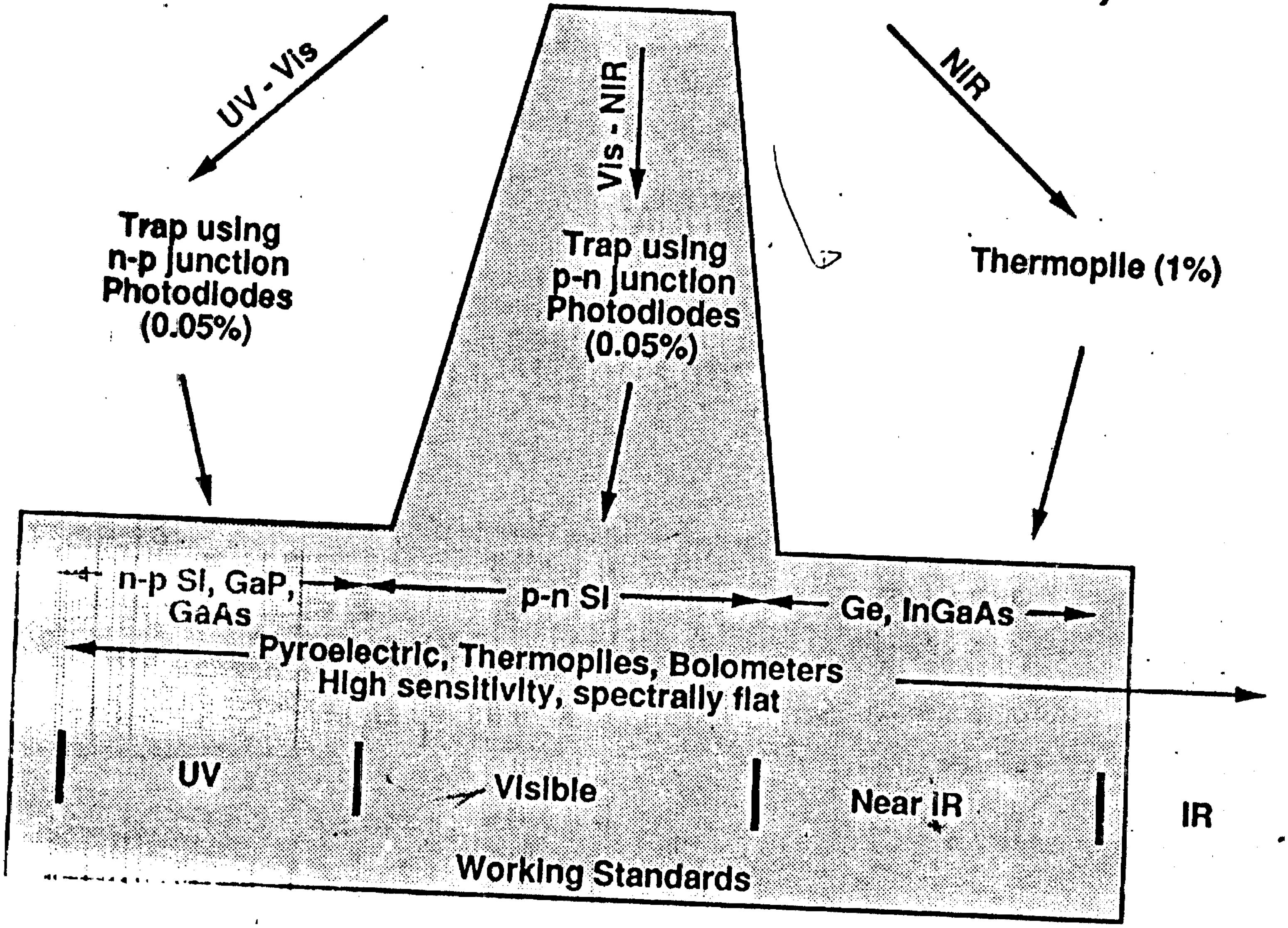
Radiance



Irradiance



Cryogenic Radiometer (0.01%)



UV - Vis

Vis - NIR

NIR

Trap using
n-p junction
Photodiodes
(0.05%)

Trap using
p-n junction
Photodiodes
(0.05%)

Thermopile (1%)

n-p Si, GaP,
GaAs

p-n Si

Ge, InGaAs

Pyroelectric, Thermopiles, Bolometers
High sensitivity, spectrally flat

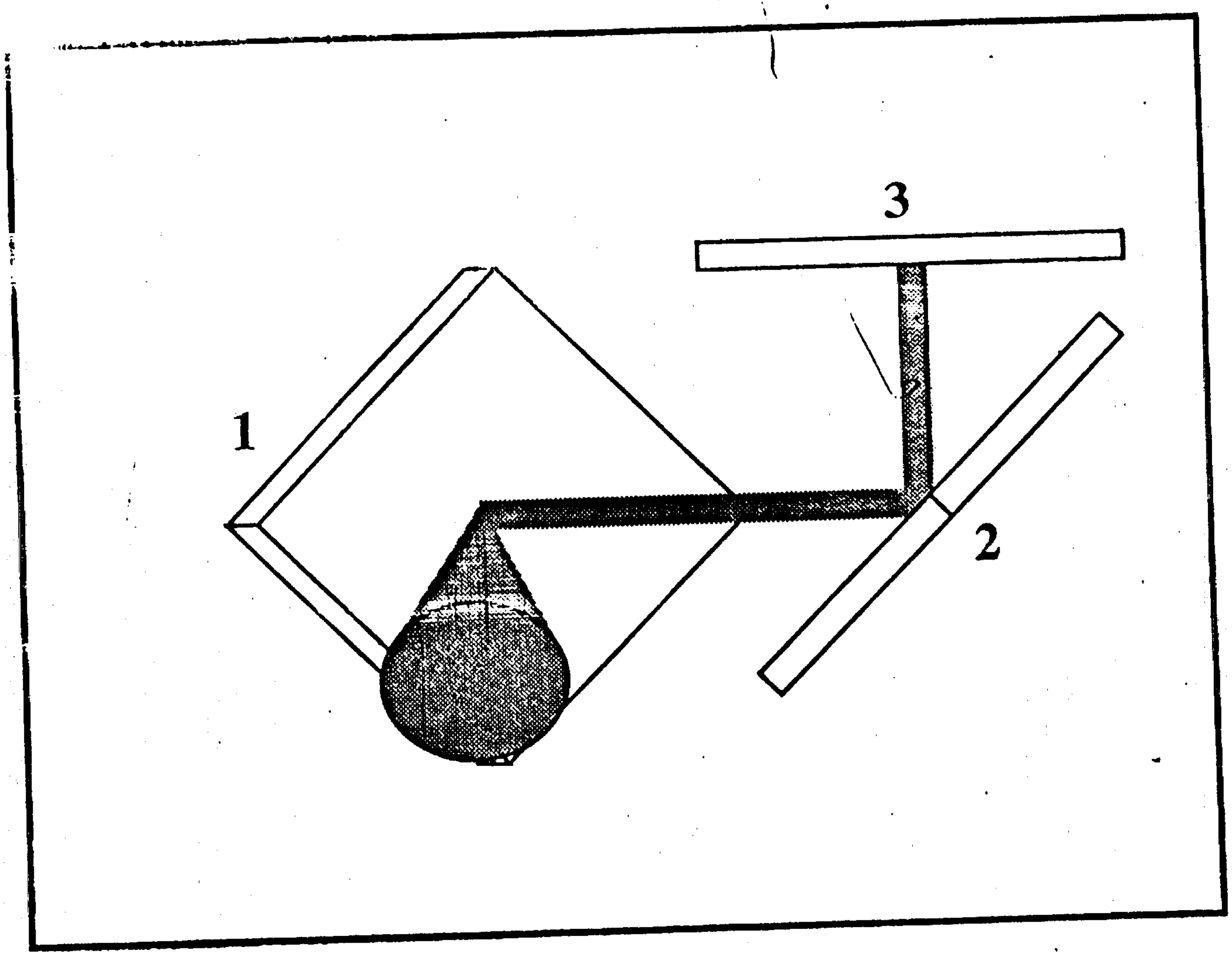
UV

Visible

Near IR

IR

Working Standards



<u>Trap Detector</u>
Arrangement of photodiodes
minimizes light lost to reflections

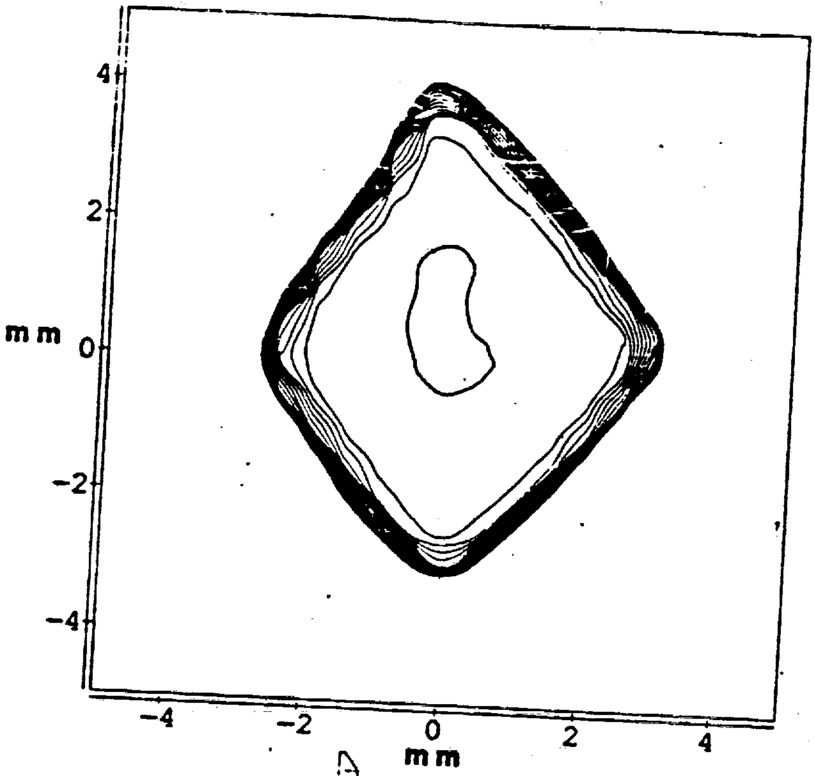


Figure 5a

Response Uniformity of Hamamatsu Trap #3
0.1% contours at 500 nm
1.1 mm resolution

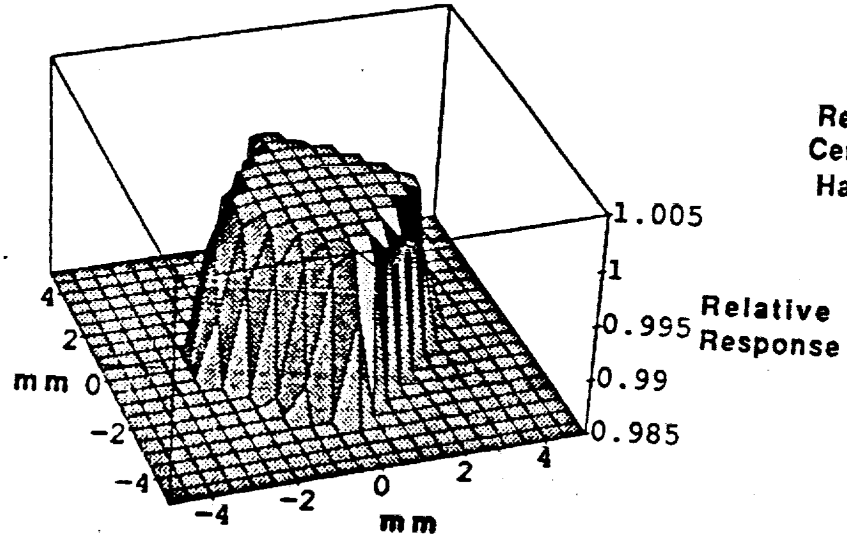
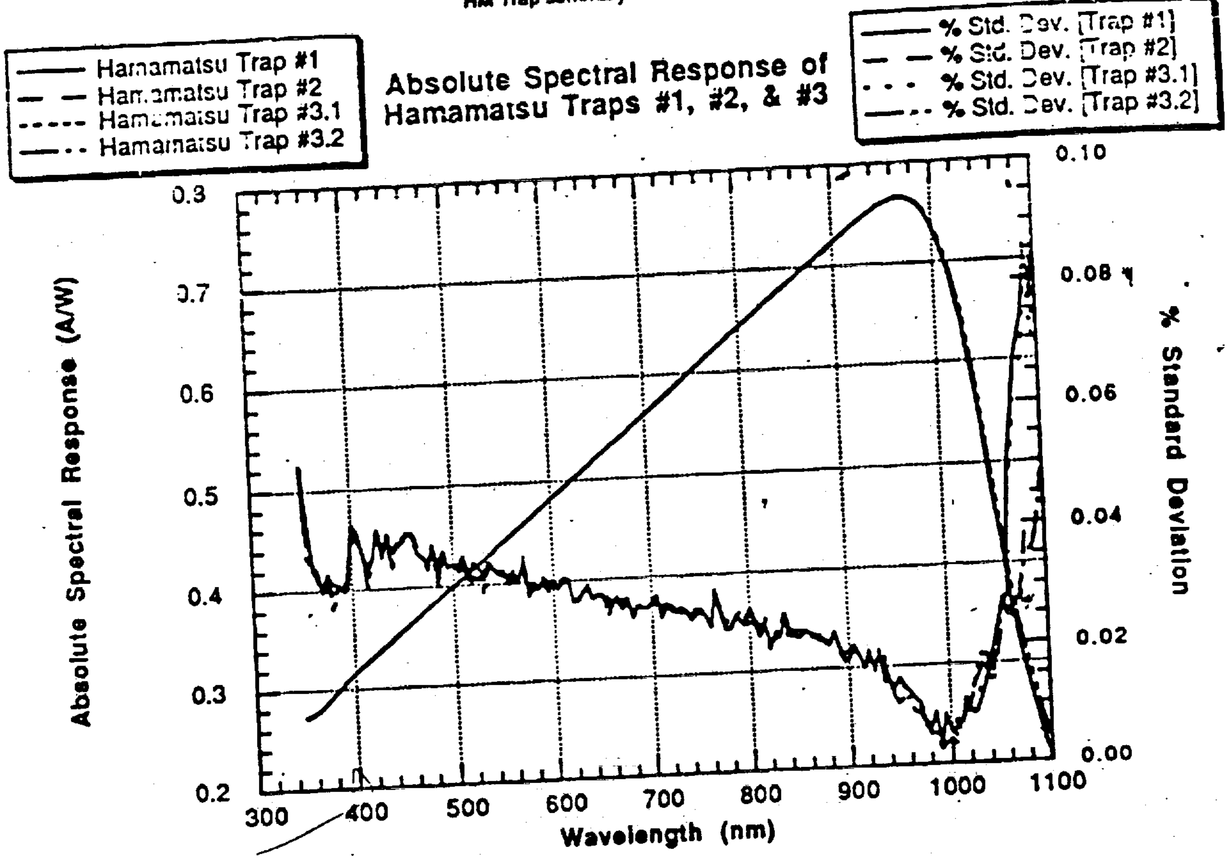


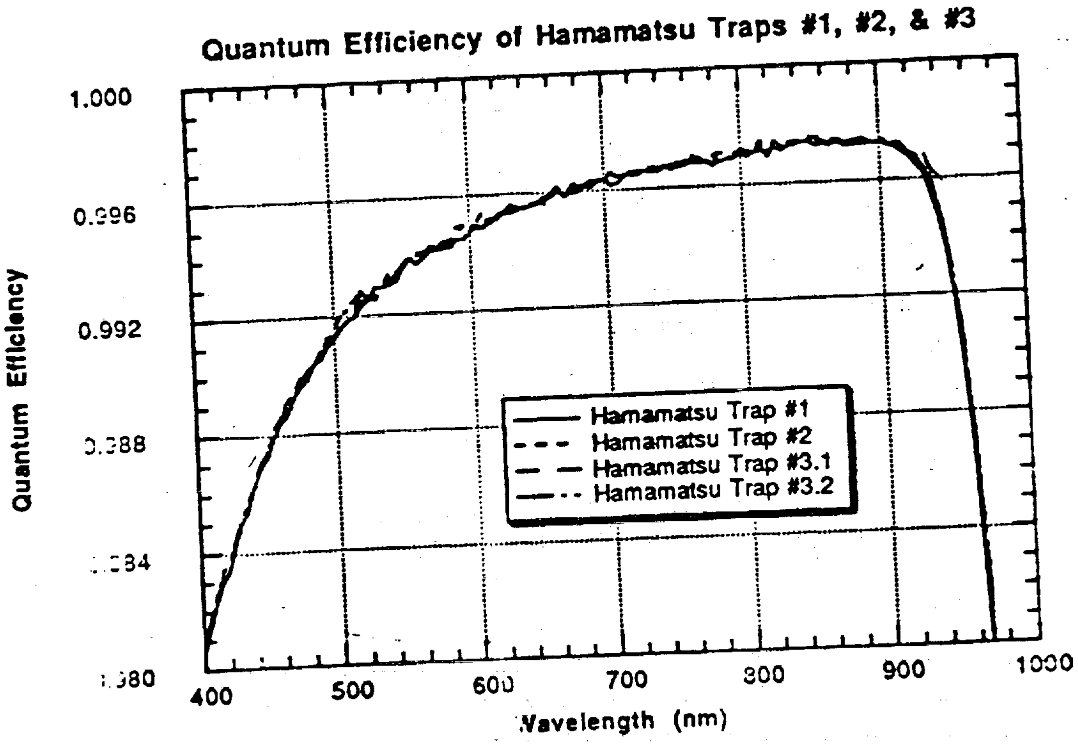
Figure 5b

3D Plot of
Response Relative to
Center of Detector for
Hamamatsu Trap #3

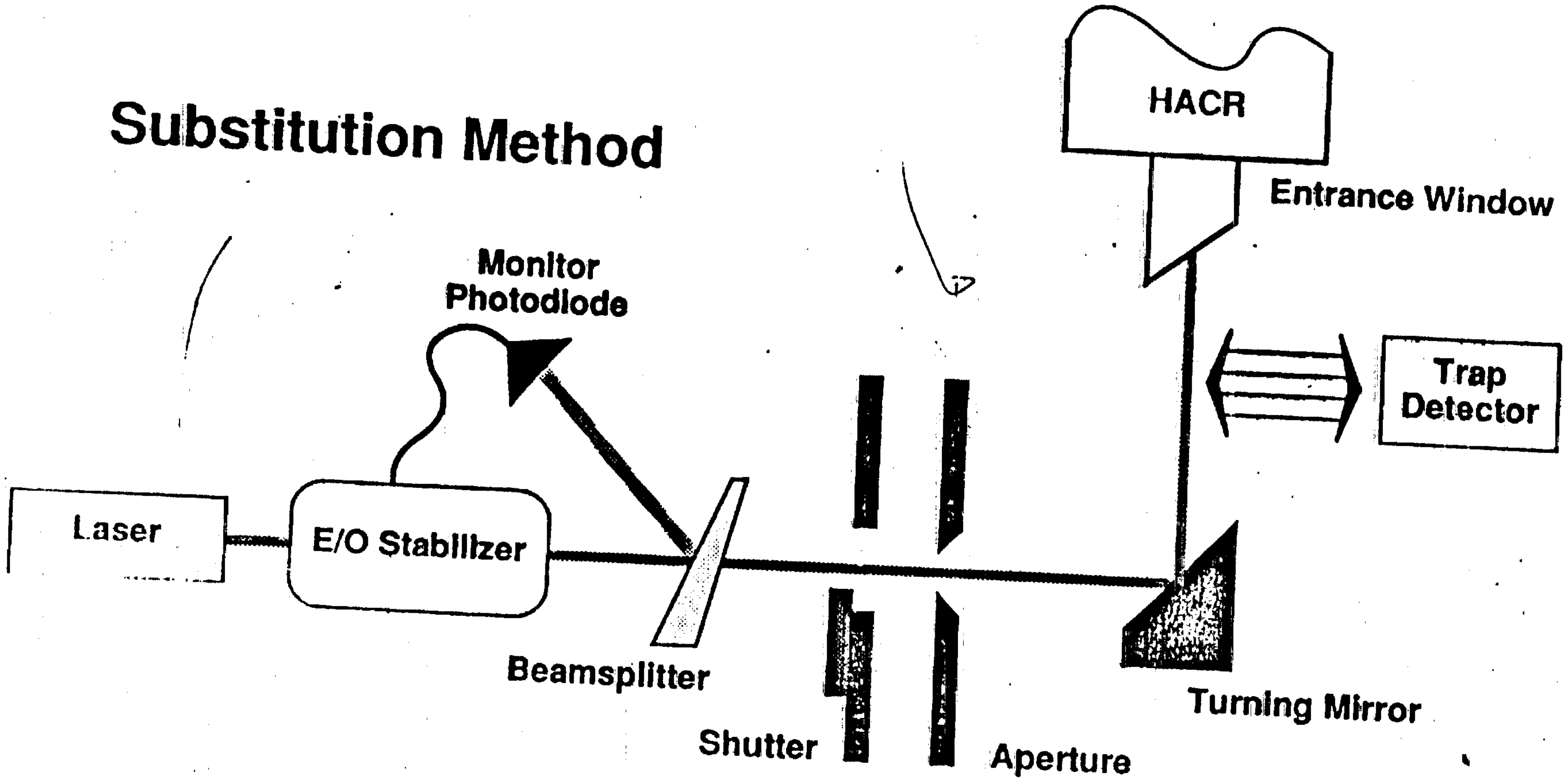
HM Trap summary.abs&%SD.text.11

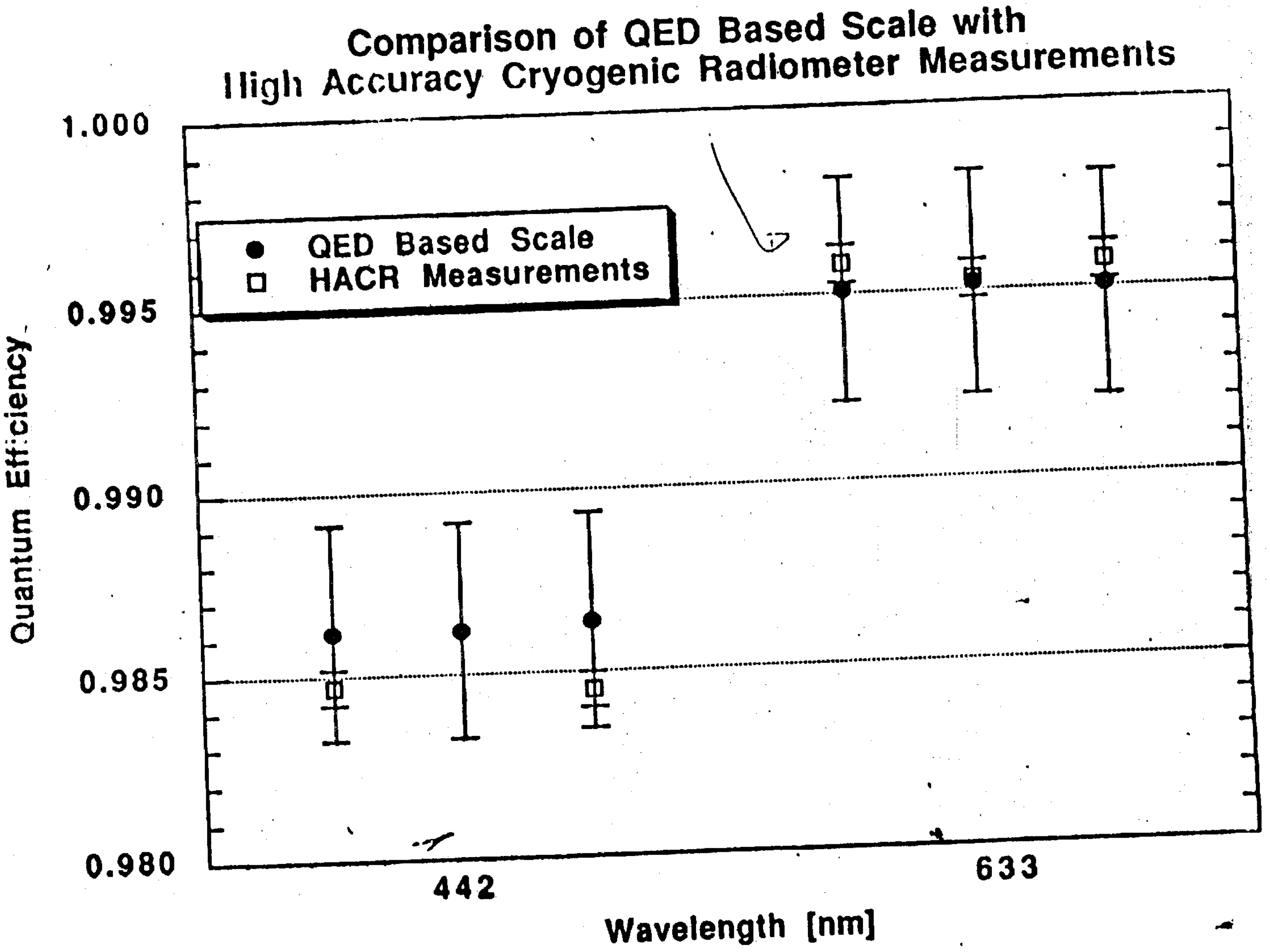


HM Trap summary.abs&%SD.text.11



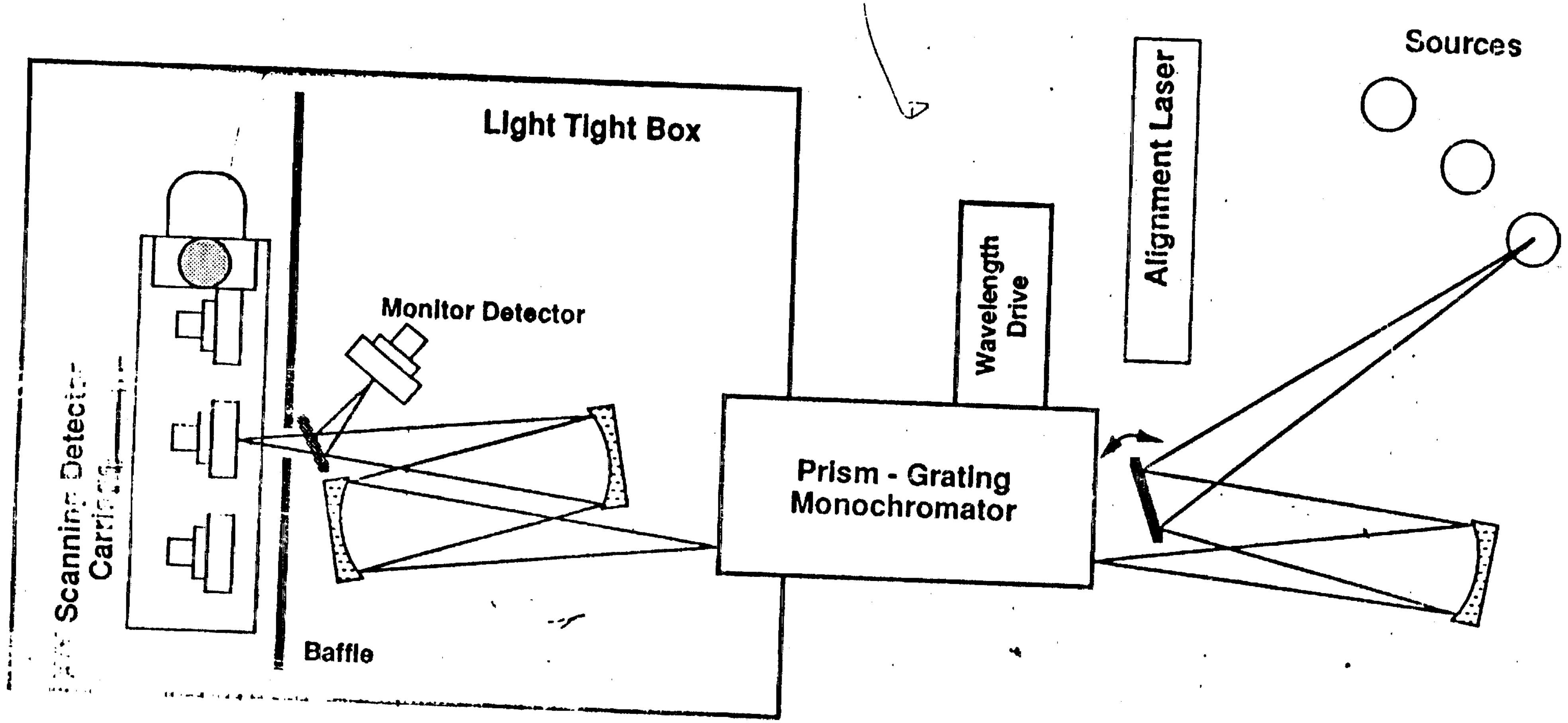
Substitution Method



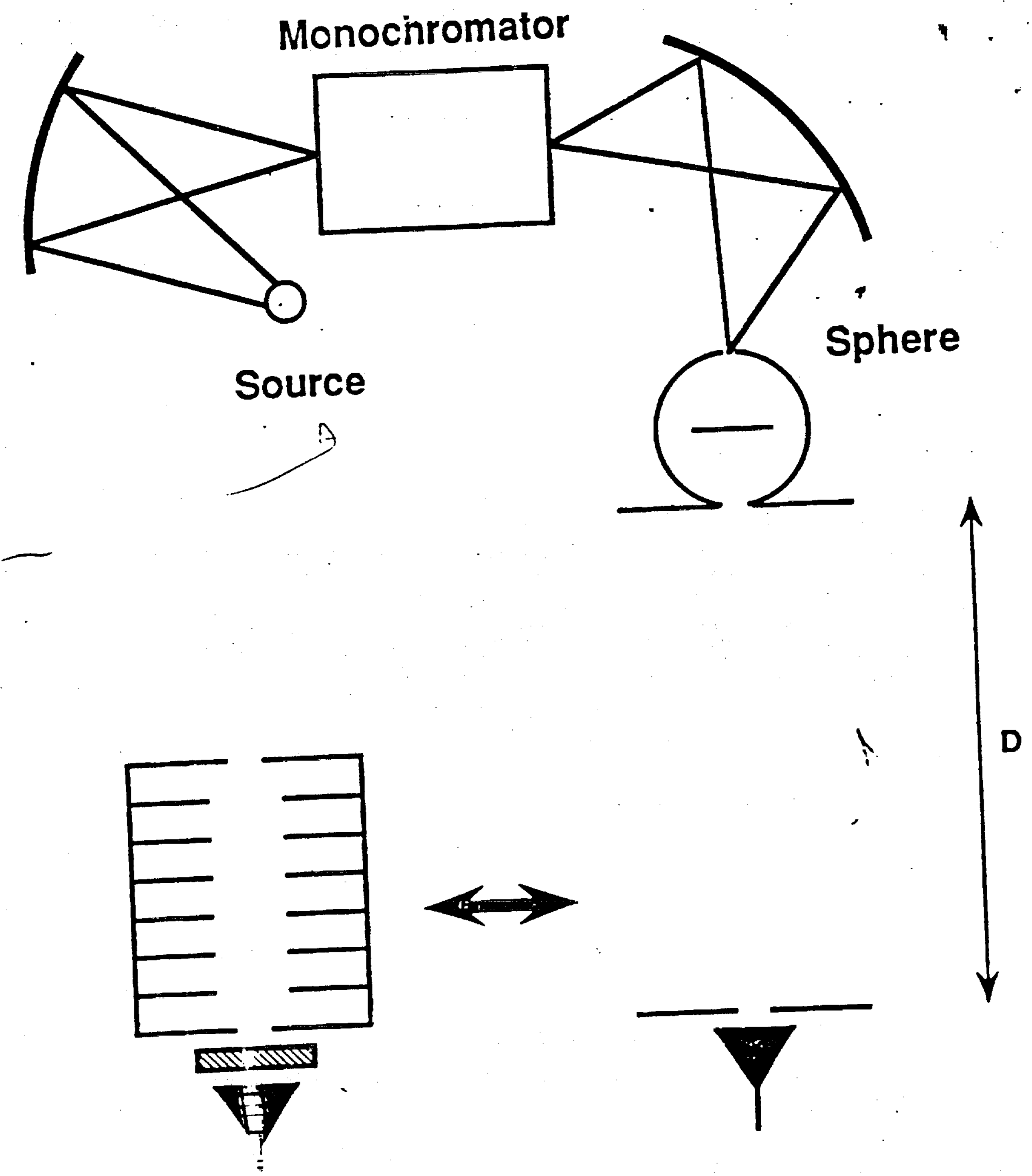


Comparison of QED Based Scale with High Accuracy Cryogenic Radiometer Measurements

Visible / Near IR Detector Comparator Facility



radiance Calibration Method



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Flight solar calibrations using the mirror attenuator mosaic (MAM): Low scattering mirror

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ABSTRACT

Measurements of solar radiances reflected from the mirror attenuator mosaic (MAM) were used to calibrate the shortwave portions of the Earth Radiation Budget Experiment (ERBE) thermistor bolometer scanning radiometers. The MAM is basically a low scattering mirror which has been used to attenuate and reflect solar radiation into the fields of view for the broadband shortwave (0.2 to 5 micrometers) and total (0.2 to 50.0+ micrometers) ERBE scanning radiometers. The MAM assembly consists of a tightly packed array of aluminum, 0.3175-cm diameter concave spherical mirrors and field of view limiting baffles. The spherical mirrors are masked by a copper plate, electro-plated with black chrome. Perforations (0.14 centimeter in diameter) in the copper plate serve as apertures for the mirrors. Black anodized aluminum baffles limit the MAM clear field of view to 7.1 degrees. The MAM assemblies are located on the Earth Radiation Budget Satellite (ERBS) and on the National Oceanic and Atmospheric Administration NOAA-9 and NOAA-10 spacecraft.

The 1984-1985 ERBS and 1985-1986 NOAA-9 solar calibration data sets are presented. Analyses of the calibrations indicate that the MAM exhibited no detectable degradation in its reflectance properties and that the gains of the shortwave scanners did not change. The stability of the shortwave radiometers indicates that the transmission of the Suprasil W1 filters did not degrade detectably when exposed to Earth/atmosphere-reflected solar radiation.

1. INTRODUCTION

The Earth Radiation Budget Experiment (ERBE) is being used to measure diurnal variability in the components of the Earth radiation budget over the entire globe as well as over geographical regions as small as 250 kilometers[1]. The components are the incoming solar radiance, the Earth/atmosphere-reflected solar radiance, and the Earth/atmosphere-emitted radiances. The solar energy absorbed by the Earth/atmosphere system should be equal to the energy lost to space by the process of emission if the system is to be in equilibrium. If the Earth/atmosphere system absorbs more energy than it loses to space, the Earth's temperature will increase until equilibrium is reached. If the Earth/atmosphere system absorbs less energy than it loses to space, the Earth's temperature will decrease. The ERBE measurements have been used to evaluate the magnitude of cloud forcing[2] on the Earth radiation budget.

ERBE has adopted a goal of measuring the components with accuracies approaching 1%. The ERBE mission objectives and scientific goals are described by Barkstrom[3]. The ERBE instrumentation consists of three Earth-viewing, narrow field of view (FOV), scanning radiometers; four Earth-viewing, wide angle, nonscanning radiometers; and an active cavity solar monitor which are located on the NASA Earth

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Radiation Budget Satellite (ERBS) and on the National Oceanic and Atmospheric Administration NOAA-9 and NOAA-10 spacecraft. The ERBS was launched September 5, 1984, while the NOAA-9 and NOAA-10 spacecraft were launched December 12, 1984, and September 17, 1986, respectively. The ERBE radiometers were designed, built, and tested under NASA contract by TRW. The scanning radiometers are described by Kopia[4] while the nonscanning radiometers are described by Luther et al.[5] The solar monitor is described by Lee et al.[6] Calibration results for the scanning and nonscanning radiometers have been presented by Lee et al.[7] and Paden et al.[8], respectively.

In this paper, the solar calibration instrumentation and approaches for the scanning radiometers are described in considerable detail. Emphasis is placed upon evaluating the stability of the MAM solar diffusing plate. Flight and ground MAM calibration measurements are presented and compared.

2. INSTRUMENTATION

The solar calibration instrumentation for the scanning radiometers is the mirror attenuator mosaic (MAM) assembly which consists of baffles and arrays of mirrors which guide the reflected sunlight into the FOV of a radiometer. The shortwave and total scanning radiometers had MAM assemblies. In Fig. 1, the shortwave and total scanner MAM baffle ports are shown in a schematic diagram of the ERBE scanning radiometric package. The telescopes of the shortwave, longwave, and total scanners are shown at the bottom of the package. The longwave radiometer did not have a MAM assembly. The longwave portion of the solar spectrum, less than 0.5% of the total energy, is difficult to measure at the 1% accuracy level. The

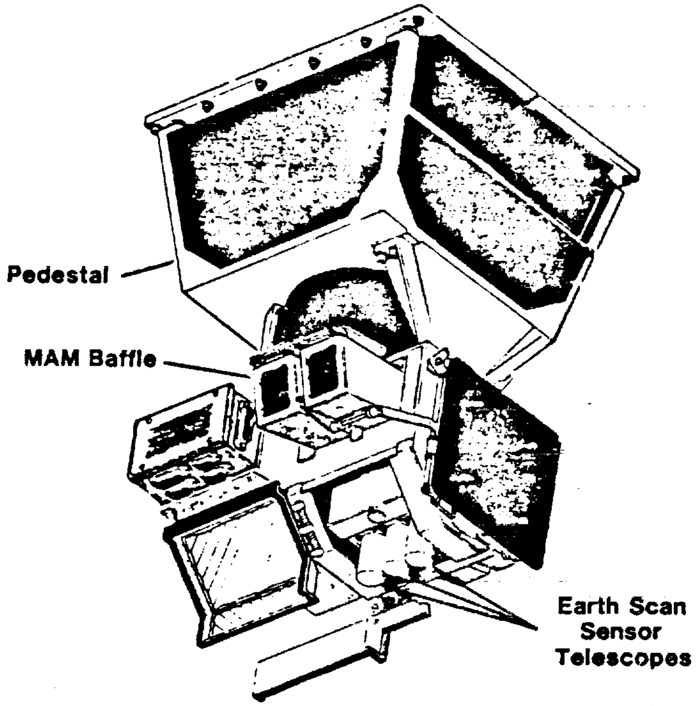

Fig. 1. Earth Radiation Budget Experiment (ERBE) scanning radiometric package.

MAM front entrance ports and baffles are designed to reject direct illumination of the MAM from either the Earth or from emitting/reflecting spacecraft components. The optical axes of the baffles are located approximately 11 degrees below any

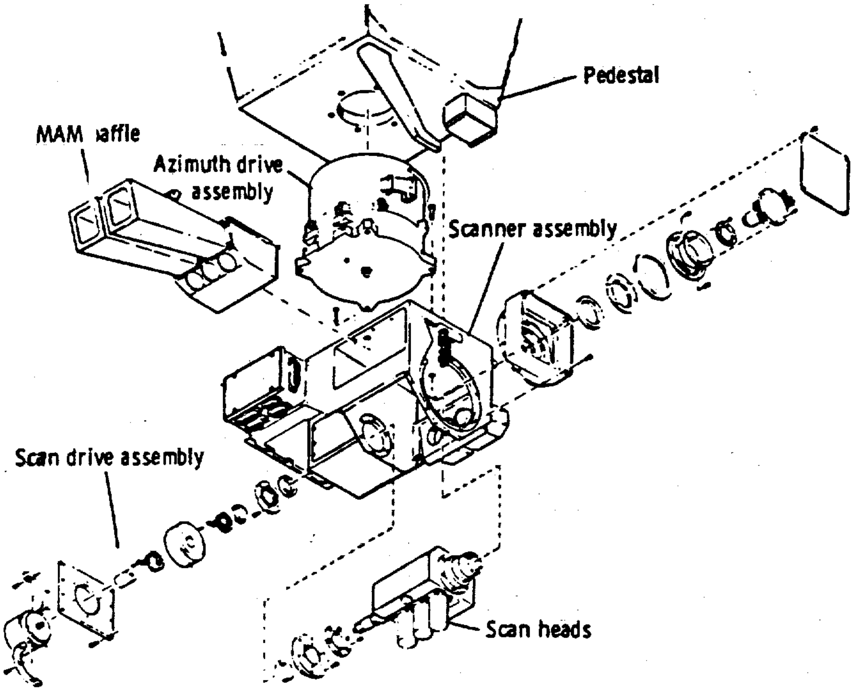

Fig. 2. Exploded diagram of the mirror attenuator mosaic (MAM) assembly.

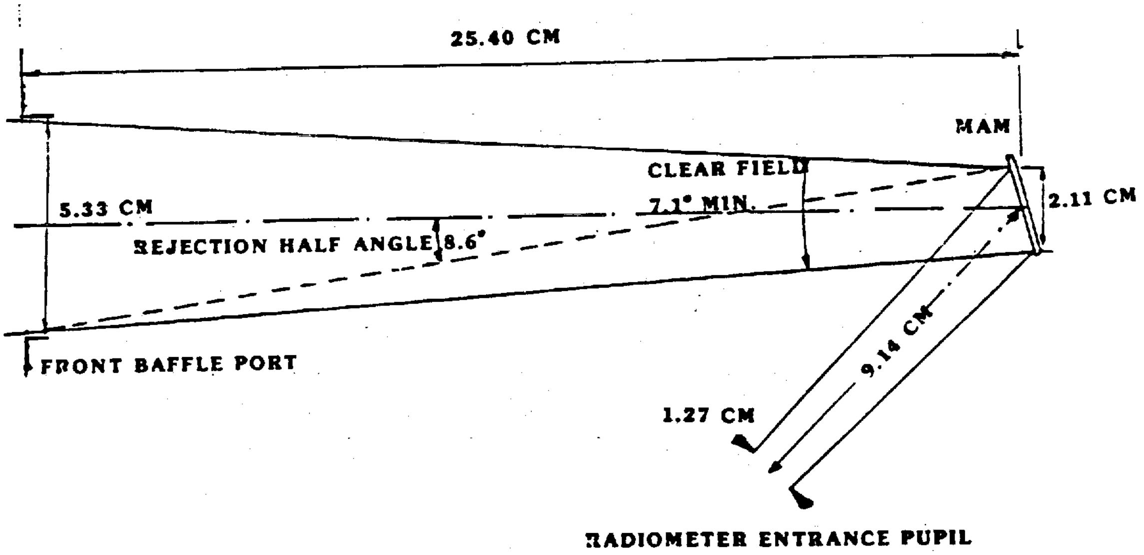

Fig. 3. Elevation view of the MAM assembly.

spacecraft structures. The minimum angle between the spacecraft structure and the Earth's horizon would be 22 degrees at the ERBS orbital altitude. Therefore, the horizon would be 11 degrees away from the optical axes. An exploded diagram of the scanning radiometric package is presented in Fig. 2. The three circular apertures in the MAM assembly permitted the scanning radiometers to view the MAM solar low scattering mirror structure. An elevation view of the MAM assembly is presented in Fig. 3. Each baffle entrance port was 5.33 centimeters (cm) in elevation height and located 25.4 cm from the MAM mirror structure. The normal to the MAM mirror structure was oriented 15 degrees below the optical axis of the baffle. The entrance pupil entrance for each radiometer was located 9.14 cm from the mirror structure. The optical axis of the radiometer was oriented 27 degrees below the normal to the mirror structure. In the elevation plane, each radiometer had an unobstructed, clear FOV of at least 7.1 degrees through the MAM ports. The ports and baffles rejected any external radiances 8.6 degrees below and above the optical axis of the baffle. The FOV of the radiometer was 4.5 degrees and the diameter of its entrance pupil was 1.27 cm.

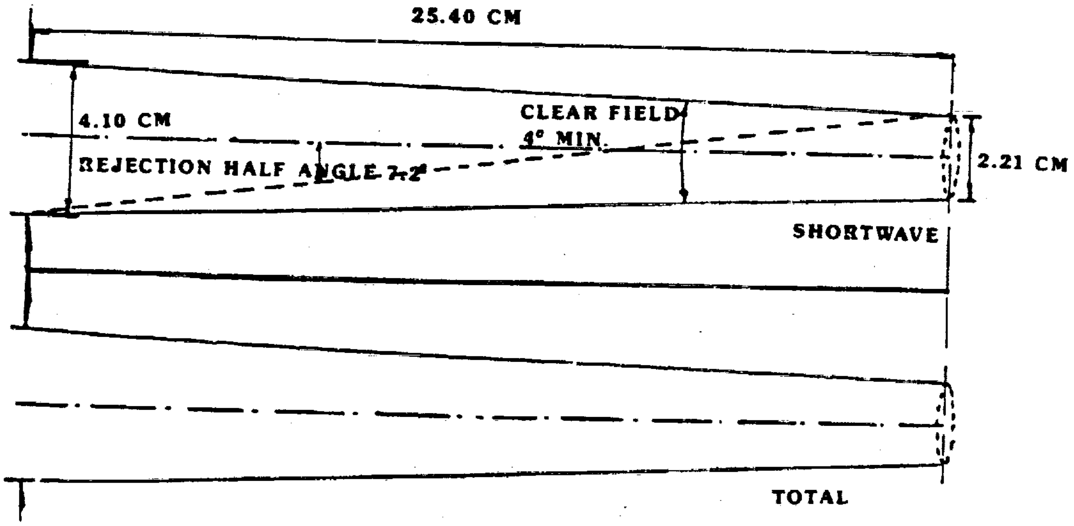

Fig. 4. Azimuthal view of the MAM assembly.

In Fig. 4, an azimuthal view of the MAM assembly shows that the MAM ports were 4.10 cm in azimuthal width. The optical axes of the shortwave and total baffles were 6.604 cm apart. In the azimuthal plane, the radiometers had clear FOV's of 4 degrees. The ports/baffles allowed only external radiances with incidence angles within ± 7.2 degrees of the baffle optical axis to be sensed by the radiometers.

The MAM mirror structure consists of an aperture mask and an array of 101 aluminum spherical mirrors. The aperture mask is made of a copper plate which is plated with a 0.0013 centimeter thick layer of nickel. Black chrome was electro-plated on the nickel layer. The thickness of the copper plate was 0.005 centimeter. The 3.175-cm by 3.175-cm mask had 0.14-cm diameter perforations which covered approximately 16% of mask area. The spherical mirrors were 0.3175 cm in diameter. The perforations served as apertures for the spherical mirrors. In Fig. 5, the geometry of a single-mirror cell is shown. The mirrors were 0.09525 centimeter deep. Incoming external radiances with the full range of incident angles between

6.4 and 23.6 degrees with respect to the mirror normal could be reflected towards the radiometer at a reflection angle of 27 degrees. The clear FOV through the baffles included incident angles between 11.4 and 18.6 degrees. The longwave radiometer sensed radiances which were emitted by the black chrome electro-plated on the copper mask with no perforations. The temperatures of MAM mirror arrays and baffles were monitored using thermistors which were embedded in each baffle and mirror array.

3. MEASUREMENTS

The ERBE scanner solar calibrations are designed to evaluate the stabilities of the shortwave scanner's gain and the shortwave portion of total scanner's gain. The calibration sequence includes observations of space (near-zero radiance source) through the MAM both before and after the observation of the Sun. The Sun is allowed to drift through the baffle FOV and within 0.5 degrees of its optical axis. The differences in scanner output signals which are measured during the solar and space observations are used to define the magnitude of the reflected solar radiance.

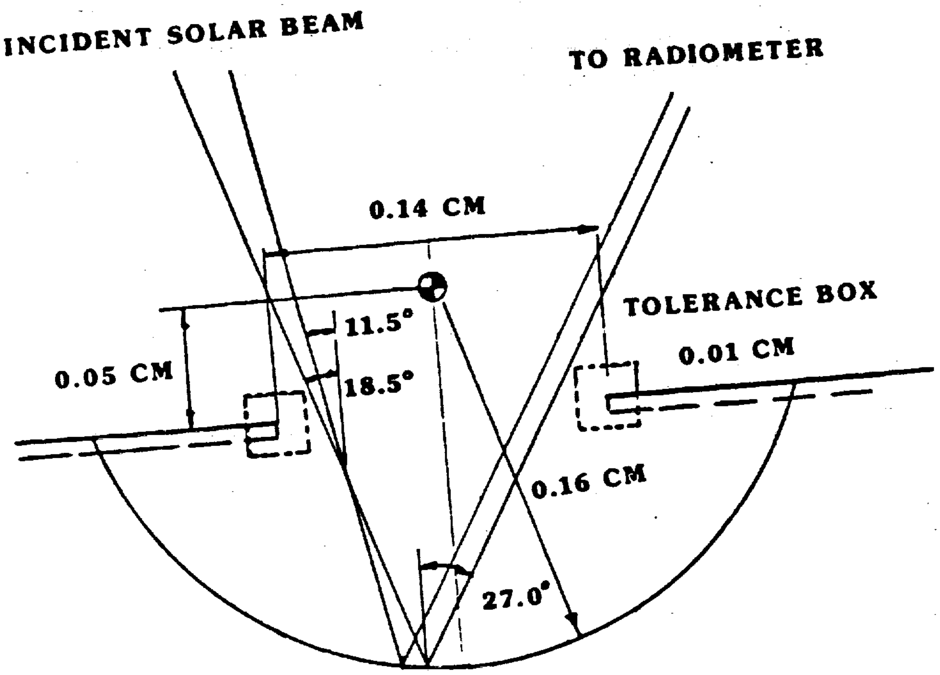

Fig. 5. Geometry of a single spherical mirror cell.

In Fig. 6, the geometry of the solar calibration measurements is illustrated. During the calibration mode, the scanners observed the MAM, the flight internal calibration module (ICM) sources, and space. The ICM sources are blackbodies for the total and longwave radiometers while the shortwave radiometer source was a tungsten lamp which was operated at four different radiance levels, including the lamp-off configuration for zero radiance. During solar calibrations, the ICM sources were not activated. Over each 4 second cycle, 74 data samples were obtained. Eight samples corresponded to reference measurements of space at an elevation angle of 163 degrees while four samples corresponded to measurements of the radiances from the ICM sources at the elevation angle of 190 degrees. The remaining samples corresponded to observations of the MAM at the elevation angle of 233 degrees. The incoming solar radiances with incident angles within ± 8.6 degrees of the baffle optical axis were reflected by the array of MAM spherical mirror cells into the scanners' FOV's. As illustrated in Fig. 6, the baffle optical axis was oriented 15 degrees above the MAM surface normal. During observations of the MAM, the orientation of the scanners' optical axes with respect to the MAM normal was fixed at 27 degrees. The output signals of the scanners were in volts, and the voltages were converted into the International System of measurement units using the equations which are described by Lee et al.[9] and Halyo et al.[10]. The clear FOV of the baffle was calculated to be approximately 7.1 degrees in the elevation direction.

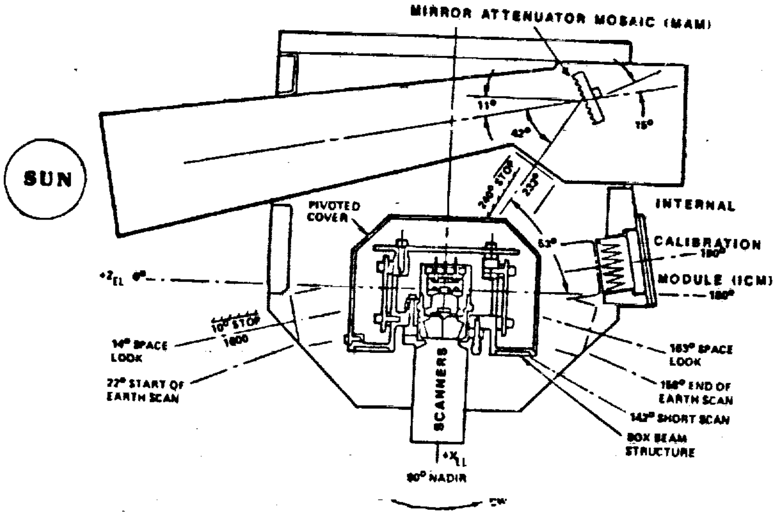

Fig. 6. Solar calibration geometry.

It was 4.0 degrees in the azimuth direction. In the elevation direction, the incident angle for the incoming solar radiances varied from 6.4 to 23.6 degrees. The angles were calculated with respect to the MAM normal. In the azimuthal direction, the incident angle varied from 15.0 to 16.6 degrees.

3.1 Ground calibration facility[12]

Using ground facilities, the MAM assemblies were evaluated to define their fields of view, the attenuation coefficients for the mirror arrays, and the quality of the scanners' gains which were derived from observations of an integrating sphere and a reference blackbody[9]. The attenuation coefficient represents the fraction of the incident shortwave radiance which is reflected by the MAM into the radiometer's FOV and is sensed by the radiometer. The MAM assemblies for the scanners were evaluated in the TRW vacuum calibration chamber[11] which are shown in Fig. 7. The chamber provided a radiometric environment which simulated the orbital conditions.

It was 2.13 meters in diameter and 2.44 meters in length. A 30.5-cm diameter, 5-kilowatt, Xenon lamp was used to simulate the radiances from the Sun. In the figure, the lamp is labeled as the solar simulator, and it was located external to the chamber. Inside the chamber, a space reference source was used to simulate the near-zero radiance of space at the elevation angle of 163 degrees. The simulated space source was a 27.9-cm diameter, grooved blackbody which was maintained at $78^{o}K$ using liquid nitrogen. The ground calibration sequence included observations of the MAM, the ICM, and the simulated space source over a 4-second cycle as described in the preceding section. The scanning radiometric package was mounted to a carousel which rotated in the elevation direction. By rotating the carousel clockwise and counterclockwise, incoming radiances were sensed over an 18-degree incident angle range. The counterclockwise direction was considered to be in the negative angular-elevation direction.

The incident radiance of the Xenon lamp was defined using an electrically calibrated pyroelectric radiometer (ECPR) and a photo solar cell which were located inside the TRW vacuum calibration facility and in the incident beam. Measurements from the ECPR and solar cell established the temporal stability of the incident radiance beam at 0.9% level over a 30-minute period. The spatial uniformity of the beam was found to be 6.7% using the ECPR measurements. During the ground characterizations of the MAM assemblies, only the solar cell was used to define the magnitude of the incident radiances. Therefore, the absolute measurements of the

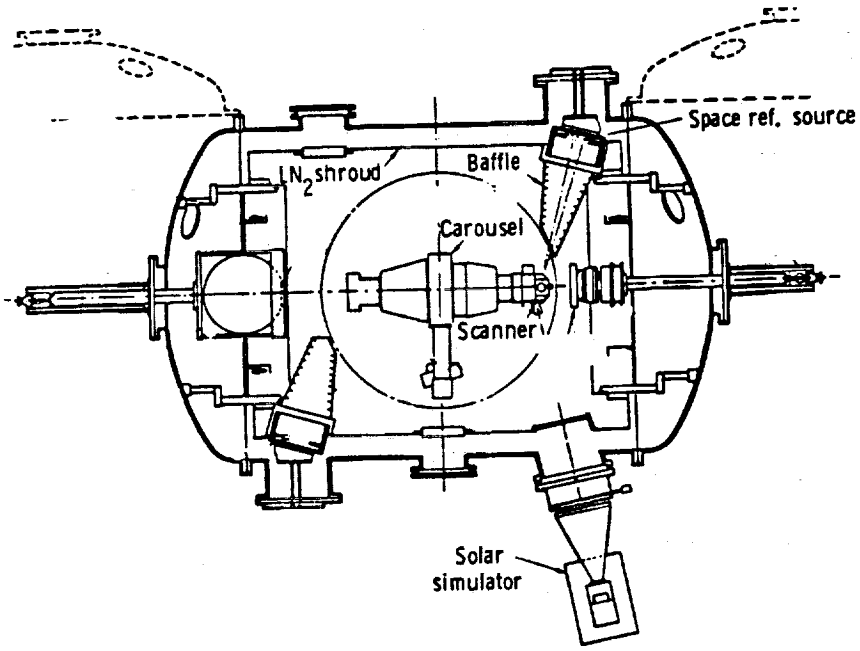

Fig. 7. ERBE vacuum calibration chamber.

ECPR had to be regressed against output voltages from the solar cell in order to calibrate and convert the cell measurements into SI units. The shortwave incident radiances, F_{sw}, were calculated using the following equation

$$F_{sw} = -4810\ (V_{sc})\ Wm^{-2}sr^{-1}mw^{-1} \qquad (1)$$

where V_{sc} is the output of the solar cell in milliwatts(mw). The angular divergence of the beam was measured and found to be less than 0.5 degree.

4. DISCUSSIONS

4.1 Ground calibration results

The solar shortwave reflected radiances should be constant[12] as the incident angle is varied between 11.4 and 18.6 degrees with respect to the normal to the MAM mirror arrays (off-axis angles of -3.6 degrees below and +3.6 degrees above the optical axes of the MAM baffles). The off-axis angle is the angle between direction to the incident radiance beam and the optical axis of the MAM baffle. This angular range represents the calculated, clear FOV interval for the MAM baffles. Therefore, the reflected solar radiances should show no detectable dependence upon the incident angle. In the ground evaluations of the MAM, the resultant measurements indicated that the magnitudes of the reflected radiances varied inversely with the incident angle of the incoming radiances. In Fig. 8, the FOV ground shortwave radiometer measurements exhibit systematic decreases in the reflected radiances of the order of 10% (ERBS and NOAA 9) to 20% (NOAA 10) over the off-axis incident angle interval between -5 to +3 degree range with respect to the baffle optical axis. This range corresponds to angles ranging from 10 to 18 degrees with respect to the MAM normal. In addition, the radiances reflected from both the ERBS and NOAA-9 shortwave MAM assemblies exhibited unexpected dips in the radiance profiles at angles approaching -1 degree, near the optical axes of the baffles. The cause of the dips is unknown. The clear FOV's (off-axis incident angle range from -5 to +3) were found to be larger than the

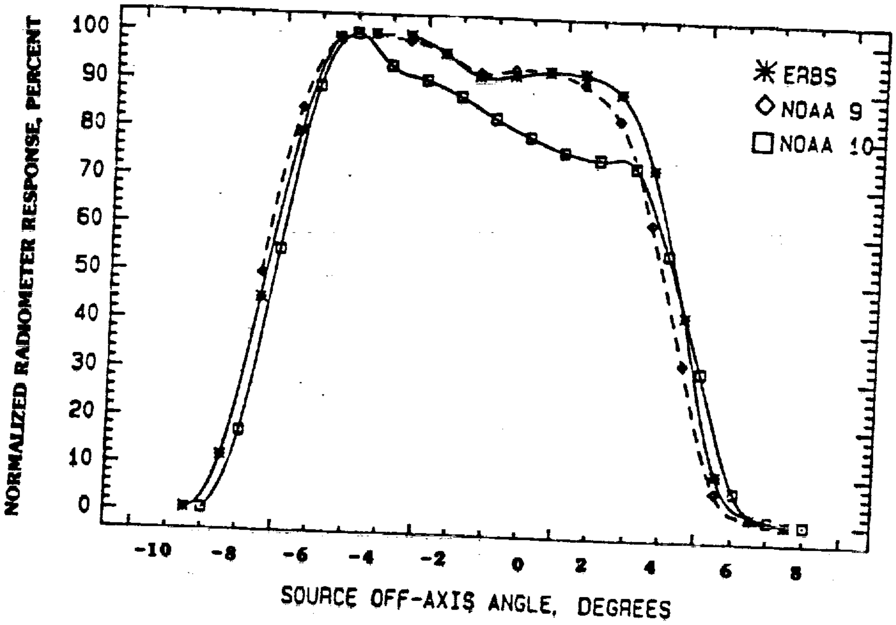

Fig. 8. Ground shortwave radiometer MAM-reflected shortwave radiances plotted against angular distance of incident beam from the optical axis of the MAM baffle.

calculated -3.6- to +3.6-degree range. The FOV cut-off angles of -9 and +8 are in agreement with the calculated ones of -8.6 and +8.6. The NOAA-9, ERBS, and NOAA-10 FOV tests were conducted on May 6, 1983, November 20, 1983, and February 18, 1984. In addition to the FOV tests, the attenuation coefficients for the shortwave radiometer MAM's were derived. The May 6, 1983, tests of the NOAA-9 scanners indicated that the MAM for the shortwave radiometers had an attenuation coefficient of 21.05% in the direction of the radiometer. The magnitude of the incident radiance from the Xenon lamp was found to be at the 426.1 $Wm^{-2}sr^{-1}$ level, according to the solar cell measurements. The magnitude of the incident radiances was calculated using Eq. 1. The shortwave radiometer sensed 89.7 $Wm^{-2}sr^{-1}$. The November 20, 1983, tests of the ERBS scanners yielded 20.00% for the shortwave radiometer MAM attenuation coefficient. The solar cell indicated that the magnitude of the incident radiances was at the 385.5 $Wm^{-2}sr^{-1}$ level. The shortwave radiometer measured 77.1 $Wm^{-2}sr^{-1}$. The February 12, 1984, tests of the NOAA-10 scanners yielded 20.67% as the attenuation coefficient for the shortwave MAM. The solar-cell measurement yielded the magnitude of the incident radiance at the 397.7 $Wm^{-2}sr^{-1}$ level. The shortwave radiometer measured the reflected radiances from the MAM at the 82.2 $Wm^{-2}sr^{-1}$ level.

The total radiometers measured not only the shortwave radiances which were reflected from the MAM's, but also the longwave radiances which were emitted and reflected by the MAM's. Therefore, the longwave components had to be subtracted from the total measurements in order to define the MAM reflected shortwave components. For the ground measurements, the longwave components were derived from the total radiometer MAM observations with the shortwave source absence from the MAM FOV.

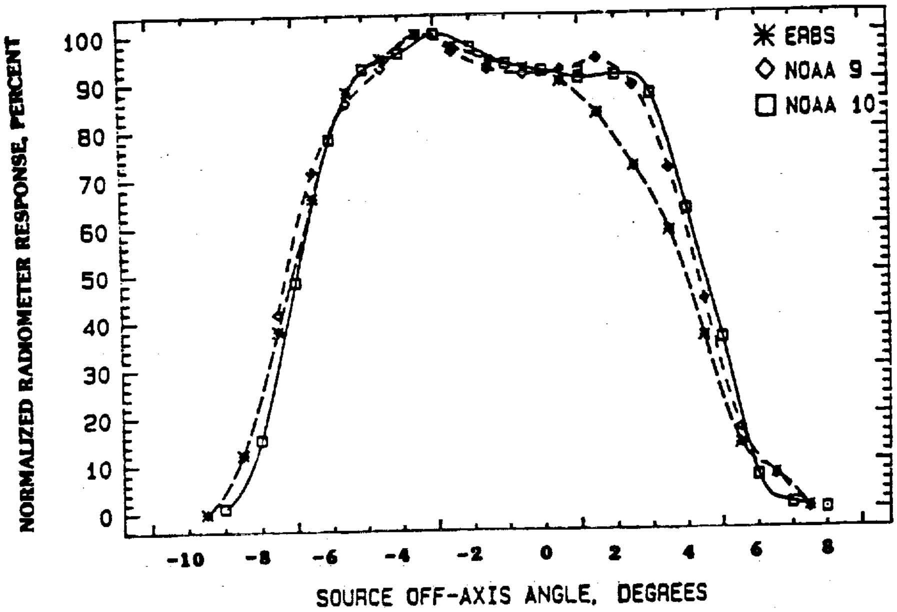

Fig. 9. Ground total radiometer MAM-reflected shortwave radiances plotted against angular distance of incident beam from the optical axis of the MAM baffle.

In Fig. 9, the total radiometer FOV measurements are presented for the same days as those for the shortwave radiometers measurements. Similar to the shortwave radiometer results, the total radiometers measurements indicated that the magnitudes of the shortwave reflected radiances varied with the off-axis incident angle. The ERBS measurements did not exhibit the dip in the reflected radiance profile which was observed in the shortwave data. The absence of the ERBS dip might have been caused by the use of a constant longwave component which might have been varying during the periods when the shortwave source was in the MAM FOV. The total NOAA-10 measurements exhibited a dip which was not present in the shortwave measurements. The measured, clear FOV's were found to be larger than the calculated ones and to lie between -5 and +3 degrees as in the cases of the shortwave radiometer MAM's. In Fig. 9, the cut-off FOV angles were found to be -9 and +8 degrees, similar to the cases of the shortwave radiometer FOV measurements.

4.2 Flight solar calibrations

Scanner solar calibrations were conducted once every 14 days during a single orbital revolution on a Wednesday. The ERBS calibrations were conducted during the November 20, 1984, through October 16, 1985, period while the NOAA-9 calibrations were conducted for a longer period of time from February 20, 1985, through December 24, 1986. The NOAA-10 calibration was limited to a single observation which occurred on November 12, 1986. The NOAA-9 calibrations were limited to a 2-year period because the scanning mechanism failed[13] on January 21, 1987. The ERBS and NOAA-10 solar calibrations were discontinued in order to prevent the scanning mechanisms from failing in the solar calibration mode[13]. The NOAA-10 and ERBS scanning radiometers failed May 1989 and February 1990, respectively.

The scanner automated solar calibration sequence[4] was divided into three measurement periods. Each period was slightly less than 7 minutes in duration. In each of the periods, the radiometers observed the MAM mirrors, space, and the ICM during each 4-second scan cycle as described Section 3. In the first period, the radiometers observed space (near-zero radiance source) through the MAM at an azimuthal "A" position where the Sun could not drift into the MAM baffle FOV's and where the Sun could not be observed directly by the radiometers at the reference space position, elevation angle of 163 degrees. In the second period, the radiometers were rotated to an azimuthal position "B" where the Sun could drift through the baffle FOV's and its radiances could be reflected by the MAM mirrors into the radiometers' FOV's. In the final period, the radiometers were rotated back to azimuthal position "A" where near-zero radiances from space could be observed in the solar-calibration scan mode.

The off-axis incident angles were calculated from the ephemerides of the Sun and spacecraft and from the alignments of the MAM baffle axes with respect to the spacecraft axes. The uncertainty in the angular calculations has been estimated to be less than 0.1 degrees.

In Fig. 10, flight shortwave radiometer solar radiances which were reflected by the MAM's are presented. The radiance measurements exhibited the same trends with varying incident angle as was observed in the ground shortwave radiometer measurements. The flight and ground radiance profiles have the same FOV angular ranges. They both exhibited the same qualitative changes in intensity with the source off-axis angle. However, the dip which was observed in the NOAA-9 ground measurements was not found in the flight measurements. In Fig. 11, flight shortwave solar radiances are presented which were measured using the total radiometers. The flight measurements exhibited a stronger variability with the off-axis incident angle than the ground measurements exhibited.

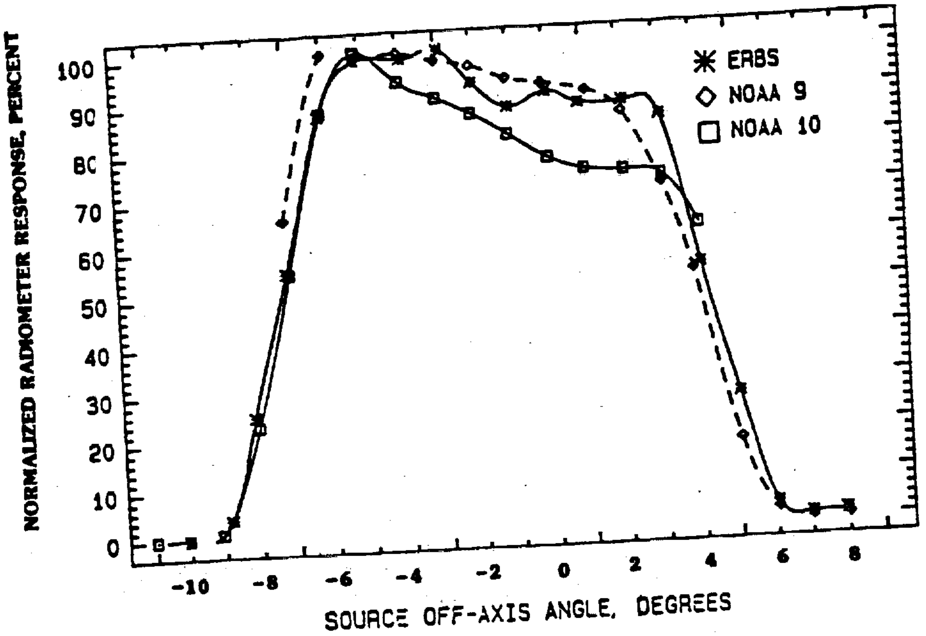

Fig. 10. Flight shortwave radiometer MAM-reflected solar radiances plotted as a function of angular distance of incident beam from the MAM baffle optical axis. In

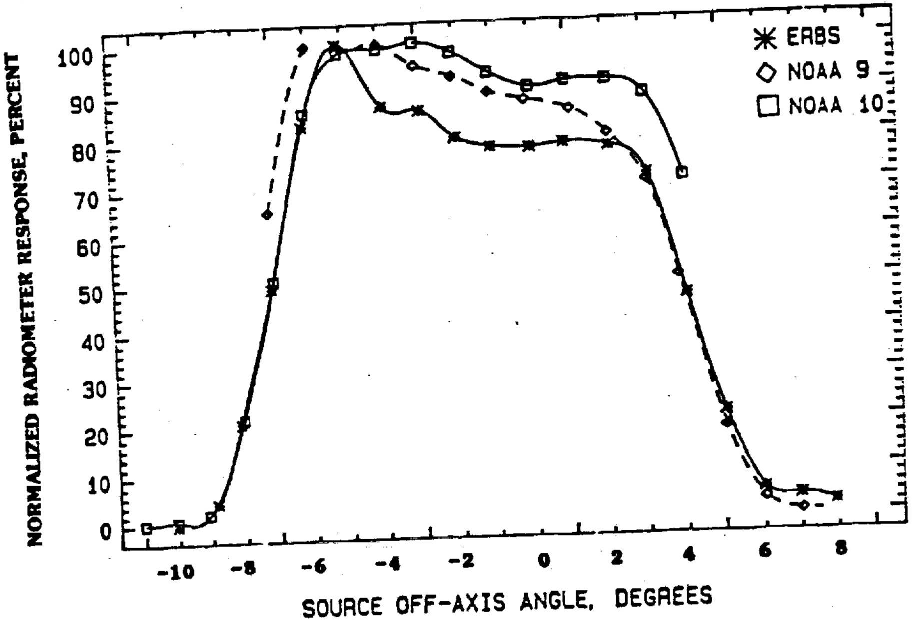

Fig. 11. Flight total radiometer MAM-reflected solar radiances plotted against angular distance of the incident beam from the optical axis of the MAM baffle.

In Fig. 12, ERBS solar calibration measurements are presented for the November 20, 1984, through October 16, 1985, period. The change in the reflected solar radiance is presented as a function of time. The reflected solar radiance values were normalized to the mean Earth/Sun distance. The November 20, 1984 measurements provided the reference by which the changes in the gains of the shortwave and total radiometers were evaluated. For the total radiometer, changes are indicative of changes in the shortwave portion of the radiometer's gain and not changes in the longwave gain. The corrections for the emitted and reflected longwave components from the MAM were derived from least squares analyses of the total radiometer measurements of the MAM with no shortwave source present and the corresponding temperatures of the baffle and MAM mirror array. During the October 1984 through December 1989 period, the incident solar radiance, normalized to the mean Earth/Sun distance, was found to be essentially constant within 0.1%[14,15] using the ERBE solar monitors. The shortwave radiometer data set indicated that the shortwave gain was stable to within ±2% during the 11-month period. The scatter in the data was primarily caused by variability in the radiances as a function of incident angle, as was illustrated in Figs. 8 through 11. Most of the scatter in the Fig. 12 would not be present if the magnitude of the reflected radiances did not vary with incident angle.

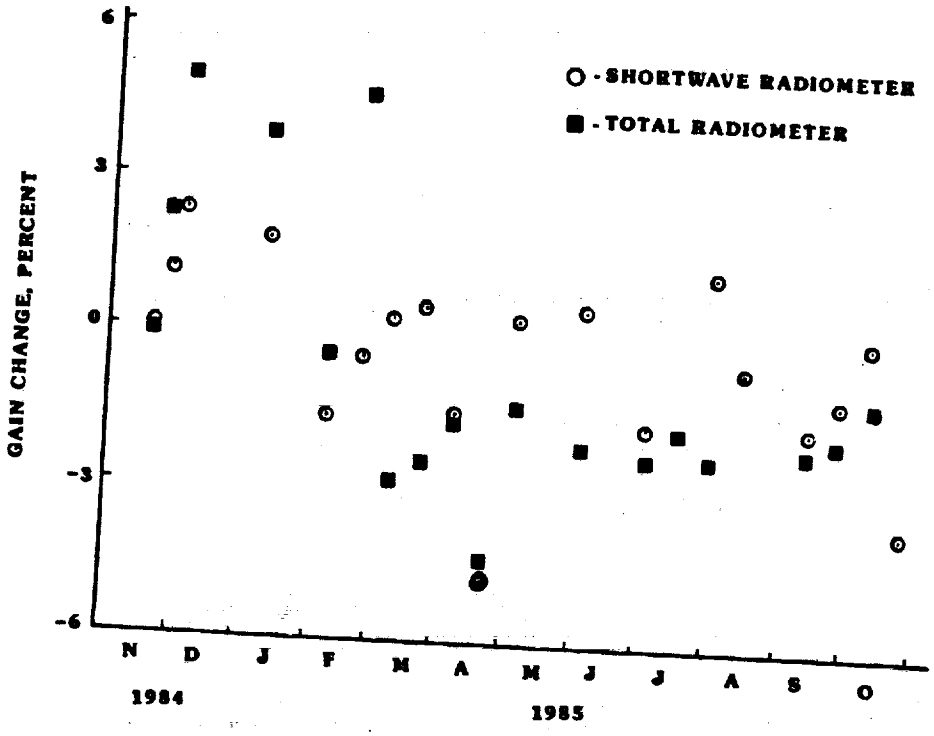

Fig. 12. ERBS solar calibrations time series.

The total radiometer data set suggests a decreasing trend. The data for the November 1984 through February 1985 period are approximately 7% higher than the data for the period after February 1985. The 7% difference represents a decrease in the sensitivity of the shortwave portion of the total radiometer. On February 28, 1985, the total and shortwave radiometers accidentally observed the Sun directly, at the space reference position, elevation angle of 14 degrees, for an extended period of time. The accident was caused by a temporary failure of the azimuthal position mechanism. The direct observations of the Sun caused decreases in the shortwave portion of the total radiometer sensitivity. The longwave gain of the total radiometer did not change[9]. The shortwave radiometer did not experience any detectable changes in its sensitivity because its two Suprasil W1 filters protected the thermistor bolometer from direct exposure to the solar radiances.

In Fig. 13, the NOAA-9 flight solar calibration results are presented for the February 20, 1985, through December 24, 1986, period. The radiance measurements for February 20, 1985 were used as references in order to detect changes in the shortwave and total radiometers gains. The time series indicate that the radiances were stable to ±2%. The scatter is primarily caused by the variability of the radiance with off-axis incident angle. The ERBS and NOAA-9 measurements indicated that the reflective characteristics of the MAM assemblies did not degrade over exposure periods to space as much as 2 years.

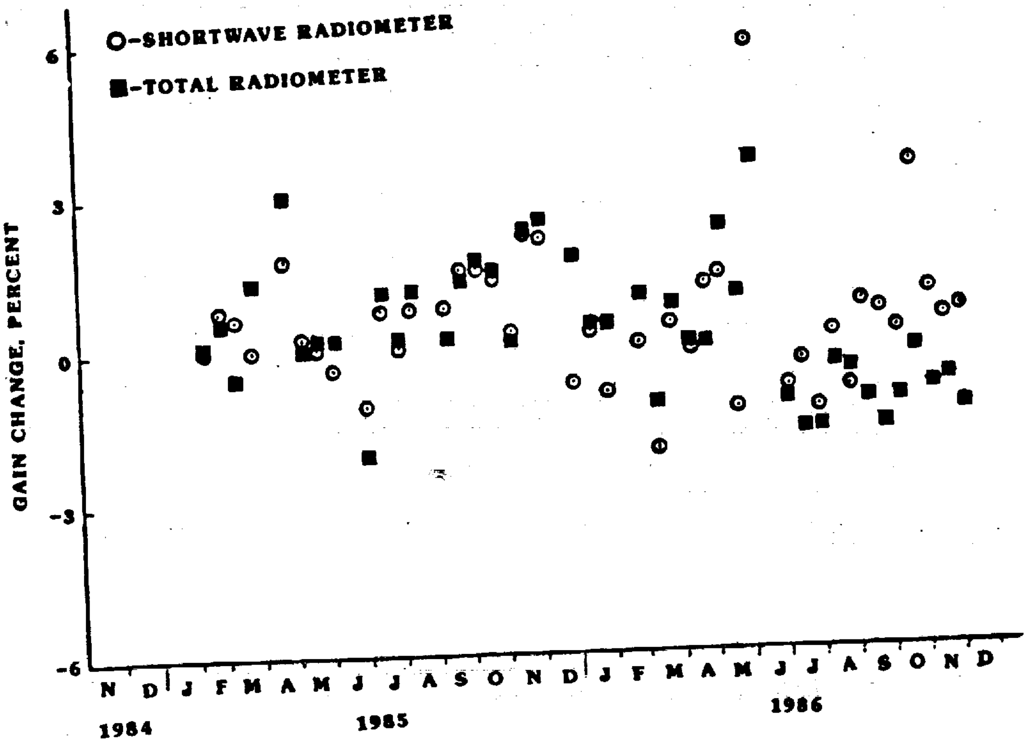

Fig. 13. NOAA-9 solar calibrations time series.

5. CONCLUSIONS

The MAM assemblies exhibited no detectable degradation in their reflectance properties over periods as much as 2 years. The flight solar calibration measurements indicate no significant changes above the 2% level in the amounts of solar radiances which were reflected by the MAM's of the shortwave radiometers. This result indicates that the reflectance properties of the MAM's did not degrade. In addition, this result suggests that the gains of the shortwave radiometers were stable at the ±2% level and that the Suprasil W1 filters did not exhibit any detectable degradation in their transmission properties. Suprasil W1 filters degrade very rapidly when exposed directly to solar ultraviolet radiation[8]. Since the aluminum telescope mirrors and the MAM minimized the amounts of indirect ultraviolet radiation which were projected upon the filters, the filters should not have exhibited any significant degradation in their transmission properties. During February 1985, the sensitivity of the shortwave portion of the ERBS total radiometers decreased approximately 7% when the radiometers were exposed directly to the Sun. A correction for this 7% decrease has been incorporated in the ERBE data reduction algorithms.

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FINAL REPORT
of the
TOVS PATHFINDER Scientific Working Group
November 25, 1991

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X. TOVS PATHFINDER PRODUCT VALIDATION AND INTERCOMPARISON

A.. Overview

Validation and intercomparison is an essential part of the Pathfinder program. Since its organization within the International TOVS Working Group, the TOVS community has continuously emphasized this aspect of the product retrieval problem. In the previous sections of this report, the TOVS Pathfinder SWG has recommended a careful and coherent reorganization and archiving of TOVS radiance data, and three distinct pathways for deriving product variables from this TOVS radiance archive. The importance in taking this multiple path approach to creating climate datasets rests in our firm belief that there is no global "absolute truth" data for any of the derived physical parameters. Each of the selected methods is based upon a different set of assumptions. Paths A and B make the attempt to account as much as possible for the physical processes in the atmosphere and surface that create the observed radiances. Path C strives to detect earth system changes as directly from the upwelling radiance data as possible. The challenge in interpreting Pathfinder data is to determine what alterations in the physical attributes of the environment contribute to evidence of global change extracted from observed or derived Pathfinder datasets. A great deal of what we are likely to learn about climate change will come by comparing the parameters derived by these methods, and understanding their similarities and differences under a range of environmental conditions. The Pathfinder validation and intercomparison activity must include validation of the *forward problem*, by which one calculates an estimate of upwelling radiance information from given earth and atmospheric data, and validation of the *inverse problem*, by which one calculates estimates of earth and atmospheric information from given upwelling satellite spectral radiance data.

The challenge in interpreting Pathfinder data is to identify changes in atmospheric, oceanic, or land processes which are responsible for any observed long–term changes in either the radiances or derived products. The validation of the forward problem involves a careful comparison between calculated and measured radiances. This may be achieved by archiving a diverse set of measured radiances and colocated independent measurements of profile parameters. In practice, this means radiosondes (although rocketsondes, lidar profiles and other measurements are potentially useful). In order to properly specify errors in the forward problem, insofar as they relate to errors in radiosonde measurements of atmospheric state, there is a need to analyze forward radiative transfer model errors as a function of: air mass type; presence of clouds; land/sea flag; viewing and solar zenith angles; and radiosonde type.

It was primarily in response to the forward problem of radiance validation that previous meetings of the International TOVS Scientific Working Group stressed the importance of a *Baseline Upper Air Network* (*BUAN*) (See WMO (1988)). At this time, a few databases containing colocated observations are available: the NESDIS operational *Data Staging Disk 5* (DSD5), the *BUAN* archive (January 15 to July 15, 1988) with about 7000 radiosonde reports, L. McMillin's long term data set, and perhaps other colocated sets unknown to the TOVS Pathfinder SWG.

Also related to validation of the forward problem, the ITRA (Intercomparison of Transmittances and Radiance Algorithms) program has been encouraged to continue its efforts towards the validation of radiative transfer codes, in particular, against high quality observations like the HIS (High resolution Interferometer Spectrometer, Smith, Rivercomb, Howell, and Woolf (1983)) spectra or ground based microwave radiometric instruments (Westwater and Grody (1980)) associated with good coincident *in situ* measurements of the atmospheric state.

The inverse problem of derived product derivation must also be subjected to careful validation and intercomparison. As part of the validation/comparison exercise, both first guess information and product retrievals should be verified against a well distributed group of colocated *in situ* and *satellite* data. In order to assist in retrieval validation studies and to illustrate the existent maturity and quality of retrieval schemes, an intercomparison of retrieved data derived from common sets of satellite radiance observations should be undertaken, following what has already been done by the International TOVS Working Group. Techniques should be tested for differing conditions of cloudiness, different geophysical domains, and differing meteorological regimes.

Specific to validation and intercomparison of Path C derived products, the candidates for intercomparisons are similar products derived from radiosondes, Path A and B products, and of course the established Spencer et al. data sets. Layer averaging of radiosondes or higher vertical resolution TOVS derived products is all that is required to make the comparisons. The temporal and spatial resolutions for intercomparison with radiance data and Path A and B products are dictated by the definition of the recommended common format data archive and, additionally, by considerations discussed in Section X. Very likely nothing can be done for the radiosondes to obtain appropriate spatial averaging. In the case of the Spencer et al. data, box–car and bell–shaped weighted averages can be compared directly, provided the weighting curves overlap and have essentially the same area under them. As a general procedure, if one of the products being compared has higher spatial or temporal resolution than the other one, averaging to the lower resolution will take care of the problem. In regions where a parameter has large gradients relative to the data sampling density, or where data sampling is very variable, an alternative approach to averaging or compressing would be used.

For climate and global change purposes, it would be useful to evaluate interannual differences of coarse layer–mean temperatures, coarse layer precipitable water, effective cloud amounts, and if available, surface skin temperatures and cloud–top temperature. Layer–mean temperatures produced among the different methodologies can be compared to rawinsonde reports, or, if not in the vicinity of rawinsonde sites, to analyzed fields from NMC or ECMWF. Use of analysis for validation allows for the examination of spatial as well as temporal variability. Interannual differences of other parameters are more difficult to validate but can be compared to each other. Because the ability to account for satellite drift and intersatellite differences is important, comparisons should include time periods measured by the same satellite (e.g., May–June 1980 and May – June 1981, both measured by NOAA 6) and by different satellites (May–June 1988, measured by NOAA 10 and 11).

Developing, to the degree possible, a quantitative understanding of the physical meaning of derived parameters, over a range of environmental conditions, is the objective of the validation effort. At least one study of this type, for sea surface temperature parameters, has been performed (Njoku et al., (1985)). A key function of a TOVS Pathfinder initiative is to ensure that data sets developed therein are as easy as possible to transport, intercompare, and validate. In general terms, there should be carefully conducted design efforts such that:

☐ *Certain steps be taken in preparing each TOVS Pathfinder data set, in anticipation of validation and intercomparison of results,*

☐ *Certain preliminary work be done in developing techniques for statistically characterizing and comparing data sets, in anticipation of validation and intercomparison of results, and*

☐ *A set of validation and intercomparison activities be selected and included as part of the plan to prepare the TOVS Pathfinder datasets for the larger community.*

The sub–sections to follow provide specifications for a validation and intercomparison study group.

B. Scientific Aspects of Validation and Intercomparison

1. *Characterizing the Assumptions Associated with Each Parameter*

Data users need to know about assumptions that could affect the interpretation of the results without becoming expert in all aspects of the instrument and analysis code. Charting techniques, based on ideas from the system design community (e.g., Yourdon and Constantine, (1979)), have been developed to summarize assumptions (See Kahn et al. (1991)). Many assumptions made in the data reduction process have the potential to affect the scientific meaning of the data. These include assumptions made in: adopting and calibrating the instrument radiances; deriving the data production algorithm (the equations); and building the data production computer code.

A deep understanding of the subtleties of the data analysis is required to identify and describe these assumptions. Therefore, a chart of all assumptions for each TOVS Pathfinder dataset needs to be produced by scientists with a deep understanding of the data.

2. *Content of Data Sets*

In addition to the physical parameter values that are reported in the data set, quantities which characterize the retrieval, such as error flags, residuals, characteristics of rejected values, and intermediate results may be critical for the validation effort. The validation effort, including members with intimate knowledge of each of the datasets, should agree on a reasonable selection of diagnostic quantities to be stored with each data product.

3. *Selecting Spatial and Temporal Regions for Comparison*

By carefully selecting spatial and temporal regions for the validation and intercomparison effort, a validation team can control to some extent the data quality, sample density, and environmental conditions in the study. The validation team should pick a reasonable number of space–time windows for validation, covering the full range of environmental conditions and surface types that are likely to occur.

4. *Finding Statistics That Characterize Key Attributes of Individual Data Sets*

Whereas arithmetic means and standard deviations are routinely used to describe data sets, other attributes, such as those that characterize sample spacing, spacing vs. gradient of the parameter value (which could be a vector quantity), measures of heterogeneity, variance surfaces, etc., also contain important information about the meaning and utility of the data for climate change studies. Providing such information for validation and intercomparison datasets would be a key contribution of the validation. Further research needs to be done, in collaboration with the statistical community, to explore these possibilities.

5. *Defining Ways to Characterize The Comparisons Among Data Sets*

The usual way of reporting comparisons between two–dimensional surfaces is by presenting difference or ratio images. Each of these methods has serious limitations, and there are no standard ways of characterizing the movement of boundaries and changes in density and density gradient for two or higher dimensions. Such comparisons are of major importance to validation and other studies of geophysical parameter fields. Research needs to be done, in collaboration with the statistical community, to explore these possibilities.

C. Technical Aspects of Validation and Intercomparison

From the available experience with intercomparing large data sets, several technical issues regarding ease of handling and exchanging data have been recognized, and at leas partial solutions have been developed. This subsection lists a few of these issues an approaches.

1. *Transportable Data File Formats*

Much work has been done to develop software that will create and read da files on a wide range of computers without additional translation steps. The HD (Hierarchical Data Format) from NCSA (National Center for Supercomputer Application U. Illinois) and netCDF (netCommon Data Format), are two of the leading exampl Both packages are distributed free of cost. Given the tremendous advantages of using su formats for a distributed effort like the Pathfinder, strong consideration should be given to adopting a transportable format for the standard distribution of TOVS Pathfinder data, including both radiance datasets and derived product datasets.

2. *Labeling Data Files*

The software for transportable file formatting generally requires that "data objects" be defined (for example, each parameter in a dataset can be designated as a separate data object), and allows for descriptions of the overall data set and each data object within it. There should be an agreement to some minimum information to be included with each data file and data object description, such as definitions of parameters, units, space and time constraints, allowed values, and references.

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Evaluating NOAA Satellite Products for Global Climate Monitoring

by

John J. Bates

NOAA Climate Monitoring and Disgnostics Laboratory

N94-23604

1. Validation criteria for satellite products
2. Long-term global validation examples
3. Lessons of history - Applications to the EOS era

1. Validation criteria for satellite products

1.1. Are the physics of the radiative transfer sound?

1.2. How do the means and higher moments compare with in situ measurements?

1.3. How do the spatial and temporal variations in the satellite data compare with other observations and hydrodynamic models?

The Forward and Inverse Problems in Remote Sensing of the Environment

The Forward Problem

Using radiative transfer theory and relavent geophysical variables, model the upwelling and scattered radiance that a particular instrument should measure

Interpreters - Required to specify a base state around which the radiative transfer equation is linearized

Class1	A priori information dependent Hydrodynamic model dependent
Class 2	A priori information dependent Hydrodynamic model independent
Class 3	A priori information independent Hydrodynamic model independent

The Inverse Problem

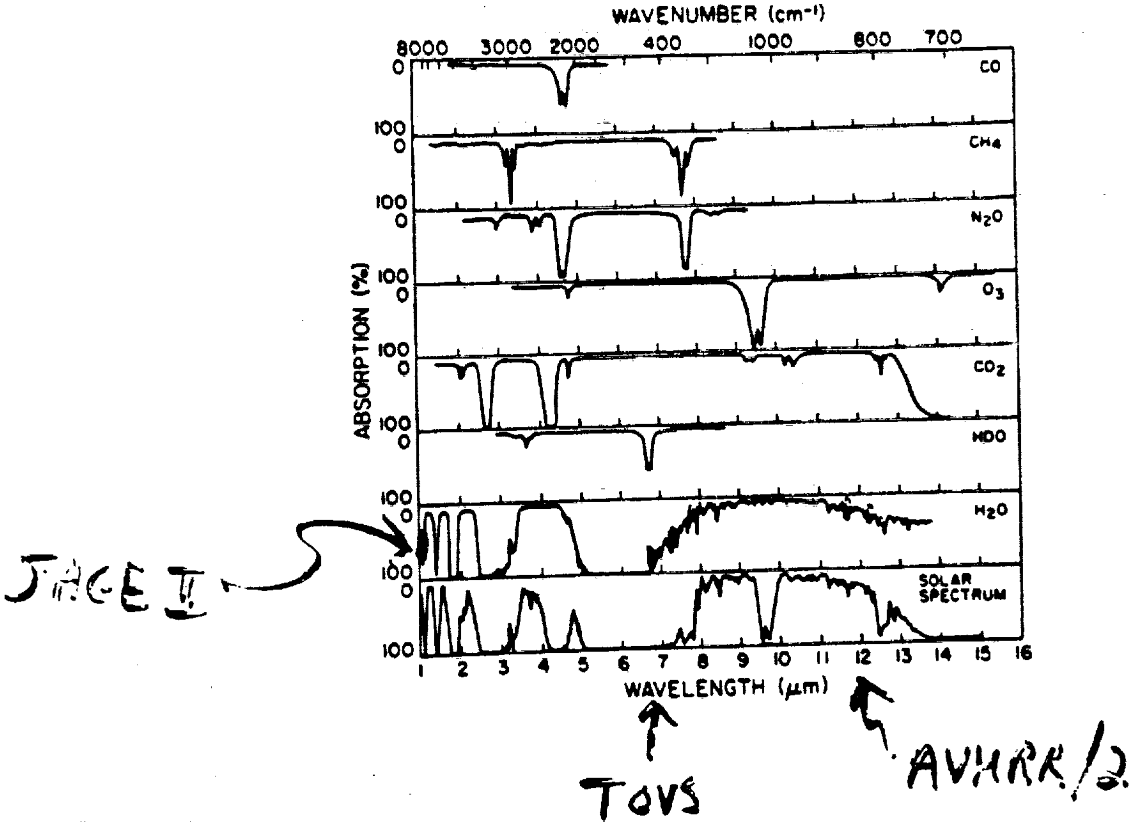
Using upwelling and scattered radiances, invert the radiative transfer equation to retrieve geophysical variables

$$R_\nu = -\varepsilon_s B_\nu(T_s)\,\tau_\nu(p_s) \quad - \underline{\text{S}}\text{urface} \rightarrow \underline{\text{C}}\text{loud EMISSION}$$

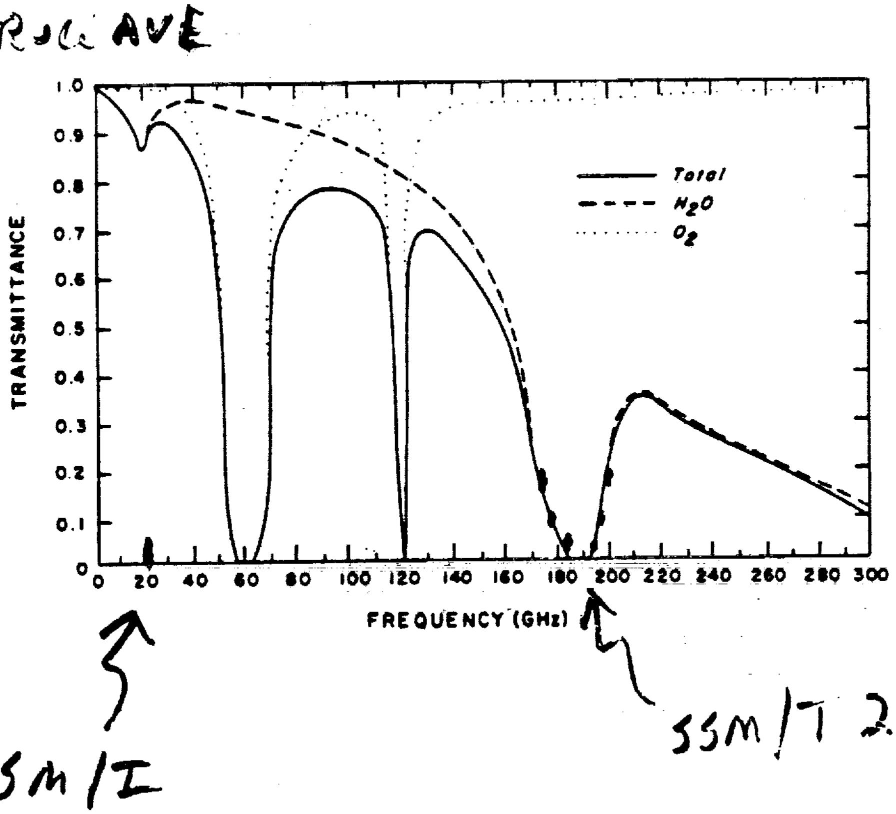
$$+ \int_{p_s}^{0} B_\nu(T(p))\,\frac{d\tau_\nu(p)}{dp}\,dp \quad - \text{ATMOSPHERIC TERM}$$

$$+ (1-\epsilon_s)\int_{0}^{p_s} B_\nu(T(p))\,\frac{d\tau^*_\nu(p)}{dp}\,dp \quad - \text{REFLECTED ATMOSPHERIC TERM}$$

INFRARED



MICROWAVE



2. Long-term global validation examples

2.1. Sea surface temperature

2.1.1. The JPL intercomparison workshops

2.1.2. Evaluation of the operational MCSST product

2.2. Global water vapor content

2.2.1. TOVS study conference comparisons

2.2.2. HIRS channel 12 brightness temperature climatology

2. Long-term global validation examples

2.1. Sea surface temperature

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2.1.2. Evaluation of the operational MCSST product

2.2. Global water vapor content

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2.2.2. HIRS channel 12 brightness temperature climatology

JPL SST INTERCOMPARISON WORKSHOP

(p) July 1982, Global

Two Degree Average SST Anomaly Cross Correlations
Region: 56.0 deg N to 56.0 deg S, 0.0 deg E to 360.0 deg E

At least 1 observation(s) at common grid points
(C--Cross Correlation, B--Bias, S--Standard Deviation
about bias, N--Number of common valid observations)
Bias is average over column temperatures minus row temperatures

	NOAA AVHRR DAY JUL	NOAA AVHRR NIGHT	NOAA AVHRR	SUSSKIND HIRS	SUSSKIND HIRS WEIGHTED	MILMAN SMMR NIGHT CELL 234	WILHEIT/MAN SMMR/SHIP COMPOSITE	BATES VAS	PAZAN SHIPS >5/CELL	PAZAN SHIPS >20/CELL	TRANSPAC XBT	CLIMATOL
NOAA AVHRR DAY JUL		C.. 0.82 B. -0.12 S.. 0.36 N.. 1652	C.. 0.95 B. -0.06 S.. 0.17 N.. 1600	C.. 0.60 B. -0.10 S.. 0.47 N.. 1600	C.. 0.59 B. -0.33 S.. 0.50 N.. 1600	C.. 0.39 B. 0.00 S.. 0.77 N.. 1422	C.. 0.55 B. 0.04 S.. 0.56 N.. 946	C.. 0.56 B. 0.45 S.. 0.40 N.. 163	C.. 0.03 B. -0.79 S.. 0.52 N.. 74	C.. 1.00 B. -0.40 S.. 0.50 N.. 5		C.. 0.00 B. -0.11 S.. 0.59 N.. 1600
NOAA AVHRR NIGHT			C.. 0.98 B. 0.05 S.. 0.17 N.. 2609	C.. 0.60 B. 0.18 S.. 0.44 N.. 2684	C.. 0.69 B. -0.14 S.. 0.60 N.. 2684	C.. 0.69 B. 0.27 S.. 0.64 N.. 2641	C.. 0.59 B. 0.41 S.. 0.61 N.. 1906	C.. 0.40 B. 0.67 S.. 0.54 N.. 247	C.. 0.64 B. 0.67 S.. 0.35 N.. 269	C.. 0.89 B. 0.56 S.. 0.40 N.. 7	C.. -0.04 B. 0.69 S.. 0.47 N.. 3	C.. 0.00 B. 0.36 S.. 0.83 N.. 2609
NOAA AVHRR				C.. 0.60 B. 0.06 S.. 0.60 N.. 3721	C.. 0.69 B. -0.17 S.. 0.59 N.. 3721	C.. 0.65 B. 0.21 S.. 0.67 N.. 2664	C.. 0.55 B. 0.30 S.. 0.63 N.. 2014	C.. 0.46 B. 0.67 S.. 0.53 N.. 249	C.. 0.70 B. 0.35 S.. 0.52 N.. 274	C.. 0.90 B. 0.45 S.. 0.43 N.. 7	C.. -0.90 B. 0.10 S.. 0.77 N.. 3	C.. 0.00 B. 0.30 S.. 0.82 N.. 3727
SUSSKIND HIRS					C.. 0.90 B. -0.26 S.. 0.14 N.. 4009	C.. 0.65 B. 0.15 S.. 0.77 N.. 2043	C.. 0.53 B. 0.21 S.. 0.52 N.. 2101	C.. 0.24 B. 0.55 S.. 0.53 N.. 254	C.. 0.70 B. -0.09 S.. 0.30 N.. 327	C.. 0.00 B. -0.15 S.. 0.00 N.. 7	C.. -0.90 B. 0.09 S.. 0.64 N.. 3	C.. 0.00 B. 0.26 S.. 0.52 N.. 4009
SUSSKIND HIRS WEIGHTED						C.. 0.44 B. 0.39 S.. 0.79 N.. 2043	C.. 0.54 B. 0.48 S.. 0.56 N.. 2101	C.. 0.17 B. 1.06 S.. 0.60 N.. 254	C.. 0.79 B. 0.25 S.. 0.30 N.. 327	C.. 0.25 B. 0.23 S.. 0.23 N.. 7	C.. -0.75 B. 0.42 S.. 0.64 N.. 3	C.. 0.00 B. 0.52 S.. 0.60 N.. 4009
MILMAN SMMR NIGHT CELL 234							C.. 0.87 B. 0.20 S.. 0.35 N.. 1703	C.. 0.50 B. 0.52 S.. 0.65 N.. 243	C.. 0.56 B. 0.69 S.. 0.60 N.. 230	C.. -1.00 B. 1.01 S.. 0.09 N.. 2	C.. 0.00 B. 0.61 S.. 0.00 N.. 1	C.. 0.00 B. 0.63 S.. 0.66 N.. 2071
WILHEIT/MAN SMMR/SHIP COMPOSITE								C.. 0.73 B. 0.42 S.. 0.34 N.. 211	C.. 0.06 B. 0.10 S.. 0.27 N.. 137		C.. 0.00 B. 0.04 S.. 0.00 N.. 1	C.. 0.00 B. -0.01 S.. 0.57 N.. 2190
BATES VAS									C.. 0.42 B. -0.55 S.. 0.27 N.. 36			C.. 0.00 B. -0.05 S.. 0.47 N.. 254
PAZAN SHIPS >5/CELL										C.. 1.00 B. 0.00 S.. 0.00 N.. 7	C.. -0.99 B. 0.06 S.. 0.30 N.. 3	C.. 0.00 B. 0.70 S.. 0.63 N.. 326
PAZAN SHIPS >20/CELL												C.. 0.00 B. 0.72 S.. 0.71 N.. 7
TRANSPAC XBT												C.. 0.00 B. 0.65 S.. 0.23 N.. 3
CLIMATOL												

INTERPRETING MULTI-CHANNEL SEA SURFACE TEMPERATURES

FOR AN INFRARED WINDOW CHANNEL

$$R_i = B_i(T_s)\tau_i + B_i(T_a)(1-\tau_i)$$

CONVERT FROM RADIANCE TO BRIGHTNESS TEMPERATURE AND USE WEAK ABSORPTION APPROXIMATION

$$T_i - T_s = k_i X(\bar{T} - T_s)$$

FOR TWO WINDOWS i AND j

$$T_s = T_i + \frac{k_i}{k_j - k_i}(T_i - T_j)$$

WHERE k_i + k_j ARE ABSORPTION COEFFICIENTS ASSUMING A SINGLE ABSORBING GAS VARIES

IN THE TWO WINDOWS

AVHRR/2 CHANNELS 4 + 5

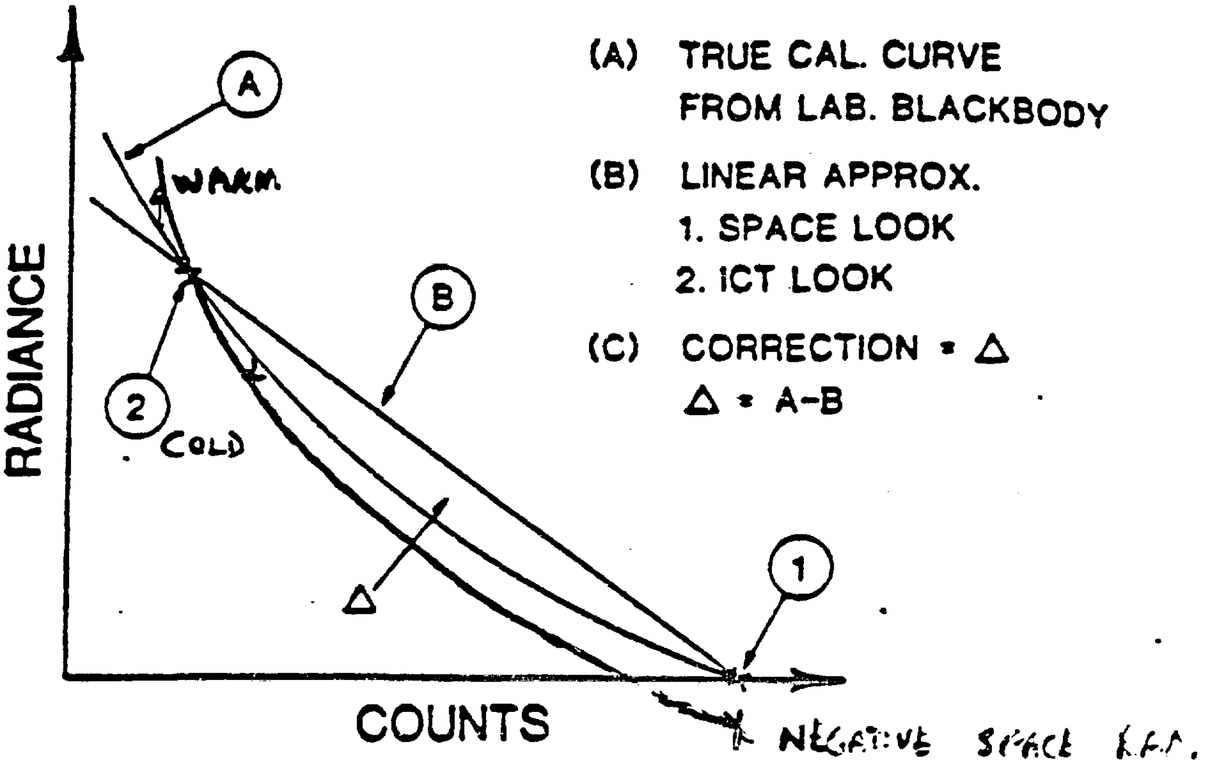

Fig. 3. Illustration of how nonlinearity correction terms are computed.

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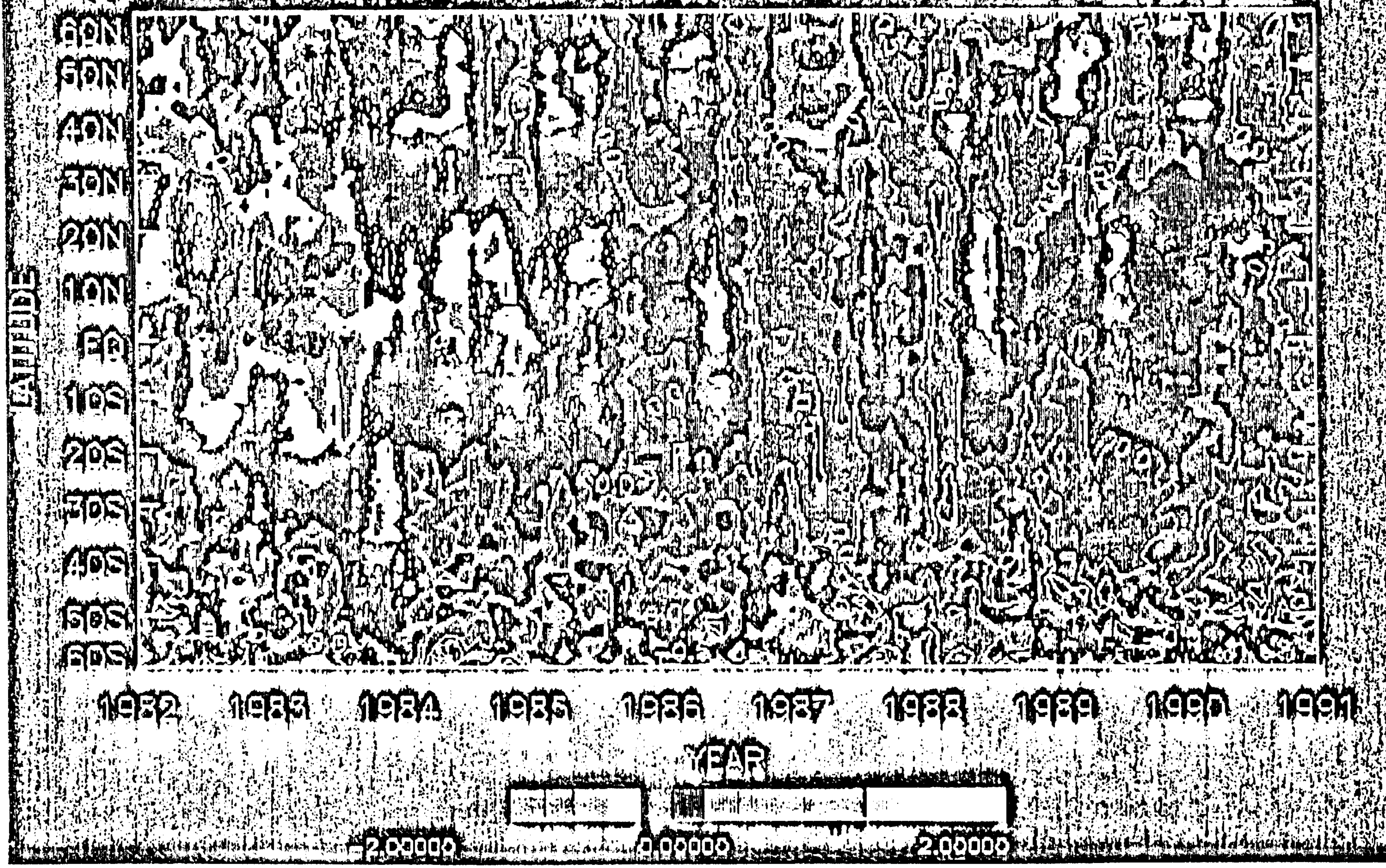
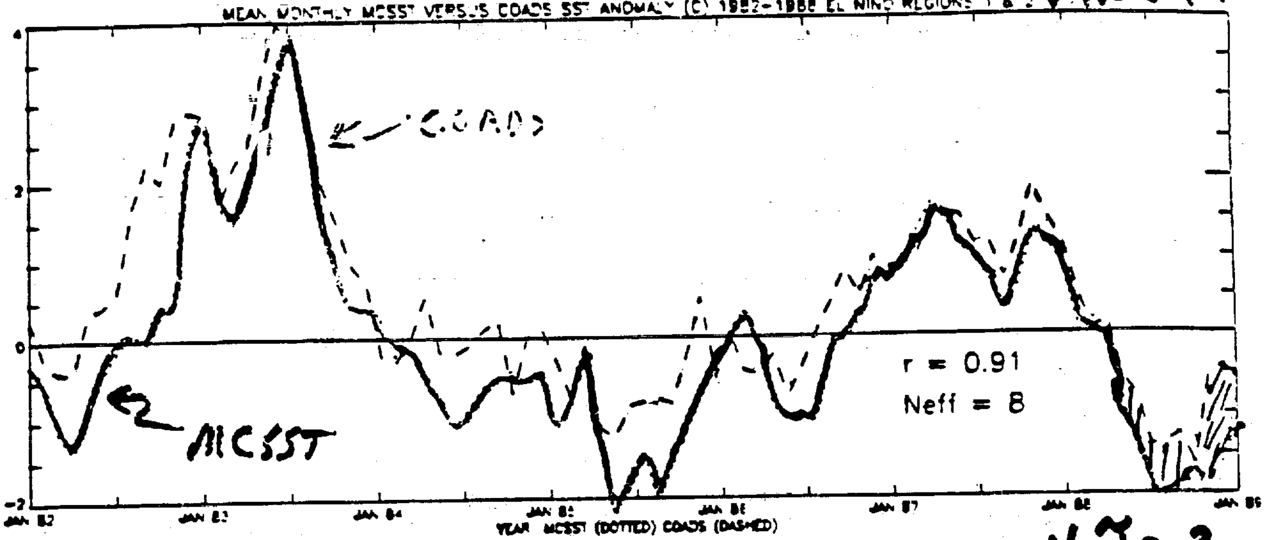
ZONALLY-AVERAGED MCSST MINUS COADS (C)



EL NIÑO REGIONS

MEAN MONTHLY MCSST VERSUS COADS SST ANOMALY (C) 1982-1988 EL NINO REGIONS 1 & 2 NIÑO 1&2



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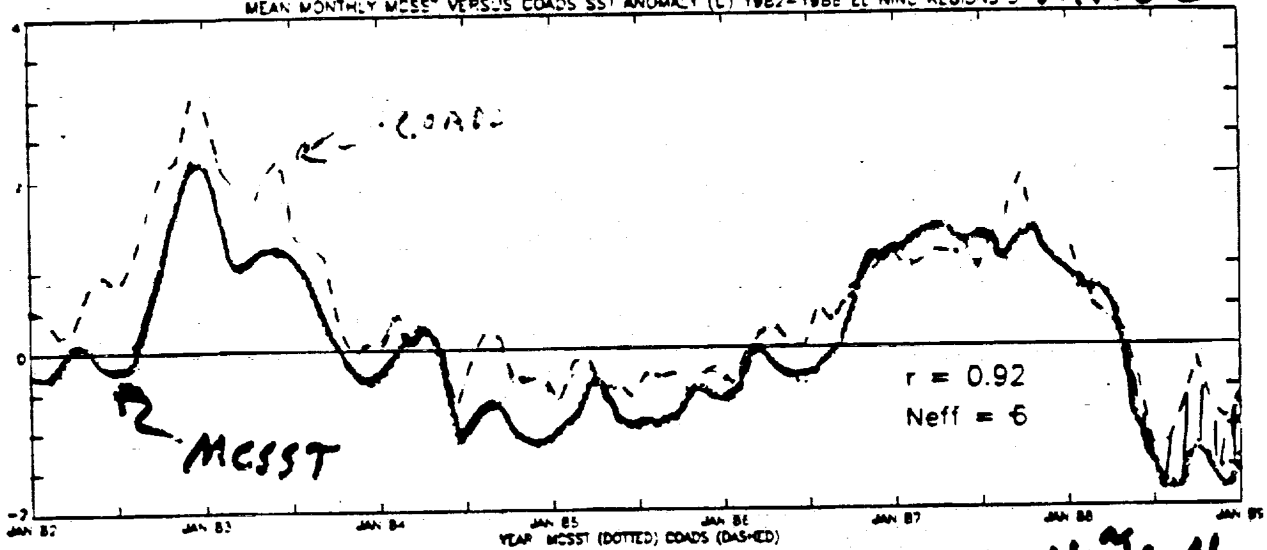

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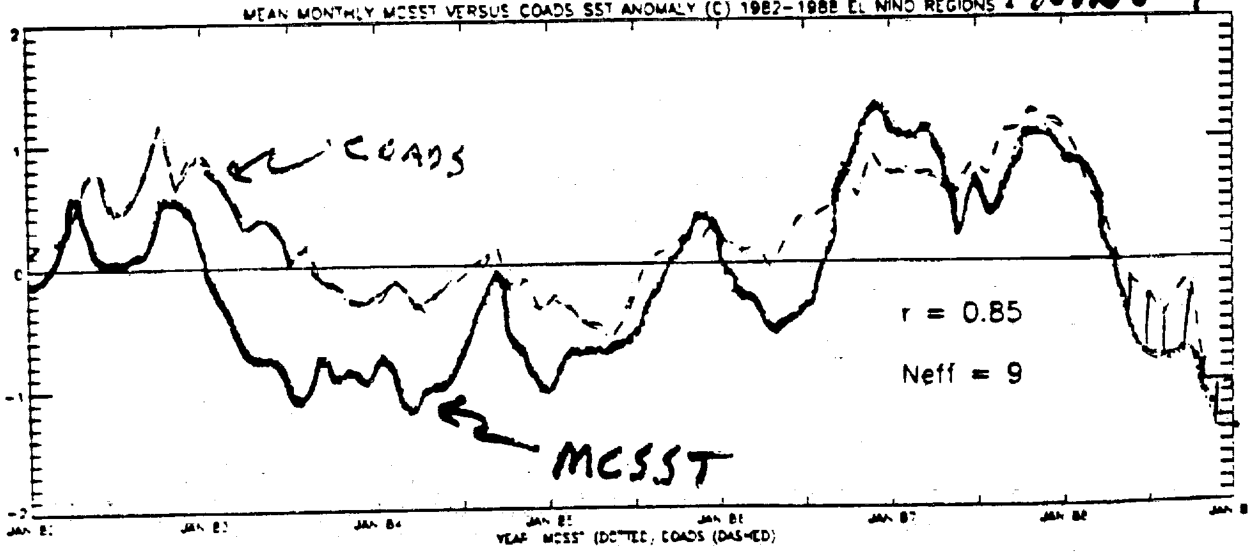


Fig. 8

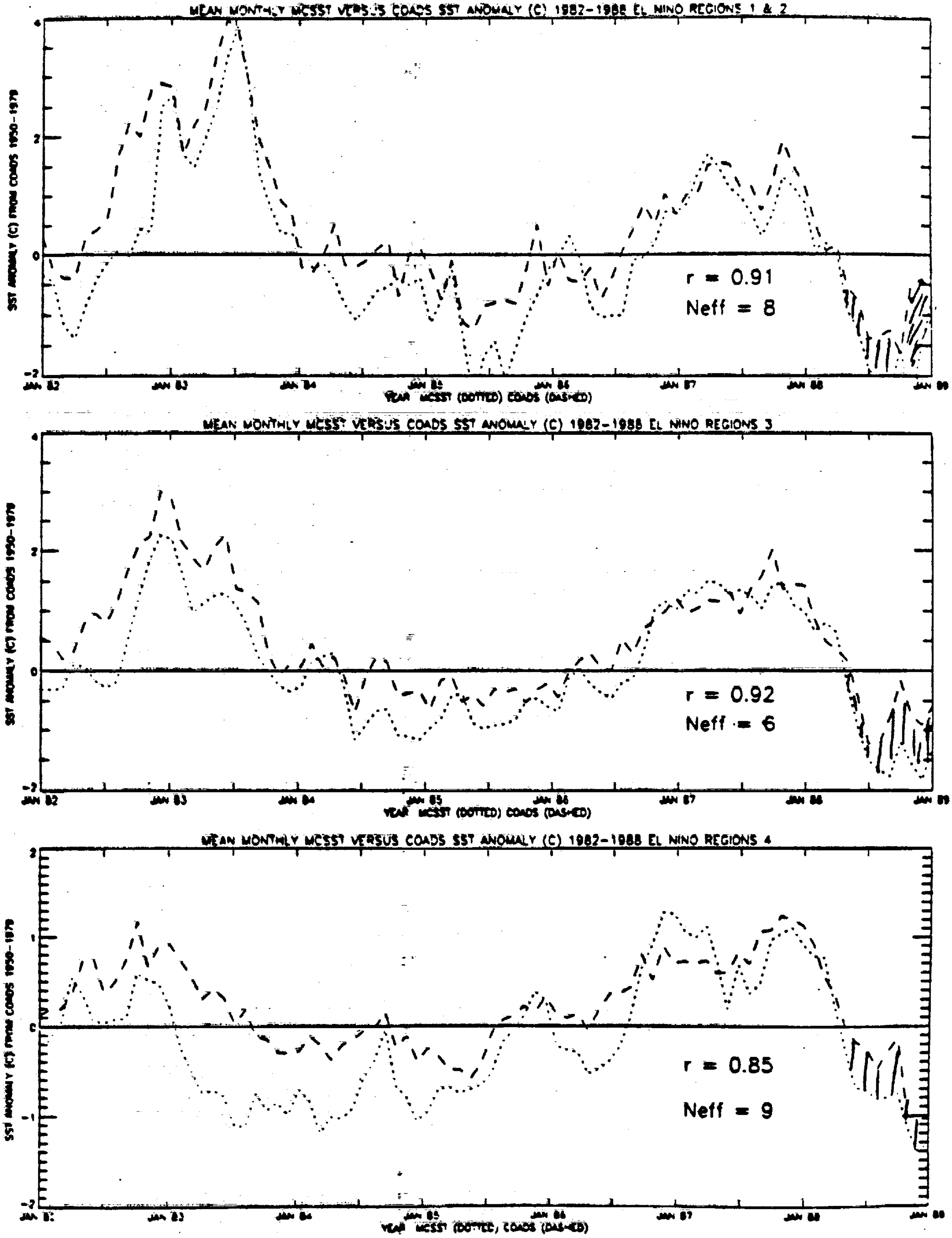

MEAN MONTHLY MCSST VERSUS COADS SST ANOMALY (C) 1982-1988 EL NINO REGIONS 1 & 2
SST ANOMALY (C) FROM COADS 1950-1979
4
2
0
-2
r = 0.91
Neff = 8
JAN 82
JAN 83
JAN 84
JAN 85
JAN 86
JAN 87
JAN 88
JAN 89
YEAR MCSST (DOTTED) COADS (DASHED)
MEAN MONTHLY MCSST VERSUS COADS SST ANOMALY (C) 1982-1988 EL NINO REGIONS 3
SST ANOMALY (C) FROM COADS 1950-1979
4
2
0
-2
r = 0.92
Neff = 6
JAN 82
JAN 83
JAN 84
JAN 85
JAN 86
JAN 87
JAN 88
JAN 89
YEAR MCSST (DOTTED) COADS (DASHED)
MEAN MONTHLY MCSST VERSUS COADS SST ANOMALY (C) 1982-1988 EL NINO REGIONS 4
SST ANOMALY (C) FROM COADS 1950-1979
2
1
0
-1
-2
r = 0.85
Neff = 9
JAN 82
JAN 83
JAN 84
JAN 85
JAN 86
JAN 87
JAN 88
JAN 89
YEAR MCSST (DOTTED) COADS (DASHED)

FIG 8

SOUTH ATLANTIC OCEAN

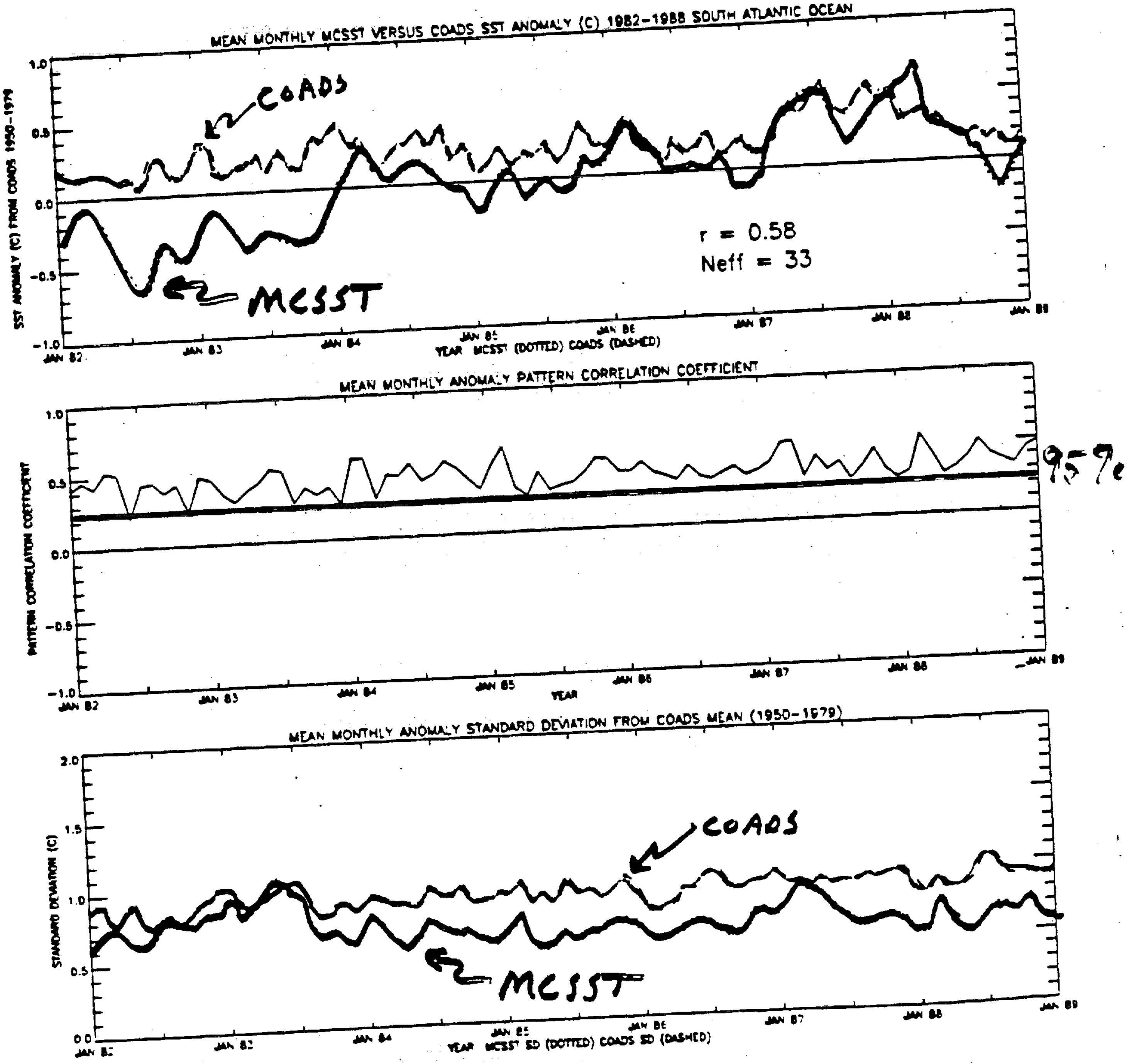


FIG ⑦

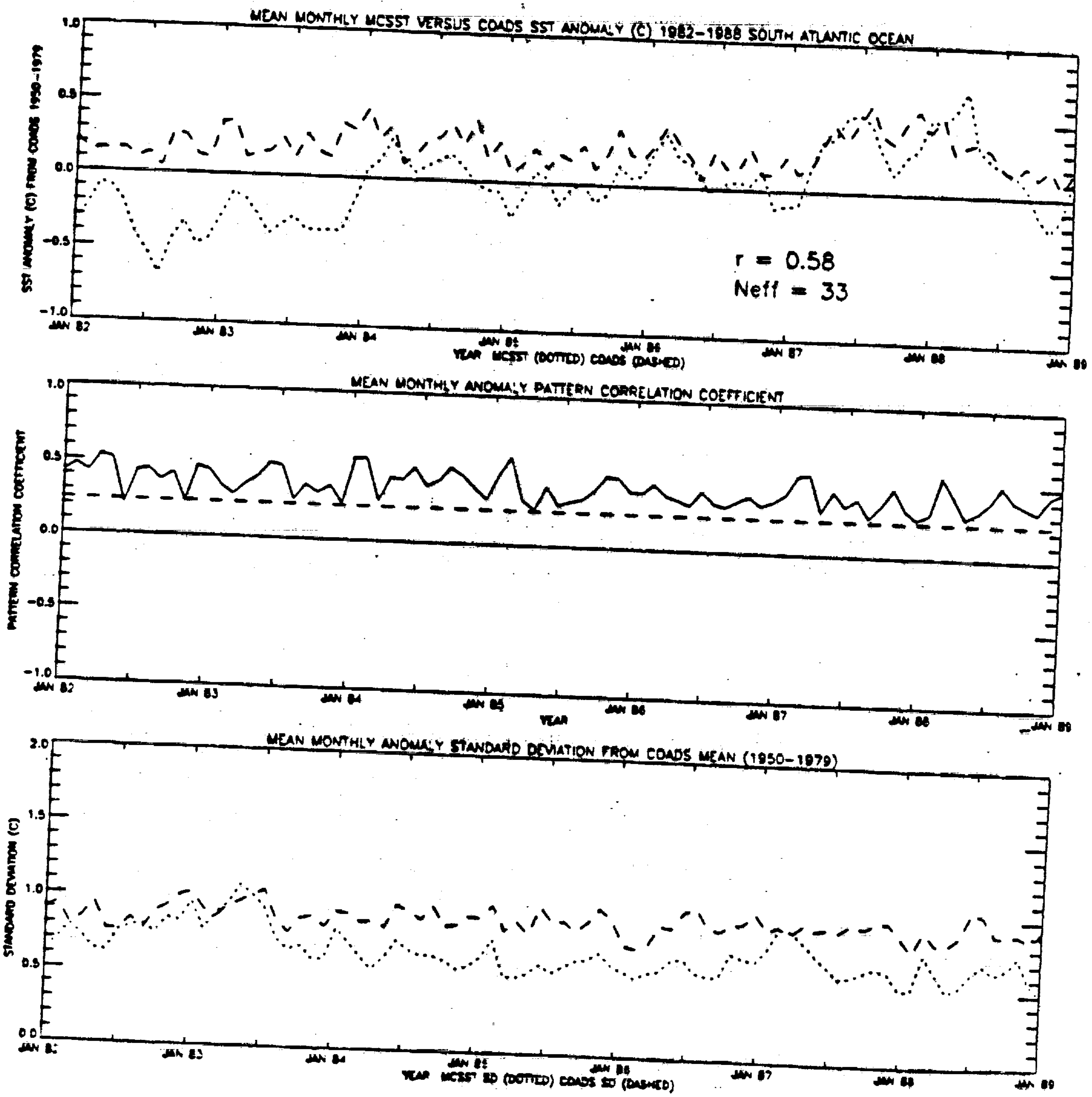

MEAN MONTHLY MCSST VERSUS COADS SST ANOMALY (C) 1982–1988 SOUTH ATLANTIC OCEAN
SST ANOMALY (C) FROM COADS 1950–1979
1.0
0.5
0.0
-0.5
-1.0
r = 0.58
Neff = 33
JAN 82
JAN 83
JAN 84
JAN 85
JAN 86
JAN 87
JAN 88
JAN 89
YEAR MCSST (DOTTED) COADS (DASHED)
MEAN MONTHLY ANOMALY PATTERN CORRELATION COEFFICIENT
PATTERN CORRELATION COEFFICIENT
1.0
0.5
0.0
-0.5
-1.0
JAN 82
JAN 83
JAN 84
JAN 85
JAN 86
JAN 87
JAN 88
JAN 89
YEAR
MEAN MONTHLY ANOMALY STANDARD DEVIATION FROM COADS MEAN (1950–1979)
STANDARD DEVIATION (C)
2.0
1.5
1.0
0.5
0.0
JAN 82
JAN 83
JAN 84
JAN 85
JAN 86
JAN 87
JAN 88
JAN 89
YEAR MCSST SD (DOTTED) COADS SD (DASHED)

FIG 7

SST SUMMARY STATISTICS

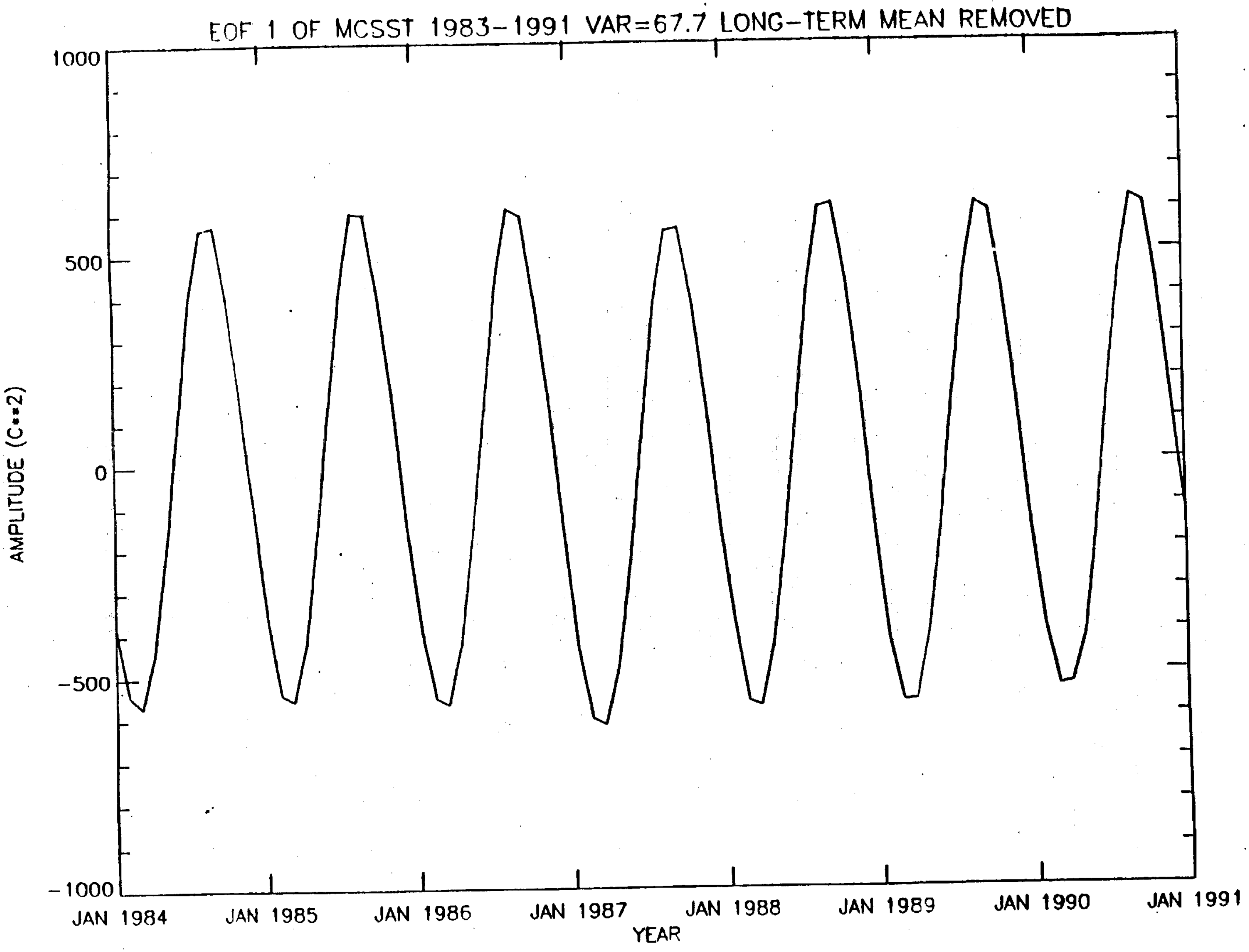
Ocean Basin or Region	Anomaly Cross Correlation	Effective Degrees of Freedom	Signal-to-Noise Variance Ratio	First Monthly Difference Cross Correlation	Mean MCSST Anomaly (°C)	Mean COADS Anomaly (°C)	Mean MCSST Standard Deviation(°C)	Mean COADS Standard Deviation(°C)
Global 60°N-60°S, 0°-360°	0.65 *	19	1.14	0.02	-0.16	0.13	0.75	0.84
Northern Hemisphere 0°-60°N, 0°-360°	0.55 *	40	0.56	0.21	-0.32	0.03	0.74	0.76
Southern Hemisphere 0°-60°S, 0°-360°	0.67 *	22	2.42	0.16	0.04	0.23	0.70	0.92
Indian Ocean 20°N-60°S, 30°E-120°E	0.70 *	21	2.93	0.30 *	0.06	0.32	0.60	0.81
North Pacific Ocean 0°-60°N, 120°E-90°W	0.66 *	26	0.59	0.23	-0.34	0.01	0.79	0.86
South Pacific Ocean 0°-60°S, 120°E-80°W	0.62 *	27	2.21	0.03	-0.04	0.15	0.70	0.95
North Atlantic Ocean 0°-60°N, 0°-90°W	0.43	20	0.49	0.36 *	-0.33	0.04	0.66	0.63
South Atlantic Ocean 0°-60°S, 0°-80°W	0.63 *	28	2.86	0.57 *	0.00	0.25	0.68	0.90
El Niño 1 & 2 0°-10°S, 80°W-90°W	0.89 *	23	4.69	0.58 *	-0.03	0.50	0.75	1.19
El Niño 3 6°N-6°S, 90°W-150°W	0.93 *	17	4.67	0.50 *	0.08	0.50	0.67	1.12
El Niño 4 6°N-6°S, 160°E-150°W	0.91 *	12	1.97	0.25	-0.17	0.22	0.62	0.89
North Pacific Region 1 50°N-60°N, 155°W-175°W	0.43 *	26	1.27	0.25	-0.14	0.17	0.34	0.37
North Atlantic Region 1 30°N-40°N, 60°W-80°W	0.69 *	23	0.51	-0.13	-0.17	0.01	0.66	0.58
North Atlantic Region 2 15°N-25°N, 40°W-60°W	0.50	23	0.34	0.51 *	-0.59	0.05	0.29	0.46

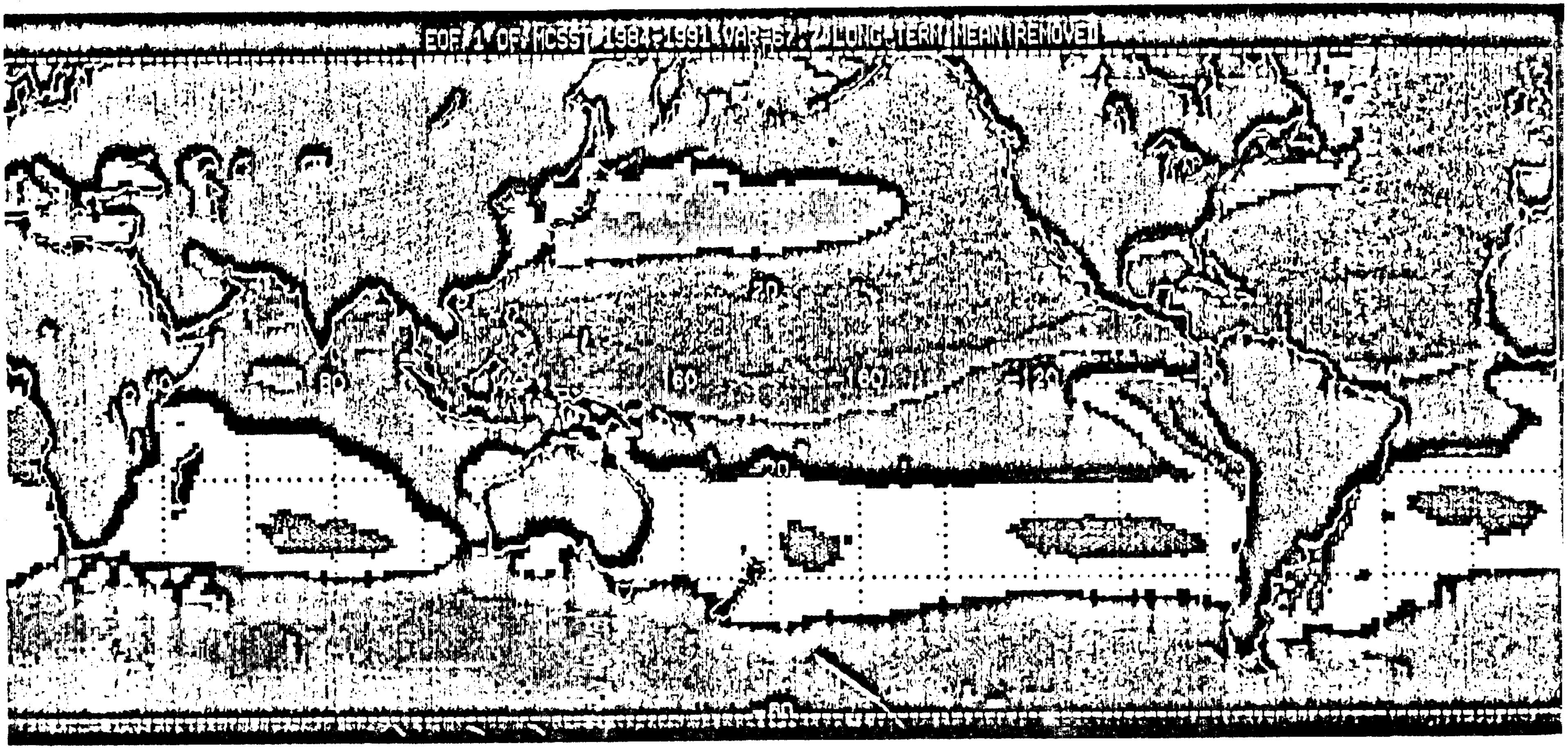
Table 3. Summary statistics for MCSST and COADS 1984-1988 anomaly cross correlations, means, and standard deviations. All anomaly cross correlations are significant at the 95% level except the North Atlantic Ocean and North Atlantic Region 2.

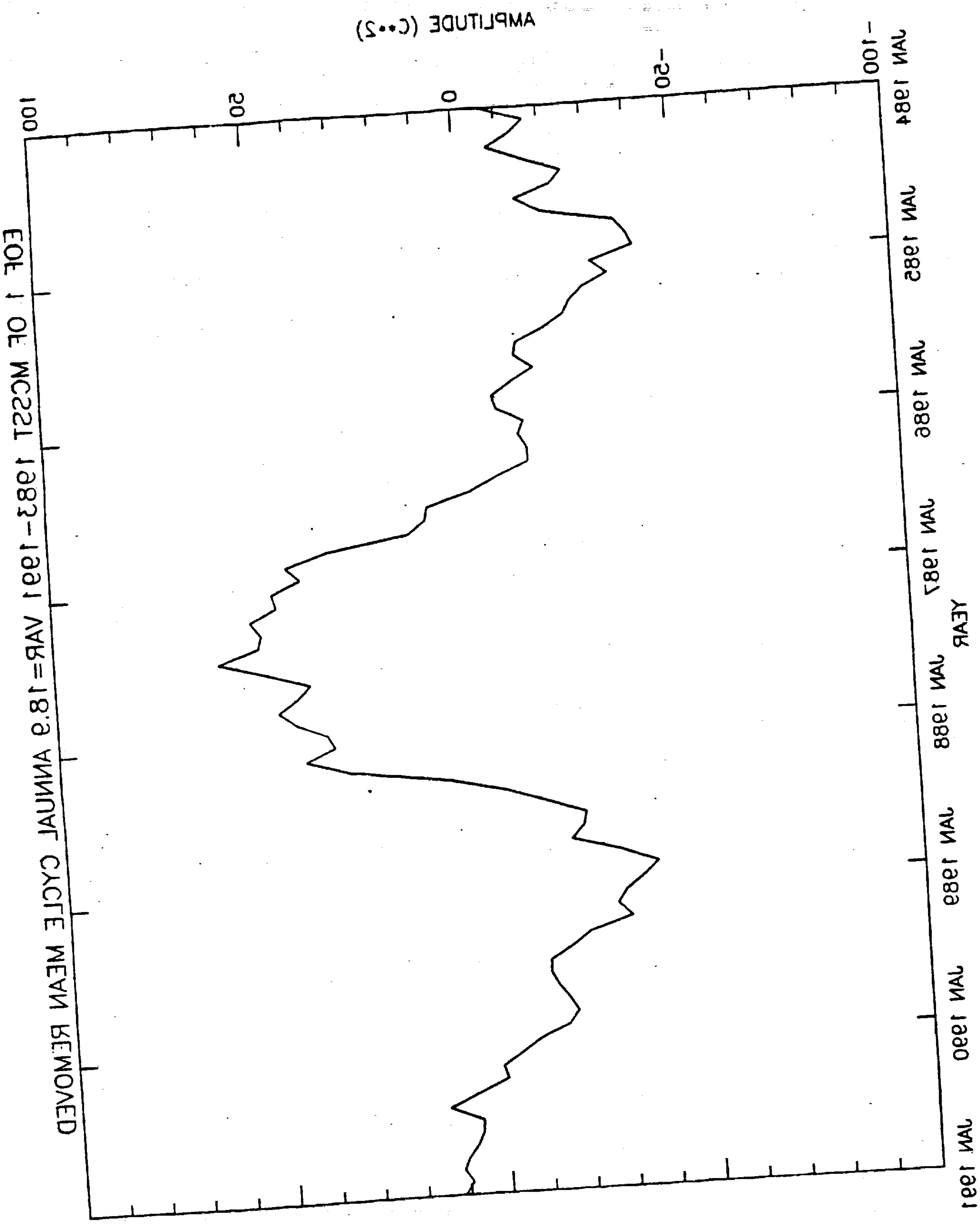
*SIGNIFICANT AT 95% FOR N_{EFF}

Ocean Basin or Region	Anomaly Cross Correlation	Effective Degrees of Freedom	Signal-to-Noise Variance Ratio	First Monthly Difference Cross Correlation	Mean MCSST Anomaly (°C)	Mean COADS Anomaly (°C)	Mean MCSST Standard Deviation(°C)	Mean COADS Standard Deviation(°C)
Global 60°N-60°S, 0°-360°	0.65	19	1.14	0.02	-0.16	0.13	0.75	0.84
Northern Hemisphere 0°-60°N, 0°-360°	0.55	40	0.56	0.21	-0.32	0.03	0.74	0.76
Southern Hemisphere 0°-60°S, 0°-360°	0.67	22	2.42	0.16	0.04	0.23	0.70	0.92
Indian Ocean 20°N-60°S, 30°E-120°E	0.70	21	2.93	0.30	0.06	0.32	0.60	0.81
North Pacific Ocean 0°-60°N, 120°E-90°W	0.66	26	0.59	0.23	-0.34	0.01	0.79	0.86
South Pacific Ocean 0°-60°S, 120°E-80°W	0.62	27	2.21	0.03	-0.04	0.15	0.70	0.95
North Atlantic Ocean 0°-60°N, 0°-90°W	0.43	20	0.49	0.36	-0.33	0.04	0.66	0.63
South Atlantic Ocean 0°-60°S, 0°-80°W	0.63	28	2.86	0.57	0.00	0.25	0.68	0.90
El Niño 1 & 2 0°-10°S, 80°W-90°W	0.89	23	4.69	0.58	-0.03	0.50	0.75	1.19
El Niño 3 6°N-6°S, 90°W-150°W	0.93	17	4.67	0.50	0.08	0.50	0.67	1.12
El Niño 4 6°N-6°S, 160°E-150°W	0.91	12	1.97	0.25	-0.17	0.22	0.62	0.89
North Pacific Region 1 50°N-60°N, 155°W-175°W	0.43	26	1.27	0.25	-0.14	0.17	0.34	0.37
North Atlantic Region 1 30°N-40°N, 60°W-80°W	0.69	23	0.51	-0.13	-0.17	0.01	0.66	0.58
North Atlantic Region 2 15°N-25°N, 40°W-60°W	0.50	23	0.34	0.51	-0.59	0.05	0.29	0.46

Table 3. Summary statistics for MCSST and COADS 1984-1988 anomaly cross correlations, means, and standard deviations. All anomaly cross correlations are significant at the 95% level except the North Atlantic Ocean and North Atlantic Region 2.


EOF 1 OF MCSST 1983-1991 VAR=67.7 LONG-TERM MEAN REMOVED
1000
500
0
-500
-1000
AMPLITUDE (C**2)
JAN 1984
JAN 1985
JAN 1986
JAN 1987
JAN 1988
JAN 1989
JAN 1990
JAN 1991
YEAR


EOF 1 OF MCSST 1984-1991 VAR=67.2 LONG TERM MEAN REMOVED
20
80
160
160
120
20
60


EOF 1 OF MCSST 1983-1991 VAR=18.9 ANNUAL CYCLE MEAN REMOVED
AMPLITUDE (C**2)
100
50
0
-50
-100
JAN 1984
JAN 1985
JAN 1986
JAN 1987
JAN 1988
JAN 1989
JAN 1990
JAN 1991
YEAR

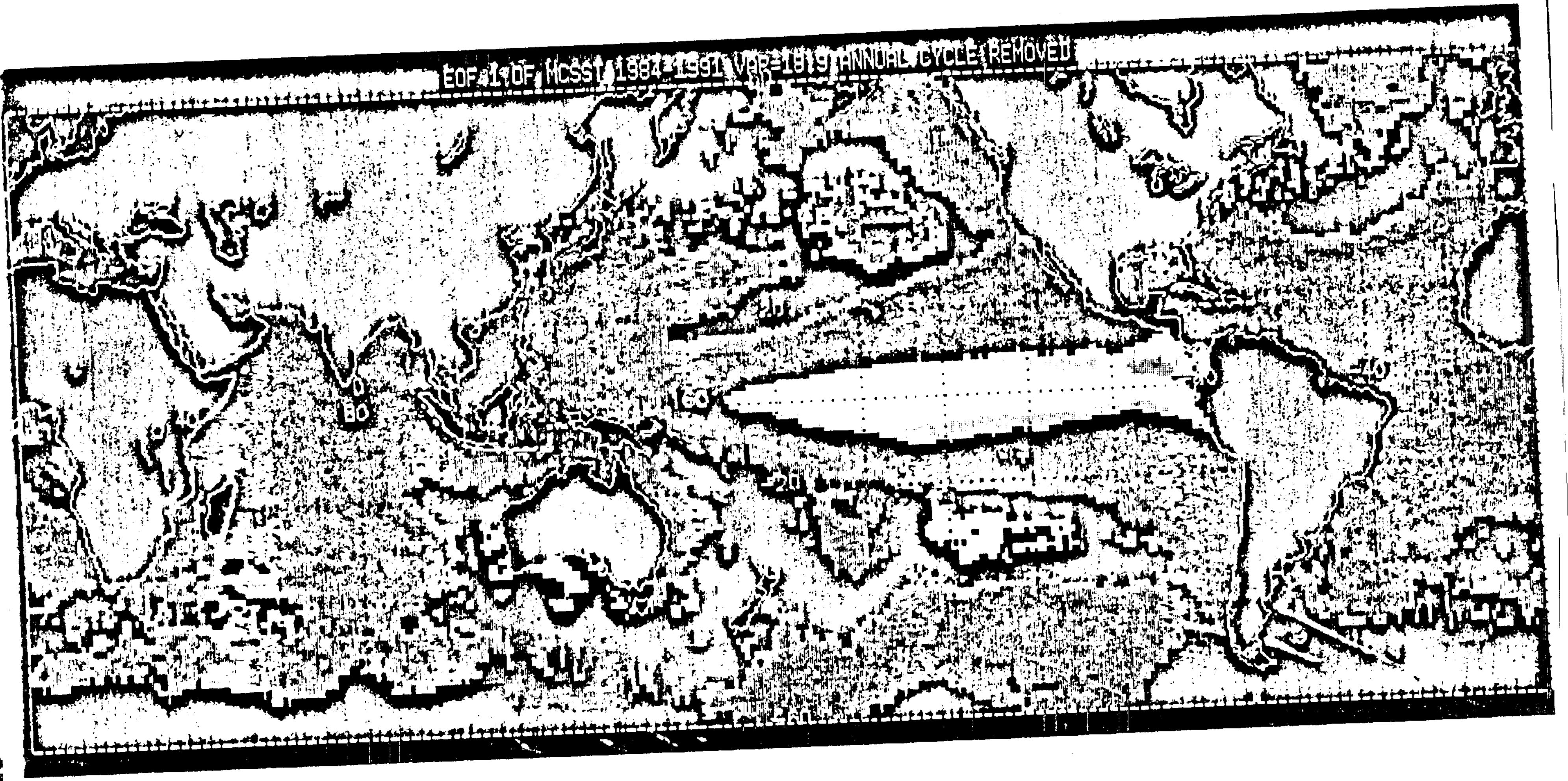
Evaluating NOAA Satellite Products for Global Climate Monitoring

by

John J. Bates

NOAA Climate Monitoring and Disgnostics Laboratory

1. Validation criteria for satellite products
2. Long-term global validation examples
3. Lessons of history - Applications to the EOS era


EOF 1 OF MCSST 1984-1991 VAR=18.9 ANNUAL CYCLE REMOVED
60
80
20

1. Validation criteria for satellite products

1.1. Are the physics of the radiative transfer sound?

1.2. How do the means and higher moments compare with in situ measurements?

1.3. How do the spatial and temporal variations in the satellite data compare with other observations and hydrodynamic models?

TOVS Study Conference Contributions

TABLE 1

Summary of contributions to the intercomparison study. (Note T represents temperature data, Z represents thickness data and P represents precipitable data, ITPP1, ITPP2, and ITPP3 represents International TOVS Processing Package 1, 2 and 3 respectively, RFG represents regression first guess, CFG represents climatology first guess, MFG represents first guess fields derived from a forecast model, SD indicates the use of surface data in the retrieval scheme, AVHRR represents the use of locally generated regression coefficients and NRC indicates the use of NESDIS regression coefficients.)

DATA ORIGIN	ALPEX	CONTENT	DATA	TOT. NOBS	NOBS (CLEAR)	RET. SCHEME
British Met. Office	ALUK	T, Z, P	clear, cloudy, and microwave	~895	~420	Statistical (Modified ITPP1, NRC)
CIMSS/NOAA-NESDIS Wisconsin	ALWI1	T, Z, P	clear only	~1719	~1719	Physical (Iterative, ITPP2, RFG, SD)
	ALWI2	T, Z, P	clear, cloudy, and microwave	~1819	~1333	Physical (One step, ITPP3, CFG, SD)
	ALWI3	T, Z, P	clear only	~1828	~1828	Physical (One step, ITPP3, RFG, SD)
DFVLR West Germany	ALDF	T, Z, P	clear only	~1389	~1389	Physical (Iterative, modified ITPP2, RFG, SD)
Laboratoire de Meteorologie Dynamique France	ALFR	T, Z	clear, cloudy, and microwave	~4180	~1879	Physical/ Statistical
NASA/GLAS United States	ALNA	T, Z, P	clear, cloudy, and microwave	~903	~614	Physical (Relaxation, MFG)
NOAA/NESDIS Washington	ALNE	T, Z	clear only	~223	~223	Statistical (Operational Algorithm)
University of Bologna Italy	ALIT1	T, Z, P	cloudy only	~1517	-	Physical (Iterative, modified ITPP2)
	ALIT2	T, Z, P	clear only	~1757	~1757	Physical (Iterative, modified ITPP2, SD)
Western Australian Institute of Tech.	ALWA	T, Z, P	clear, cloudy, and microwave	~2808	~1757	Statistical (Modified ITPP1, NRC)

DATA ORIGIN	TASMAN	CONTENT	DATA	TOT. NOBS	NOBS (CLEAR)	RET. SCHEME
Bureau of Meteorology Australia	TAAU	T, Z, P	clear, cloudy, and microwave	~2037	~859	Physical (Modified ITPP3, RFG)
CIMSS/NOAA-NESDIS	TAWI	T, Z, P	clear only	~1626	~1626	Statistical (ITPP2, RFG, SD)
NOAA-NESDIS	TANE	T, Z	clear only	~229	~229	Statistical (Modified ITPP1, NRC)
New Zealand Meteorological Service	TANZ	T, Z, P	clear, cloudy, and microwave	~2049	~1329	Statistical (Operational Algorithm)

DATA ORIGIN	US	CONTENT	DATA	TOT. NOBS	NOBS (CLEAR)	RET. SCHEME
Atmospheric Environment Services (AES) Canada	USCA	T, P	clear, cloudy, and microwave	~192	~95	Statistical (Modified ITPP1, NRC)
British Met. Office	USUK	T, Z, P	clear, cloudy, and microwave	~163	~83	Statistical (Modified ITPP1, NRC)
CIMSS/NOAA-NESDIS	USWI	T, Z, P	clear, cloudy,	~134	~42	Physical (Iterative, AVHRR)

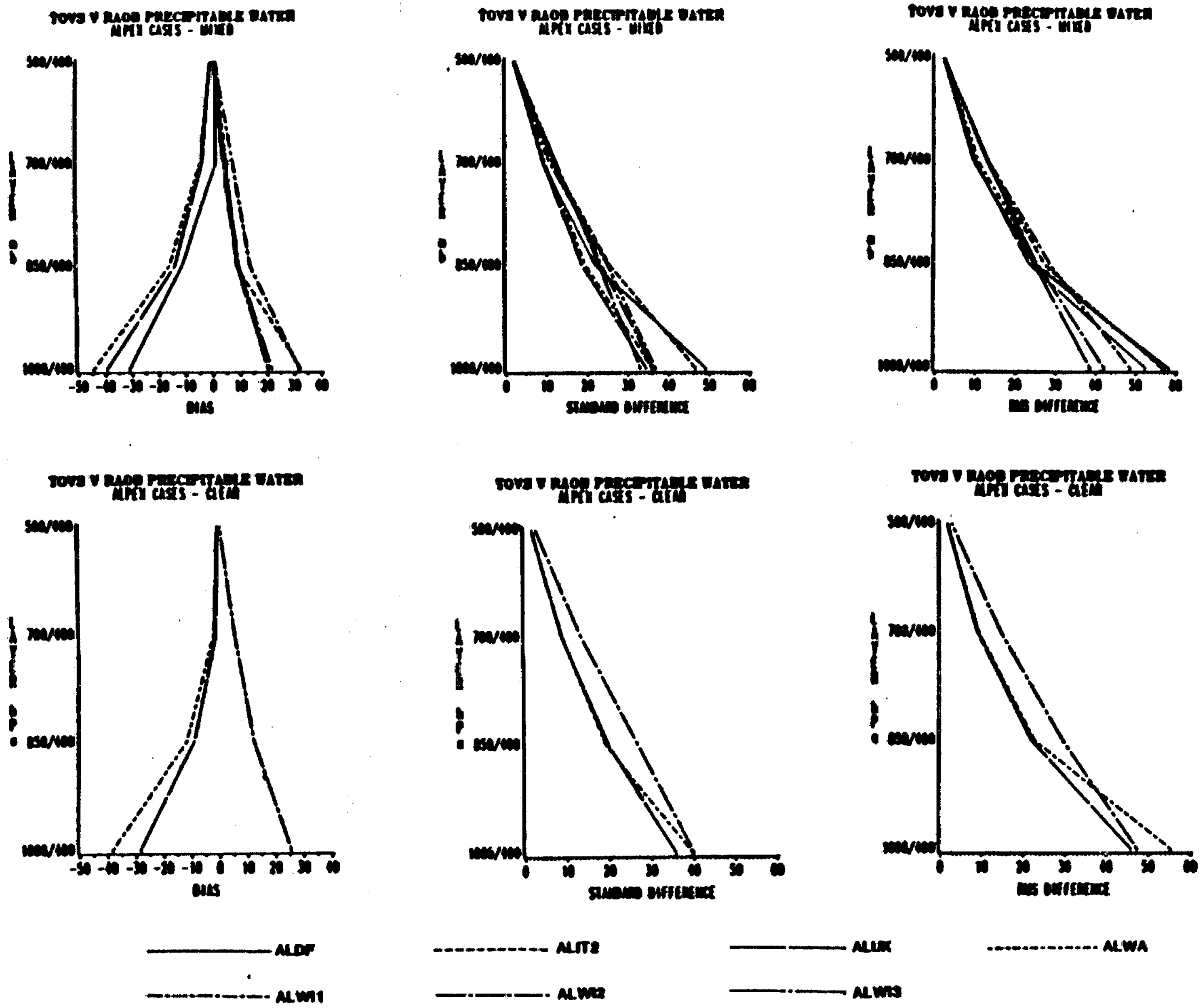


Figure 9. Basic statistics for TOVS retrievals compared with radiosondes for precipitable water observations for both the mixed and clear case. Precipitable water units (cm x 100)

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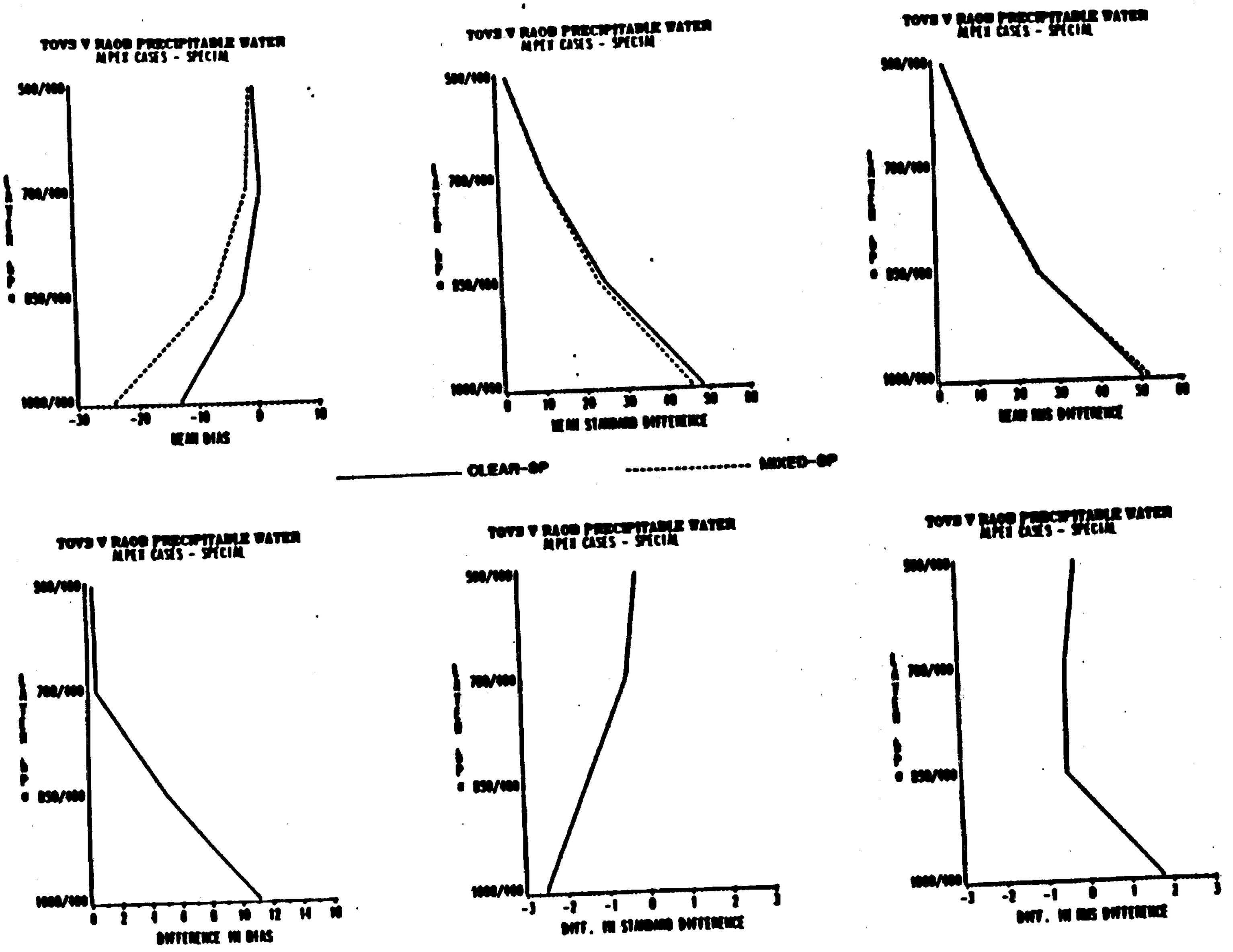

Figure 10. Mean statistics and the difference in mean statistics for precipitable water for the ALUK, ALWA and ALW2 cases.

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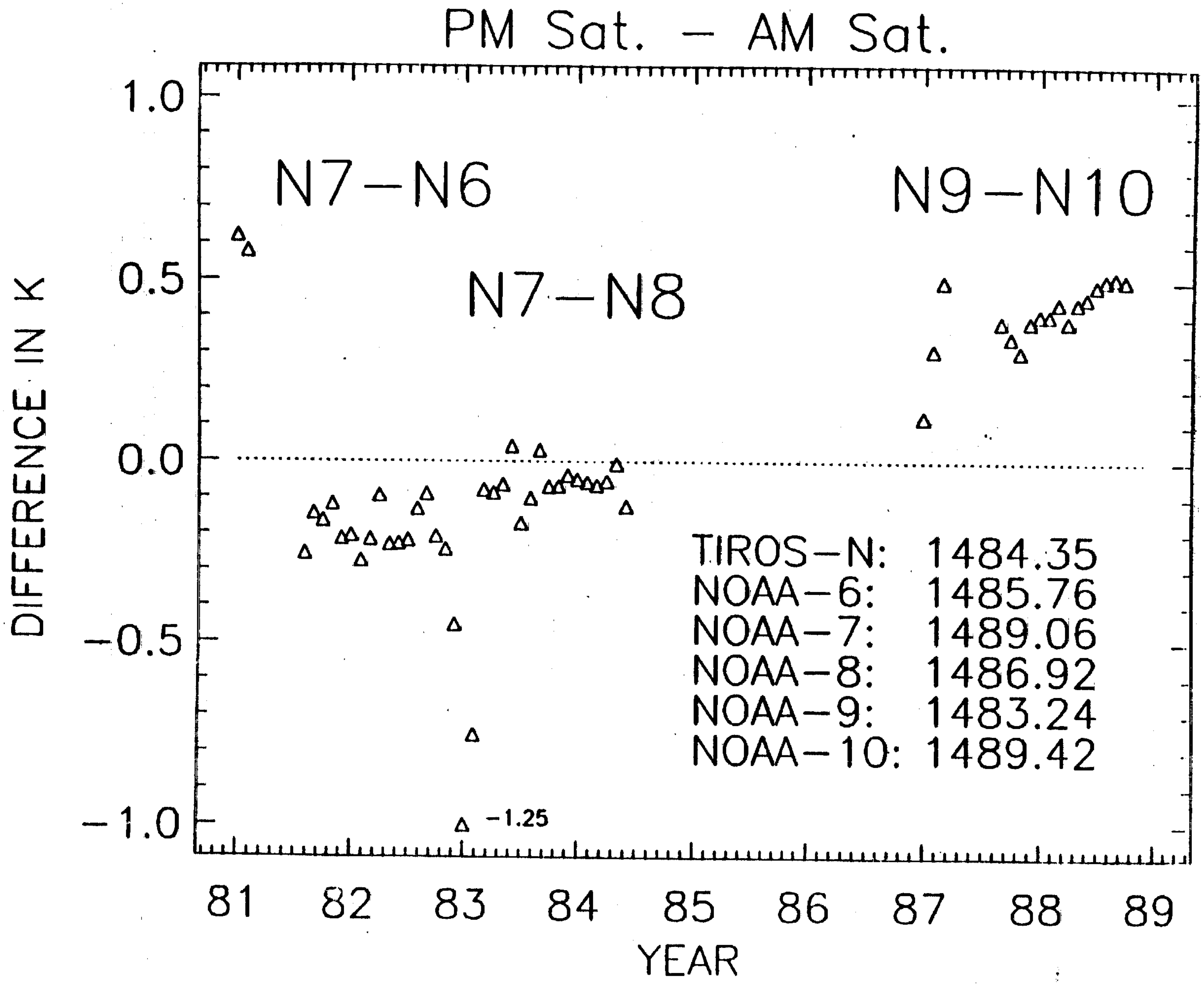
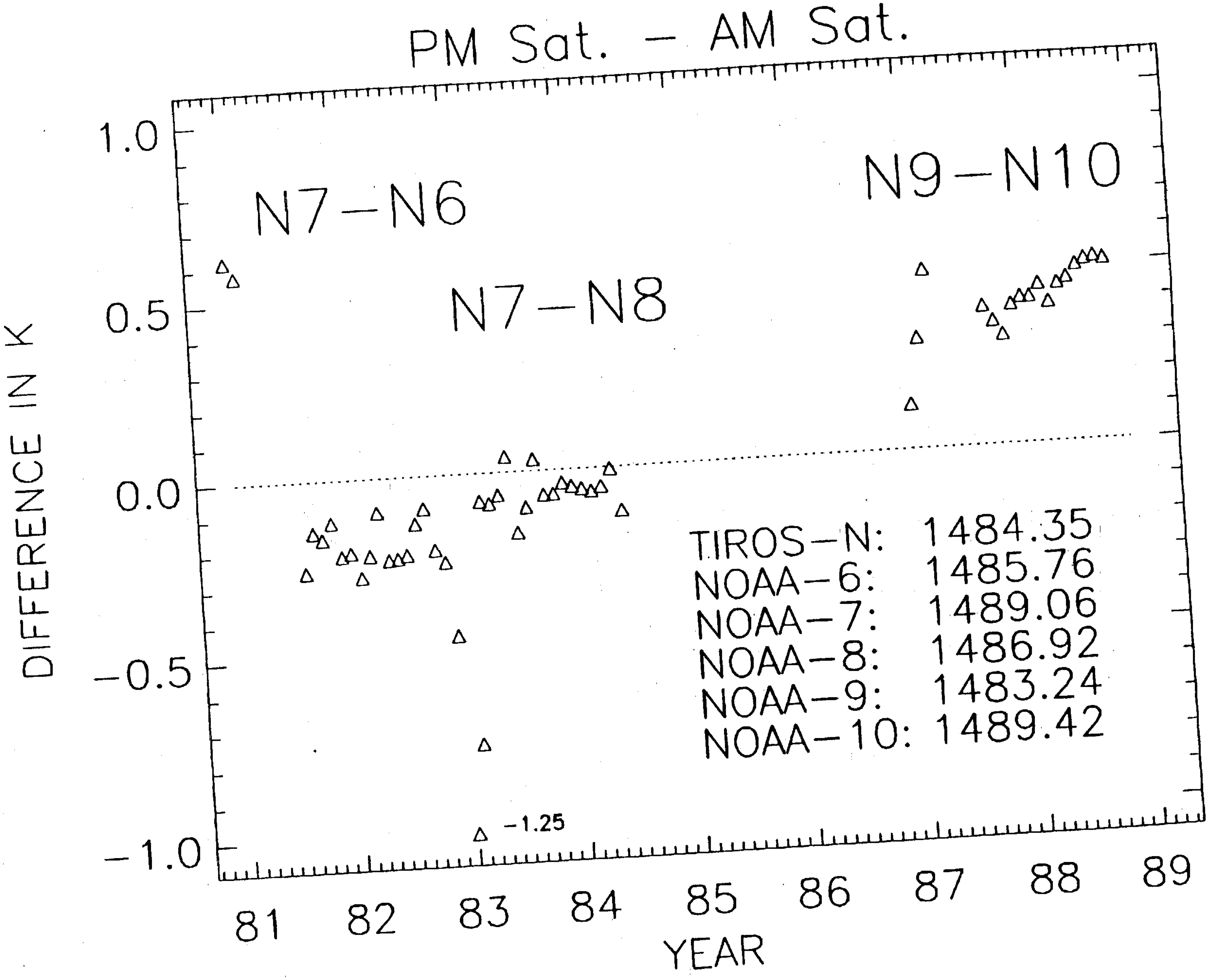
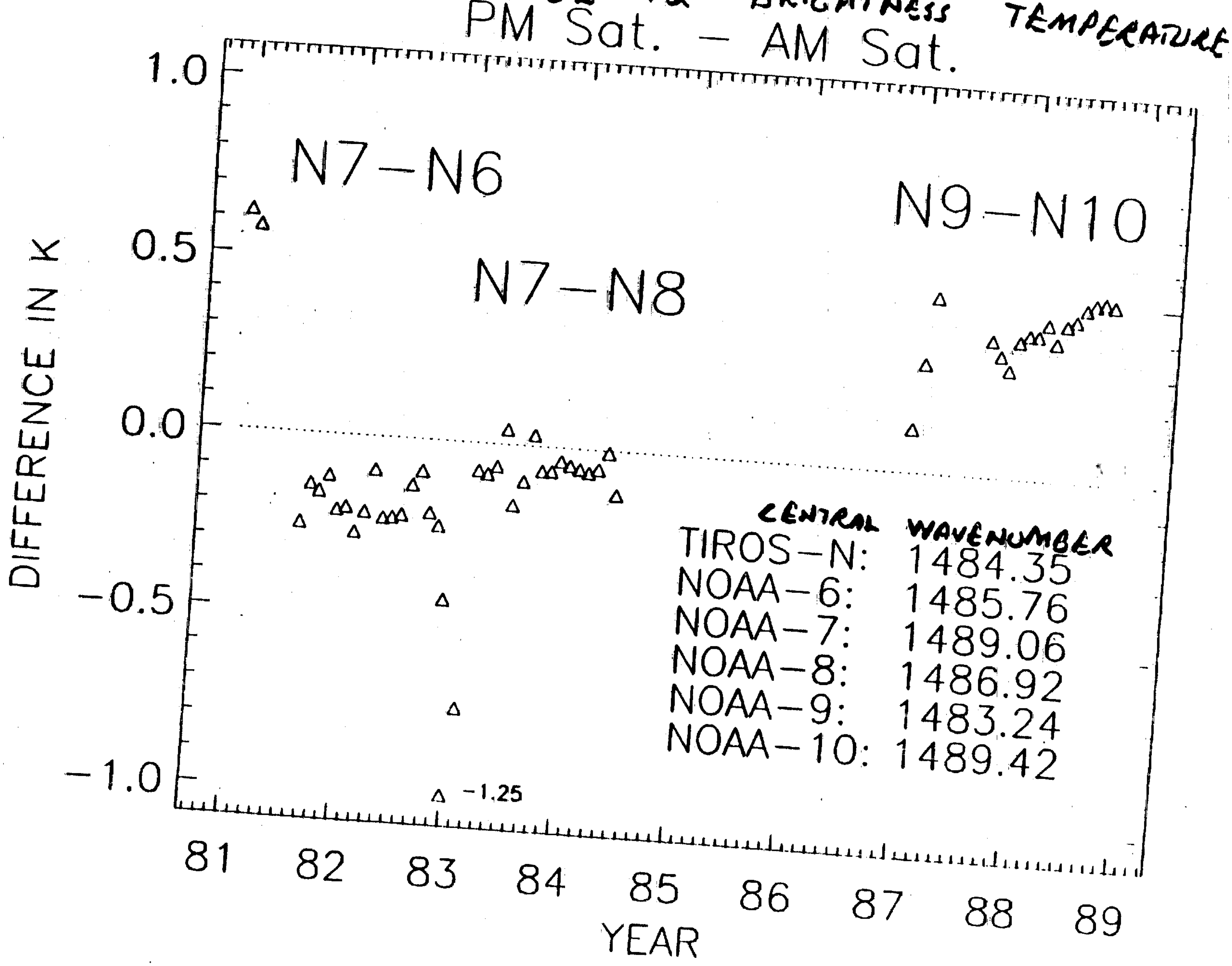

PM Sat. – AM Sat.
N7–N6
N7–N8
N9–N10
−1.25
TIROS–N: 1484.35
NOAA–6: 1485.76
NOAA–7: 1489.06
NOAA–8: 1486.92
NOAA–9: 1483.24
NOAA–10: 1489.42
DIFFERENCE IN K
1.0
0.5
0.0
−0.5
−1.0
YEAR
81
82
83
84
85
86
87
88
89

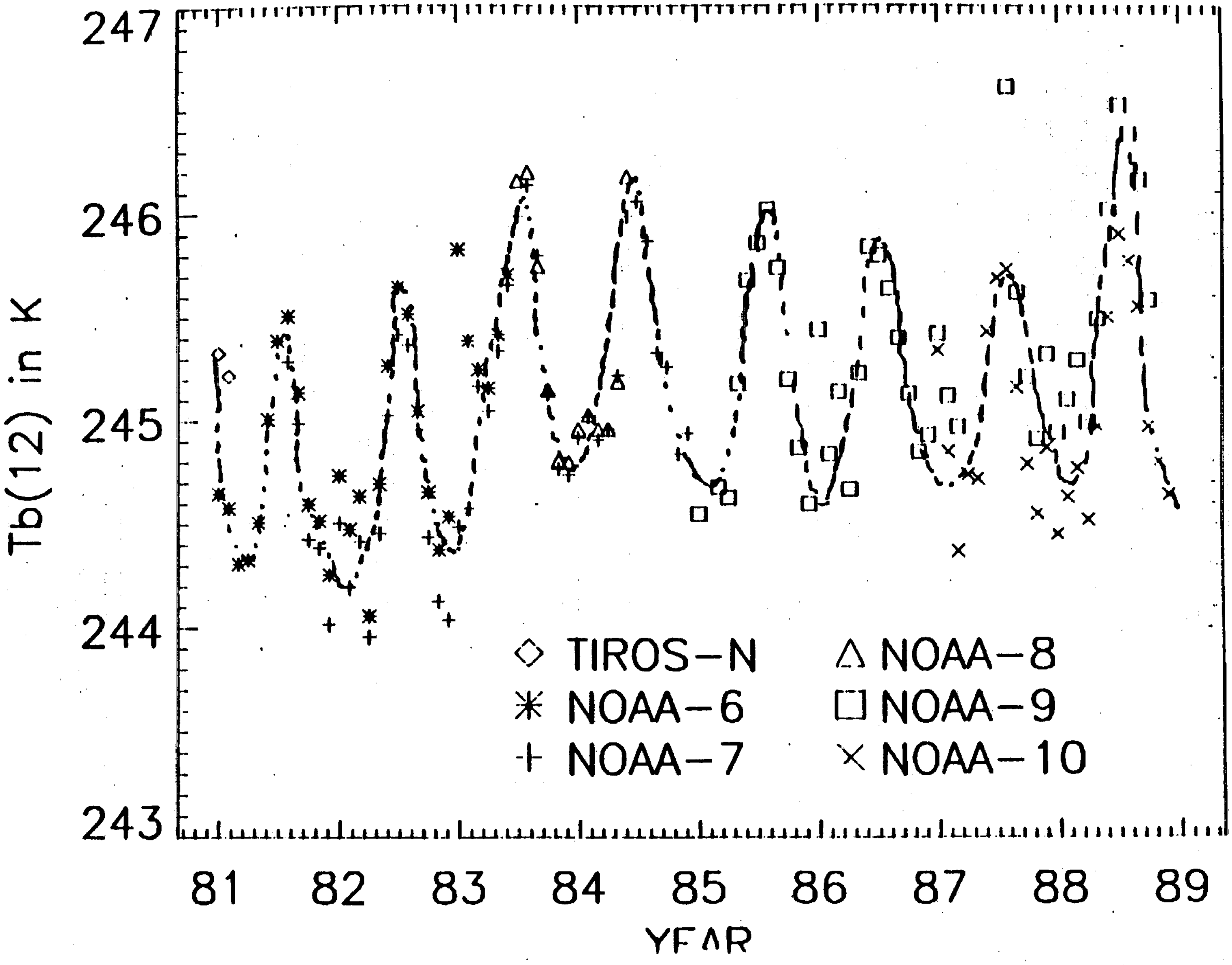
[illegible]

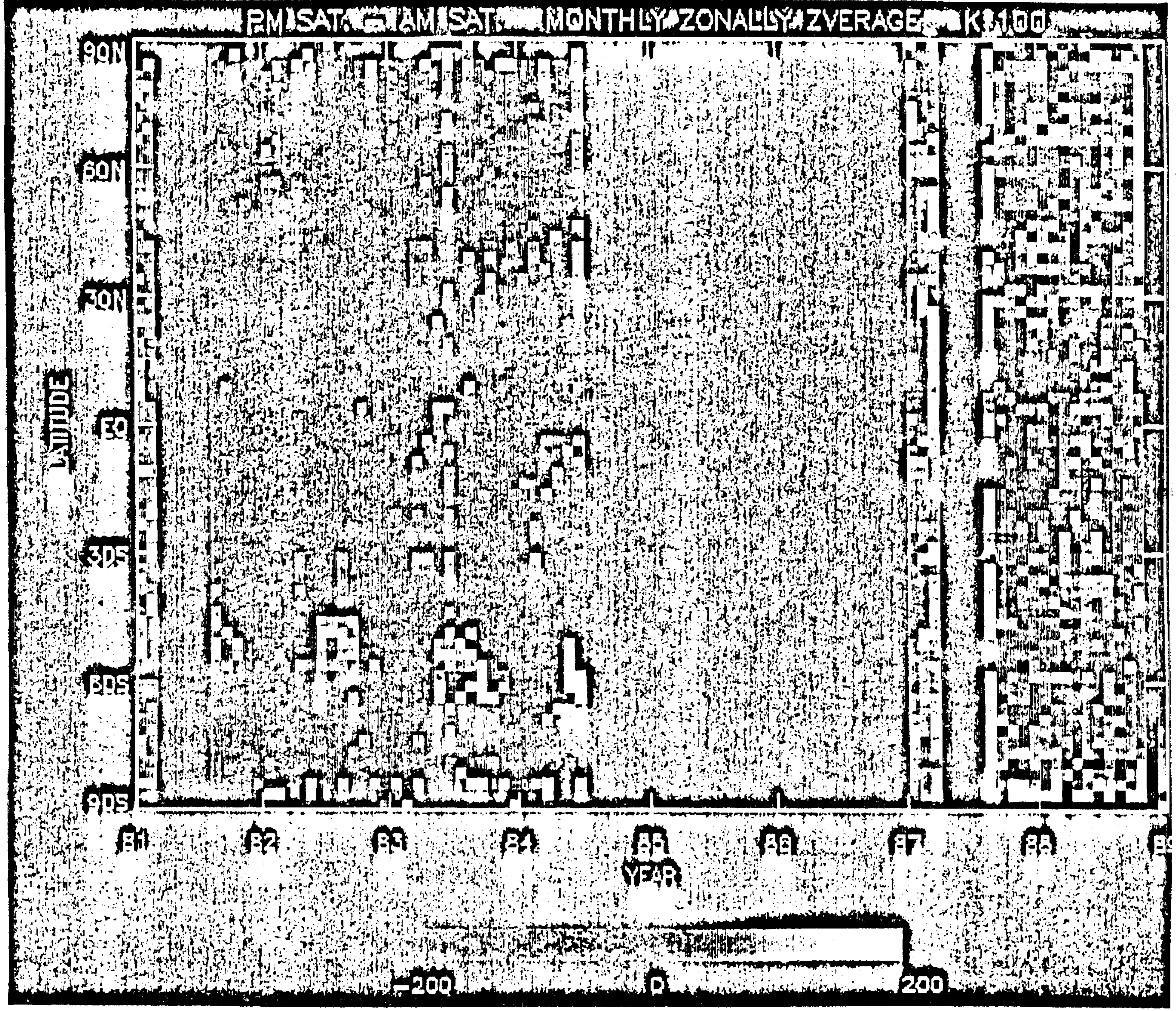

PM Sat. – AM Sat.
N7–N6
N7–N8
N9–N10
DIFFERENCE IN K
1.0
0.5
0.0
–0.5
–1.0
–1.25
YEAR
81
82
83
84
85
86
87
88
89
TIROS–N: 1484.35
NOAA–6: 1485.76
NOAA–7: 1489.06
NOAA–8: 1486.92
NOAA–9: 1483.24
NOAA–10: 1489.42

GLOBAL HIRS CHANNEL 12 BRIGHTNESS TEMPERATURE



GLOBAL, MONTHLY HIRS CHANNEL 12





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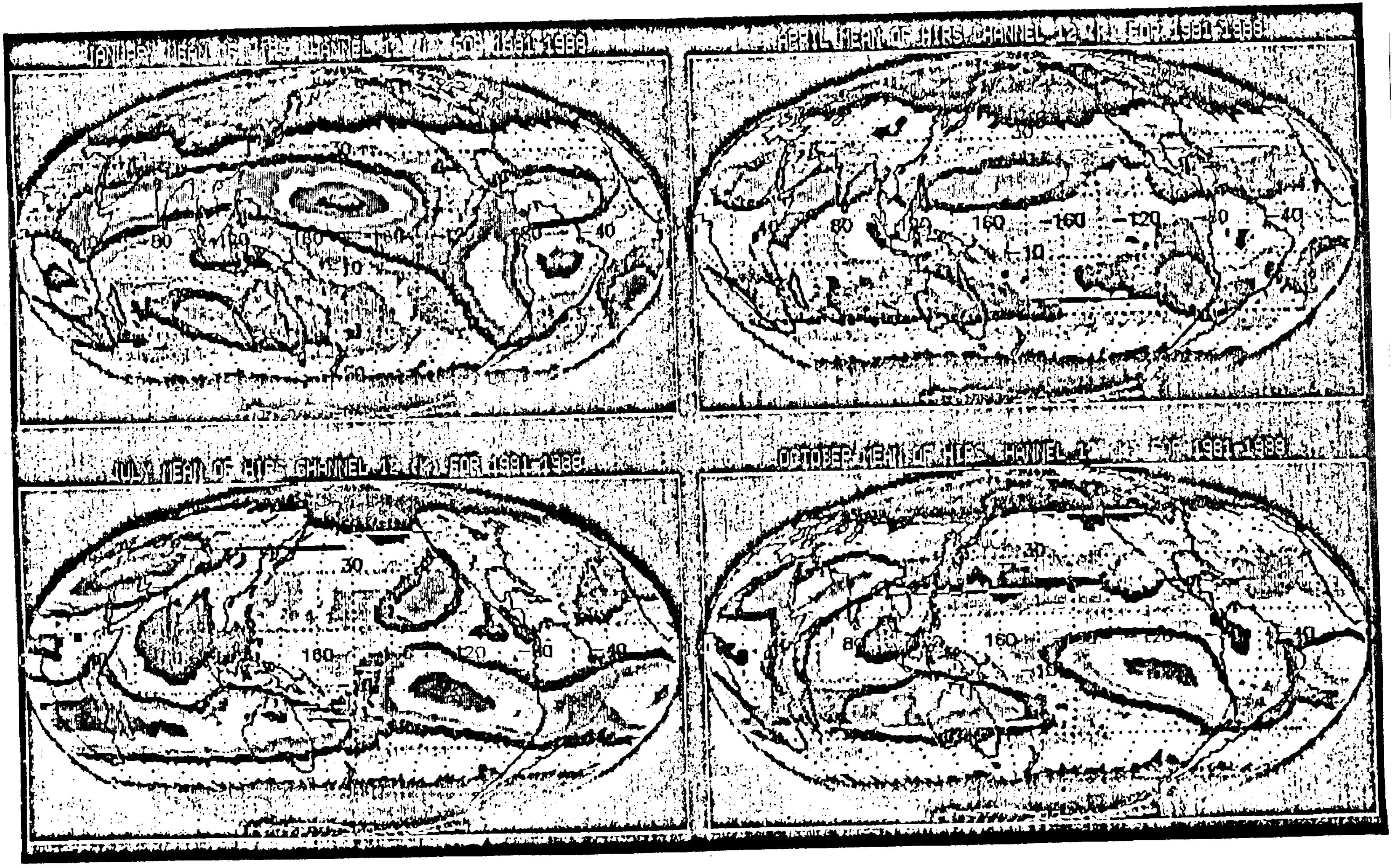

JANUARY MEAN OF HIRS CHANNEL 12 (K) FOR 1981-1988

APRIL MEAN OF HIRS CHANNEL 12 (K) FOR 1981-1988

JULY MEAN OF HIRS CHANNEL 12 (K) FOR 1981-1988

OCTOBER MEAN OF HIRS CHANNEL 12 (K) FOR 1981-1988

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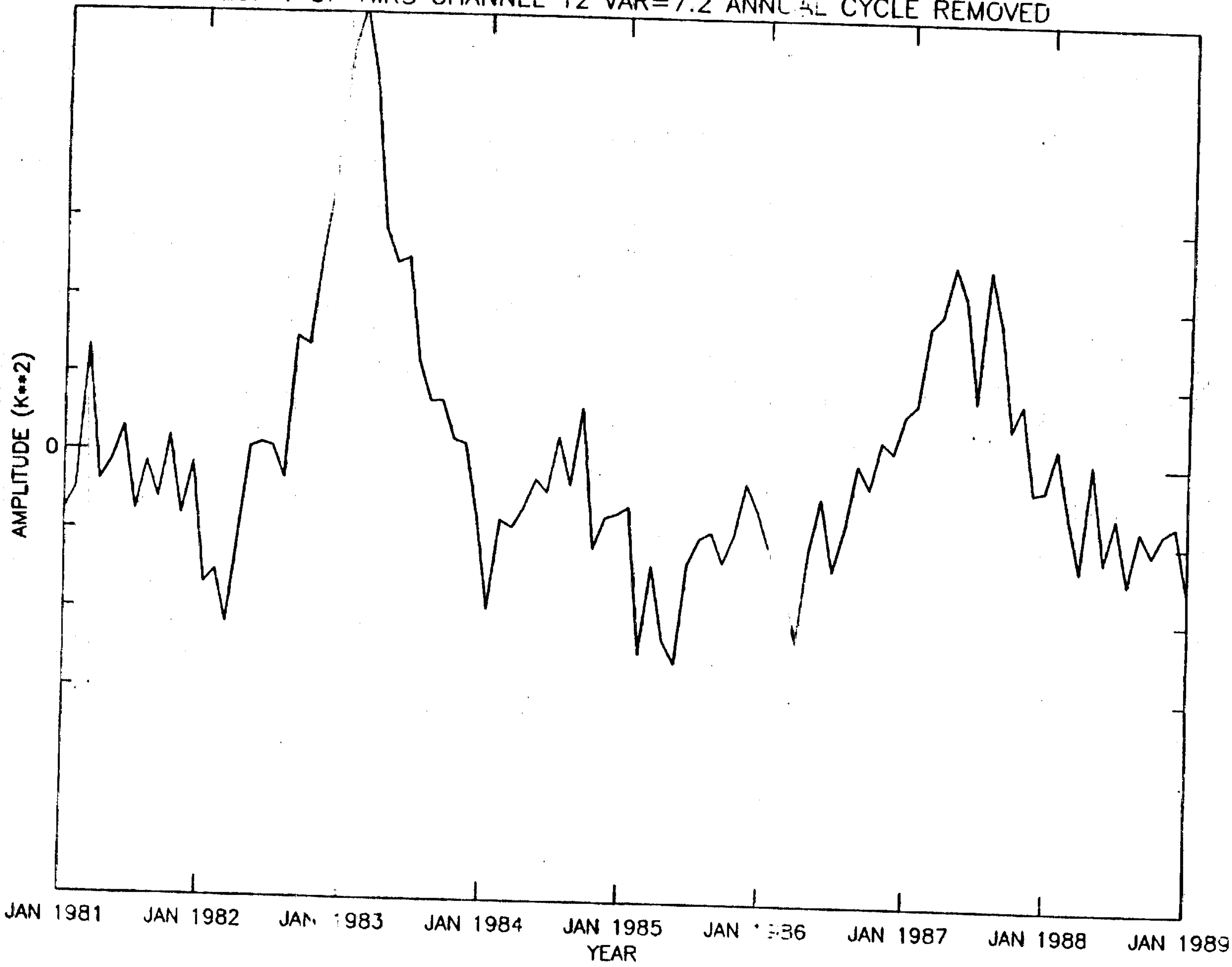
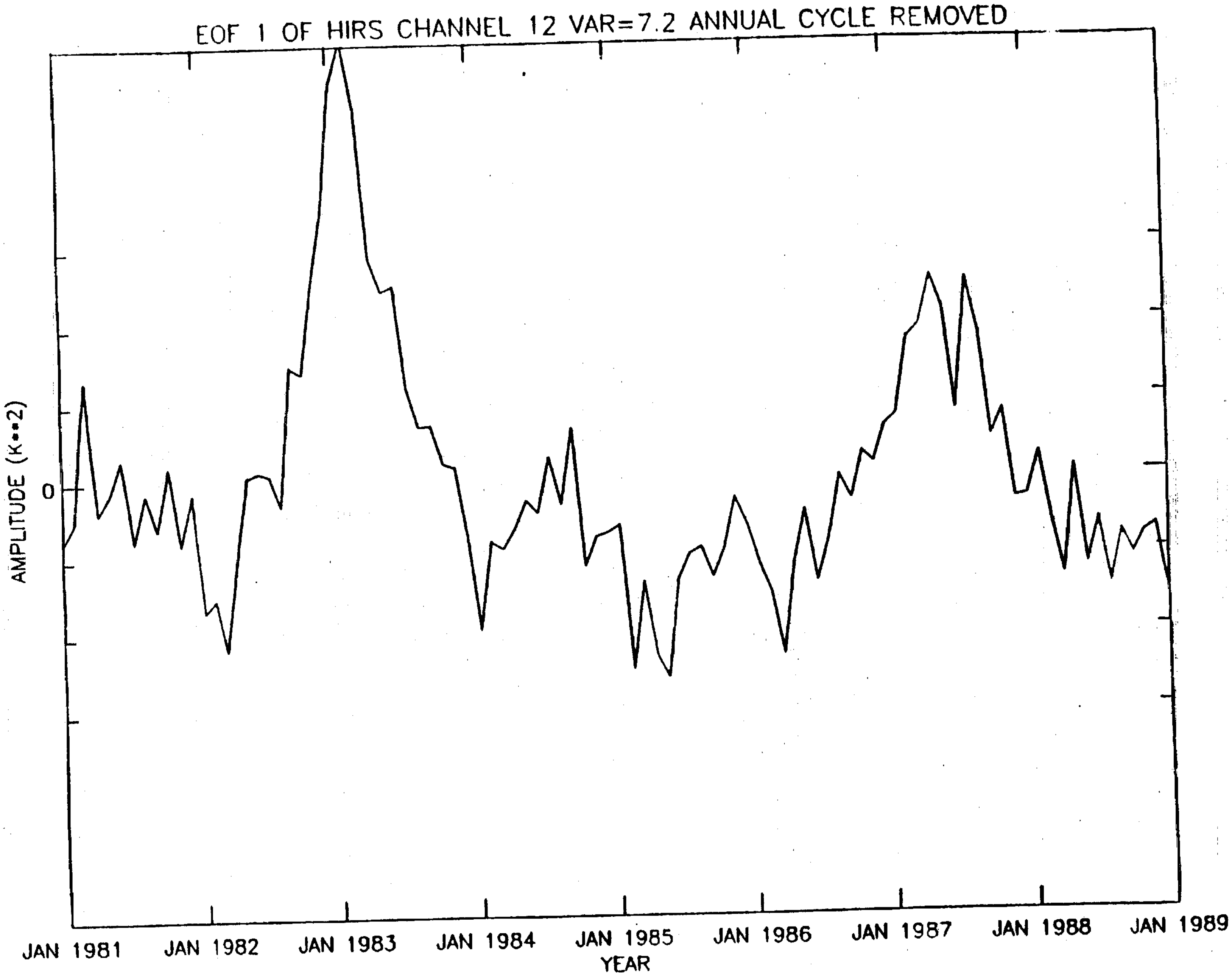
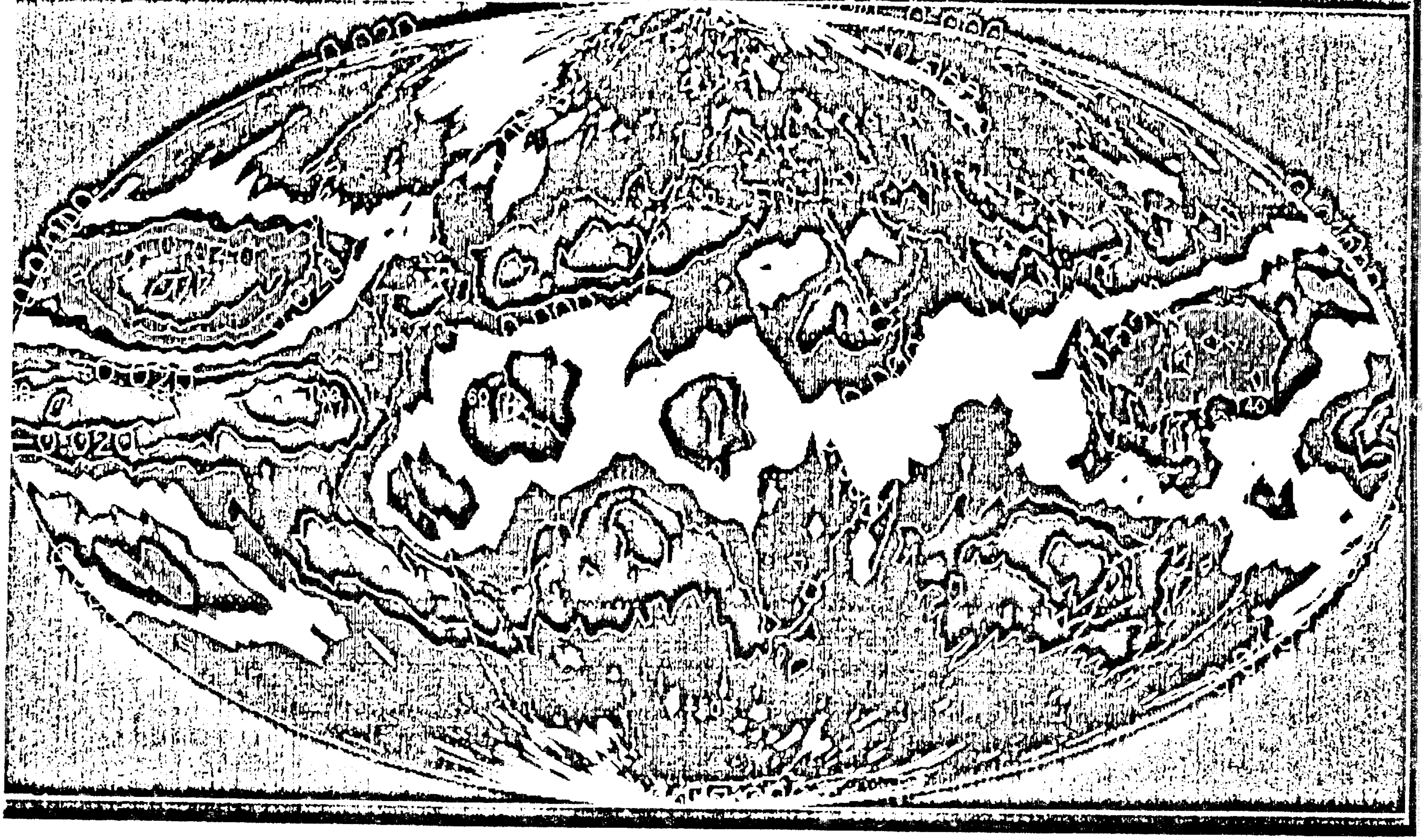
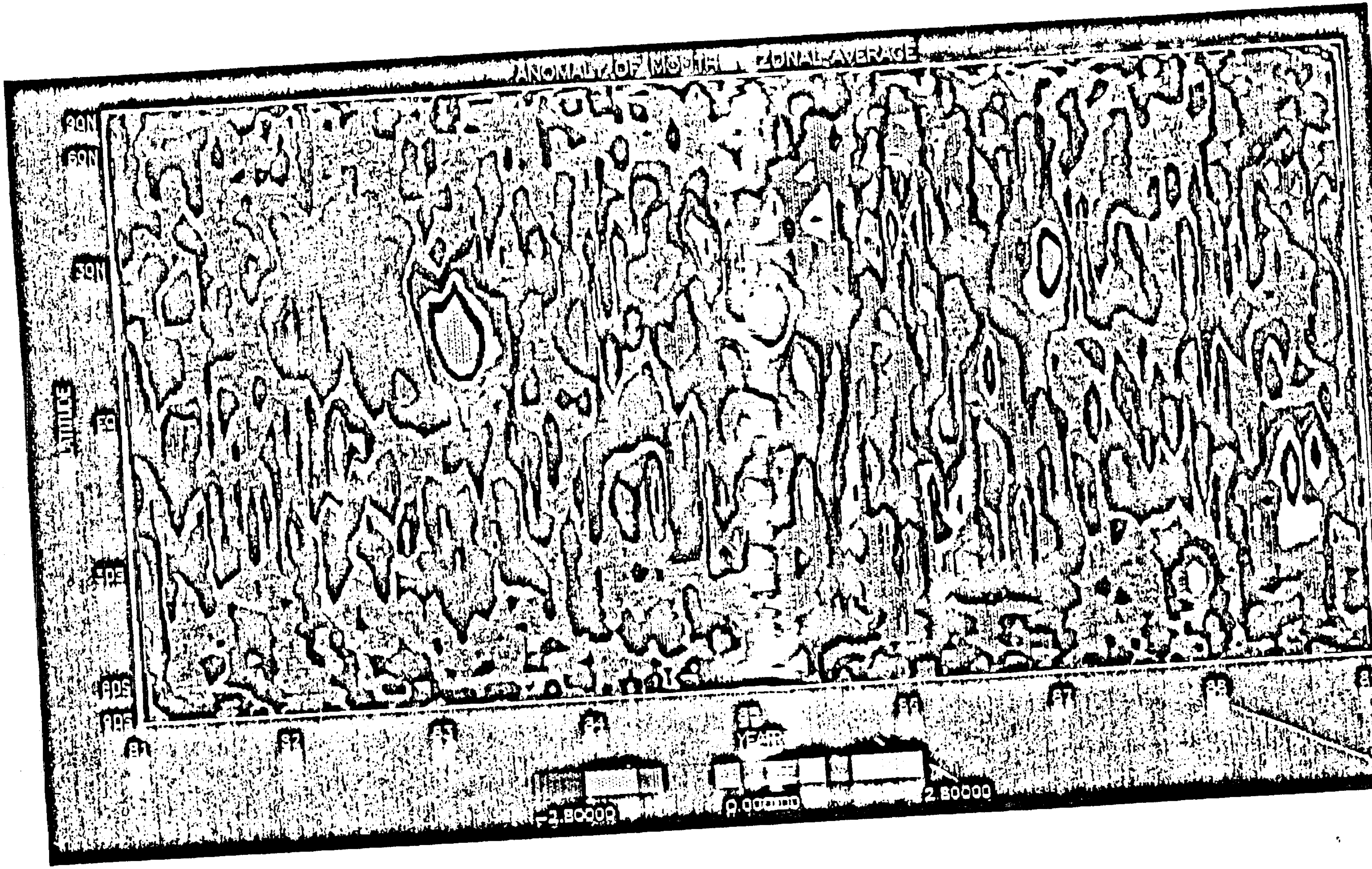
EOF 1 OF HIRS CHANNEL 12 VAR=7.2 ANNUAL CYCLE REMOVED




EOF 1 OF HIRS CHANNEL 12 VAR=7.2 ANNUAL CYCLE REMOVED

EOF 1 OF HIRS CHANNEL 12 1981-1988 ANNUAL CYCLE REMOVED




ANOMALY OF MONTH - ZONAL AVERAGE
90N
60N
30N
EQ
30S
60S
90S
LATITUDE
81
82
83
84
85
86
87
88
89
YEAR
-2.80000
0.000000
2.80000

3. Lessons of history - Applications to the EOS era

3.1. We must establish long-term, global validation programs based on the three principles of validation

3.2. Both satellite and in situ data must be subject to rigorous quality control and continuous monitoring

3.3. Extend and examine the overlap periods of similar instruments on different satellites

3.4. Sampling of most fields must extend over several ENSO cycles, since most fields show large interannual variability related to ENSO.

~~3. Lessons of history - Applications to the EOS era~~

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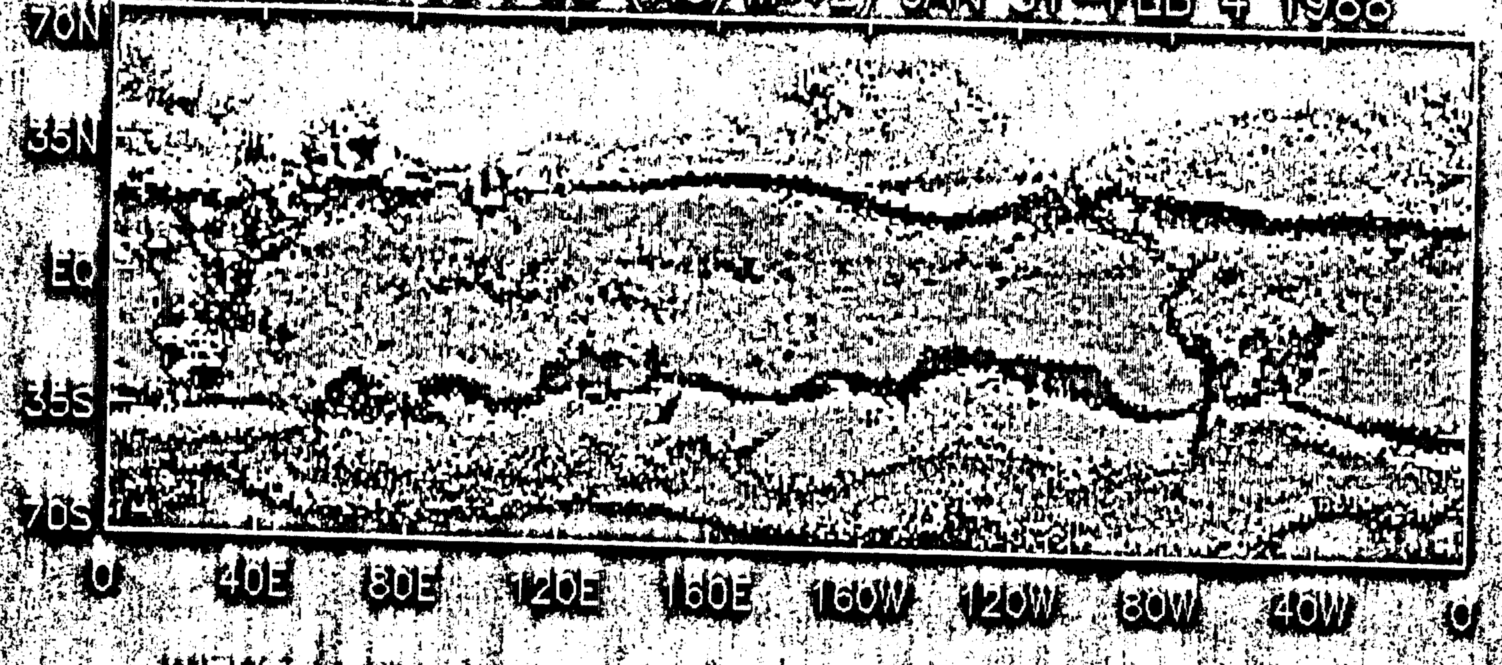
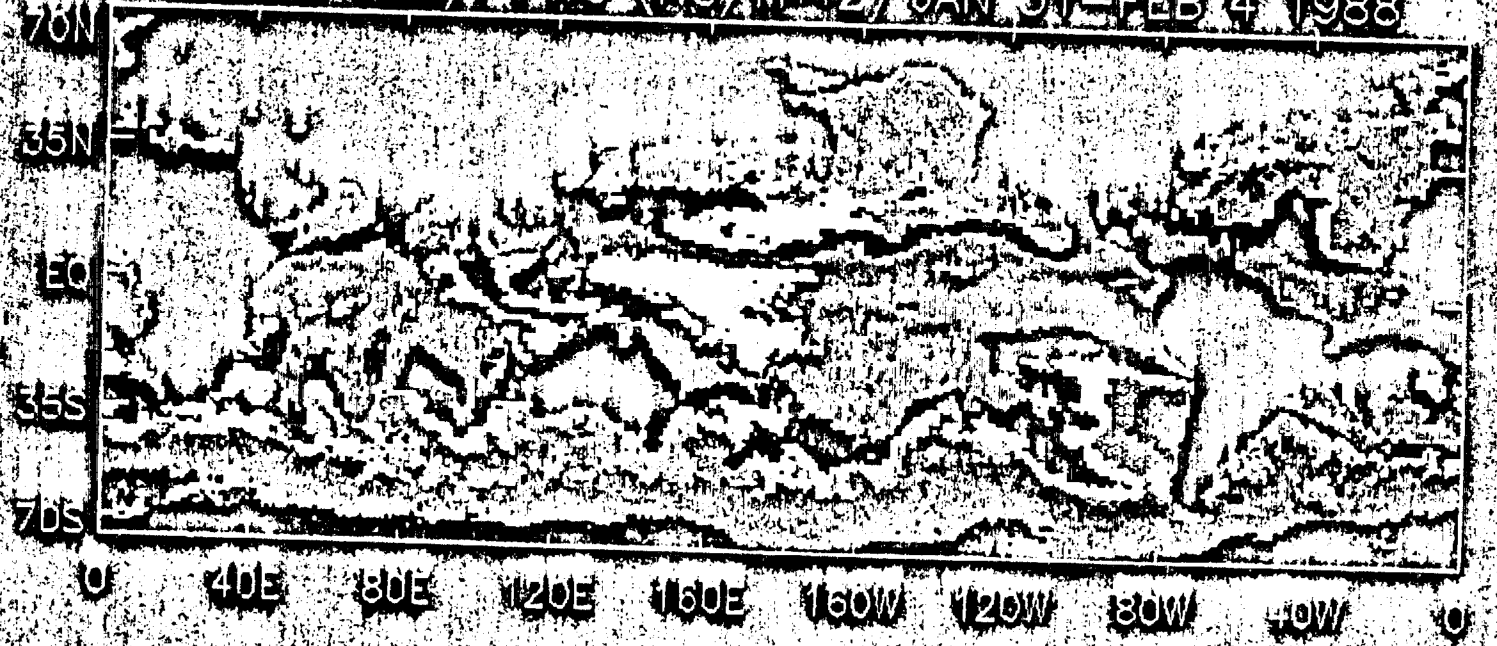
31 NOAA-10 PWC (KG/M**2) JAN 31–FEB 4 1988



WENTZ SSM/I PWC (KG/M**2) JAN 31–FEB 4 1988



510-43

172301

N94-23605

NIST
National Institute of Standards and Technology

Non-regulatory agency (Department of Commerce)

Congressional mandate:
    Assist US industry; Improve health, safety, and environment; Conduct fundamental research in science and engineering

1989 Trade Bill added responsibility for extramural programs, especially in the areas of "competitiveness".

Radiometric Physics Division

National standards in radiation thermometry, spectroradiometry, photometry, and spectrophotometry;

Dissemination of these standards by providing measurement services to customers requiring calibrations of the highest accuracy;

Conduct fundamental and applied research to develop the scientific basis for future measurement services.

NIST SRM's
Standard Reference Materials
SP-260 and Appendix
(301) 975-6776

EXAMPLES

SRM 740 and 741. Defining fixed point for freezing zinc (419.58 °C) and tin (231.9681 °C) for calibrating thermometers and thermocouples.

SRM 1967. High purity platinum wire for thermocouple construction.

SRM 1920 (0.74-2.0 μm). Reflectance standard for establishing the accuracy of the wavelength scale of a reflectance spectrophotometer.

SRM 2021 (0.28-2.5 μm). Directional-hemispherical reflectance (black porcelain enamel)

NIST Calibration Services
SP 250 and Appendix
(301) 975-2002

EXAMPLES

Contact Thermometry: Calibration of thermometers, thermocouples, and platinum, germanium, and rhodium-iron resistance thermometers

Radiation Thermometry: Calibration at 650 nm of optical pyrometers or ribbon filament lamps, 800 °C to 4200 °C

Optical Radiation Measurements:

- Spectral transmittance and reflectance, 0.25 to 2.5 μm;
- Spectral radiance ribbon filament lamps, 0.225 to 2.4 μm;
- Spectral irradiance lamps 0.25 to 2.4 μm;
- Photodiode (silicon) spectral response rental package, 0.2 to 1.1 μm;
- Special tests of radiometric detectors, 0.2 to 1.8 μm, 10 μW and greater power levels;

Selected R/D Programs

Ambient Environment

TASK	λ	WHO	DATE
Ambient IR Facility for radiance temperature, minimum resolvable temperature, and imaging studies	3-14	Navy	1987
Calibration of commercial blackbody, 10 °C to 80 °C	8-14	Navy	1989
Characterization of commercial IR spectroradiometer	8-14	Navy	92-94
Calibrate 10-cm aperture water-bath blackbody (10 °C to 80 °C)	3-14	Navy	92-94
Build and characterize tin-point standard blackbody (231.928 °C)		Air Force	92-93
Calibrate blackbody source for radiance temperature and uniformity		SDIO	1992
Detector comparator facility for absolute calibration; develop IR detector standards	1.5-25	Air Force	91-94
Extend photodetector transfer standards to IR; calibrate with the HACR (High Accuracy Cryogenic Radiometer)	to 10.6	Air Force	91-93

Selected NIST R/D Programs

Cryogenic Environment

TASK	λ	WHO	DATE
Cryogenic facility for calibration of blackbodies from total power measurements (LBIR)	0.3-30	SDC Army	1989
Calibration of blackbody sources from 150 K to 1000 K			1989
Add spectral capability to LBIR	2-30	SDIO SDC	1992
Spectral calibration of cryogenic sources, detectors, and filters			1993
Extend noise floor of LBIR detector from 20 nW to 70 pW		SDIO	1992

Selected NIST R/D Programs

Spectrophotometric Measurements

TASK	λ	WHO	DATE
Calibration facility for bidirectional reflectance distribution function	0.33-10.6	Air Force	90-93
Develop IR diffuse reflectance standards	2-20	Navy	91-93
Optical heterodyne densitometry (12 decades; cryogenic operation by 1992)	0.633 & 10.6		1990

Relevance to EOS/TIR Calibration
Current Capabilities

AMBIENT (minimum 1 meter path length)

<u>Calibrate customer blackbody sources</u>

Calibrate unknown blackbody for radiance using a well-characterized NIST blackbody source by matching the radiant fluxes with an IR radiometer (Barnes): absolute uncertainty 0.11 °C at 10 °C; 0.25 °C at 45 °C; capable of precision of 1 mK;

Measure uniformity of unknown blackbody source with a minimum resolvable temperature difference of 50 mK at 33 °C (Barnes)

Relevance to EOS/TIR Calibration
Current Capabilities

CRYOGENIC (20 K shield; 4 K ESR detector)

Calibrate customer blackbodies

Total radiant flux measurements; size of BB aperture and temperature are constrained by the detector;

Calibrate thermometers of source with respect to radiance temperature as a function of BB aperture size;

Absolute radiometric uncertainty at the 95% level is about 1%, corresponds to about 1.2% uncertainty in radiance temperature;

No uniformity studies are possible and strict vacuum requirements apply ($<1.33\text{x}10^{-6}$ Pa total pressure and $<1.33\text{x}10^{-8}$ Pa hydrocarbons before cooling with the 15 K helium gas).

Next LBIR workshop is scheduled for Tuesday morning, September 15, in conjunction with the 3rd annual SDL/USU Symposium on Cryogenic IR Radiometric Sensor Calibration and the EOS/TIR Peer Review Workshop.

EOS TIR Instruments

Overall Spectral Coverage (μm)

AIRS	3.4 - 15.4 0.4 - 1.7
ASTER	8 - 12, 1.6 - 2.5, 0.5 - 0.9
CERES	0.3 - 50, 8 - 12, 0.3 - 5
HIRDLS	6 - 12
MODIS-N	0.415 - 14.24
MOPITT	2.3 - 4.7
SAFIRE	62.5 - 125, 25.6 - 32.3, 6.4 - 15.9
TES	2.3 - 16.7

EOS/TIR Lab Source Verification
TIR Round Robin

Definition TIR Round Robin to VERIFY the calibration of the sources that are used for the absolute radiometric calibration of the individual EOS sensors

Requirements (preliminary)

Spectral response: 2.3 - 15

3% total absolute uncertainty in radiance at the 3σ level

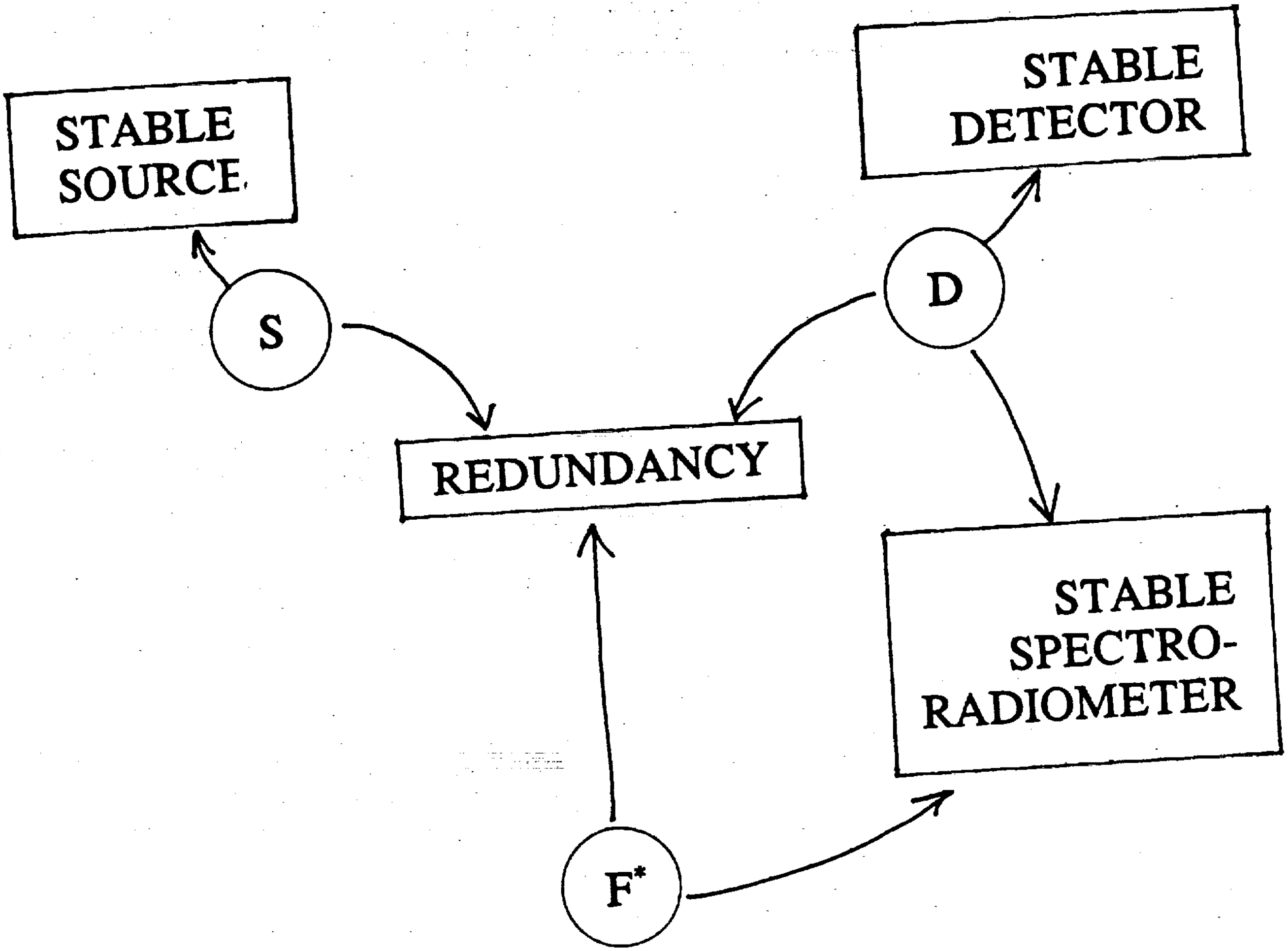
Long term stability

Proven vacuum compatibility

Meets EOS schedule

Calibration at NIST, or NASA-acceptable traceability

Philosophy of Lab Source Verification



STABLE SOURCE

STABLE DETECTOR

S

D

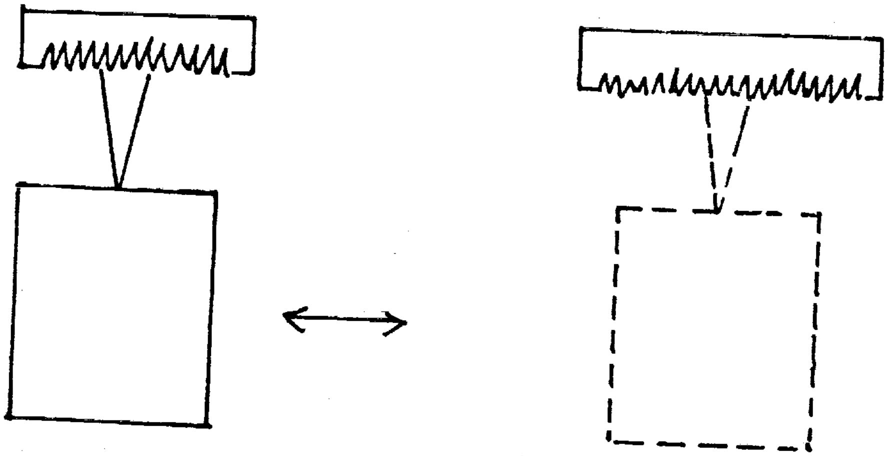
REDUNDANCY

STABLE SPECTRO-RADIOMETER

F*

* Filter, monochromator, or interferometer

STABLE SOURCE



EOS LAB SOURCE

ROUND ROBIN SOURCE
(Blackbody)

EOS Instrument

PRT resistance vs T_λ of the RR source is NIST "traceable"

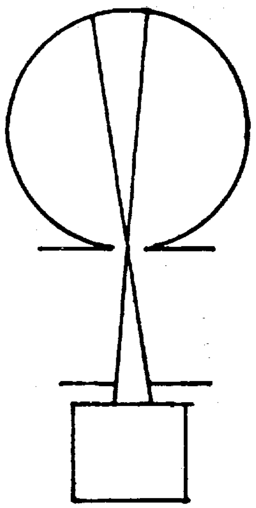
<u>Problem</u> Thermal radiation properties of the RR Source could change

Return to NIST often?
Design way to monitor $\epsilon(\lambda)$?

<u>Option</u> Circulate a RR detector (not necessarily stable) to compare the sources

STABLE RADIOMETER

(broadband or spectral)
(irradiance or radiance mode)



EOS LAB SOURCE

ROUND ROBIN
RADIOMETER

Calibration constants determined or confirmed by NIST

Round robin source could be included for redundancy

DESIRED INFORMATION

INSTRUMENT SPECIFICATIONS

CALIBRATION METHODS (pre-flight and on-board)

ROUND ROBIN

Overall Philosophy
Laboratory Sources to be verified
Environment for measurements
Revised Requirements

JPL

Diffuse Panel Studies

Conclusions

MISR

Multi-angle
Imaging
Spectro-
Radiometer

In the evaluation of new candidate materials for flight applications, considerations are given to
* optical performance (lambertian, spatially and spectrally uniform, high reflectance),
* static charge build-up,
* environmental stability (ruggedness, UV exposure, particle bombardment, etc.), and
* fabricability

ITO coated Spectralon appears to have produced a conductive material

Many other design issues remain

S1-43

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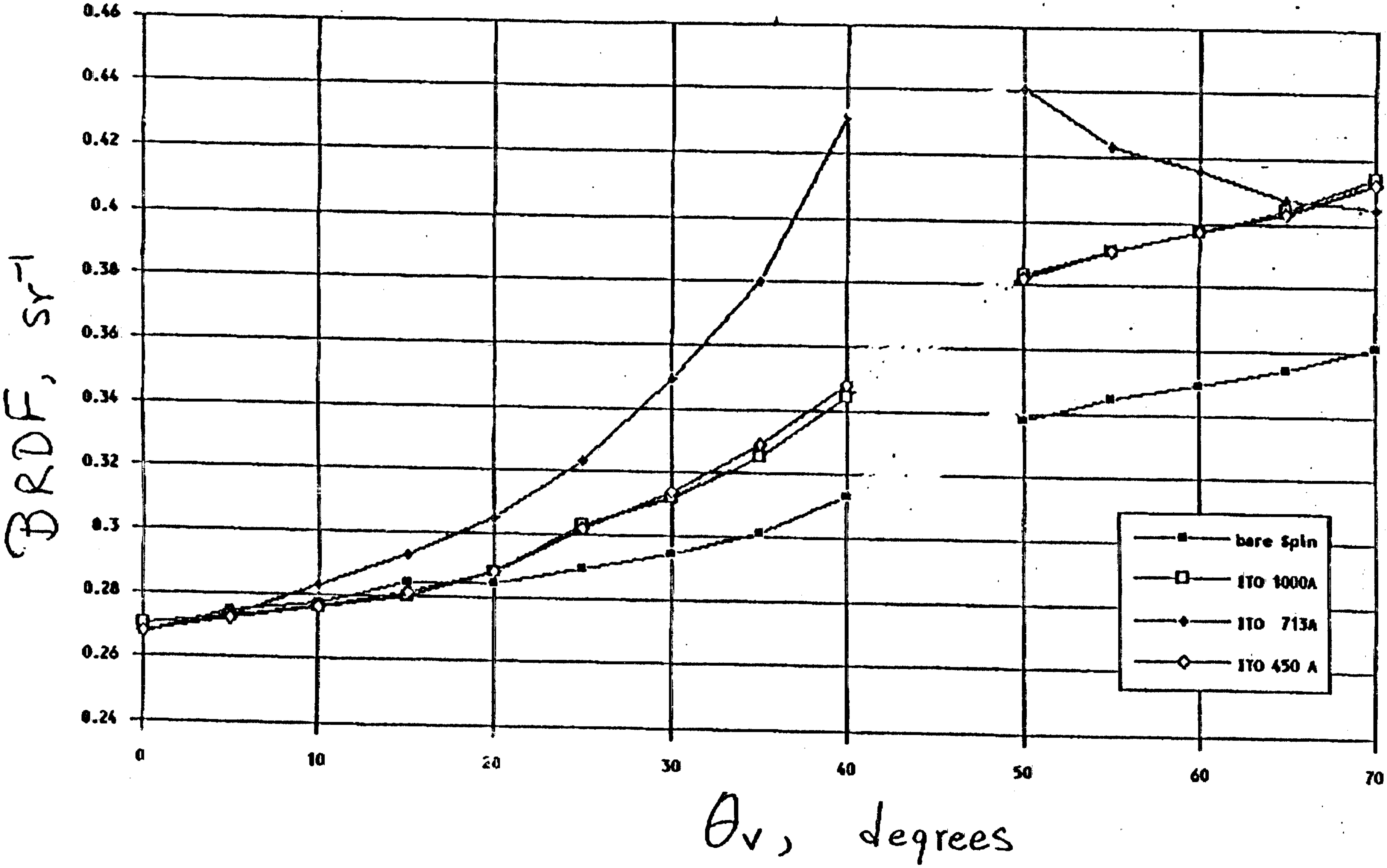
N94-23606

TRW
Pete Jarecke
24mar 92

ITO-Coated
Spectralon

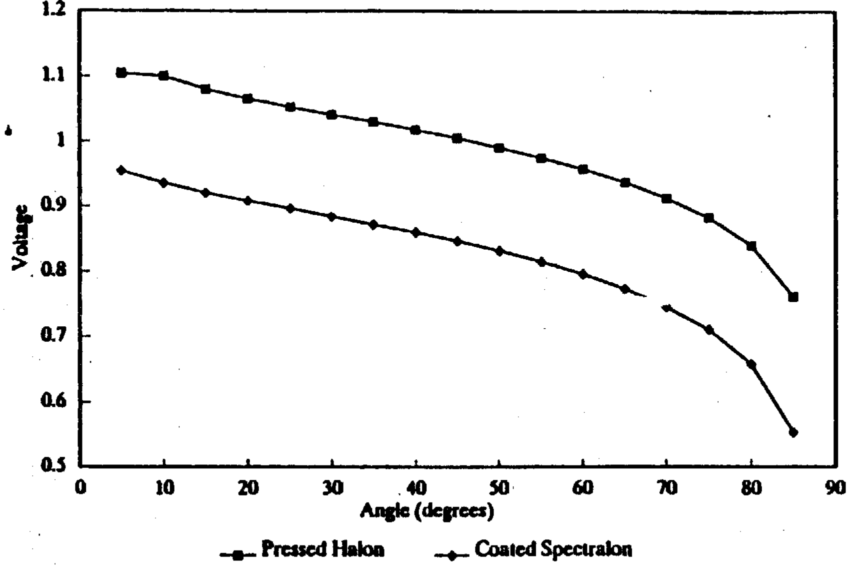


U of A
Stuart Biggar
20 Mar 92

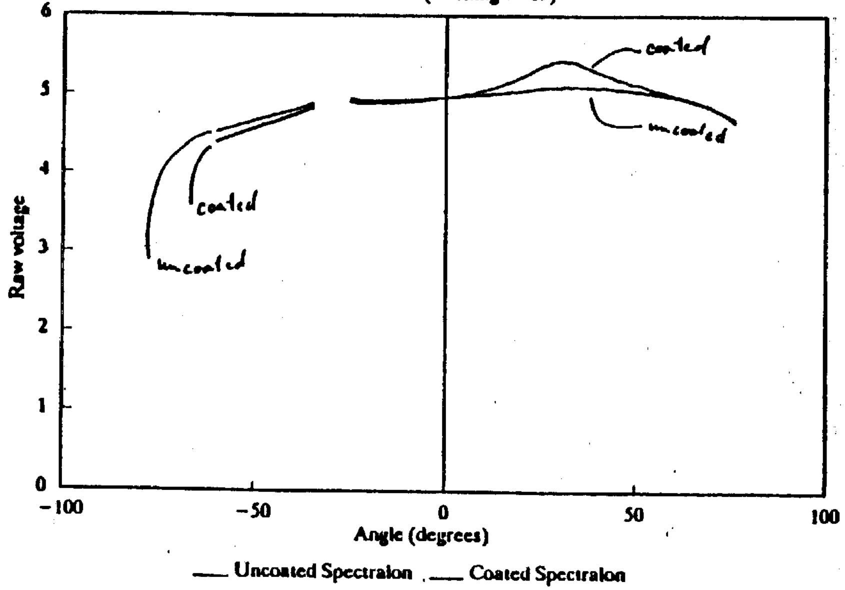
ITO - Coated
Spectralon
(1074Å layer)

Reflectance Factor, 450 nm

Normal view, varying incidence, halogen DXW source

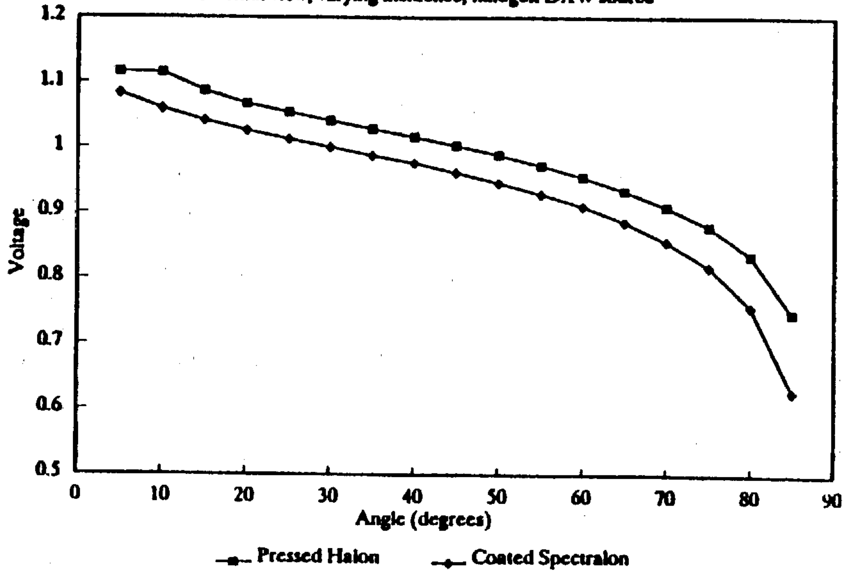


Raw voltages, -30 degree illumination, varying view
Filtered source (Corning 7-69)



Reflectance Factor, 650 nm

Normal view, varying incidence, halogen DXW source



Static Charge Data

Requirement

Materials exposed to the space environment cannot charge more than 100 V, and cannot be an electrostatic discharge source. If a charged particle detector is on the platform, the requirement may drop to 10 V. This requirement ensures that no charge arcing will occur which may affect the performance of other instruments, or the platform.

Charge data, V

Spectralon (pure PTFE, and carbon doped)
* Test results at 5 nA/ cm^2 current density, EOS simulated conditions

Energy (keV)	Requirement	sample 1 (ρ~99%)	sample 2 (ρ=94.75%)	sample 3 (ρ=77%)	ITO-Coated Spectralon
3	100	670	410	200	20V
5	100	1600	1150	1100	
10	100	3260	2560	2320	
15	100	4647	4515	3150	

Resistivity data, Ω/cm^2

Requirement	Pure PTFE	YB-71 (ZOT)	ITO coated (713 Å)
10^{10}	10^{12}	10^{12}	10^{5}

JPL

Diode Dilemmas

MISR
Multi-angle
Imaging
Spectro-
Radiometer

Goal: Highest accuracy

- High QE trapped devices are accurate because no need to characterize!
- Continuity of pre-flight facility approach
  - but -
    - Trapping adds complexity with uncertain gain.
    - NIST relies on single-diode approach with reflectance characterization.

Goal: Single diode vendor

-$$$
  -but
    - Inversion layer (UDT) best for blue, different vendor required for red (unless A-UV technology proven)

Goal: Buy American

  -but
    -Hamamatsu wins 4 year stability study
    -Hamamatsu recognized standard for red, and used by NIST

on the other hand,
-international procurement difficult
-still have problem with blue channel.

Goal: Redundancy in Approach

- Precision provides evidence of accuracy in view of different degradation mechanisms.
- Perhaps rad-hard and high QE in red, with rad-hard biased and unbiased in blue fulfills this desire with advantage of single vendor.

CJB 2/7/92

Fidelity Interval Study

Conclusions

Determined calibration accuracy will not be limited by system noise (verify SNR specification)

Predict uncertainty for very low signal levels (those specified as "best effort")

Allows tradeoff study involving calibration procedures versus accuracy
* Multiple radiometric levels required for calibration
* Radiometric levels must span range of instrument dynamic range for highest accuracy
* Sets limits for test plan (defines sufficient number of redundant measurements, etc.)

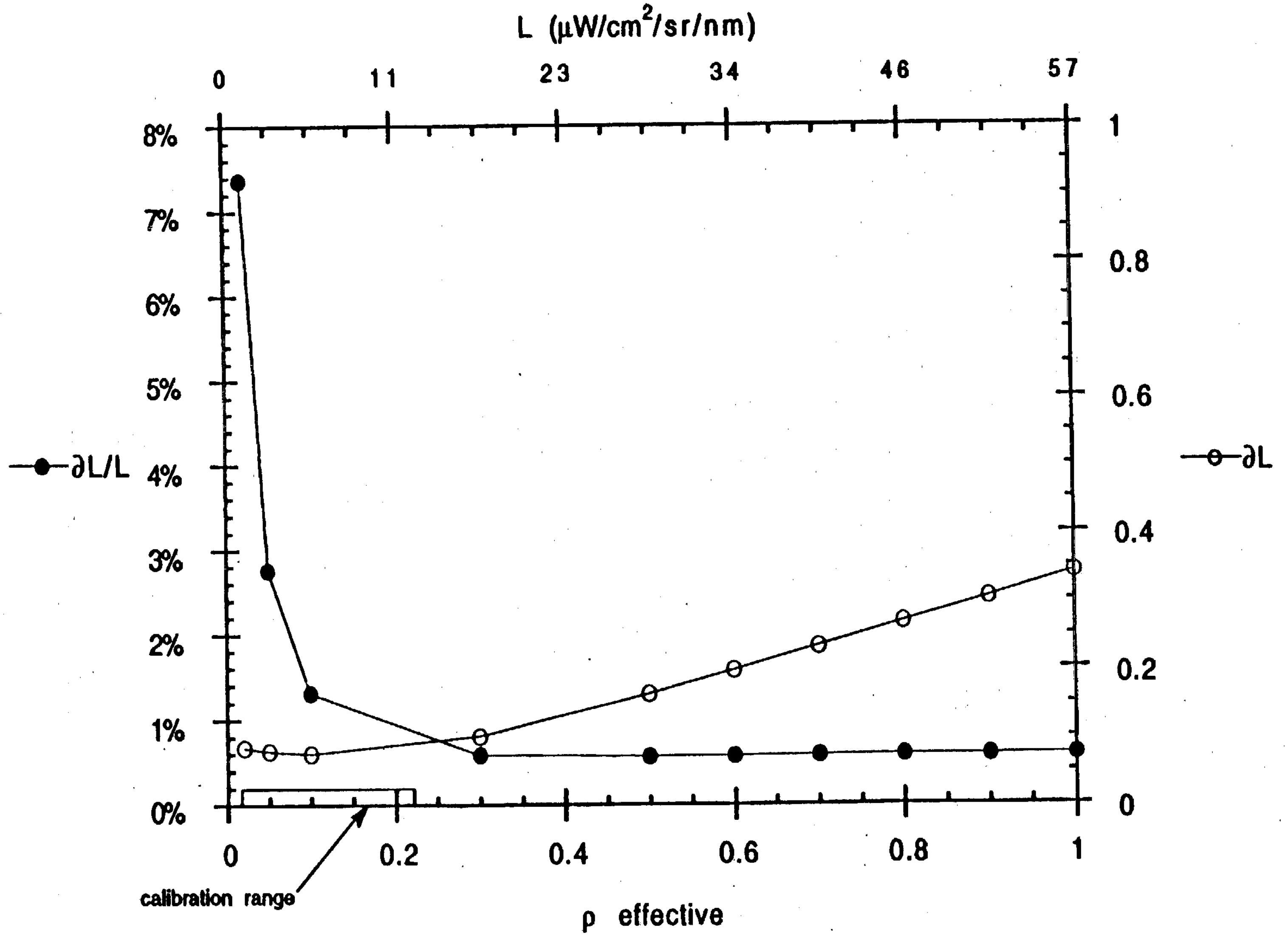
Defines the statistical tools to be used for uncertainty evaluation of calibration test data

JPL

Uncertainty due to instrument noise: Relative and absolute radiance uncertainties

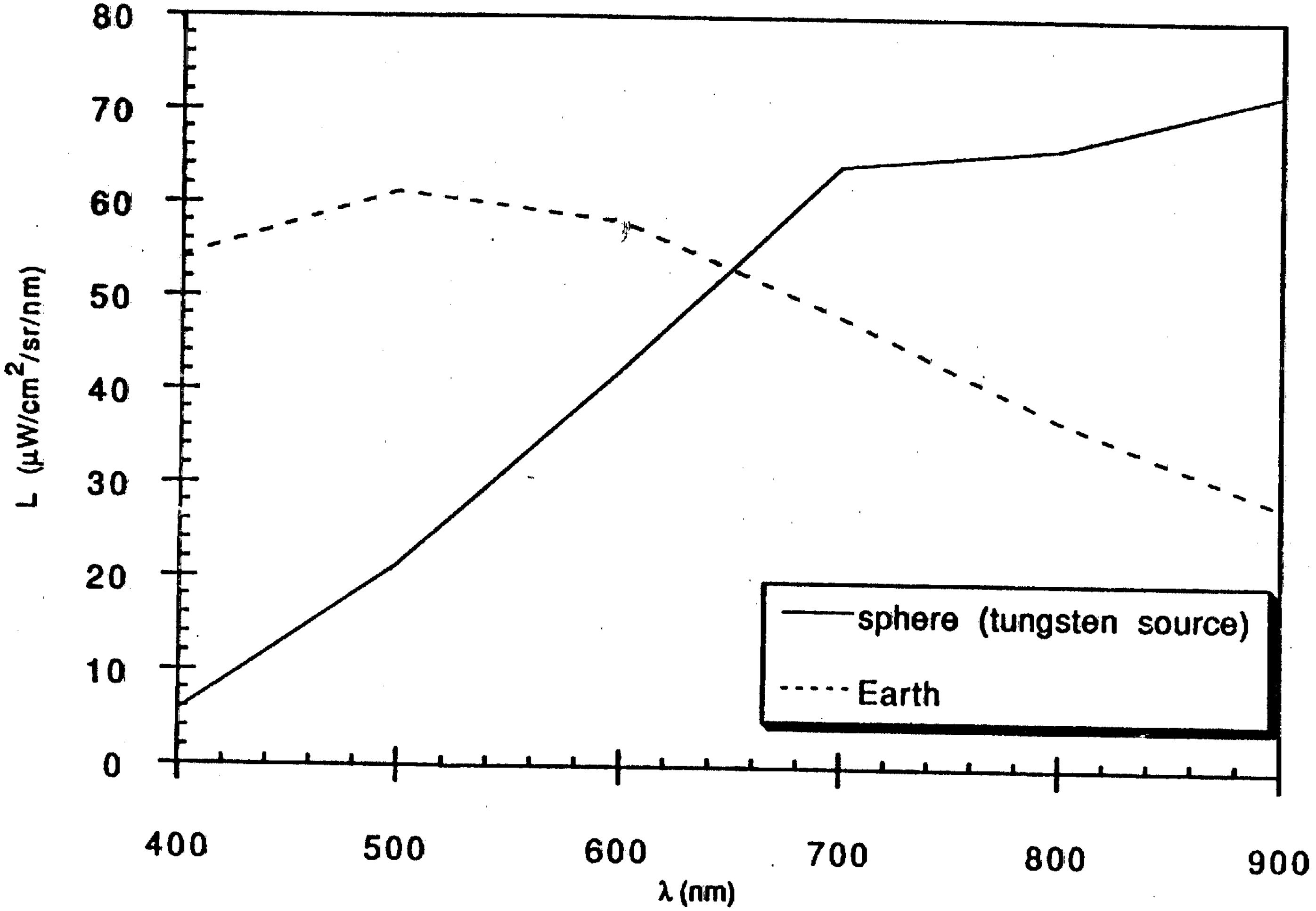
Multi-angle
Imaging
Spectro-
Radiometer

Band 1 N= 10, R= 3, α= 99%



Fidelity Intervals: Calibration source versus expected maximum scene radiance

Expected integrating sphere vs Earth radiance at $\rho = 1.0$



Fidelity Interval
Simplified

For a well behaved system,

$$\left(\frac{t \cdot s}{\hat{G}^{-1}}\right)^2 \left(\frac{1}{S_{LL}}\right) \approx 0, \qquad (1)$$

and

$$L_{u,l} = \hat{L} \pm (t \cdot \hat{G} \cdot s) \sqrt{1 + \frac{1}{N \cdot R} + \frac{(\hat{L} - \bar{L})^2}{S_{LL}}} \qquad (2)$$

Given the estimated radiance, $\hat{L}$, the calibration parameters, $\hat{G}$, s, v, N, R, $\bar{L}$, and S_{LL}, and a confidence level, α, we can calculate the limits, L_u and L_l, within which we expect the true radiance to lie with probability α.

Keypoints

Uncertainty minimum for
- small Student t value (lower stated confidence level)
- smaller gain slope, $\hat{G}$
- lower system noise, s
- sufficiently large N, number of radiometric levels, and R, repetitions
- mean of calibration radiance levels, $\bar{L}$, close to that to be estimated
- large spread in calibration radiance levels, S_{LL}

Fidelity Intervals

Statistical determination

Consider the calibration equation

$$L_\lambda = G(DN - DN_o)$$

where

L_λ is the incoming spectral radiance incident on the entrance aperture, G is the gain coefficient in W m^{-2} sr^{-1} μm^{-1}, DN is the digital output counts when viewing a spectral radiance field, L_λ, DN_o is the digital counts when viewing a zero radiance field, and λ is wavelength.

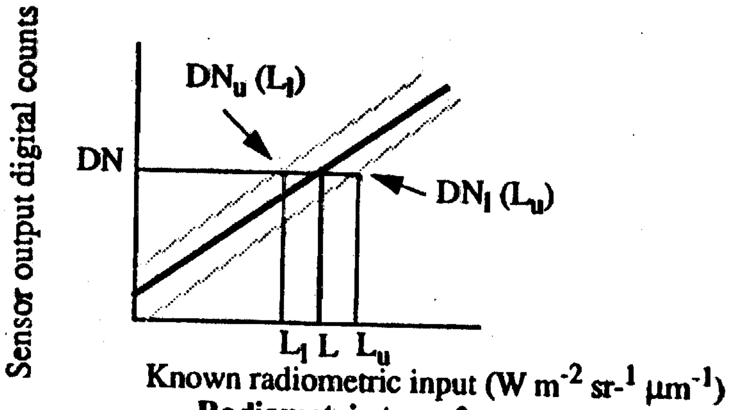
A statistical determination of the coefficients G and DN_o will be made, along with their uncertainties, via an analyses such as that reported by

Barkstrom, Bruce R. Some thoughts on procedures for estimating measurement uncertainties in radiometric instruments. NASA Langley Research Center, September 1990.

C-4

Example

These are the limits in radiance about the radiance estimated from the calibration regression, or the *fidelity intervals*



Radiometric transfer curve

On-Board Calibrator
(OBC)

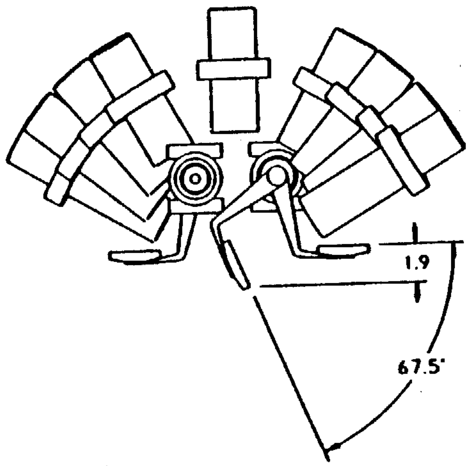
OBC elements

Two diffuse panels
- * deploy over the poles for solar reflection into the cameras

High QE diodes
- * assess panel stray-light/ shadowing
- * validate ground calibration
- * monitor panel degradation (initial post-launch)

Radiation resistent diodes
- * improved stability over mission life
- * monitor panel degradation

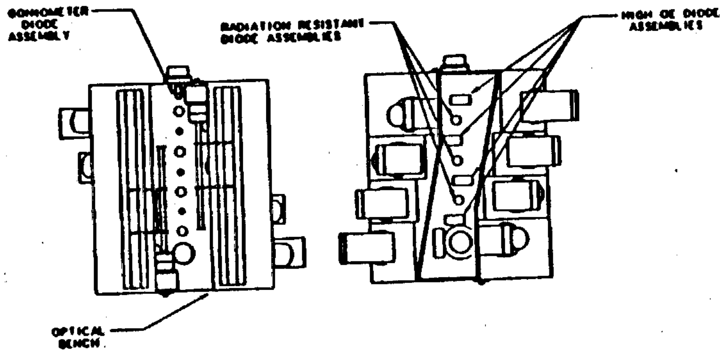
Goniometer diode
- * angular characterization of diffuse panels using radiation resistent diodes



Utilization of OBC

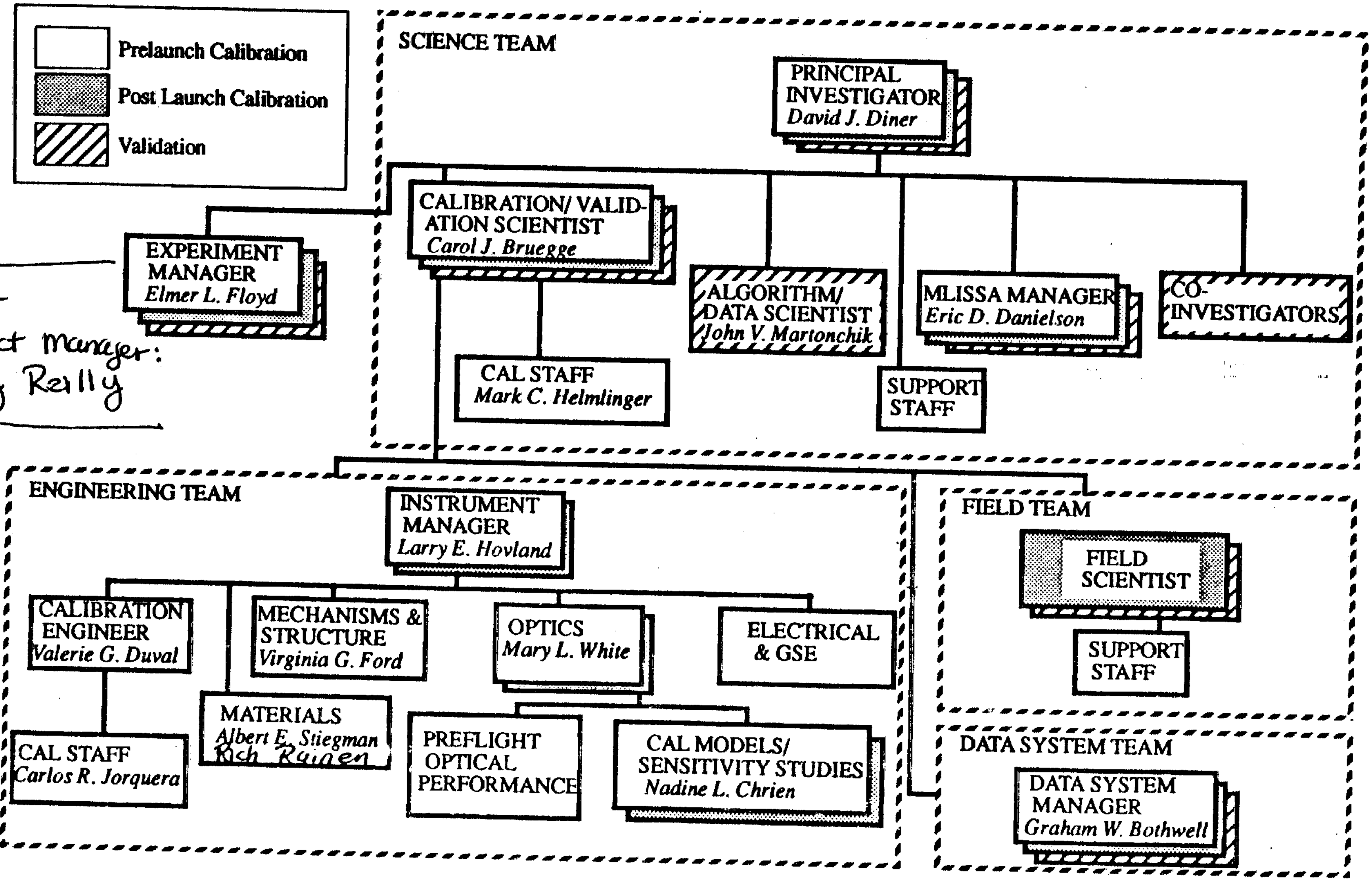
Allows frequent (~monthly) calibrations

Calibrate the OBC during semi-annual ground calibration exercises



JPL

Calibration Support Team



- ☐ Prelaunch Calibration
- ▒ Post Launch Calibration
- ▨ Validation

SCIENCE TEAM

- PRINCIPAL INVESTIGATOR *David J. Diner*
  - CALIBRATION/ VALIDATION SCIENTIST *Carol J. Bruegge*
    - CAL STAFF *Mark C. Helmlinger*
  - ALGORITHM/ DATA SCIENTIST *John V. Martonchik*
  - SUPPORT STAFF
  - MLISSA MANAGER *Eric D. Danielson*
  - CO-INVESTIGATORS

EXPERIMENT MANAGER *Elmer L. Floyd*

2/92 -
Project manager:
Terry Reilly

ENGINEERING TEAM

- INSTRUMENT MANAGER *Larry E. Hovland*
  - CALIBRATION ENGINEER *Valerie G. Duval*
    - CAL STAFF *Carlos R. Jorquera*
  - MATERIALS *Albert E. Stiegman*
    Rich Rainen
  - MECHANISMS & STRUCTURE *Virginia G. Ford*
  - OPTICS *Mary L. White*
    - PREFLIGHT OPTICAL PERFORMANCE
    - CAL MODELS/ SENSITIVITY STUDIES *Nadine L. Chrien*
  - ELECTRICAL & GSE

FIELD TEAM

- FIELD SCIENTIST
  - SUPPORT STAFF

DATA SYSTEM TEAM

- DATA SYSTEM MANAGER *Graham W. Bothwell*

Quarterly Review

CJB 12/11/91

omit

THERMAL INFRARED WORKSHOP

TOPICS TO COVER

Importance of Cross-calibration - provided by Interdisciplinary Investigators

Mathematical Modeling of Thermal Infrared Instruments

- RADIOMETRIC CALIBRATION
  - Standards
  - Working Standards and transfer standards
  - Transfer Radiometers
  - Internal Standards
  - Use of Standards
  - Data Analysis and Archiving

- SPECTRAL RESPONSE
  - Measurement Methods
  - Out-of-band Response
  - Filters, aging, orbital degradation and witness samples
  - Data Analysis and archiving
  - In-orbit Verification

- SPATIAL RESPONSE
  - Measurement Methods
  - Quantities to be Measured
  - Test Equipment
  - Off-Axis
  - Cleanliness, BRDF
  - Data Analysis and Archiving
  - In-Orbit Verification

- TEMPORAL RESPONSE
  - Measurement Methods
  - Test Equipment
  - Data Analysis and Archiving
  - Memory Effects

- POINTING PRECISION AND ACCURACY 1)
  - Measurement Methods
  - Equipment
  - Achievable Precision
  - Data Analysis and Archiving

- SUMMARY

1) Pointing precision and accuracy may cut across several spectral intervals. This topic might be considered for a separate short workshop.

THERMAL IR WORKSHOP

~~New Orleans~~

~~January 1992~~

PROPOSED TOPICS FOR PRESENTATION

~~IMPORTANCE OF CROSS CALIBRATION~~

~~GENERAL CHARACTERISTICS OF TIR INST.~~

MATHEMATICAL MODELING OF THERMAL IR INSTRUMENTS

RADIOMETRIC CALIBRATION

- STANDARDS - NIST (AL PARR) John Martin (NPL)
  - Design, Construction, Factors affecting accuracy
  - Testing, Achievable (Demonstrable) accuracy and precision
  - International Standards
  - Wave Length Dependence
- WORKING STANDARDS AND TARGETS NIST Fred Bartels
  - Design and Construction, Thermal uniformity
  - Testing and comparison to standards - traceability
  - Achievable accuracy, repeatability and precision, stability
  - Transfer radiometers
- INTERNAL SOURCES
  - Accuracy, emissivity, stability, λ dep.
- USE OF STANDARDS Frank Malinowski Claire Wyatt
  - Test facilities, target fixtures, thermal uniformity
  - Instrument mounting considerations
  - Stray light problems, polarization issues Bob Breault
  - Formal procedures and documentation
  - Data analysis and quick look
  - Temperature and other dependence
  - Linearity
  - Model verification

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[DATA ANALYSIS AND ARCHIVING]

SPECTRAL RESPONSE Jim Palmer (U. of Arizona)

- METHODS FOR MEASURING SPECTRAL RESPONSE John Vincent (SBRC)
  - Spectrometer and monochromator sources Zissis (ERIM)
  - Reference detector response Stierwalt
  - Temperature dependence
- OUT OF BAND RESPONSE
- FILTERS, AGING, ORBITAL DEGRADATION, WITNESS SAMPLES - N. Kolet, OCLI (Jim Rancourt) Reading, Jim Heaney (GSFC)
- DETECTOR AGING, WITNESS SAMPLES - LORAL, SBRG
- IN ORBIT VERIFICATION
- [DATA ANALYSIS AND ARCHIVING]

SPATIAL RESPONSE **Claire Wyatt, AEOC (Tullahoma)**

- METHODS FOR MEASUREMENT
- MEASURES -
  - MTF, Encircled Energy
- TEST EQUIPMENT
- FLAT-FIELD UNIFORMITY
  - Pixel-pixel response, x-talk, blooming
- OFF-AXIS RESPONSE DETERMINATION
  - Cleanliness, BRDF -- Jean Bennett
- OFF AXIS RESPONSE DETERMINATION
  - Achievable accuracy
- [DATA ANALYSIS AND ARCHIVING]
- IN ORBIT VERIFICATION

TEMPORAL RESPONSE **Malinowski, Jim Young (SBRC)**

- MEASUREMENT METHODS
- TEST EQUIPMENT
- DATA ANALYSIS AND ARCHIVING
- "MEMORY"
- S. ATLANTIC ANOMALY, ETC.

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CROSS CALIBRATION METHODOLOGY

PT. SPREAD FN, SAMPLING, TIME CONST.

PRE-FLIGHT

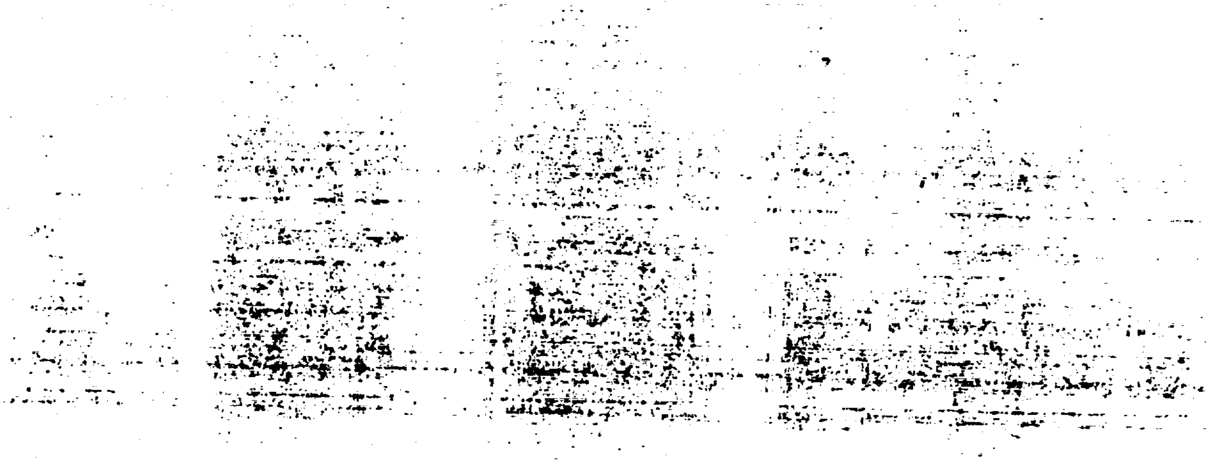
SAME TARGETS

IN-FLIGHT.

SAME SCENES, &

END-TO-END RESULTS ACHIEVED

TALES OF THE REAL WORLD



N94-23607

Calibration of a helium-cooled infrared spatial radiometer and grating spectrometer

5/2-43
171303
P-11

Larry Jacobsen, Steve Sargent, Clair L. Wyatt, Allan J. Steed

Space Dynamics Laboratory
Utah State University, Logan, UT 84321-4140

ABSTRACT

Methods used by the Space Dynamics Laboratory of Utah State University (SDL/USU) to calibrate infrared sensors are described, using the Infrared Background Signature Survey (IBSS) spatial radiometer and grating spectrometer as examples. A calibration equation and a radiometric model are given for each sensor to describe their responsivity in terms of individual radiometric parameters. The calibration equation terms include dark offset, linearity, absolute responsivity, and measurement uncertainty, and the radiometric model domains include spatial, spectral, and temporal domains. A portable calibration facility, designed and fabricated by SDL/USU, provided collimated, extended, diffuse scatter, and Jones sources in a single cryogenic dewar. This multi-function calibrator allowed calibration personnel to complete a full calibration of the IBSS infrared radiometer and spectrometer in two 15-day periods. A calibration data system was developed to control and monitor the calibration facility, and to record and analyze sensor data.

1. INTRODUCTION

Electro-optical systems require calibration to verify instrument design, create algorithms necessary for data reduction, and estimate measurement uncertainties. The Space Dynamics Laboratory of Utah State University (SDL/USU) has been calibrating electro-optical instruments since 1970. This paper describes the methods used to calibrate the infrared (IR) sensor of the Infrared Background Signature Survey (IBSS) experiment. The calibration approach is discussed, as well as the data collection and processing methods. Examples of the results obtained by these methods are also provided.

The IBSS experiment is a Strategic Defense Initiative Organization (SDIO)-sponsored shuttleborne program designed to measure ultraviolet (UV), visible, and IR signatures from various sources. The prime contractor for this program is Messerschmitt-Bolkow-Blohm (MBB) of the Federal Republic of Germany. The IBSS hardware includes a cryogenically cooled IR sensor; a UV, visible, and near-infrared spectrograph/imager; a low-light-level television; and additional instrumentation. These primary instruments are located on a shuttle pallet satellite (SPAS) that is based in the shuttle orbiter until deployed for measurement missions.

The IBSS IR sensor consists of a high off-axis rejection telescope, a spatial radiometer, and an Ebert-Fastie grating spectrometer. The radiometer and spectrometer obtain their input energy from the telescope, which focuses energy on the instrument's detector arrays. The fields of view of the 29 radiometer detectors are scanned in object space by an internal scan mirror. The radiometer has a multi-position filter wheel to select a bandpass filter. The 12-detector spectrometer array measures 6 different spectral ranges simultaneously as the diffraction grating is scanned. The sensor operates in the 2.5 - 24 μm infrared spectral region and is housed in a helium-cooled dewar. Both the radiometer and spectrometer have dedicated on-board signal processors that DC restore the chopped detector responses. The IBSS experiment is described in Lange et al.[1]

2. METHODS

2.1. Calibration approach

The approach used by SDL/USU to calibrate radiometric sensors involves generating a specific calibration equation and radiometric model for the sensor being tested. The calibration equation and radiometric model describe the overall responsivity of the sensor in terms of separate radiometric parameters.[2] The calibration equation correlates sensor output to measured flux, while the radiometric model describes the measured flux as a function of the actual flux. The calibration equation for the IBSS radiometer is:

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$$\Phi_m = \frac{1}{\Re_{filt}} L_R(Resp - DO_R) \pm \sigma_{filt} \tag{1}$$

where Φ_m is measured flux, $\Re_{filt}$ is absolute responsivity for a given radiometer filter, L_R is the radiometer linearity correction transfer function, Resp is radiometer response, DO_R is radiometer dark offset, and σ_{filt} is measurement uncertainty for a given radiometer filter.

The calibration equation for the IBSS spectrometer is:

$$\Phi_m(\lambda) = \frac{1}{\Re(\lambda)} L_S[Resp(\lambda) - DO_S] \pm \sigma(\lambda) \tag{2}$$

where Φ_m (λ) is measured spectral flux, $\Re(\lambda)$ is absolute spectral responsivity, L_S is the spectrometer linearity correction transfer function, Resp(λ) is spectrometer response, DO_S is spectrometer dark offset, and $\sigma(\lambda)$ is spectrometer measurement uncertainty.

The radiometric models for the IBSS radiometer and spectrometer characterize their spectral, spatial, and temporal domains. The relative spectral responsivity describes the spectral domain of the radiometer. The grating position, line shape, and spectral leakage analyses describe the spectrometer spectral domain. The field-of-view response maps, detector positions, scatter coefficients, effective fields of view, modulation transfer functions, and scan mirror transfer function describe the spatial domain of the radiometer and spectrometer. The radiometer and spectrometer frequency responses describe the temporal domains of the sensor.

Each term in the calibration equation and each domain in the radiometric model describes a specific radiometric parameter. The goal of the calibration is to characterize each parameter independently of the others. Together, these individually characterized radiometric parameters comprise a complete calibration of a radiometric sensor.

2.2. Portable calibration source (PCS)

Since individual parameters of the sensor calibration equation and radiometric model are best measured with different optical source configurations, SDL/USU personnel designed and fabricated a portable calibration source (PCS) that incorporated four optical functions into a single, cryogenically cooled dewar. These functions included a collimated source; an extended source; a near, small-area (Jones) source; and a diffuse scatter source. This multiple-function calibration source eliminated the sensor warm-up cycles usually required to mate different calibration sources to the sensor, enabling calibration personnel to collect all data required for a full calibration in two 15-working day periods. Wyatt et al.[3] provides a full description of the PCS.

2.3. Calibration data system

SDL/USU personnel developed a computerized calibration data system, consisting of commercially-available and SDL/USU-designed hardware and software, to control the PCS, collect the IBSS telemetry stream, and analyze the resulting calibration data. The system recorded individual "snapshots" of the telemetry stream, automatically inserted a header describing the current configuration of the calibration source, and stored the snapshots on a peripheral optical-media mass-storage device. The data system then retrieved, processed, and organized the snapshots into a calibration data base. This system greatly reduced the time previously required to complete data analysis, allowing calibration personnel to perform all analyses needed to prepare quick-look reports within two weeks of data collection, and to complete the final calibration report in six months.

2.4. Data processing

The IBSS sensor design incorporates a chopper and a signal processor that DC restores the detector responses, giving a complex output. Since this complex output represents a real radiant flux, it must be converted to a real number. Therefore, the calibration described in this paper correlates the amplitude of the complex response to radiant flux. All operations on low-level responses were performed before conversion to amplitude, to avoid misinterpretation of random noise as signal. Throughout this paper, the IBSS response is given in counts as computed by the onboard signal processor, and reported by telemetry.

3. RESULTS

Calibration personnel devised and carried out tests to determine each term in the calibration equations, and to characterize each responsivity domain in the radiometric models. The test results presented in this paper are examples of the data obtained for the IBSS calibration. Where applicable, data from the same detectors are presented. A full description of the IBSS calibration tests and results for all radiometer and spectrometer detectors is presented in the final IBSS calibration report.[4]

3.1. Calibration equation parameters

Calibration personnel measured dark offset, linearity, absolute responsivity, and measurement uncertainty for the IBSS spectrometer and radiometer calibration equations.

Dark offset

To apply the calibration equation, dark offset must first be subtracted from the sensor response. Calibration personnel determined the mean dark offset prior to each calibration test to offset-correct the results of that test. Typical radiometer dark offsets were approximately 8e+3 counts, and typical spectrometer dark offsets were approximately 1e+3 counts.

Linearity

The next step in applying the calibration equation is to linearize the sensor response. The linearity calibration provides a transfer function of actual response to ideal linearized response throughout the sensor dynamic range. Once the sensor response has been linearized, a single coefficient, found during the absolute responsivity calibration, converts linearized response to measured flux. By analyzing linearity independently of the absolute responsivity and other radiometric parameters, calibration personnel can more easily identify errors in the absolute calibration due to sensor spectral leaks and source uncertainties. In addition, since the linearity function covers the entire dynamic range, the absolute (extended) source need not cover the sensor dynamic range in the absolute responsivity calibration.

The ideal source for a linearity calibration provides a wide range of flux without changing the spectral, spatial, or temporal characteristics of the flux. The SDL/USU calibrator offers two sources for the linearity calibration: the Jones source and the collimator. Both sources give fluxes proportional to their aperture areas, but only the smallest collimated apertures fit entirely within the fields of view of the small radiometer detectors; therefore, the Jones source was chosen for the radiometer linearity calibration. Because the Jones source failed to give adequate signal over the spectrometer dynamic range, the collimator was used for the spectrometer linearity calibration. Calibration personnel varied the input flux in known ratios with the set of calibrator precision apertures, and used multiple source temperatures to cover the dynamic range of both sensors.

The radiometer responses to each input flux were offset corrected with dark responses, plotted versus relative flux, and fit to a piecewise, polynomial linearity-correction function. Fig. 1 shows the results of the linearity calibration for radiometer detector 13, which is typical of the radiometer detectors. Linearity uncertainties, computed as the standard deviation of the curve-fit residuals, were less than 2.5% for most detectors. Similar analyses were performed for the spectrometer detectors, which also showed linearity uncertainties of a few percent.

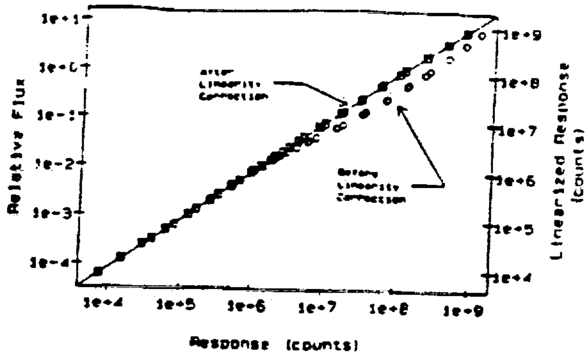

Fig. 1. Radiometer detector 13 linearity calibration.

Absolute responsivity

The absolute responsivity coefficient converts the offset-corrected and linearized sensor response to measured flux. The IBSS spectrometer absolute calibration is presented to illustrate the method used to determine the absolute responsivity coefficient.

The preferred source for the absolute calibration is the extended source because its flux is subject only to temperature and emissivity uncertainties. However, since the extended source has a limited temperature range, other sources, such as the Jones source, can be used to augment the extended source data at short wavelengths. Both the extended and Jones sources were used for the IBSS spectrometer absolute responsivity calibration.

Responses to a number of known fluxes were curve-fit at each wavelength by:

$$\Phi_c(\lambda) = \frac{1}{\mathcal{R}(\lambda)}\left[\mathrm{Resp}_L(\lambda)\right] \tag{3}$$

where $\Phi_c(\lambda)$ = computed spectral radiance in W cm^{-2} sr^{-1} μm^{-1}, $\mathcal{R}(\lambda)$ = absolute spectral responsivity in counts/W cm^{-2} sr^{-1} μm^{-1}, and $\mathrm{Resp}_L(\lambda)$ = offset-corrected and linearized response in counts.

The offset-corrected and linearized responses were curve-fit to equation 3 at each wavelength to give the absolute spectral responsivity. Fig. 2 shows the results of the absolute calibration for detector 5. Curve-fit uncertainties are also shown in this figure. As described in equation 3, the absolute spectral responsivity is given in radiance with units of counts/W cm^{-2} sr^{-1} μm^{-1}. Another useful parameter is the irradiance spectral responsivity, which is the absolute responsivity in flux density with units of counts/W cm^{-2} μm^{-1}. This irradiance responsivity was found by dividing the spectral radiance responsivity by the effective field of view, a parameter discussed in the spatial domain characterization section of this paper.

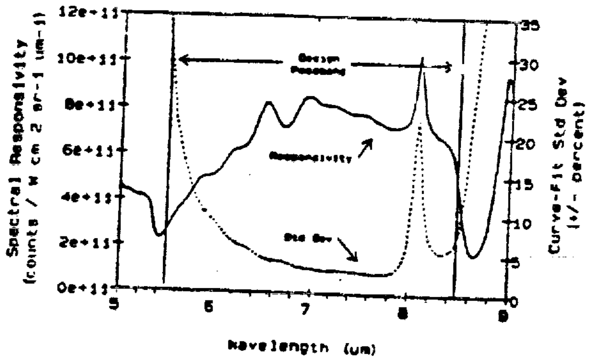

Fig. 2. Spectrometer detector 5 absolute spectral responsivity calibration.

The radiometer absolute calibration was similar, except that the source flux was multiplied by the radiometer relative spectral responsivity, discussed in the spectral domain characterization section of this paper, and integrated over the spectral passband to give a non-spectral absolute responsivity. This analysis was repeated for each detector-filter combination. Curve-fit uncertainties were good, and no spectral errors were observed.

Measurement uncertainties

The calibration equation includes an estimate of the sensor's measurement uncertainty. This estimate consists of the sensor precision and the calibration accuracy. Precision is the reproducibility or consistency of individual measurements. Accuracy is the correlation of the sensor's calibrated response to the true radiometric value. Sensor precision is determined from dark noise, uncertainty of dark offset, signal-to-noise ratio, and long-term repeatability. The total calibration accuracy is given by the root-sum-square combination of the uncertainties from the linearity calibration, absolute responsivity calibration, extended source emissivity, and extended source temperature. The total measurement uncertainty is then determined by the root-sum-square combination of the total sensor precision and total calibration accuracy.

Dark noise is the precision of individual measurements at the minimum detectable signal level. To characterize the dark noise of the IBSS radiometer and spectrometer, calibration personnel collected telemetry data with the IBSS filter wheel in the closed position and used Fourier techniques to compute dark noise spectra. These spectra were then integrated over the noise bandwidth to compute total rms dark noise. These spectra contained noise from the 50-Hz (European) power distribution system, which accounted for about one-half of the total rms noise. It was assumed that this noise will not be present during the deployment of IBSS, and was therefore omitted from the integrations for the total rms dark noise. Typical radiometer dark noise was 3e+3 rms counts and typical spectrometer dark noise was 1e+4 rms counts. The spectrometer dark noise was independent of grating position.

Uncertainty from the long-term drift of dark offset also degrades sensor precision at the bottom of the dynamic range. Calibration personnel recorded dark offsets of the IBSS radiometer and spectrometer each day throughout the data-collection period to measure the dark offset long-term drift. Fig. 3 shows the range of the daily means of the dark offsets for each radiometer detector. Although most calibration results are reported as the amplitude of the complex response, dark offset is presented as a complex number because offset correction of the signal responses must be performed before conversion to amplitude. The ranges shown indicate the uncertainty due to long-term drift of the dark offset.

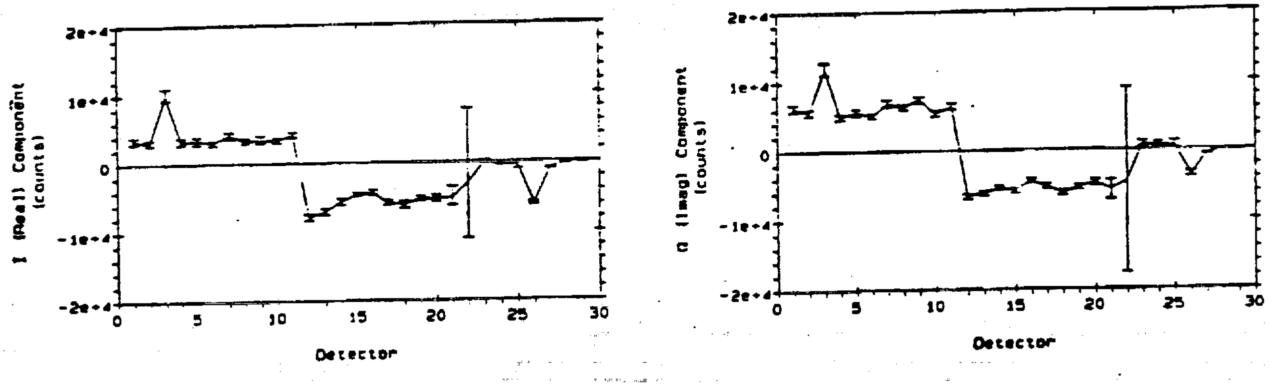

Fig. 3. Dark offsets for all radiometer detectors.

Dark noise and dark offset uncertainty only determine the precision at the bottom of a sensor's dynamic range. At higher flux levels, other noise sources, such as photon noise and digitization noise, must also be considered. The signal-to-noise ratio (SNR) and sensor long-term repeatability provide an indication of precision throughout the entire dynamic range. The total sensor precision can be determined from the SNR and the long-term repeatability, as follows:

$$\sigma_{\text{Precision}} = \sqrt{\frac{1}{\text{SNR}^2} + \sigma_{\text{Rep}}^2} \tag{4}$$

where $\sigma_{\text{Precision}}$ = total sensor precision, SNR = signal-to-noise ratio, and σ_{Rep} = long-term repeatability.

The spectrometer SNR was characterized by recording the spectrometer's response to collimated sources of various sizes and temperatures. The resulting signals were offset corrected, and the noise for each snapshot was corrected to remove the 50-Hz components. Fig. 4 presents the SNR for one spectrometer detector. As expected, the SNR increased with increasing response. Similar analyses were performed for all other spectrometer and radiometer detectors.

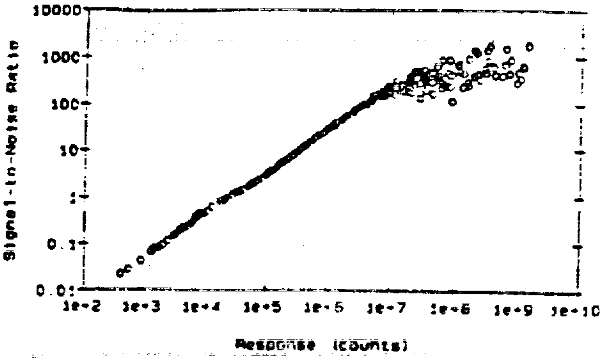

Fig. 4. SNR throughout the dynamic range for detector 5.

To measure the sensor's long-term repeatability, calibration personnel recorded the sensor's response to both the IBSS internal source and the calibrator Jones source daily throughout the calibration period. It was necessary to obtain a comparison between the sensor's response to both sources to evaluate the stability of the IBSS internal source, which is ultimately used to verify the sensor's stability. The standard deviations of the daily internal source and Jones source responses, given as percentages of the overall means, showed that the response to the IBSS internal source was repeatable within ±10 to ±30% for the radiometer detectors, and ±5 to ±17% for the spectrometer detectors. The response to the calibrator Jones source was repeatable within ±5 to ±8% for the radiometer detectors, and ±1 to ±5% for the spectrometer detectors. The Jones source repeatability, depending on the detector, was up to a factor of 4 times better than the internal source repeatability. This indicates that the IBSS internal source itself, rather than the sensor, limited the repeatability of the internal source response.

Fig. 5 presents the total calibration accuracy for all radiometer detectors with one radiometer filter. Analyses for all filter-detector combinations showed typical accuracies of ±5 to ±10%. Fig. 6 presents the total calibration accuracy for spectrometer detector 5. The peak at 8μm is due to a spectral leak, discussed in the spectral domain characterization section of this paper. Typical total calibration accuracies were ±5 to ±12% for the spectrometer detectors.

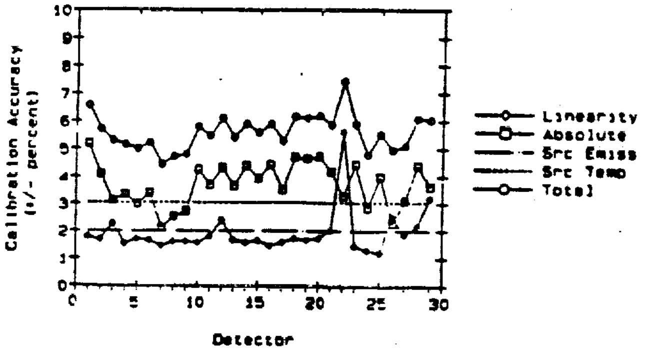

Fig. 5. Calibration accuracy estimates for radiometer filter 0 and all detectors.

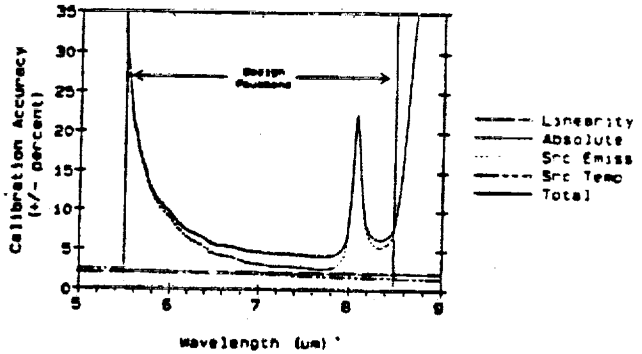

Fig. 6. Calibration accuracy estimate for spectrometer detector 5.

3.2. Radiometric Model Parameters

Spectral domain characterization

The radiometer's radiometric model includes the relative spectral responsivity, which is the peak-normalized responsivity as a function of the wavelength of the measured radiation. This parameter is used to calculate the effective flux for the absolute calibration and to interpret on-orbit data. Calibration personnel determined the relative spectral responsivity of the IBSS radiometer with each IBSS filter, using an externally chopped blackbody, grating monochromator, and calibrator Jones source. The IBSS internal chopper was turned off, the onboard signal processor was bypassed, and the output was fed into an external lock-in amplifier. The DC-restored output of the lock-in amplifier was normalized with a spectrally flat external reference detector to calculate the spectral responsivity. The spectral responsivity was then normalized to its own peak. Fig. 7 gives the radiometer relative spectral responsivities for each of the IBSS filters.

The spectrometer's radiometric model includes grating position transfer functions, line shape characterization, and spectral leakage analysis. To determine the IBSS spectrometer grating position transfer functions, calibration personnel illuminated the spectrometer with an external monochromator through the Jones source at approximately ten different wavelengths in each grating order. These data were then fit to linear transfer functions. Fig. 8 presents the grating position calibration for each grating order. The end points of each line represent the passband for that grating order. The grating position calibration uncertainties were approximately equal to the design spectral resolution, given by $\Delta\lambda = \lambda/300$ (λ = wavelength).

The line shape calibration evaluates the spectrometer's spectral resolution by measuring its response to a monochromatic source. To determine the IBSS spectrometer line shape, calibration personnel illuminated the spectrometer with a 3.391-μm helium-neon (HeNe) laser through the Jones source. The center wavelength determined by this calibration agreed with the theoretical center wavelength within the grating position calibration uncertainty. The half-power width agreed with the IBSS specified resolution.

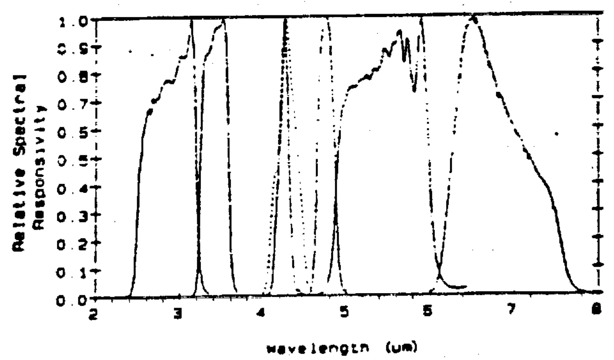

Fig. 7. Radiometer relative spectral responsivity.

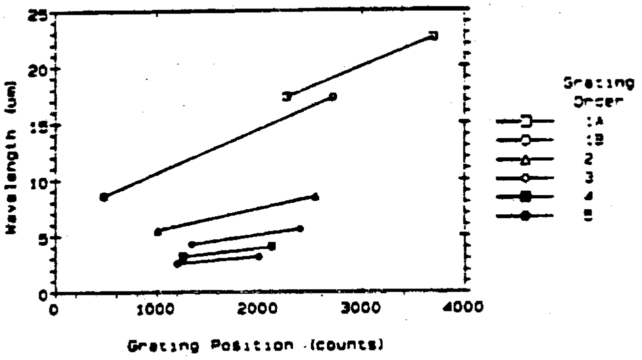

Fig. 8. Spectrometer grating position calibration.

The spectrometer radiometric model also characterizes the sensor's spectral purity, which is its ability to measure radiation at only the desired wavelength. Since each grating order diffracts energy of a different specific wavelength onto a given detector at a given grating angle, the IBSS spectrometer detectors are covered by order-sorting bandpass filters. The wavelength for higher grating orders are related to that of the first grating order by:

$$\lambda_N = \frac{\lambda_1}{N} \qquad (5)$$

where λ_N = wavelength for order N in μm, λ_1 = wavelength for order 1 in μm, and N = the grating order (1, 2, 3, ...).

The order-sorting filters that cover the IBSS spectrometer detectors are designed to select radiation from only the desired spectral order. However, at certain grating angles, some order-sorting filters also pass radiation of an undesired spectral order. This results in the spectrometer detector simultaneously responding to radiation from more than one wavelength for a given grating angle. Since radiation is "leaking" to the detector from an undesired wavelength, it is said to be the result of a "spectral leak."

To identify spectral leaks, calibration personnel compared the spectrometer's relative spectral responsivities measured using blackbody sources at different temperatures. Ideally the relative spectral responsivity measurement is independent of source temperature. But for grating positions with long-wavelength leaks, a low-temperature source gives an erroneously high relative spectral responsivity. This is because low-temperature sources have proportionately more energy at long wavelengths, which make the long-wavelength leaks more significant. Similarly, for grating positions with short-wavelength leaks, a high-temperature source shows an erroneously high relative spectral responsivity.

Fig. 9 shows the superimposed spectrometer detector 5 relative spectral responsivities measured using Jones and extended source temperatures from 185 to 1269 Kelvin. Three spectral leaks are identified. Calibration personnel quantified these leaks by computing the ratio of the absolute responsivity at the leaked wavelength to the absolute responsivity at the unleaked wavelength. This ratio was 3% for the leak at 5.49 μm, 20% for the leak at 8.08 μm, and 9% for the leak at 8.33 μm. Two additional spectral leaks were characterized in the other four spectral grating orders.

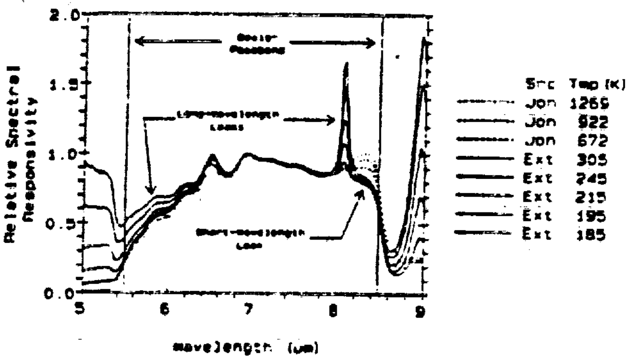

Fig. 9. Spectrometer detector 5 spectral leakage characterization.

Spatial domain characterization

The spatial domain characterization is best illustrated by the IBSS radiometer spatial calibration; therefore, only radiometer data is discussed. Calibration personnel measured the radiometer's spatial responsivity by positioning an 80-μrad collimated source at 0.1 mrad increments over the entire focal plane. The detector responses at each location were offset corrected, linearity corrected, and peak normalized. These data were then analyzed to provide field-of-view response maps, relative detector positions, scatter coefficients, effective fields of view, and modulation transfer functions (MTF). A similar calibration was performed for the spectrometer, with the grating stopped.

Figs. 10 and 11 give field-of-view response maps for radiometer detectors 13 and 29. These maps are useful to subjectively evaluate the spatial response, especially to reveal vignetting problems and locate sources of scatter. These maps are logarithmic plots of the relative spatial responsivity, with each contour representing a response of a factor of 2 below the preceding contour. Ten contours are shown in the figures, representing responses down to .001 of the peak. The map for detector 13, which is typical of the small radiometer detectors, shows that the major scatter areas included nearby detectors on the same substrate and regions

For all small detectors, the solid angles defined by the 0.5 contour were consistent with the design fields of view. More than half of their response to a spatially uniformly scene was from regions outside their 0.5-response contours. Using a 0.1-contour threshold, the solid angles were typically 5 times larger than the design solid angle, and scatter coefficients ranged from 30 to 50%, depending on detector.

The effective field-of-view solid angle of a sensor correlates its point-source response to its extended-source response. This correlation allows irradiance responsivity to be determined from radiance responsivity. The effective field-of-view solid angle is defined in terms of a hypothetical, spatially ideal sensor. This hypothetical sensor has the following characteristics: 1) The ideal sensor's response is zero at all spatial positions outside its field of view; 2) The ideal sensor's response to a point source at all spatial positions within its field of view is equal to the sensor's peak spatial response; and 3) The ideal sensor's response to an extended, spatially uniform source is equal to the actual sensor's response to the same spatially uniform source. The effective field-of-view solid angle of an actual sensor is equal to the field-of-view solid angle of this ideal sensor.

Effective field-of-view solid angles were computed for the IBSS radiometer detectors by:

$$\Omega_{eff} = \Delta X \Delta Y \sum_{Total\ FP} Resp \tag{8}$$

where Ω_{eff} = effective field-of-view solid angle in steradians, $\Delta X \Delta Y$ = incremental solid angle for each spatial response data point in steradians, and Resp = point-source responses. The effective fields of view were larger than design values for most detectors. This increase was mostly due to scatter.

The spatial response of a radiometer can also be evaluated in terms of its modulation transfer function (MTF), which describes its relative responsivity to different spatial frequencies. The MTF of a sensor can be computed using Fourier analysis of a point-source scan or a slit-source scan. The slit-source method shows the full MTF degradation due to scatter, while the point-source method is less affected by scatter, giving a more realistic MTF for point sources.

Calibration personnel computed a mean point-source scan for the radiometer detectors by averaging two or three spatial scans through each detector. The mean scans were then Fourier transformed and peak-normalized to give the MTFs. The slit-source MTFs were calculated in the same way as the point-source MTFs, except that all spatial response data were used to calculate the mean scans. This is equivalent to the scan of a long slit which covers the full height of the radiometer field of view. Figs. 12 and 13 present the MTF analysis for detector 13 in the X direction. A similar analysis was performed for each radiometer detector, in both the X and Y directions.

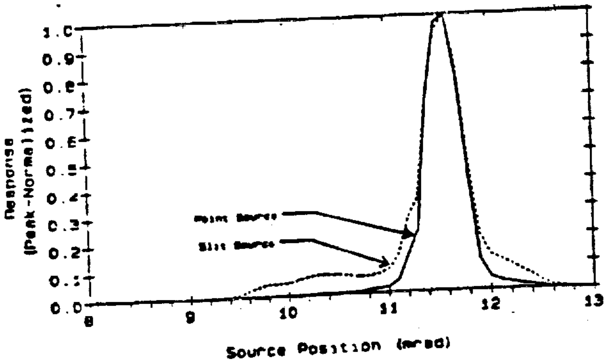

Fig. 12. Mean spatial scans for radiometer detector 13 in the X direction.

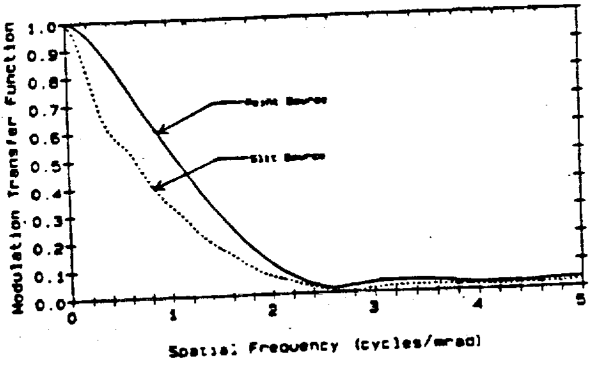

Fig. 13. MTFs for radiometer detector 13 in the X direction.

The sensor radiometric model includes the scan mirror position calibration, relating the sensor line of sight to scan mirror position reported by telemetry. The IBSS scan mirror position was calibrated by placing a collimated, 80-µrad source at fifteen different positions in object space, and collecting data with the IBSS mirror scanning. For each calibrator point-source position, the corresponding IBSS scan mirror position in counts was determined from the peak response of a chosen detector. These fifteen points were curve-fit to give a linear transfer function of scan mirror position in telemetry counts to sensor line of sight in mrad.

Temporal domain characterization

As with other sensors, the IBSS radiometer and spectrometer are frequency band-limited systems which cannot measure rapid scene modulations exactly. By understanding the sensor frequency response, however, experimenters may predict the effects of changing scenes on sensor response. Flux modulations result directly from time-varying sources, spatial scans of a spatially modulated scene for the radiometer, or spectral scans of a spectrally modulated scene for the spectrometer.

To measure the IBSS frequency response, calibration personnel illuminated the radiometer and spectrometer with radiation modulated by an external chopper at frequencies from 5 to 35 Hz for the radiometer and 10 to 100 Hz for the spectrometer (with the grating stopped). Fourier analysis of the resulting responses gave the energy in the chopper fundamental frequency. The response at each frequency was converted to decibels relative to the lowest chopper frequency measured. Fig. 14 shows the resulting relative frequency responses for the radiometer and spectrometer.

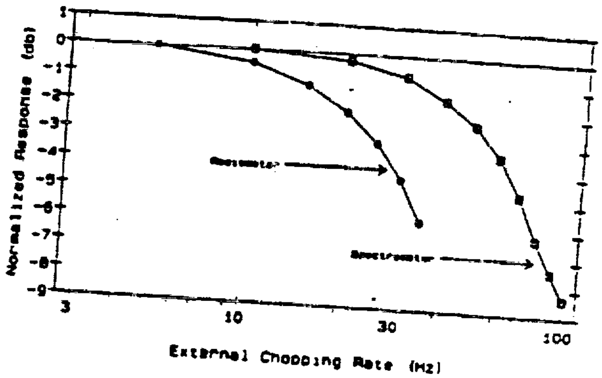

Fig. 14. Radiometer and spectrometer frequency response.

4. SUMMARY

This paper describes the methods used by SDL/USU to calibrate radiometric sensors. The calibrations of the IBSS infrared radiometer and spectrometer were given as specific examples using this calibration approach.

The calibration involved generating a specific calibration equation and radiometric model to describe the overall sensor responsivity with individual radiometric parameters. Calibration tests were then devised to characterize each radiometric parameter independent of the others. A cryogenic four-function calibration source was designed and fabricated to perform these tests. This source enabled calibration personnel to collect all data required for a full calibration in two 15-working day periods. This paper included terms from the IBSS calibration equation describing sensor dark offset, linearity, absolute responsivity, and measurement uncertainties. It also characterized the IBSS radiometric model in the spectral, spatial, and temporal responsivity domains.

5. ACKNOWLEDGMENTS

This work has been supported under contract with the Strategic Defense Initiative Organization, and their support is gratefully acknowledged. The authors express appreciation to the Messerschmitt-Bolkow-Blohm (MBB) IBSS team for their help in calibrating the IBSS radiometer and spectrometer.

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INFRARED CALIBRATION

AT

THE SPACE DYNAMICS LABORATORY
UTAH STATE UNIVERSITY

LOGAN, UTAH

LARRY JACOBSEN
801-750-~~2944~~ 4880

- HISTORY
- CURRENT EFFORTS
- CALIBRATION APPROACH
  - CALIBRATION OBJECTIVES
  - LOW-BACKGROUND CALIBRATION CHAMBERS
  - CALIBRATION RESULTS

RECENT CALIBRATION EFFORTS AT SDL/USU

- * IBSS (INFRARED BACKGROUND SIGNATURE SURVEY)
  - RADIOMETER
    - 30 DETECTORS
    - 12-COLOR FILTER WHEEL, 2.5 TO 8.0 UM
  - SPECTROMETER
    - EBERT-FASTIE GRATING, 2.5 TO 24 UM
    - 12 DETECTORS
- * CIRRIS-1A (CRYOGENIC INFRARED RADIANCE INSTRUMENTATION FOR SHUTTLE) POST FLIGHT
  - RADIOMETER
    - 14 DETECTORS
    - 8-COLOR FILTER WHEEL, 2 TO 24 UM
  - SPECTROMETER
    - MICHELSON INTERFEROMETER 2 TO 24 UM
    - 4 DETECTORS

RECENT CALIBRATION EFFORTS, CONT

* SPIRIT II (SPATIAL INFRARED ROCKETBORNE INTERFEROMETER TELESCOPE)

RADIOMETER
    300 DETECTORS
    6 COLORS, 6 TO 30 UM

SPECTROMETER
    MICHELSON INTERFEROMETER 3 TO 30 UM
    6 DETECTORS

* SPIRIT III

RADIOMETER
    4000 DETECTORS
    5 COLORS, 6 TO 30 UM

SPECTROMETER
    MICHELSON INTERFEROMETER, 3 TO 30 UM
    6 DETECTORS

OPTICAL CALIBRATION OBJECTIVES

1. CHARACTERIZE EACH OF THE SENSOR RESPONSIVITY DOMAINS
    - LINEARITY RESPONSIVITY
    - ABSOLUTE RESPONSIVITY
    - SPECTRAL DOMAIN
    - SPATIAL DOMAIN
    - TEMPORAL DOMAIN

2. DESIGN CALIBRATION EXPERIMENTS WHICH CHARACTERIZE EACH PARAMETER INDEPENDENTLY OF THE OTHERS

3. CALIBRATE THE SENSOR IN THE MODE THAT IT WILL MAKE MEASUREMENTS

MULTIPLE SOURCE CONFIGURATIONS REQUIRED ⟶ MULTI-FUNCTION CALIBRATION CHAMBER

SDL/USU Low-Background Calibration Chambers

- MIC-1
  (Multi-function Infrared Calibrator)

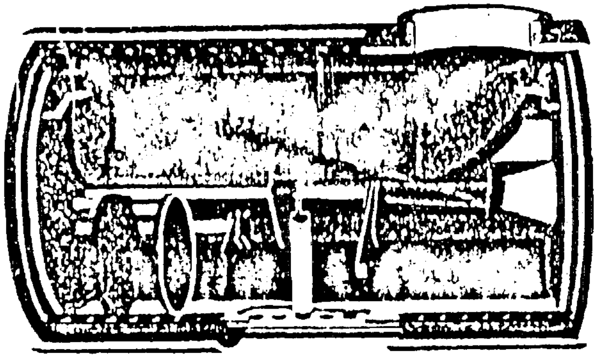
  6-inch circular exit pupil
  Developed on IBSS program

- MIC-2

  21-inch X 11-inch elliptical exit pupil
  Developed on SPIRIT II program

- MIC-3

  17.5-inch circular exit pupil
  Developed on SPIRIT III program



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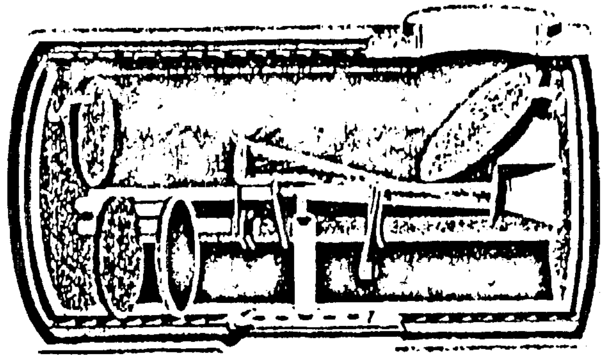

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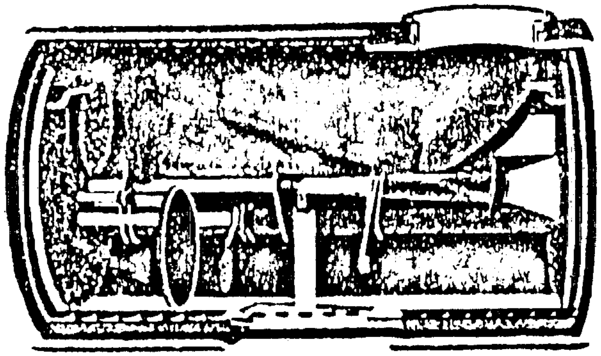

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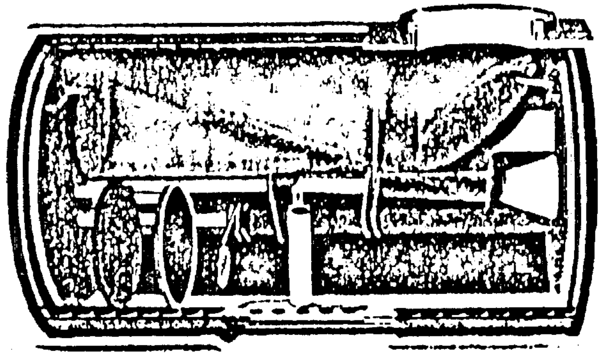

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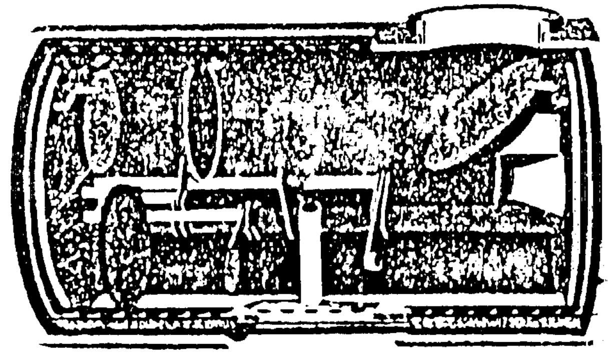


C

THE ILLUSTRATIONS SHOW THE BASIC OPTICAL CONFIGURATIONS OF THE CALIBRATOR AS FOLLOWS:

A. COLLIMATOR (POINT SOURCE)
B. SCATTER PLATE (DIFFUSE SOURCE) - for spectral cals - alternate signal.
C. EXTENDED AREA BLACKBODY
D. JONES SOURCE (NEAR, SMALL AREA SOURCE)
E. COLLIMATOR PLUS BACKGROUND

Optical Sources Provided by Multi-function Infrared Calibrators

* Collimator

Full entrance pupil
Partial field stop
Size of point source depends on precision aperture in collimator focal plane

Typical applications:
- Linearity for large field-of-view detectors
- Spatial domain characterizations
- Direct irradiance responsivity calibration
- Point source flat field

* Jones Source

Partial entrance pupil
Full field stop
Flux throughput depends on precision aperture in calibrator

Typical applications:
- Linearity for small field-of-view detectors
- Spectral domain characterizations
- Temporal domain characterizations
- Bench-mark (long-term repeatability) characterizations

Optical Sources Provided by Multi-function Infrared Calibrators, cont

- Scatter Source

  Full entrance pupil
  Full field stop
  Flux throughput depends on precision aperture in calibrator
  Flux throughput attenuated by scatter surface

  Typical applications:
    Relative spectral responsivity for spectrometers with large entrance pupils

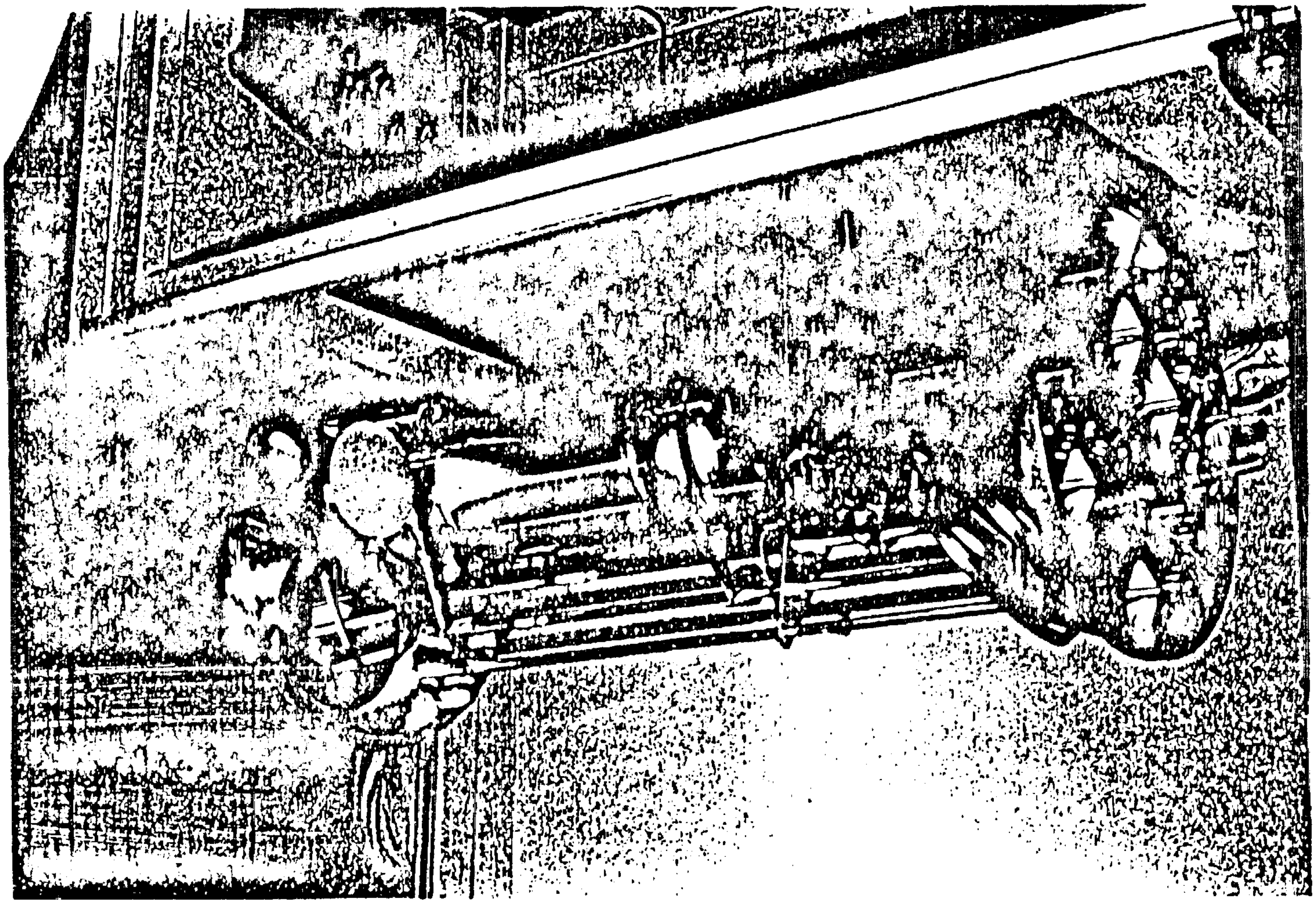
- Extended Source

  Full entrance pupil
  Full field stop

  Typical applications:
    Direct radiance responsivity calibration
    Extended source flat field

- Background Source

  Point source on background source



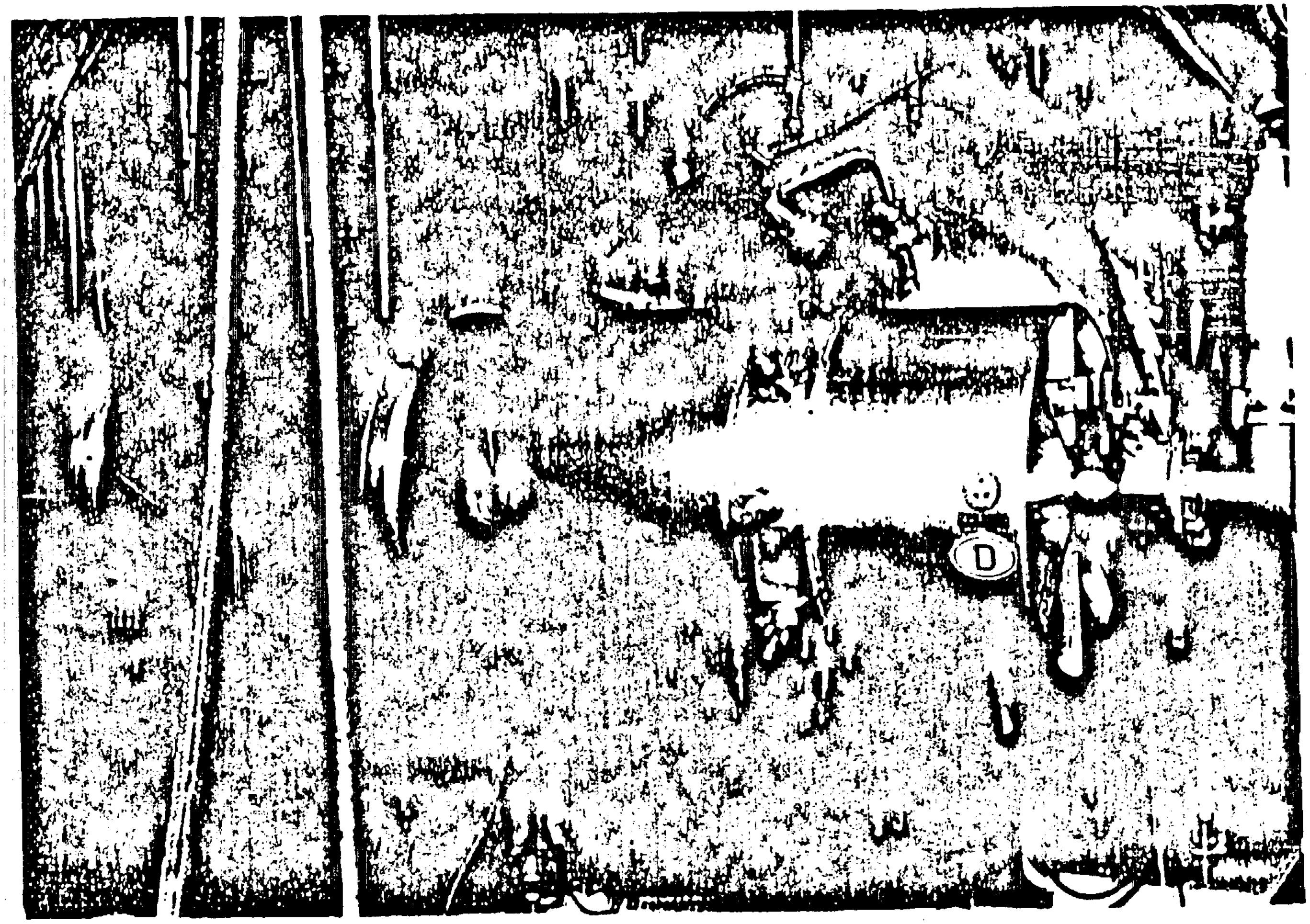
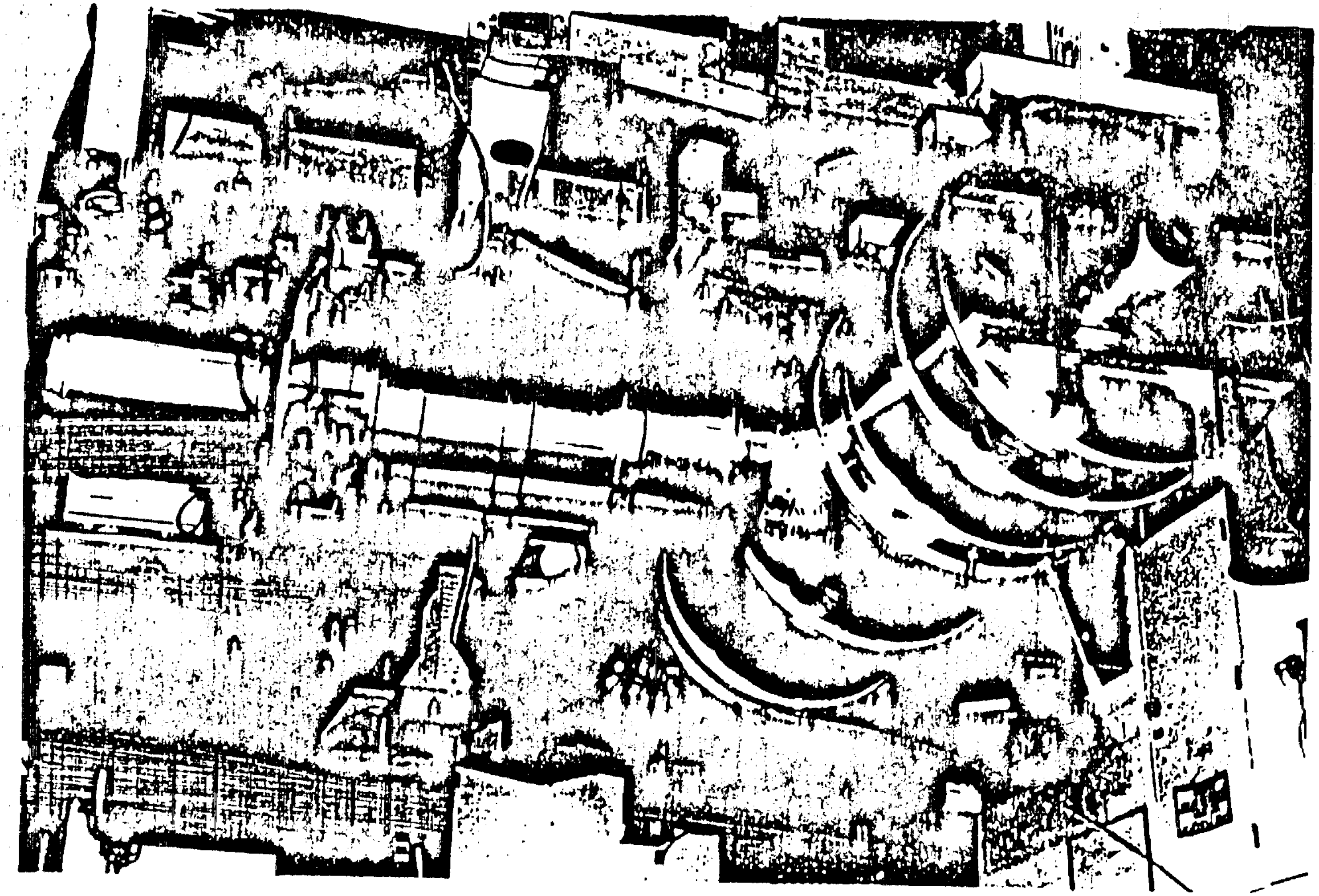
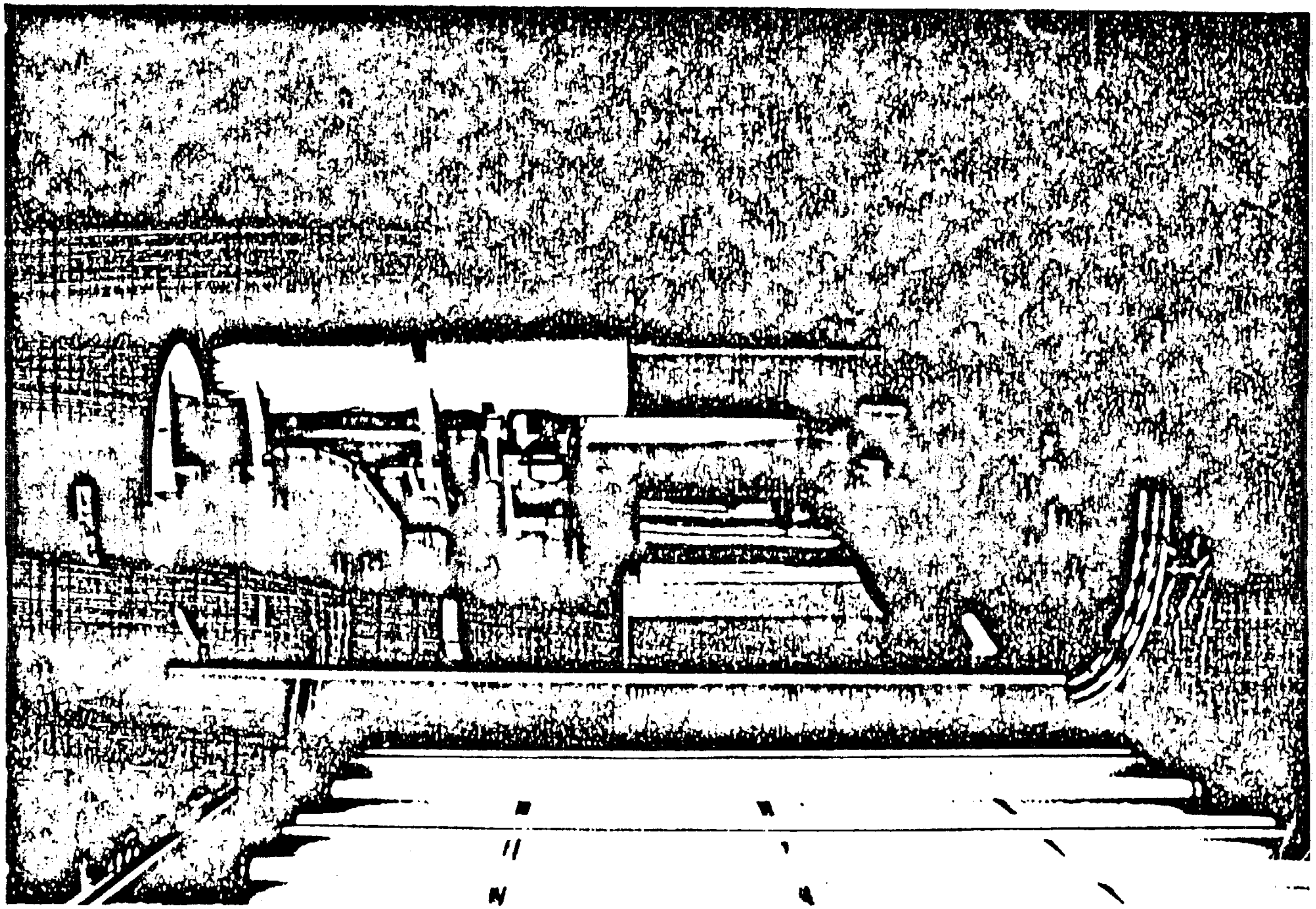


Figure 3.1-2. Photograph of the PCS mounted to the IBSS IR sensor during calibration.





SPIRIT III CALIBRATION CHAMBER

EXTENDED-AREA SOURCE

- 19.5 inch diameter blackbody simulator
- Flux on focal plane is proportional to aperture area
- Fills Full-Field and Full-Aperture of sensor under test
- Temperature Range 25 Kelvin - 300 Kelvin
- Temperature Uncertainty ±0.5 Kelvin (NIST traceable PRT)
- Emissivity 0.99 ±1%

BACKGROUND SOURCE

- Near Small-Area source
- Used with the collimator to provide uniform background illumination with a point source
- **Single aperture**
- **Temperature Range** **20 Kelvin - 300 Kelvin**

EXTERNAL SOURCES for CALIBRATION CHAMBER

BLACKBODY SIMULATORS

• Temperature Ranges	
High Temperature	400 Kelvin - 1200 Kelvin
Low Temperature (Calibrated by NIST)	30 Kelvin - 400 Kelvin
Temperature Uncertainty	1 Kelvin
Emissivity	0.99 ±0.01

SPECTRAL SIMULATORS

• Monochromator	3 - 25 μm
• Absorption cells	Water, Methane, Polystyrene, etc.
• IR Laser	3 μm
• Michelson Interferometer	(5 cm^{-1} resolution)

~~SPIRIT~~ III CALIBRATION CHAMBER

JONES SOURCE

• Near Small-Area source which illuminates the entire focal plane of the sensor	
• Flux on focal plane is proportional to aperture area	
• Effective Aperture sizes	
Area dynamic range	1024:1
Area resolution	2:1
• Optical Filters	
(Neutral Density)	10%, 1%, & 0.1% Transmission
(Spectral)	16 positions available

SCATTER SOURCE

• Fills Full-Field and Full-Aperture of sensor under test	
• Flux on focal plane is proportional to aperture area	
• Apertures	
Area dynamic range	1024:1
Area resolution	2:1
• Optical Filters	(Same as Jones Source

SPIRIT III CALIBRATION CHAMBER

(MIC3)

EXIT BEAM

• Geometry	17.5 inch circular
• Positioning:	
Full-Scale Two-dimensional travel	10 degrees (174 mrad)
Settability	4.1 µrad
Accuracy	±20.5 µrad

COLLIMATOR

• Focal Length	300 inches
• Apertures (11)	26.4 µrad - 0.833 mrad
Area dynamic range	1024:1
Area resolution	2:1
• MTF reticles and/or Scene Simulators (at focal plane of collimator)	11 positions available
• Optical Filters	
(Neutral Density)	10%, 1%, & 0.1% Transmission
(Spectral)	16 positions available

CONCEPT OF ASTER CALIBRATION REQUIREMENT

PRESENTED AT
5TH CAL/VAL PANEL MEETING
APRIL 7 TO 10, 1992
BOULDER, COLORADO

A. ONO
NATIONAL RESEARCH LABORATORY OF METROLOGY, MITI

S14-43
171305
p-18

N94-23600

ASTER CALIBRATION REQUIREMENT

(FIRST DRAFT, JANUARY 1992)

Content

0 Introduction
1 Spectral Characteristics of Operating Band
2 Offset
3 Nonlinearity
4 Absolute Responsivity, Gain Ratio, and Temperature Scale
5 Responsivity Ratio and Temperature Scale Difference among Bands
6 Responsivity Ratio and Temperature Scale Difference among Detector Elements in a Band
7 Polarization Characteritics
8 Stray Light Characteristics

0 Introduction

The document of ASTER Calibration Requirement specifies the following items related to spectral and rediometric characteristics of the ASTER instrument:
① Characteristics whose knowledge is specified,
② Requirement for knowledge of the characteristics,
③ Methodology for characteristics evaluation, and
④ Supplementary information and data related with characteristics evaluation.

This document is applicable to the document of the ASTER Instrument Specification on Observational Performances, and will be a part of the ASTER Calibration Plan.

ASTER Calibration Requirement is scheduled to establish the concept and framework by March 1992 when the 5th Calibration and Data Validation Panel Meeting is held, and to determine details including requirement values and evaluation methodologies by October 1992 around which the Calibration Peer Review may be held. The ASTER Calibration Plan is planned to finish by the same time.

[CHARACTERISTICS WHOSE KNOWLEDGE IS TO BE SPECIFIED]

1. Center wavelength and half width of operating band
2. Offset
3. Nonlinearity
4. Absolute responsivity, gain ratio, and temperature scale
5. Responsivity ratio and temperature scale difference among bands
6. Responsivity ratio and temperature scale difference among detector elements in a band
7. Polarization characteristics
8. Stray light characteristics

[COMPOSITION OF DOCUMENT]

[Knowledge]

1. Knowledge requirements for individual characteristics of the instrument are specified.

[Verification]

2. Methodology for calibration and uncertainty analyses are required to be reported by the contractors in terms of budget and design so that the instrument provider verifies the knowledge requirements from the uncertainty analyses.

[Supplementary information]

3. Supplementary information related to the instrument calibration is required to be reported by the contractors so that the instrument users understand nature and quality of the instrument data.

1. Spectral Characteristics of Operating Band

1.1 Requirement for knowledge of spectral characteristics

The center wavelengths of bands and band widths shall be evaluated within the accuracies in 3σ listed in Table 1.1 until the end of anticipated life, i.e. 5 years.

Table 1.1 Requirement for knowledge of spectral characteristics

Band No.	Center Wavelength/μm	Band Width/μm
1	±0.005	±0.01
2	±0.005	±0.01
3N	±0.005	±0.01
3B	±0.005	±0.01
4	±0.005	±0.01
5	±0.0035	±0.005
6	±0.0035	±0.005
7	±0.0035	±0.005
8	±0.005	±0.0075
9	±0.005	±0.0075
10	±0.04	±0.04
11	±0.04	±0.04
12	±0.04	±0.04
13	±0.05	±0.06
14	±0.05	±0.06

1.2 Methodology for spectral characteristics evaluation

The sources of knowledge uncertainty as listed in Table 1.2 shall be evaluated by testing and/or analysis, and Table 1.2 shall be filled out.

Table 1.2 Uncertainty in the Prelaunch Knowledge of Center Wavelength of Operating Bands (Band No.:   )

Sources of uncertainty		Uncertainty/μm (3σ)		Method of testing, analysis, and evaluation
		Budget	Design*	
1. Spectral transmissivity of band pass filter				RSS of sources
Source	Measurement			
	Nonuniformity			
	Air-to-vacuum shift			
2. Spectral responsivity of detector elements				RSS of sources
Source	Measurement			
	Nonuniformity			
3. Spectral reflectivity/transmissivity of dichroic mirror				same as the measurement uncertainty
Source	Measurement			
4. Spectral transmissivity and reflectivity of optical system				same as the measurement uncertainty
Source	Measurement			
5. Total spectral responsivity				RSS of sources
Source	Measurement			
	Nonuniformity			
Total (RSS)				

* Present design status

1.3 Supplementary information and data for evaluation of spectral characteristics

The following information and data of spectral characteristics shall be submitted.

1.3.1 Measurement apparatus and method of analysis for spectral characteristics evaluation

1.3.2 Measurement apparatus and method of analysis for in-orbit degradation

1.3.3 Spectrum and numerical table of filter transmissvity

To be taken at the both ends, the middle, a quarter, and three quarters of band.

1.3.4 Spectrum and numerical table of transmissivity and reflectivity of dichroic mirror

To be taken at the both ends, the middle, a quarter, and three quarters of band.

1.3.5 Spectrum and numerical table of transmissivity and reflectivity of optical system

1.3.6 Spectrum and numerical table of responsivity of detector elements

To be taken at the both ends, the middle, a quarter, and three quarters of band.

1.3.7 Spectrum and numerical table of total responsivity, and the 1st-, 2nd-, and 3rd-order moments

To be taken at the both ends, the middle, a quarter, and three quarters of band.

2 Offset

2.1 Requirement for knowledge of offset

The instrument offset shall be determined at any instance of the life within the accuracies listed below for the individual gain setting.

Table 2.1 Requirement for knowledge of offset

Band No.	Knowledge (3σ)			
	High Gain	Normal gain	Low gain-1	Low gain-2
1	±4 DN	±2 DN	±2 DN	N/A
2	±4 DN	±2 DN	±2 DN	
3N	±4 DN	±2 DN	±2 DN	
3B	±4 DN	±2 DN	±2 DN	
4	±4 DN	±2 DN	±2 DN	±2 DN
5	±4 DN	±2 DN	±2 DN	±2 DN
6	±4 DN	±2 DN	±2 DN	±2 DN
7	±4 DN	±2 DN	±2 DN	±2 DN
8	±4 DN	±2 DN	±2 DN	±2 DN
9	±4 DN	±2 DN	±2 DN	±2 DN
10	N/A	± 6 DN[•]	N/A	N/A
11		± 7 DN[•]		
12		± 8 DN[•]		
13		±11 DN[•]		
14		±12 DN[•]		

[•] Offset knowledge related to only instrument temperature variation is specified in 2.1. Offset knowledge related to onboard blackbody is specified as knowledge of temperature scale in 4.2.

3 Nonlinearity

The nonlinearity of input-to-output relation, NL, is defined as the ratio of the deviation of the input-to-output curve from the line connecting the output for the high level input and the offset to the response for the high level input as referred to in the ASTER Instrument Specification.

3.1 Requirement for knowledge of nonlinearity

Table 3.1 Requirement for knowledge of VNIR and SWIR nonlinearity, NL

Band No.	NL knowledge (3σ)
1	±1 %
2	±1 %
3N	±1 %
3B	±1 %
4	±1 %
5	±1 %
6	±1 %
7	±1 %
8	±1 %
9	±1 %

Table 3.2 Requirement for knowledge of TIR nonlinearity, NL

Band No.	NL knowledge (3σ)
10	±1 %
11	±1 %
12	±1 %
13	±1 %
14	±1 %

4 Absolute Responsivity, Gain Ratio, and Temperature Scale

4.1 Requirements for the knowledge of absolute responsivity, temperature scale, and gain ratio

Requirements for the knowledge of absolute responsivity and temperature scale are referred to the item of 20 of the ASTER Performance Specification. The requirements are specified at the high level input radiance for VNIR and SWIR and all through the anticipated ASTER life time.

Knowledge of the gain ratios among the high, normal, low-1, and low-2 gains should is required to be the same level as the item 28 of ASTER Performance Specification, i.e. 1%.

4.2 Methodology for evaluation of responsivity, gain ratio, and temperature scale

VNIR and SWIR is calibrated referring to the absolute standards of spectral radiance. TIR is calibrted referring to the temperature standards.

Uncertainty in the responsivity determination of VNIR and SWIR should be analyzed to fill out the following table.

Table 4.1 Analysis of uncertainty in the responsivity determination of VNIR and SWIR

Phase	Source of uncertainty	Uncertainty /% (3σ)		Comments
		Budget	Design	
Prelaunch	Fixed-point blackbody			
	Standard spectrometer			
	Variable temperature blackbody			
	Comparison spectrometer			
	Integrating sphere			
	Radiometer output measurement			
	Photomonitor output measurement			
	Air-to-vacuum shift of center wavelength			
	Subtotal (RSS)			
Postlaunch	Temperature of photomonitor			
	Degradation of photomonitor			
	Photomonitor output measurement			
	Gravity shift of lamp radiance			
	Radiometer output measurement			
	(Nonuniform contamination of radiometer aperture optics)			
	Subtotal (RSS)			
	Total (RSS)			

5 Responsivity Ratio and Temperature Scale Difference among Bands

5.1 Requirement for knowledge of responsivity ratio and temperature scale difference among bands

Table 5.1 Requirement for knowledge of responsivity ratio and temperature scale difference among bands

Operating bands	Knowledge of responsivity ratio and temperature scale difference among bands, (3σ)
VNIR	6%
SWIR	6%
TIR	
200 K～240 K	1.5 K
240 K～270 K	1.0 K
270 K～340 K	0.5 K
340 K～370 K	1.0 K

6 Responsivity ratio and temperature scale difference among detector elements of a band

6.1 Requirement for knowledge of responsivity ratio and temperature scale difference among detector elements of a band

Table 6.1 Requirement for knowledge of responsivity ratio and temperature scale difference among detector elements of a band

Operating bands	Knowledge of responsivity ratio and temperature scale difference among detector elements in a band (3σ)
VNIR	2%
SWIR	2%
TIR	
200 K～240 K	0.8 K
240 K～270 K	0.5 K
270 K～340 K	0.25K
340 K～370 K	0.5 K

7 Polarization Characteristics

7.1 Requirement for knowledge of polarization characteristics

Table 7.1 Requirement for knowledge of polarization characteristics

Operating band	Knowledge of polarization characteristics (3σ)
VNIR	1%
SWIR	1%
TIR	NA

8 Stray Light Characteristics

8.1 Requirement for stray light characteristics and its knowledge

Radiometer response may change for radiant sources with different sizes even if the radiance is exactly same due to stray light effect of radiometers. The stray light characteristics is defined by the relative response difference of radiometer when observing the earth disk and the standard radiation source (integrating sphere for VNIR and SWIR, and standard blackbody for TIR) which is required to be less than the required values listed in the following table.

Table 8.1 Requirement for stray light characteristics

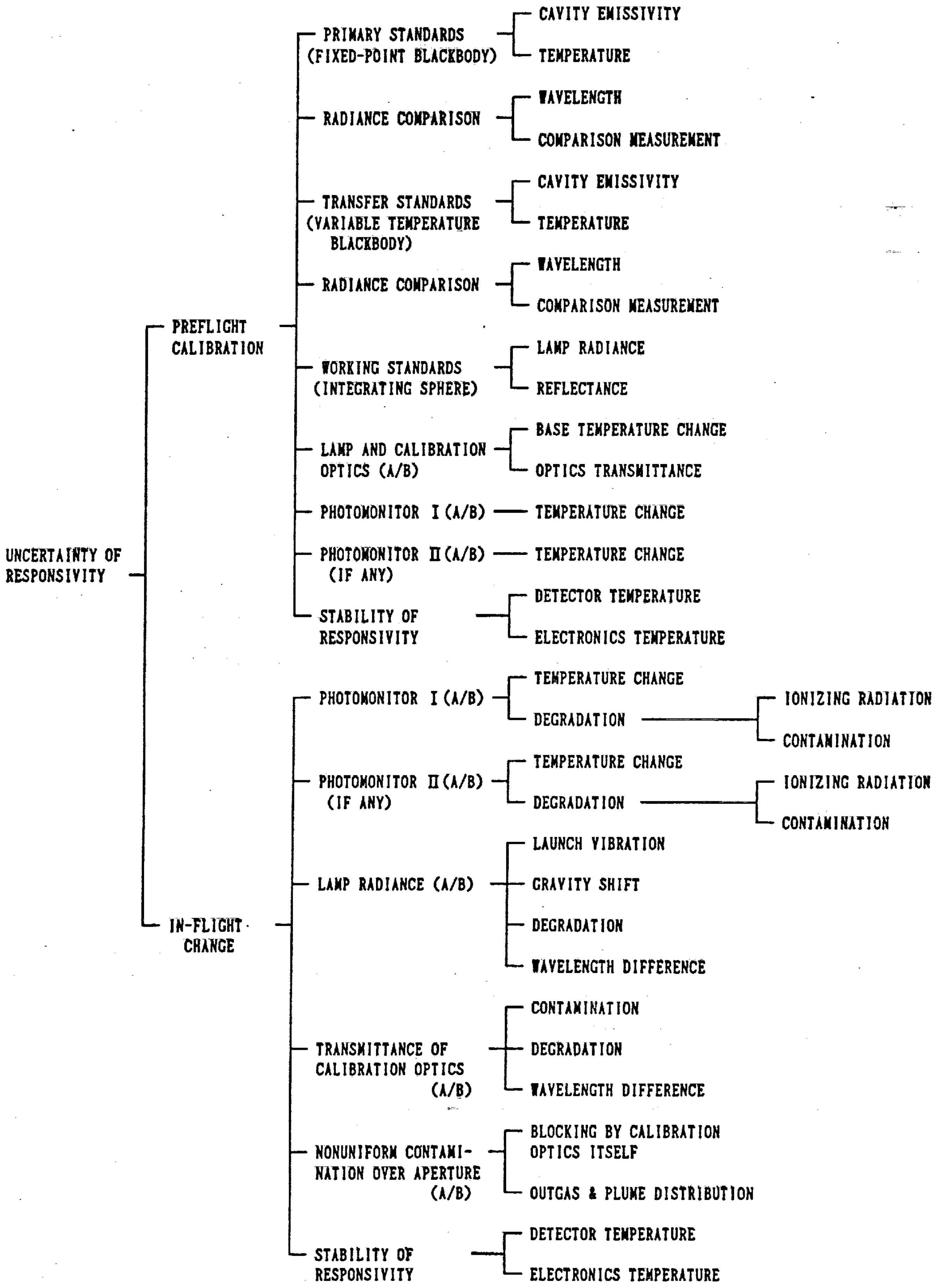
Operating band	Stray light characteristics
VNIR	2%
SWIR	2%
TIR	1%

The stray light characteristics shall be determined with the knowledge as listed in the following table.

Table 8.2 Requirement for knowledge of stray light characteristics

Operating band	Knowledge of stray light characteristics
VNIR	1%
SWIR	1%
TIR	0.5%

ERROR BUDGET FOR VNIR & SWIR RESPONSIVITY CALIBRATION



- UNCERTAINTY OF RESPONSIVITY
  - PREFLIGHT CALIBRATION
    - PRIMARY STANDARDS (FIXED-POINT BLACKBODY)
      - CAVITY EMISSIVITY
      - TEMPERATURE
    - RADIANCE COMPARISON
      - WAVELENGTH
      - COMPARISON MEASUREMENT
    - TRANSFER STANDARDS (VARIABLE TEMPERATURE BLACKBODY)
      - CAVITY EMISSIVITY
      - TEMPERATURE
    - RADIANCE COMPARISON
      - WAVELENGTH
      - COMPARISON MEASUREMENT
    - WORKING STANDARDS (INTEGRATING SPHERE)
      - LAMP RADIANCE
      - REFLECTANCE
    - LAMP AND CALIBRATION OPTICS (A/B)
      - BASE TEMPERATURE CHANGE
      - OPTICS TRANSMITTANCE
    - PHOTOMONITOR I (A/B)
      - TEMPERATURE CHANGE
    - PHOTOMONITOR II (A/B) (IF ANY)
      - TEMPERATURE CHANGE
    - STABILITY OF RESPONSIVITY
      - DETECTOR TEMPERATURE
      - ELECTRONICS TEMPERATURE
  - IN-FLIGHT CHANGE
    - PHOTOMONITOR I (A/B)
      - TEMPERATURE CHANGE
      - DEGRADATION
        - IONIZING RADIATION
        - CONTAMINATION
    - PHOTOMONITOR II (A/B) (IF ANY)
      - TEMPERATURE CHANGE
      - DEGRADATION
        - IONIZING RADIATION
        - CONTAMINATION
    - LAMP RADIANCE (A/B)
      - LAUNCH VIBRATION
      - GRAVITY SHIFT
      - DEGRADATION
      - WAVELENGTH DIFFERENCE
    - TRANSMITTANCE OF CALIBRATION OPTICS (A/B)
      - CONTAMINATION
      - DEGRADATION
      - WAVELENGTH DIFFERENCE
    - NONUNIFORM CONTAMINATION OVER APERTURE (A/B)
      - BLOCKING BY CALIBRATION OPTICS ITSELF
      - OUTGAS & PLUME DISTRIBUTION
    - STABILITY OF RESPONSIVITY
      - DETECTOR TEMPERATURE
      - ELECTRONICS TEMPERATURE

8 Stray Light Characteristics

8.1 Requirement for stray light characteristics and its knowledge

Radiometer response may change for radiant sources with different sizes even if the radiance is exactly same due to stray light effect of radiometers. The stray light characteristics is defined by the relative response difference of radiometer when observing the earth disk and the standard radiation source (integrating sphere for VNIR and SWIR, and standard blackbody for TIR) which is required to be less than the required values listed in the following table.

Table 8.1 Requirement for stray light characteristics

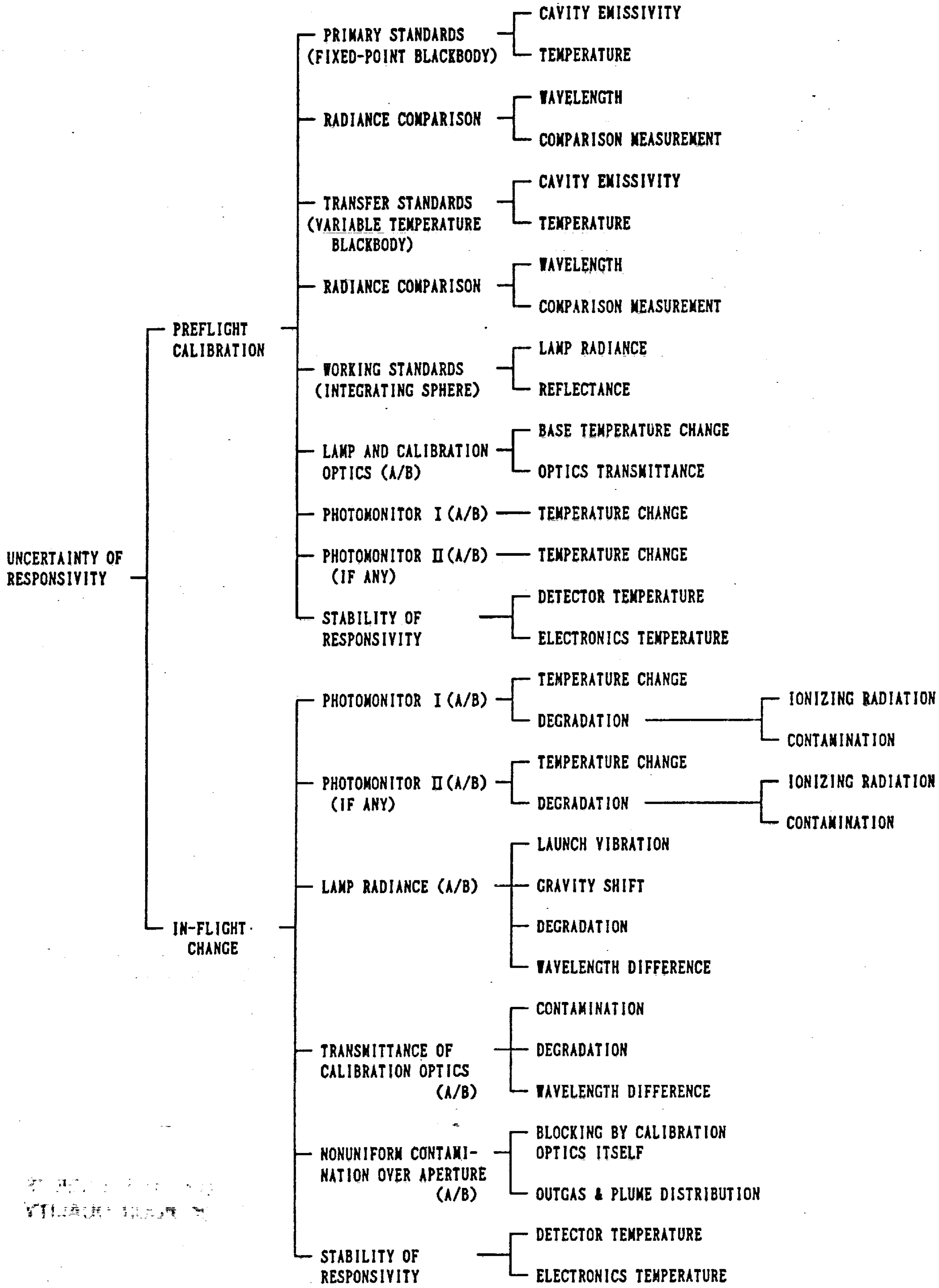
Operating band	Stray light characteristics
VNIR	2%
SWIR	2%
TIR	1%

The stray light characteristics shall be determined with the knowledge as listed in the following table.

Table 8.2 Requirement for knowledge of stray light characteristics

Operating band	Knowledge of stray light characteristics
VNIR	1%
SWIR	1%
TIR	0.5%

ERROR BUDGET FOR VNIR & SWIR RESPONSIVITY CALIBRATION



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VNIR AND SWIR TRANSFER RADIOMETERS DEVELOPED AT NRLM FOR PREFLIGHT LABORATORY CROSS-CALIBRATION

5TH CAL/VAL PANEL MEETING
APRIL 7 TO 10, 1992
BOULDER, COLORADO

A. ONO
NATIONAL RESEARCH LABORATORY OF METROLOGY
MITI

[PURPOSE OF PREFLIGHT LABORATORY CROSS-CALIBRATION]

Avoiding Mistake

1. To avoid incorrect setting of instrument dynamic range due to calibration mistake at individual instrument manufacturers.

Relative Consistency

2. To make corrections of instrument responsivities to have consistent radiance scales among instruments.

Absolute Accuracy

3. To clarify the state of the art in the absolute responsivity determination of VIS/NIR and SWIR instruments in the EOS era.

4. To improve the preflight calibration accuracy if necessary to meet the EOS requirement.

[INTERCOMPARISON AT TWO LEVELS]

1. Intercomparison of spectral radiances established for standard radiant sources at individual instrument manufacturers and platform integrator.

2. Intercomparison of spectral radiance standards at national standards laboratories.

[ROUND-ROBIN MEASUREMENT]

(1) Circulating transfer radiometers through instrument manufacturers where the responsivity is calibrated against standard sources of individual instrument manufacturers.

(2) Circulating transfer radiometers through the national standards laboratories.

(3) Redundancy to be considered to enhance the intercomparison reliability (contingency in transfer radiometers); more than one radiometers with a radiant source if necessary.

[COMPARISON ACCURACY]

Desirable comparison accuracy is more than twice higher than the calibration accuracy stated by individual instrument teams; e.g. a level of 1% comparison accuracy.

[REQUIREMENT TO TRANSFER RADIOMETERS]

1. High stability in responsivity during circulation (environment and time)
2. Sufficient linearity
3. Small or known temperature coefficient of responsivity
4. Known spectral profile
5. Small size-of-source effect
6. Light weight and small volume

[VIS/NIR AND SWIR TRANSFER RADIOMETER]

1. Ambient temperature silicon photodiode filter radiometers with operating wavelengths of 0. 56μm, 0. 65μm, and 0. 81μm.
2. Electronically cooled germanium photodiode filter radiometer with an operating wavelength of 1. 6μm.
3. Liquid nitrogen cooled indium arsenide photodiode filter radiometer with an operating wavelength of 2. 2μm.

Specifications of Si photodiode radiometer

Operating wavelength	
Center wavelength	560 nm 660 nm 810 nm
Full width at half maximum	80 nm 60 nm 100 nm
Target distance	variable (40 cm ～ ∞)
Nominal target size	3 mm in diameter at a target distance of 40 cm
Field of view	0.54° (flexible)
Detector	silicon photodiode (Hamamatsu Photonics)
Size-of-source effect	less than 0.5% between 6 mm and 50 mm at a target distance of 40 mm
Detector temperature monitor	Transistor thermometer
Mass	4 kg
Power voltage	100 V AC, 50 Hz
Mounting	tripod

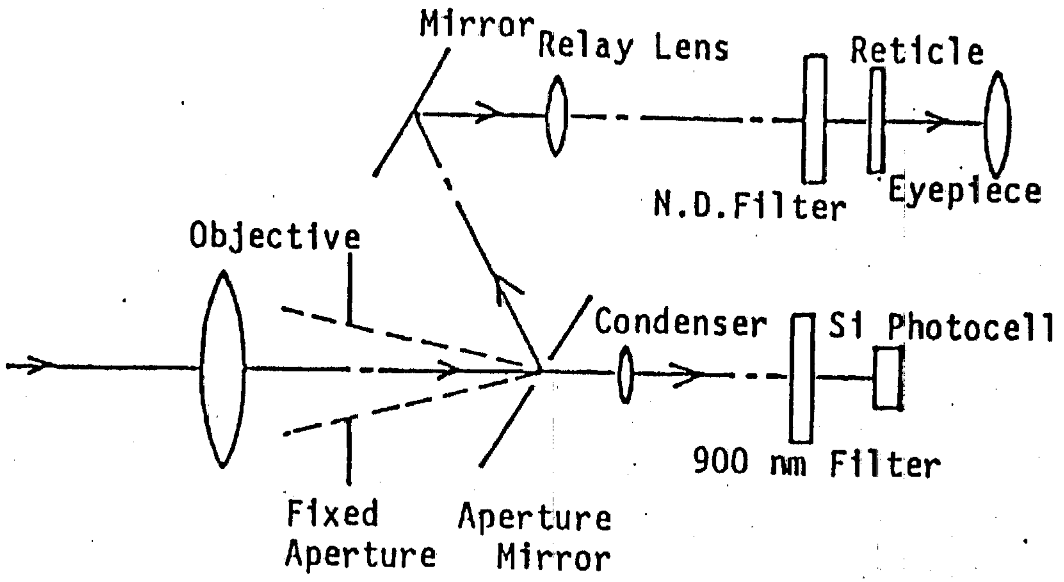
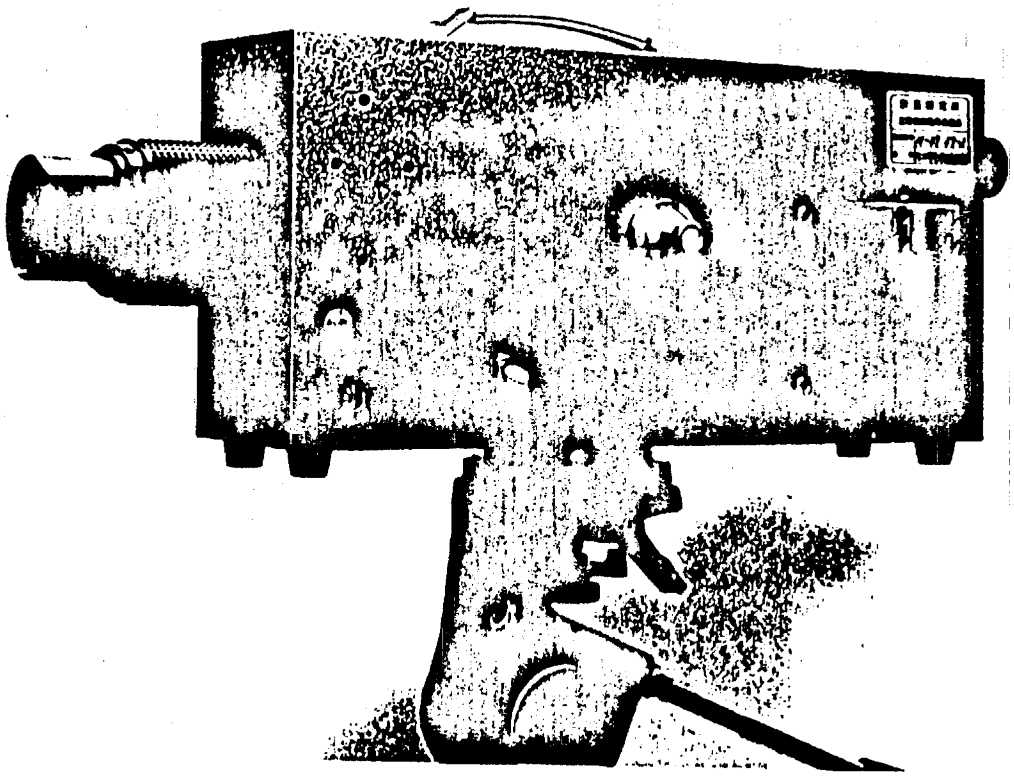
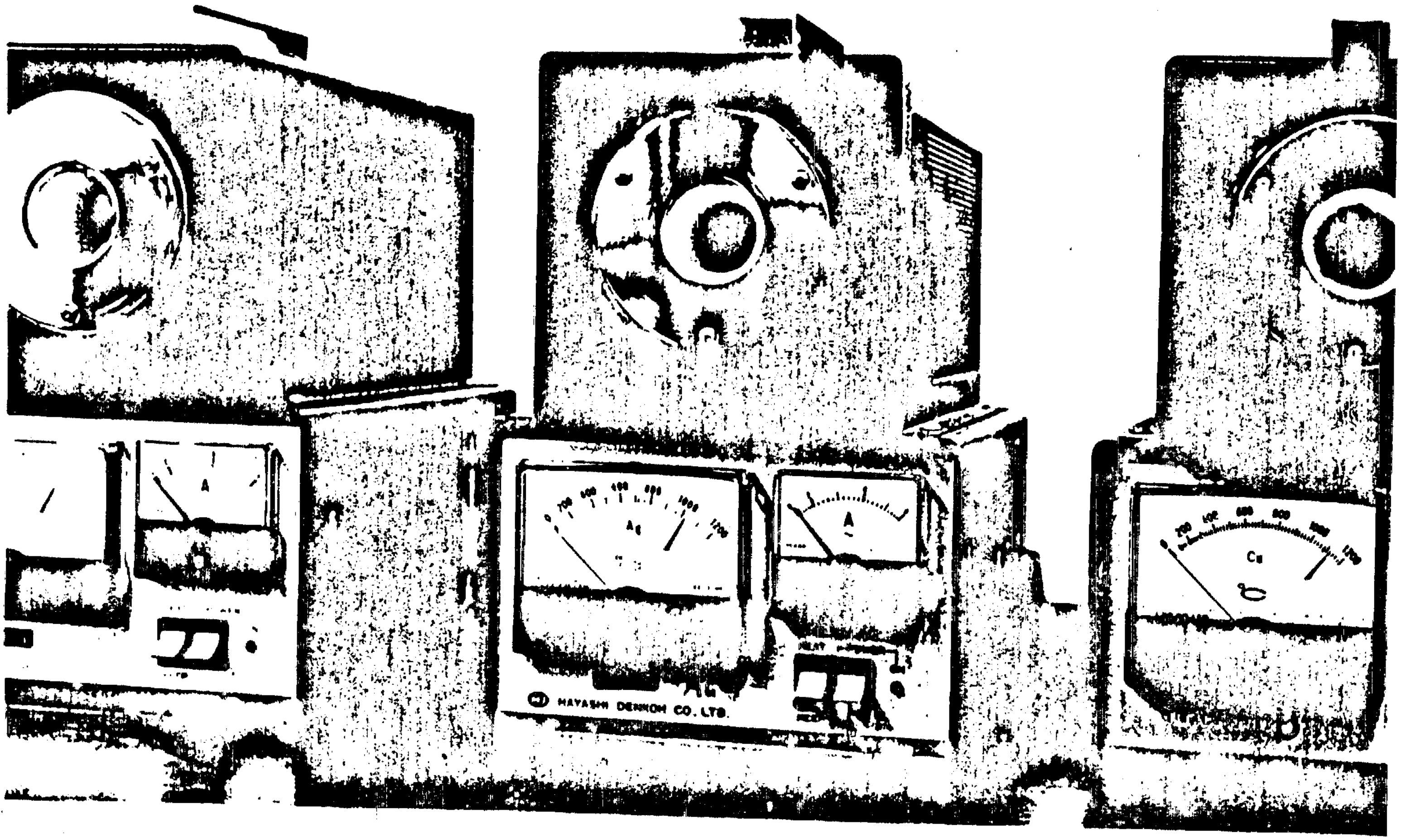
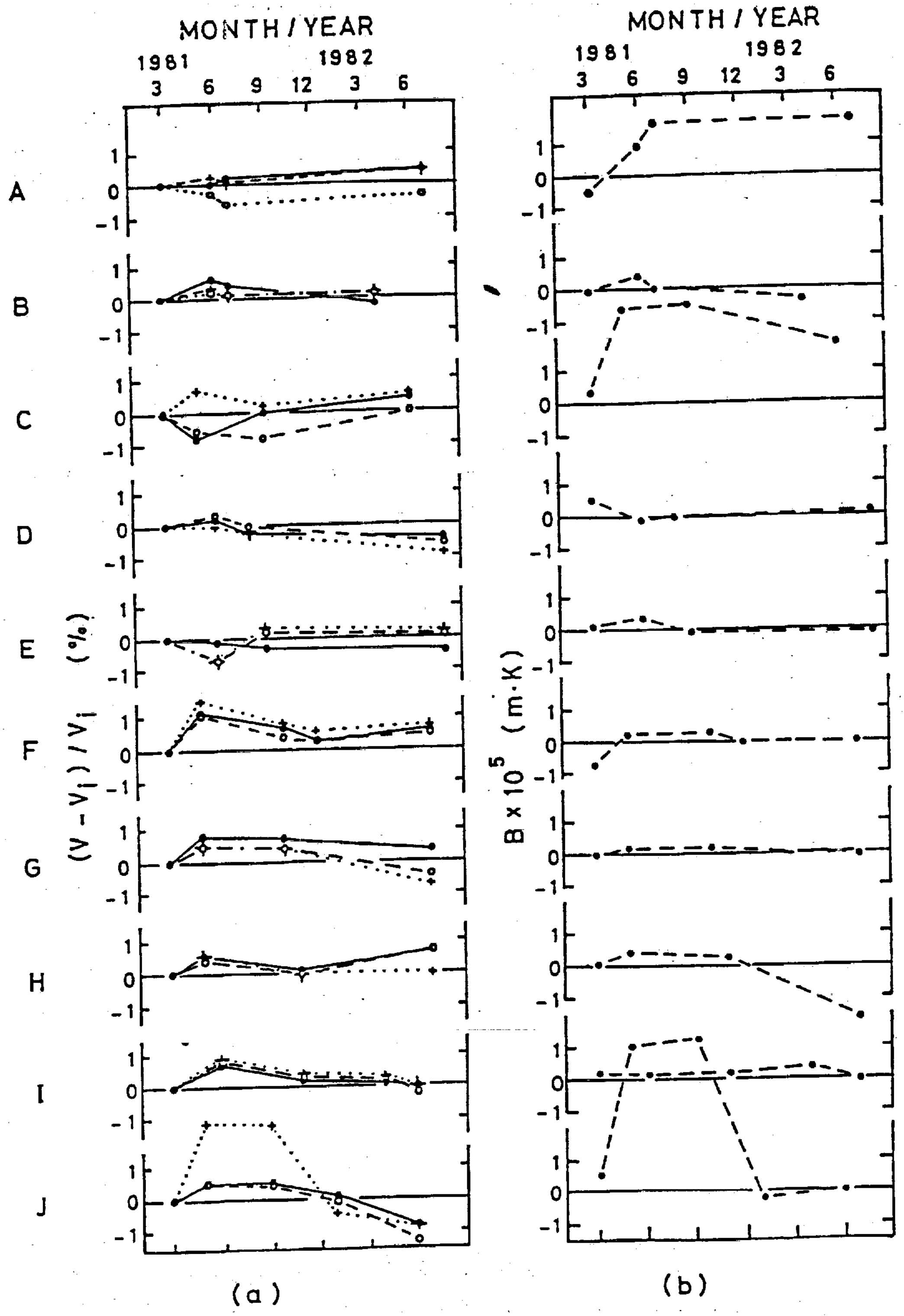


Figure 14.6 Schematic optics of silicon-based standard radiation thermometer.[7)]

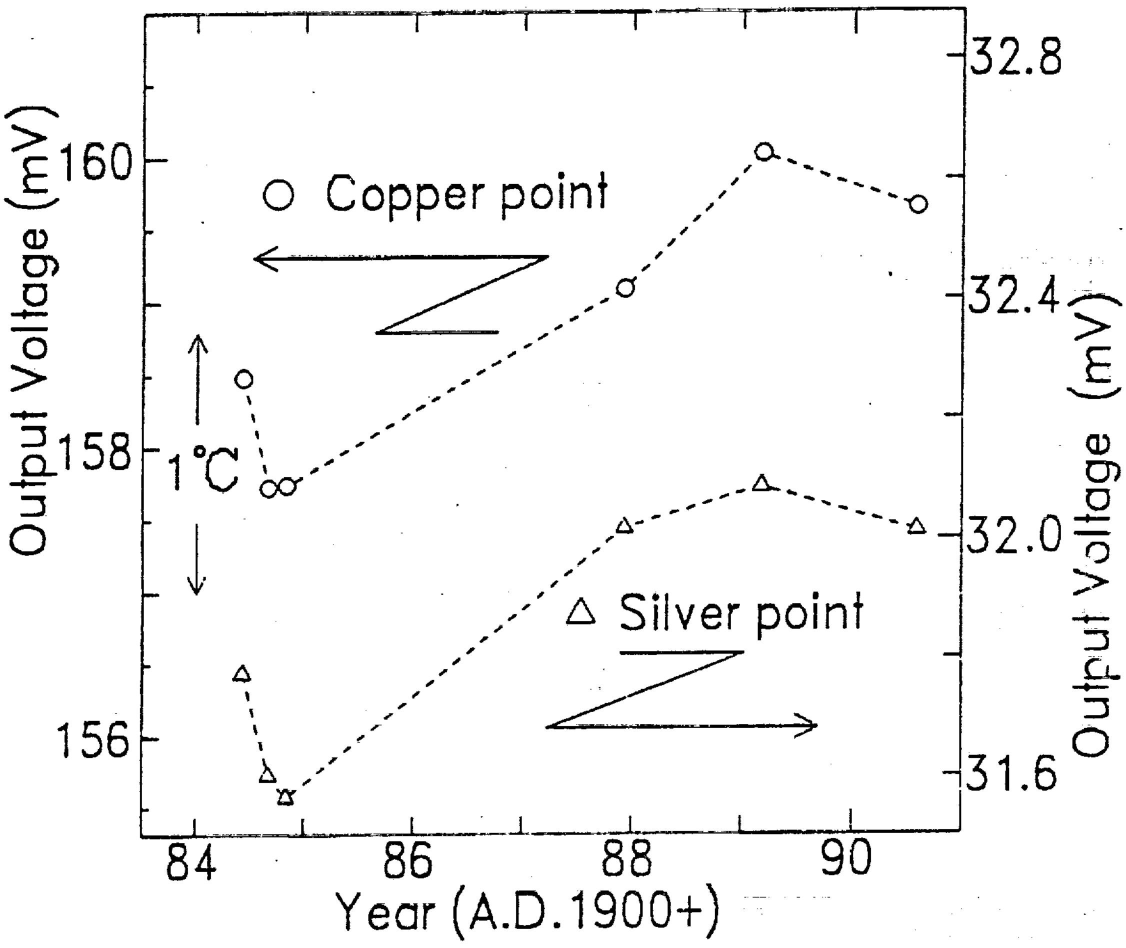


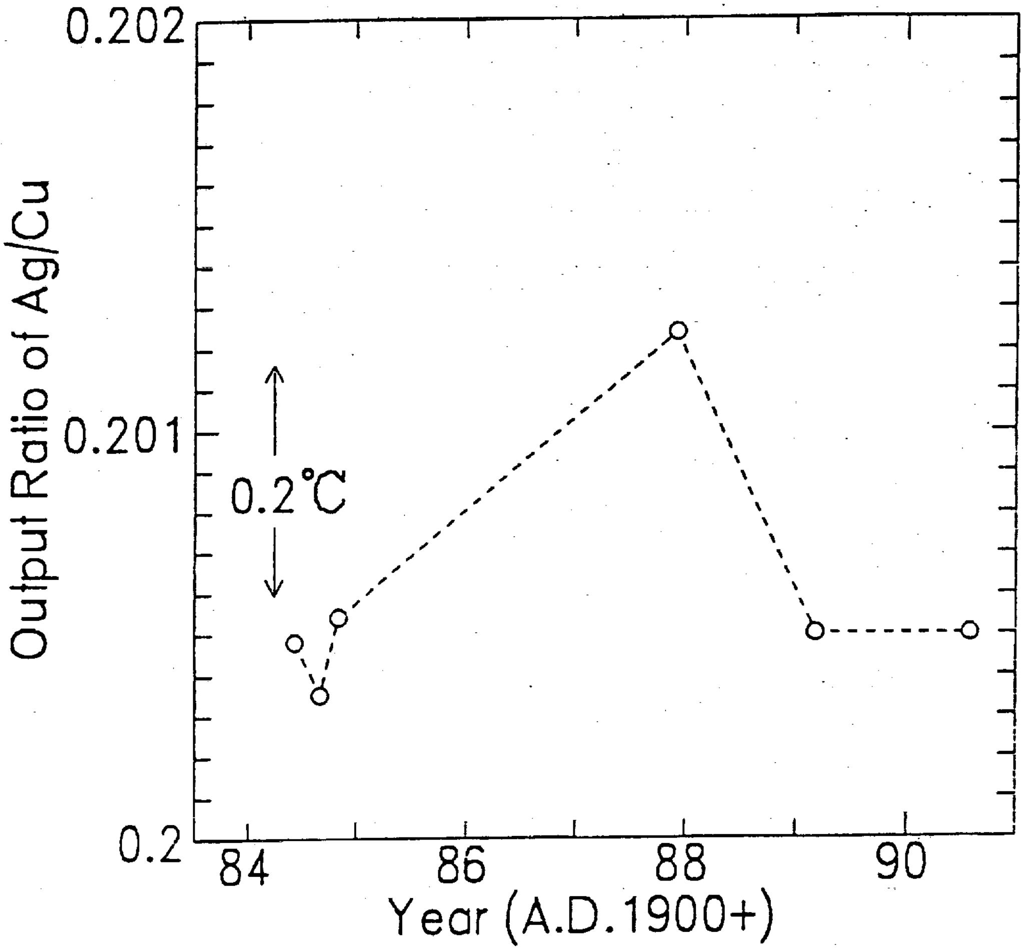

A
0
200
400
600
800
1000
1200
A
HEAT
HAYASHI DENKOH CO. LTD.
0
200
400
600
800
1000
1200
Cu

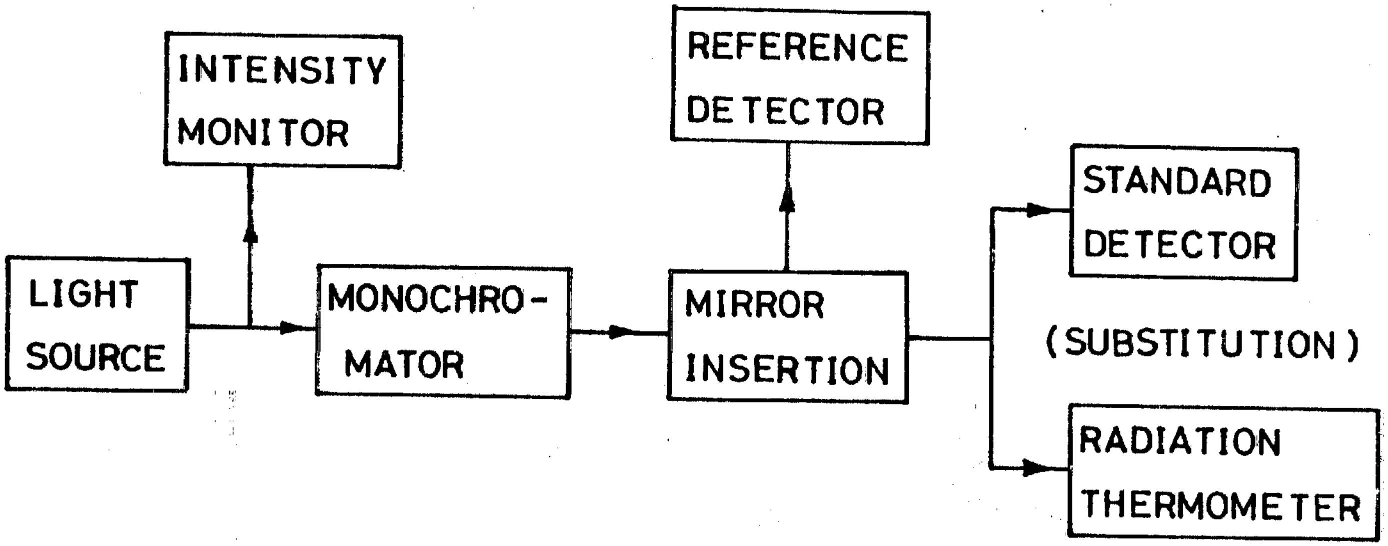


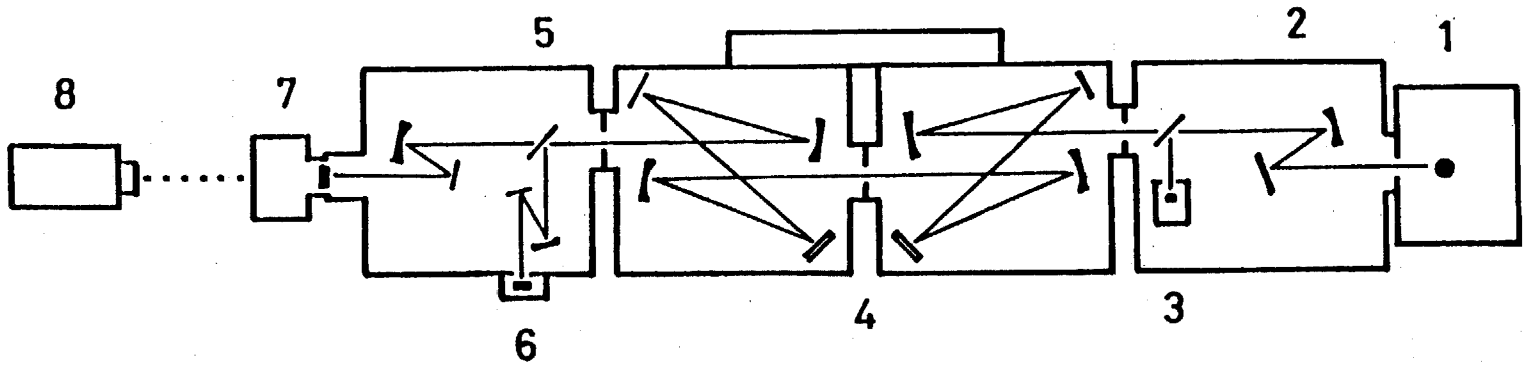
MONTH / YEAR
1981
1982
3
6
9
12
3
6
A
B
C
D
E
F
G
H
I
J
1
0
-1
(V - V1) / V1 (%)
B x 10^5 (m·K)
(a)
(b)

Figure 14.9


Output Voltage (mV)
160
158
156
○ Copper point
1°C
△ Silver point
84
86
88
90
Year (A.D.1900+)
32.8
32.4
32.0
31.6
Output Voltage (mV)

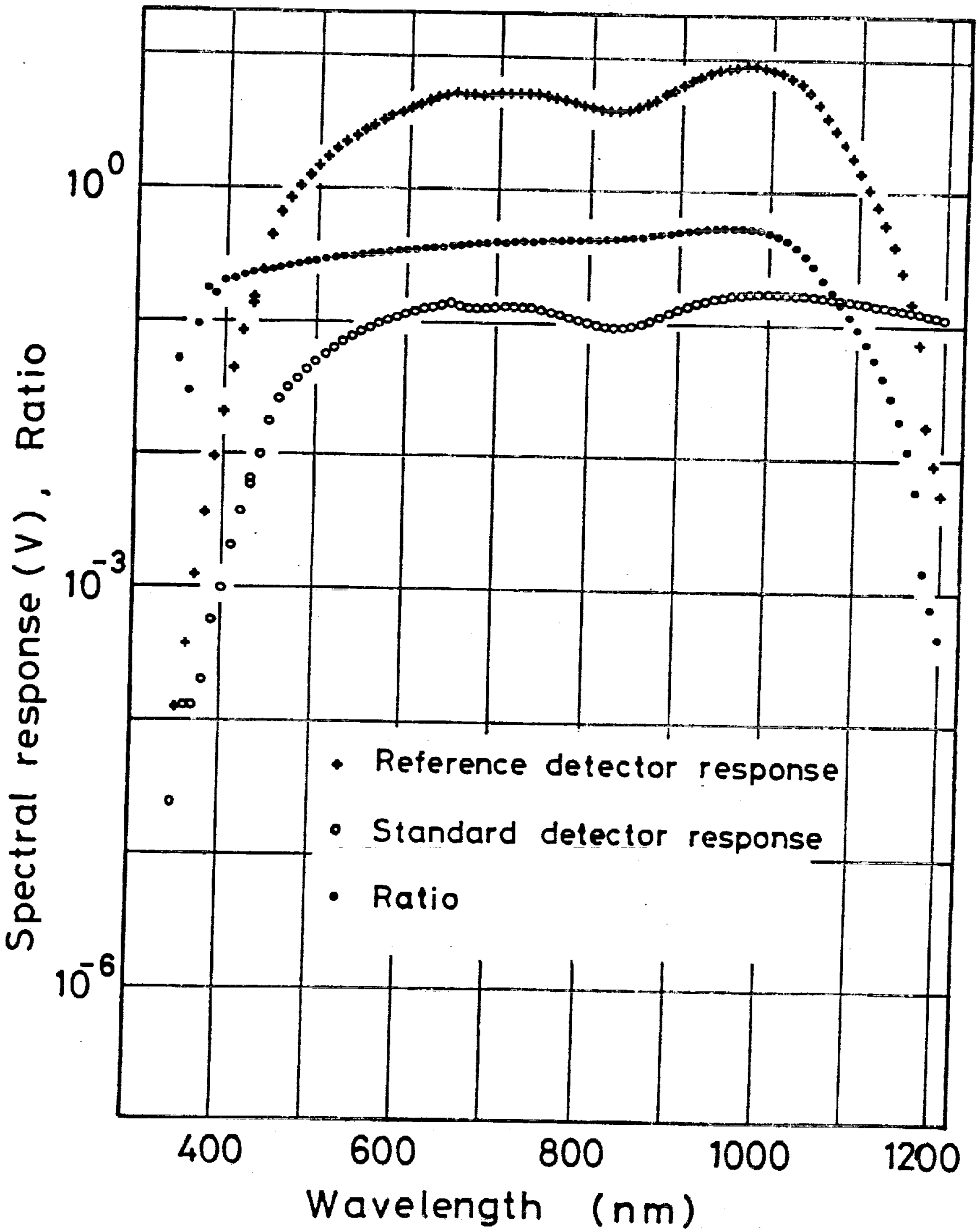

0.202
0.201
0.2
Output Ratio of Ag/Cu
0.2°C
84
86
88
90
Year (A.D.1900+)

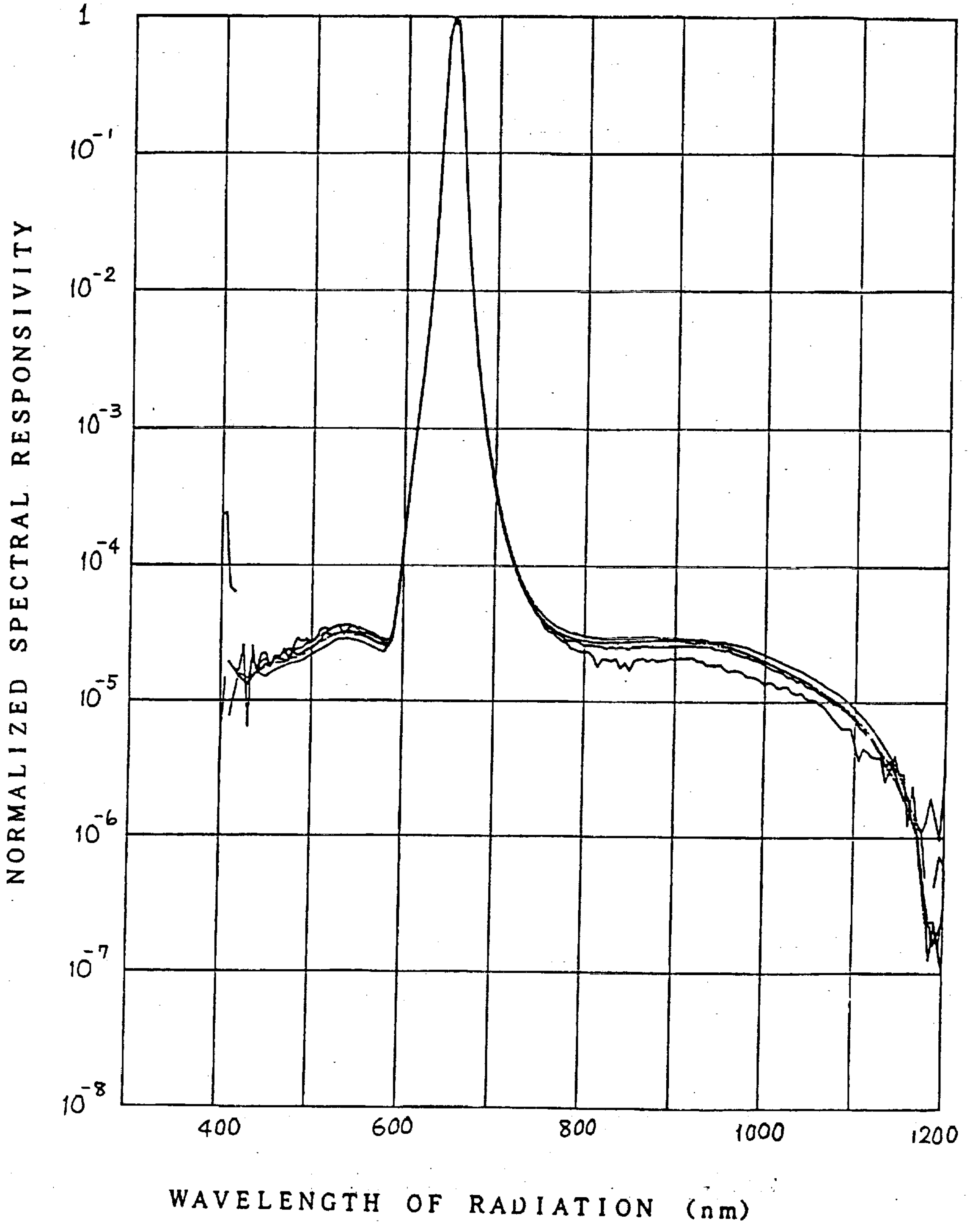

INTENSITY MONITOR
REFERENCE DETECTOR
STANDARD DETECTOR
LIGHT SOURCE
MONOCHRO-MATOR
MIRROR INSERTION
(SUBSTITUTION)
RADIATION THERMOMETER



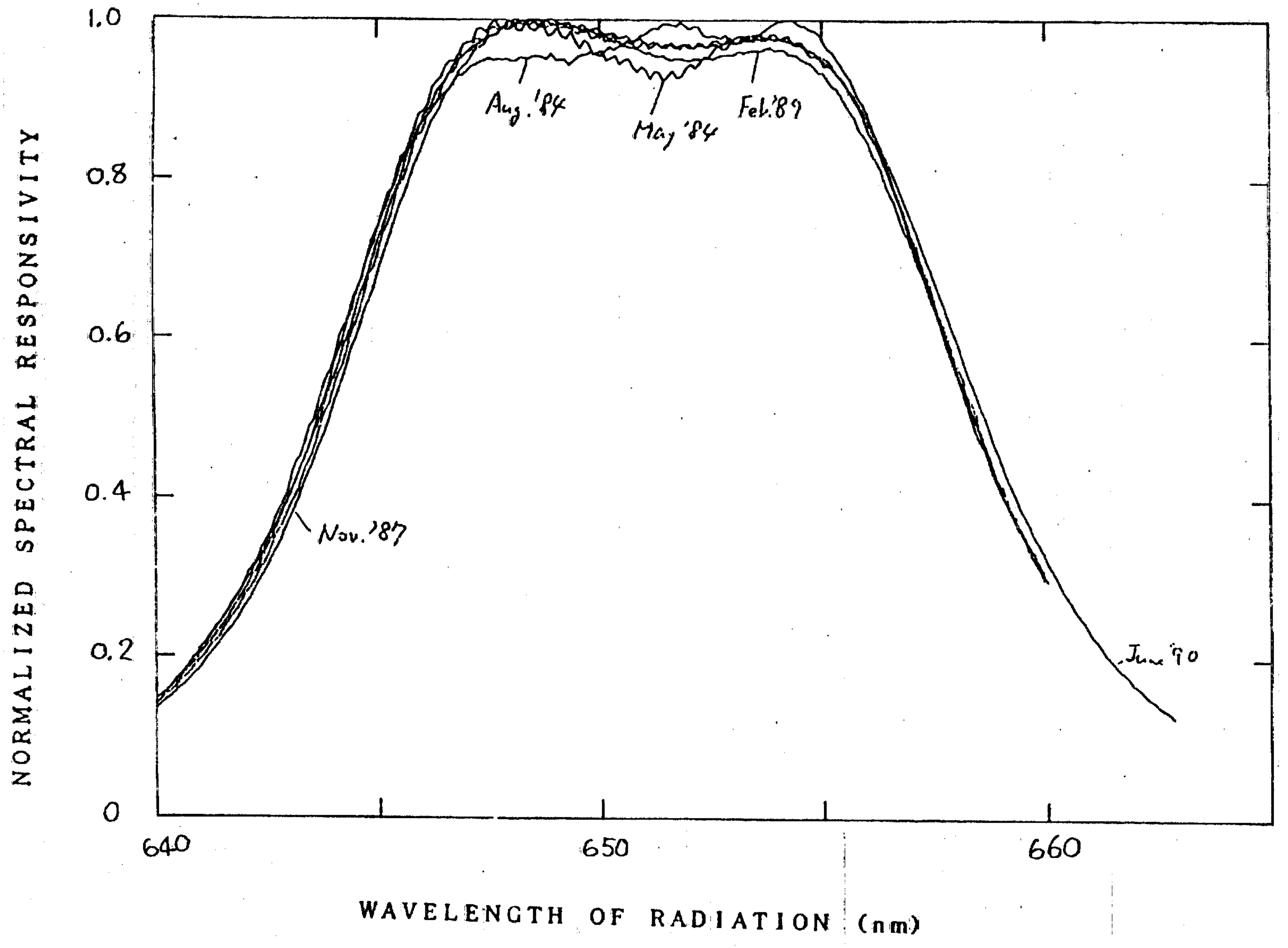
OPTICAL SCHEME FOR MEASURING THE SPECTRAL RESPONSIVITY DISTRIBUTION OF RADIOMETER

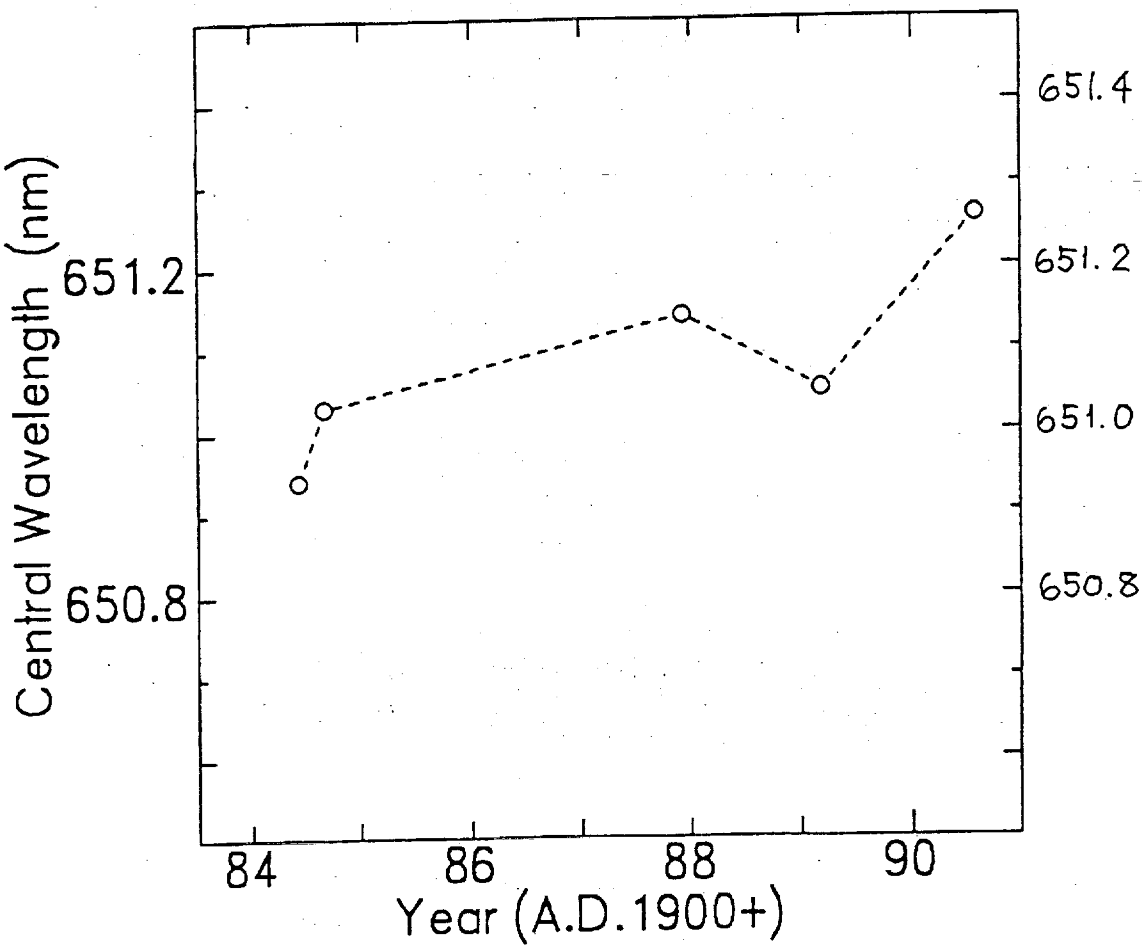
1, radiation source; 2, collimator; 3, source monitor; 4, double grating monochromator;
5, switching mirror; 6, reference detector; 7, standard detector; 8, radiometer

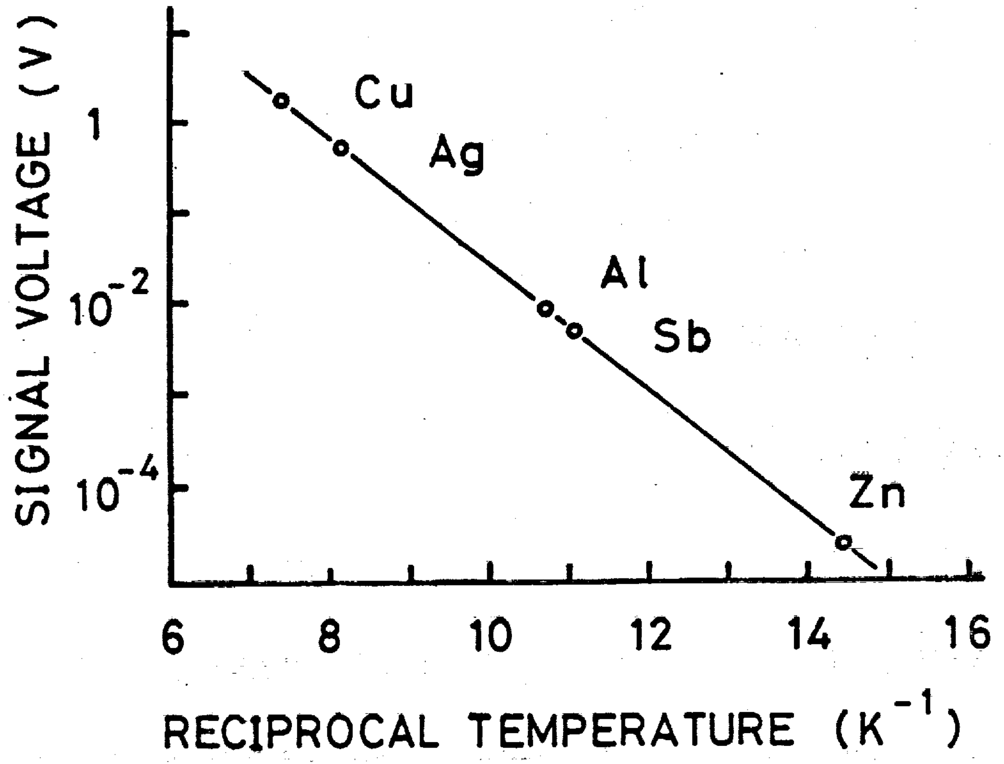

10^0
10^-3
10^-6
Spectral response (V), Ratio
400
600
800
1000
1200
Wavelength (nm)
Reference detector response
Standard detector response
Ratio



1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
NORMALIZED SPECTRAL RESPONSIVITY
400
600
800
1000
1200
WAVELENGTH OF RADIATION (nm)


NORMALIZED SPECTRAL RESPONSIVITY
1.0
0.8
0.6
0.4
0.2
0
640
650
660
WAVELENGTH OF RADIATION (nm)
Aug. '84
May '84
Feb.'89
Nov. '87
June '90


651.4
651.2
651.0
650.8
651.2
650.8
Central Wavelength (nm)
84
86
88
90
Year (A.D.1900+)



SIGNAL VOLTAGE (V)
1
10^{-2}
10^{-4}
Cu
Ag
Al
Sb
Zn
6
8
10
12
14
16
RECIPROCAL TEMPERATURE (K^{-1})

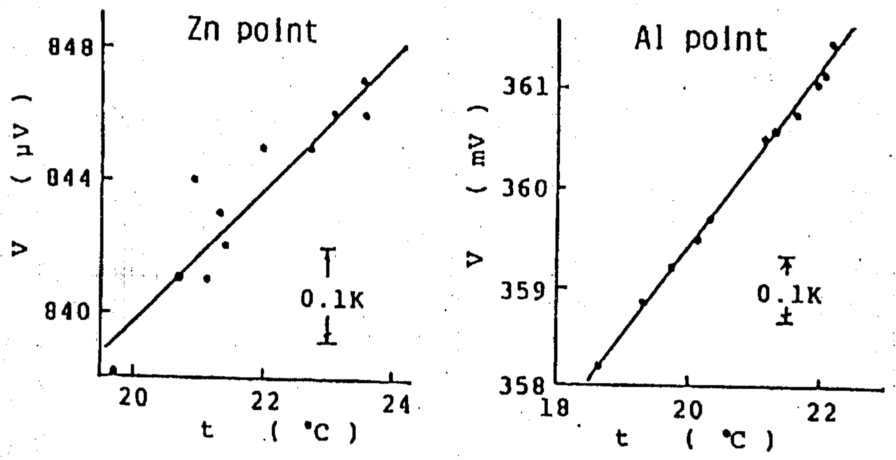
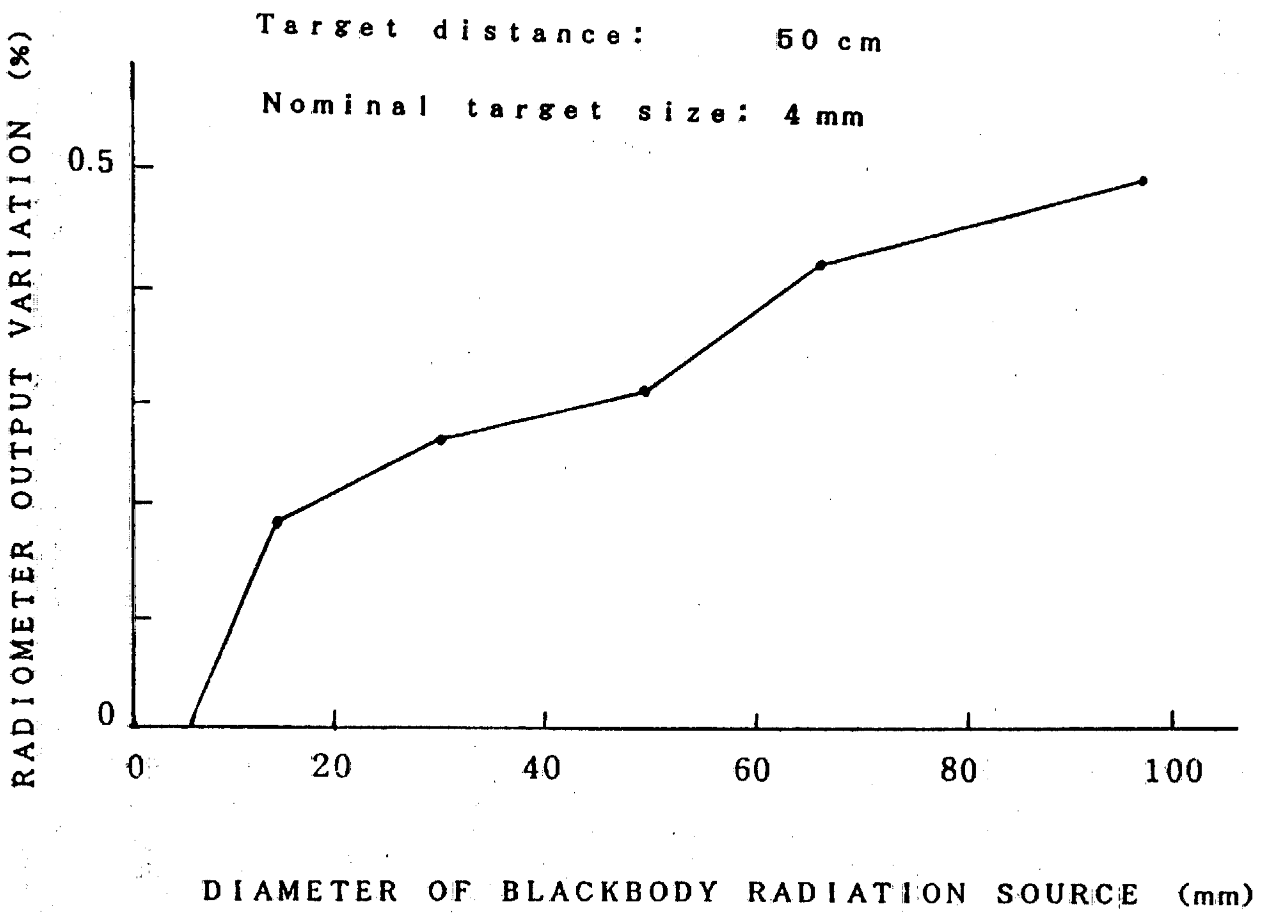
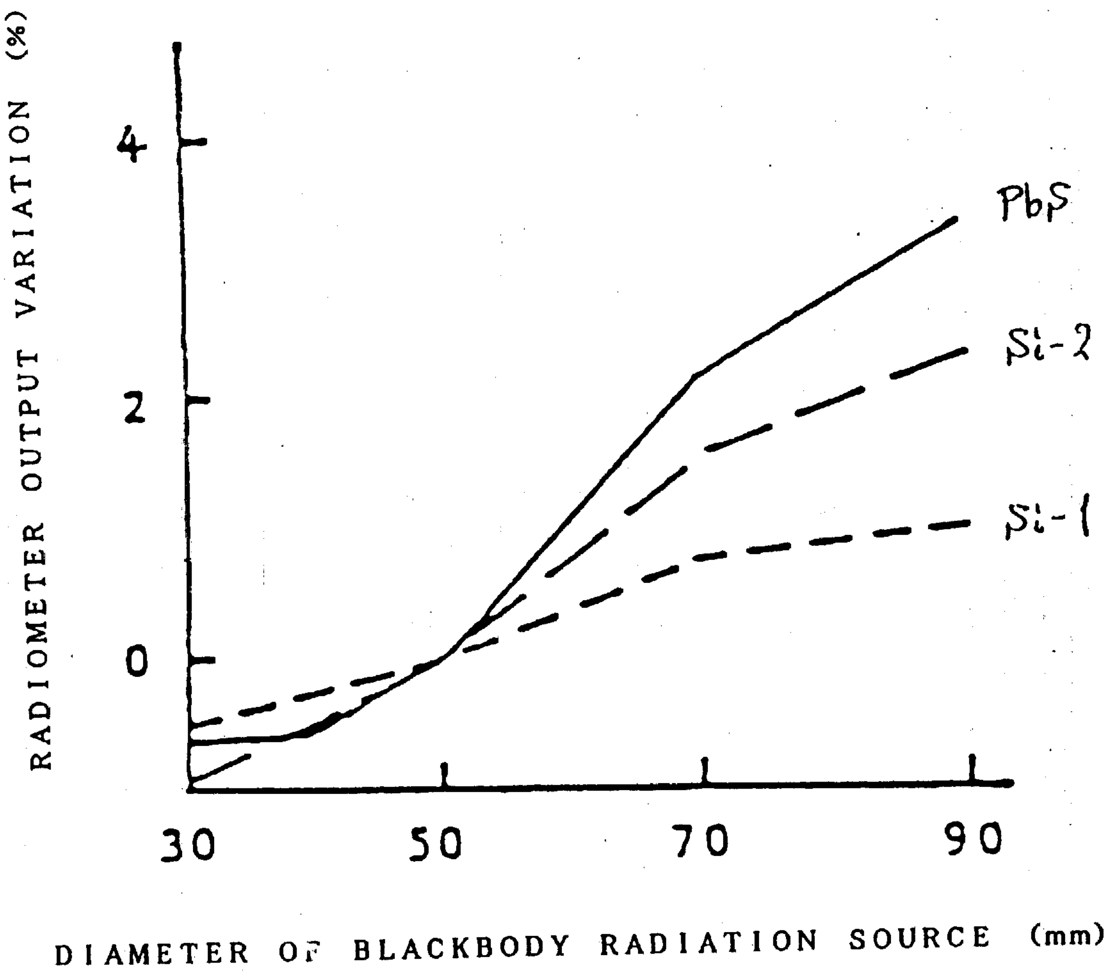


Figure 14.7 Relation between the signal level and the instrument temperature of a silicon-based standard radiation thermometer (the broader band interference filter).[8)]

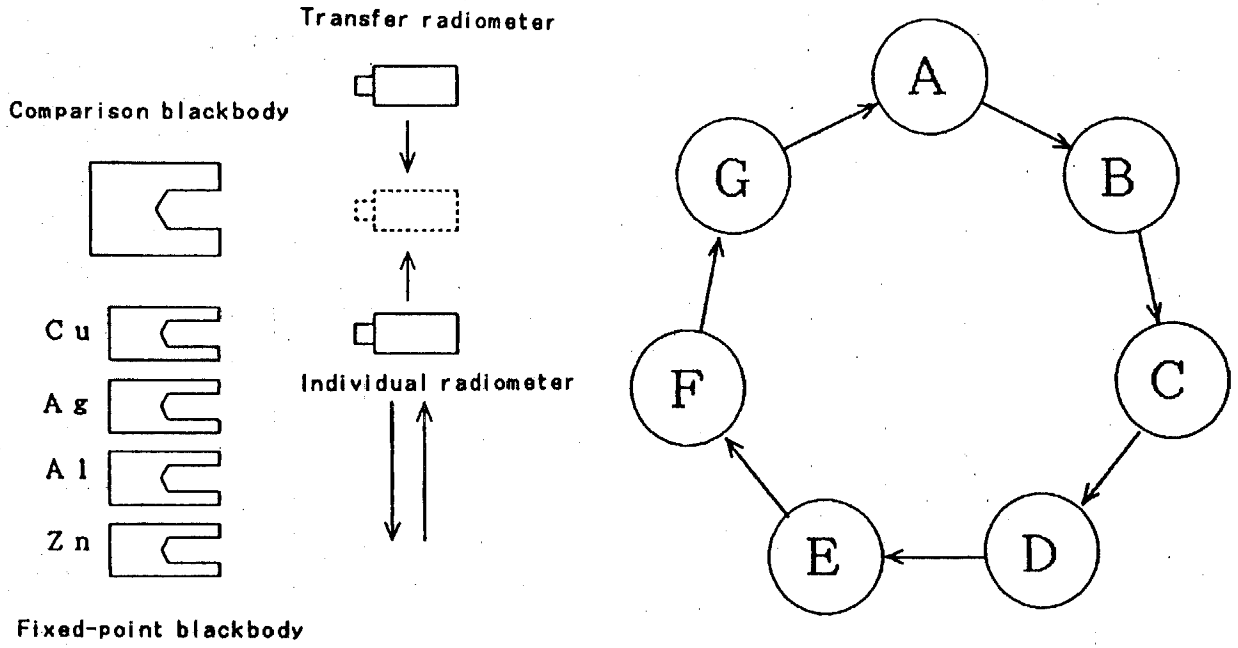

Target distance: 50 cm
Nominal target size: 4 mm
RADIOMETER OUTPUT VARIATION (%)
0.5
0
0
20
40
60
80
100
DIAMETER OF BLACKBODY RADIATION SOURCE (mm)



RADIOMETER OUTPUT VARIATION (%)
4
2
0
PbS
Si-2
Si-1
30
50
70
90
DIAMETER OF BLACKBODY RADIATION SOURCE (mm)

Table 1. Specifications of the Ge and InAs photodiode radiation thermometers.

Model	IR-RST-160	IR-RST-220
Detector type	Ge photodiode	InAs photodiode
Cooling of detector	Thermo-Electric cooling(-25℃)	LN_2 cooling (-195℃)
Wavelength (half width)	1.610μm (0.15μm)	2.183μm (0.17μm)
Temperature range	300 - 2000℃	200 - 2000℃
Gain of amplifier	×10, ×1, ×0.1, ×0.01	×10, ×1, ×0.1, ×0.01
Resolution	0.1℃(330℃), 0.01℃(1085℃)	0.03℃(230℃), 0.2℃(1085℃)
Object distance	400mm - ∞	400mm - ∞
Target size	3mmφ (at 400mm)	3mmφ (at 400mm)
Response	100μs(DC) / 0.1s(DC)	100μs(DC) / 0.1s(AC)
Output Voltage	0 - 10V	0 - 10V
Size	140×150×400mm	140×200×400mm



SCHEME FOR ROUND ROBIN TEST OF RADIATION TEMPERATURE SCALES

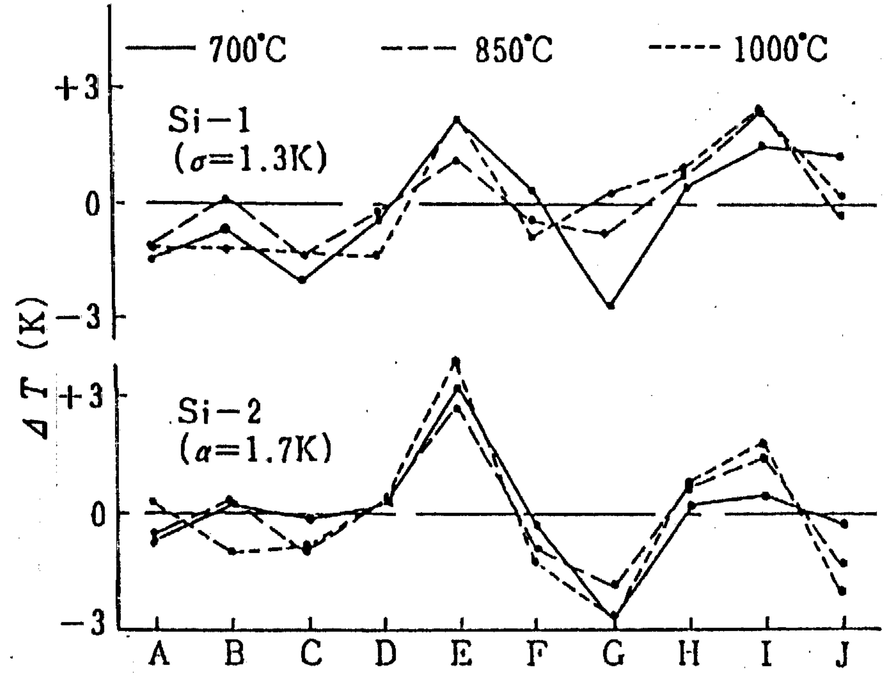
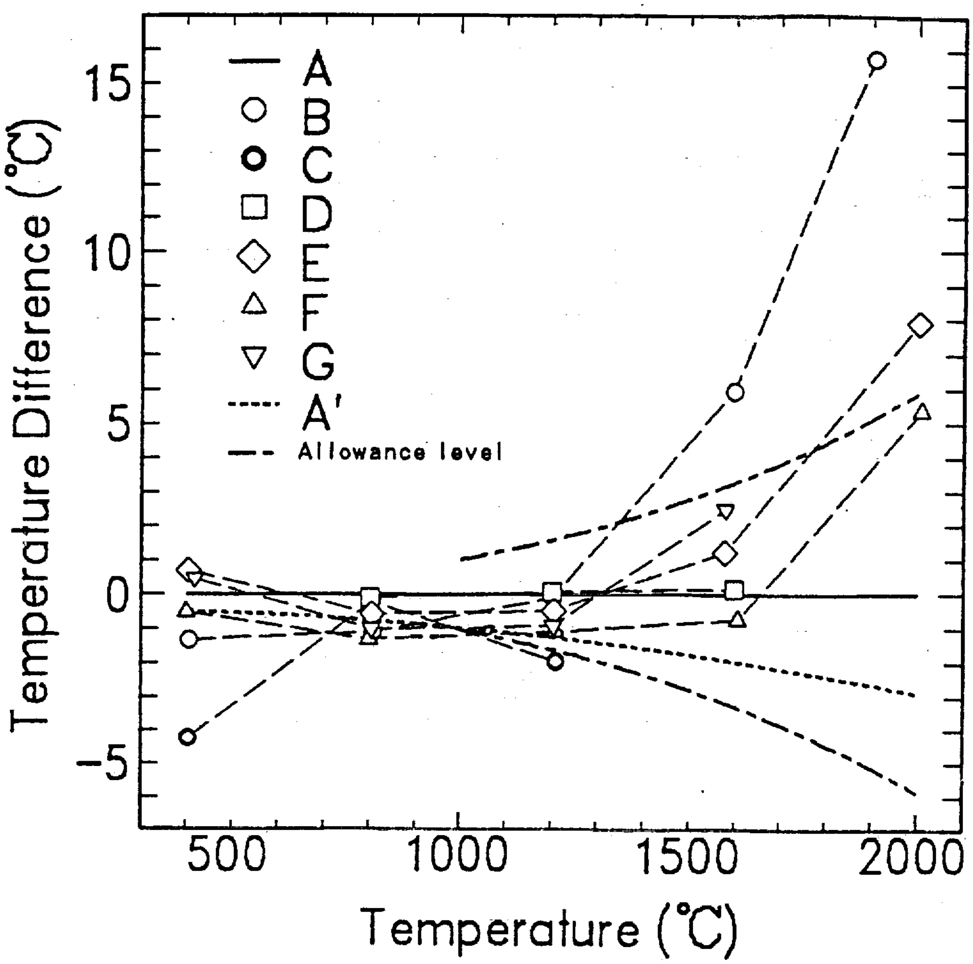
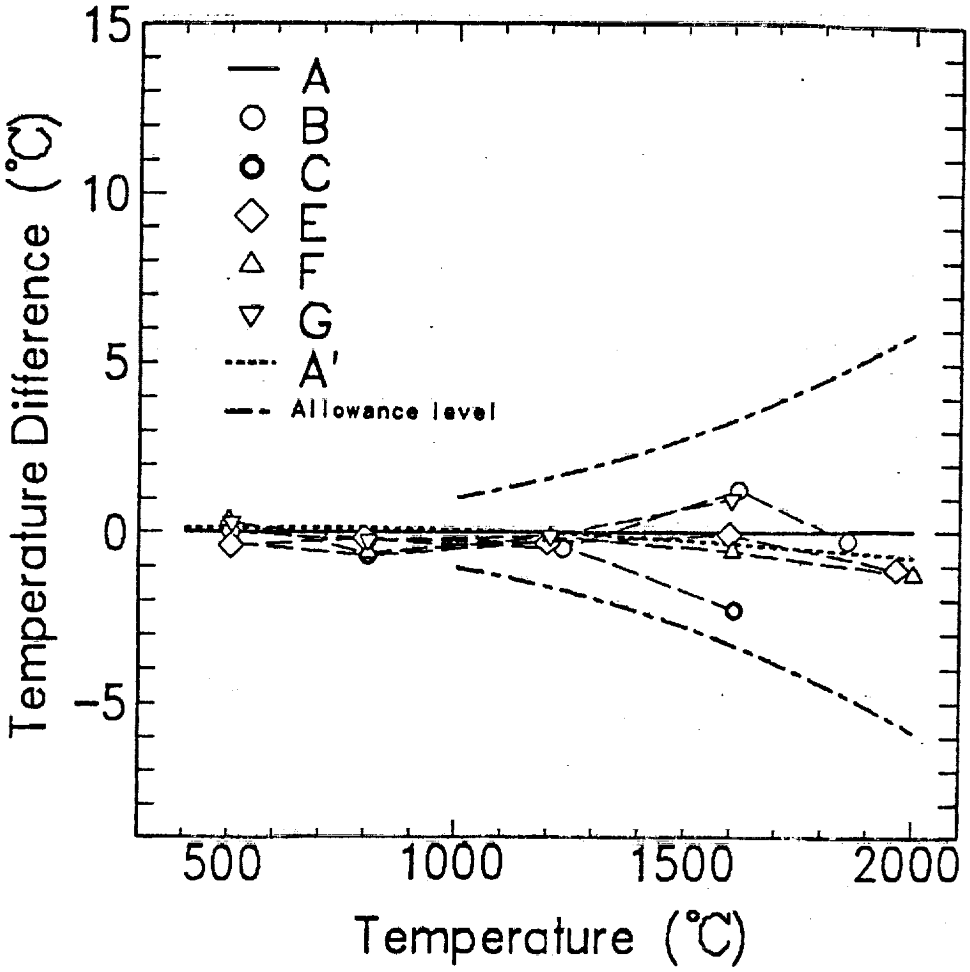


Figure 14.12 Intercomparison of the temperature standards.[8)]



ROUND ROBIN TEST IN 1989



ROUND ROBIN TEST IN 19~~88~~ 90

Yasushi Yamaguchi
ASTER Team
Geological Survey of Jap

S16-43
171307
p. 8
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In-Flight Cross-Calibration of ASTER/TIR and MODIS-N

1. Purpose

-Improve Absolute Radiometric (Temperature) Accuracy of ASTER/TIR
(particularly in the low temperature region)

2. In-Flight Calibration Targets

<Conditions>

1) Low Temperature
2) Spectrally Constant and High Emissivity
3) Spatially homogeneous
4) Smaller Atmospheric Effects (High elevation) low humidity)
5) Frequent visit by EOS-AM1

--> -Snow/ice Fields in Antarctica, Greenland
- Temperature < 220 K
- Snow Emissivity > 0.98
- Elevation > 3 km
- Homogeneity ????

-Top of Cumulonimbus

In-Flight Cross-Calibration of ASTER/TIR and MODIS-N

3. Spectral Bandpasses (μm)

ASTER	MODIS-N
(10) 8.125-8.475	
(11) 8.475-8.825	(29) 8.40-8.70
(12) 8.925-9.275	
	(30) 9.58-9.88
(13) 10.25-10.95	
(14) 10.95-11.65	(31) 10.78-11.28

4. Error Sources

1) Co-location Error

2) Different Spatial Resolution: 90m vs. 1000m
   - Spatial Averaging Errors
   - Inhomogeneity of the Targets

3) Different Spectral Bandpasses
   - Inconstant Emissivity of the Targets
     Snow: > 10.5μm
   - Atmospheric Effects
     Transmittance

We don't have AIRS on EOS-AM1.
↓
MODIS-N, Atmospheric Model (LOWTRAN, Meteorological Researc
Insitite's Mo

ASTER/TIR

-Ground Resolution: 90m

-Absolute Radiometric Accuracy Requirement:

200 K~240 K: ±3 K
240 K~270 K: ±2 K
270 K~340 K: ±1 K
340 K~370 K: ±2 K

-NEΔT: 0.3 K

-T_{max}: 370 K

On-board Blackbody
270-340°K

MODIS-N

-Ground Resolution: 1000m
-Absolute Radiometric Accuracy Requirement: 1 %
-Typical Scene Temperature:

(29)	300 K
(30)	250 K
(31)	300 K

-NEΔT:

(29)	0.05 K
(30)	0.25 K
(31)	0.05 K

-T_{max}:

(29)	324 K
(30)	275 K
(31)	400 K

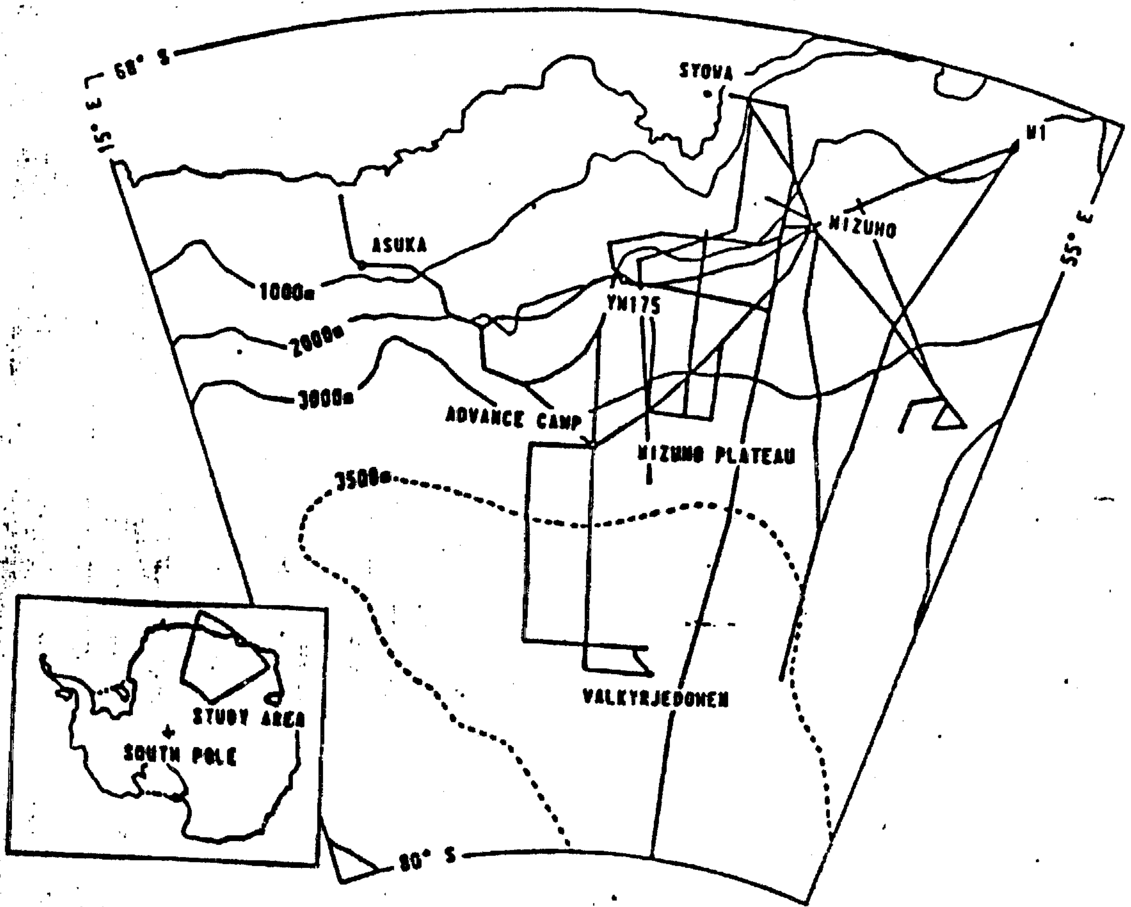

Figure 1. Map of study area and JARE traverse routes (1963–1987).

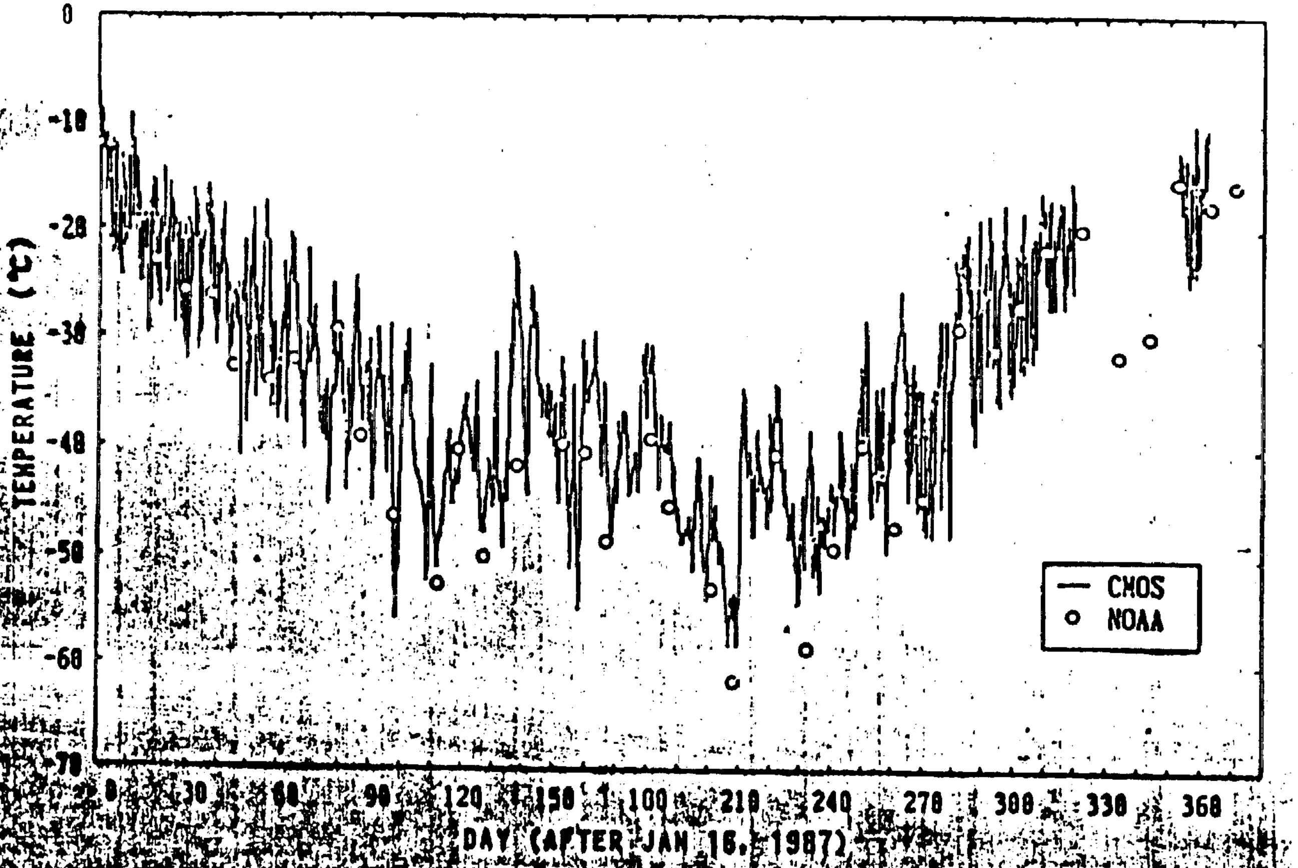

Figure 3. Air and brightness temperatures as meausred by automatic weather recorder (CMOS) and by NOAA channel 5 thermal infrared radiometer, respectively.

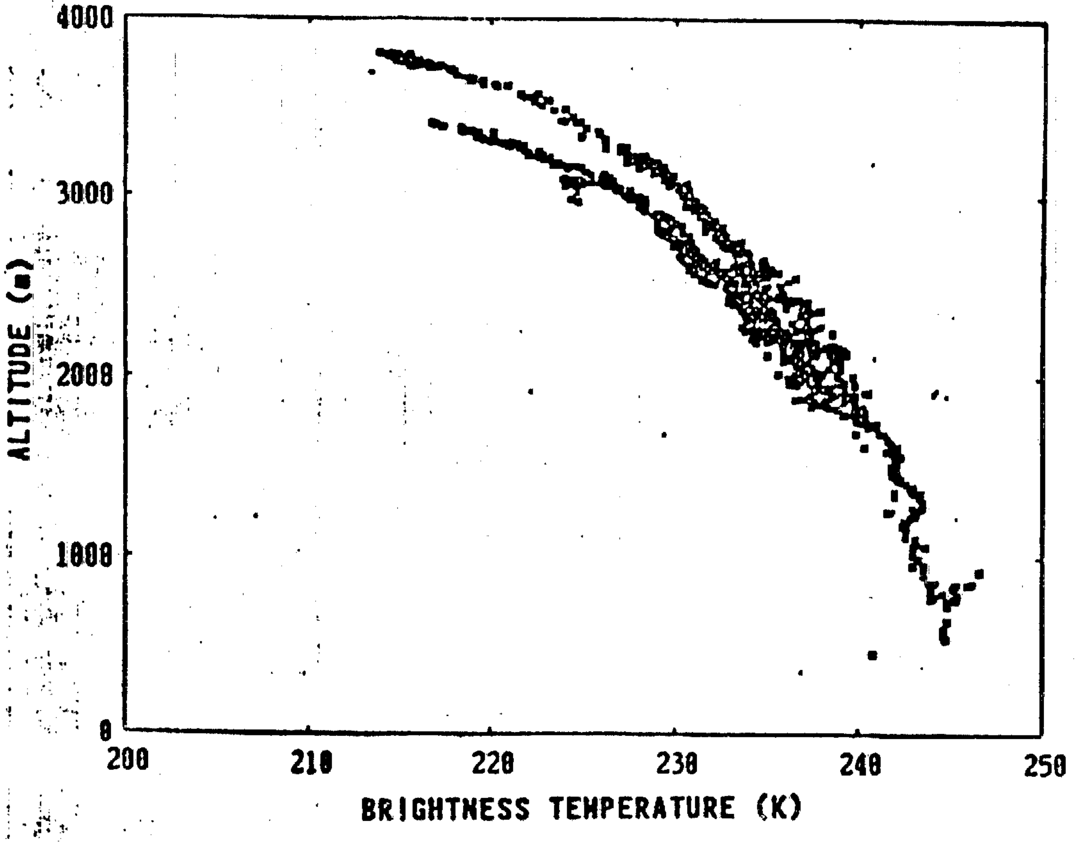

Figure 6. Average NOAA channel 5 brightness temperature plotted against the altitude of the traverse stations on the ice sheet.

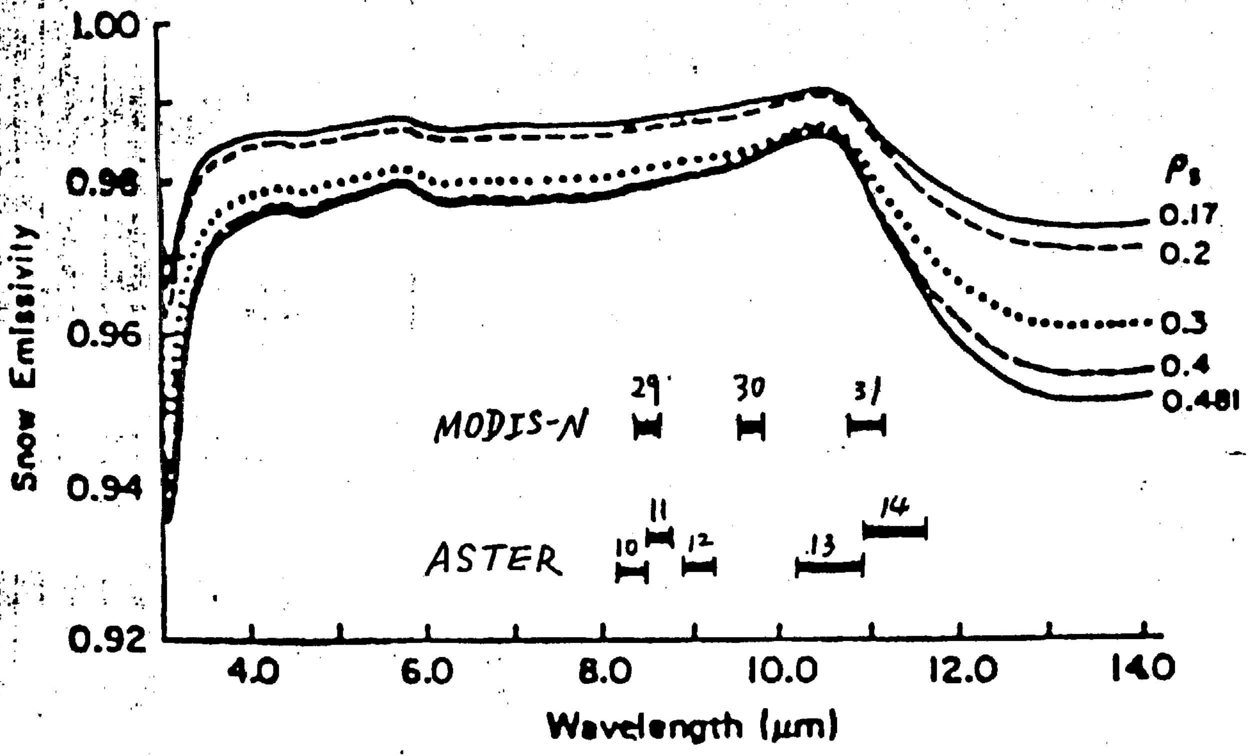

Fig. 17. Emissivity as a function of wavelength for various snow densities, according to the model of *Berger* [1979]. (Figure 7 of *Berger* [1979].)

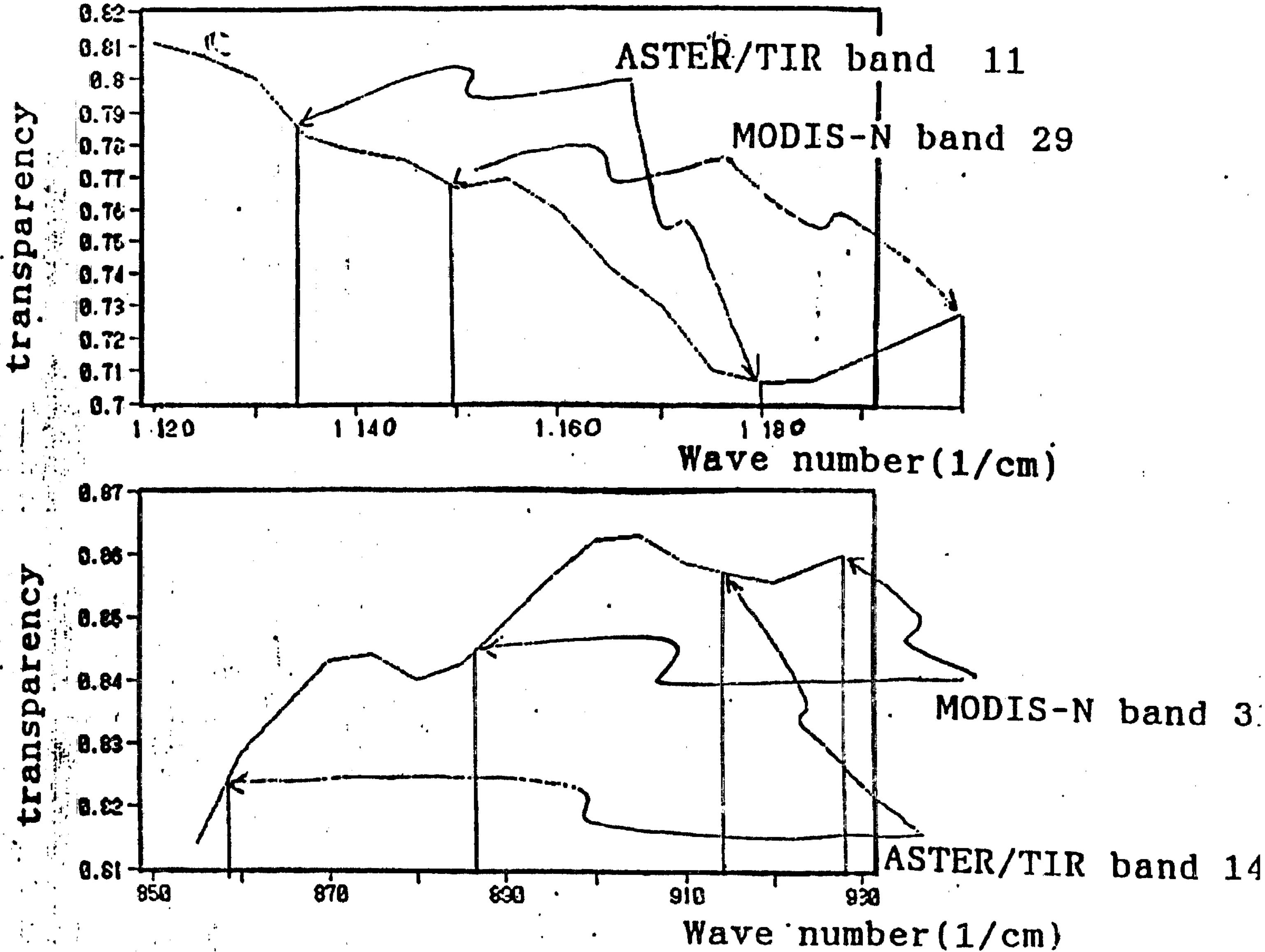

Fig.1 The atmospheric transparencies for ASTER/TIR band 11 and MODIS-N band 29 and ASTER/TIR band 14 and MODIS-N band 31

GAF-14-057

5th Earth Observing System Investigator Working Group
Calibration & Data Product Validation Panel

Apr. 7-9,1992 at Broker Inn

ASTER TIR Subsystem & Calibration

S17-43
171308
p-24

N94-23612

Hirokazu OHMAE
FUJITSU LIMITED

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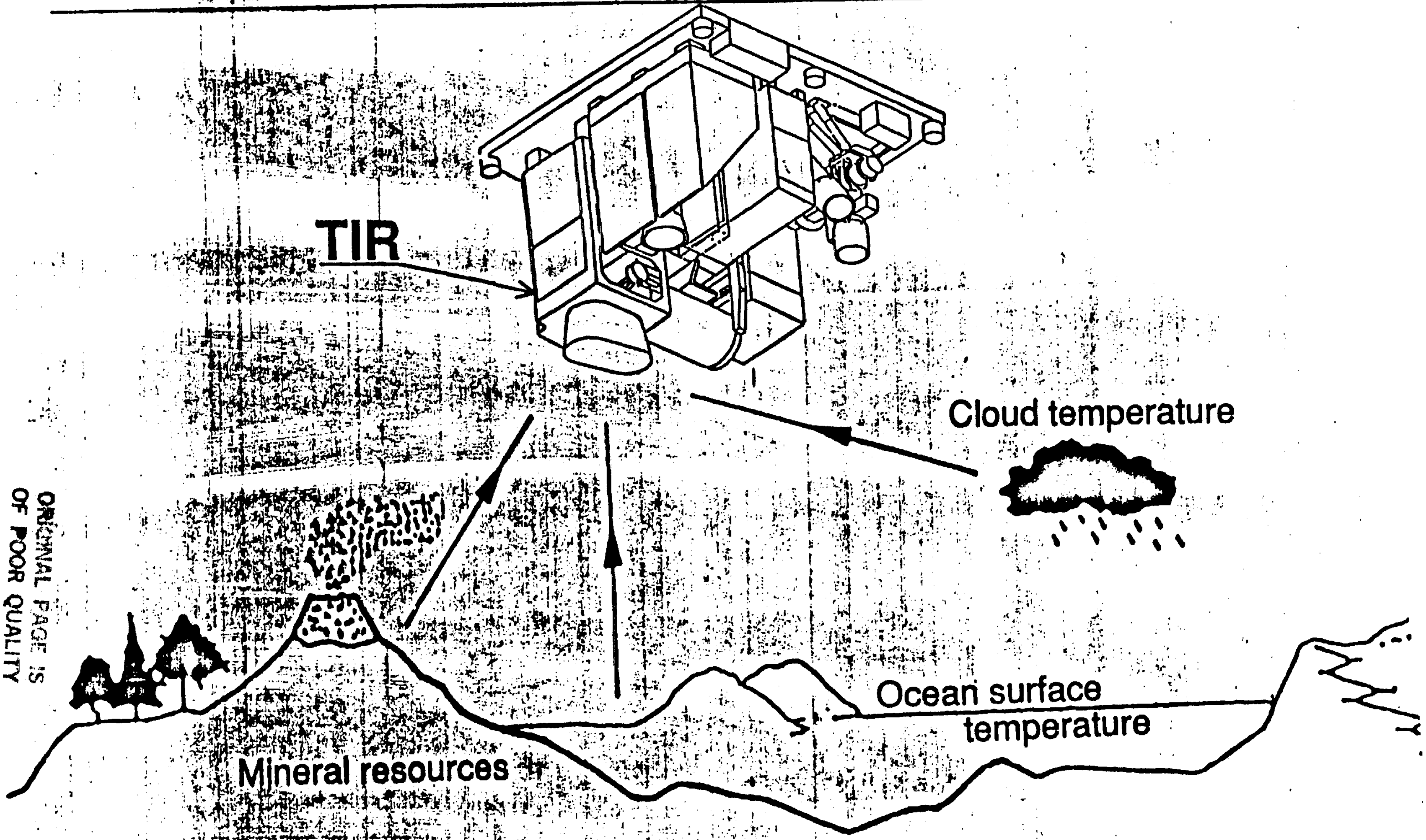
Outline

1. Purpose of TIR
2. Major functions
3. Characteristics and design of various components
4. Calibration


TIR
Cloud temperature
Ocean surface temperature
Mineral resources

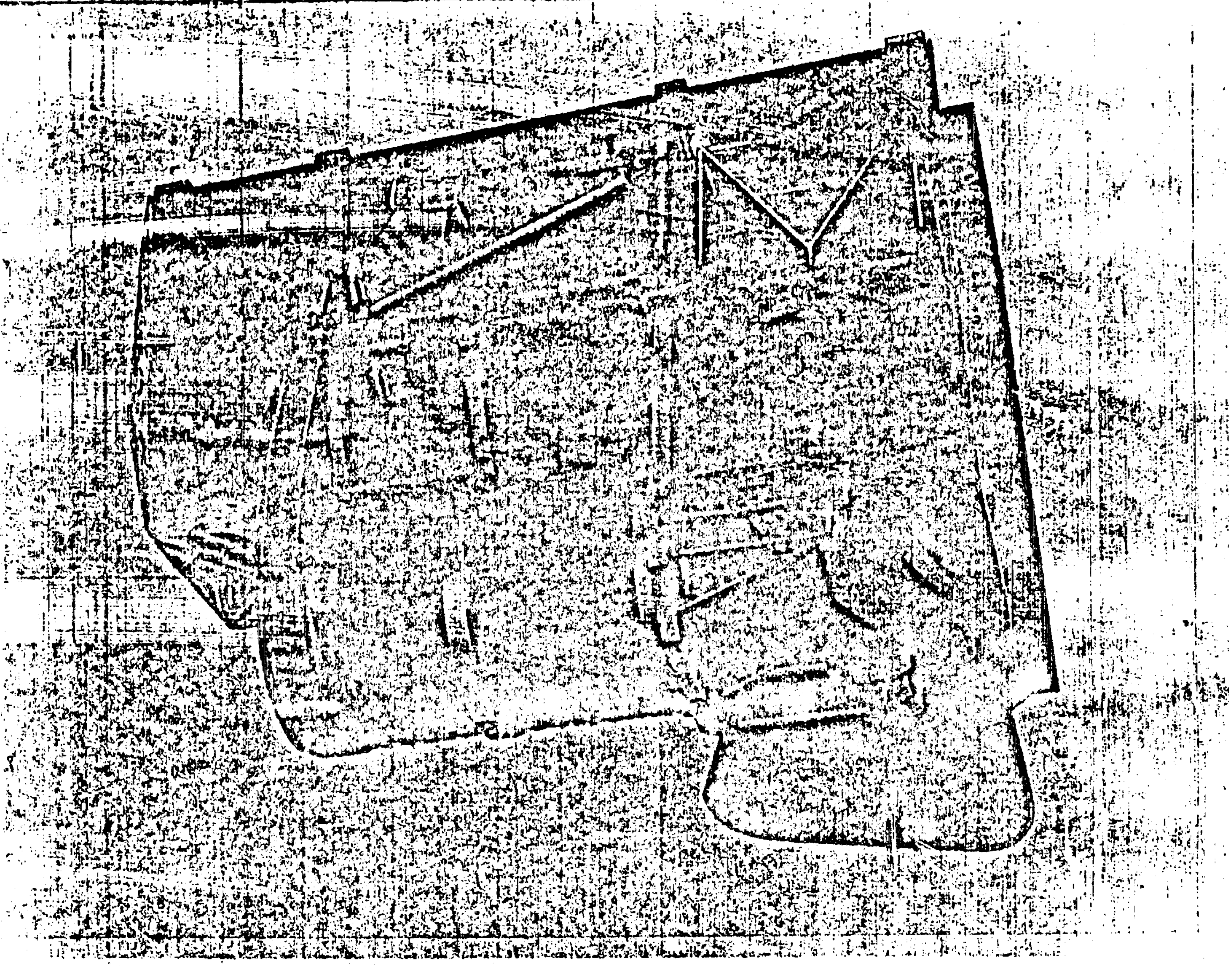
Functions

- -to acquire image data on the earth's surface in thermal infrared wavelength band, using mercury cadmium telluride (HgCdTe) detectors, the detectors are cooled about 80K
- -to convert the obtained image data into the digital data to meet the Common Signal Processer(CSP) interface, and output the signals
- -pointing function in cross-track direction to get the wide swath of 232km
- -to calibrate the whole TIR with the blackbody on orbit, then the amplifer and subsequent transmission units are calibrated electrically

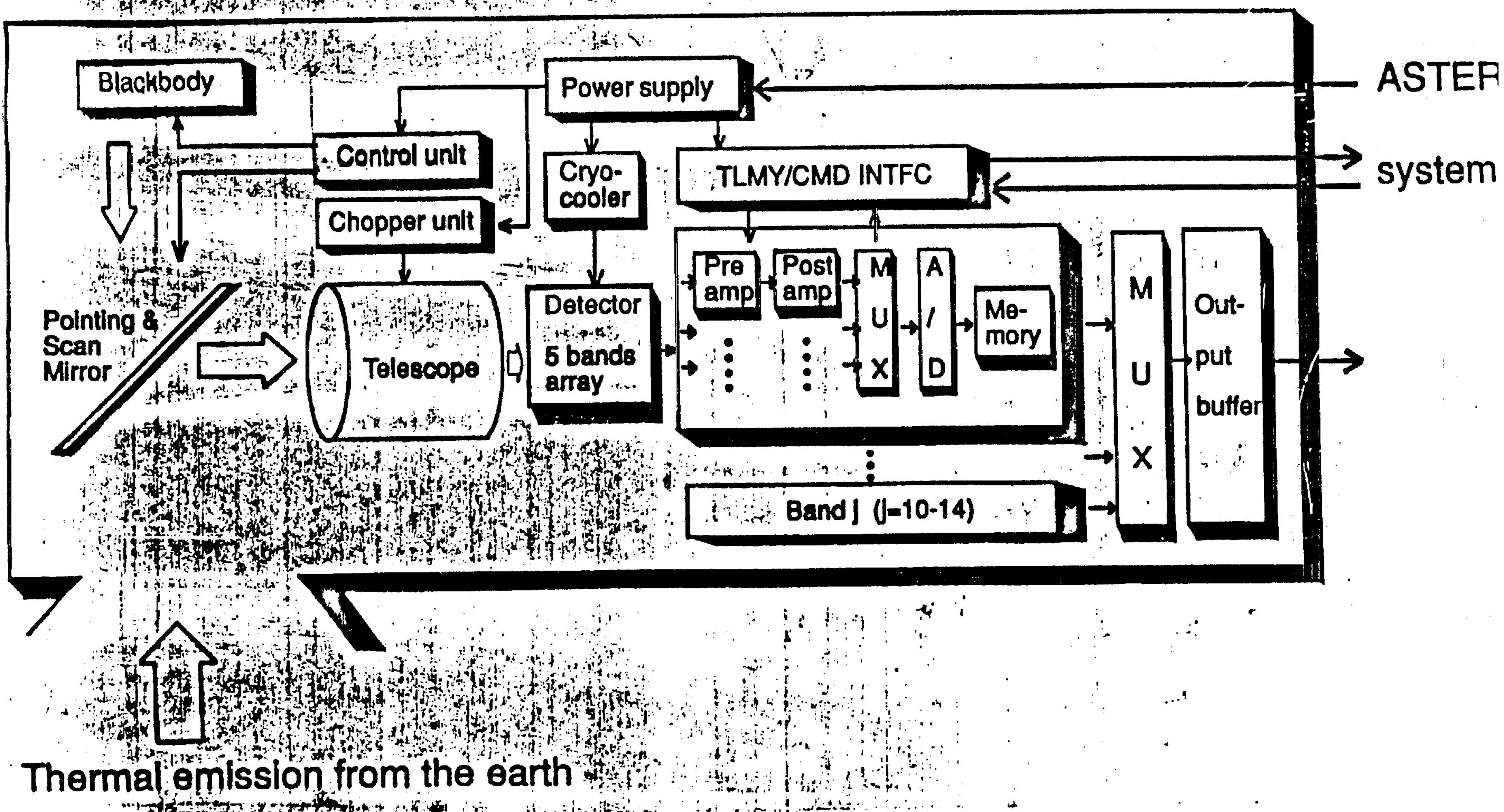
TIR General Specifications

Spectral coverage	Band10	8.125 to 8.475 µm
	Band11	8.475 to 8.825 µm
	Band12	8.925 to 9.275 µm
	Band13	10.25 to 10.95 µm
	Band14	10.95 to 11.65 µm
Swath width		60 km
Geometric Resolution		90 m
IFOV		127.6 µrad
MTF at Nyquist freq		0.25
Signal Quantization level		12bit
Pointing Coverage		± 8.55 deg
Radiometric resolution		NEΔT: < 0.3 K

Cutaway view of the TIR



TIR block diagram



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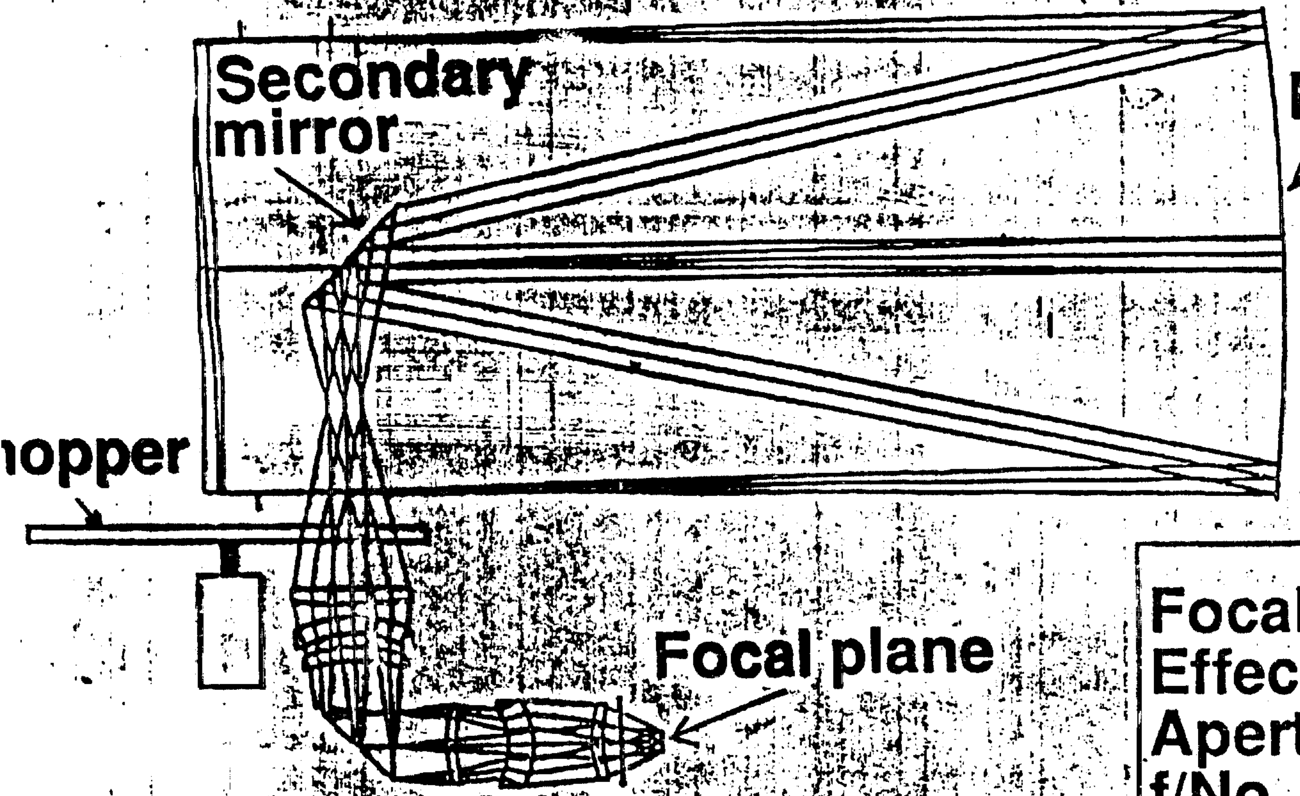
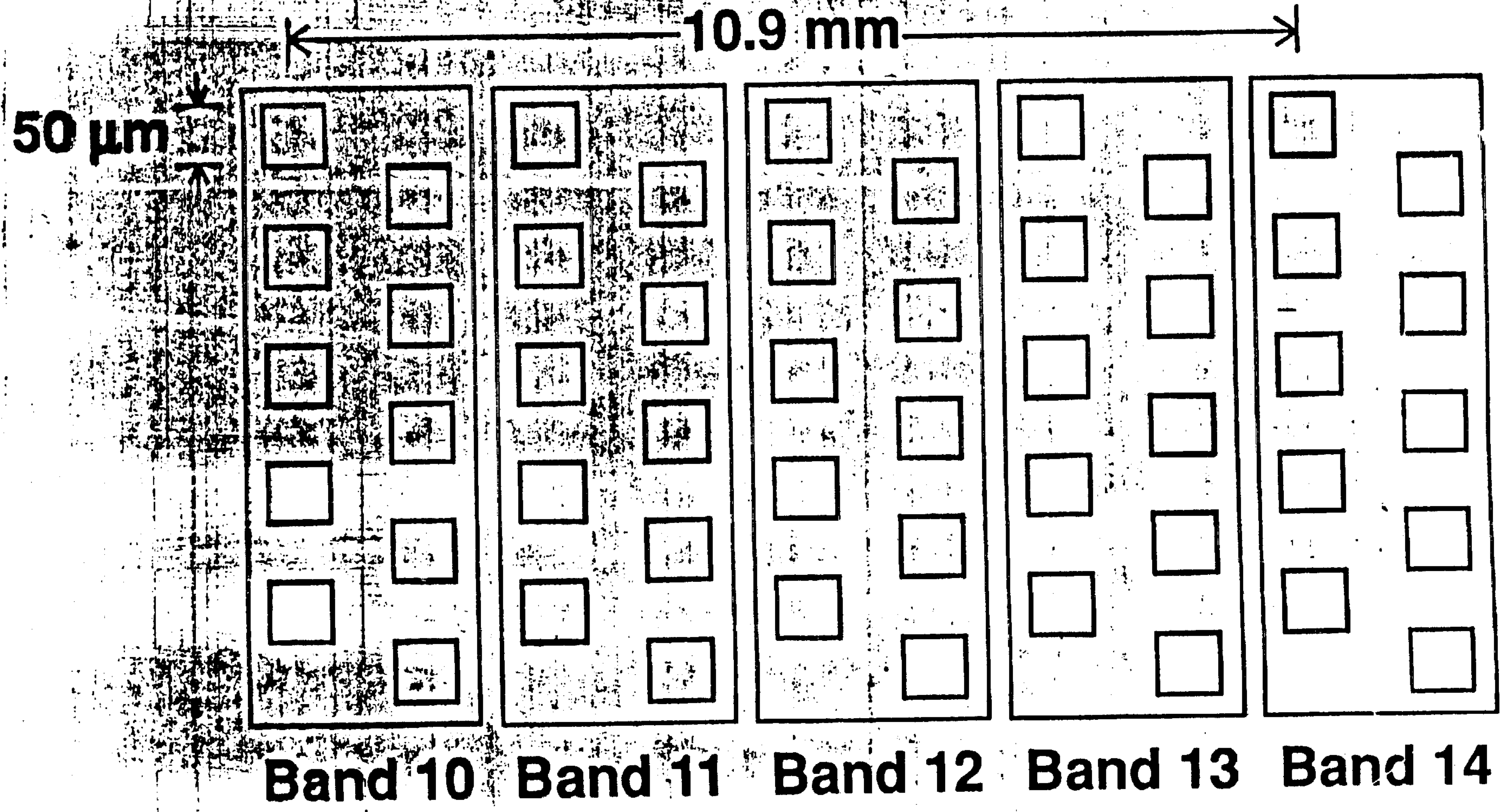
Telescope



Newtonian Catadioptric

Focal Length	392 mr
Effective Clear Aperture Diameter	240 mr
f/No	1.57
FOV	1.67 de

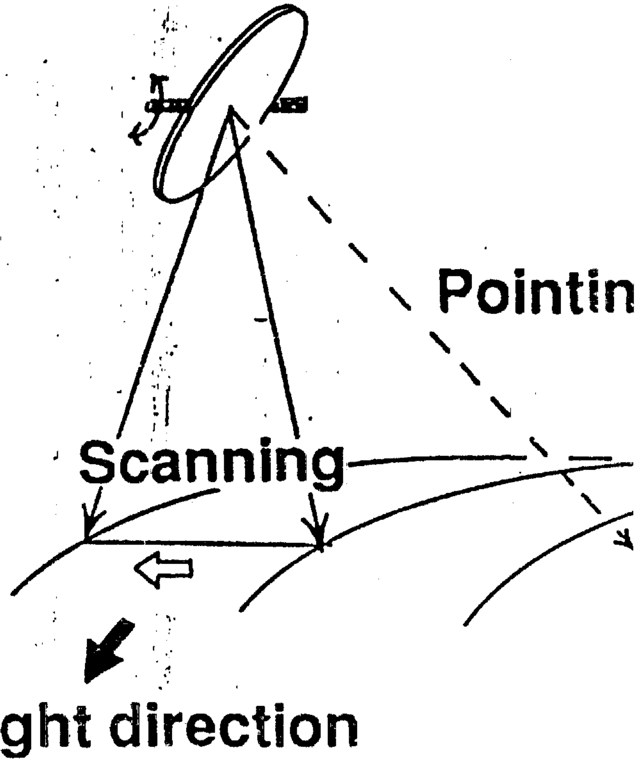
HgCdTe Detectors



Focal plane projection

Scanner

Pointing and Scanning	
Scanning method	Mechanical scan by vibration of scan mirror ± 3.4deg (at pointing center)
Pointing(off-nadir)	scan mirror ± 8.55 deg (off-nadir angle)
Mirror size	460mm X 280mm
Mirror material	Beryllium



Calibration Accuracy Requirement

200 K to 240 K	3K
240 K to 270 K	2K
270 K to 340 K	1K
340K to 370 K	2K

Calibration methods

Pre-launch calibration

- TIR acceptance test(AT) ---> calibration data map ---> characteristics equation of TIR and data set of calibration
- Cross calibration with other EOS-AM1 sensors

Calibration methods

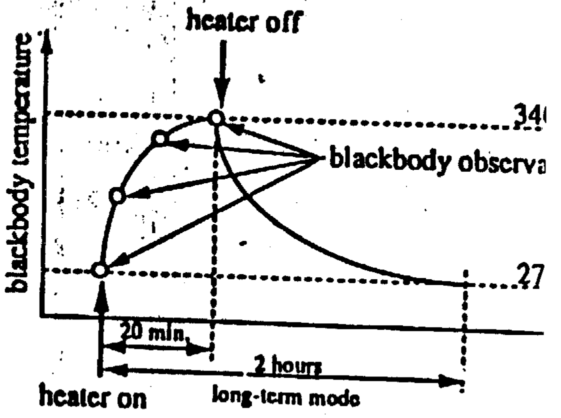
In-flight calibration

calibration methods

calibration	mode	input
optical calibration	short-term calibration	blackbody radiation
	long-term calibration	blackbody radiation
electrical calibration	electrical calibration	step electric signals

calibration data

mode	blackbody temperature	calibration time
short-term calibration	270K	several ten seconds
long-term calibration	270K - 340K 3-temperature:270K 300K 340K or more temperature	20 minutes approx. (observation of blackbody) 2 hours approx. (heat-up & cool-down)

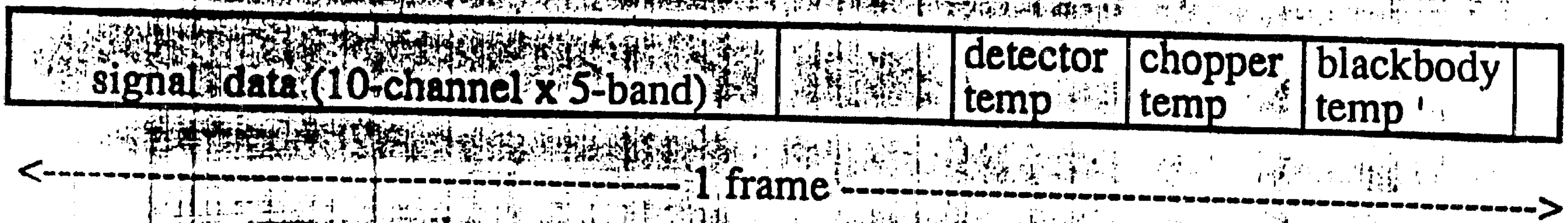


Calibration methods

Usable data for calibration

(1) Image data

- digitized signal data(blackbody radiation) ;same as observation data
- blackbody temperature ;inserted signal data
- chopper temperature ;ditto
- detector temperature ;ditto

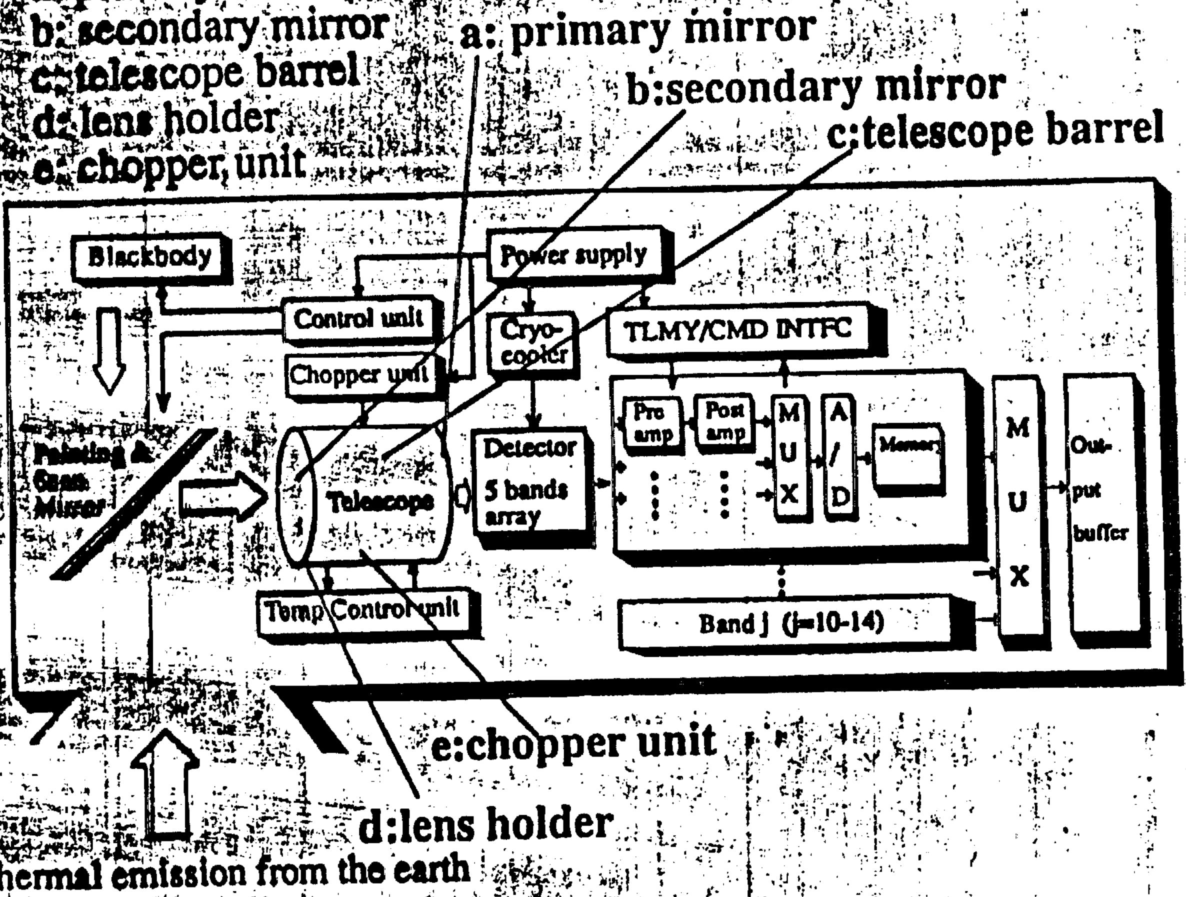


Calibration methods

Usable data for calibration

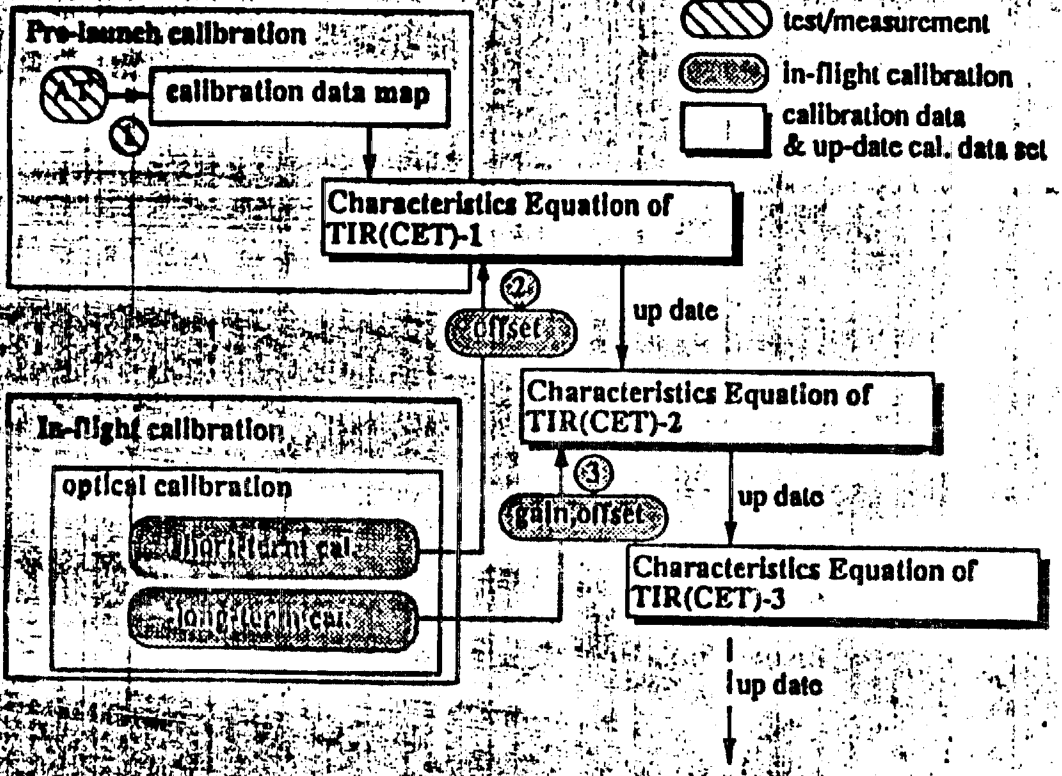
(2) Monitor data/ telemetry data

- TIR temperature
  - a: primary mirror
  - b: secondary mirror
  - c: telescope barrel
  - d: lens holder
  - e: chopper unit



Calibration methods

Calibration data management



Pre-launch calibration

① calibration data map

Characteristics Equation of TIR(CET)-1

② offset

up date

Characteristics Equation of TIR(CET)-2

③ gain,offset

up date

Characteristics Equation of TIR(CET)-3

up date

In-flight calibration

optical calibration

short term cal.

long term cal.

▨ test/measurement

● in-flight calibration

☐ calibration data & up-date cal. data set

Calibration methods

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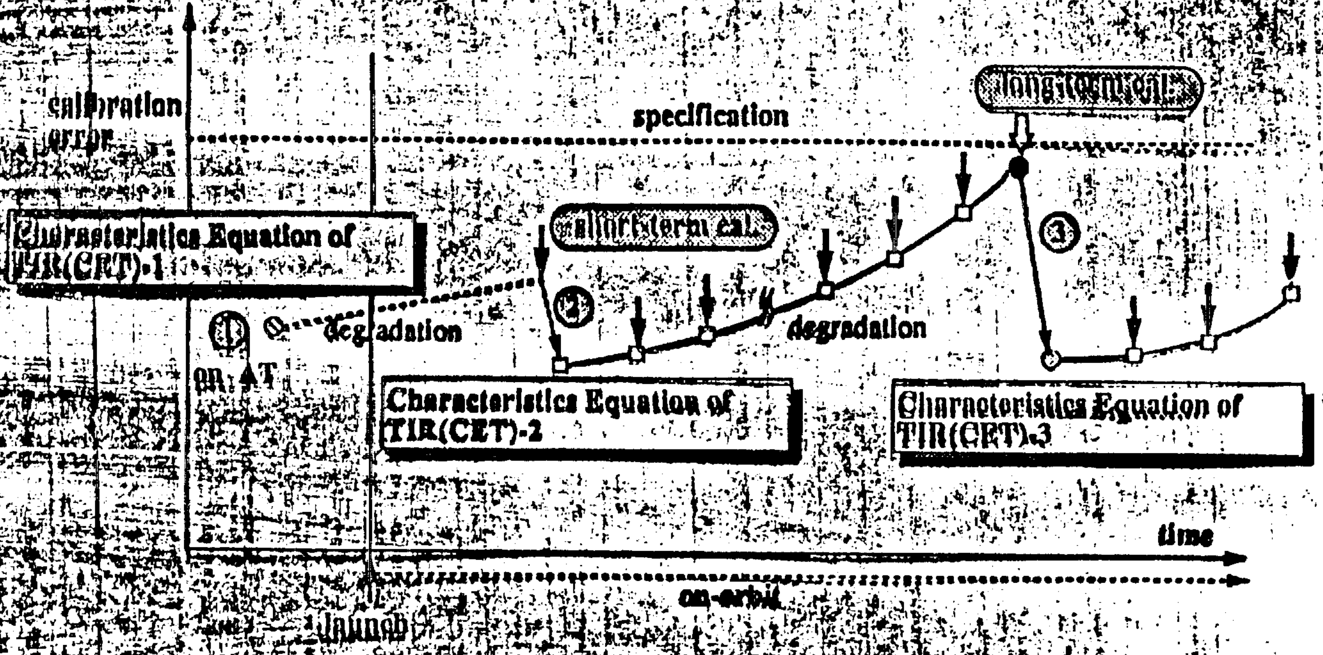
Calibration data management



TIR calibration concept

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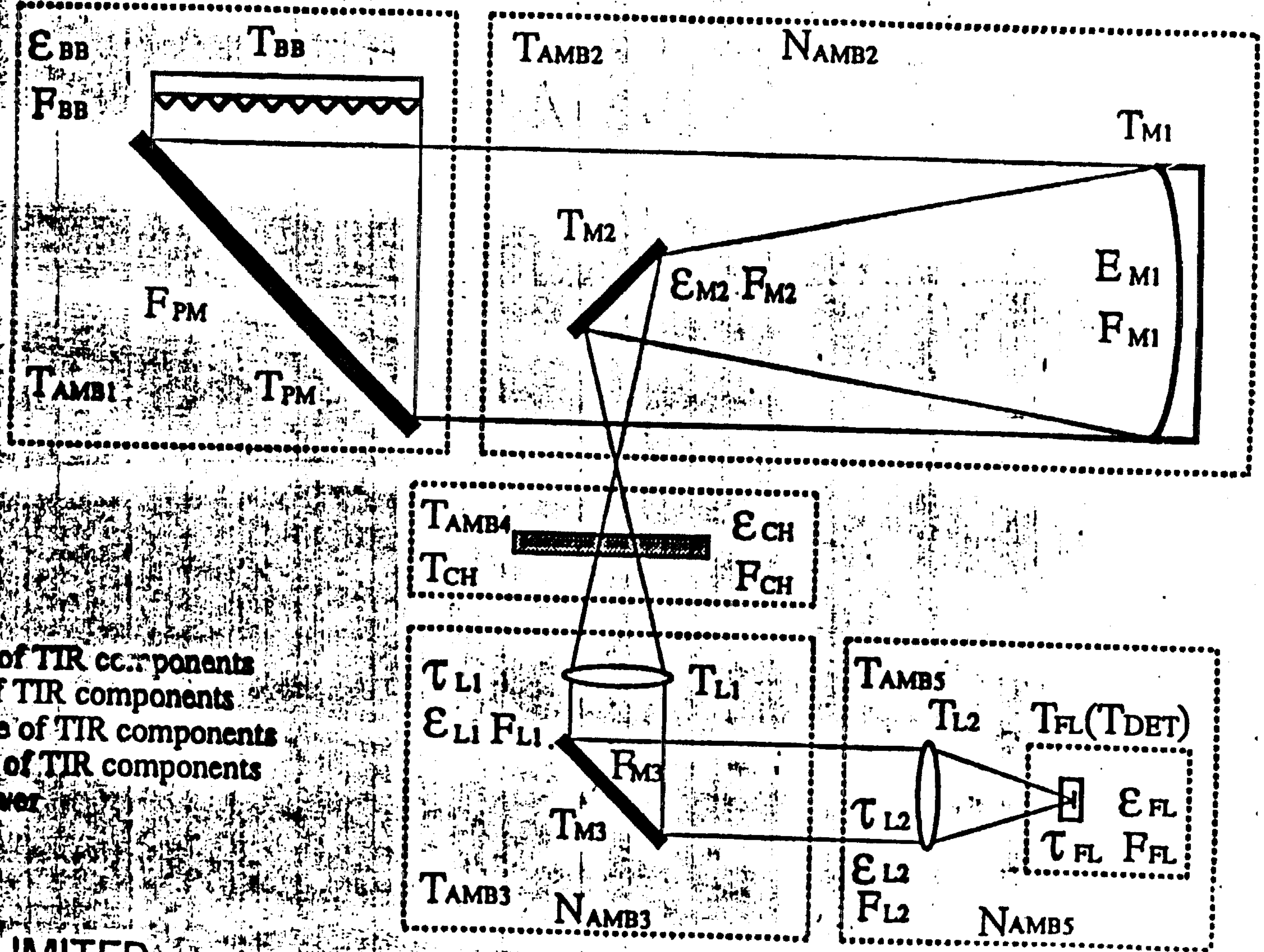
Calibration methods

Summary of calibration methods

stage		usable data	calibration
Pre-launch calibration		calibration data map	- remove the fixed error - determine the characteristics equation
In-flight calibration	short-term calibration mode	- image data :1-temperature radiation - monitor data	- update of the data map ---> improve offset
	long-term calibration mode	- image data :3- or more temperature radiation - monitor data	- update of the data map ---> improve offset and gain and the characteristics equation

Mathematical model

Outline of mathematical model



T_i :temperature of TIR components
ε_i :emissivity of TIR components
τ_i :transmittance of TIR components
F_i :shape factor of TIR components
N :radiation power

Mathematical model

Value of mathematical parameter

stage	critical parameters		comments
	items	value for model	
Pre-launch calibration	emissivity accuracy of standard blackbody	$\varepsilon=0.995$ $\Delta\varepsilon=0.005$	
In-flight calibration	emissivity degradation of on-board blackbody	BOL=0.990 EOL=0.980	degradation test by using test piece

Error Budget for TIR Temperature Scale Calibration

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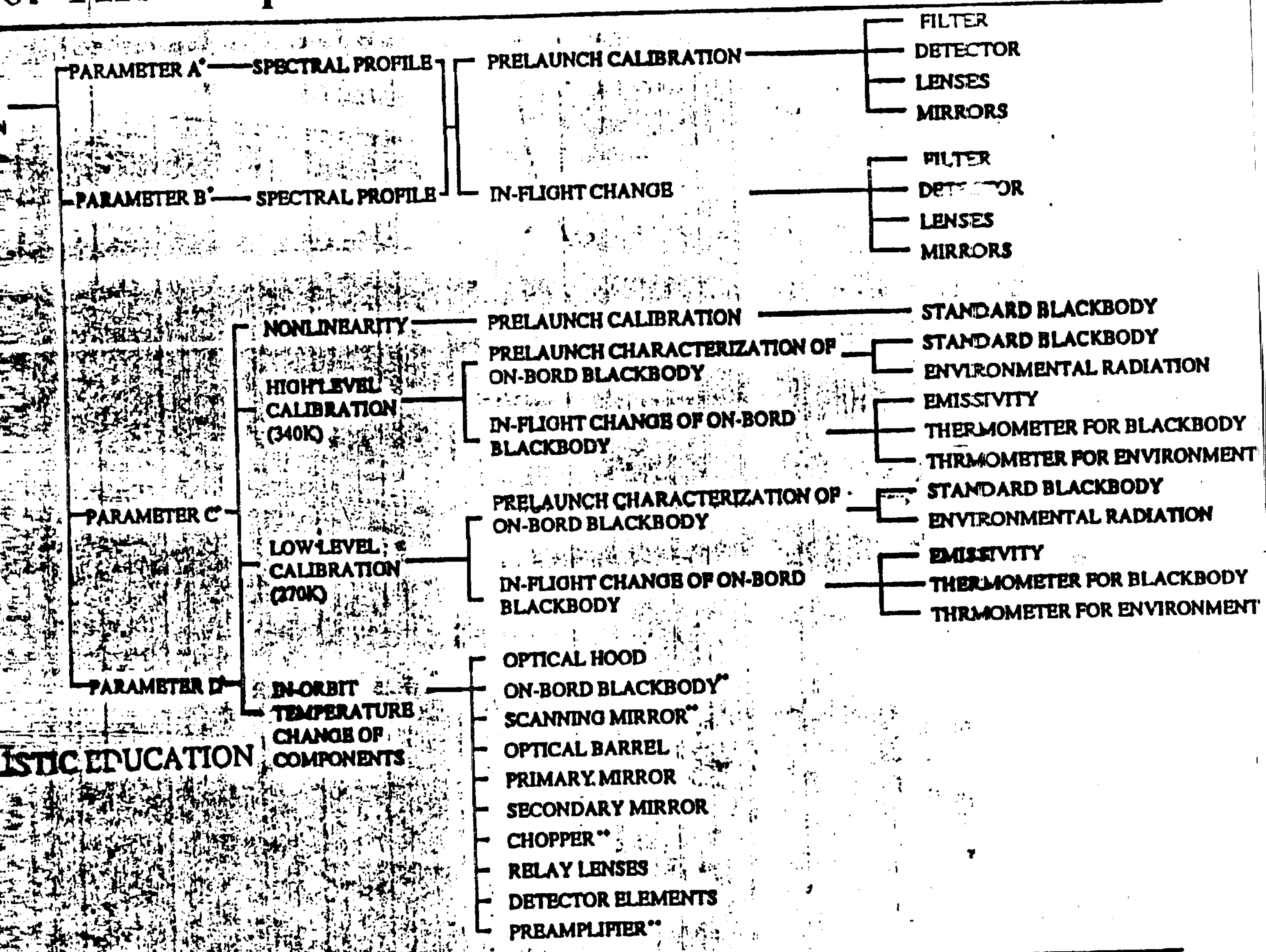

CERTAINTY OF TEMPERATURE SCALE INTERPOLATION AND EXTRAPOLATION

- PARAMETER A* — SPECTRAL PROFILE
- PARAMETER B* — SPECTRAL PROFILE
  - PRELAUNCH CALIBRATION
    - FILTER
    - DETECTOR
    - LENSES
    - MIRRORS
  - IN-FLIGHT CHANGE
    - FILTER
    - DETECTOR
    - LENSES
    - MIRRORS
- PARAMETER C*
- PARAMETER D*
  - NONLINEARITY
    - PRELAUNCH CALIBRATION
      - STANDARD BLACKBODY
  - HIGH LEVEL CALIBRATION (340K)
    - PRELAUNCH CHARACTERIZATION OF ON-BORD BLACKBODY
      - STANDARD BLACKBODY
      - ENVIRONMENTAL RADIATION
    - IN-FLIGHT CHANGE OF ON-BORD BLACKBODY
      - EMISSIVITY
      - THERMOMETER FOR BLACKBODY
      - THRMOMETER FOR ENVIRONMENT
  - LOW LEVEL CALIBRATION (270K)
    - PRELAUNCH CHARACTERIZATION OF ON-BORD BLACKBODY
      - STANDARD BLACKBODY
      - ENVIRONMENTAL RADIATION
    - IN-FLIGHT CHANGE OF ON-BORD BLACKBODY
      - EMISSIVITY
      - THERMOMETER FOR BLACKBODY
      - THRMOMETER FOR ENVIRONMENT
  - IN-ORBIT TEMPERATURE CHANGE OF COMPONENTS
    - OPTICAL HOOD
    - ON-BORD BLACKBODY*
    - SCANNING MIRROR**
    - OPTICAL BARREL
    - PRIMARY MIRROR
    - SECONDARY MIRROR
    - CHOPPER**
    - RELAY LENSES
    - DETECTOR ELEMENTS
    - PREAMPLIFIER**

± K at 200K	± K at 300K
± K at 240K	± K at 340K
± K at 270K	± K at 370K

at 8.3μm, 8.65μm, 9.1μm, 10.6μm, and 11.3μm

AMETERS IN CHARACTERISTIC EDUCATION

$$\Gamma) = \frac{C}{\exp\left(\frac{C_2}{AT+B}\right)-1} + D$$

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** INCLUDE TEMPERATURE CHANGES DURING WARMING UP

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Error Budget for TIR Temperature Scale Calibration

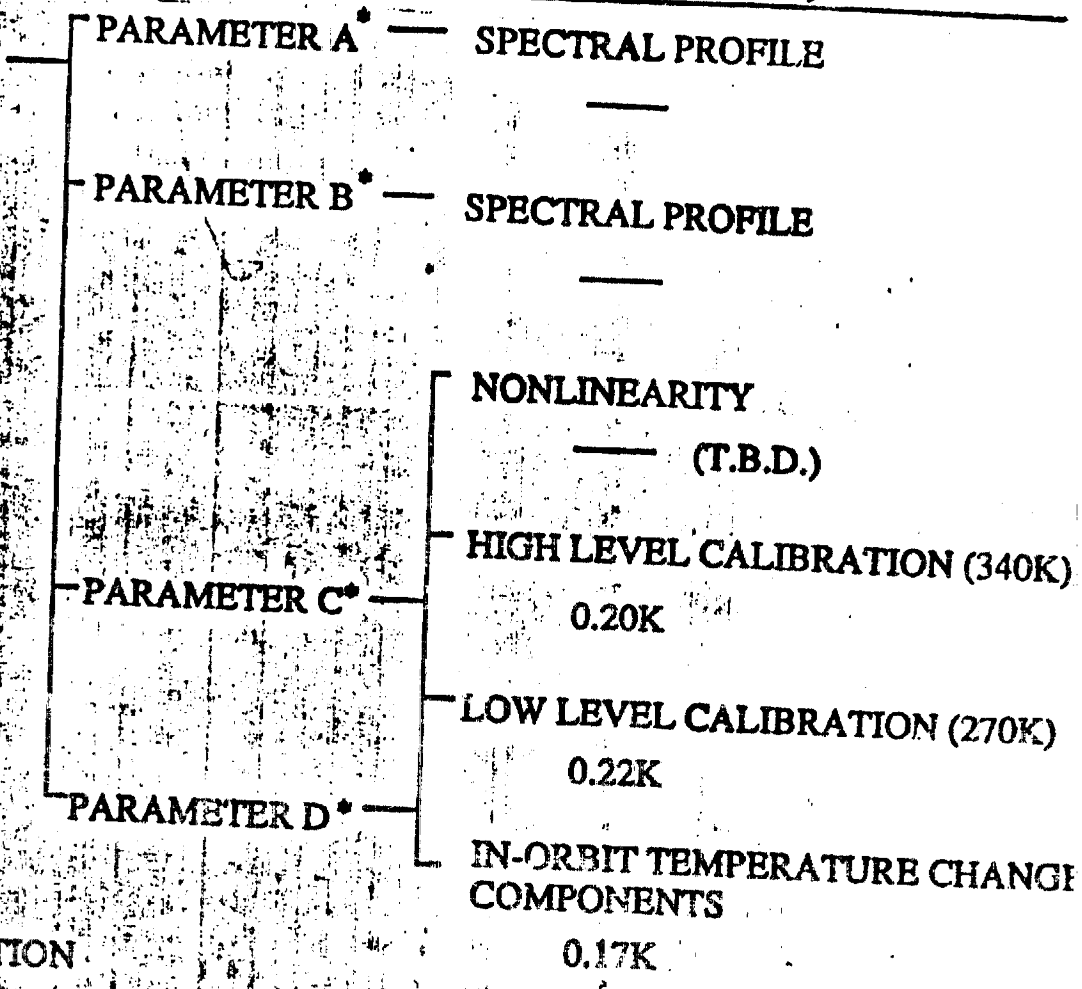
UNCERTAINTY OF TEMPERATURE SCALE BY INTERPOLATION AND EXTRAPOLATION

DISTRIBUTED VALUE

ACCURACY

± 2.9 K at 200K	± 0.26 K at 300K
± 0.79 K at 240K	± 0.26 K at 340K
± 0.27 K at 270K	± 0.43 K at 370K

at 8.3µm, 8.65µm, 9.1µm, 10.6µm, and 11.3µm.



PARAMETER A* — SPECTRAL PROFILE

—

PARAMETER B* — SPECTRAL PROFILE

—

PARAMETER C*

PARAMETER D*

NONLINEARITY

— (T.B.D.)

HIGH LEVEL CALIBRATION (340K)

0.20K

LOW LEVEL CALIBRATION (270K)

0.22K

IN-ORBIT TEMPERATURE CHANGE COMPONENTS

0.17K

* PARAMETERS IN CHARACTERISTIC EDUCATION

$$V(T)=\frac{C}{\exp\left(\frac{C_2}{AT+B}\right)-1}+D$$

Cross-calibration

Application of cross calibration data

- Cross calibration is very effective method for validation of observation data
- Some requirements for TIR are shown as follows:
  - temperature range for cross calibration : 200K-370K
  - the minimum size of the cross calibration blackbody :
    - larger than 400 mm for full aperture which include pointing and scanning.
    - 330mm-diameter for just scanning

Cross-calibration

Kendall radiometer

- NASA/GSFC recommends to use the Kendall radiometer for round robin measurements of the instrument manufacture's standard blackbodies.
  Kendall radiometer includes the radiometer and measuring system.
- Our comments for using Kendall radiometer are as follows:
  - It is better to use Kendall radiometer with the standard blackbody togather with a transfer blackbody
  - Kendall radiometer needs to fit configuration of the instrument manufacture's standard blackbody
    - standard blackbody specifications and conditions for TIR as follows:

      size :larger than 13-inch X 15-inch plate
      surface figure :Hexaprismatic surface
      temperature range:100-400K
      setting position :just in front of TIR aperture with hood

- We need Kendall radiometer in EM and PFM phase

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p. 15

OASIS-CC

OASIS-CC PRESENTATION

Laboratory for Atmospheric and Space Physics
Operations and Information Systems Group

University of Colorado at Boulder

University of Colorado
LASP Space Technology Building
Campus Box 590
Boulder, Co 80309-0590
Phone: (303) 492-6792
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OASIS-CC

CU/LASP Organization

Laboratory for Atmospheric and Space Physics

- Scientific Division
- Engineering Division
- Operations and Information Systems Division

CU/LASP employs 100 professional researchers and engineers and 60 undergraduate and graduate student researchers

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OASIS-CC

CU/LASP Flight Projects

LASP scientists and engineers have participated in the following NASA space flight missions

Orbiting Solar Observatory 5
Orbiting Geophysical Observatory 4, 5 & 6
Orbiting Astronomical Observatory 2
Mariner Venus 5

- Mariner Mars 6 & 7
- Mariner Mars 9
- Orbiting Solar Observatory 8
- Atmosphere Explorer C & D
- Voyager 1 & 2
- Pioneer Venus Orbiter
- Solar Mesosphere Explorer
- Spartan Halley
- Galileo Jupiter Orbiter

Hubble Space Telescope

- Upper Atmosphere Research Satellite

Mars Observer

- Cassini Saturn Orbiter
- Earth Observing System
- ~ 200 Sub-Orbital Rocket Experiments

Asterisks denote projects for which LASP built or is building one or more instruments

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OASIS-CC

What is the OASIS Project?

- The Operations and Science Instrument Support (OASIS) project is a long-term effort to help produce operations capabilities that can support space science missions of the next century
  - Past funding from NASA Office of Space Science and Applications and Goddard Space Flight Center
  - By providing a comprehensive concept for future mission operations systems we can enable new kinds of missions by increasing flexibility and functionality while substantially reducing life-cycle costs and project development time
- We have implemented portions of the OASIS concept in software under the general name OASIS-R/T
  - OASIS-CC — OASIS Command and Control, for monitoring and controlling science instruments and spacecraft during test, integration, launch and on-orbit operations
  - OASIS-PS — OASIS Planning and Scheduling, for scheduling instrument and spacecraft operations

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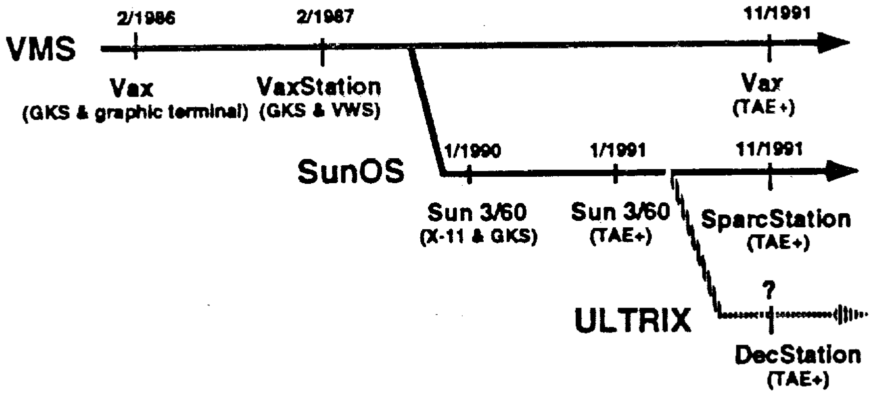
OASIS-CC

Fundamental User Requirements for OASIS-CC Software

- Usable by scientists and engineers who aren't programmers and who don't want to be programmers
  - Software must be easy to install, tailor for application, and operate
  - Must perform all primary functions without need for any additional software coding and without need for other costly software packages
- Applicable throughout the project life cycle:
  - Instrument development, test and integration, launch, and on-orbit operations
- Extremely flexible
  - Need to be able to modify data definitions and processing functions quickly and easily without writing new software
  - Built-in support for a wide variety of communications protocols
- Good user interface
  - Graphical user interface that can be tailored by users
  - Operations language that is more English-like and which eliminates the main deficiencies of STOL

OASIS-CC

OASIS-CC Evolution



OASIS-CC FUNCTIONALITY DESCRIPTION

- User Interface
- CSTOL
- Language processing
- Communications
- Data processing
- Data transfer
- Recording
- Command

Something to remember

OASIS-CC is table driven. Most of what follows are generic capabilities of the system. Users only need to provide the contents of the tables.

OASIS-CC

OASIS-CC: User interface

- The interface uses the Transportable Application Environment Plus (TAE +)
  - TAE+ is a Motif-compliant, portable environment for developing and running interactive, window, text and graphical object-based application systems
  - TAE+ is developed and supported by GSFC
  - TAE+ includes a workbench, an intuitive tool that supports the design and layout of an application's user interface
  - Code (Ada or C) generated by the workbench is linked with the OASIS-CC code to generate the executable program
- Using TAE+ a user can develop simple or extremely elaborated user interfaces.

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OASIS-CC

OASIS-CC: User interface (cont.)

- User input is done via :
  - push button
  - slider
  - form-filling
  - radio button
  - check box
  - menu selection
- The user can also input CSTOL statements via keyboard entry

- Data in the OASIS-CC current value table can be used to:
  - Drive alphanumeric display
  - Animate icons (rotation, distortion, translation)
  - Drive icons that represent a system's state
  - Drive stripchart-like plots

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OASIS-CC

OASIS-CC: CSTOL

- The Colorado System Test and Operations Language (CSTOL) is derived from GSFC's STOL.
- Improvements over STOL:
    - A distinctly English-like syntax
    - The ability to access database tables through a query language
    - A mechanism for expanding the language through macros
    - Support of engineering units
- CSTOL is designed for scientists, engineers, ground controllers who develop, test and operate spacecraft and payloads
- CSTOL was built as a test for many of the requirements for the Space Station User Interface Language
- CSTOL accomodates people with little or no programming experience
- CSTOL's English-like syntax makes it readable and self-documenting

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OASIS-CC

OASIS-CC: CSTOL (cont.)

CSTOL provides users with the means to perform the following functions :

- Evaluate expressions, where variables in the expression can be data from a spacecraft or instrument
- Make decisions based on information returned by the spacecraft or instrument
- Initiate and control procedures written in CSTOL
- Maintain the OASIS database
- Call up and terminate displays
- Make and break communication links
- Send commands to the spacecraft or instrument

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OASIS-CC: Communications

- Generic protocol support is provided:
  - DECNET, mailbox and RS-232 for the VMS version
  - TCP/IP (stream socket) and RS-232 for the SunOs version
- Other protocol handlers can be developed if required by an application (example: NASCOM for the RHISE application and the LDBP application, DADS/ADS for the SSFP DMS testbed application, 16-bit parallel interface)
- The VMS version provides an IEEE-488 capability

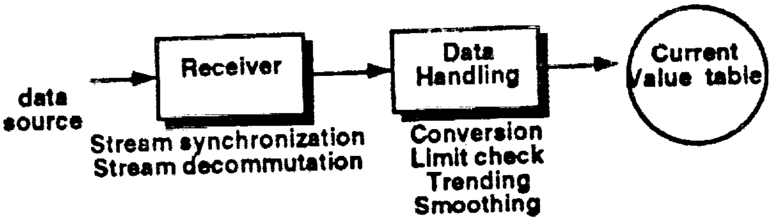
Future developments:
  - IEEE-488 for SunOs version
  - 1153 for SunOS version

OASIS-CC: Data processing

- Stream synchronization
- Stream decommutation (super-commutation, sub-commutation, packetized telemetry)
  - Binary data
  - Floating point data
  - ASCII formatted data (I, F or A format)
  - Interfacing to a hardware decommutator may be done in the near future (concept already tested)
- Conversion from raw (unsigned integer) values to unitized real values
- Conversion from raw discrete values to state values (like ON, OFF)
- Limit checking
  - High/Low, Red/Yellow
    - Red limit can trigger the execution of a CSTOL procedure
  - State check
    - Unsafe state can trigger the execution of a CSTOL procedure
  - Delta check

OASIS-CC: Data processing (cont.)

- Smoothing and trending
- Print-on-change
- Pseudo-measurement generation:
  - Generically via the execution of a CSTOL procedure by the equation-CLP

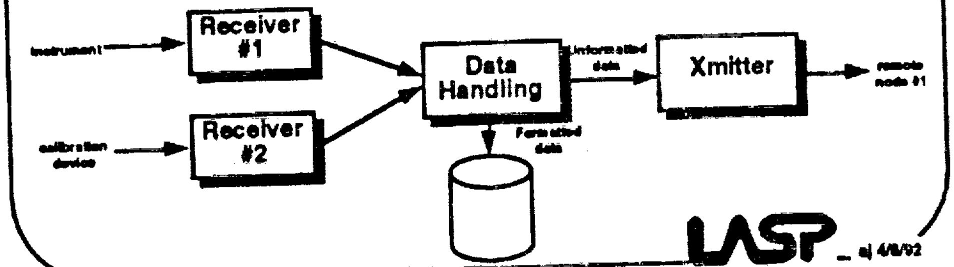


OASIS-CC: Data transfer

- Two mechanisms are provided: Bridge and Router
- Both mechanisms use the communication services provided by OASIS-CC

Bridge:

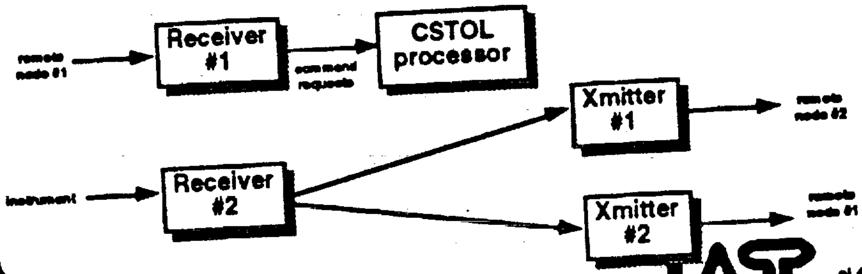
- Allows transfer via file or over communication links of processed data in a format defined by the user
- Useful to transfer time-correlated science and engineering data for quick-look processing



OASIS-CC

OASIS-CC: Data transfer (cont.)

- Router:
  - Bi-directional mechanism:
    - Allows the transfer of raw data over communication links
    - Allows the transfer to a CSTOL processor of CSTOL statements received on communication links
  - Useful for distributing realtime data to remote nodes or executing command requests from remote nodes



aj 4/8/92

OASIS-CC

OASIS-CC: Recording

- Recording of downlink data
  - Raw data can be recorded and replayed
  - Processed data can be recorded (via the Bridge capability)
  - Comments can be added by the user at recording time to qualify the recorded data
- Event messages can be recorded

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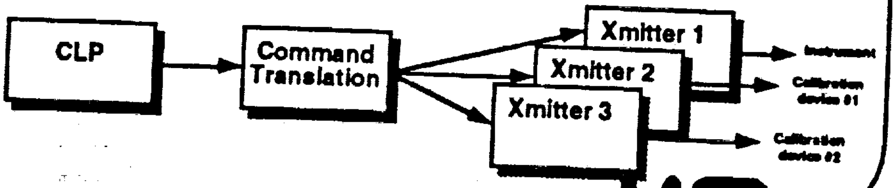
OASIS-CC: Command

- Translation from an high-level (e.g., CSTOL) representation of a command into an instrument command
  - Examples:

CSTOL	TRANSLATION
slew grating to 1800	=> CC229F08
slew grating to 1216.0 a	=> CC229F08
set observation list to 5	=> CC220605
set entrance slit to stellar	=> CC220780
move extender to 10.0 mm	=> 3FCC280C83
move extender to 1.0 cm	=> 3FCC280C83
close gripper	=> move gripper to 6.0 cm

OASIS-CC: Command (cont.)

- Instrument commands can be:
  - Binary (when the natural representation of the instrument command is a bit pattern)
  - ASCII (when the natural representation is a character string)
- Instrument commands can be:
  - Discrete
  - Serial (i.e., a command containing subfields)
- Instrument microprocessor load support
- From one CLP, commands can be directed to multiple targets over multiple communication lines



OASIS-CC

OASIS-CC SUPPORT

Utility programs
Documentation
Support office
Anomaly reporting and configuration management
Release documentation

LASP ej 4/8/92

OASIS-CC

OASIS-CC: Utility programs

- **Database-related programs:**
  - **Load Database: from ASCII to internal representation**
  - **Dump Database: from internal representation to ASCII**
  - **Report Database: from internal representation to report format**
  - **DDP (Database Development Package): a user-friendly database builder program, using TAE+ (in development)**
- **Parser-related program:**
  - **Convert Table: from ASCII to internal representation**
- **Event log file:**
  - **Dump Events: to search and create a printable file from the event log file**

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OASIS-CC

OASIS-CC: Documentation

- CSTOL Reference Manual
- Database Guide
- System Manager's Guide
- Installation Guide
- Graphics Editor User's Guide

- Up-to-date with the current version of OASIS-CC, with TAE+ version-specific documentation:
  - Installation guide
  - Application developer's guide

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OASIS-CC

OASIS-CC: Support office

Four types of support can be provided:

- Phone support for application developer
- Applications developer class
- Specific code development
- Application development

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OASIS-CC

OASIS-CC Anomaly reporting and release documentation

- Reporting mechanism existing currently on the SPAN network:
  - Allows the users to report anomalies or request enhancements
  - Each report is automatically assigned a number
  - Users can refer to this number to track their reports
  - The reports are also used to support configuration management
- Each new release is documented in a release note:

```
**************** Release of OASIS V02.05.03************12/18/90
This is the release note for OASIS V02.05.03.
VMS version:
The following program and parser file have been released:
  executable    version        filename
 * OASIS        V02.05.03      OASIS_DEC.EXE (GPX version)
 * PARSER table                PARSER_INT.DAT
 * REPORT       V02.05.03      REPORT.COM
This version of OASIS is compiled using Dec/Ada 1.5 and has been tested under
the following configurations:
        VMS    Dec/GKS   VWS
        4.7     3.1      3.2
        5.0     3.1      4.0
        5.1     3.0      4.0
        5.1     3.1      4.1
        5.3     4.1      4.2
```

OASIS-CC

OASIS-CC AS A TOOL

Examples of utilization

Support of instrument development

Support of spacecraft integration and test

Support of flight operations

OASIS-CC: Examples of utilization

- UARS/SOLSTICE instrument

OASIS-CC is used to support instrument functional test, calibration, integration and flight operations

- JSC Space Station Freedom DMS testbed

OASIS-CC was used in four nodes of the testbed (OMA, OMGA, APEM and POIC nodes) located at JSC and at MSFC

- ESA Astronaut training

OASIS-CC is used to access MSFC's Payload Crew Training Complex from ESTEC in Noordwijk

- Long Duration Balloon Project

OASIS-CC will be used along with OASIS-PS to acquire balloon experiment data, TDRSS ODM messages and issue GCM requests

OASIS-CC: Examples of utilization (cont.)

- SOLCON flight operations

From ESTEC in Noordwijk, OASIS-CC was used to monitor and control the SOLCON experiment aboard the last ATLAS flight

- DMSP and DSCS ground station demonstration

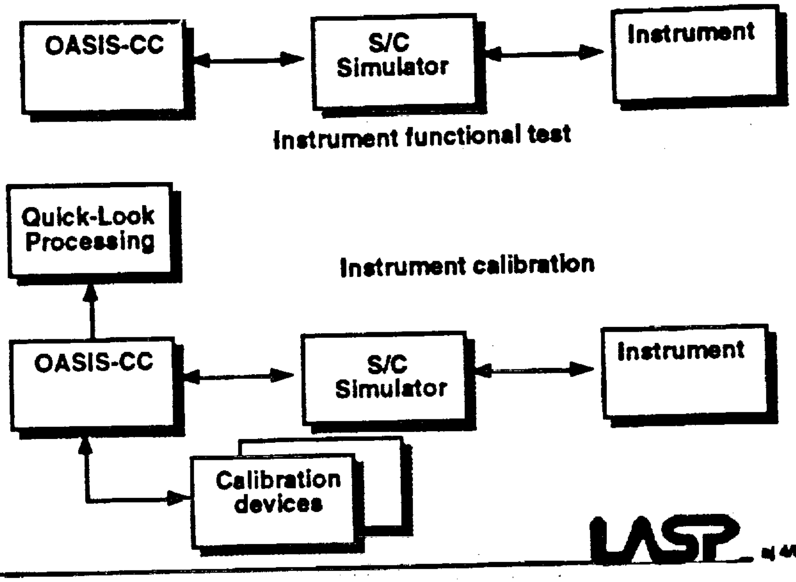
OASIS-CC was used to demonstrate low-cost, transportable satellite operation and control systems

- EOS/SOLSTICE II and CASSINI/UVIS

OASIS-CC will be used during the functional tests, calibration and integration of these two instruments

OASIS-CC

OASIS-CC: Instrument development support



OASIS-CC

S/C Simulator

Instrument

Instrument functional test

Quick-Look Processing

Instrument calibration

OASIS-CC

S/C Simulator

Instrument

Calibration devices

aj 4/8/92

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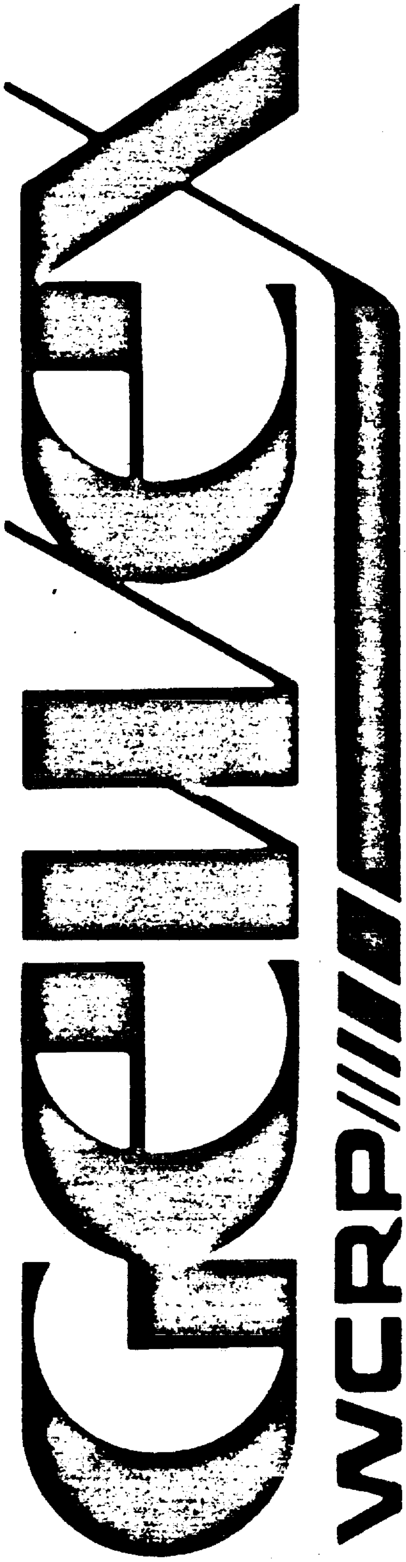

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CLIMATE CHANGE BUILDING BLOCKS

- IPCC PRIORITIES:
  1. SOURCES AND SINKS OF GREENHOUSE GASES
  2. CLOUDS AND RADIATIVE BALANCE, INCLUDING PRECIPITATION
  3. OCEANS
  4. LAND-SURFACE HYDROLOGICAL PROCESSES
  5. POLAR ICE SHEETS
  6. ECOLOGICAL PROCESSES

- EOS PRIORITIES:
  1. WATER AND ENERGY CYCLES (2)
  2. OCEANS (3)
  3. CHEMISTRY OF TROPOSPHERE AND LOWER STRATOSPHERE (1)
  4. LAND SURFACE HYDROLOGY AND ECOSYSTEM PROCESSES (4&6)
  5. GLACIERS AND POLAR ICE SHEETS (5)

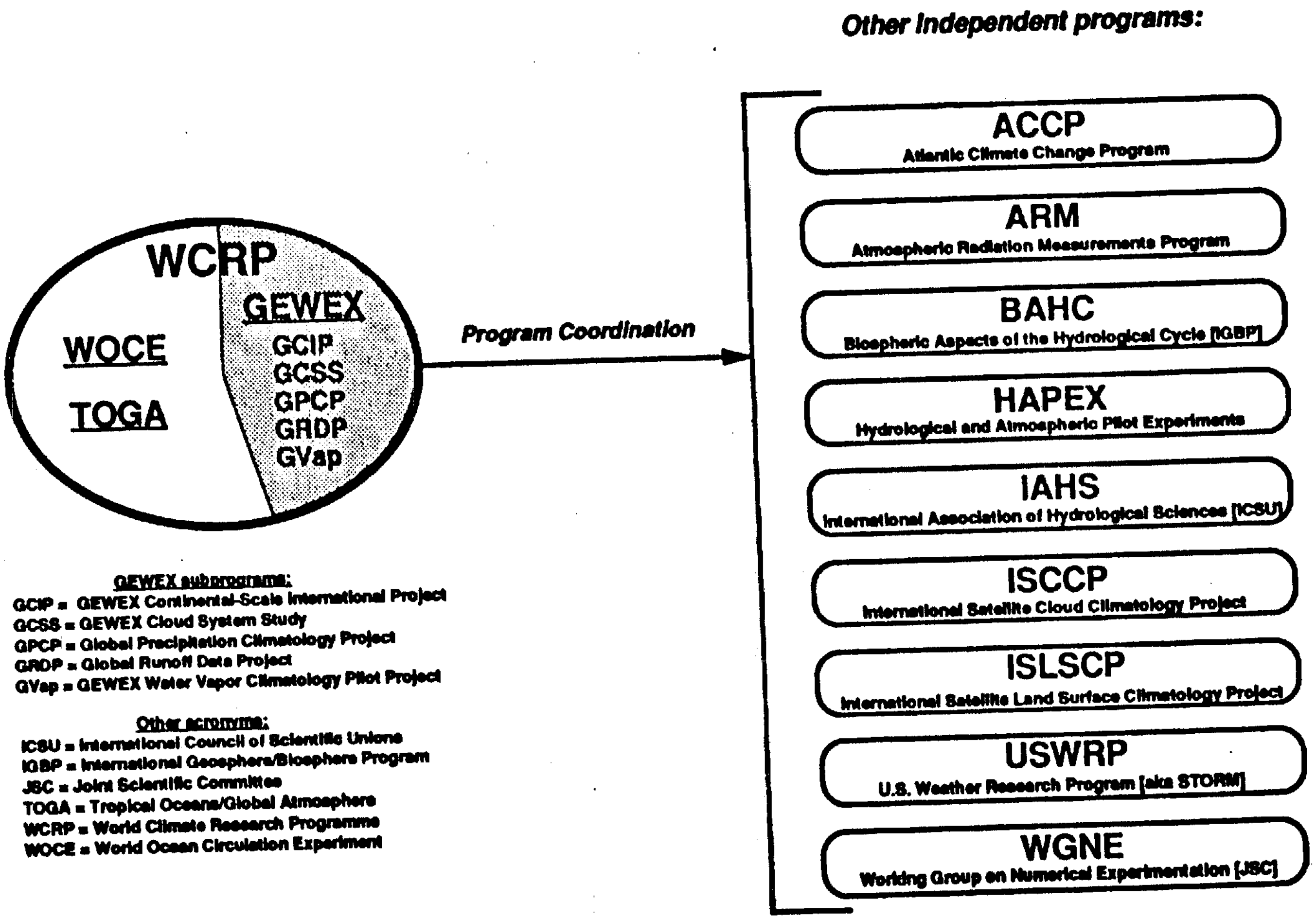
GEWEX OBJECTIVES

- DETERMINE THE HYDROLOGIC CYCLE AND ENERGY FLUXES BY MEANS OF GLOBAL MEASUREMENTS OF OBSERVABLE ATMOSPHERIC AND SURFACE PROPERTIES
- MODEL THE GLOBAL HYDROLOGIC CYCLE AND ITS EFFECTS ON THE ATMOSPHERE AND OCEANS
- FOSTER THE DEVELOPMENT OF OBSERVING TECHNIQUES AND DATA MANAGEMENT AND ASSIMILATION SYSTEMS
- DEVELOP THE ABILITY TO PREDICT THE VARIATIONS OF GLOBAL AND REGIONAL HYDROLOGIC PROCESSES AND WATER RESOURCES, AND THEIR RESPONSE TO ENVIRONMENTAL CHANGE

GEWEX STRATEGY

- BUILD ON EXISTING PROGRAMS AND DATA
- MAKE RECOMMENDATIOS TO ESA, NASA AND NASDA WITH RESPECT TO INSTRUMENTS PLANNED FOR SPACE PLATFORMS
- CONDUCT MODELLING PROGRAMS
    - MODEL ALL ASPECTS OF THE HYDROLOGIC AND ENERGY CYCLES WITH EVOLVING, FULLY COUPLED ATMOSPHERE-LAND-OCEAN MODEL COMPONENTS
- CONDUCT PILOT PROJECTS
    - INTERNATIONAL PARTICIPATION
    - ENCOMPASS FULL RANGE OF EXPERIMENT SCALES
    - SMALL-SCALE (1X1 TO 100X100 KM) PROCESS STUDIES
    - CONTINENTAL SCALE
    - GLOBAL

RELATIONSHIP OF GEWEX TO OTHER PROGRAMS AND ACTIVITIES



Other Independent programs:

- **ACCP** Atlantic Climate Change Program
- **ARM** Atmospheric Radiation Measurements Program
- **BAHC** Biospheric Aspects of the Hydrological Cycle [IGBP]
- **HAPEX** Hydrological and Atmospheric Pilot Experiments
- **IAHS** International Association of Hydrological Sciences [ICSU]
- **ISCCP** International Satellite Cloud Climatology Project
- **ISLSCP** International Satellite Land Surface Climatology Project
- **USWRP** U.S. Weather Research Program [aka STORM]
- **WGNE** Working Group on Numerical Experimentation [JSC]

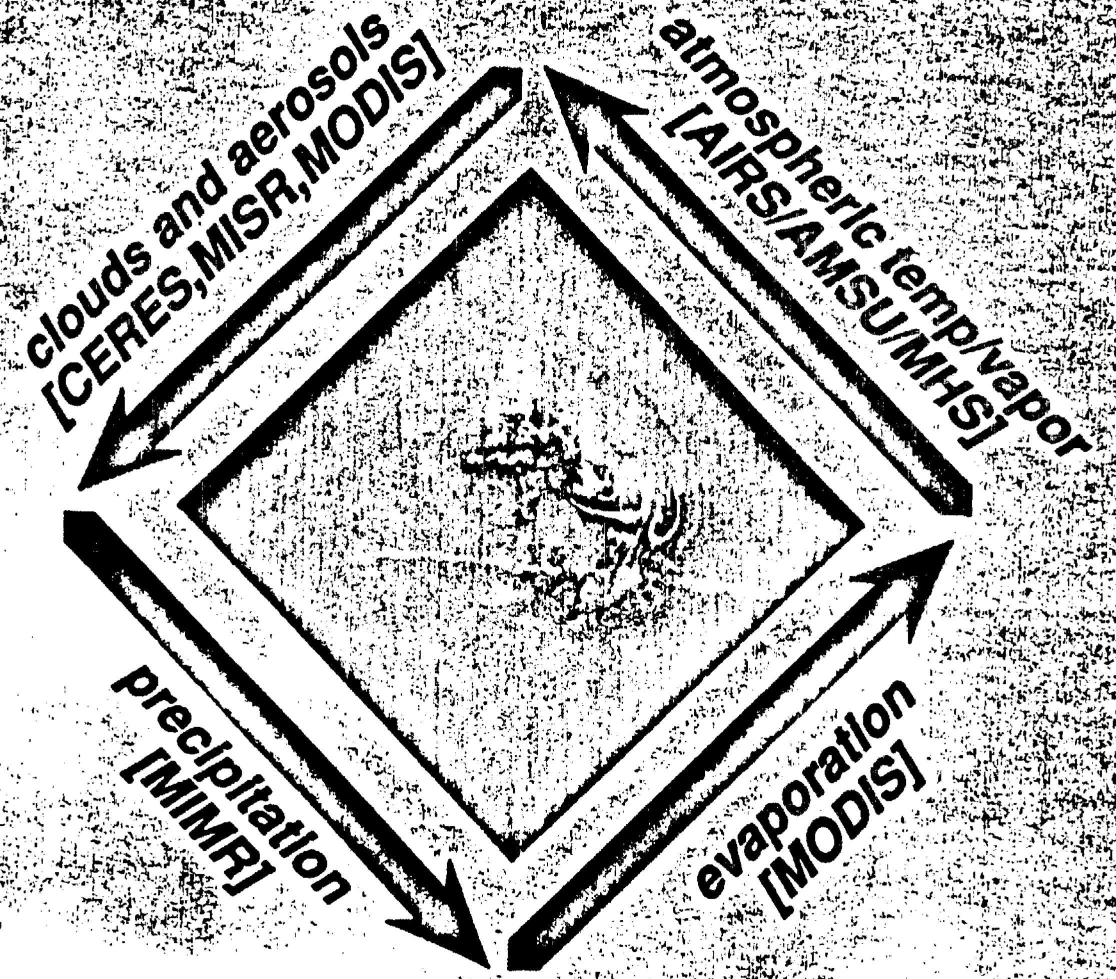
GEWEX subprograms:

GCIP = GEWEX Continental-Scale International Project
GCSS = GEWEX Cloud System Study
GPCP = Global Precipitation Climatology Project
GRDP = Global Runoff Data Project
GVap = GEWEX Water Vapor Climatology Pilot Project

Other acronyms:

ICSU = International Council of Scientific Unions
IGBP = International Geosphere/Biosphere Program
JSC = Joint Scientific Committee
TOGA = Tropical Oceans/Global Atmosphere
WCRP = World Climate Research Programme
WOCE = World Ocean Circulation Experiment

USING EOS
TO STUDY THE ROLE OF WATER IN CLIMATE CHANGE



clouds and aerosols
[CERES,MISR,MODIS]

atmospheric temp/vapor
[AIRS/AMSU/MHS]

precipitation
[MIMR]

evaporation
[MODIS]

TYPES OF GLOBAL DATA NEEDED FOR GEWEX

BASIC METEOROLOGICAL PARAMETERS

- ATMOSPHERIC TEMPERATURE AND HUMIDITY
- OCEAN SURFACE TEMPERATURE, STRESS AND TOPOGRAPHY
- SURFACE METEOROLOGICAL OBSERVATIONS

TROPOSPHERIC WIND VECTOR

- GLOBAL DOPPLER WIND LIDAR*
- UPPER AIR WINDS

PRECIPITATION

- GLOBAL RAIN RADAR DATA**
- RAIN GAUGE AND LAND-BASED RAIN RADAR DATA
- OCEAN SALINITY

RADIATION AND CLOUDS

- SOLAR IRRADIANCE
- SPECTRAL OUTGOING LONG-WAVE RADIATION
- REFLECTED SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE
- NET FLUX AT THE SURFACE
- EARTH RADIATION BUDGET
- GREENHOUSE TRACE GASES
- AEROSOLS
- STRATOSPHERIC WATER VAPOR
- CLOUD AMOUNT, TYPE AND HEIGHTS OF BASE AND TOP

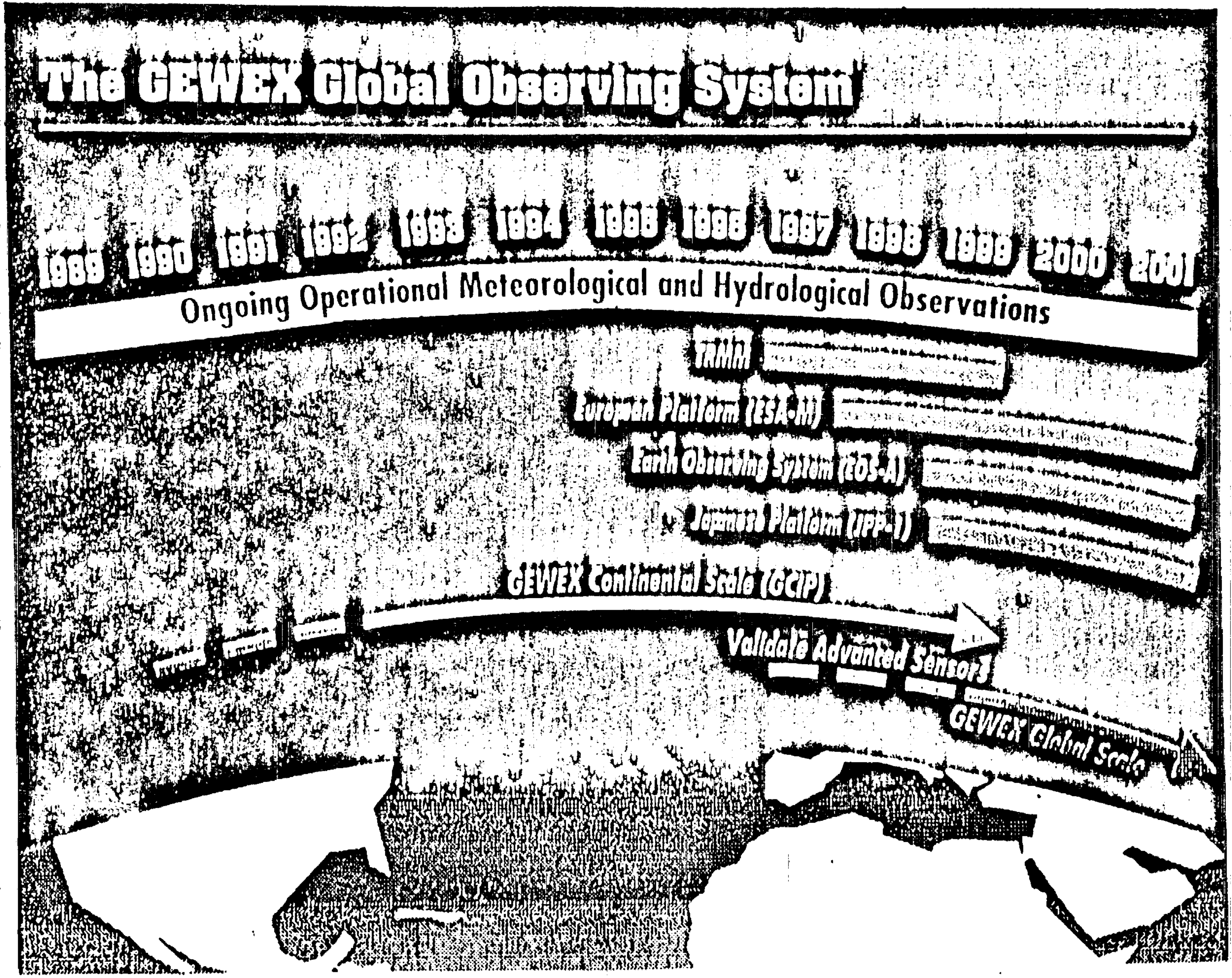
LAND SURFACE DATA

- SURFACE ALBEDO AND ROUGHNESS
- SKIN SURFACE TEMPERATURE AND EMISSIVITY
- VEGETATION INDEX
- SNOW COVER, DEPTH AND WATER CONTENT
- SOIL MOISTURE AND WATER RUNOFF

* REQUIRES 3000 WATTS OF POWER ON-ORBIT

** NON-SUNSYNCHRONOUS ORBIT REQUIRED TO SAMPLE DIURNAL VARIABILITY

The GEWEX Global Observing System



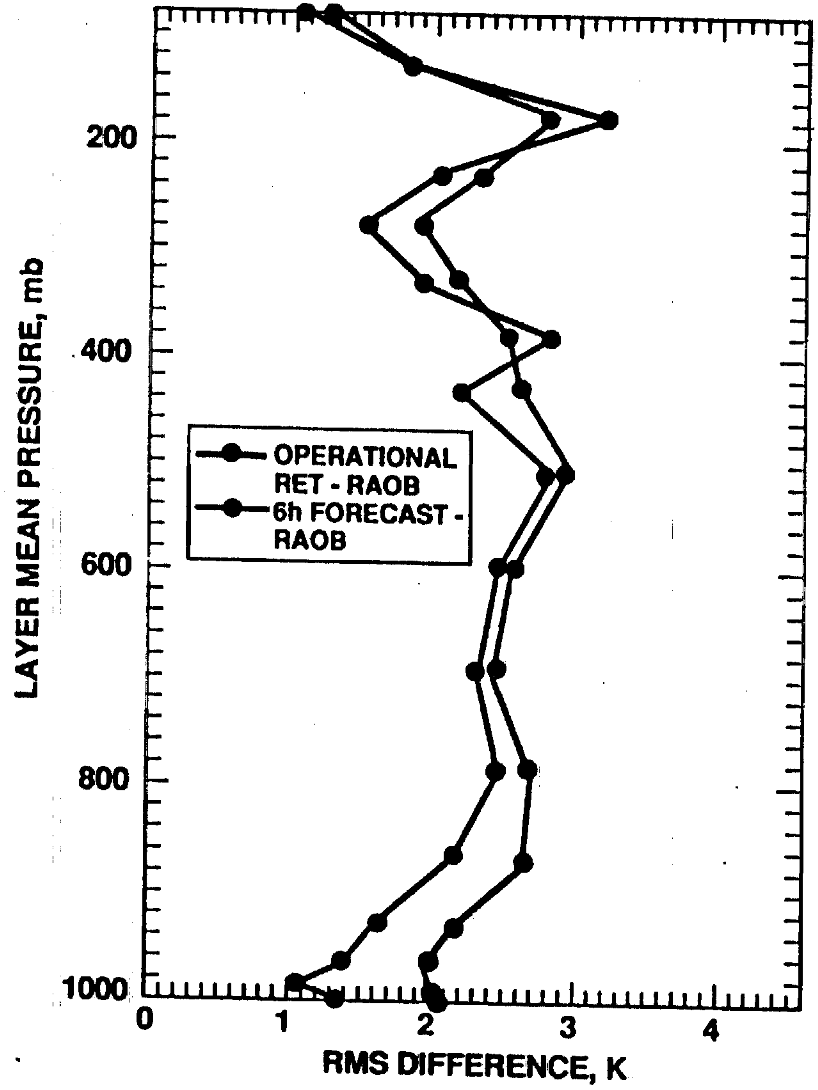
4-D DATA ASSIMILATION

- IS THE BASIS FOR UNDERSTANDING AND PREDICTING GLOBAL ENERGY AND WATER CYCLES
- SHORT-RANGE FORECASTS ARE A KEY TOOL
  - -- TO PRODUCE COHERENT DATA SETS FROM INCOMPLETE OBSERVATIONAL DATA
  - -- TO VALIDATE AND CONSTRAIN SURFACE FLUXES

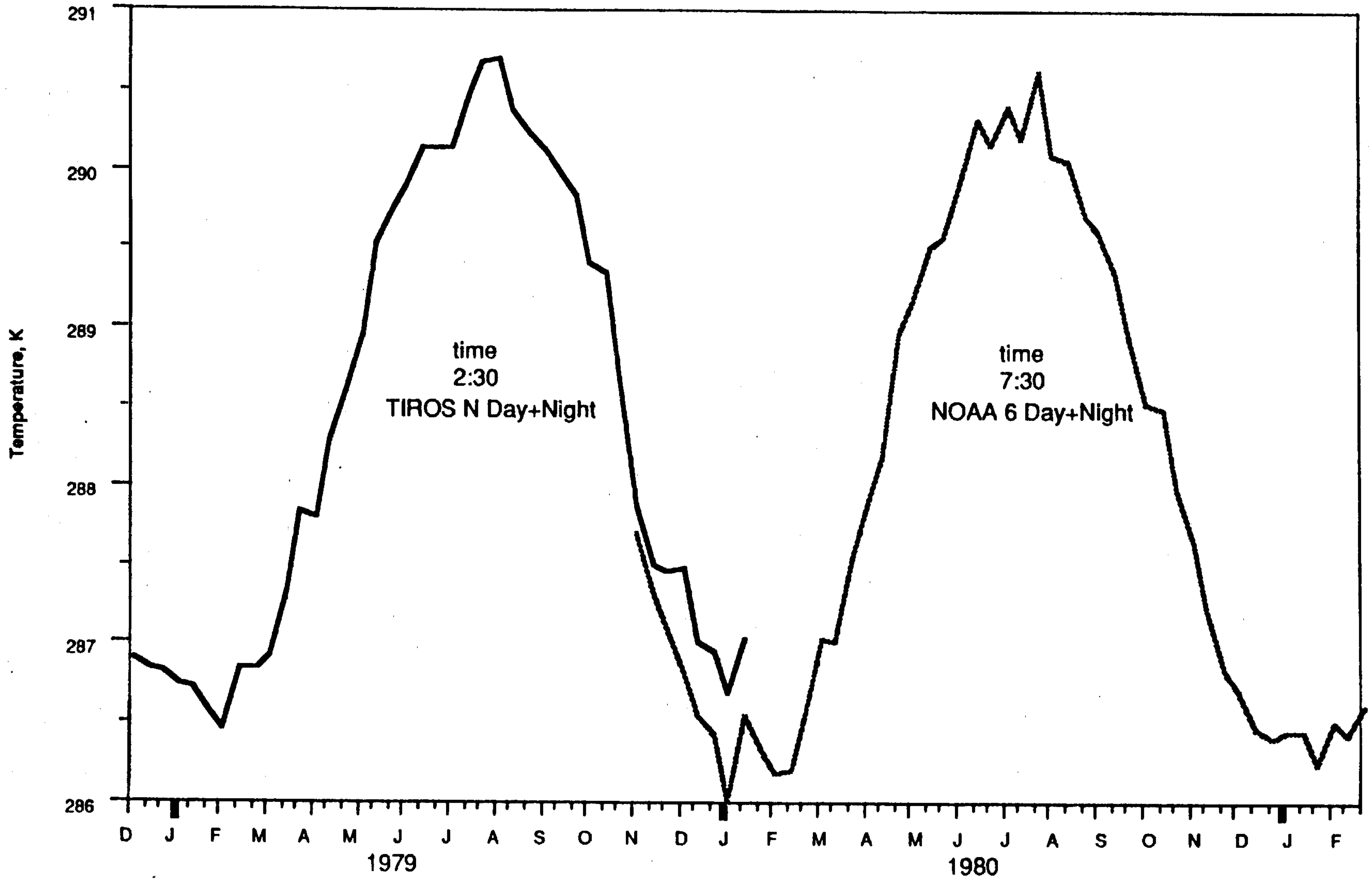
ACCURACY OF THE OPERATIONAL SATELLITE RETRIEVAL AND NMC MODEL 6h FORECAST (RAOB DIFFERENCES) CLEAR OCEAN CASES ± 60° LAT

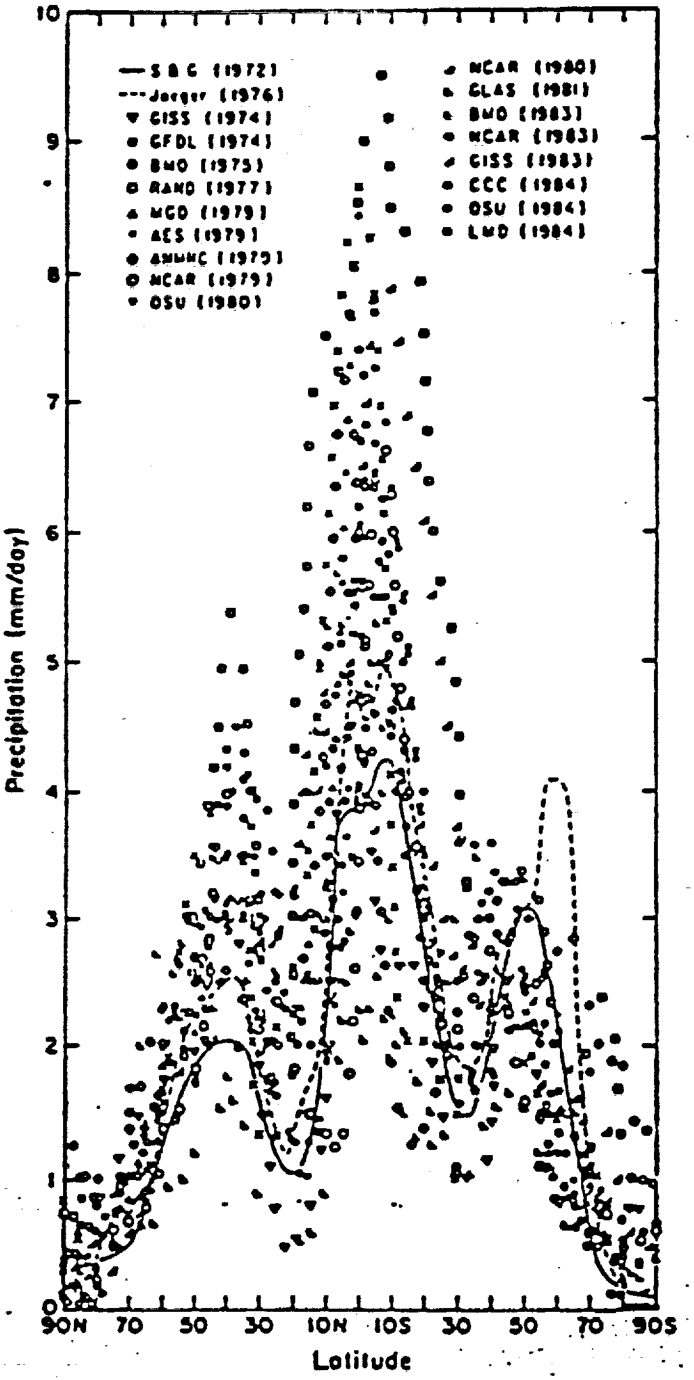
CASE STUDY - 02/08/91 (SAMPLE=44)

CLEAR OCEAN -60 TO +60 LAT



HIRS2/MSU Retrieved Day + Night Surface Temperature
December 1978 - February 1981





— S & G (1972)
--- Jaeger (1976)
▼ GISS (1974)
● GFDL (1974)
● BMO (1975)
○ RAND (1977)
▲ MGO (1979)
• AES (1979)
● ANMRC (1979)
○ NCAR (1979)
▼ OSU (1980)
NCAR (1980)
GLAS (1981)
BMO (1983)
NCAR (1983)
GISS (1983)
CCC (1984)
OSU (1984)
LMD (1984)
Precipitation (mm/day)
0
1
2
3
4
5
6
7
8
9
10
90N
70
50
30
10N
10S
30
50
70
90S
Latitude

GCIP LOCATION: MISSISSIPPI RIVER BASIN

GCIP OBJECTIVES

- DETERMINE THE TIME/SPACE VARIABILITY OF THE HYDROLOGIC AND ENERGY BUDGETS OVER A CONTINENTAL-SCALE REGION
- DEVELOP AND VALIDATE MACRO-SCALE HYDROLOGIC MODELS, RELATED HIGH RESOLUTION ATMOSPHERIC MODELS, AND COUPLED HYDROLOGIC/ATMOSPHERIC MODELS
- DEVELOP AND VALIDATE INFORMATION RETRIEVAL SCHEMES INCORPORATING EXISTING AND FUTURE SATELLITE OBSERVATIONS COUPLED WITH ENHANCED GROUND-BASED OBSERVATIONS
- PROVIDE A CAPABILITY TO TRANSLATE THE EFFECTS OF A FUTURE CLIMATE CHANGE INTO IMPACTS ON WATER RESOURCES AND TEMPERATURE ON A REGIONAL BASIS

GCIP IMPLEMENTATION

- MISSISSIPPI BASIN CHOSEN AS PRIMARY LOCATION, SUPPLEMENTED BY FIELD STUDIES IN OTHER REGIONS, AS REQUIRED
- MAKE FULL USE OF EXISTING AND PLANNED NETWORKS OF SURFACE OBSERVATIONS, AIRCRAFT DATA AND SATELLITE DATA
- SUBSTANTIAL INTERNATIONAL PARTICIPATION REQUIRED
- RELY ON AND COLLABORATE WITH EXISTING AND PLANNED PROGRAMS AS MUCH AS POSSIBLE, E.G.:
  - STORM
  - ARM
  - INTERNATIONAL PROGRAMS, IGBP, ETC.
- COLLECT A COMPREHENSIVE DATA SET OF HYDROMETEOROLOGICAL VARIABLES FOR AN EXTENDED PERIOD OF TIME TO TEST AND VALIDATE MODELS

GCIP DATABASE

- **REMOTELY SENSED**

  RADAR PRECIPITATION (NEXRAD)
  SATELLITE RADIATION
  – LONG AND SHORT-WAVE AT T.O.A.
  – DERIVED FLUXES AT SURFACE
  SATELLITE AND AIRCRAFT VIS, IR, AND μWAVE
  AVHRR NDVI
  CLOUD DISTRIBUTION/RADIATION CHARACTERISTICS ([ISCCP]
  WATER VAPOR

- **GEOPHYSICAL DATA**

  HYDROLOGIC BOUNDARIES
  STREAMS
  TOPOGRAPHY
  SOILS
  VEGETATION
  LAND USE
  SNOW COVER
  ALBEDO

- **DERIVED DATA FIELDS**

  NMC GRID POINT INITIALIZATIONS
  PRECIPITATION (MERGED NEXRAD/SATELLITE/GROUND)
  OROGRAPHIC PRECIPITATION
  SOIL MOISTURE
  EVAPOTRANSPIRATION

- **IN-SITU**

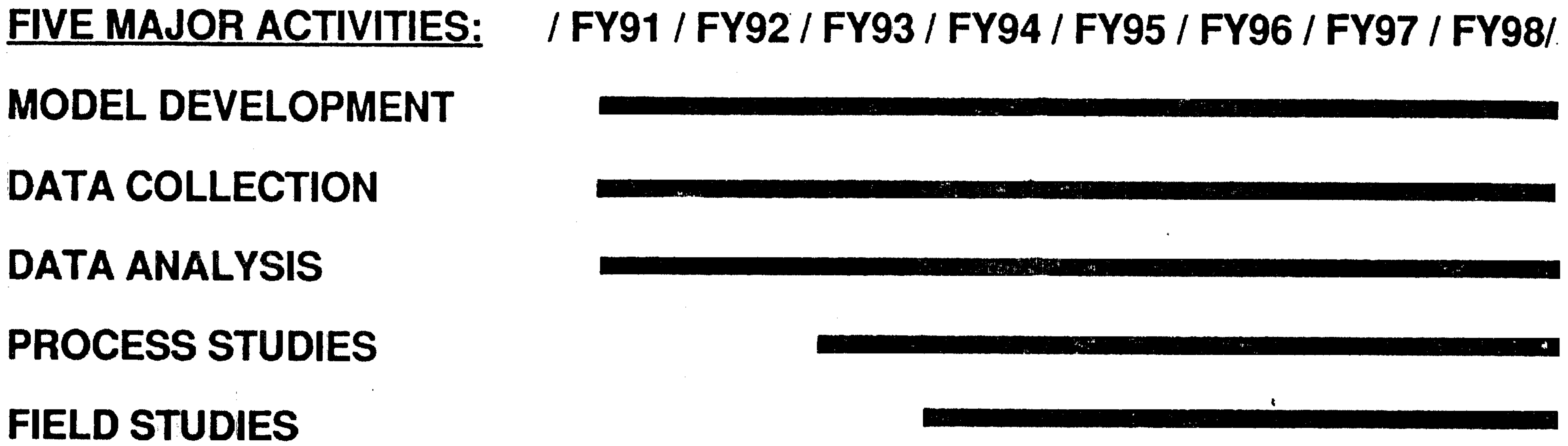
  RADIOSONDE
  SURFACE METEOROLOGICAL OBSERVATIONS (ASOS, ETC)
  SUPPLEMENTAL RAIN GAUGES
  WIND PROFILERS
  HYDROLOGIC OBSERVATIONS (RIVER RUNOFF, ETC)

POTENTIAL U.S. AGENCY INVOLVEMENT IN GCIP

	IN-SITU MEASUREMENTS	REMOTE MEASUREMENTS	MODELLING	DATA ARCHIVING
NASA	√	√	√	√
NOAA	√	√	√	√
NSF			√	
USGS	√		√	√
EPA	√		√	
DOE	√		√	
ARMY CORP OF ENG	√			√
BUREAU OF REC.	√			√
SOIL CONS. SERVICE	√		√	√
U.S. FOREST SERVICE	√			√
USDA	√		√	√

GLOBAL ENERGY AND WATER CYCLE EXPERIMENT
(GEWEX)

GCIP IMPLEMENTATION



FIVE MAJOR ACTIVITIES: / FY91 / FY92 / FY93 / FY94 / FY95 / FY96 / FY97 / FY98/

MODEL DEVELOPMENT

DATA COLLECTION

DATA ANALYSIS

PROCESS STUDIES

FIELD STUDIES

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Validating a Large Geophysical Data Set: Experiences with Satellite-Derived Cloud Parameters

Ralph Kahn, Robert D. Haskins, James E. Knighton,
Andrew Pursch, and Stephanie Granger-Gallegos
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract

We are validating the global cloud parameters derived from the satellite-borne HIRS2 and MSU atmospheric sounding instrument measurements, and are using the analysis of these data as one prototype for studying large geophysical data sets in general. The HIRS2/MSU data set contains a total of 40 physical parameters, filling 25 MB/day; raw HIRS2/MSU data are available for a period exceeding 10 years. Validation involves developing a quantitative sense for the physical meaning of the derived parameters over the range of environmental conditions sampled. This is accomplished by comparing the spatial and temporal distributions of the derived quantities with similar measurements made using other techniques, and with model results.

The data handling needed for this work is possible only with the help of a suite of interactive graphical and numerical analysis tools. Level 3 (gridded) data is the common form in which large data sets of this type are distributed for scientific analysis. We find that Level 3 data is inadequate for the data comparisons required for validation. Level 2 data (individual measurements in geophysical units) is needed. A sampling problem arises when individual measurements, which are not uniformly distributed in space or time, are used for the comparisons. Standard 'interpolation' methods involve fitting the measurements for each data set to surfaces, which are then compared. We are experimenting with formal criteria for selecting geographical regions, based upon the spatial frequency and variability of measurements, that allow us to quantify the uncertainty due to sampling. As part of this project, we are also dealing with ways to keep track of constraints placed on the output by assumptions made in the computer code. The need to work with Level 2 data introduces a number of other data handling issues, such as accessing data files across machine types, meeting large data storage requirements, accessing other validated data sets, processing speed and throughput for interactive graphical work, and problems relating to graphical interfaces.

KEY WORDS: large data sets, validation, satellite data analysis

1. Introduction

NASA's Earth Observing System (EOS) will generate vast quantities of data. Hundreds of terabytes of data will be acquired from orbit to characterize the Earth's environment with the kind of spatial and temporal detail needed to study climate change. Such high resolution is required to properly sample the non-linear impact of small-scale phenomena, which can make significant contributions to the global-scale budgets of heat and momentum. It is also expected that the data will be analyzed not just in the traditional manner, concentrating on a single data set at a time, but in new ways that involve routinely comparing data sets from multiple sources. Part of the need to study multiple data sets comes from a growing appreciation for the importance to global conditions of transports across boundaries such as the air-ocean interface (e.g., Earth System Science Committee, 1988).

We are undertaking the validation of cloud parameters derived from the High Resolution Infrared Radiation Sounder 2 (HIRS2) and the Microwave Sounding Unit (MSU) instruments aboard the NOAA polar orbiting meteorological satellites. The instruments provide one of the few global measures of cloud properties extending over many years. They are also capable of obtaining near-simultaneous constraints on the physical characteristics of the atmosphere and surface needed to derive cloud properties. One goal of this work is to learn about analyzing large geophysical data sets in general.

Radiances from the HIRS2 and MSU instruments have been analyzed by Susskind and co-workers using an algorithm that accounts self-consistently for the first-order physical quantities affecting the emergent radiation (Susskind et al., 1984; 1987). The standard data products are (1) monthly mean values for forty meteorological parameters, including effective cloud amount and effective cloud top height, on a grid of boxes 2 degrees in latitude by 2.5 degrees in longitude, and (2) 'daily data' with twice-daily temporal sampling, a spatial resolution of about 125 km, and spacing between points of about 250 km. The monthly mean data are referred to as a 'Level 3' (gridded) product, and the daily data is called a 'Level 2' product (individual measurements reduced to geophysical units) (Space Science Board, 1982; EOS Data Panel, 1986). The size of the uncompressed Level 3 data is about 4 MB/month, whereas the Level 2 product fills about 25 MB/day (750 MB/month).

By validation we mean 'developing a quantitative sense for the physical meaning of the measured parameters,' for the range of conditions under which they are acquired. Our approach involves: (1) identifying the assumptions made in deriving parameters from the measured radiances, (2) testing the input data and derived parameters for statistical error, sensitivity, and internal consistency, and (3) comparing with similar parameters obtained from other sources using other techniques. A study of this type was performed for sea surface temperature (Njoku, 1985), and our project is one of several parallel efforts currently underway to validate different cloud climatologies (e.g., Rossow et al., 1985; 1990). The validation effort we are undertaking introduces a number of problems that may be of interest to specialists in computational statistics, such as the INTERFACE community, as well as to those involved in research directly related to interpreting large geophysical data sets. This article summarizes the key data handling issues we have encountered.

2. The Need for 'Level 2' Data

Large geophysical data sets, such as cloud climatologies, are often distributed to researchers in gridded (Level 3) form. This can reduce the data volume by orders of magnitude relative to the parameter values for each individual sounding (Level 2), and provides the user with a 'spatially uniform' data product. For example, Figure 1A is the global, monthly-mean cloud amount map for July 1979 from the HIRS2/MSU data, in the original 2 degree by 2.5 degree averaging bins. All accepted cloud amount data from the individual atmospheric soundings that fell within each geographic box were summed, and mean and variance values for each box were calculated.

Several problems occur when using Level 3 products for validation. First, if only the Level 3 parameter values and associated variances are available, there is no way to assess how much of the reported variance is due to inherent non-uniformity of the parameter over the averaging region. Essentially, the instrument resolution is degraded to a scale comparable to the box size, and information originally acquired to measure smaller-scale phenomena in both the spatial and temporal domains is lost. For example, in a 2 by 2.5 degree box, the surface temperature may exhibit random fluctuations of half a degree and may change systematically by several degrees, whereas the box average variance will assign all the variability to random error.

We encountered a second problem when making comparisons among Level 3 products with different gridding schemes. The best concurrent cloud climatology available for comparison with the data in Figure 1A was derived from the Temperature Humidity Infrared Radiometer/Total Ozone Mapping Spectrometer (THIR/TOMS) on the NASA Nimbus 7 satellite (Stowe et al., 1988; 1989). The standard THIR/TOMS Level 3 data product was binned according to a global 500 by 500 km grid that is also used for Earth radiation budget studies. The July 1979 HIRS2/MSU Level 3 data, degraded using area-weighted averaging to the THIR/TOMS spatial grid, is shown in Figure 1B. We then resampled the degraded HIRS2/MSU data back to the 2 by 2.5 degree grid, and subtracted it from the original HIRS2/MSU data (Figure 1C). Note that the differences are nearly as large as the range of the signal, with both positive and negative values. The pattern of differences varies with the location of edges in the original data, and is modulated by the relative position of grid boundaries. Differences are especially large at high latitudes, where the spatial resolution of the THIR/TOMS grid is much lower than that of the HIRS2/MSU grid, and wherever there are sharp edges generated by cloud patterns, such as in the intertropical convergence zone and monsoon areas.

With the Level 2 products, we have access to physical quantities at the full resolution acquired by the instruments, and avoid introducing additional artifacts into the comparison between data sets. Level 2 data are not uniformly distributed over the surface. At low latitudes there are gores in the HIRS2 sampling between orbits, whereas at high latitudes, the surface is heavily oversampled. Data dropouts and calibration lines occur at all latitudes. The sample resolution changes by more than a factor of 2 from nadir to the limits of each scan. As a first step toward making comparisons among Level 2 data sets, surfaces that take account of non-uniform clustering of data points may be fit to the data. We have begun experimenting with locally adaptive surface fitting techniques (e.g., Renka, 1988), and are exploring the use of methods that generate variance surfaces together with each fitted surface (Cresse, 1989, and references therein).

Binning, which is traditionally used to make comparisons among global data sets, is performed as an automatic procedure. In using Level 2 data for validating data sets, geographic sub-regions of the globe must be selected for surface fitting, based upon some criterion that evaluates the density of points relative to the size of local gradients of the parameter field, possibly in several directions. Figure 2 illustrates the role of interactive geographic subset selection a part of the software we are assembling to perform the HIRS2/MSU validation. 'HDF' in this figure refers to Hierarchical Data Format, a transportable file format that eliminates all but an initial file conversion for exchanging data among DEC, Sun, MacIntosh, and other machines used in the validation (NCSA Software Tools Group, 1990).

This allows us to store single copies of data files on centrally located disks, that are accessible across the network to machines with differing architectures. We are currently investigating the criteria for accepting subsets, choice of method for surface fitting, and methods for making formal comparisons among surfaces fitted to data from different sources. The important question of interpolation in the temporal domain we set aside for the present.

To summarize: in spite of the much larger volume of the Level 2 data, relative to Level 3, and the collection of issues related to the spatial and temporal sampling of Level 2 data, we need the ability to access, store, and process Level 2 data for (1) studies of the internal consistency and precision of the data set and (2) comparisons with other cloud climatologies, that are involved in the validation of the HIRS2/MSU cloud parameters. We anticipate that similar needs will arise for interdisciplinary process studies, and in work directed toward using observations to better understand mesoscale climatological phenomena.

3. Tracking Assumptions in the Code

Another issue that bears upon the degree to which we may perform validation, and other scientific analysis on large data sets, is our ability to grasp the collection of constraints imposed on parameter values by the code that generates them. An assumption embedded in a large data handling code may produce results that hide important information in the data, or may produce patterns in the data that could be incorrectly interpreted as scientifically meaningful.

We are experimenting with methods of charting the collection of assumptions, as a way of calling the attention of the user to areas where the code may influence the output parameters. We are using standard charting symbols as much as possible (e.g., Yourdon and Constantine, 1979). An example of this type of chart is Figure 3. This shows the flow of control and the flow of assumptions made in a relatively small part of the HIRS2/MSU analysis code that produces Level 3 data from Level 2 products. This chart made clear the number and complexity of the assumptions involved in generating Level 3 products, and it played a role in our assessment of the value of Level 3 data for the validation exercise.

Charting the flow of control provides a needed context for the constraints placed on the data. These charts take a step in the direction of making it *possible* to keep track of assumptions, but they do not eliminate the work involved in carefully assessing the meaning of derived parameters.

4. Conclusions

The HIRS2/MSU cloud parameter validation effort raises a number of data handling issues that are likely to arise frequently when scientific analysis is attempted on large geophysical data sets. We need Level 2 data (individual measurements in geophysical units) (A) to perform comparisons among data sets with different sampling, and (B) to understand the effects of spatial and temporal sampling on the 'average' values obtained from a single data set. The need for Level 2 data severely complicates data handling. Among the areas where advances would be most helpful are:

1. Surface fitting software for data distributed non-uniformly in 2-dimensional space, and ways to obtain some measure of the associated variances.

2. Software for making formal comparisons among fitted surfaces from several sources, and their associated variance surfaces.

3. Ways of documenting software and data files so they may be exchanged and used by others easily.

4. Ways of documenting the assumptions embedded in retrieval and processing algorithms, so a researcher studying the data products can grasp the collection of constraints placed on the output data by the code.

5. Additional ways of storing data. For a given Level 2 data product, we need readily accessible data storage capacity of between one and two *orders of magnitude* the size of the basic data set, for intermediate and derived products that are created as part of the validation.

Several longer-term needs include:

6. The development of validation procedures that are easy enough to apply so that it will be feasible to generate and access a large number of validated geophysical data sets for interdisciplinary studies of all types.

7. Ways of fitting surfaces to data values distributed non-uniformly in 2-dimensional space and in time, and obtaining a measure of the associated variances.

8. Better ways of discovering patterns and surprises in high-dimensional data sets.

9. Ways of fitting hyper-surfaces to higher dimensional data sets, and techniques for studying them.

We have described our data, the collection of problems we are facing in the validation work, and our approaches to some of these issues. Solutions or partial solutions may exist to some of the problems that are not widely known outside specialized data handling and computational statistics communities. We hope to stimulate experts in these fields to participate in the effort to improve our understanding of Earth through the study of large, geophysical data sets.

Acknowledgments

We thank Paul Tukey for inviting us to participate in the INTERFACE 91 conference, and Daniel Carr, Jeff Dozier, Mike Freilich, Wes Nicholson, Bill Rossow, Victor Zlotnicki, and Richard Zurek for stimulating discussions on many aspects of this work. This project is supported in part by the NASA Earth Sciences Interdisciplinary Program in the Earth Science and Applications Division, and by the Jet Propulsion Laboratory Director's Discretionary Fund. The work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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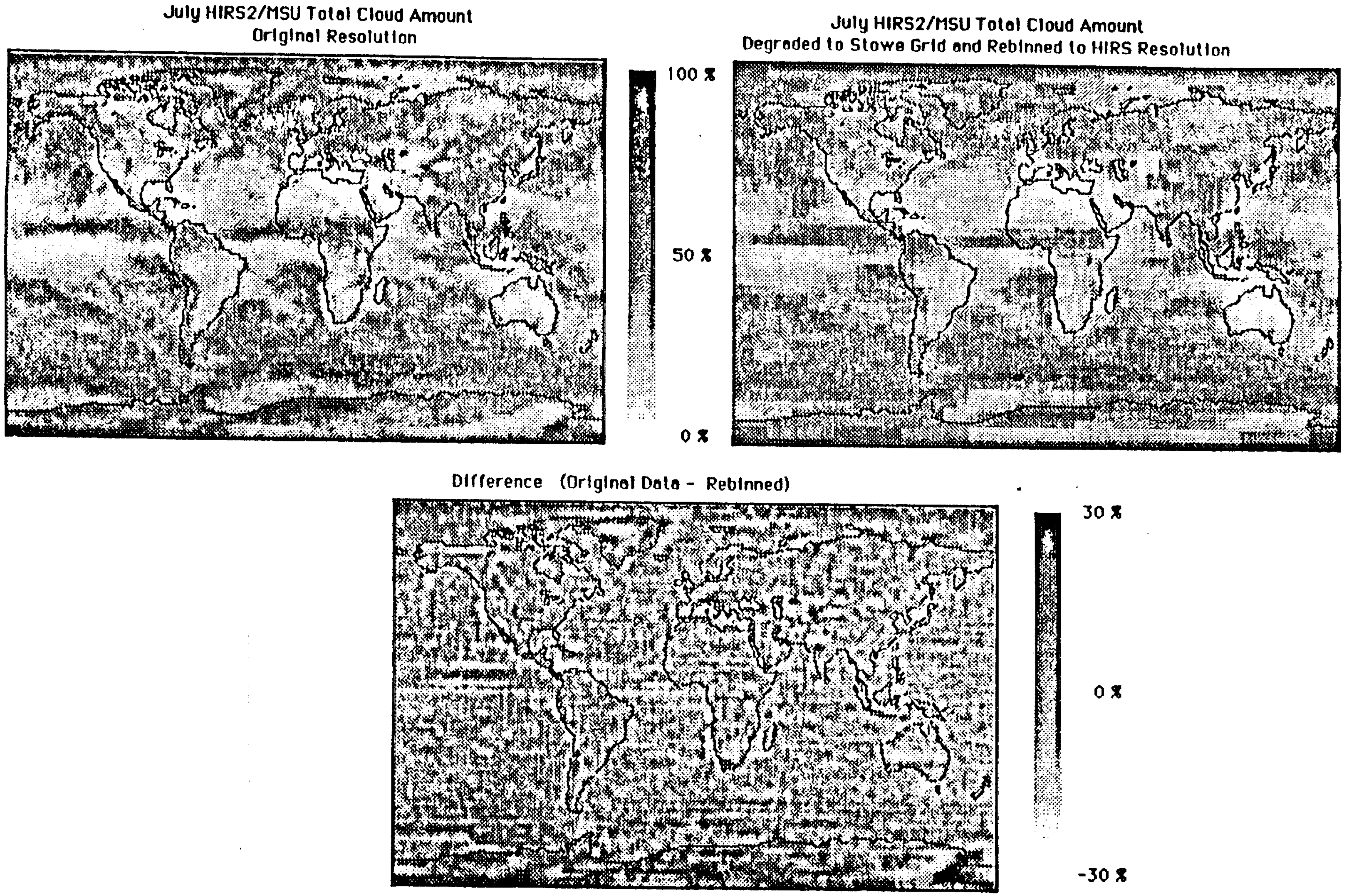

July HIRS2/MSU Total Cloud Amount
Original Resolution

July HIRS2/MSU Total Cloud Amount
Degraded to Stowe Grid and Rebinned to HIRS Resolution

Difference (Original Data - Rebinned)

Figure 1. The Effect of Rebinning on Global Cloud Amount

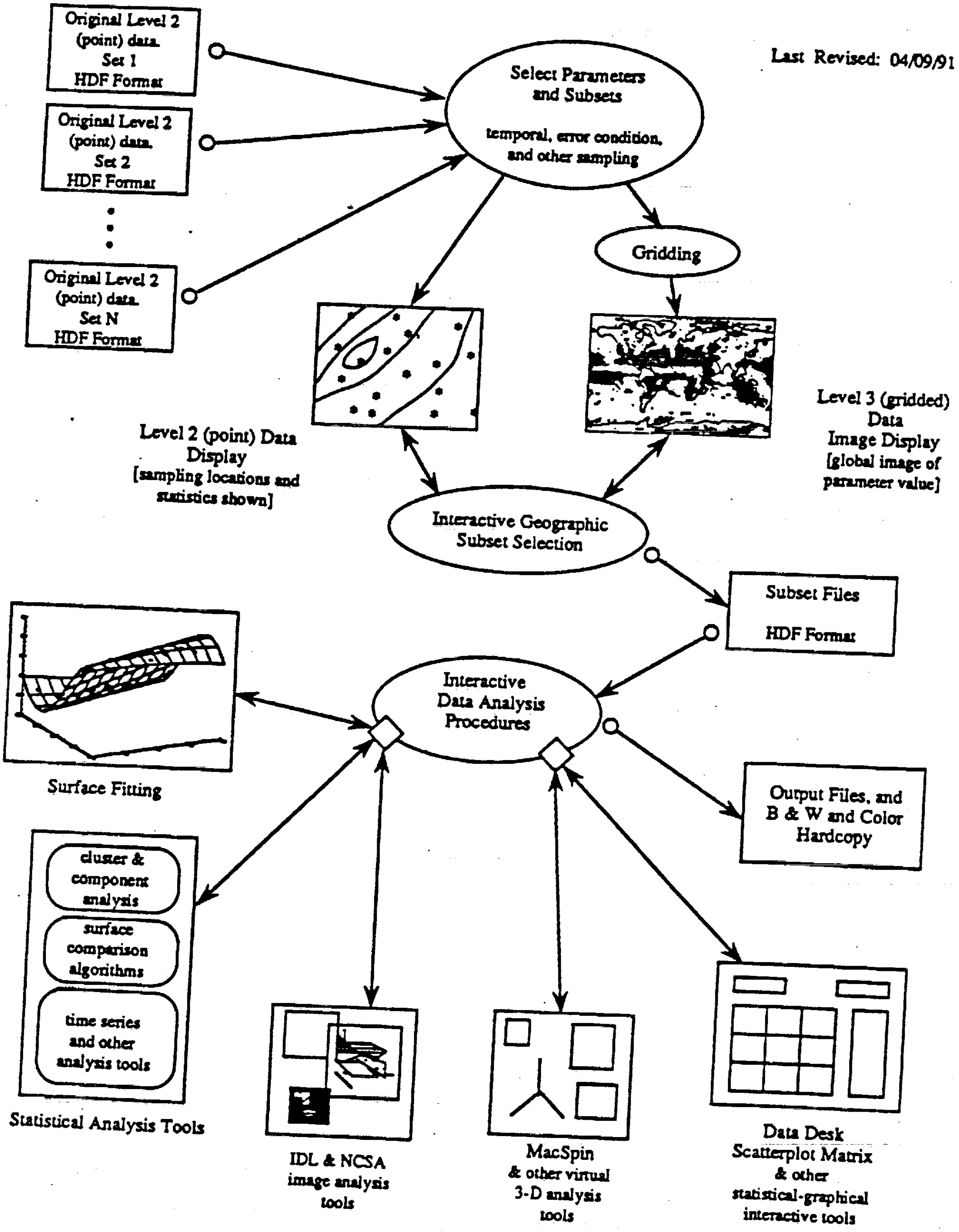

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Figure 2. Level 2 Data Analysis Software

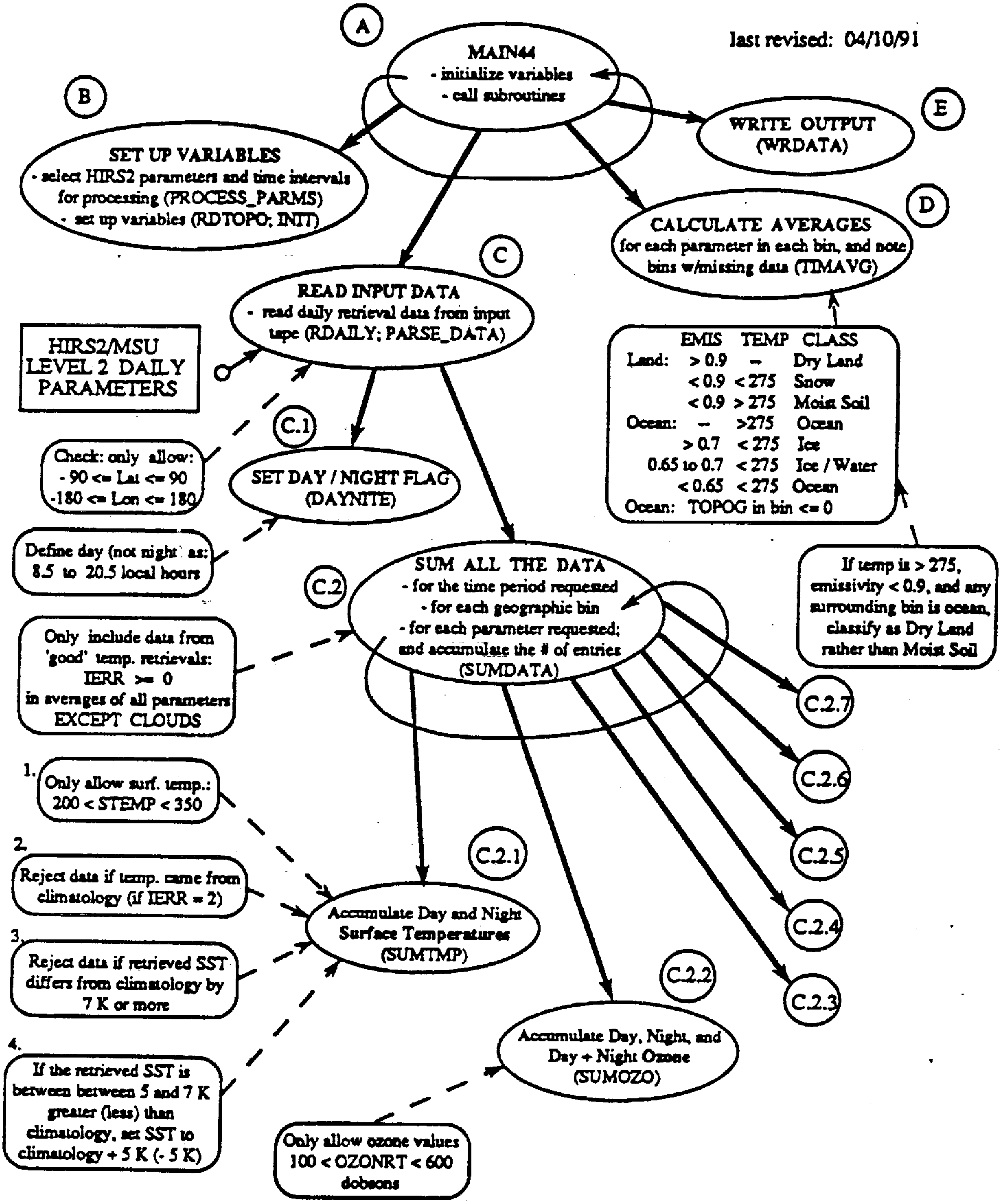

Figure 3. HIRS2 Level 2 to 3 Software Overview / Assumptions

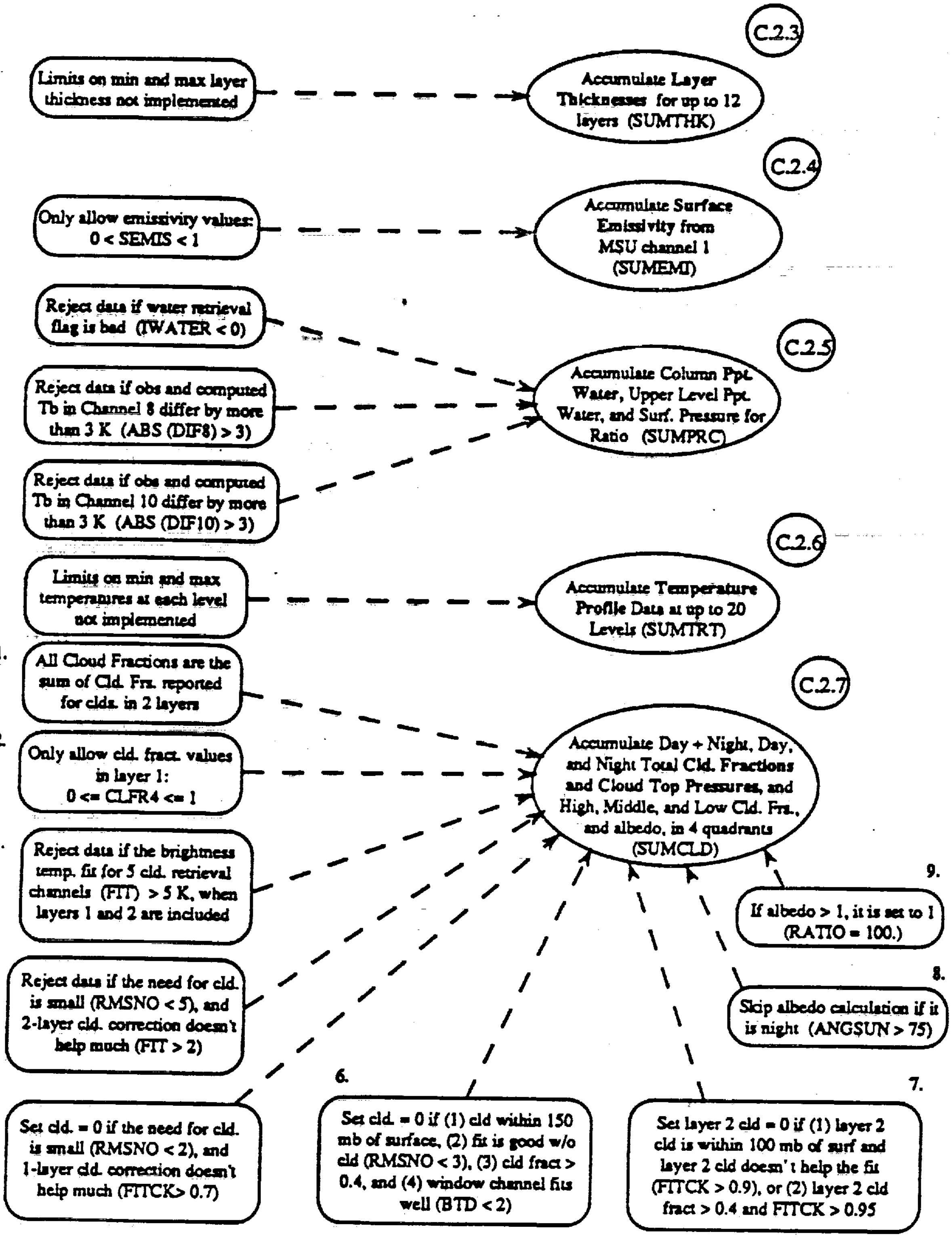

Figure 3. HIRS2 Level 2 to 3 Software Overview (Continued)

R. Kahn
April, 1992

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Experience of the JPL Exploratory Data Analysis Team at Validating HIRS2/MSU Cloud Parameters

Ralph Kahn, Robert Haskins,
Stephanie Granger-Gallegos, and Andy Pursch

Jet Propulsion Laboratory, California Institute of Technology

and

Anthony Del Genio

Goddard Institute for Space Studies

Where We Began:

The Cloud/Climate Feedback Problem

Key Measurements Addressing the Cloud-Climate Feedback Problem

Microphysical parameters:

1. $\beta = d(\ln m) / dT$ — dependence of cloud water (liquid and ice) content on temperature (including liquid to solid transition temperature and small ice particle concentrations)

2. $\gamma = d(\ln \tau) / dT$ — dependence of cloud opacity on temperature (implicitly, dr / dm; dr / dT)

Cloud properties:

3. $n(q, w, T)$ — dependence of cloud amount on relative humidity, vertical velocity, temp., and other environmental parameters

4. cloud top height dependence on temperature, relative humidity, vertical velocity, and and other environmental parameters

5. variability in cloud behavior (diurnal, seasonal, interannual; land & ocean)

Cloud-related processes:

6. distinguish T from dynamical effects on clouds (sign & size of feedbacks)

7. determine large-scale conditions for formation and breakup of marine stratocumulus (Cloud Top Entrainment Instability)

8. determine the relationship between deep convection and upper troposphere water

SENSITIVITY OF DERIVED EFFECTIVE CLOUD AMOUNT TO SURFACE TEMPERATURE

$$\left.\frac{\partial N}{\partial T_s}\right|_{p_c} = \frac{\varepsilon_s\, e^{-t_0}\,(1 - N)\,\dfrac{\partial B_\nu(T_s)}{\partial T_s}}{\varepsilon_s\, B_\nu(T_s)\, e^{-t_0} + R_s\, e^{-t_0} + \displaystyle\int_{t_1}^{t_0} B_\nu(T')\, e^{-t'} dt' - B_\nu(T_c)\, e^{-t_1}}$$

On the right side, the terms in the denominator account for:

(1) direct radiation from the surface

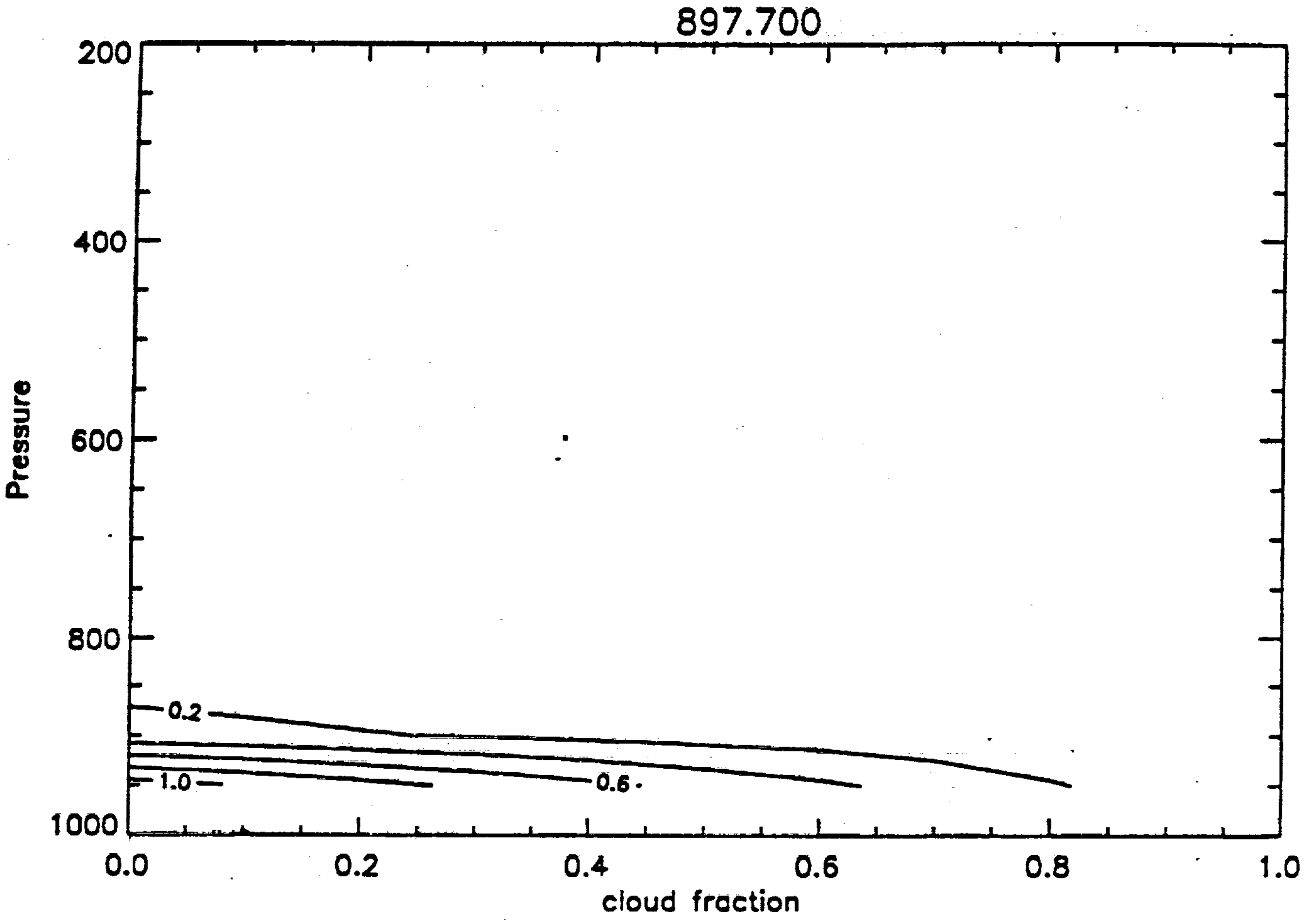
(2) solar radiation reflected by the surface

(3) emission of the atmosphere below the cloud level

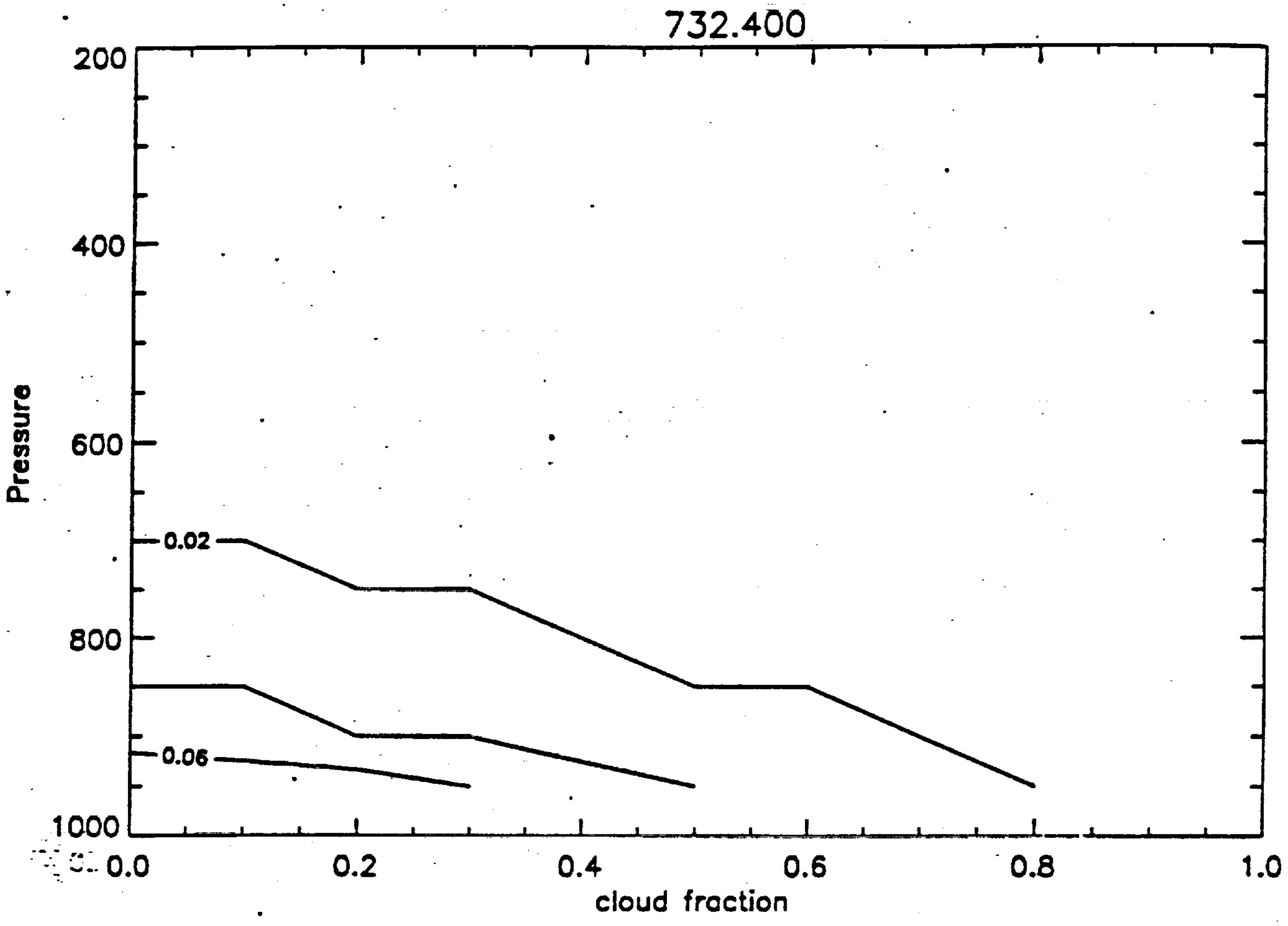
(4) emission from the cloud surface.

The terms are wavelength dependent

The derived cloud amount is less sensitive to surface temperature for higher clouds. This occurs because as the cloud elevation increases, the difference between T_S and T_C increases, so only a small change in cloud amount is needed to effect a large change in radiance at the detector.



$\frac{\partial N}{\partial T_s}\Big|_{p_c}$ [window channel]



$\frac{\partial N}{\partial T_s}\Big|_{p_c}$ [725mb peak channel]

Definition of Validation

By **'Validation'**, we mean **'developing a quantitative sense for the physical meaning of the measured parameters'**, by:

(1) identifying the **assumptions** involved in deriving parameters from the measured radiances

(2) **testing the input** data and derived parameters for statistical error, sensitivity, and internal consistency

(3) **comparing with similar parameters** obtained from other sources using other techniques

Identifying the Assumptions

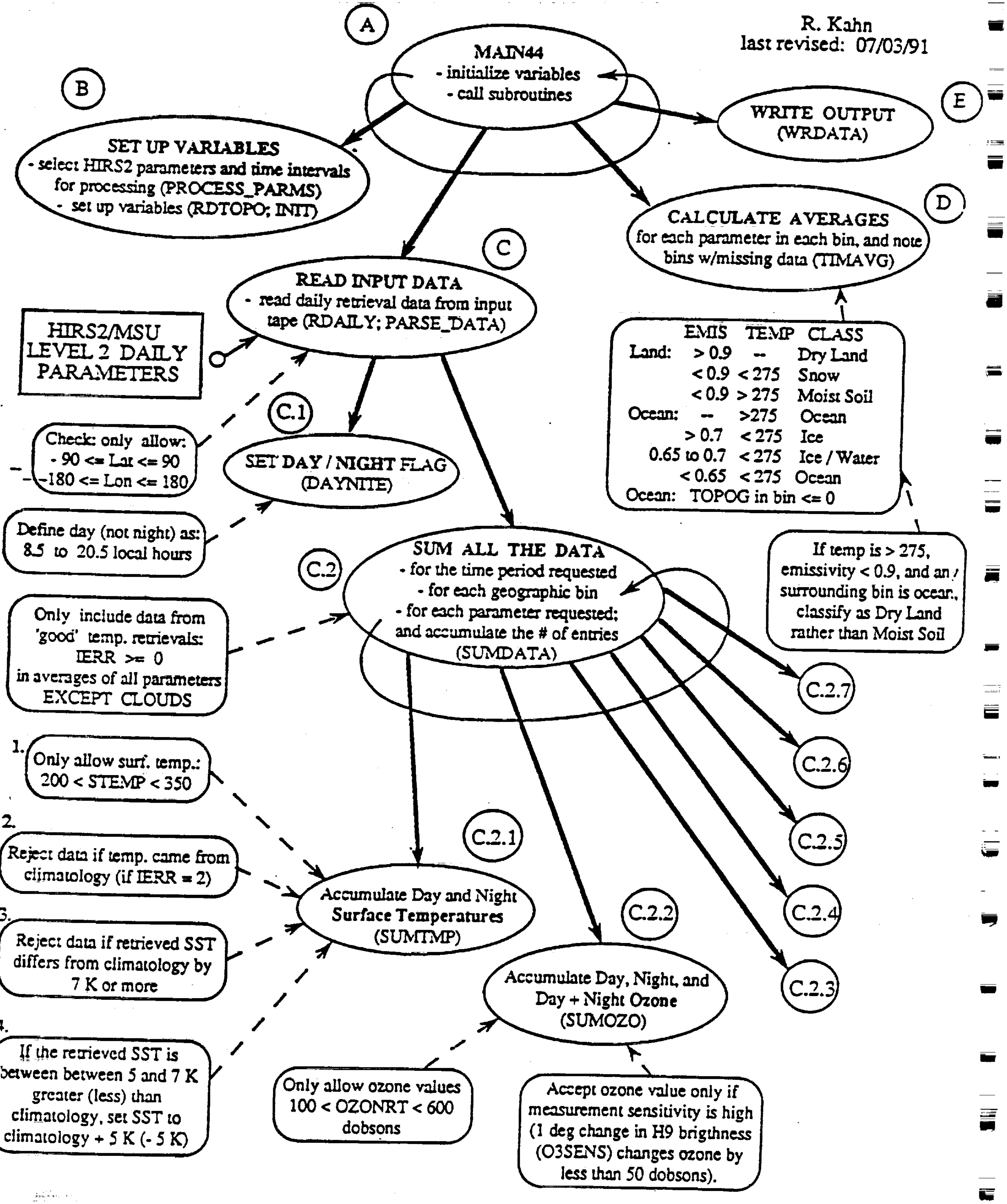
-- in the **Measurements** (instrument, technique)

-- in the **Algorithm** (retrieval equations)

-- in the **Code** ('if' statements)

GSFC HIRS2 Level 2 to 3 Software Overview / Assumptions

R. Kahn
last revised: 07/03/91



Check: only allow:
- 90 <= Lat <= 90
-180 <= Lon <= 180

Define day (not night) as:
8.5 to 20.5 local hours

Only include data from 'good' temp. retrievals:
IERR >= 0
in averages of all parameters EXCEPT CLOUDS

1. Only allow surf. temp.: 200 < STEMP < 350

2. Reject data if temp. came from climatology (if IERR = 2)

3. Reject data if retrieved SST differs from climatology by 7 K or more

4. If the retrieved SST is between between 5 and 7 K greater (less) than climatology, set SST to climatology + 5 K (- 5 K)

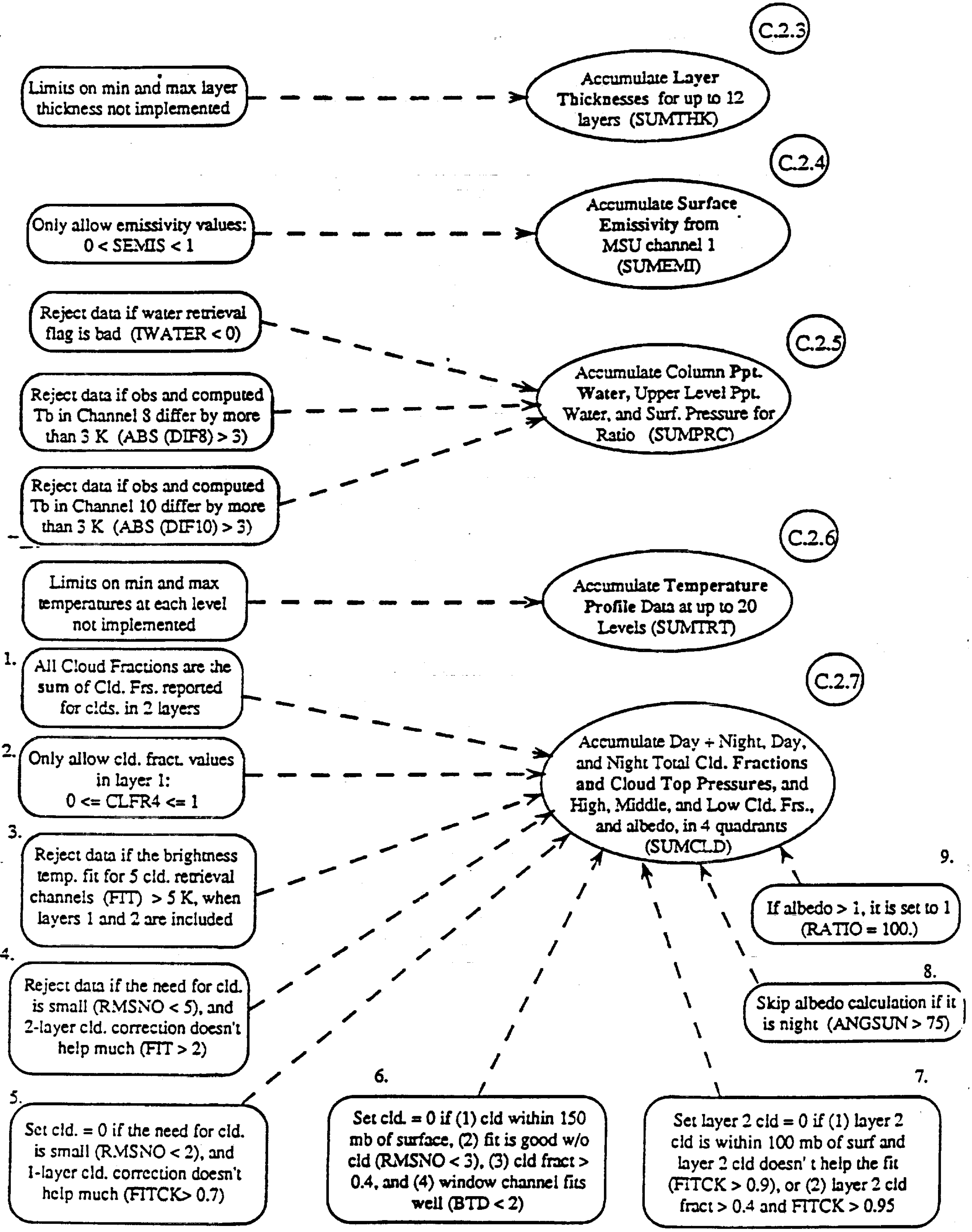
Only allow ozone values 100 < OZONRT < 600 dobsons

Accept ozone value only if measurement sensitivity is high (1 deg change in H9 brigthness (O3SENS) changes ozone by less than 50 dobsons).

	EMIS	TEMP	CLASS
Land:	> 0.9	--	Dry Land
	< 0.9	< 275	Snow
	< 0.9	> 275	Moist Soil
Ocean:	--	>275	Ocean
	> 0.7	< 275	Ice
	0.65 to 0.7	< 275	Ice / Water
	< 0.65	< 275	Ocean

Ocean: TOPOG in bin <= 0

If temp is > 275, emissivity < 0.9, and an surrounding bin is ocean, classify as Dry Land rather than Moist Soil


C.2.3
Limits on min and max layer thickness not implemented
Accumulate Layer Thicknesses for up to 12 layers (SUMTHK)
C.2.4
Only allow emissivity values: 0 < SEMIS < 1
Accumulate Surface Emissivity from MSU channel 1 (SUMEMI)
Reject data if water retrieval flag is bad (IWATER < 0)
Reject data if obs and computed Tb in Channel 8 differ by more than 3 K (ABS (DIF8) > 3)
Reject data if obs and computed Tb in Channel 10 differ by more than 3 K (ABS (DIF10) > 3)
C.2.5
Accumulate Column Ppt. Water, Upper Level Ppt. Water, and Surf. Pressure for Ratio (SUMPRC)
C.2.6
Limits on min and max temperatures at each level not implemented
Accumulate Temperature Profile Data at up to 20 Levels (SUMTRT)
C.2.7
1. All Cloud Fractions are the sum of Cld. Frs. reported for clds. in 2 layers
2. Only allow cld. fract. values in layer 1: 0 <= CLFR4 <= 1
3. Reject data if the brightness temp. fit for 5 cld. retrieval channels (FIT) > 5 K, when layers 1 and 2 are included
4. Reject data if the need for cld. is small (RMSNO < 5), and 2-layer cld. correction doesn't help much (FIT > 2)
5. Set cld. = 0 if the need for cld. is small (RMSNO < 2), and 1-layer cld. correction doesn't help much (FITCK> 0.7)
Accumulate Day + Night, Day, and Night Total Cld. Fractions and Cloud Top Pressures, and High, Middle, and Low Cld. Frs., and albedo, in 4 quadrants (SUMCLD)
6. Set cld. = 0 if (1) cld within 150 mb of surface, (2) fit is good w/o cld (RMSNO < 3), (3) cld fract > 0.4, and (4) window channel fits well (BTD < 2)
7. Set layer 2 cld = 0 if (1) layer 2 cld is within 100 mb of surf and layer 2 cld doesn't help the fit (FITCK > 0.9), or (2) layer 2 cld fract > 0.4 and FITCK > 0.95
8. Skip albedo calculation if it is night (ANGSUN > 75)
9. If albedo > 1, it is set to 1 (RATIO = 100.)

HIRS2/MSU PHYSICAL RETRIEVAL:
OVERVIEW of CLOUD PARAMETER DERIVATION

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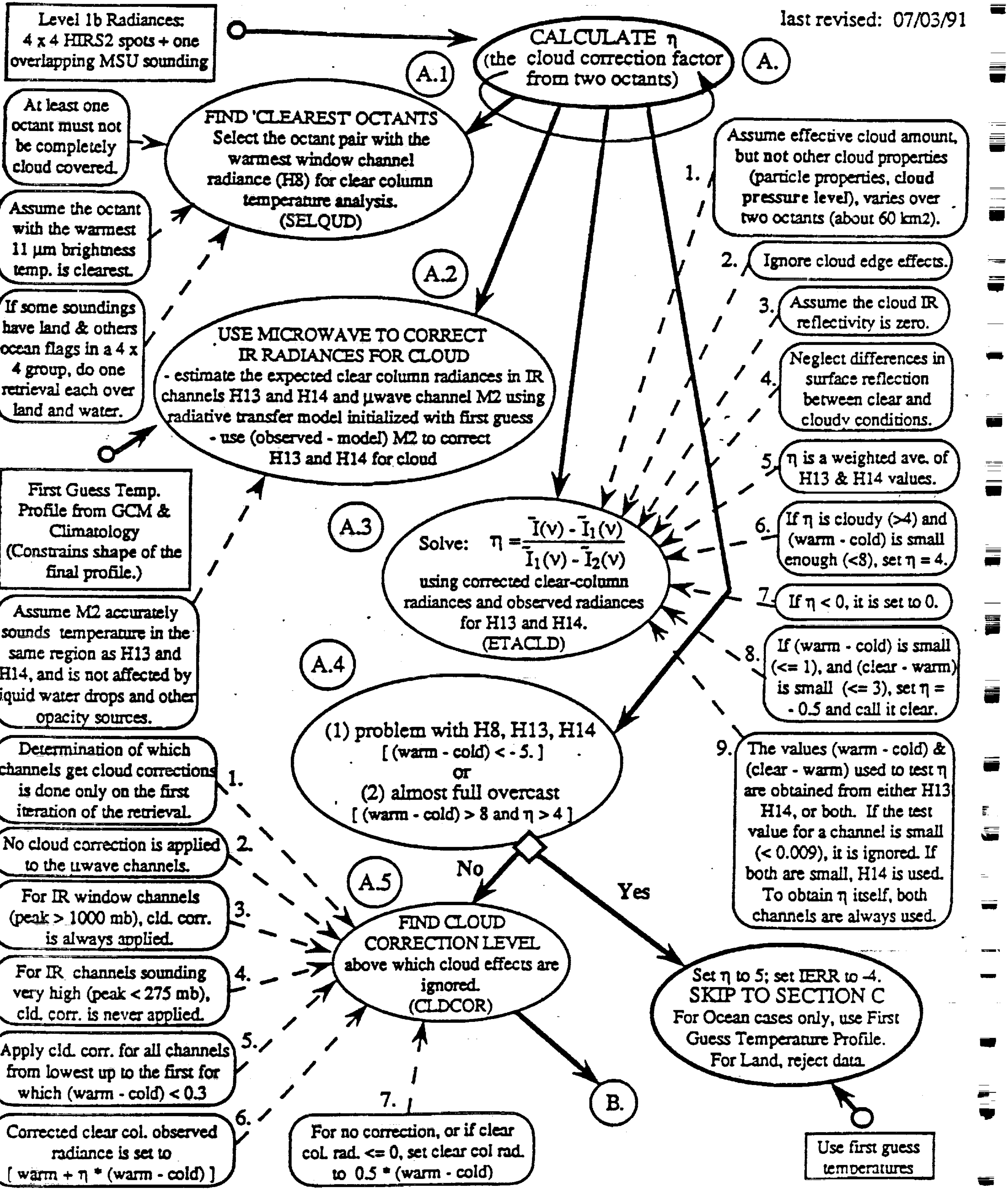


Level 1b Radiances: 4 x 4 HIRS2 spots + one overlapping MSU sounding

(A.) CALCULATE η (the cloud correction factor from two octants)

(A.1) FIND 'CLEAREST' OCTANTS Select the octant pair with the warmest window channel radiance (H8) for clear column temperature analysis. (SELQUD)

At least one octant must not be completely cloud covered.

Assume the octant with the warmest 11 μm brightness temp. is clearest.

If some soundings have land & others ocean flags in a 4 x 4 group, do one retrieval each over land and water.

(A.2) USE MICROWAVE TO CORRECT IR RADIANCES FOR CLOUD
- estimate the expected clear column radiances in IR channels H13 and H14 and μwave channel M2 using radiative transfer model initialized with first guess
- use (observed - model) M2 to correct H13 and H14 for cloud

First Guess Temp. Profile from GCM & Climatology (Constrains shape of the final profile.)

Assume M2 accurately sounds temperature in the same region as H13 and H14, and is not affected by iquid water drops and other opacity sources.

(A.3) Solve: $\eta = \dfrac{\bar{I}(\nu) - \bar{I}_1(\nu)}{\bar{I}_1(\nu) - \bar{I}_2(\nu)}$ using corrected clear-column radiances and observed radiances for H13 and H14. (ETACLD)

1. Assume effective cloud amount, but not other cloud properties (particle properties, cloud pressure level), varies over two octants (about 60 km2).
2. Ignore cloud edge effects.
3. Assume the cloud IR reflectivity is zero.
4. Neglect differences in surface reflection between clear and cloudy conditions.
5. η is a weighted ave. of H13 & H14 values.
6. If η is cloudy (>4) and (warm - cold) is small enough (<8), set η = 4.
7. If η < 0, it is set to 0.
8. If (warm - cold) is small (<= 1), and (clear - warm) is small (<= 3), set η = - 0.5 and call it clear.
9. The values (warm - cold) & (clear - warm) used to test η are obtained from either H13 H14, or both. If the test value for a channel is small (< 0.009), it is ignored. If both are small, H14 is used. To obtain η itself, both channels are always used.

(A.4) (1) problem with H8, H13, H14 [(warm - cold) < - 5.] or (2) almost full overcast [(warm - cold) > 8 and η > 4]

Yes

Set η to 5; set IERR to -4. SKIP TO SECTION C For Ocean cases only, use First Guess Temperature Profile. For Land, reject data.

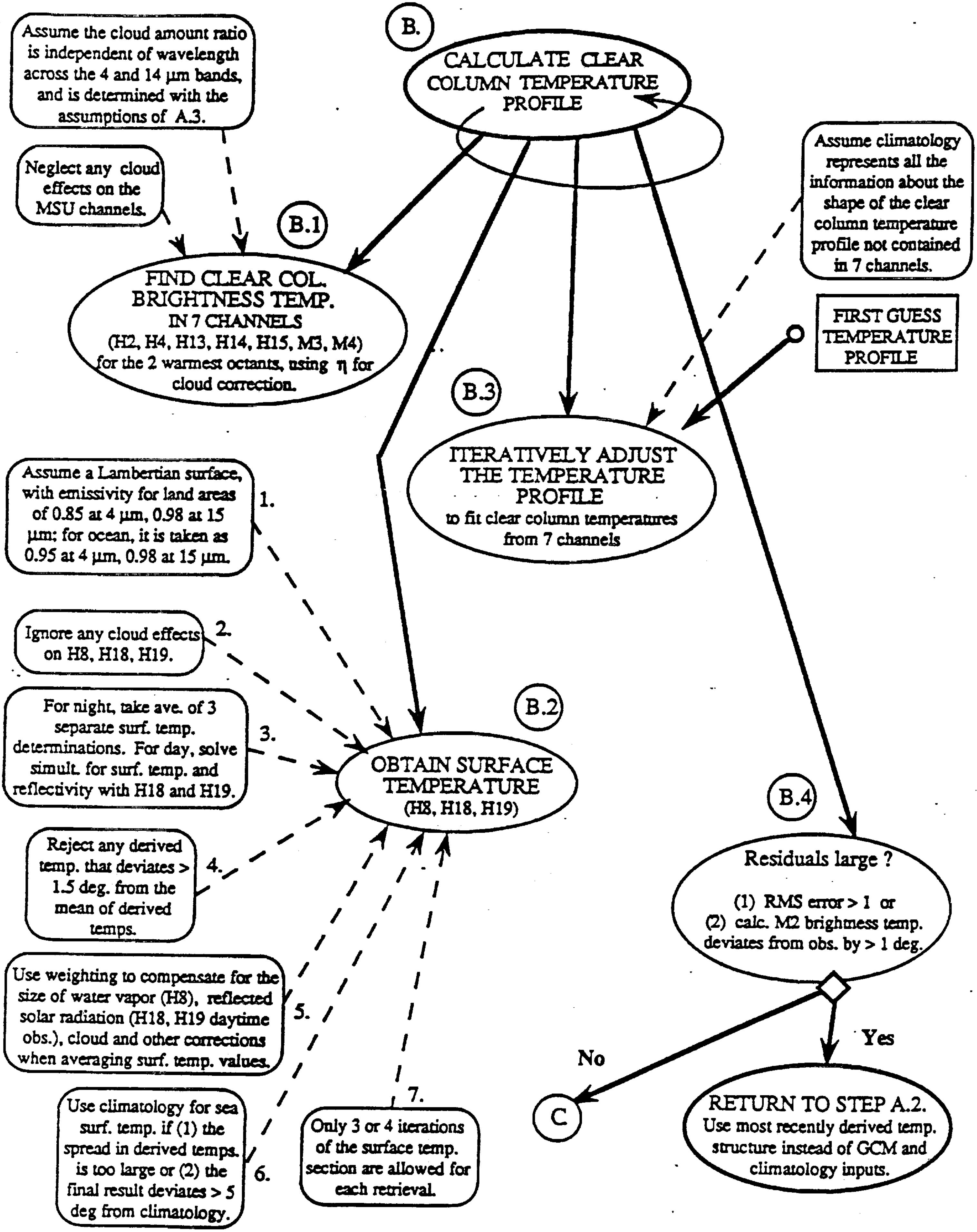
Use first guess temperatures

No

(A.5) FIND CLOUD CORRECTION LEVEL above which cloud effects are ignored. (CLDCOR)

1. Determination of which channels get cloud corrections is done only on the first iteration of the retrieval.
2. No cloud correction is applied to the μwave channels.
3. For IR window channels (peak > 1000 mb), cld. corr. is always applied.
4. For IR channels sounding very high (peak < 275 mb), cld. corr. is never applied.
5. Apply cld. corr. for all channels from lowest up to the first for which (warm - cold) < 0.3
6. Corrected clear col. observed radiance is set to [warm + η * (warm - cold)]
7. For no correction, or if clear col. rad. <= 0, set clear col rad. to 0.5 * (warm - cold)

(B.)



CALCULATE CLEAR COLUMN TEMPERATURE PROFILE

Assume the cloud amount ratio is independent of wavelength across the 4 and 14 µm bands, and is determined with the assumptions of A.3.

Neglect any cloud effects on the MSU channels.

FIND CLEAR COL. BRIGHTNESS TEMP. IN 7 CHANNELS (H2, H4, H13, H14, H15, M3, M4) for the 2 warmest octants, using η for cloud correction.

Assume climatology represents all the information about the shape of the clear column temperature profile not contained in 7 channels.

FIRST GUESS TEMPERATURE PROFILE

ITERATIVELY ADJUST THE TEMPERATURE PROFILE to fit clear column temperatures from 7 channels

1. Assume a Lambertian surface, with emissivity for land areas of 0.85 at 4 µm, 0.98 at 15 µm; for ocean, it is taken as 0.95 at 4 µm, 0.98 at 15 µm.

2. Ignore any cloud effects on H8, H18, H19.

3. For night, take ave. of 3 separate surf. temp. determinations. For day, solve simult. for surf. temp. and reflectivity with H18 and H19.

4. Reject any derived temp. that deviates > 1.5 deg. from the mean of derived temps.

5. Use weighting to compensate for the size of water vapor (H8), reflected solar radiation (H18, H19 daytime obs.), cloud and other corrections when averaging surf. temp. values.

6. Use climatology for sea surf. temp. if (1) the spread in derived temps. is too large or (2) the final result deviates > 5 deg from climatology.

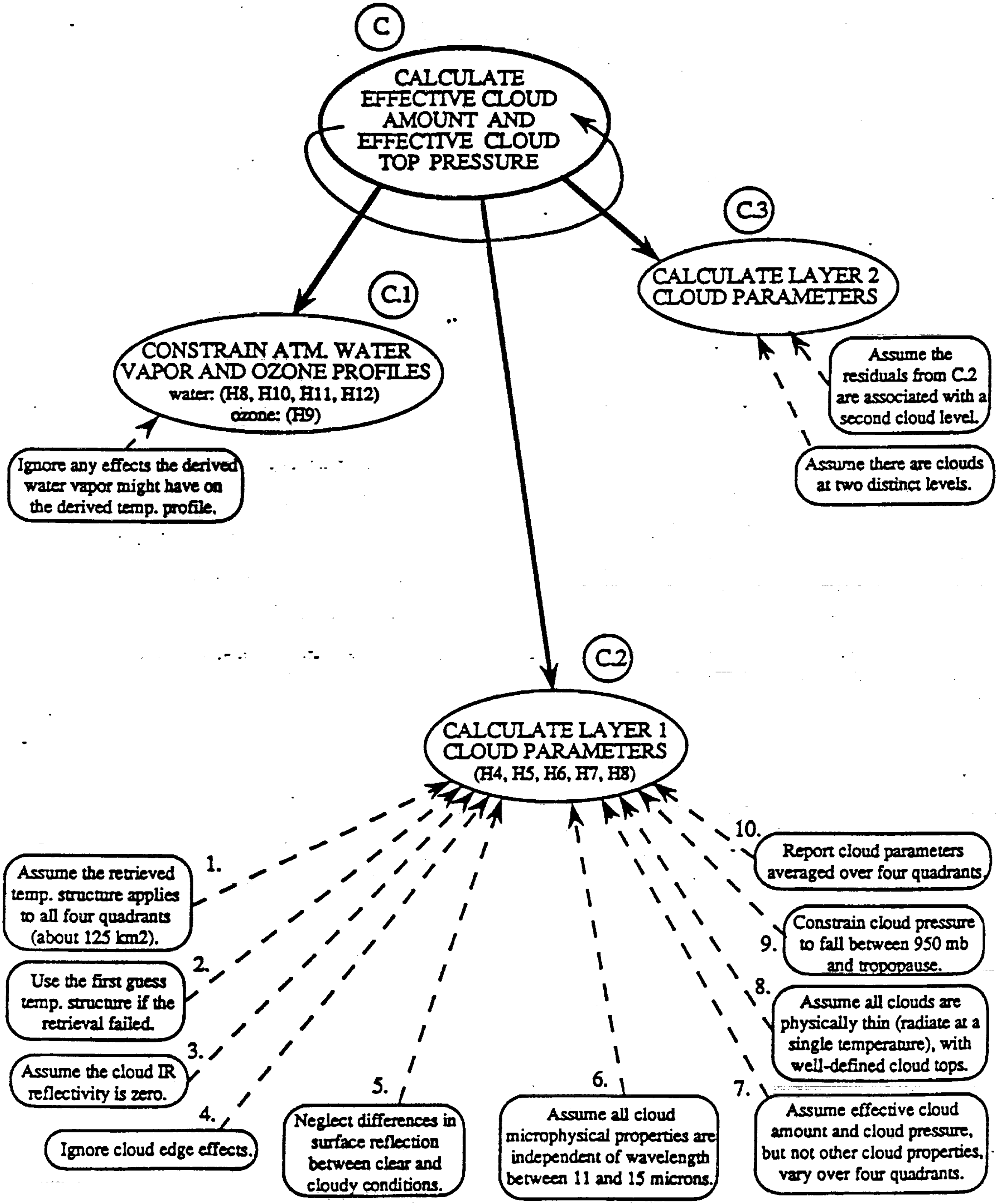
7. Only 3 or 4 iterations of the surface temp. section are allowed for each retrieval.

OBTAIN SURFACE TEMPERATURE (H8, H18, H19)

Residuals large ?

(1) RMS error > 1 or
(2) calc. M2 brightness temp. deviates from obs. by > 1 deg.

RETURN TO STEP A.2. Use most recently derived temp. structure instead of GCM and climatology inputs.


C
CALCULATE EFFECTIVE CLOUD AMOUNT AND EFFECTIVE CLOUD TOP PRESSURE
C.1
CONSTRAIN ATM. WATER VAPOR AND OZONE PROFILES
water: (H8, H10, H11, H12)
ozone: (H9)
Ignore any effects the derived water vapor might have on the derived temp. profile.
C.3
CALCULATE LAYER 2 CLOUD PARAMETERS
Assume the residuals from C.2 are associated with a second cloud level.
Assume there are clouds at two distinct levels.
C.2
CALCULATE LAYER 1 CLOUD PARAMETERS
(H4, H5, H6, H7, H8)
1.
Assume the retrieved temp. structure applies to all four quadrants (about 125 km2).
2.
Use the first guess temp. structure if the retrieval failed.
3.
Assume the cloud IR reflectivity is zero.
4.
Ignore cloud edge effects.
5.
Neglect differences in surface reflection between clear and cloudy conditions.
6.
Assume all cloud microphysical properties are independent of wavelength between 11 and 15 microns.
7.
Assume effective cloud amount and cloud pressure, but not other cloud properties, vary over four quadrants.
8.
Assume all clouds are physically thin (radiate at a single temperature), with well-defined cloud tops.
9.
Constrain cloud pressure to fall between 950 mb and tropopause.
10.
Report cloud parameters averaged over four quadrants.

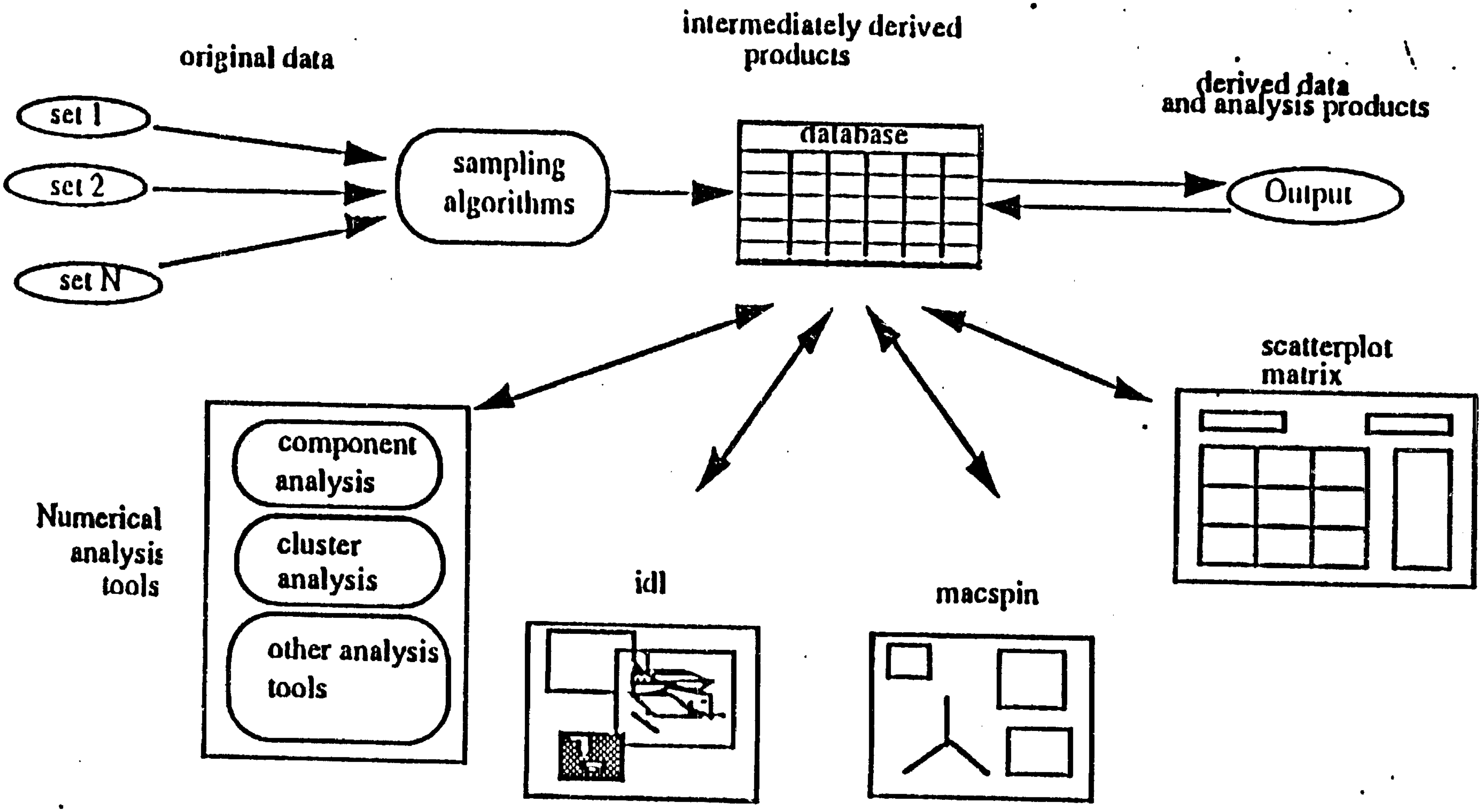


Figure 3. Interactive Data Extraction and Analysis System

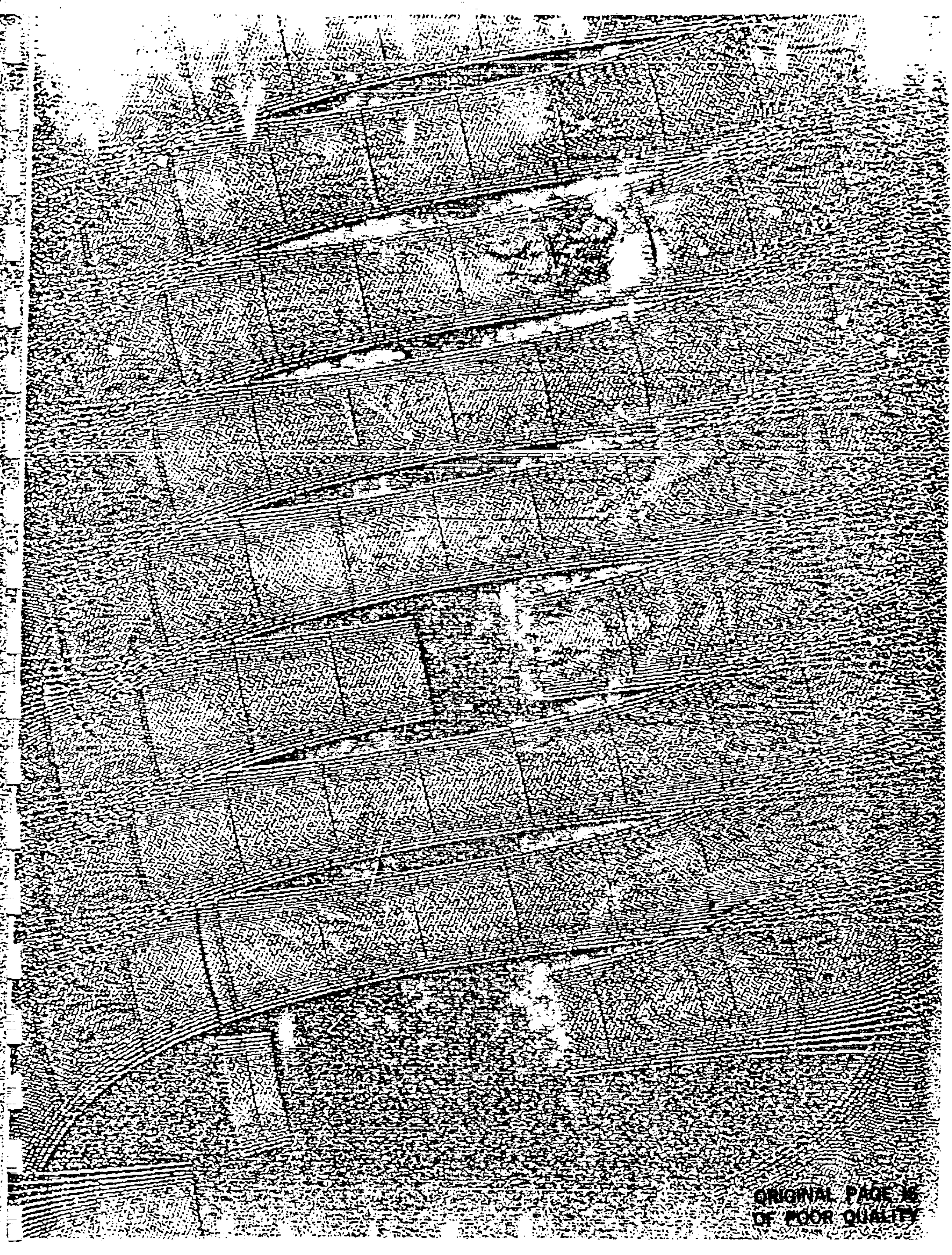
THE NEED FOR LEVEL 2 DATA

3 COLOR IMAGES SHOW HIRS2 JULY 1979 CLOUDS

(1) 2 X 2.5 DEGREE BIN,

(2) 500 X 500 KM BIN

AND (2) - (1)



Exploratory Data Analysis Acitvities

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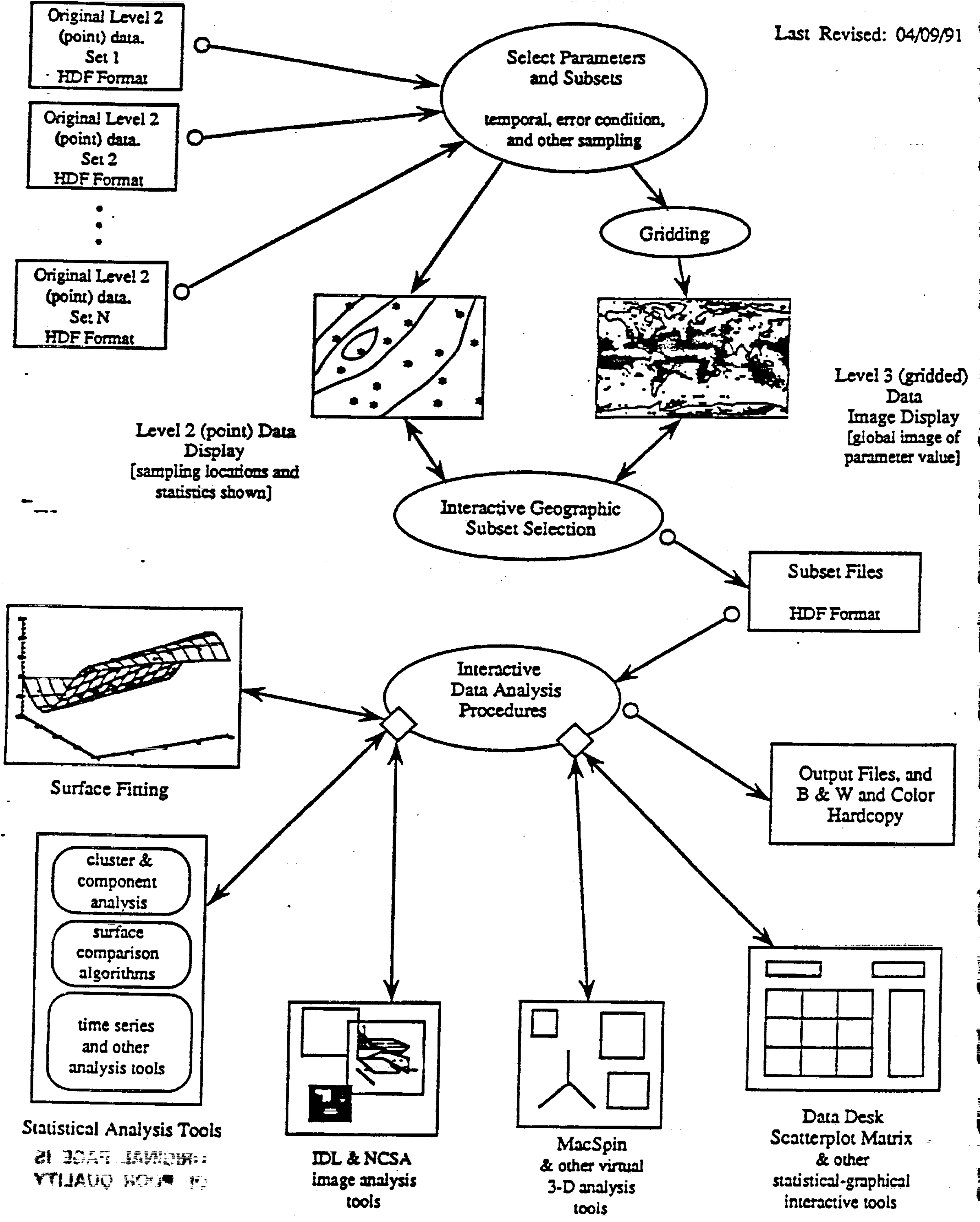


FIGURE A.6

WIGSS MENUS

last revised: 04/03/92

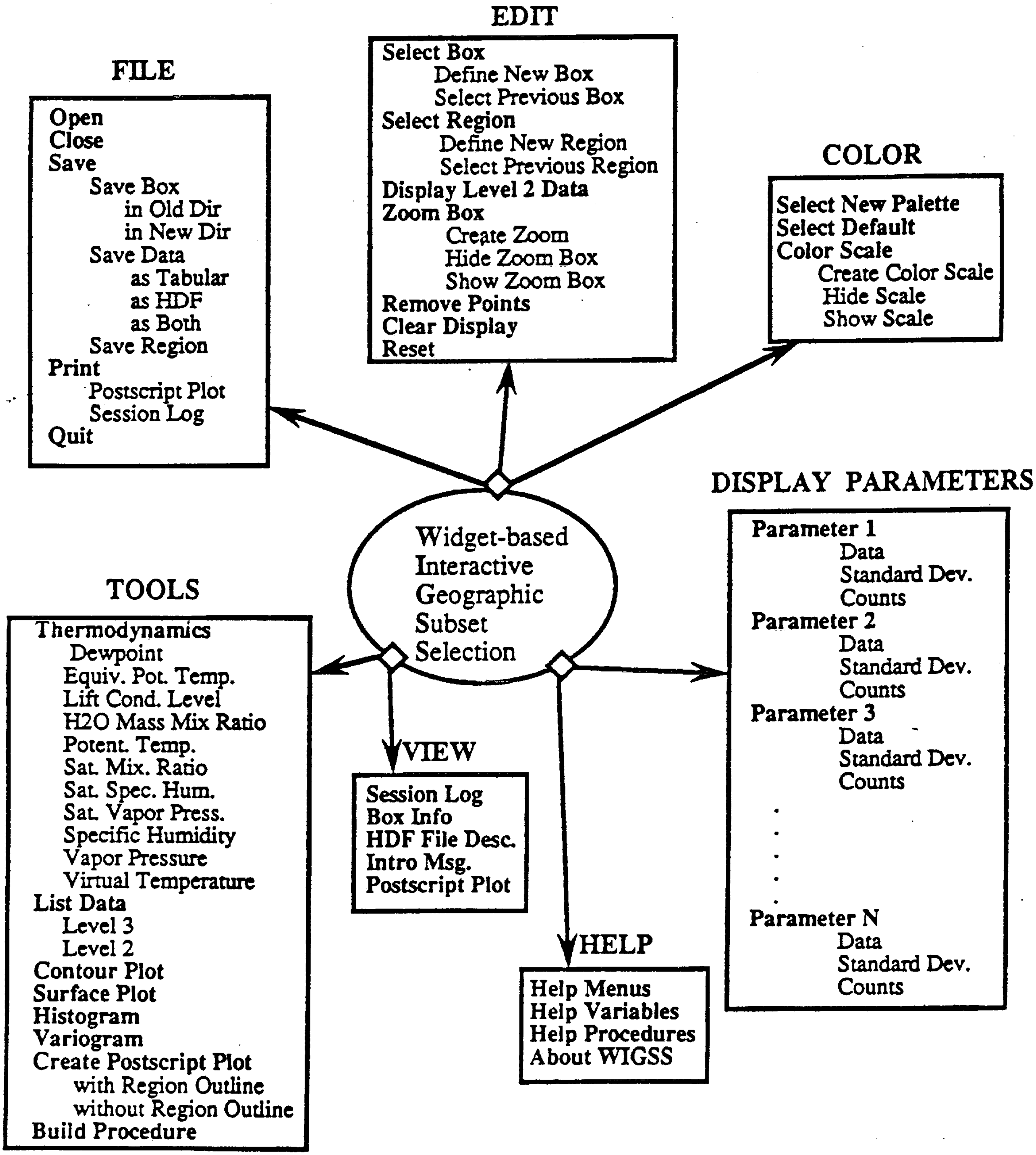
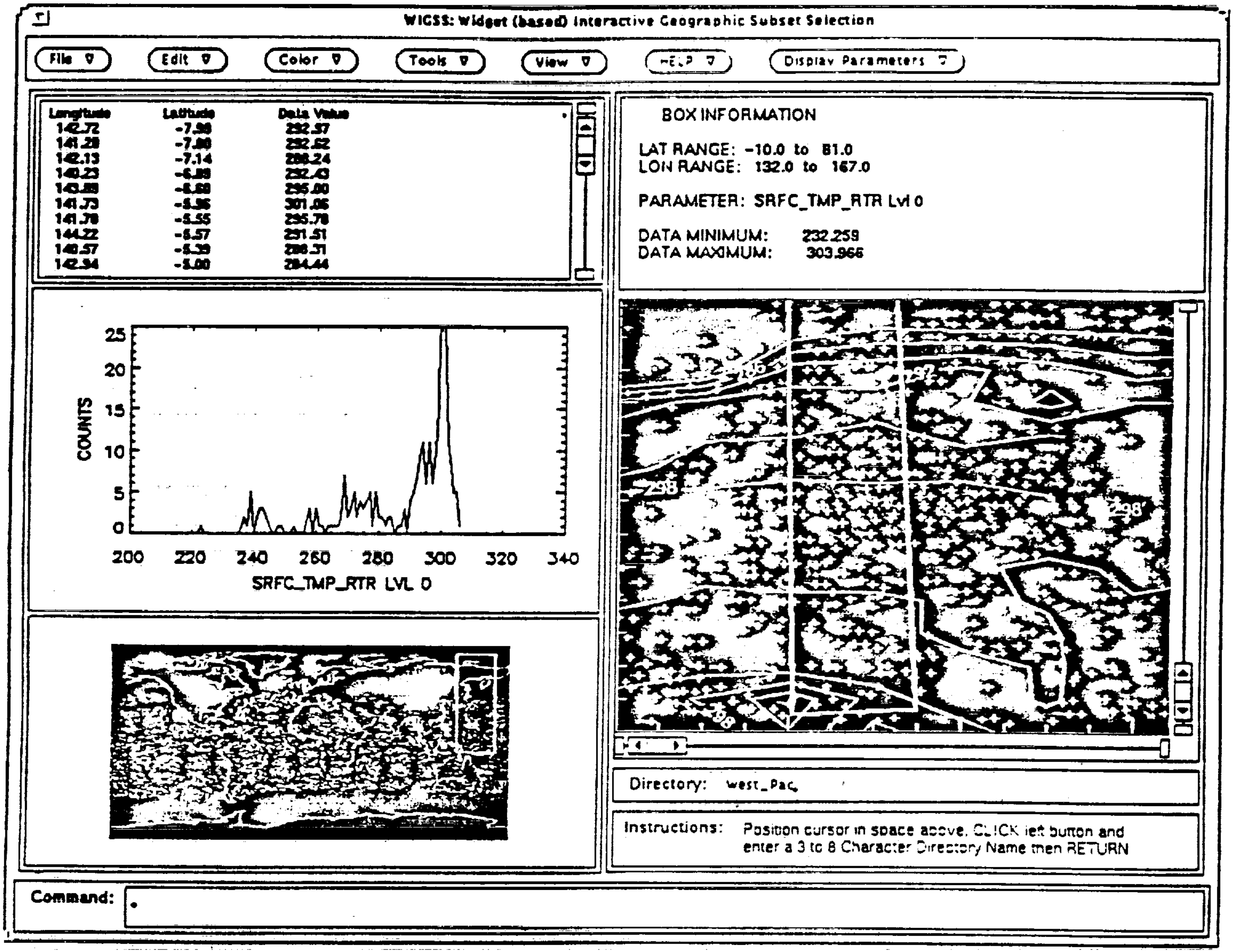


FIGURE A.7



Longitude	Latitude	Data Value
142.72	-7.98	292.57
141.28	-7.88	292.62
142.13	-7.14	288.24
140.23	-6.88	292.43
143.88	-6.68	296.00
141.73	-5.96	301.06
141.78	-5.55	295.78
144.22	-5.57	291.51
140.57	-5.39	288.31
142.94	-5.00	294.44

BOX INFORMATION

LAT RANGE: -10.0 to 81.0
LON RANGE: 132.0 to 167.0

PARAMETER: SRFC_TMP_RTR Lvl 0

DATA MINIMUM: 232.259
DATA MAXIMUM: 303.966

Directory: west_Pac

Instructions: Position cursor in space above. CLICK left button and enter a 3 to 8 Character Directory Name then RETURN

Command:

EDA HIRS2/MSU STANDARD DATA FILES PROCESSING

-- Problem of multiple machine architectures

We converted our data files to Hierarchical Data Format (HDF).

[Developed at NCSA (National Center for Supercomputer Applications)]

-- Problem of data documentation
[How are the fields stored, what do they mean (units, definitions, assumptions)?]

HDF solves a part of these problems (some information about 'data objects' is stored in HDF files)

What We Have Learned About Standard Data Handling Time Scales:

-- To discover the need for HDF, learn HDF, and apply it - **~ 1 year**

-- Knowing what we now know, to rebuild from scratch - **~ 6 months**

-- To create HDF files for a different data set, of comparable complexity, in an arbitrary format -
<~ 2 months, depending on the documentation and hardware availability

-- To ingest a different data set, of comparable complexity, that is already in HDF format -
~ 2 weeks to read data, test, and to study the documentation

For data analysis, the issue of **assumptions** is a large one, not addressed in the standard data processing (discussed later).

Partial List of Software That Automatically Reads Files in HDF Format

Currently Available:

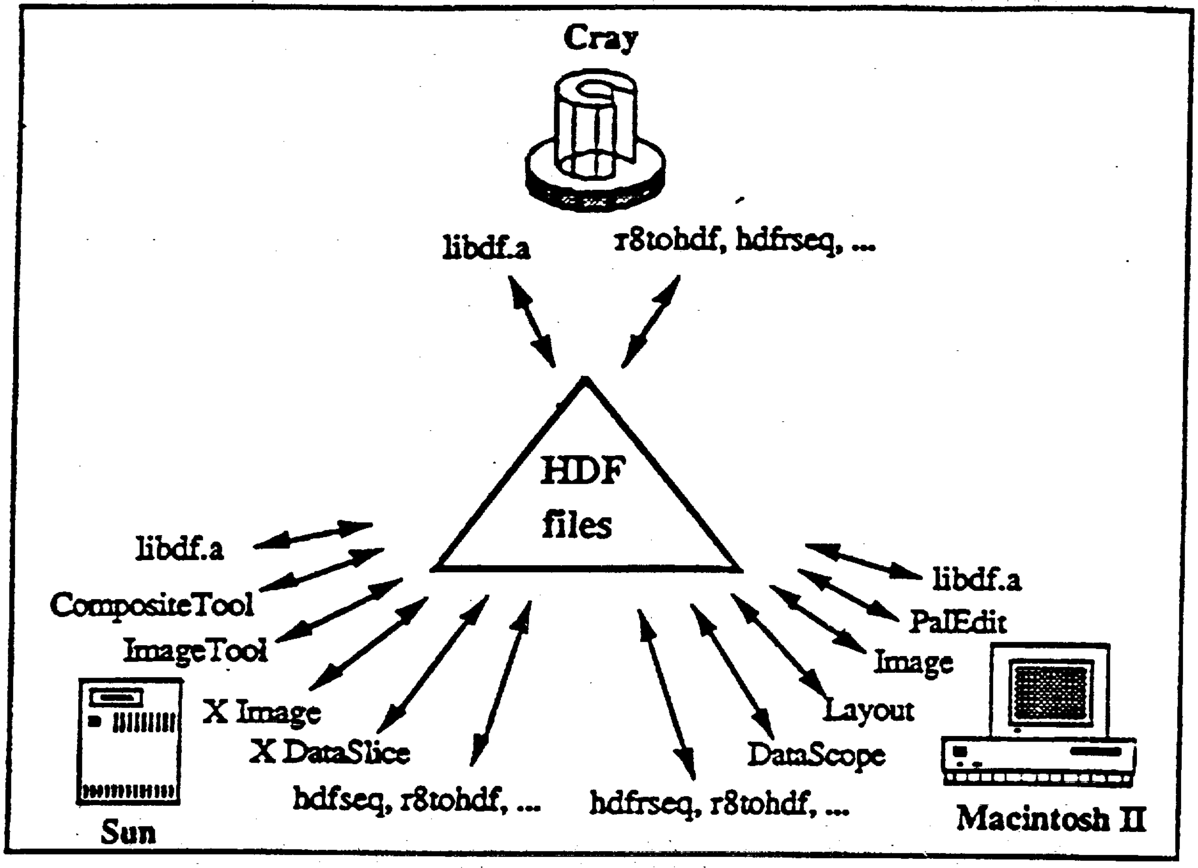
NAME	Platform	Source	Comments
Data Scope	Mac	NCSA	Display, manipulate arrays & images
Image Tool	Mac	NCSA	Display, animate image & color bar
Layout	Mac	NCSA	Create presentation from images, text
Transform	Mac	Spyglass	Combines Data Scope & Image Tool
Format	Mac	Spyglass	Similar to Layout
Dicer	Mac	Spyglass	Select & view sections of 3-D display
X-Image	Sun*	NCSA	Combines Data Scope & Image Tool
XDS	Sun	NCSA	Similar to Dicer
Reformat	Sun	NCSA	Convert FITS, TIFF, GIF, SUN, raw raster files, & x-window dumps to HDF
APE 2.0	Sun	Ohio State	Object-oriented prog. language

In Development or Testing:

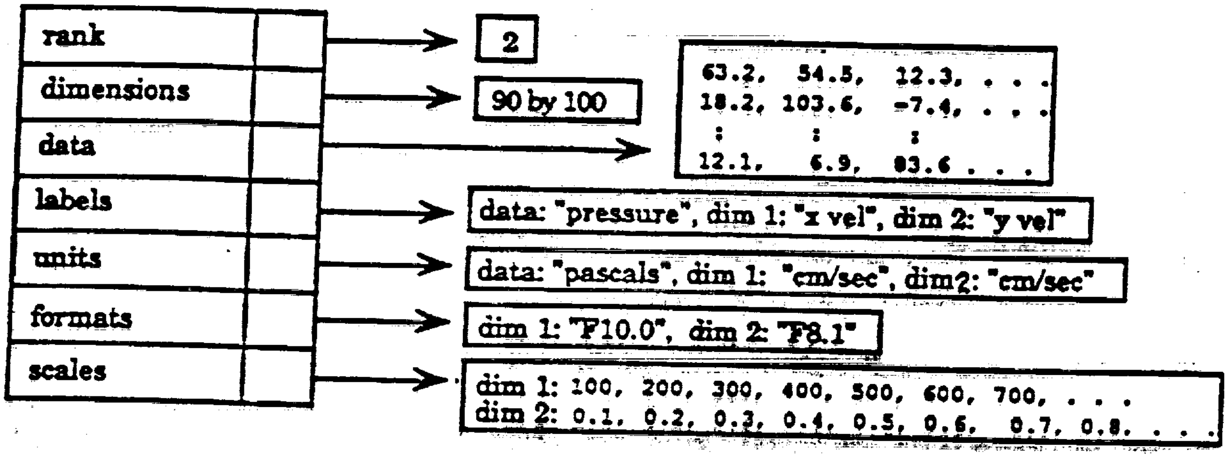
IDL	Sun	RSI	Interactive graphics prog. language
IGSS	Sun	JPL/EDA	Interactive Geographic Subset Selection
netCDF filter	Sun	NSF	Convert netCDF to HDF

* 'Sun' also runs on many other UNIX platforms, including Apollo, Alliant, Convex, Cray, DEC-ULTRIX, and IRIS Workstations.

HDF Software in an Integrated Computing Environment



HDF File with Scientific Dataset



```
FORTRAN:
INTEGER          DFSDsetdims, DFSDsetdatastrs, DFSDsetdimstrs
INTEGER          DFSDsetdimscale, DFSDputdata
REAL             press1(90,100), press2(90,100)
REAL             den1(90,100),den2(90,100)
INTEGER          shape(2), ret
REAL             xscale(90), yscale(100)

shape(1) = 90
shape(2) = 100

ret = DFSDsetdims(2, shape)
ret = DFSDsetdatastrs('pressure 1','Pascals','E15.9','')
ret = DFSDsetdimstrs(1,'x vel','cm/sec','F10.0')
ret = DFSDsetdimstrs(2,'y vel','cm/sec','F8.1')
ret = DFSDsetdimscale(1, shape(1), xscale)
ret = DFSDsetdimscale(2, shape(2), yscale)
ret = DFSDadddata('SDex4.hdf', 2, shape, press1)

ret = DFSDsetdatastrs('pressure 2','Pascals','E15.9','')
ret = DFSDadddata('SDex4.hdf', 2, shape, press2)

ret = DFSDclear()
ret = DFSDsetdatastrs('density 1','g/cm3','E15.9','')
ret = DFSDadddata('SDex4.hdf', 2, shape, den1)

ret = DFSDsetdatastrs('density 2','g/cm3','E15.9','')
ret = DFSDadddata('SDex4.hdf', 2, shape, den2)
  .
  .
  .
```

HIRS2/MSU HDF LABEL

FILE IDENTIFIER LENGTH: 5
FILE IDENTIFIER: LABEL
FILE DESCRIPTOR LENGTH: 1831
FILE DESCRIPTION:

Description: HIRS2/MSU parameters retrieved using the Goddard Laboratory for Atmospheres (GLA) Physical Inversion Algorithm Baseline 4.0. They are stored as individual objects of an HDF file. These files are the standard data source for most data analysis applications. Most of the parameters delivered on the original GSFC tapes are included. The following parameters were eliminated (either because of questions about definition, redundancy, or problems of interpretation of the values): tau; dlat; dlon; np; cldhgt; cldfrc; retwat(1); retwat(5); humret(13); rthick. Thirty_seven paramaters remain. They are listed and defined in /edal/doc/hirs_daily/rec.doc.

Level 2 data for: 06 jul 79, 0Z - 24Z. Platform: TIROS-N

Reference: Susskind, J., J. Rosenfield, D. Reuter and M. T. Chahine, 1984: Remote sensing of weather and climate parameters from HIRS2/MSU on TIROS-N. J. Geophys. Res. 89, 4677-4697.

Contact:
Robert Haskins
Jet Propulsion Laboratory
Mail Stop 183 - 301
4800 Oak Grove Dr
Pasadena, CA 91109-8001

(818)354-6893

Regional Boundaries are: Global

Number of Parameters: 37

Parameters:
YYMMDD, HHMMSS, QUADLATS, QUADLONS, DNFLAG, LANDWTR_FLAG, SAT_ZEN_ANGLE, GEOPOT_THICK, HIRS8_OBS, VIS_REFLECTANCE, SRFC_EMIS_MW, SRFC_PRES TROP_PRES_RTR, SRFC_TMP_RTR, SST_ANOMALY, TMP_PROFILE_RTR, QUAD_NUM_TMPS, QUAD_FLAG, TMP_RTR_FLAG, TB_RESIDUAL, TB_RMS_TMP, RHUM_PROF_RTR, PRECIP_WTR, WATER_FLAG, TB_RMS_WTR, HIRS8_TBDIF_WTR, HIRS10_TBDIF_WTR, CLOUD_EFRAC_L1, CLOUD_TOP_PRES_L1,CLOUD_EFRAC_L2, CLOUD_TOP_PRES_L2, RMS_ERR_INCCLD, RMS_ERR_PRECLD, CLOUD_CLEAR_PARM, HIRS8_TBDIF_CLD, OZONE_RTR, O3SENS

Comments:

Binary HDF file creation date: Mon Nov 4 16:42:31 EST 1991
Binary HDF file created on a CRAY Y-MP

SDS COUNT: 37

SDS DATA DIMENSIONS: 4 x 44821

SDS DATA LABEL: QUADLATS
SDS DATA UNITS: Degrees
SDS DATA FORMAT: F6.2
HDF OBJECT REFERENCE NUMBER: 9
HDF OBJECT DESCRIPTION:
Latitudes of four individual quadrants for cloud retrieval

--- Original Name = FLAT ---

SDS DATA DIMENSIONS: 4 x 44821
SDS DATA LABEL: QUADLONS
SDS DATA UNITS: Degrees
SDS DATA FORMAT: F7.2
HDF OBJECT REFERENCE NUMBER: 12
HDF OBJECT DESCRIPTION:
Longitudes of four individual quadrants for cloud retrieval.

--- Original Name = FLON ---

SDS DATA DIMENSIONS: 1 x 44821
SDS DATA LABEL: TMP_ERR_FLAG
SDS DATA UNITS: N/A
SDS DATA FORMAT: I3
HDF OBJECT REFERENCE NUMBER: 57
HDF OBJECT DESCRIPTION:
Error flag for temperature retrieval.

=> Positive IERR means successful temp retrieval and retrieved temp was used for water, ozone, and cloud retrieval.

=> Negative IERR means temp retrieval failed and first guess temp and moisture is used in subsequent cloud retrieval.

1000+K	Converged on Kth iteration in retrieval This parameter is always stored as 1 on the tapes that we receive from GSFC.
1100	Did not converge after 9 iterations. This parameter is always stored as 1 on the tapes that we receive from GSFC (The information about whether or not the retrieval converged is lost.)
2	SST retrieval was not attempted over ocean, climatology SST is used.
3	Residual for HIRS2 channel 2 was large. Ignore retrieved temperatures above 200 mb.
-4	Cloud clearing was not attempted; too cloudy to do a retrieval.
-5	Big (1 degree) RMS on Tb residual in temp sounding channels, or in MW2 channel.
-6	Not used.

.
.
.

EDA HIRS2/MSU STANDARD DATA FILES PROCESSING

Hierarchical Data Format

We have developed software that:

1. Automatically moves HIRS2/MSU physical retrieval data from the IBM tape archive to the GSFC Cray
2. Automatically converts the data into HDF format, including adding file labels and detailed parameter descriptions
3. Automatically transfers the HDF files to a user-specified remote node via the FTP utility

We also have some standard utilities, and there is software in development, that takes HDF files and

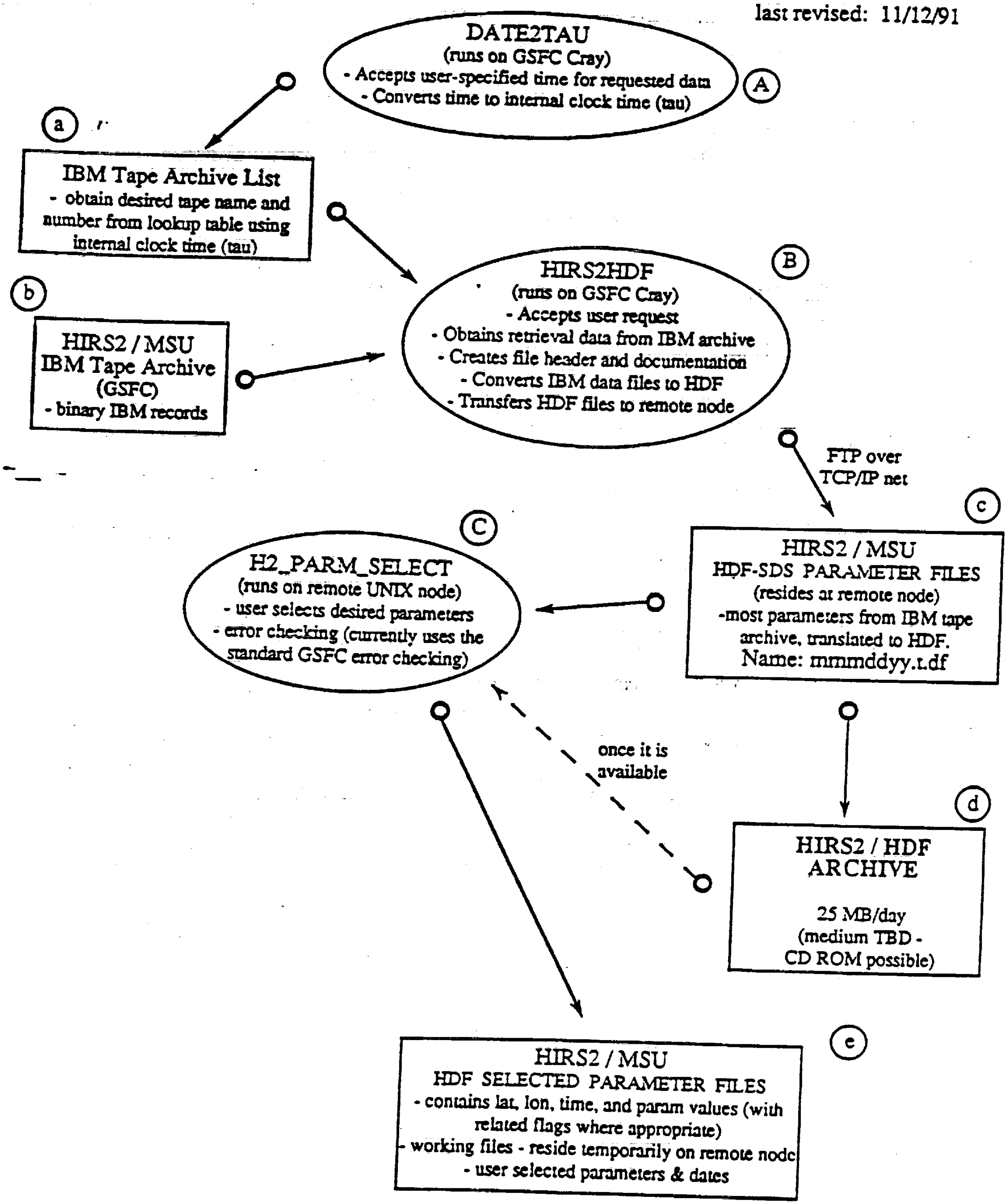
displays HDF label information

creates floating point image data from HDF vector data

displays floating point image HDF files and performs several kinds of analysis

EDA HIRS2/MSU STANDARD DATA FILES PROCESSING

last revised: 11/12/91



Ⓐ **DATE2TAU**
(runs on GSFC Cray)
- Accepts user-specified time for requested data
- Converts time to internal clock time (tau)

ⓐ **IBM Tape Archive List**
- obtain desired tape name and number from lookup table using internal clock time (tau)

Ⓑ **HIRS2HDF**
(runs on GSFC Cray)
- Accepts user request
- Obtains retrieval data from IBM archive
- Creates file header and documentation
- Converts IBM data files to HDF
- Transfers HDF files to remote node

ⓑ **HIRS2 / MSU IBM Tape Archive (GSFC)**
- binary IBM records

FTP over TCP/IP net

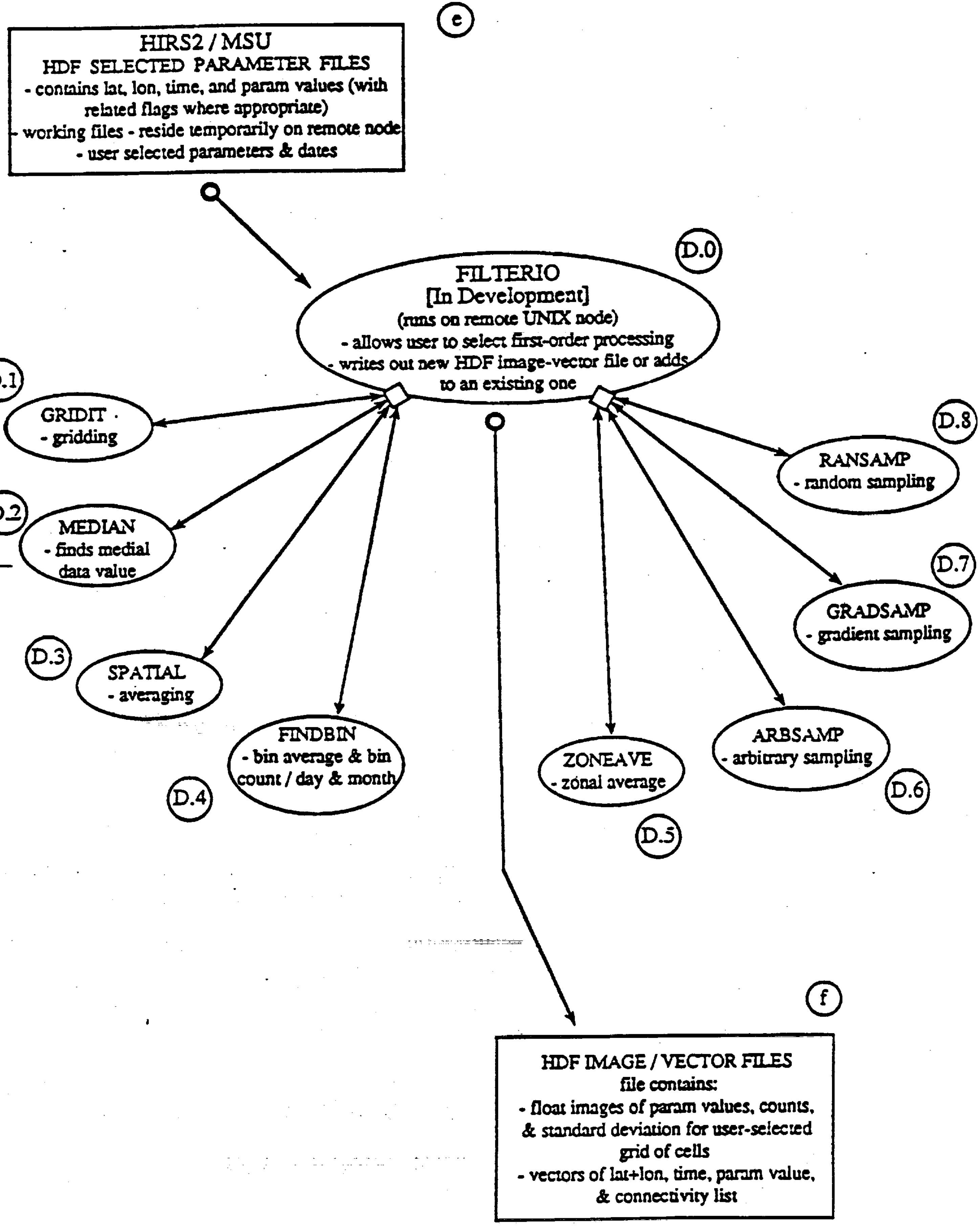
ⓒ **HIRS2 / MSU HDF-SDS PARAMETER FILES**
(resides at remote node)
-most parameters from IBM tape archive, translated to HDF.
Name: mmmddyy.t.df

Ⓒ **H2_PARM_SELECT**
(runs on remote UNIX node)
- user selects desired parameters
- error checking (currently uses the standard GSFC error checking)

once it is available

ⓓ **HIRS2 / HDF ARCHIVE**
25 MB/day
(medium TBD - CD ROM possible)

ⓔ **HIRS2 / MSU HDF SELECTED PARAMETER FILES**
- contains lat, lon, time, and param values (with related flags where appropriate)
- working files - reside temporarily on remote node
- user selected parameters & dates


(e)
HIRS2 / MSU
HDF SELECTED PARAMETER FILES
- contains lat, lon, time, and param values (with related flags where appropriate)
- working files - reside temporarily on remote node
- user selected parameters & dates
(D.0)
FILTERIO
[In Development]
(runs on remote UNIX node)
- allows user to select first-order processing
- writes out new HDF image-vector file or adds to an existing one
(D.1)
GRIDIT
- gridding
(D.2)
MEDIAN
- finds medial data value
(D.3)
SPATIAL
- averaging
(D.4)
FINDBIN
- bin average & bin count / day & month
(D.5)
ZONEAVE
- zonal average
(D.6)
ARBSAMP
- arbitrary sampling
(D.7)
GRADSAMP
- gradient sampling
(D.8)
RANSAMP
- random sampling
(f)
HDF IMAGE / VECTOR FILES
file contains:
- float images of param values, counts, & standard deviation for user-selected grid of cells
- vectors of lat+lon, time, param value, & connectivity list

SUMMARY

Validation Issues

Statistical characterization of data sets

Finding statistics that characterize key attributes of the data sets

Defining ways to characterize the comparisons among data sets (Scale issues, statistics,...)

Selection of specific intercomparison exercises

Selecting characteristic spatial and temporal regions for intercomparisons

Impact of validation exercises on the logistics of current and planned field campaigns and model runs

Preparation of data sets for intercomparisons

Characterization of assumptions

Transportable data formats

Labeling data files

Content of data sets

Data storage and distribution (EOSDIS interface)

AN OVERVIEW OF THE UARS DATA VALIDATION EFFORT

S23-45
N94-23617
171313

p. 22

Presented to
The EOS Calibration/Data Product Validation Panel

Boulder, Colorado

April 7-10, 1992

C-6

UARS: An Introduction

1) Upper Atmosphere Research Satellite

- •) Launched Sept. 1991
- •) In planning and development stages since late 1970's
- •) Measures temperature, chemical species, winds, solar inputs

2) Similarities to EOS

- •) Data collected and processed at a Central Data Handling Facility.
- •) Data distributed via high speed network to Remote Analysis Computers at investigator sites
- •) Science Team (users) include instrument PIs and theoretical PIs.

3) Differences

- •) UARS is a one platform mission
- •) Highly focused on upper atmosphere research
- •) Quantitative global measurements of atmospheric parameters (as opposed to determination of spectral or spatial contrast, event counting, etc)
- •) No imagery

UARS Validation Chronology

1) Validation not recognized as a fundamental requirement at the outset of the program. (due to semantics, oversight??)

2) A series of events in 1988 focused the need:

   A) Within the UARS team it became apparent that some additional structure was required to unify;
      - •) Calibration
      - •) Algorithm verification
      - •) Error analysis
      - •) Correlative measurements
      - •) A priori knowledge: (climatology, theory, modeling)

   B) The release of the Ozone Trends Panel Report

3) UARS Validation Working Group created 1989

4) Validation Plan completed 1991

5) Plan Implementation 1991-92

NASA
Reference
Publication
1208

1988

Present State of Knowledge of the Upper Atmosphere 1988: An Assessment Report

R. T. Watson and Ozone Trends Panel,
M. J. Prather and Ad Hoc Theory Panel,
and M. J. Kurylo and NASA Panel for
Data Evaluation
NASA Office of Space Science and Applications
Washington, D.C.

NASA recognizes the need for timely international scientific assessments when important new information becomes available as has occurred since the last major international scientific assessment (WMO, 1986). Reports based on Nimbus 7 satellite Solar Backscatter Ultraviolet (SBUV) and Total Ozone Mapping Spectrometer (TOMS) data claimed that large global decreases have occurred since 1979 in the total column of ozone (about 1% per year) and in its concentration near 50 km altitude (about 3% per year). Data from the ground-based Dobson network also indicated that the total column content of ozone had decreased on a global scale significantly since 1979, although to a lesser extent than suggested by the satellite data. Further, there has been a significant amount of new research focussed on understanding the extent and cause of the depletion of ozone in the spring-time over the Antarctic.

NASA and the rest of the scientific community believed that it was imperative to evaluate whether the Nimbus 7 satellite data had ~~been analyzed correctly~~, and if so, whether the reported decreases were due to natural causes such as a decrease in solar radiation (from solar maximum in 1979 to solar minimum in 1986), the 1982 volcanic eruption of El-Chichon, or the 1982 El-Nino event, or whether it was due to human activities such as the use of chlorofluorocarbons (CFCs). Therefore, during the fall of 1986 NASA decided to coordinate and cosponsor with the Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA), the World Meteorological Organization (WMO), and the United Nations Environmental Program (UNEP) a major review of all ground-based and satellite ozone data. A panel (the Ozone Trends Panel) composed of eminent scientists from federal agencies, research institutions, private industry, and universities was selected.

NASA
National Aeronautic
and Space Administr

Scientific and Tech
Information Divisior

Zen And The Art Of Data Validation (circa 1989)

1) What Is Data Validation?

A) What it is not.

i) Header information
ii) Flags marking data anomalies
iii) Limit checks
iv) Verifying that the software didn't bomb
v) Documentation

(These are all Quality Assurance Issues...Necessary but not Sufficient)

B) Also, What it is not: Comparing Profiles With Someone Else. *(A component but not an end in itself)*

C) What it might Be. *(The Process of Demonstrating that a Collection of Data Represents the Real Atmosphere Within a Quantifiable Uncertainty)*

D) What it always is.

i) Overlooked in program planning.
ii) Underestimated in terms of time, effort and resources required.
iii) The most frustrating part of the mission.

2) Why Is It Important?

UARS is not measuring <u>anything</u> for the <u>first</u> time. It is adding to a cumulative base of knowledge (in some cases, extensive) and therefore must be compatible with existing and future sources of information

Evolution of UARS Data Validation Plan

1) Identification of issues within the Validation Working Group.

2) Mandatory requirement that each investigation team prepare a plan for their activities.

3) Creation of a "Generic" plan outline.

4) Development of Investigator specific plan outlines.

5) Review of Investigator specific draft plans

6) Investigator specific final plans

7) Collection of all investigator plans into overall plan

Pre/Post Launch Validation Activities

1) Pre-launch:

A) Formulate Plans
B) Identify resource requirements
C) Begin development of tools and procedures

2) Post-launch:

A) Organize into issue/parameter specific Validation Sub-Groups
  •) Temperature/Pressure/Altitude registration
  •) Trace gas concentration
  •) Winds/Dynamics
  •) Solar Measurements
  •) Data gridding/mapping procedures
  •) Energetic Particles

B) Investigator teams work through their validation plans

C) Report findings

D) Take corrective actions as necessary (instrument operation, data processing)

GENERIC P.I. DATA VALIDATION PLAN OUTLINE

1.0 INTRODUCTION

1.1 Brief Experiment Overview, Including Measurements to be Validated and Altitude Ranges

1.2 Brief Validation Criteria

1.3 Validation Approach

- Approach to Level 1, 2, and 3 validation (e.g. validate most understood parameters first, e.g. temperature and least understood parameters last)

2.0 DESCRIPTION OF EXPERIMENT PHYSICAL MODEL

2.1 Instrument Concept and Basic Equations

2.2 Forward Radiance Model

- Radiative transfer
- Numerical approximations
- Physical constraints (e.g. line parameters summary, plus reference)

2.3 Inversion Approach

- Brief description of basic approach
- Constraint methods
- Numerical approximations
- Use of a priori information

3.0 DESCRIPTION OF INSTRUMENT CHARACTERIZATION AND CALIBRATION

3.1 Accuracy and Stability

- IFC, temperature effects, noise, scale, and bias error stability

3.2 Spectral Response and Registrations

3.3 Spatial Response

- FOV
- Off-axis rejection
- Crosstalk

3.4 Pointing

3.5 Electronics Response

- Amplitude and phase
- Crosstalk

3.6 Data System Errors

- Gain uncertainties
- Digitization errors

3.7 Summary of Uncertainties with References

4.0 ERROR ANALYSIS

4.1 Sensitivity to Errors in Instrument Model

4.2 Sensitivity to Errors in Forward Radiance Model

4.3 Sensitivity to Inversion Algorithm Errors, Including A Priori Assumptions

4.4 Spacecraft Effects

- Altitude
- Attitude rates
- Ephemeris

4.5 Uncertainties Due to Data Transmission (e.g. altitude Interpolation, True to Earth to IAU)

4.6 Estimate of Total Measurement Error

5.0 PRE-LAUNCH ACTIVITIES

5.1 Instrument P.I. Obligations

5.1.1 Define post-launch instrument verification procedures

5.1.2 Creation and comparison of Level 3AL data

- Sample test atmosphere for 3 days
- Synthesize radiances with production algorithm and add errors
- Perform retrievals
- Translate to standard latitudes for comparison

5.1.3 Identify and develop tools and methods which will expedite post-launch validation

5.2 Theoretical P.I. Support

- Contributions by theoretical P.I.'s that will aid data validation

6.0 POST-LAUNCH ACTIVITIES

6.1 Instrument P.I. Obligations

6.1.1 Implement instrument verification procedure

- Monitor calibration stability (e.g. scale factor, bias)
- Verify spectral registration
- Verify spatial response characteristics
- Evaluate correlation of instrument signals with orbital events such as (e.g. south Atlantic anomaly, other instrument turn-on events, terminator crossing)

6.1.2 Update error analysis as necessary

6.2 Theoretical P.I. Support

- Contributions by theoretical P.I.'s that will aid data validation

6.3 Intercomparisons

6.3.1 Guidelines

- Number of comparisons with correlative measurements, locations, times, coincidence criteria (time, space)

6.3.2 Climatology

6.3.3 Correlative measurements

6.3.4 Other UARS measurements

6.3.5 Theory and derived products

6.3.6. Targets of opportunity (e.g. ATLAS, NDSC)

7.0 IMPLEMENTATION

7.1 Detailed Schedule with Milestones

- Completion of on-orbit instrument verification in procedure plan
- Completion of on-orbit instrument verification in procedure plan
- Completion of initial on-orbit instrument verification procedures
- Validation of Level 1 products
- Validation of Level 2 products
- Validation of Level 3 products

7.2 Resource Requirements

- Personnel and equipment
- Funding
- Other

Lessons Learned
(Or Should Have Been)

1) Start Early: Should be part of initial program planning.

2) Put in adequate resources to support the goals
    - •) If you want fast results, expect to pay
    - •) If you want to save money, expect to wait

3) Maintain better coordination between Validation planning/implementation and Correlative Measurement programs. Make sure they really compliment each other.

4) Test correlative measurements data flow and validation procedures/tools well before launch.

5) Divide the work:
    - •) Instrument PIs are often overworked before and immediately after launch.
    - •) Theoretical PIs are often under-utilized during this period.

6) Learn from the successes and mistakes of others: Be willing to adapt as time goes along.

7) Be realistic: (HQ is much better at setting goals than in providing the means to reach them.)

Implications for EOS

1) Use UARS as a "Living Laboratory" in an attempt to identify:
   - •) what works
   - •) what doesn't
   - •) how to do it better
   - •) what is realistic

2) Make sure Correlative Measurement programs are planned with validation requirements in mind. Make sure they have appropriate resources, lead time and coordination with EOS.

3) Enlist the "user" community to lend a hand: How should the work be divided?
   - A) Instrument Teams take the lead in:
     - •) Calibration
     - •) Error analysis
     - •) Level-1 data products
     - •) Level-2 data products
   - B) EOS "Users" take the lead in:
     - •) Validation program planning
     - •) Working group coordination
     - •) Correlative measurement liaison
     - •) Level-3 data products

4) Validation activities continue for the life of the program
   - •) There is an initial large "impulse" of activities with each launch
   - •) There is an ongoing "maintenance" effort for the life of each instrument

Statistical Characterization Group

① Stats. that characterize key attributes of Individual Data Sets

- char. sample spacing (vector?)
- char. spacing vs. gradient of parameter value (vector?)
- measures of heterogeneity
- variance surfaces / spatial interpolation
- n-dim. space-time interpolation

② Ways to characterize the Comparisons Among Data Sets.

- differences & ratios of 2-D & higher fields.
- movements of boundaries (2-D & higher)
- changes in density & density gradient (2-D & higher).

③ Representation Issues (including visualization

④ Interpretation Issues (patterns & exceptions)
Projection/map units....

EOS Project Science Office
Data Product Validation Policy

D R A F T

March 31, 1992

INTRODUCTION

EOS is a planned 15 year, multiple instrument/platform in the Mission to Planet Earth (MTPE) program designed to monitor changes in the earth system. Numerous users of EOS data will rely on accurate EOS data products to derive higher generation data products. These data products and the resulting scientific analyses will serve to guide environmental and economic policy. The scientific community will rely on the veracity of the data products developed in part because of our validation policy for those products, and in part on the basis of the scientific reputation of the investigators who are responsible for those products.

In past satellite-based scientific investigations, data product validation has encompassed: (1) quality control checks on raw data; (2) generation of community-consensus, peer-reviewed algorithms that transform the radiance or reflectance measurements obtained from sensors into geophysical variables; and, (3) comparison of data products derived from satellite measurements with data products independently derived through techniques from orbiting, airborne, and ground-based instruments.

REQUIREMENTS LEVIED BY THE 1988 EOS ANNOUNCEMENT OF OPPORTUNITY

Validation of the data products is established by comparing data products with measurement values acquired by conventional measurement and analysis approaches. This experiment validation must be included in the Calibration Plan provided in the proposed Instrument Investigation. The Data Product Validation Plan must define the correlative measurements and in-orbit calibration plan which establishes conformance to the EOS Project Data Product Validation strategy. The instrument observables usually will be interpreted as physical parameters, and are represented as data products. Validation of the data products is established by comparing data products with those acquired by conventional measurement, analysis, and other approaches.

Specifically, the Data Product Validation Plan at a minimum must include:

(1) A description of independent measurement and analysis approaches to be used in experiment validation and how the validation data products are to be compared to the instrument-derived data products.

(2) A description of how the calibrations of instruments used in the validation network will be compared to the calibration of the instruments in space.

(3) An estimate of the accuracy and precision required in the validation data products so that they will be useful for this investigation.

(4) An estimate of the frequency, duration, location, and any appropriate special observing conditions required for the data validation measurements.

(5) Description of EOS validation measurement programs and the relationship between EOS validation measurement requirements and supporting major

national and international science field measurement campaigns, such as FIFE, GEWEX, TOGA, etc.

EOS PROGRAM OFFICE DATA PRODUCTS VALIDATION DEFINITIONS AND POLICY

According to the EOS program office an EOS data product of level 1 to 4 is considered to be validated when several criteria are chronologically met by that particular data products. The raw level 0 data from which the level 1 to 4 data products are derived must first pass a series of automated quality control (QC) checks by the Distributed Active Archive Centers (DAACs) for bit errors and data dropouts. Level 0 data is then transformed to a level 1 data product using level 1 algorithms and calibration coefficients. The Level 1 algorithms must pass preflight algorithm validation review, as must the calibration techniques used to determine the calibration coefficients. Level 1 testing and algorithms must pass a Peer Calibration Review process.

This perspective for data product validation does not include the comparison of EOS derived data products with independently derived non-EOS data products obtained through truth co-located measurements. This omission does not imply that the EOS program (1) does not recognized the importance of these data verification activities; (2) anticipates that these verification activities will not take place; or, (3) does not encourage that these verification activities take place. In fact, campaigns to compare EOS data with truth co-located measurements are viewed by the EOS program office as an important vehicle in broadening the scientific community's interest in EOS. The main ramification of removing these activities from under the data product validation umbrella is that correlative measurement campaigns are not planned to be funded by the EOS program.

The EOS Program Office definition of data product validation forces instrument investigators to more fully understand their instruments and algorithms by placing more importance on preflight calibration and characterization tests that represent instrumental flight operations, instrumental mathematical models, and algorithm verification. It also prompts instrument investigators and data producers to examine more closely their criteria for either accepting or rejecting a particular data set.

EOS PROJECT SCIENCE OFFICE POLICY

While it is the policy of the EOS Project Science Office that the guidelines identified in the Announcement of Opportunity are still useful, there are few funds available to do more than verify--via peer-reviewed processes--the suitability of algorithms. A measurement-based algorithm verification process likely will be over a rather limited time frame and for a limited set of environmental conditions for most of the data products. Still to be determined is how to deal with short-comings in a given algorithm after its official acceptance, whether these short-comings are due to incomplete capture of knowledge or due to a change in environmental parameters.

EOS PROJECT SCIENCE OFFICE

CROSS-CALIBRATION PLAN

DRAFT
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INTRODUCTION

Synergistic use of EOS data requires that instruments produce compatible measurements, even when several sensors/satellites are used. The Project must develop a technique that yields congruous Level 1 data products when the instruments are calibrated by the individual sensor builders. The approaches being developed to accomplish this are round-robin laboratory comparisons and exposure of instruments to a common source after final calibration but previous to sensor integration onto the flight platform.

In addition, there exists the perception that all instruments will degrade in orbit, each at its own characteristic rate. By knowing how the instruments compare on the ground before launch, the earliest in-orbit comparisons will assist in establishing how these instruments have changed during launch. The combination of the long-term data sets then can be used to improve our understanding of each of these data sets. Our primary approach to supplementing the individual instrument calibrations for accomplishing this requirement of EOS is described in the Cross-calibration Plan.

In some sense. absolute calibration is not required for this activity. In principle, stable and precise calibrations could be used to meet these objectives. Nevertheless, experience has demonstrated that absolute calibrations are the only reliable approaches for accomplishing stable and precise calibrations. Cross-calibration has been added to supplement instrument absolute calibrations as the approach to making congruent data sets.

Cross-calibration was made an EOS baseline requirement as defined in the 1988 Announcement of Opportunity (AO). Each Instrument Investigation is required to allow for such activities.

There are several pre-flight instrument calibration alternatives:

(1) Bring all instruments to a single facility where final radiometric and geometric calibration will be validated. This might provide the best calibration, but it could be very expensive and establish delays in getting the flight instruments delivered.

(2) Have a transportable system that will be carried to the location where the instruments are being calibrated. This transportable system would be used to validate the local

calibration system and assure more compatibility between systems. This offers many of the advantages of the first, and fewer of the disadvantages.

(3) Depend upon each instrument builder to provide the transfer of the calibration through analysis and testing traceable to NIST sources. This approach is now commonly used, and generally suffers from a lack of adequate documentation. The results depend very much upon the specific people performing the calibration and the project requirements.

From a logistical standpoint a single calibration facility or set of sources could lead to difficulties in launch scheduling. One cannot calibrate instruments until they have been built. Calibration is done as the last activity before shipping for integration. The use of a single set of sources or a single facility could lead to real difficulties in meeting the launch schedule. Cross-calibrations before instrument delivery also interfere with normal Project-contractor management interfaces.

Thermal detectors for satellite radiometry always should be calibrated in a vacuum. Therefore, vacuum calibration facilities should be the norm for calibration on most of the EOS instruments. Such a facility will need to accommodate any of the instruments, and certain benefits result if the facility is large enough to accommodate the entire EOS satellite. Sources for calibration will operate in a vacuum. The sources must be mounted precisely within the instrument field-of-view.

For EOS, a calibration scheme has been proposed that consists of several portable radiometers, each optimized for a certain spectral region. It is proposed that these radiometers be used in each instrument manufacturer's facility for comparison of the instrument calibration source scales. We refer to these as portable or traveling radiometers.

Great strides have been made in the past years in detector-based precision radiometry. For the visible portion of the spectrum quantum-response detectors are now available that have uncertainties on the order of 0.1%. There is a high probability that comparable accuracies can be achieved at wavelengths extending to 1500nm in the next several years. Thermal detectors operated at room temperature are accurate to 0.1% for high input power levels and 1% for lower power levels. Cryogenic radiometers are now available with uncertainties approaching 0.025% at modest power levels. This technology can be used directly in the construction of high-accuracy radiometric instruments or indirectly in the calibration of stable instruments. These technologies could be well-matched to verification of the manufacturer's calibration source scale.

There are pre-launch plans for the careful cross-calibration of the various laboratory sources using portable spectroradiometers and for a final cross-calibration of the instruments themselves at the spacecraft integration facility.

ROUND-ROBIN CROSS-CALIBRATION

During instrument construction, the prime means of comparison should be through the circulation of transfer radiometers. These would compare the working targets that are used in the calibration of individual instruments. The primary function of these detectors is to verify the calibration of sources that are used to calibrate EOS instruments with VIS/NIR channels (e.g., MODIS-N, ASTER, MISR). There is no perceived need for the circulation of standards for spectral or spatial calibration, as these topics can be handled through the use of standard procedures.

Radiometers used as transfer standard radiometers must be shown to be stable, and their use must be documented through an error budget analysis.

The AM Observatory is scheduled to be launched in June, 1998, and instruments will be delivered beginning two years before launch. The cross-calibration radiometers must be available by the summer of 1994 to support two years of testing before the instrument delivery.

CROSS-CALIBRATION AT INTEGRATOR'S SITE

The primary objective of the cross-calibration at the integrator's site is to determine the instrument-to-instrument bias when each instrument is looking at a well-controlled radiation field. This approach can establish the responsivitity of one instrument to another, but may not be useful in setting the absolute calibration scale of any one of them.

The EOS cross-comparison setup must accommodate a variety of instrument fields of view and aperture sizes, as well as operate over the full 0.4 µm to 15.4 µm waveband. Only radiometric comparisons will be made. Absolute calibration of the instruments shall be performed by the instrument builders prior to cross-comparison. The requirements for cold space view (i.e., 4K cold plate) are TBD for cross-comparison.

Cross-comparison will occur at the spacecraft integrator's site. The integrator must provide support for cross-comparisons in their integration and test flow procedures. It is not necessary to accomplish an observatory level (all instruments at once) cross-calibration, and most calibrations should be performed during thermal vacuum testing. The Panel recommendation that there be separate calibration sources for visible/near IR and thermal IR calibrations. For thermal IR the panel recommended a more extended source, not an integrating sphere.

Problems of cross-calibration at the spacecraft integrator's facility include tight schedules, difficulty in developing well-characterized targets of an appropriate common aperture, and the problem of controlling the setup and surroundings. There must be adequate time and facilities for detailed functional testing in thermal vacuum.

CONCLUSIONS

[TBD]

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