MODIS Algorithm Team (MAT)
Meeting Minutes, 2MAR94

ATTENDEES:

Abel, Peter		**Goldberg, Larry**	
Anuta, Paul		**Knight, Edward**	
Baden, Joan	*Rapporteur*	**Kvaran, Geir**	
Bryant, Tom		**Montgomery, Harry**	*Chair*
Che, Nianzeng		**Ungar, Stephen**	
Farwell, Lester		**Wolfe, Robert**	
		Zukowski, Tmitri J.	

The next meeting has been scheduled for Wednesday, March 9, 1994, from 9 - 12:00PM, in Building 16, Room 242. Contact Joan Baden for copies of presentations (286-1378). Attached is the current scheduled listing of MAT meetings for 1994 and the MAT member listing.

It was agreed that standard notation, as close to SBRC's as is practical, will be utilized in all MAT documentation and software. A list of standard notation and definitions will be maintained by Joan Baden. Names of variables are limited to those allowed under ASCII C (i.e., TBD by Joan Baden).

ACTION ITEMS ASSIGNED 2MAR94:

28.MAT Joan Baden to begin list of standard notation and definitions.

AGENDA

MODIS Algorithm Team (MAT) Meeting
Guest: Michael Weinreb/NOAA Calibration Scientist
March 9, 1994
(9AM-12PM)
Building 16, Room 242
NASA/GSFC

9:00AM The MODIS Blackbody (BB) (Dan Knowles)

9:15AM Solar Diffuser (SD) & Solar Diffuser Stability Monitor (SDSM) (Paul Anuta)

9:30AM Spectral Radiometric Calibration Assembly (SRCA)
Spectral Calibration (Ed Knight)

9:50AM Radiometric Calibration (Nianzeng Che)

10:10AM Spatial Calibration (Tim Zukowski)

10:30AM Synthesis (Nianzeng Che)

11:00AM Discussion

11:30AM Adjourn

MODIS ALGORITHM TEAM MEETING

2 MARCH 1994

9:00	THE MODIS BLACKBODY (BB) (DAN KNOWLES)
9:30	REGISTRATION (SRCA) (TIM ZUKOWSKI)
10:00	LEVEL 1B SOFTWARE PROTOTYPE (GEIR KVARAN)
11:00	ADJOURN

MODIS Algorithm Team (MAT) 3/2/94

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Goddard Space Flight Center	Greenbelt, Md. 20771
Ball Aerospace Sys. Div.	7500 Greenway Center Dr., Suite 700, Greenbelt, Md. 20770

OFFICIAL
MODIS ALGORITHM TEAM (MAT) SCHEDULED MEETINGS 1994

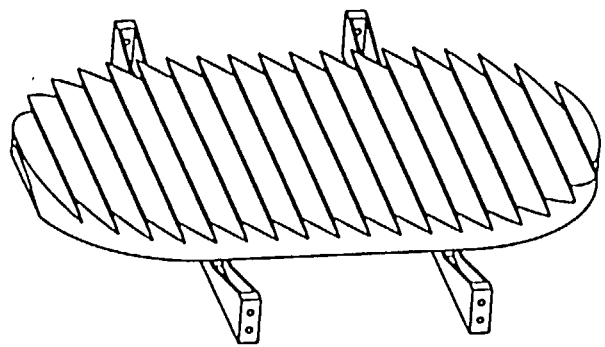
Day	Date	Room	Time
Wed	Feb 2	BLDG 22/G95	9-11AM
Wed	Feb 9	BLDG 22/271	9-11AM
Wed	Feb 16	BLDG 22/G95	9-11AM
Wed*	**Feb 23**	**BLDG 22/G95**	**9-10:30AM**
Wed	March 2	BLDG 22/G95	9-11AM
Wed*	**March 9**	**BLDG 16/242**	**9-12PM**
Wed	March 16	BLDG 22/G95	9-11AM
Wed	March 30	BLDG 22/G95	9-11AM
Mon	April 4	BLDG 22/G95	9-11AM
Mon	April 11	BLDG 22/G95	9-11AM
Mon	April 25	BLDG 22/G95	8:30-10AM
Mon	May 2	BLDG 22/G95	9-11AM
Mon	May 9	BLDG 22/G95	9-11AM
Mon	May 16	BLDG 22/G95	9-11AM
Mon	May 23	BLDG 22/G95	9-10AM
Mon	May 30	BLDG 22/G95	9-11AM
Mon	June 6	BLDG 22/G95	9-11AM
Mon	June 13	BLDG 22/G95	9-11AM
Mon	June 20	BLDG 22/G95	9-11AM
Mon	June 27	BLDG 22/G95	9-11AM
Wed	July 6	BLDG 22/G95	9-11AM

*Recently scheduled additions

NOTE: Michael Weinreb/NOAA Calibration Scientist will be the "subject" of the March 9, 1994 MAT meeting from 9-12p.m.

The MODIS On-Board Blackbody

Predicted Emissivity

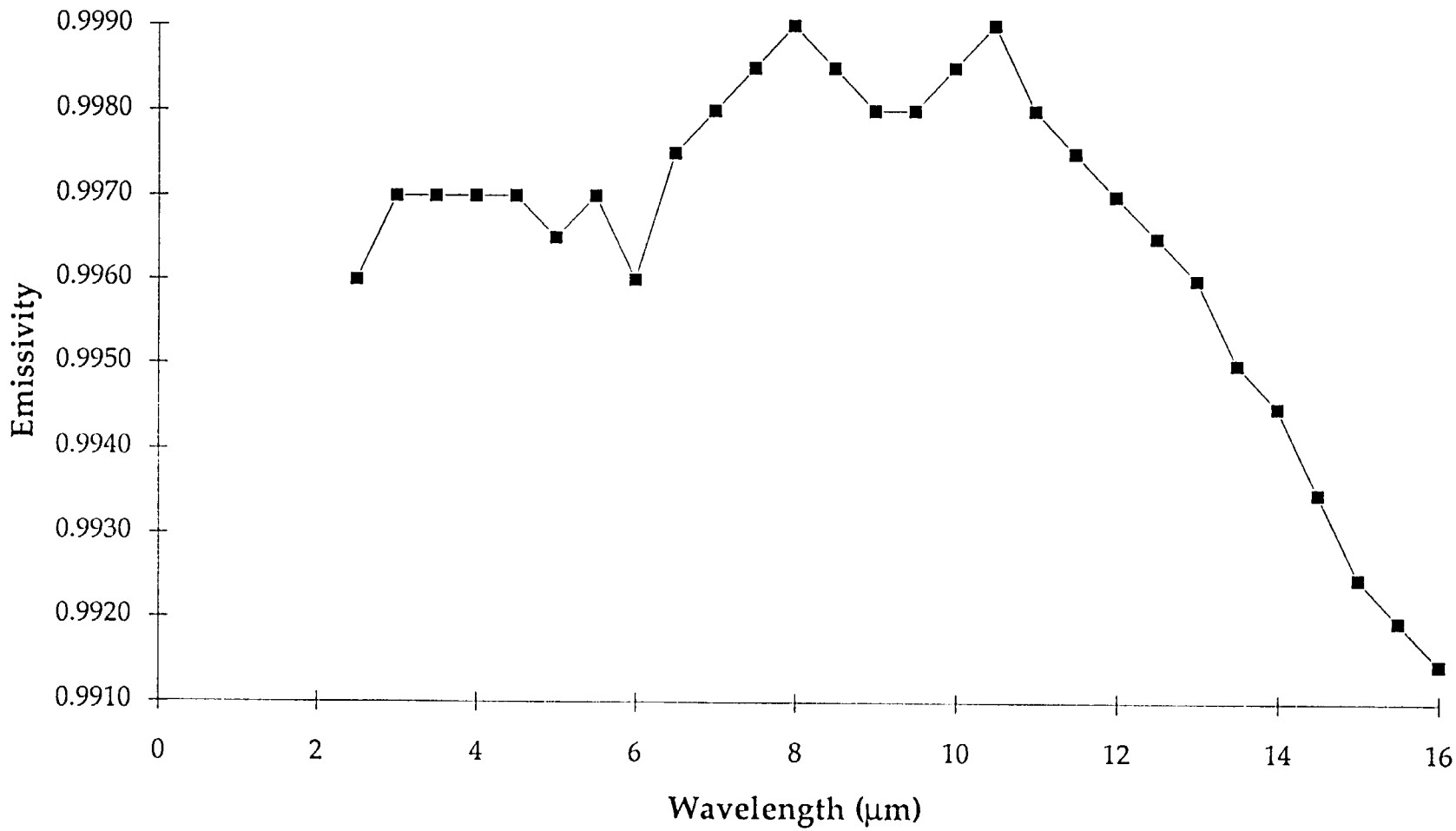


Dan Knowles Jr.

MODIS Algorithm Team Meeting
2 Mar, 1994

MODIS Blackbody Emissivity vs Wavelength

- Calculation based on type II anodized aluminum data applied to the SBRC emissivity equation

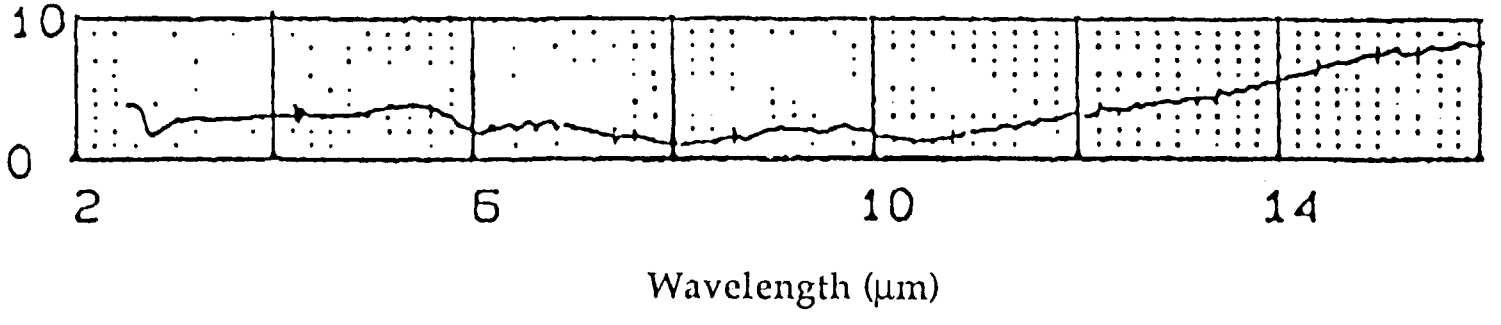


Reflectance of Black Anodized Aluminum

Candidate Anodized Aluminum Material for MODIS Blackbody:

- 6101-T6
- 1100-H18
- 1100-annealed

%Reflectance Plot of Type II Black Anodized Aluminum



Derivation of V-Groove Blackbody Emissivity Equation

$$\varepsilon(\lambda)=1-P(\lambda)$$

where; $P(\lambda)$ = reflectance of blackbody

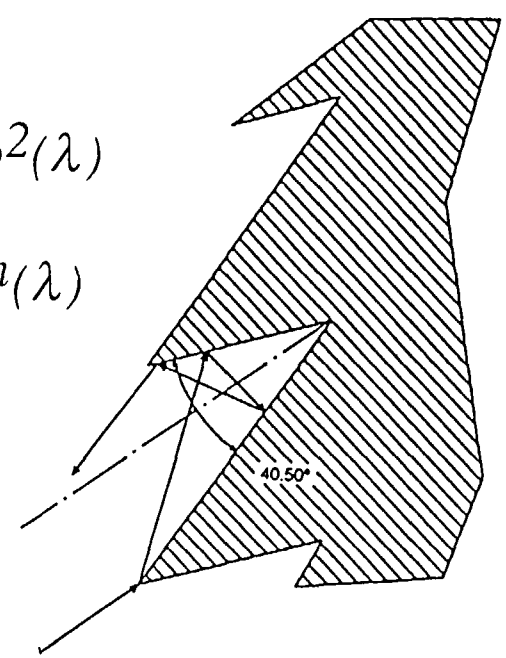
if light undergoes one specular reflection then $P_1(\lambda)=\rho(\lambda)$

if light undergoes two specular reflections then $P_2(\lambda)=\rho(\lambda)P_1(\lambda)=\rho^2(\lambda)$

if light undergoes n specular reflections then $P_n(\lambda)=\rho(\lambda)P_{n-1}(\lambda)=\rho^n(\lambda)$

if light undergoes a variety of reflections with k as its maximum then

$$\varepsilon(\lambda)=1-\sum_{n=1}^{k} w_n \rho^n(\lambda)$$



Calculated Emissivity of the MODIS Blackbody

$$\varepsilon(\lambda)=1-\sum_{n=1}^{k} w_n \rho^n(\lambda)$$

k = # of spectral reflections

$\rho(\lambda)$ = reflectance of black anodized aluminum

w_1 = 0.1 (10% weight for one specular reflection)

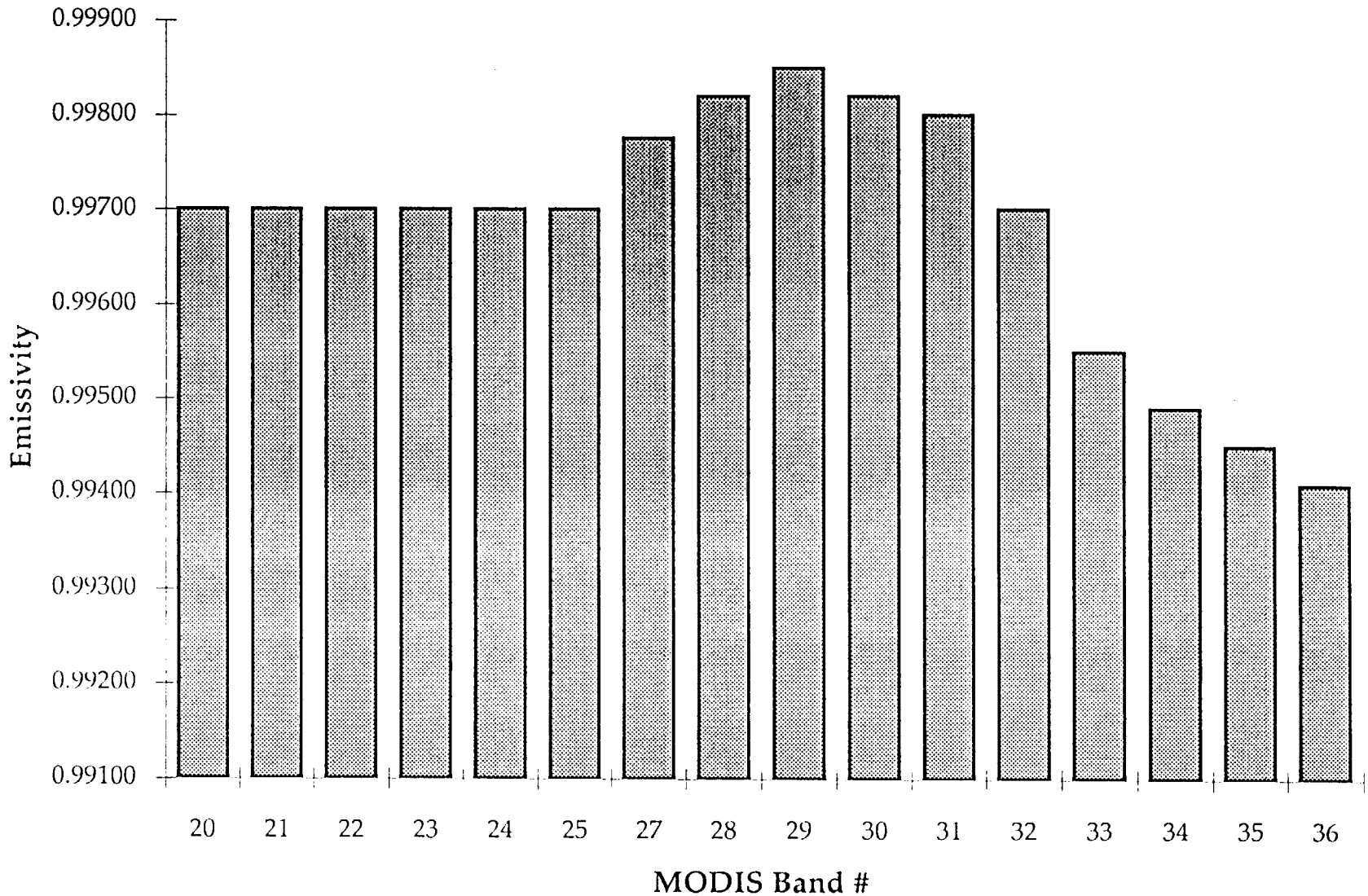
w_4 = 0.9 (90% weight for four specular reflections)

The MODIS V-groove blackbody is designed such that 90% of the reflected light undergoes at least four specular reflections. The remaining 10% undergoes at least one specular reflection. Therefore, emissivity can be calculated as follows:

$$\varepsilon(\lambda)\geq 1-(w_4\rho^4(\lambda)+w_1\rho(\lambda))$$

Emissivity vs MODIS Band

• Calculation based on type II anodized aluminum data applied to the SBRC emissivity equation



Level-1B Heritage Delivery

Djikstraa Diagrams

Top Level Flow Diagrams

Space View Emissive, Blackbody & Emissive Characterization Diagrams

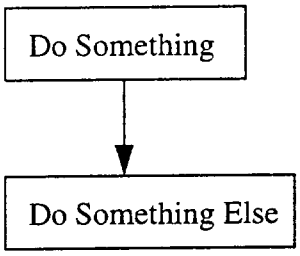
Comparison of Heritage to proposed SBRC treatment of blackbody

Elements of Djikstraa Diagrams

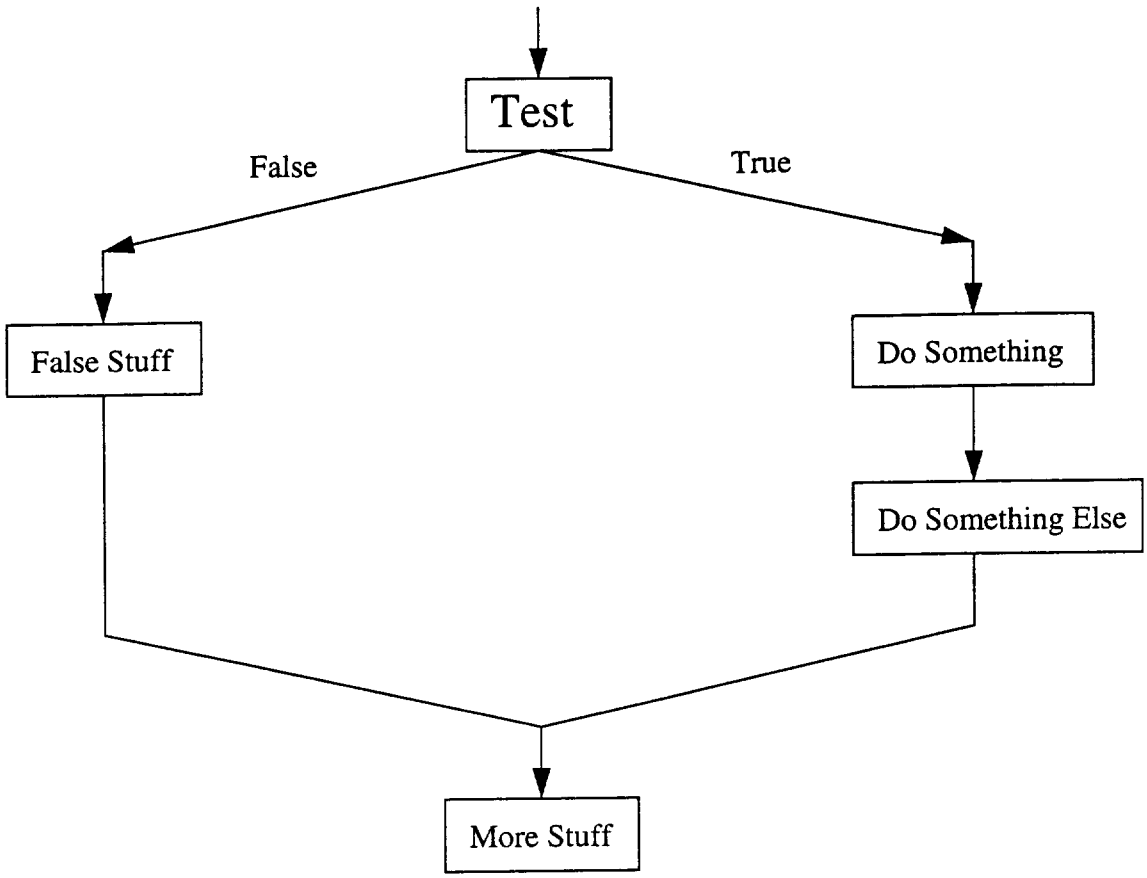
Indicates start of program or sub-routine

Indicates end of sub-routine

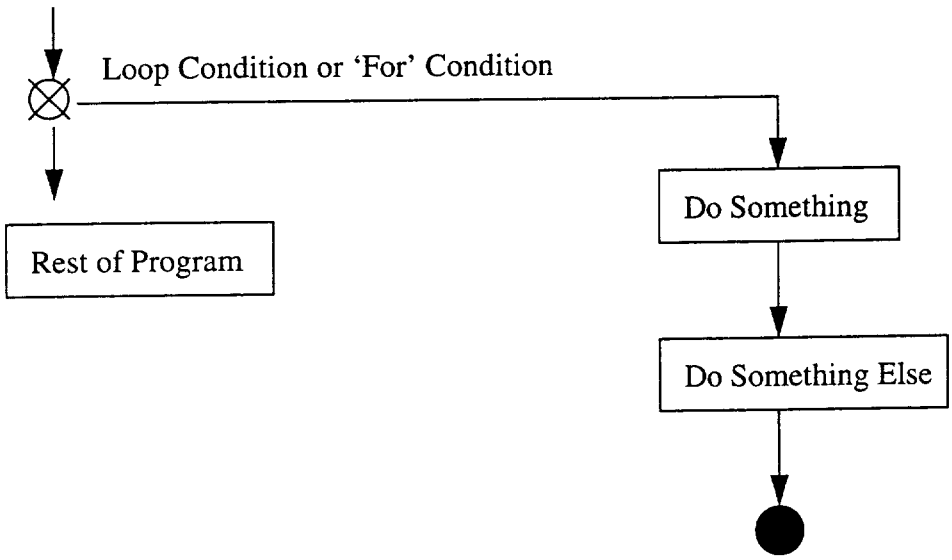
Indicates end of program



Indicates Flow of Controll

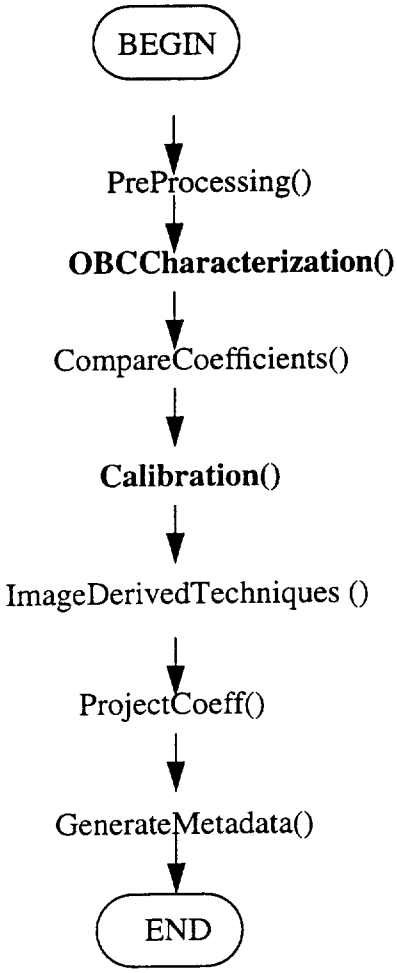


Indicates a branch

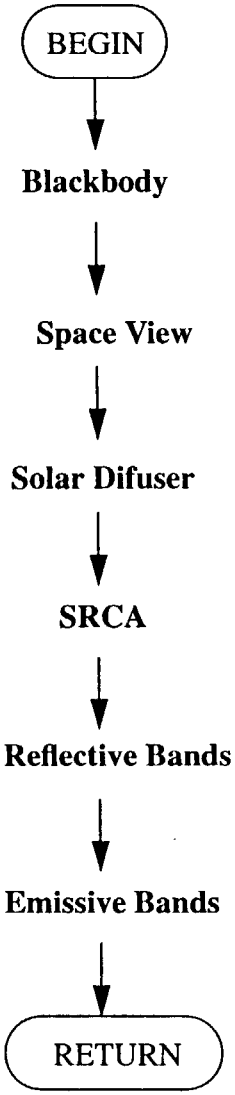


Indicates a Pre-Test Loop

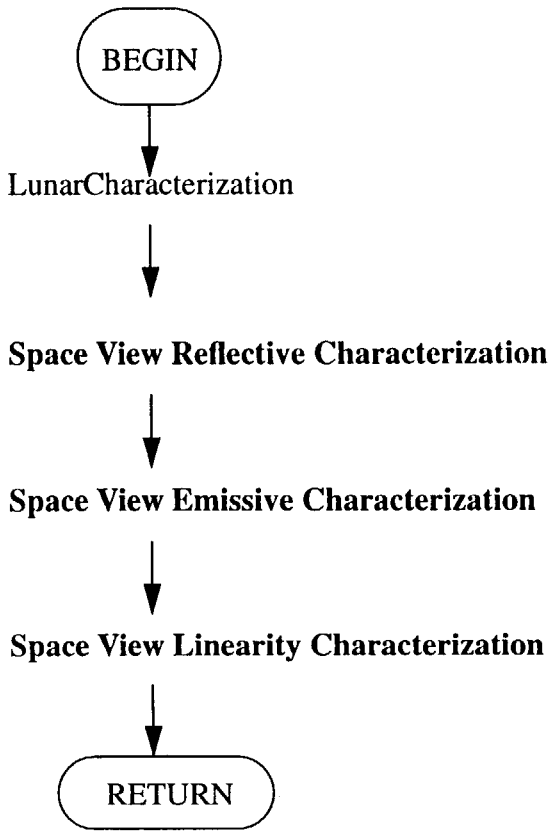
Level 1B Processing



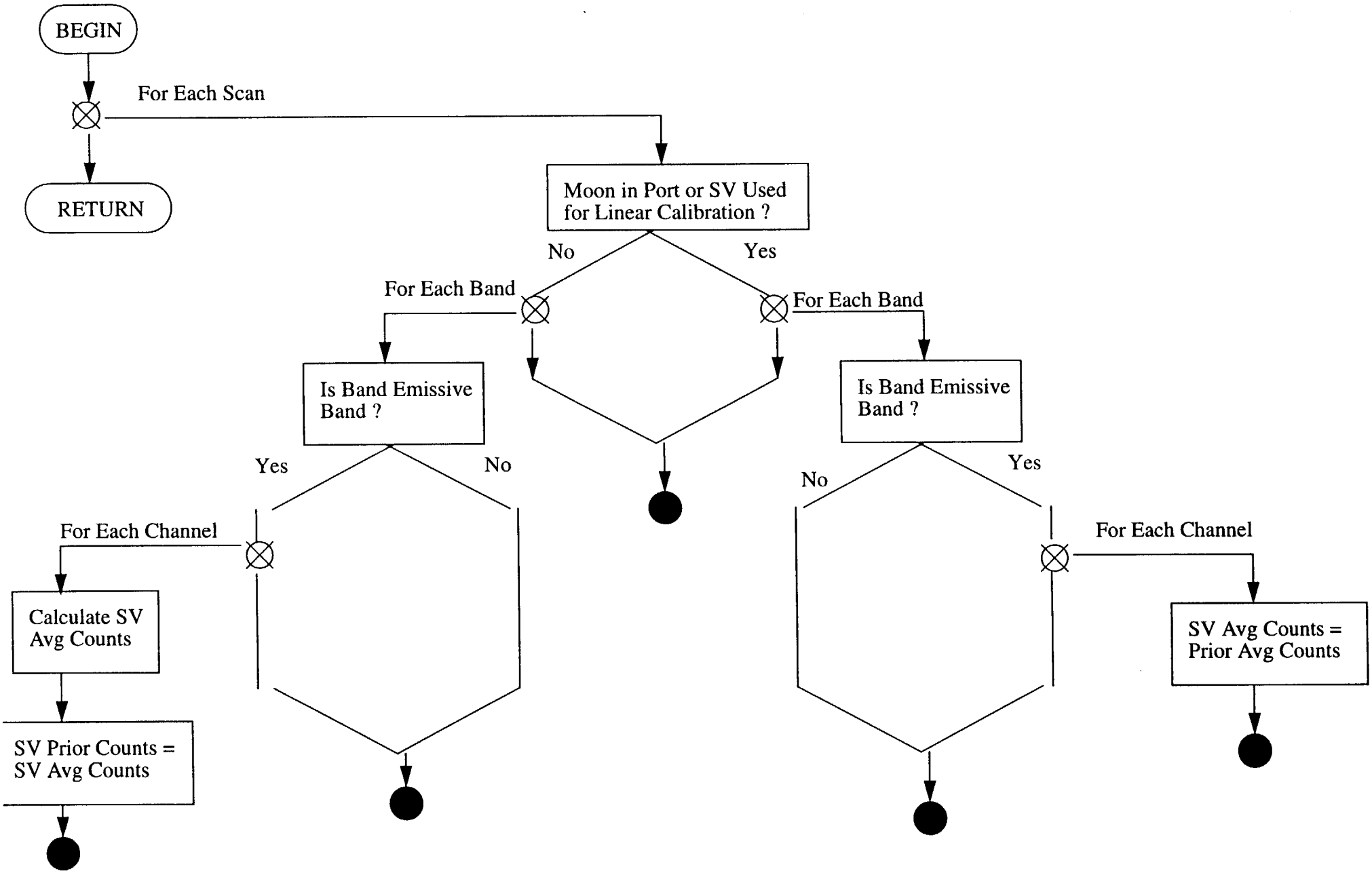
OBCCharacterization



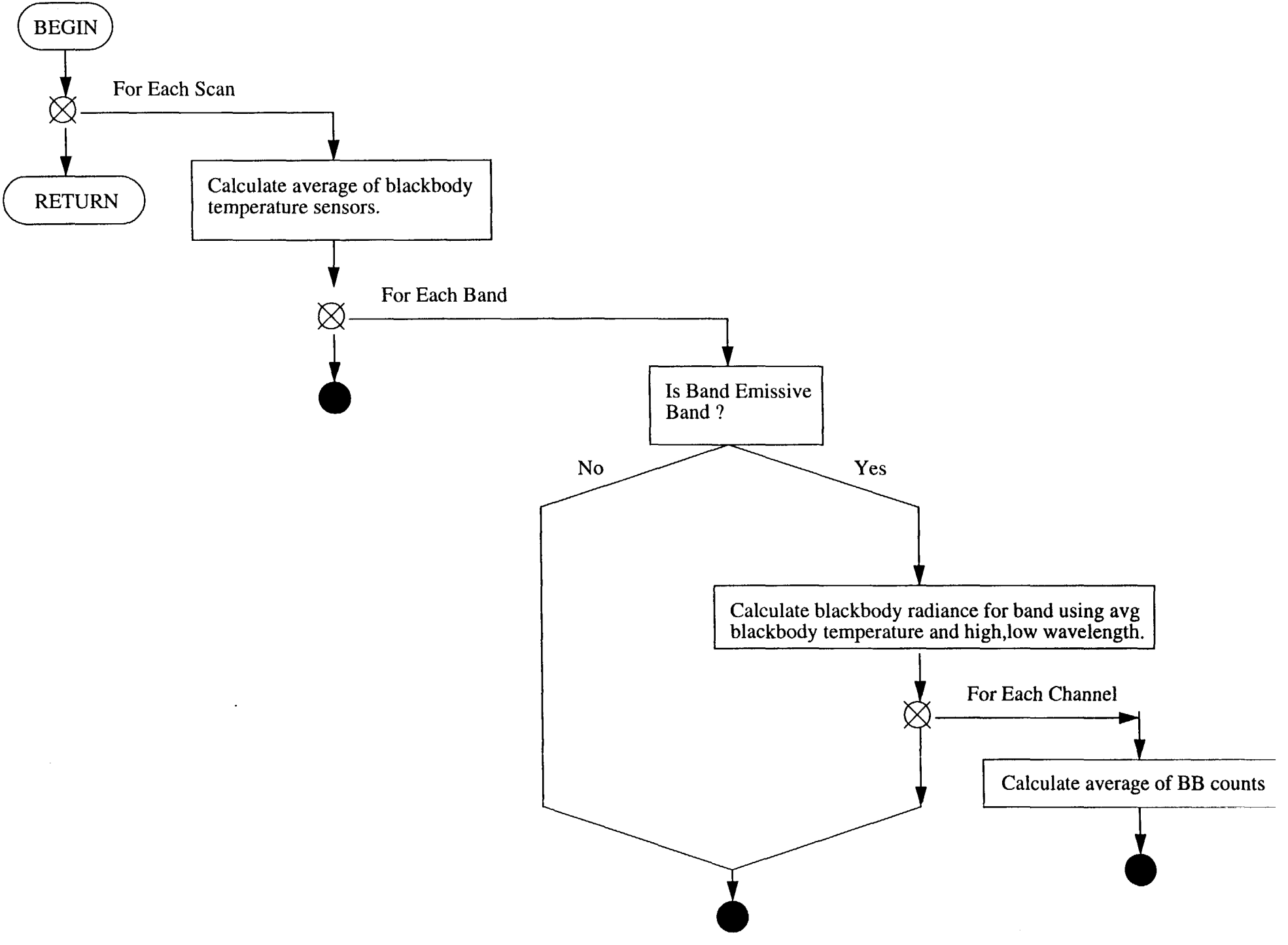
Space View Characterization

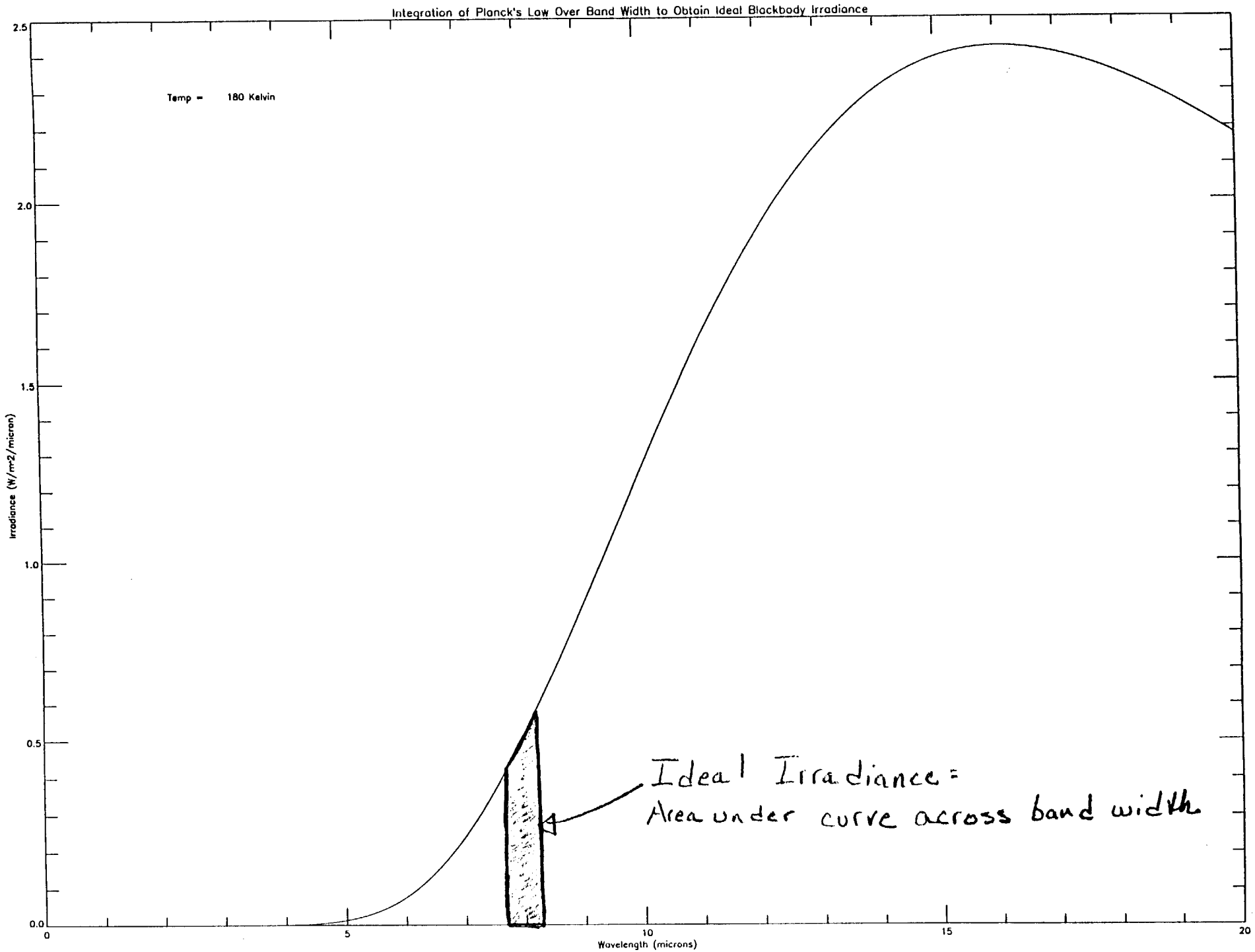


Space View Emissive Characterization

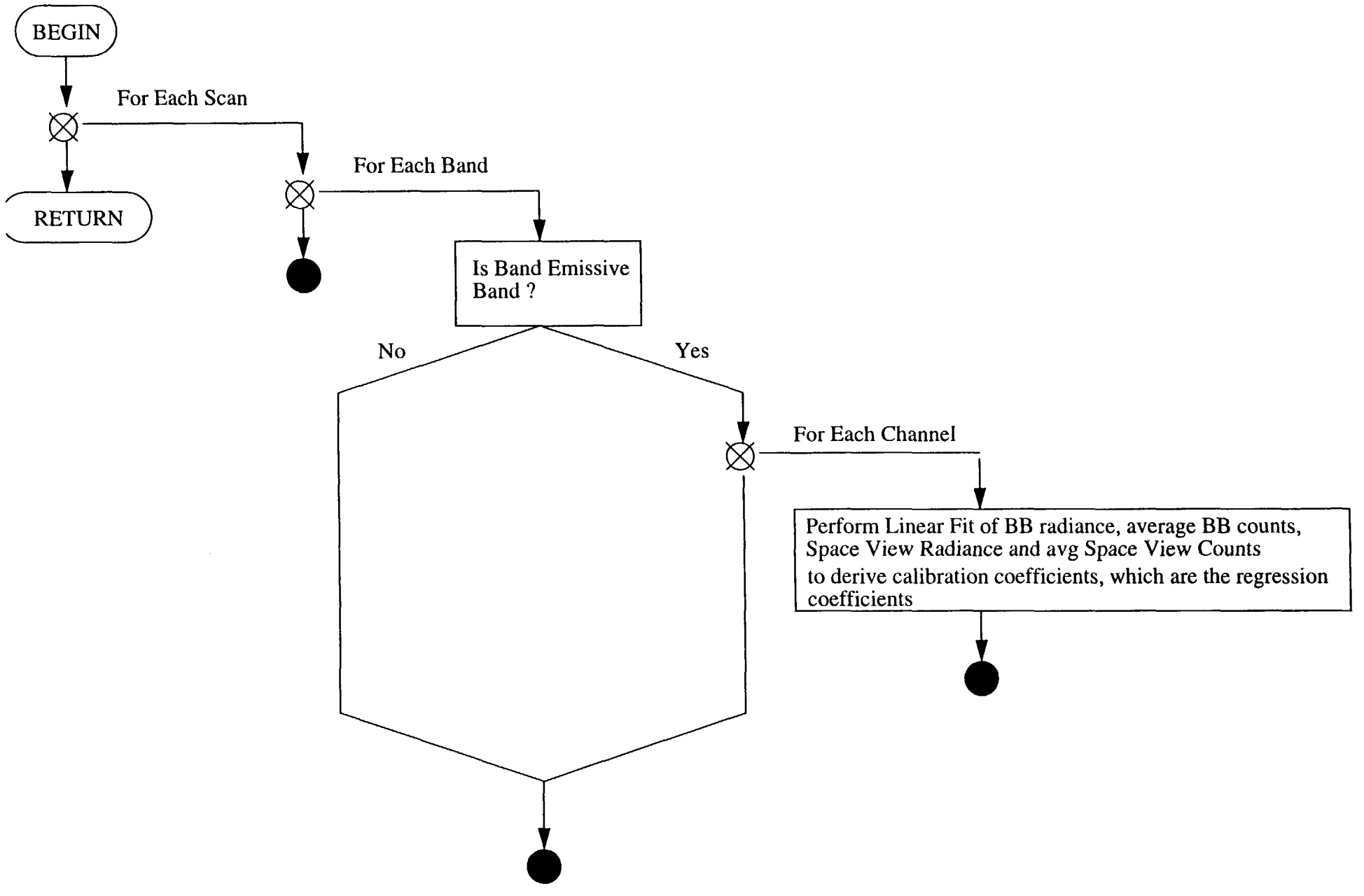


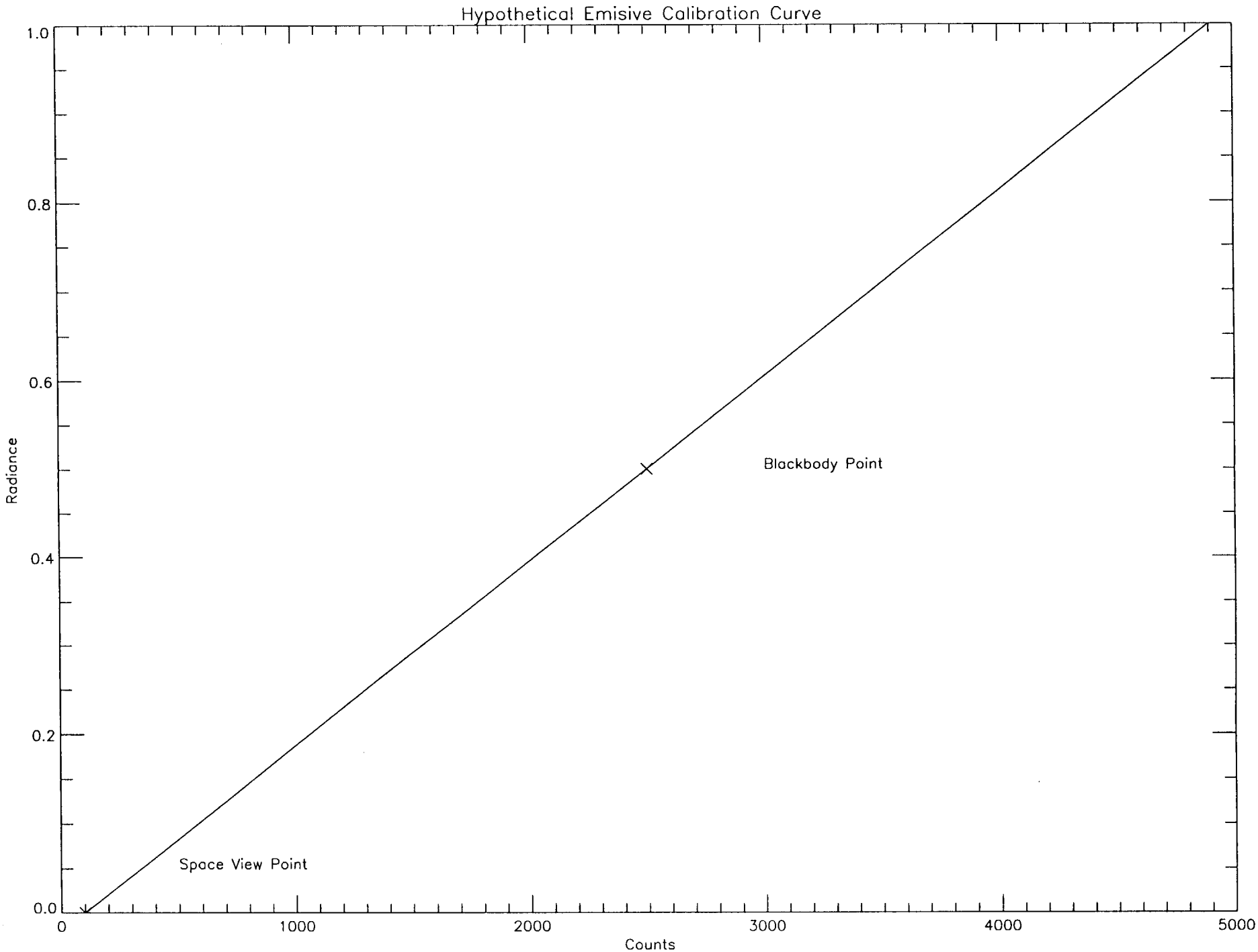
Blackbody Characterization




Integration of Planck's Law Over Band Width to Obtain Ideal Blackbody Irradiance
Temp = 180 Kelvin
Irradiance (W/m^2/micron)
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
Wavelength (microns)
Ideal Irradiance =
Area under curve across band width

Emissive Characterization




Hypothetical Emisive Calibration Curve
Radiance
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
Counts
Blackbody Point
Space View Point

3.3 Blackbody Radiometric Calibration (MWIR/LWIR) IN-FLIGHT ALGORITHMS

The OBC blackbody and space views are used to calibrate all MWIR and LWIR bands and channels. This calibration involves several phases briefly outlined below. The scenario assumes that the blackbody has an emissivity less than unity and its temperature nonuniformity needs to be corrected. Preliminary thermal modeling indicates temperature gradients of less than 0.03K and 0.3K for ambient and 315K operation, respectively. The following steps are used:

- Record all blackbody temperature sensors (12),Tbbi.
- Record scan cavity wall temperature sensors, Tcavity.
- Calculate effective blackbody temperature for all MODIS signals. Note that MODIS entrance aperture is scanned across the blackbody. In addition the detector array length produces a projection translation along track.
- For a given channel (Ch#) of spectral band (B#) the temperature used in the dc restoration algorithm is the average of effective temperature along scan.
- Record all MODIS signals, DN_bb (B#, Ch#, FD#), as system is scanned across the blackbody.
- Record all MODIS signals, (DN_sp (B#, Ch#, FD#), as they scan across the space view port.
- Calculate temperature gradient across paint layer, ΔTp. This can be a single value for all locations on the blackbody.
- Calculate average space signal: $DN_sp_avg(B\#,Ch\#) = \frac{\sum DN-sp(B\#,Ch\#,FD\#)}{\sum FD\#}$
- Calculate responsivity:

$$R(B\#,Ch\#,FD\#) = \frac{DN_bb(B\#,Ch\#,FD\#) - DN_sp_avg(B\#,Ch\#)}{\Delta L}$$

where

$$\Delta L(B\#,Ch\#,FD\#) = Ebb * L(Teff(B\#,Ch\#,FD\#)) + \frac{(1-Ebb) * Lcavity * \Omega cavity}{\pi} + \frac{(1-Ebb) * Learth * \Omega earth}{\pi}$$

- Calculate average responsivity: $R(B\#,Ch\#) = \frac{\sum R(B\#,Ch\#)}{\sum FD\#}$
- Scene radiance algorithm

$$L(B\#,Ch\#) = \frac{DN_scene(B\#,Ch\#,FD\#) - DN_sp_avg(B\#,Ch\#,FD\#)}{R(B\#,Ch\#)}$$

The final algorithms are expected to include effects of varying MODIS instrument thermal backgrounds. It is expected that at least the PC HgCdTe detectors will need to have this type of correction.

Some SRCA Spatial Calibration Issues:

Error sources in centroid determination

- Low SNR
- MTF degradation - SRCA image quality v.s. MODIS changes
- Distortion, relative rotations of FPAs and SRCA
- Along track- detector-to-detector variations
- Non-uniform SRCA illumination
- Scan dependencies due to SRCA optical configuration (MTF variation, illumination angle)
- Reticle repeatability - mechanical tolerances of SRCA/environmental influences
- integrator reset time

Additional analyses of SRCA Spatial Calibration data

- MTF/LSF - separation of MODIS effects
- IFOVs - input to geometrical correction of images?
- statistics - can enough data be gathered, and can measurement driftsbe accounted for?

MAT Presentation

MODIS Solar Diffuser Geometry

MODIS Algorithm Team of the
MCST (MODIS Characterization Support Team)

Harry Montgomery, Manager
MODIS Instrument Characterization

Code 925 - Sensor Development and Characterization Branch
NASA / Goddard Space flight Center, Greenbelt, Maryland 20771
FAX: (301) 286-1757

Paul E. Anuta, Edward Knight, Tom Bryant

Research and Data Systems Corporation (RDC)
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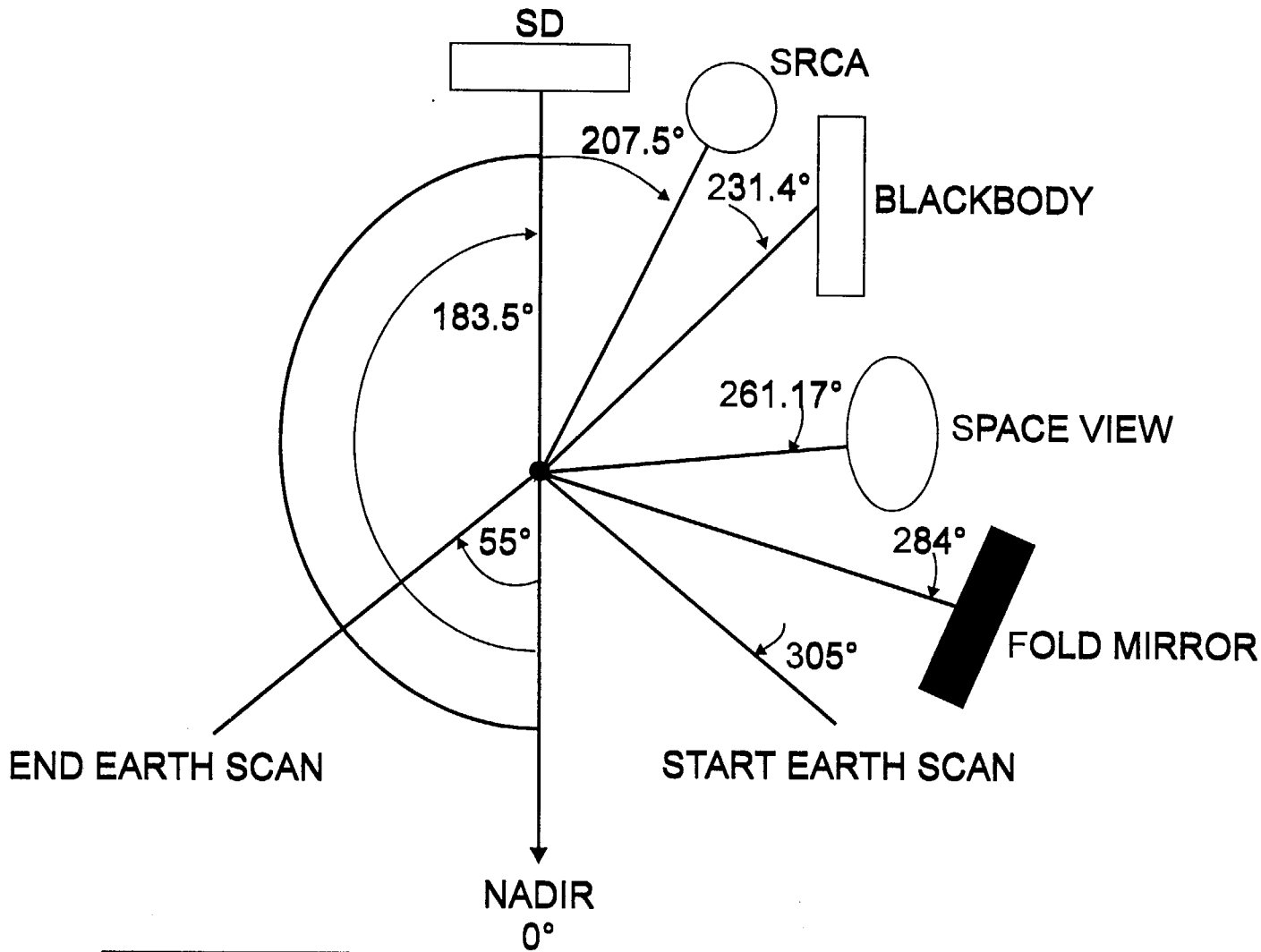
Presented by Paul E. Anuta

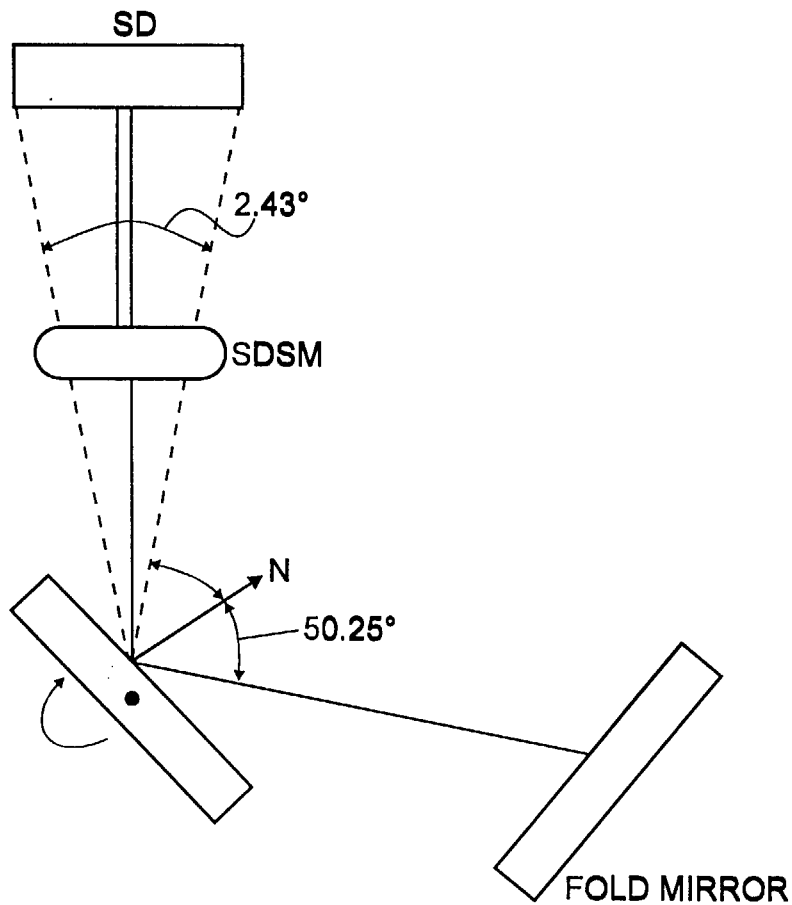
February 23, 1994

MODIS Event Angles



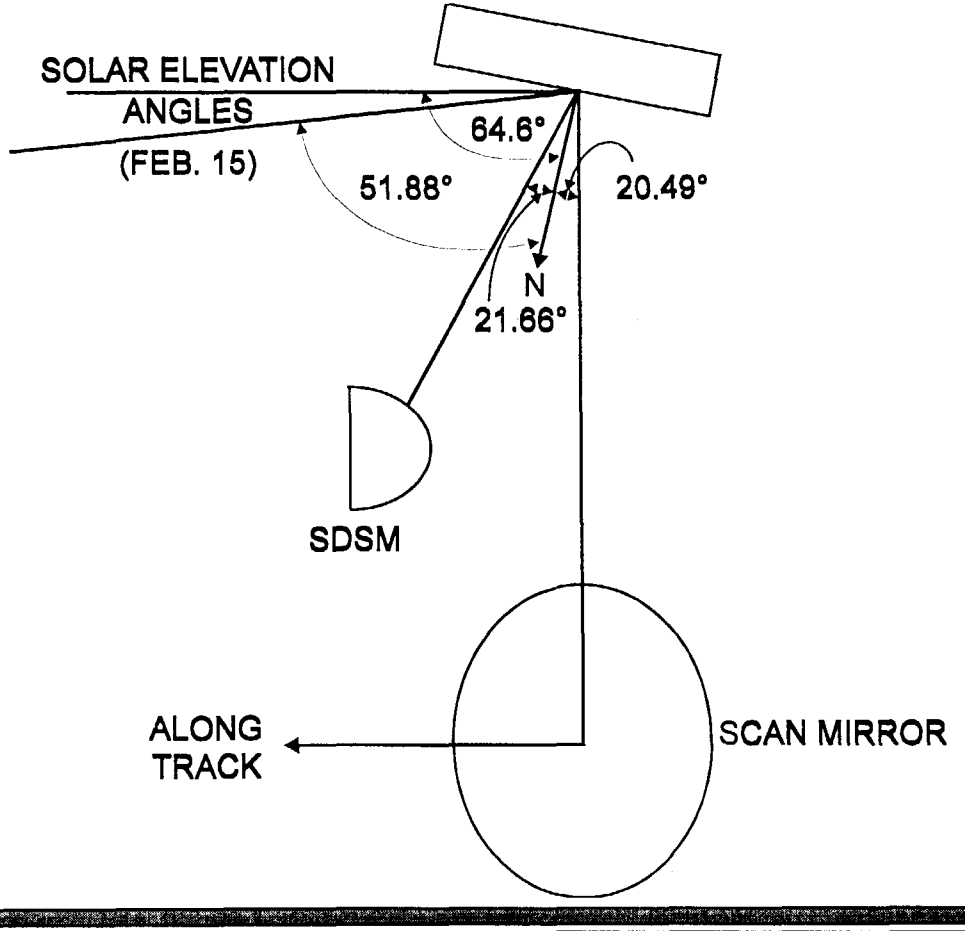
MODIS Solar Diffuser Geometry–I

FORWARD ALONG TRACK VIEW



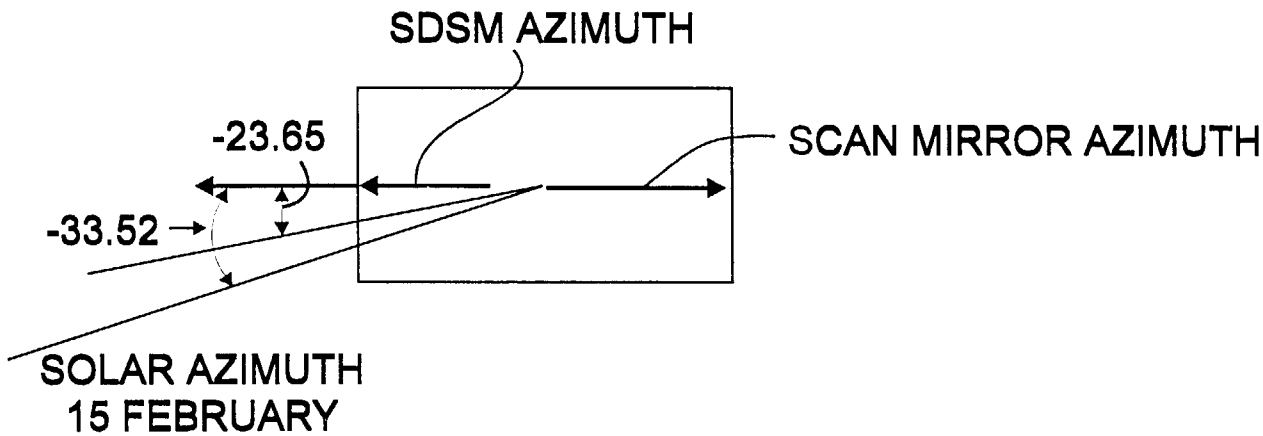
MODIS Solar Diffuser Geometry–II

ACROSS TRACK VIEW



MODIS Solar Diffuser Geometry-III

UPWARD ZENITH VIEW



Scan Mirror Angle of Incidence

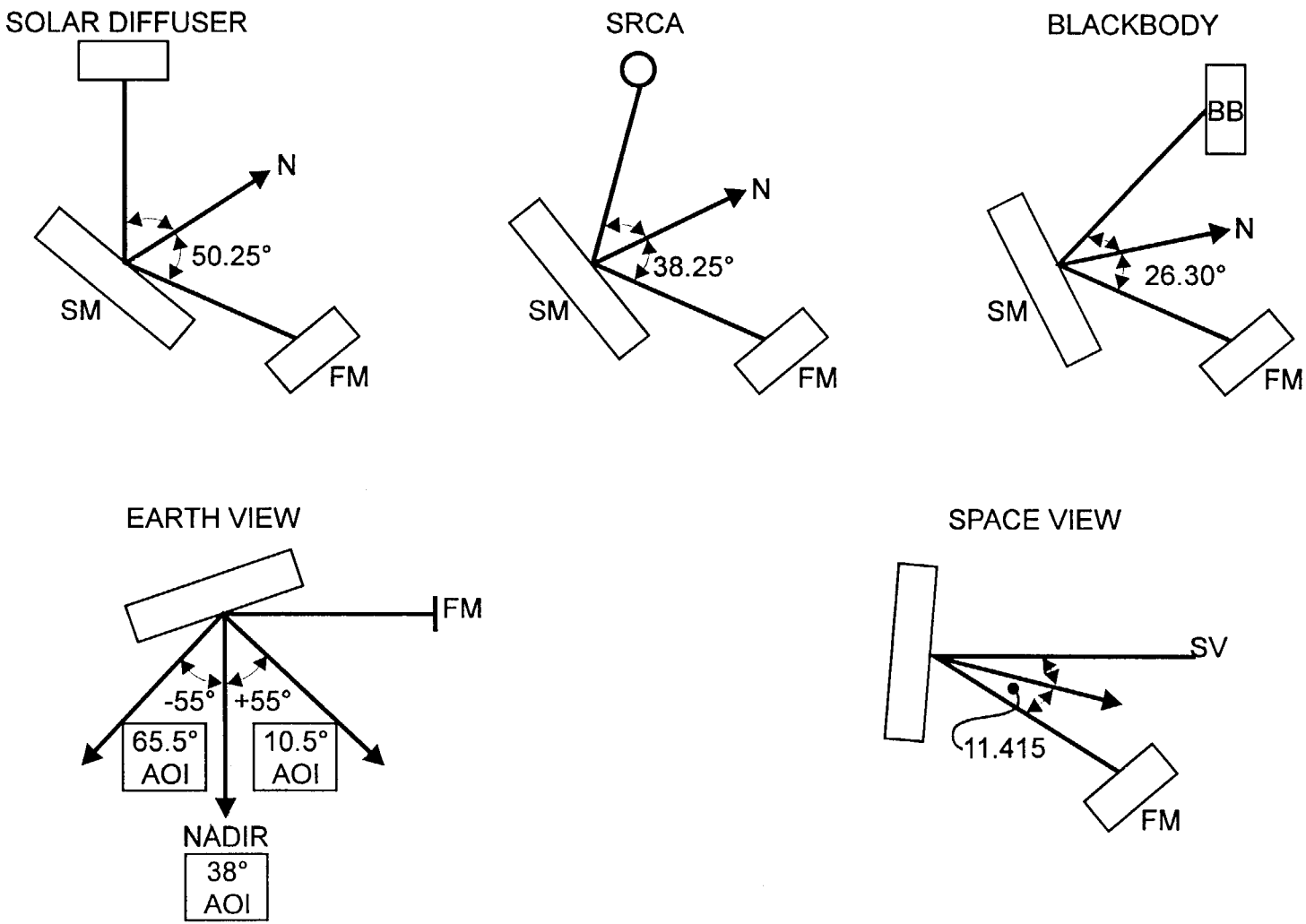


Table VII
Solar Diffuser Albedo for 15 February, + Orbit Tolerance
for Solar Diffuser Inclination Angle = 20.2 Degrees

Orbit Angle in Deg	Solar Decl in Deg	Eq. of Time & Tolerance in Deg	Hmin in Km	Solar View Decl in Deg	Solar View Az in Deg	Solar Incidence Angle on SD	Albedo	SD_Fwd_Ray in Km from Terminator
254.06	-12.6	7.32	211.86	21.92	-33.52	51.88	0.611	2359.7
254.56	-12.6	7.32	230.99	21.5	-33.41	52.26	0.606	2313.9
255.06	-12.6	7.32	249.79	21.08	-33.31	52.64	0.601	2267.8
255.56	-12.6	7.32	268.26	20.66	-33.2	53.02	0.596	2221.3
256.06	-12.6	7.32	286.4	20.25	-33.1	53.4	0.59	2175.1
256.56	-12.6	7.32	304.2	19.83	-33	53.79	0.585	2129.3
257.06	-12.6	7.32	321.67	19.41	-32.9	54.18	0.579	2082.4
257.56	-12.6	7.32	338.79	18.99	-32.81	54.57	0.574	2035.8
258.06	-12.6	7.32	355.57	18.57	-32.72	54.95	0.568	1989.5
258.56	-12.6	7.32	372	18.15	-32.63	55.35	0.563	1943.2
259.06	-12.6	7.32	388.08	17.72	-32.54	55.74	0.557	1896.1
259.56	-12.6	7.32	403.81	17.3	-32.46	56.13	0.552	1849.4
260.06	-12.6	7.32	419.19	16.88	-32.37	56.52	0.546	1803.1
260.56	-12.6	7.32	434.22	16.46	-32.29	56.92	0.54	1756.1
261.06	-12.6	7.32	448.88	16.04	-32.21	57.31	0.535	1708.9
261.56	-12.6	7.32	463.19	15.61	-32.14	57.71	0.529	1662.2
262.06	-12.6	7.32	477.13	15.19	-32.07	58.11	0.523	1615.9
262.56	-12.6	7.32	490.71	14.77	-32	58.51	0.517	1568.2
263.06	-12.6	7.32	503.93	14.34	-31.93	58.91	0.511	1521
263.56	-12.6	7.32	516.77	13.92	-31.86	59.31	0.505	1474.2
264.06	-12.6	7.32	529.25	13.49	-31.8	59.71	0.499	1427.6
264.56	-12.6	7.32	541.35	13.07	-31.73	60.12	0.493	1379.7
265.06	-12.6	7.32	553.08	12.64	-31.67	60.52	0.487	1332.4
265.56	-12.6	7.32	564.44	12.22	-31.62	60.92	0.481	1285.7
266.06	-12.6	7.32	575.42	11.79	-31.56	61.33	0.475	1238.6
266.56	-12.6	7.32	586.02	11.36	-31.51	61.74	0.469	1190.6
267.06	-12.6	7.32	596.25	10.94	-31.46	62.14	0.463	1143.3
267.56	-12.6	7.32	606.09	10.51	-31.41	62.55	0.456	1096.7
268.06	-12.6	7.32	615.55	10.08	-31.36	62.96	0.45	1049.1
268.56	-12.6	7.32	624.62	9.66	-31.31	63.37	0.444	1001.1
269.06	-12.6	7.32	633.31	9.23	-31.27	63.78	0.437	953.8
269.56	-12.6	7.32	641.62	8.8	-31.23	64.19	0.431	907.4
270.06	-12.6	7.32	649.54	8.37	-31.19	64.6	0.425	859.3

Solar Diffuser Albedo for 15 February, - Orbit Tolerance
for Solar Diffuser Inclination Angle = 20.2 Degrees

Orbit Angle in Deg	Solar Decl in Deg	Eq. of Time & Tolerance in Deg	Hmin in Km	Solar View Decl in Deg	Solar View Az in Deg	Solar Incidence Angle on SD	Albedo	SD_Fwd_Ray in Km from Terminator
257.26	-12.6	-0.2	255.05	20.97	-25.27	51.14	0.621	2212.8
257.76	-12.6	-0.2	274.89	20.52	-25.19	51.57	0.615	2162.8

SWALES & ASSOCIATES, INC.

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Feb. 25, 1994

To: H. Montgomery, Code 925.0

From: I.L. Goldberg, SAI

Subject: Comments On SBRC Memo Concerning MODIS Calibration

Reference: "Gain Coefficients for Radiometric Calibration: Version 2", T. Pagano, October 4, 1993, PL3095-M03082.

My intention is to make some constructive criticisms. In this memo I write neither to praise nor bury SBRC (although, in general, I think SBRC is praiseworthy).

1. There seems to be an oversight in the information that is needed for the calibration of a detector (particularly Hg CdTe operating in the thermal infrared) when it is <u>inside an instrument</u> like MODIS. This is apparent from remarks made in the Introduction. "The technique defined in this memo calibrates the system in a way that is independent of the internal optics temperature." and "The technique refers all measurements of digital number back to the FPA signal voltage. In doing so, the source of the nonlinearity, the detectors, are calibrated". The system voltage measurements can be referred back to the FPA (focal plane array) signal output, but calibration of a detector also requires (in addition to the effect of background radiation) knowledge of <u>signal</u> irradiance (actually the incident signal radiant power is more fundamental). The magnitude of the non-linearity of the transfer curve depends on the maximum signal irradiance at the detector in the calibration measurements. <u>Signal irradiance is optics temperature sensitive</u>. The effect on calibration due to a temperature change in the optical system (transmission, image quality) is usually greater than that due to the background radiation change (see my report "Behavior of PC HgCdTe Radiometer Channels").

2. In the section <u>Nonlinear Gain Correction</u> the voltage V_{ij} of the output of the FPA is described as a quadratic function of the sum of scene radiance L_{ij} and effective radiance due to the background L_0 in the form

$$V_{ij} = a_{1i}(L_{ij}+L_0) + a_{2i}(L_{ij}+L_0)^2 + V_0$$

This is not the preferred way to describe the behavior of signal voltage. From the dominant term (first term on the right hand side) it would appear that V_{ij} would increase if L_0 is increased when the opposite would actually occur. Of course the coefficients

would have to be adjusted to agree with the data, but the form of the equation unnecessarily complicates matters, particularly when it is realized that neither the slope nor the curvature of V_{ij} is proportional to the term $(L_{ij}+L_0)$.

In orbit, L_0 varies much more slowly than V_{ij}. In fact L_0 is essentially constant during a line scan. In the laboratory, changes that occur in the optical system and background when the instrument temperature is changed are reflected in the a_{ij} and V_0 values of the conventional calibration equation in which L_0 does not appear.

3. At the end of the <u>Nonlinear Gain Correction</u> section it is recommended that polynomials of higher degree than 2 be used. It states, "This is recommended since it is better to gain correct with a curve more representative of the final response than the second order polynomial used originally". This statement is not as obvious as it appears to be. If the non-linearity is no greater than a few % then expressing signal voltage with higher order terms is not necessarily better because it may too closely resemble the imperfect data and defeat the purpose of a LMS fit. As an illustration take the extreme case of a sufficiently high order polynomial curve that passes through every data point. The RMS deviation of the measurements from this curve is zero! Is this ideal? Even if the curve is well behaved it is not as good as a lower order curve that smoothes out the random measurement errors. From the data I have seen so far I am of the opinion that the calibration equation does not warrant the third degree.

Larry Goldberg

P.S. It would be very helpful in understanding what actually takes place in the HgCdTe channels if a thorough description of the characteristics and behavior of the HIT detectors that will be used on MODIS is made available. At least one of the MODIS teams should be interested in such detailed knowledge.

cc: J. Barker, Code 925.0
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SANTA BARBARA RESEARCH CENTER
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INTERNAL MEMORANDUM

TO: Distribution	CC: L. Candell	DATE:	October 4, 1993
	R. Durham	REF:	PL3095-M03082
	O. Weinstein	FROM:	T. Pagano
	G. Barnett	BLDG:	B32
		MAIL STA:	79
		EXT:	7343

SUBJECT: Gain Coefficients for Radiometric Calibration: Version 2

References

1) "Gain/Offset and SNR Algorithms for MODIS (Preliminary)", T. Pagano, June 29, 1993, PL3095-M02698

2) "Gain Coefficients for Radiometric Calibration", T. Pagano, August 25, 1993, PL3095-2950

3) "Linearity Measurement Concept for MWIR and LWIR Regions", J. Young, June 30, 1993, PL3095-N02693

Introduction

This memorandum defines a way to calibrate the MODIS response in a way that is independent of variations in optics temperature. It is an update from the previous memo (reference 2) and includes more explicit expressions for the variables.

Typically system responses are found for every possible instrument operating temperature during thermal vacuum. This can lead to errors in that the in-orbit configuration may not be acurately simulated during thermal vac. The technique defined in this memo calibrates the system in a way that is independent of the internal optics temperature. The technique refers all measurements of digital number back to the FPA signal voltage. In doing so, the sources of the nonlinearity, the detectors, are calibrated. It is assumed that this response is more stable than the responses that would normally be found through thermal vacuum temperature cycling. Both methods ultimately will be compared to verify the approach.

Transfer Curve Measurement

The standard approach for measuring the transfer curve of the MODIS is to vary the source radiance and acquire numerous data points. Three conditions must be satisfied to acquire accurate data:

1) Source absolute radiance must be known to within allowable budget: 2.28% radiance, 1.25% reflectance in reflective bands, and 0.45% in emissive bands except 31, and 32 which need 0.16% (see Table 1).

2) Source stability must be maintained throughout measurement to within 0.05% (IR), 0.25% (Reflective). If this is not possible, then knowledge of the stability to these values will suffice.

3) Sufficient samples must be acquired to achieve an SNR of 1000:1 (IR), and 1000:1 (Reflective). The number of samples required to achieve this depends on the radiance level under measurement. Total samples includes all frames within the FOV and multiple scans of data.

The key to determining the transfer curve is the correction for 1st order gain based on the on-board calibrator data, and the corrections applied to the calibration source for instabilities. This algorithm description addresses the former, and not the latter.

Digital Number vs Radiance

The objective of this measurement is to derive a set of calibration coefficients that describe the MODIS digital number, DN, vs radiance, L; i.e. the transfer curve. The calibration coefficients are coefficients of an Nth order polynomial which describes the transfer curve. Since the data is acquired over a long period of time, a correction must be made for drifts in instrument responsivity and background from the optics. This correction is made using the on-board calibrator and the space view respectively. Once the transfer curve is known, then it can be used in-orbit in conjunction with the on-board calibrator DN to determine the instrument radiance. A technique for non-linear gain correction and background/drift correction are described below.

The VIS, NIR and SWIR bands most likely will not require drift correction since the measurement can be made over a significantly shorter time period. If drift correction is required, then see the SNR algorithm for correction using the FPA temperature telemetry. The algorithm described below applies to all bands, however, since it may be desireable to use a calibration target equivalent to the on-board blackbody for the reflective bands.

Nonlinear Gain Correction

The non-linear gain correction method involves using the original data set to get an estimate of the shape of the transfer curve first, then returning to the original data and applying the non-linear correction curve rather than a linear correction. By iterating the process, a better fit to the true transfer curve can be obtained (reference 3)

The process begins with obtaining a sample on the ground based calibrator and another sample on the on-board calibrator for a single scan. A second order polynomial is fit to the two points. We must work in the voltage domain at the output of the FPA to allow for changes in background and to include the effects of DC restore

$$V_{ij} = a_{1i} (L_{ij} + L_o) + a_{2i} (L_{ij} + L_o)^2 + Vo$$

where

V_{ij} = Voltage of the output of the FPA

Vo = Voltage From the FPA for Zero Radiance at the FPA

L_{ij} = Radiance at the Aperture of the MODIS

L_o = Effective Radiance at the Space Port Due to the Background of the Instrument

a_{1i} = gain coefficient of the 1st order term

a_{2i} = gain coefficient of the 2nd order term

We can obtain the voltages at the FPA from the digital number measured with knowledge of the analog electronics gain and offset to 12 bits.

$$V_{ij} = \frac{DN_{ij} - DN_o}{G\ R_{A/D}} - \Delta V_i - Vo$$

where

DN_{ij} = Measured Digital Number
DN_o = Digital Number Offset Programmed into AEM
G = Gain for particular channel in the AEM (Volts/Volts)
$R_{A/D}$ = Responsivity of the A/D (DN/Volts)
ΔV_i = Offset Applied in the AEM

The coefficients must be evaluated for every pair of ground based and on-board calibrator data points. The method of solving for the coefficients uses the two data points. It can be shown with a little algebra (see attachment) that

$$a_{1i} = \frac{(V_{iF3} - Vo)\ (L_{iF2} + L_o)^2 \ - (V_{iF2} - Vo)\ (L_{iF3} + L_o)^2}{(L_{iF3} + L_o)\ (L_{iF2} + L_o)\ (L_{iF2} - L_{iF2})}$$

and

$$a_{1i} = \frac{(V_{iF2} - Vo)\ (L_{iF3} + L_o) \ - (V_{iF3} - Vo)\ (L_{iF2} + L_o)}{(L_{iF3} + L_o)\ (L_{iF2} + L_o)\ (L_{iF2} - L_{iF2})}$$

with

$$L_{oi} = \frac{-B - \sqrt{B^2 - 4\ AC}}{2\ A}$$

and

$$A = (V_{iF1} - Vo)\ (L_{iF2} - L_{iF3}) - (V_{iF3} - Vo)\ (L_{iF2} - L_{iF1}) + (V_{iF2} - Vo)\ (L_{iF3} - L_{iF1})$$

$$B = (V_{iF1} - Vo)\ (L_{iF2}^2 - L_{iF3}^2) - (V_{iF3} - Vo)\ (L_{iF2}^2 - L_{iF1}^2) + (V_{iF2} - Vo)\ (L_{iF3}^2 - L_{iF1}^2)$$

$$C = (V_{iF1} - Vo)\ (L_{iF2} - L_{iF3}) L_{iF2}\ L_{iF3} - (V_{iF3} - Vo)\ (L_{iF2} - L_{iF1}) L_{iF2}\ L_{iF1} + (V_{iF2} - Vo)\ (L_{iF3} - L_{iF1}) L_{iF3}\ L_{iF1}$$

where

F1 = Average Frame of the Space View Look
V_{iF2} = Voltage Measured When Viewing the Space View Port
L_{iF1} = Radiance in the Space View Port
F2 = Frame of the Ground Based Calibrator
V_{iF2} = Voltage Measured When Viewing the Ground-Based Calibrator
L_{iF2} = Radiance of the Ground Based Calibrator for the ith scan
F3 = Average Frame of the On-Board Calibrator
V_{iF3} = Average Voltage Measured When Viewing the on the On-Board Calibrator
L_{iF3} = Average Radiance of the On-Board Calibrator for the ith scan

The explicit forms above for a_1, a_2, and L_o in terms of measured variables is a refinement in the technique over that described in reference 2. a_1, a_2, and L_o are calculated for every scan (i). By computing the average of the polynomial coefficients, we can determine a single curve to which we can normalize all the data for gain correction.

$$a_{1av} = \frac{1}{NS}\sum_{i=1}^{NS} a_{1i} \cdot \frac{p_1}{p_i} \qquad a_{2av} = \frac{1}{NS}\sum_{i=1}^{NS} a_{2i} \cdot \frac{p_1}{p_i}$$

Offset correction is applied for every scan by the calculation of L_{oi}.

The average second order fit to the data set is simply

$$V_{ijav} = a_{1av}(L_{ij} + L_o) + a_{2av}(L_{ij} + L_o)^2 + Vo$$

This should be a reasonable second order fit to the entire data set.

Note that there is nothing preventing the algorithm from having more than one frame, j, of data per scan. An additional point in a single scan can be treated as having additional scan of data. The software should be capable of treating this situation. **Please note that every L_{ij} must be characterized a priori and independently of this algorithm.**

Now we can use the second order polynomial above and the on-board calibrator data to gain correct the original data set before we curve fit for higher orders. Each signal value obtained in the original data set must be "gain corrected" using the following equation

$$V_{iF2}'' = V_{iF2} \cdot \frac{V_{iF2av}}{V_{iF2}'}$$

where
V_{iF2} = Signal acquired when viewing the ground based calibratior for the ith scan
V_{iF2av} = Average second order fit to the data set evaluated at L_{F2}
V_{iF2}' = New Function which fits the on-board calibrator to the average curve. Evaluated at L_{F2}. See Below

This process corrects the original data point with the ratio of the value at L_{F2} of the average curve fit to the value at L_{F2} of the average curve fit scaled to the on-board calibrator. In other words, we use the average curve fit and the calibrator to scale, or normalize, the original data point. The process is shown graphically in Figure 1.

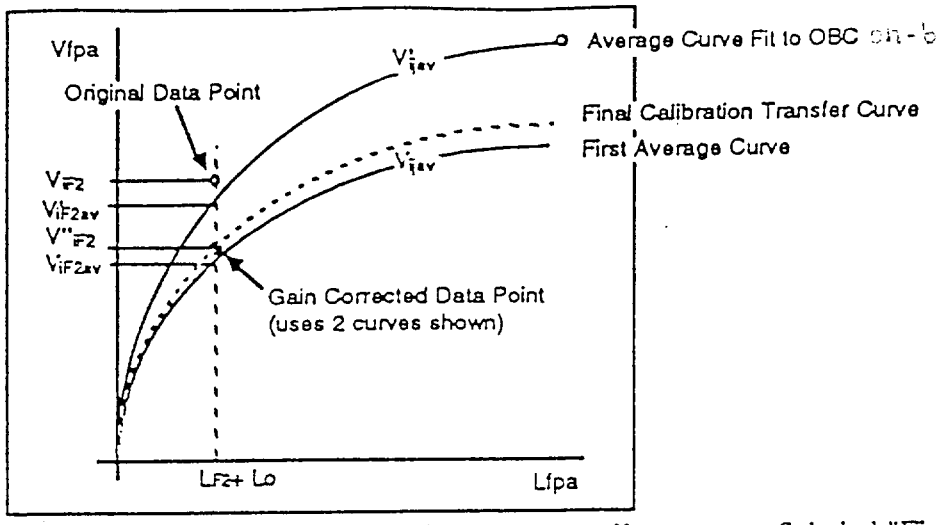

Figure 1. The process of non-linear gain correction uses a non linear curve (labeled "First Average Curve") to correct each data point. First the curve is normalized to the OBC value by modifying the first order coefficient. Then the ratio of the new curve to the original curve is used to scale the original data point. A third curve that fits the new scaled data represents the final calibration transfer curve.

To scale the average curve fit to intercept the on-board calibrator data point, and thereby obtain V_{iF2}' for the above equation, we solve for the first-order coefficient; i.e. we make a first order correction of the average curve using the on-board calibrator data.

$$a_{1i}' = \frac{V_{iF3} - V_o - a_{2av}(L_{iF3} + L_o)^2}{(L_{iF3} + L_o)}$$

so

$$V_{ij}' = a_{1i}'(L_{ij} + L_o) + a_{2av}(L_{ij} + L_o)^2 + V_o$$

and

$$V_{iF2}' = a_{1i}'(L_{iF2} + L_o) + a_{2av}(L_{iF2} + L_o)^2 + V_o$$

We must now average over successive scans to achieve adequate SNR. Note that each V_{ij}' is gain corrected. We only need to compensate for the different reflectances of the scan mirror.

$$V_j'' = \frac{1}{NS}\sum_{i=1}^{NS} V_{ij}'' \cdot \frac{p_1}{p_i} \qquad L_j = \frac{1}{NS}\sum_{i=1}^{NS}(L_{ij} + L_o)$$

A curve fit of the corrected data set (V_j'', L_j) can now be obtained, giving the final pre-flight calibration coefficients.

$$V_{ij}(L) = \sum_{n=1}^{N} a_n (L_{ij} + L_o)^n + V_o$$

At this point we can return to the original data set and use the above higher order polynomial to gain correct the data; i.e. compute a_{1i}' based on the higher order polynomial. This is recommended since it is better to gain correct with a curve more representative of the final response than the second order

polynomial used originally. Successive iterations on the calculation of the final response curve is recommended.

Subsequent Correction Using the On-Board Calibrator

After calibration using the ground based calibrator, to calibrate using the on-board calibrator it is necessary to perform a 1st order correction to the polynomial as done above with V_{ij}', second order terms remain as determined initially.

$$V_{ij}(L)' = a_{1i}\,(L_{ij} + L_o) + \sum_{n=2}^{N} a_{ni}\,(L_{ij} + L_o)^n + Vo$$

where the on-board calibrator determines the first order coefficient

$$a_{1i} = \frac{V_{iF3} - Vo - \sum_{n=2}^{N} a_{ni}\,(L_{ij} + L_o)^n}{(L_{iF3} + L_o)}$$

Simulation

The above algorithm was coded in an Excel spreadsheet. A simulation was performed and the results demonstrate that dispite significant gain and background variations, the method works well. Figure 2 shows the original data, uncorrected, and the corrected data. In this simulation, as much as 40% of full scale background variation, and 10% gain variation was applied.

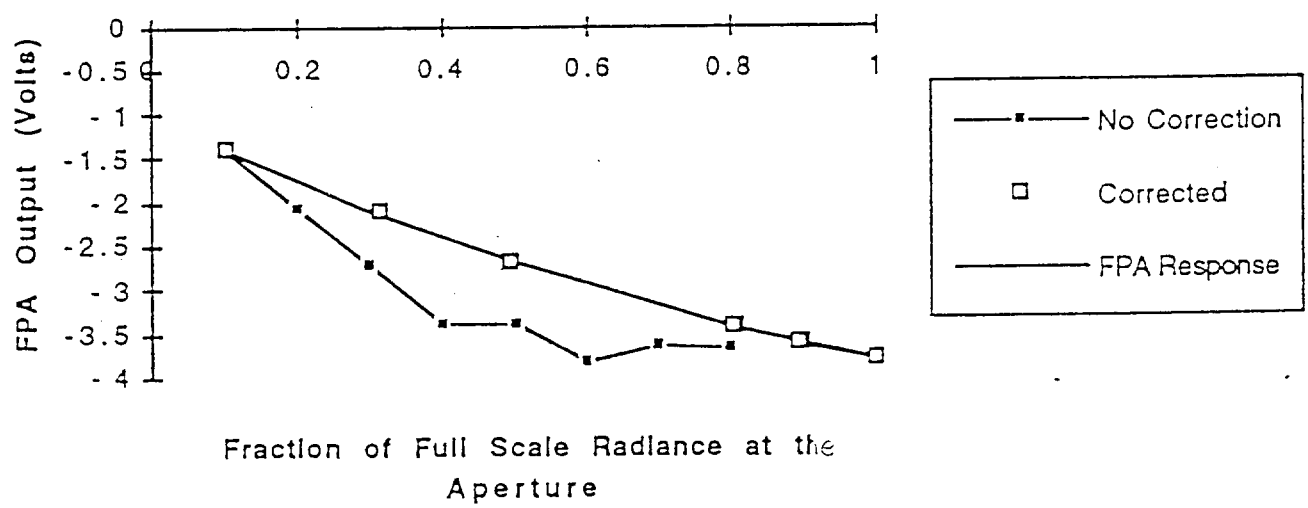

Figure 2. Example of the gain and background correction technique described above. In this example, as much as 40% background variation and 10% gain variation were applied.

Error Analysis

Each parameter was given an SNR, and the standard deviation of the measurement calculated. It turns out that if we know the AEM Gain, G, to 1%, the AEM Offset ΔV to 8 bits, and AEM Responsivity of the A/D to 8 bits, we can achieve the 0.2% accuracy for a non linear term that is 30% of the linear term. Actual tolerances will depend on the actual shape of the MODIS detector curves, but this result

is encouraging. The current system telemetry will be adequate. In addition the detector offset voltage Vo need only be stable to 1% also.

Summary and Conclusions

Determination of the calibration coefficients for the polynomials that define the MODIS transfer curve are critical to successful calibration of the MODIS instrument. These calibration coefficients will be used throughout the pre-flight and on-orbit calibration of the data acquired. The algorithms presented above provide methods for determining these calibration coefficients.

Coefficients are calculated in the voltage domain to allow for background variation and the DC restore process. These algorithms should provide the basis of the radiometric calibration of the MODIS instrument pre-flight and in-orbit.

A simulation program was developed in an Excel Spreadsheet (Attached). The results gave the errors allowable on the variables. The results indicate that the current design can achieve the allowable 0.2% radiometric error for this measurement.

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