MODIS Algorithm Team (MAT)
Meeting Minutes, 9 Feb 94

1. MINUTES

Harry Montgomery reviewed the attached major MAT milestone chart. Additional milestones will be added (action item 9.MAT). Harry introduced the attached agenda of specific MODIS topics, noting that each agenda item would be revisited over several meetings, as necessary, until the MAT could reasonably prepare an authoritative source document. These documents will be updated on a regular basis and will become a primary source for the preparation of calibration algorithms.

Copies of the viewgraphs presented by each speaker are available from Joan Baden. A list of attendees is in section 3.

The next meeting is scheduled for 16 Feb 94 at 9 a.m. in room G95.

2. NEW AND UNCOMPLETED ACTION ITEMS

9.MAT	2/9/94	Ed Knight and Tim Zukowski to provide critical additions to the MAT milestone chart at the next meeting.
10.MAT	2/9/94	Tom Goff to discuss at the next meeting: (1) SDST scan cube data products; (2) MCST-to-SDST deliverables; (3) software coding languages and standards.
11.MAT	2/9/94	Dan Knowles to provide a copy of relevant SBRC memos on the relative merits of glass bead thermistors and platinum resistance thermometers (PRTs) to Bill Barnes.
12.MAT	2/9/94	Jim Butler to discuss BRDF and stability of Spectralon at the next meeting, including fluorescence effects.
13.MAT	2/9/94	Tim Zukowski to discuss MODIS calibration/GSE system at the next meeting.

3. CONCERNS

1.MATC	2/9/94	Phil Ardanuy is concerned that the Antarctic ice cap may disturb the DC restore level on the BB for the visible/near IR bands, due to BB emissivity being relatively low. **TBA**
2.MATC	2/9/94	Paul Anuta is concerned that the BRDF of the scan mirror may be a significant modifier of the effective solar diffuser (SD) BRDF. ****TBA ??****

4. ATTENDEES

Name	Address	Phone No.	Email
Peter Abel	GSFC/925	286-6829	
Paul Anuta	GSFC/RDC	286-9412	
Philip Ardanuy	RDC	982-3714	
W. L. Barnes	GSFC/970	286-8670	
Ken Brown	GSFC/925	286-3296	
Jim Butler	GSFC/925	286-4606	
Tom Bryant	RDC	982-3769	
Nianzeng Che	SWALES	572-1365	
Lester C. Farwell	BASG	220-5694	
Tom Goff	RDC	982-3704	teg@modis1.rdsc.com
Dave Goodwin	SWALES	595-5500	
Douglas Hoyt	RDC	982-3700	
Ed Knight	GSFC/RDC	286-2382	
Dan Knowles	GSFC/RDC	286-1378	
Geir Kvaran	RDC	982-3716	
Marvin Maxwell	SWALES	572-1206	
Al McKay	GSFC/RDC	286-6739	
Harry Montgomery	GSFC/925	286-7087	
Tmitri J. Zukowski	SWALES	572-1292	

MODIS ALGORITHM TEAM MEETING

9 FEBRUARY 1994

9:00	MAT SCHEDULE (HARRY MONTGOMERY)
9:10	THE MODIS BLACKBODY (BB) (DAN KNOWLES)
9:30	SOLAR DIFFUSER (SD)/SD STABILITY MONITOR (SDSM) (PAUL ANUTA)
10:00	SPECTRAL RADIOMETRIC CALIBRATION ASSEMBLY (SRCA) (ED KNIGHT)
10:30	"L-1A" PRODUCT: THE SDST SCAN CUBE FOR MODIS (TOM GOFF)
10:45	SDST EXPECTED ALGORITHM DELIVERABLES (TOM GOFF)
11:00	ADJOURN

MODIS ALGORITHMS TEAM (MAT) MILESTONES (2-9-94)

1994

TASK	2/2	2/9	3/2	3/9	3/16	3/23	3/30	4/4	4/11	4/25	5/2	5/9	5/16	5/23	6/6	6/13	6/20	6/27	7/6	7/15	6/15/95	12/15/95	6/15/96	1/1/97	1/1/98
MAT MEETING	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ						
			(Weinreb)																						
DELIVER ROUGH ALGS TO MCST																				Δ					
ENG MODEL T/V																					Δ				
DELIVER INT LEVEL ALGS																						Δ			
PROTO MODEL DELIVERY																							Δ		
DELIVER ALGS TO SDST																							Δ		
DELIVER ALGS TO SDST																								Δ	
LAUNCH																									Δ

2/8/94

ACTIVITY	FUNCTION	PERSON	TIME
SENSOR DEVELOPMENT	SUPPORT WEBER	ED KNIGHT	0.9
SENSOR DEVELOPMENT	SUPPORT WEBER (PROGRAMMER)	TBD	1
SENSOR DEVELOPMENT	PRE-LAUNCH TESTING AS IT AFFECTS CALIBRATION	TIM ZUKOWSKI	0.5
SENSOR DEVELOPMENT	DATA SYSTEMS FORMATS AND TIME AS THEY AFECTS CALIBRATION	TIM ZUKOWSKI	0.25
SENSOR DEVELOPMENT	PRE-LAUNCH TESTING COMPUTER SUPPORT AS IT AFFECTS ALGORITHMS	TOM BRYANT	0.25
SENSOR DEVELOPMENT	ON-SITE REPRESENTATIVE AT SBRC	KEN ANDERSON (TBD)	
SENSOR DEVELOPMENT	HI-LEVEL DATA TECH TO HANDLE TV DATA TAPES	TBD	
SENSOR DEVELOPMENT	UNDERSTAND MODIS MACROS AND WRITE NEW ONES	TBD	
MODIS ALGORITHM TEAM	CONSULTANTS FOR OVERALL SYSTEM	GOLDBERG/MAXWELL	0.5
MODIS ALGORITHM TEAM	SYNTHESIS OF ONBOARD CALIBRATORS, TESTING, ETC	CHE	0.5
MODIS ALGORITHM TEAM	BLACK BODY (KEY POINT OF CONTACT)	DAN KNOWLES	1
MODIS ALGORITHM TEAM	SRCA/SPECTRAL (KEY POINT OF CONTACT)	ED KNIGHT	0.1
MODIS ALGORITHM TEAM	SRCA/RADIOMETRIC (KEY POINT OF CONTACT)	CHE	0.5
MODIS ALGORITHM TEAM	SRCA/SPATIAL (KEY POINT OF CONTACT)	TIM ZUKOWSKI	0.25
MODIS ALGORITHM TEAM	SD/SDSM (KEY POINT OF CONTACT)	PAUL ANUTA	0.5
MODIS ALGORITHM TEAM	SD/SDSM GEOMETRY AS BUILT AND AS AFFECTED BY ORBIT, ETC	TOM BRYANT	0.25
MODIS ALGORITHM TEAM	SD/SDSM (OPTICAL PROPERTIES OF DIFFUSER, ETC.)	JIM BUTLER	0.1
MODIS ALGORITHM TEAM	SV/LUNAR CALIBRATION (AS RELATED TO SPACE AND EARTH PORT)	TOM BRYANT	0.25
MODIS ALGORITHM TEAM	GHOSTING/CROSSTALK	KEN BROWN/TBD	0.25
MODIS ALGORITHM TEAM	C++ PROGRAMMER	TOM BRYANT	
MODIS ALGORITHM TEAM	C++ PROGRAMMER	JOAN BADEN	0.5
MODIS ALGORITHM TEAM	C++ PROGRAMMER	TBD	0.5
MODIS ALGORITHM TEAM	RAPPORTEUR	JOAN BADEN	0.5
FLIGHT SOFTWARE		SBRC/TBD	

TWO SPARC-10'S

CONTRACTOR TRAVEL =$5K/MONTH

CIVIL SERVICE TRAVEL =$1K/MONTH

The MODIS Blackbody

Dan Knowles Jr.

MODIS Algorithm Team Meeting
9 Feb, 1994

Outline

- Function of MODIS Blackbody
- GSFC Radiometric Calibration Needs
- SBRC Blackbody Requirements
- Physical Layout of Blackbody
- Focal Plane Viewing of Blackbody
- Blackbody Parameters Summary
- SBRC Radiometric Calibration Procedures
- SBRC Radiometric Calibration Algorithm

Function of the MODIS Blackbody

- Full Aperture Radiometric Calibration for Bands 20-25, 27-36
- Full Aperture DC Restoration for all bands

GSFC Radiometric Calibration Needs

The absolute radiometric calibration Phase C/D requirement for wavelengths greater than 3000 nm is 1%

SBRC Blackbody Requirements

Blackbody spatial and temperature knowledge - 0.1K

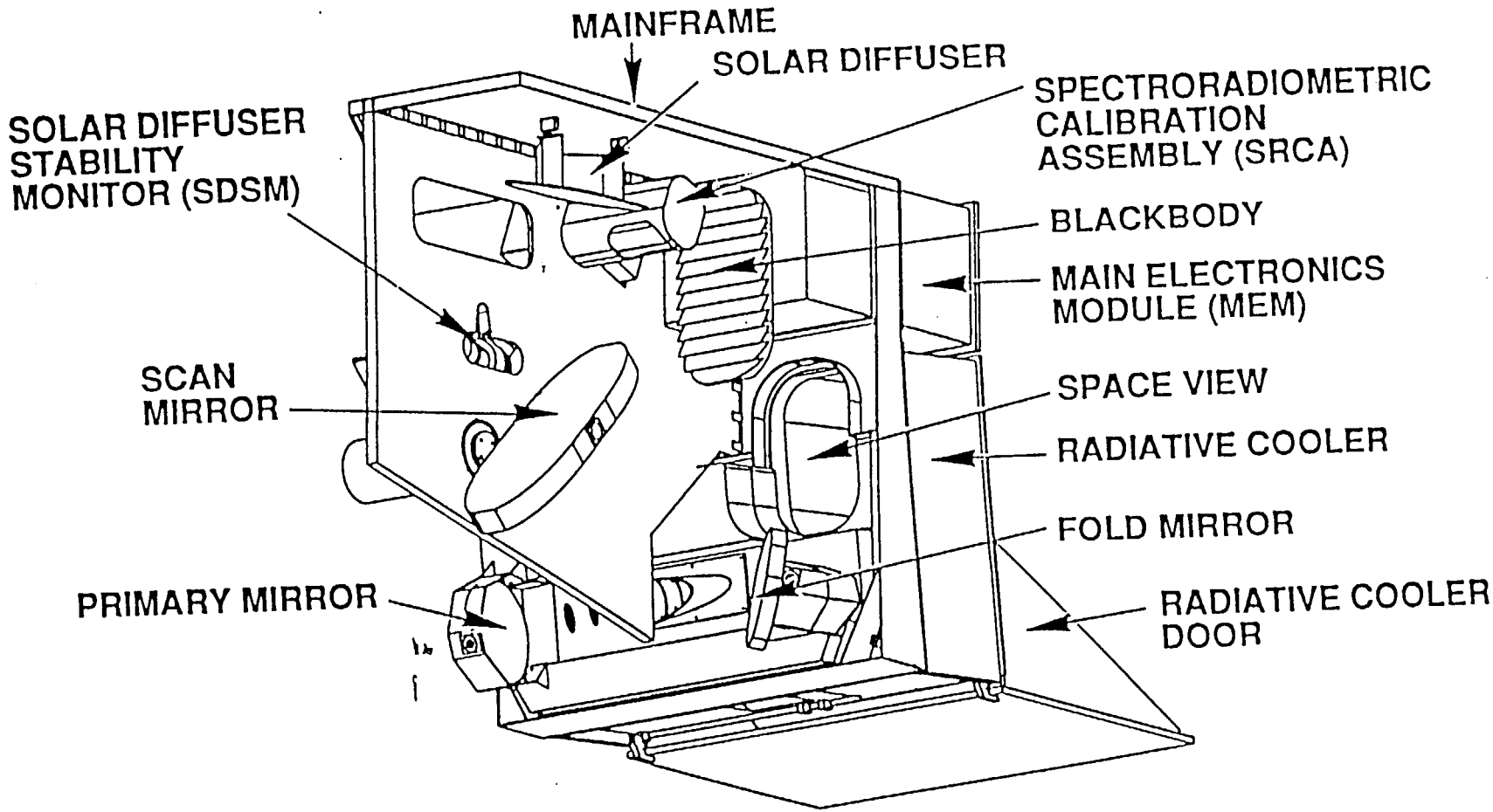
Emissivity - > 0.992

Cavity V-Groove Included Angle 40.5

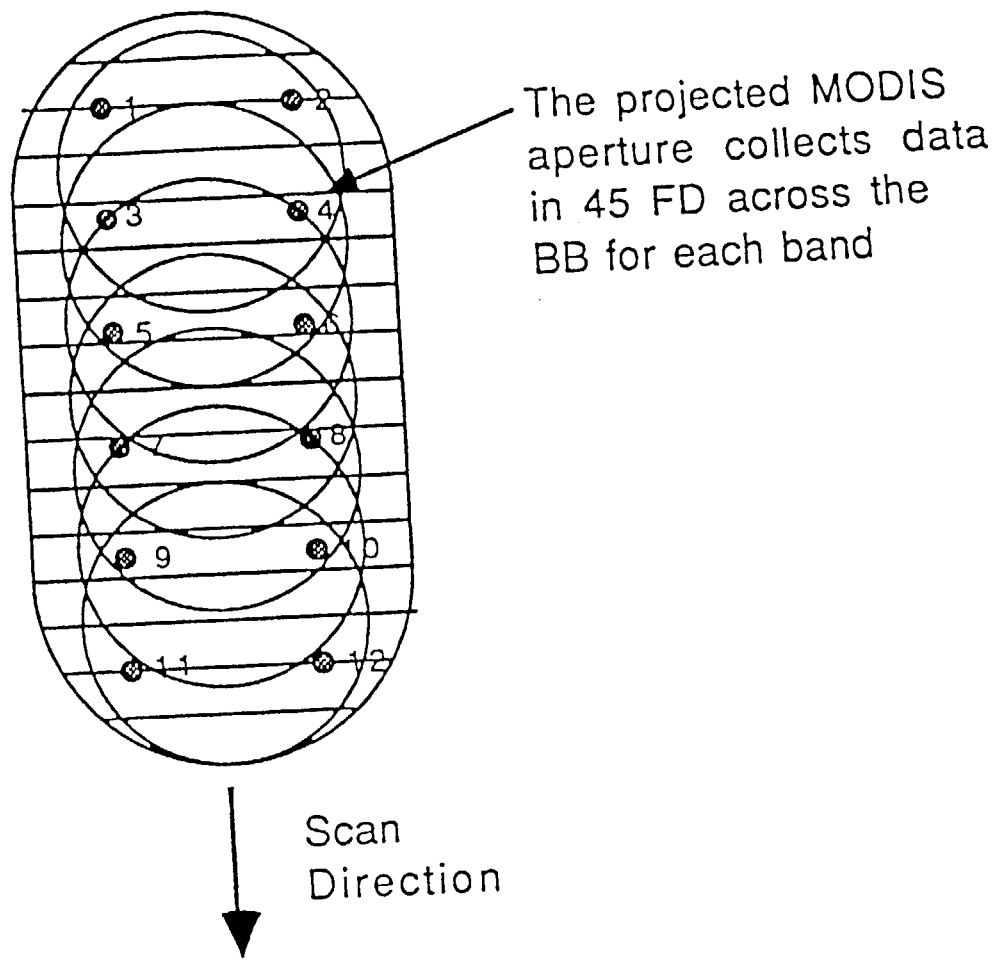
Groove Tip and Valley Area Effects < 10%

Calibration Accuracy Prediction 0.7 - 0.2%

Physical Layout

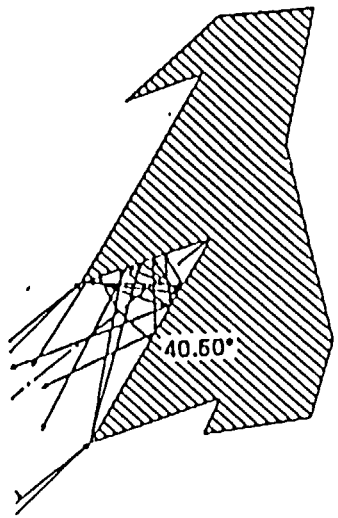


Focal Plane Viewing



Blackbody Parameter Summary

Material - anodized aluminum
Height - 15"
Width - 10"
Thickness - 1"
Weight - 8.3 lbs
Heaters - 4
Thermistors - 12 PRT
Blackbody "heat up" (285 - 315) - 130 minutes
Blackbody "cool down" (315 - 285) - 100 minutes
Scan Angle Range "clear view" - (230.750 - 232.050)
Number of Frames of "clear view" Data - 16
Included Groove Angle - 40.5



SBRC Calibration Procedures

- Record all Blackbody Temperature sensors
- Record scan cavity wall temperature sensors
- Calculate effective blackbody temperature for all MODIS signals
- For a given channel and band, the temperature used in the DC restoration algorithm is the average of the effective blackbody temperatures.
- Record all MODIS signals as system is scanned across the blackbody
- Calculate average space signal
- Calculate responsivity and average responsivity
- Calculate scene radiance

SBRC's Radiometric Calibration Algorithm

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

L = Radiance of the scene
DN_scene = MODIS digital signal of the scene
DN_sp_avg = Average MODIS digital signal of the space view
R = Average responsivity of the blackbody

MAT Presentation

MODIS Solar Diffuser Calibration Algorithms

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

Harry Montgomery, Manager
MODIS Instrument Characterization

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NASA / Goddard Space flight Center, Greenbelt, Maryland 20771
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Paul E. Anuta, Edward Knight, Tom Bryant

Research and Data Systems Corporation (RDC)
7855 Walker Drive, Greenbelt, MD, 20770
FAX: (301) 982-3749

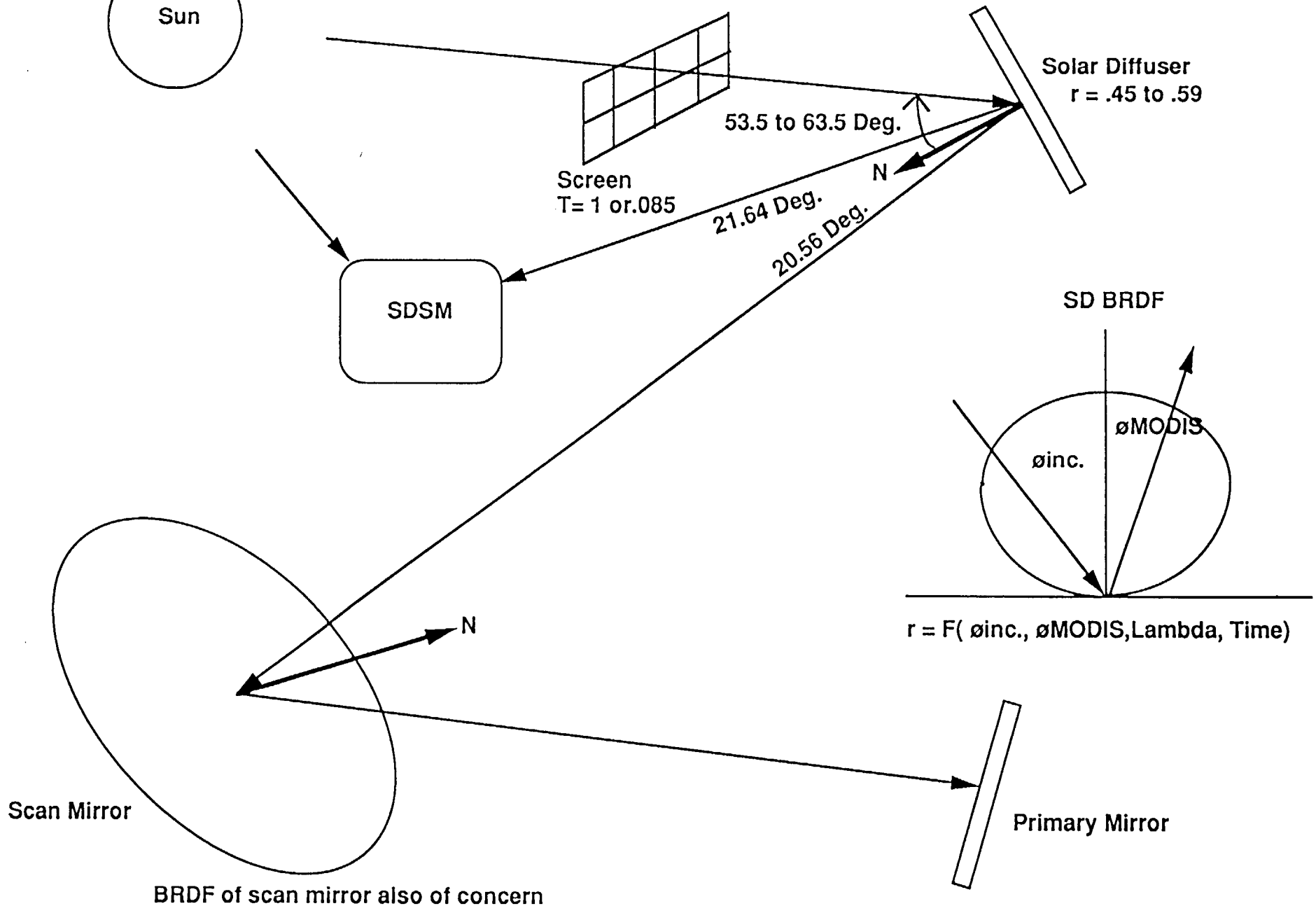
Presented by Paul E. Anuta

February 9, 1994

Outline

- Solar Diffuser Geometric Considerations
- In-Flight Solar Diffuser Calibration Equations
- In-Flight SDSM Equations
- SBUV Diffuser Calibration Experience
- SSBUV Diffuser Experiment Results

Geometry Relevant to MODIS Solar Diffuser Calibration
.4 to 2.2 Microns



SBRC In-Flight Solar Diffuser Calibration Equations

- Select reflectance or radiance calibration mode: same data collected but data reduction differs.
- Select calibration level: high - without screen; low - with screen
- Time of year: TOY
- Sun-to-diffuser angle of incidence: $\varnothing inc(FD\#, \alpha hor)$
- Record MODIS signals when viewing solar diffuser: DN_sd(B#, Ch#, FD#)
- Record MODIS signals when viewing space port: DN_sp(B#, Ch#, FD#)
- Calculate average space signal: $DN_sp_avg(B\#, Ch\#) = \frac{DN_sp(B\#,Ch\#,FD\#)}{\Sigma F\#}$
- Calculate responsivity - radiance mode

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

- Calculate responsivity - reflectance mode

$$R_\rho(B\#, Ch\#, F\#) = \frac{DN_sd(B\#, Ch\#, F\#) - DN_sp_avg(B\#, Ch\#)}{\Delta \rho}$$

where $\Delta L(B\#, Ch\#, \varnothing inc) = BRDF(\varnothing inc, \varnothing modis) * Esun(B\#) * \cos(\varnothing sun_sd)$

$\Delta \rho(B\#, Ch\#, \varnothing inc) = BRDF(\varnothing inc, \varnothing modis) * \cos(\varnothing sun_sd)$

- Calculate average radiance responsivity:

$$R_L_avg(B\#, Ch\#) = \frac{\Sigma R_L(B\#, Ch\#, FD\#)}{\Sigma\ FD\#}$$

SBRC In-Flight Solar Diffuser Calibration Equations Cont.

- Calculate average reflectance responsivity:

$$R\rho_avg(B\#, Ch\#) = \frac{\Sigma R\rho(B\#, Ch\#, FD\#)}{\Sigma\ FD\#}$$

- Scene radiance algorithm:

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

- Scene reflectance algorithm:

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

4.4 SDA Required Data (TBD)

The required data includes the following variables:

- The spectral BRDF over the region used.
- Is the attenuation screen in or out?
- The attenuation screen transmissio
- Solar spectral irradiance
- Angular relationship of sun and solar diffuser normal
- MODIS relative spectral response functions
- SDSM data to be used to correct solar diffuser BRDF, if needed

SBRC In-Flight Solar diffuser Stability Monitor (SDSM) Equations

- Last update value of solar diffuser BRDF - BRDF_prev(BB#)
- Last update value for SDSM correction factor - Fcorr_prev(BB#)
- Select calibration level: High - without screen; low - with screen
- Time of year - TOY
- Sun to diffuser angle of incidence: Øinc(F#, αhor, SL#)
- SDSM detector signals all bands dc restore function - DN_dcr(SL#, BB#)
- SDSM detector signals all bands direct sunlight - DN_sun(SL#, BB#)
- SDSM detector signals all bands solar diffuser - DN_sd(SL#, BB#)

  NOTE: DC restore signal and either direct sun or solar diffuser signals are obtained each scan line throughout the one minute used to obtain solar diffuser calibration and SDSM data.
- Calculate SDSM correction factor for each scan line set and SDSM bands:

$$\mathrm{Fcorr}(SL\#, BB\#) = \frac{DN_sd(SL\#, BB\#) - DN_dcr(SL\#, BB\#)}{\mathrm{COS}(Ø sun_sd)} * \frac{\mathrm{COS}(Ø sun_att\ scr)}{DN_sun(SL\#, BB\#) - DN_dcr(SL\#, BB\#)}$$

- Calculate current average SDSM correction factor for each SDSM band:

$$\mathrm{Fcorr_current}(BB\#) = \frac{\Sigma\, \mathrm{Fcorr}(SL\#, BB\#)}{\Sigma\, SL\#}$$

SBRC In-Flight Solar Diffuser Stability Monitor (SDSM) Equations Cont.

- As this correction factor changes it needs to be applied as a correction to the solar diffuser BRDF. In principle, the following ratio will be used:

$$\frac{\text{BRDF_current(BB\#)}}{\text{Fcorr_current(BB\#)}} = \frac{\text{BRDF_prev(BB\#)}}{\text{Fcorr_prev(BB\#)}}$$

- The BRDF as given above would be at the SDSM spectral regions. BRDF for the MODIS spectral bands would be derived from these.

5.4 SDSM Required Data (TBD)

The required data includes the following variables:

- File of previous SDSM outputs
- Attenuation screen in / out
- SDSM detector signals for solar diffuser, dc restore, and direct sun viewing
- Special test wherein SDSM is used to support transfer of preflight calibration to inflight includes numerous preflight calibration files

Experience With SBUV Solar Diffuser Calibration

from Cebula (1988)

- Ground aluminum diffusers used in SBUV series
- Contaminant sources: Outgassing from satellite
  Direct solar radiance
  Solarization of contaminants
- Solar irradiance stable to 4%
- SBUV Instrument wavelength range: 250 to 340 nm
- Reflectance typically degraded 40% in 5 years (600 hrs. of exposure)
- Negative Exponential Model Established:

$$F\lambda = F\lambda(t_0)P(t_0)e - r\lambda\, E(t)\, e^{-S\lambda t} e^{-\delta}\lambda\, G(\lambda) \quad \text{accurate to 2\%}$$

- SBUV/2 on NOAA–11 diffuser degrading linearly in first 4 years
- Observed degradation with time even when not exposed to Sun

Causes of Solar Diffuser Degradation

Hilsenrath–SPIE–March 1993

- Major Causes
  - Ultraviolet Radiation (UV)
  - Molecular and Particulate Contamination (from spacecraft surfaces and propulsion systems)
  - Atomic Oxygen Erosion
- A Function of:
  - Wavelength
  - Optical properties of contaminant
  - Surface temperature
  - Orbit/altitude parameters
- UV Photopolymerizes Contaminants
  - Changes optical properties
- Possible Synergistic Effects

Shuttle Diffuser Experiment Results

from Hilsenrath (1993)

- Three Missions with SBUV Payload – SSBUV: August 91, March 92, April 93
- Two Materials: Roughened Aluminum
  Polytetrafluroethylene (PTFE) also called Spectralon and Halon
- No In–Flight Data from samples
  - Reflectance and surface chemical composition measured before and after flights
- Exposure Times:

Flight	Sun View	Earth View
SSBUV-3	3.3 hours	60.0 hours
SSBUV-4	5.2 hours	82.5 hours
SSBUV-5	9.2 hours	106.5 hours

- Shuttle Contaminants: Silicones, Hydrocarbons
- Results: Reflectance Degradation Ratio: Post-flight/Pre-flight

	Alumunimum			Spectralon		
MISSION	300 nm	600 nm	900 nm	300 nm	600 nm	900 nm
SSBUV-3	0.96	0.98	0.98	0.87	1.00	1.00
SSBUV-4	0.73	0.94	0.97	0.85	1.00	1.00
SSBUV-5	0.975	0.99	1.00	0.925	1.00	1.00

- Conclusions: Ground Aluminum less sensitive to reflectance change than Spectralon in UV. Small to non-existent change occurred above 400 nm for both materials.

References

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SPECTRORADIOMETRIC CALIBRATION ASSEMBLY (SRCA)

Calibrator Overview

Modes and Frequency of Use

SBRC Preliminary Algorithms

SRCA CONSISTS OF THREE FUNCTIONAL SUBSYSTEMS

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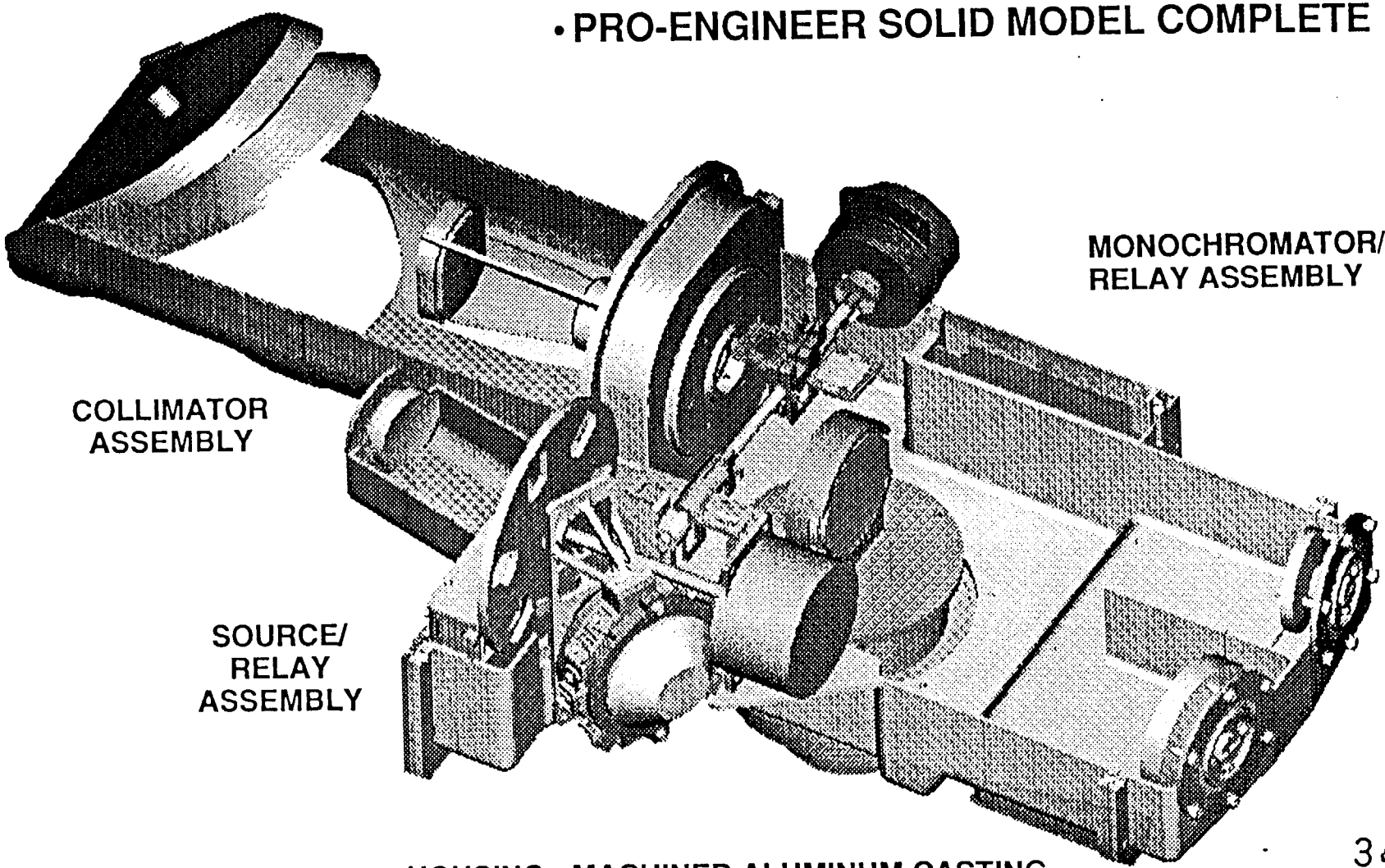
- PRO-ENGINEER SOLID MODEL COMPLETE



HOUSING: MACHINED ALUMINUM CASTING

SRCA PROVIDES COLLIMATED PARTIAL APERTURE CALIBRATION SOURCE

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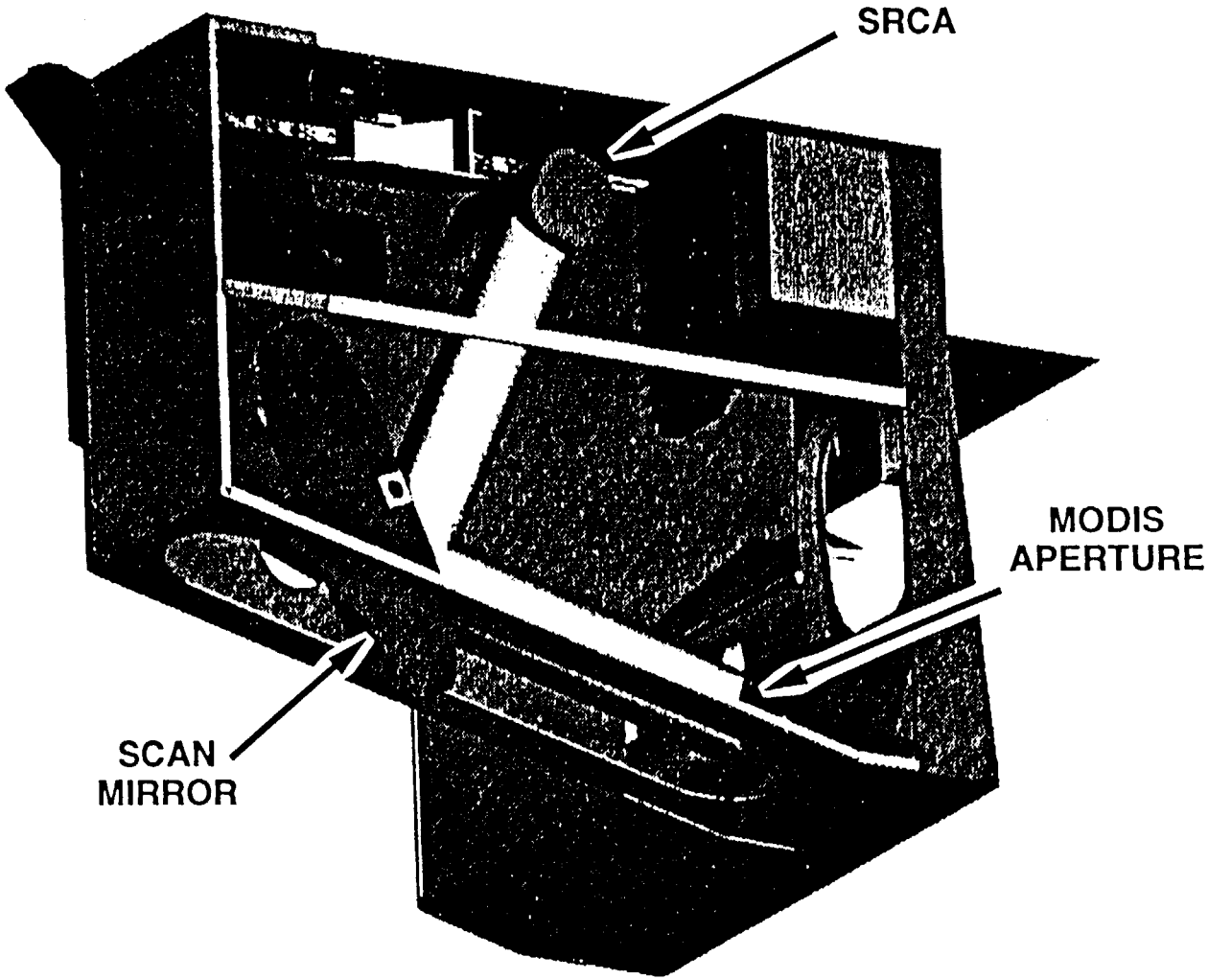

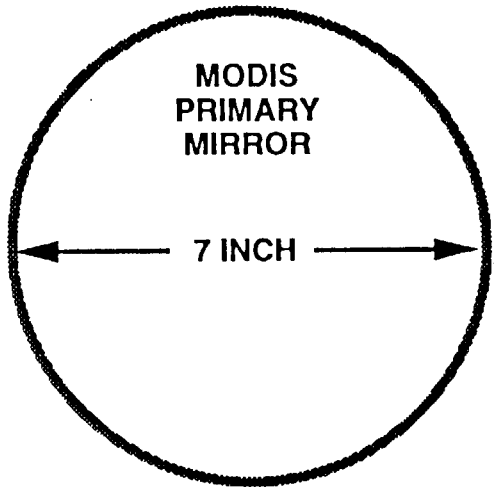

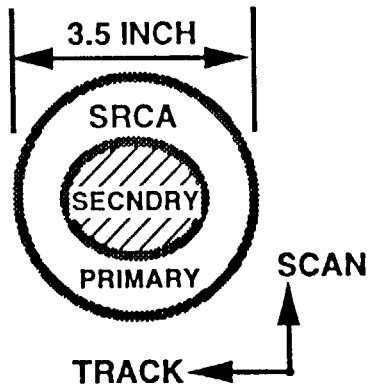

SRCA IS MULTI-FUNCTIONAL

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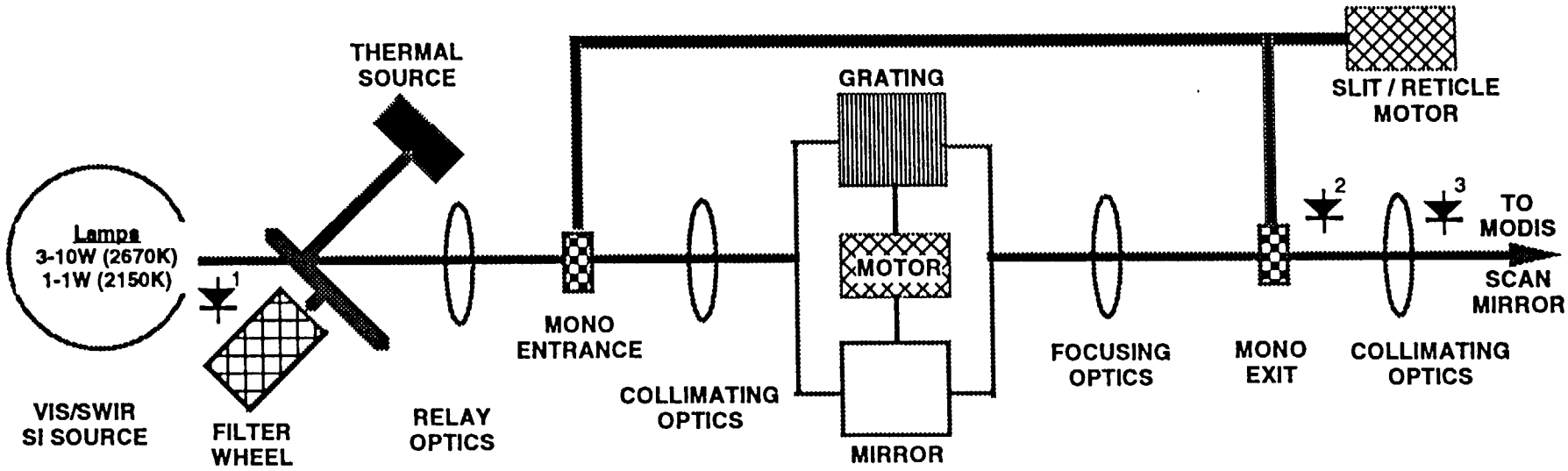


DETECTORS: 1 = SIS FEEDBACK CONTROL, 2 = DIDYMIUM SPECTRAL SELF CAL , 3 = SPECTRAL REFERENCE

CALIBRATION MODE	SOURCE	FILTER	MONO ENTRANCE	GRATING / MIRROR	MONO EXIT	ESTIMATED TIME REQRD *
RADIOMETRIC	VIS/SWIR	CLEAR & ND	OPEN	MIRROR	OPEN	20 min
SPECTRAL	VIS/SWIR	ORDER (3)	SLIT	GRATING	SLIT / SIPDs	70 min
SPATIAL	VIS/SWIR & THERM	ITO DICHROIC	OPEN	MIRROR	RETICLES	40 min

* DOES NOT INCLUDE TIME REQUIRED FOR TEMPERATURE STABILIZATION OF HEATED COMPONENTS: THERMAL SOURCE AND SIS FEEDBACK CONTROL DETECTOR

SCOPE OF THE PROBLEM

- SRCA Is Complicated
  - Configurations
  - Numerous steps in operating modes
  - Required characterizations

- SRCA is Over-Flexible
  - Large array of modes of use
  - More data available than SBRC needs

- Using the SRCA to Calibrate MODIS is Complicated
  - Partial aperture with obscuration
  - Large number of engineering telemetry points needed

MODES AND FREQUENCY OF USE

Reference: Frequency of Use of the On-Board Calibrators, B. Guenther and E. Knight, Dec. 21, 1993.

PHILOSOPHY

The SRCA will be used to:

1. Transfer ground calibration and characterization to orbit during A & E; identify and measure changes.
2. Verify Instrument Stability during A & E; specifically intra-orbit.
3. Monitor the instrument during the operational phase.
4. Troubleshoot as necessary.

ASSUMPTIONS

1. Instrument will behave properly; safety margins not included.
2. First order estimate of 100 uses to do meaningful characterization.
3. Worst changes occur at launch; instrument stable (characterizable) after that.
4. No challenge to either bulb or motor lifetimes.

MODES AND FREQUENCY OF USE

limitations: bulb lifetimes, motor lifetimes, thermal source lifetime, thermal constraints.

MODE	USAGE DURATION	FREQ. A&E	FREQ. ON-ORBIT
Full Radiometric	17 min.	100 times	1/month
10 W bulb Radiometric (intra-orbit check VIS/NIR (2,11,12,18)	1 orbit (50 min)	100 times	1/week
1 W bulb Radiometric (intra-orbit check NIR/SWIR (5-7,13-17,19,26)	1 orbit (50 min)	100 times	1/week
Full Spectral	75 min.	100 times	1/month
Partial Spectral (check single band)	TBD	TBD	TBD
Full Spatial	37 min.	100 times	(4/year)
Scan Direction Spatial (adjust readout; extends lifetime; suff. as monitor)	32 min.	none	4/year
1 W bulb Spatial (checks NIR/SWIR; extends lifetime)	16 min.	none	TBD
Bulb Rotation (extends lifetime)			

SBRC PRELIMINARY ALGORITHMS

RADIOMETRIC

Pre-flight:

- Calibrate MODIS with SIS(100), then calibrate SRCA
- Test subset of source configurations (20-22 of 88)
  - Bulb Level (30 W, 20 W, 10 W, 10 W filtered, 1 W, 1 W filtered)
  - Controller (primary, redundant)
  - Control Mode (radiative feedback, constant current)

On-Orbit:

1. Collect 5-7 data frames/scan
2. Check Saturation
3. Determine Weighted Average
4. Determine light level from telemetry (bulbs + feedback diode)
5. Consult pre-flight lookup table

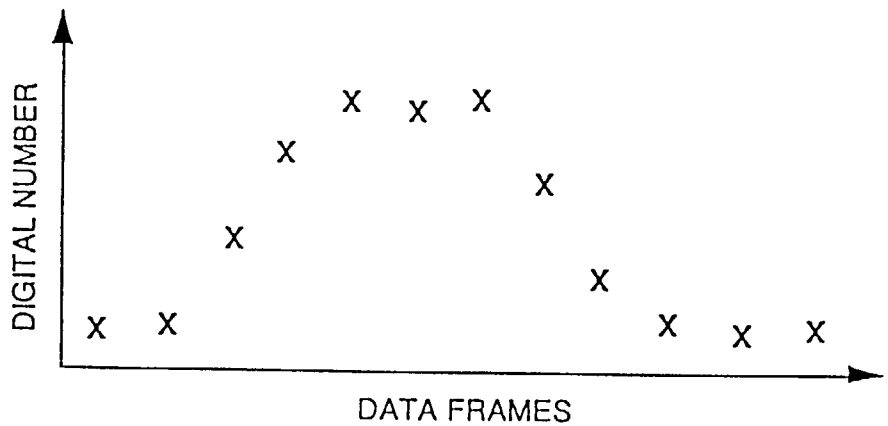
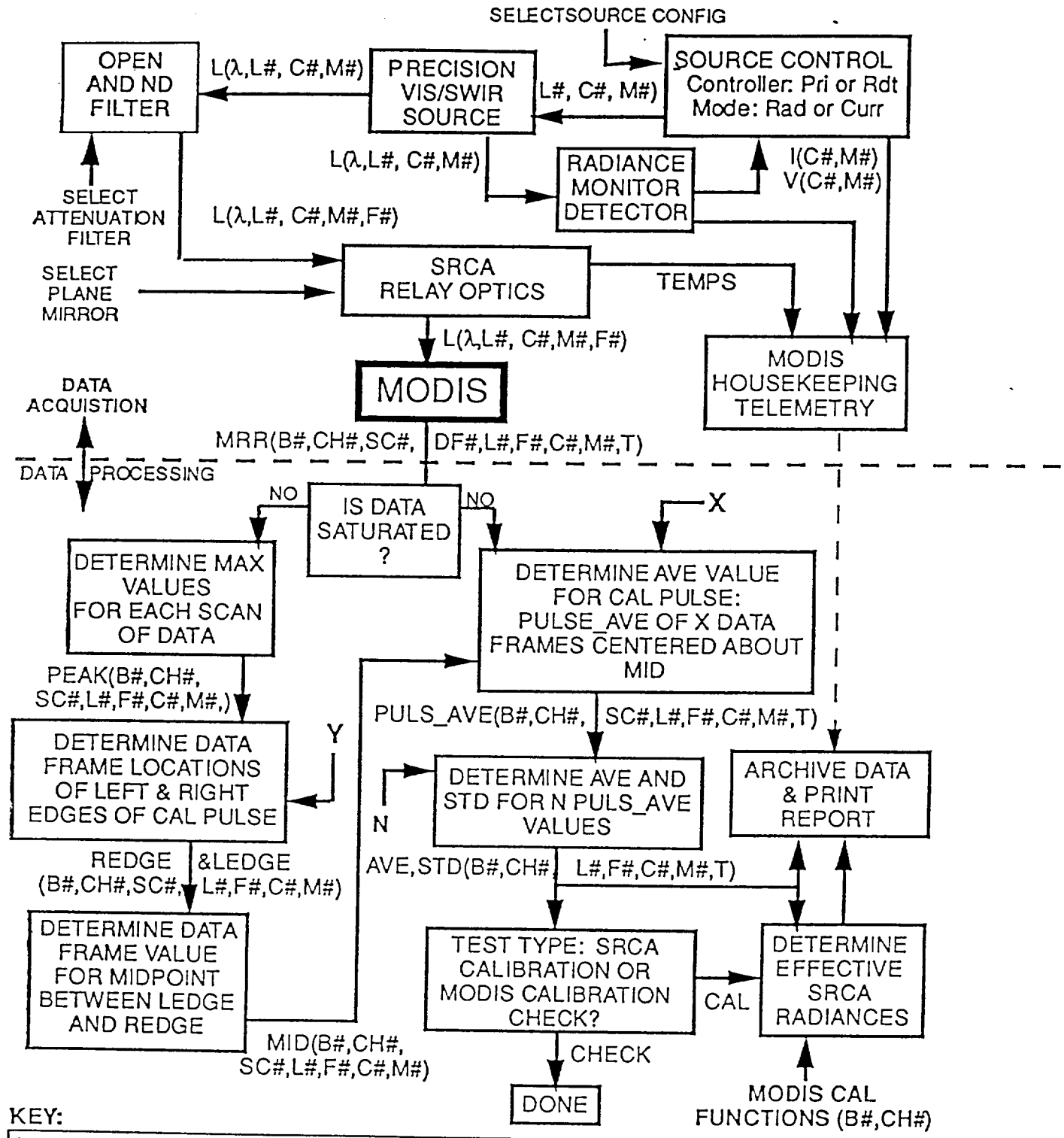


Figure 6.2 Typical Response to SRCA Calibration Source.



KEY:

B# = MODIS Band No.	SC# = Scan No.	
CH# = Detector Channel No.	L = Radiance	T = Time & Date
DF# = Data Frame No.	V = Voltage	I = Current
L# = Lamp Config No.	N = No. of Scans Collected	
M# = Source Control Mode	Y = Fraction of Peak Value Defining Pulse Edges	
C# = Source Controller Type	X = No. of Data Frames used in Puls_AVE	
MRR = MODIS Radiometric Response (Digital)		

Figure 6.3 Typical SRCA Radiometric Calibration Flow

SBRC PRELIMINARY ALGORITHMS

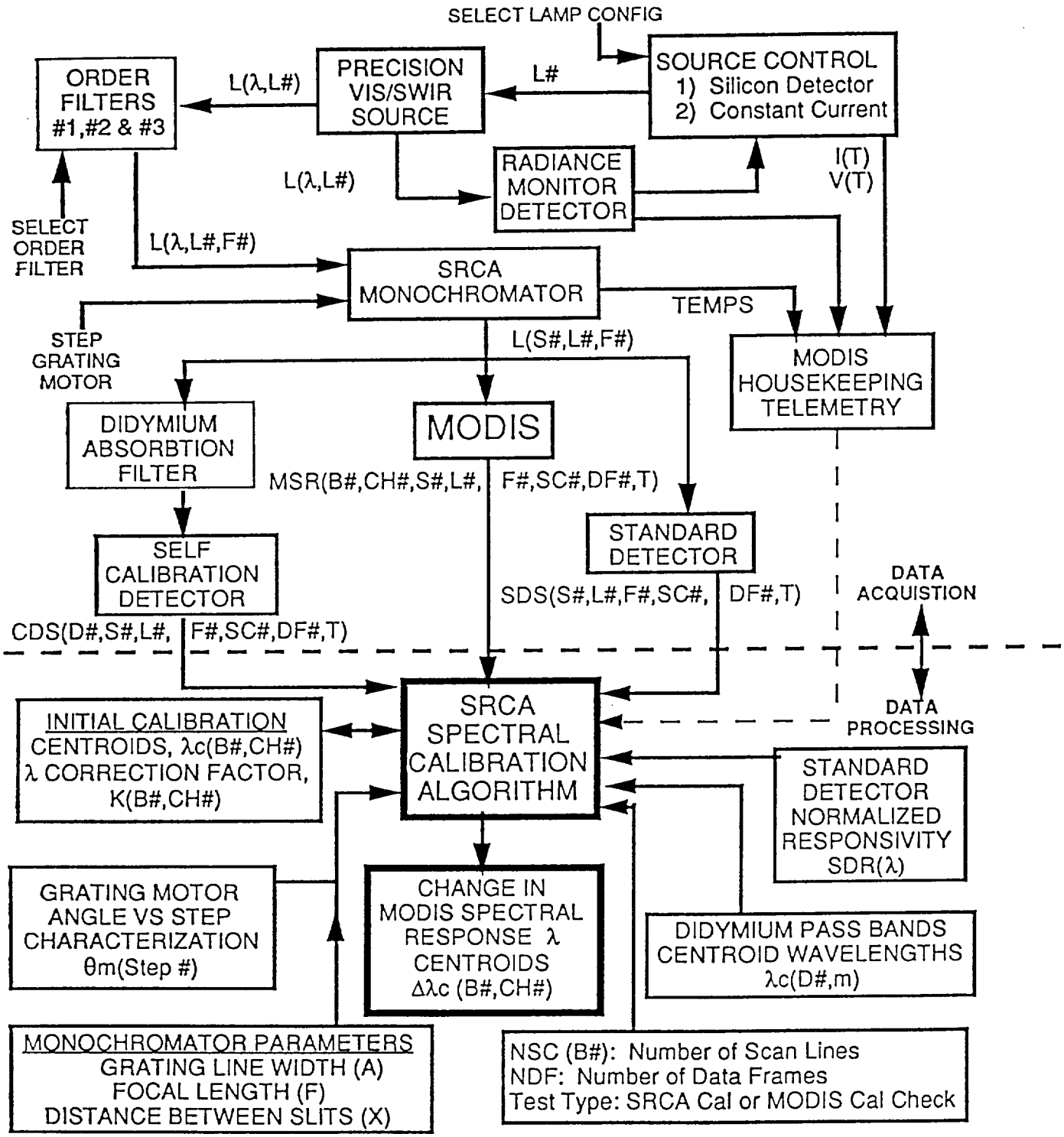
SPECTRAL

Pre-flight:

- Characterize MODIS with MGBC, then characterize SRCA
  Establish Correction Factor
- Characterize Didymium pass bands
- Determine grating characteristics, slit offsets with high accuracy

On-Orbit:

1. Determine expected spectral level from telemetry (bulbs, order filters, grating position).
2. Collect data.
3. Use Didymium SiPD and Reference SiPD to self-calibrate.
4. Look-up instrument parameters.
5. Solve complicated algorithm to determine CW shift.



KEY:

B# = MODIS Band No.	D# = Didymium Band No.	F# = Filter No.
CH# = Detector Channel No.	m = Diffraction Order	SC# = Scan No.
S# = Grating Motor Step No.	L = Radiance	V = Voltage
DF# = Data Frame No.	L# = Lamp Config No.	I = Current
λc = Centroid Wavelength	CDS = Calibration Detector Signal	
SDS = Standard Detector Signal	MSR = MODIS Spectral Response (Digital)	
NDF = No. of Data Frames	NSC = No. of Scan Lines	T = Time & Date

Figure 6.5 Spectral Calibration Plan

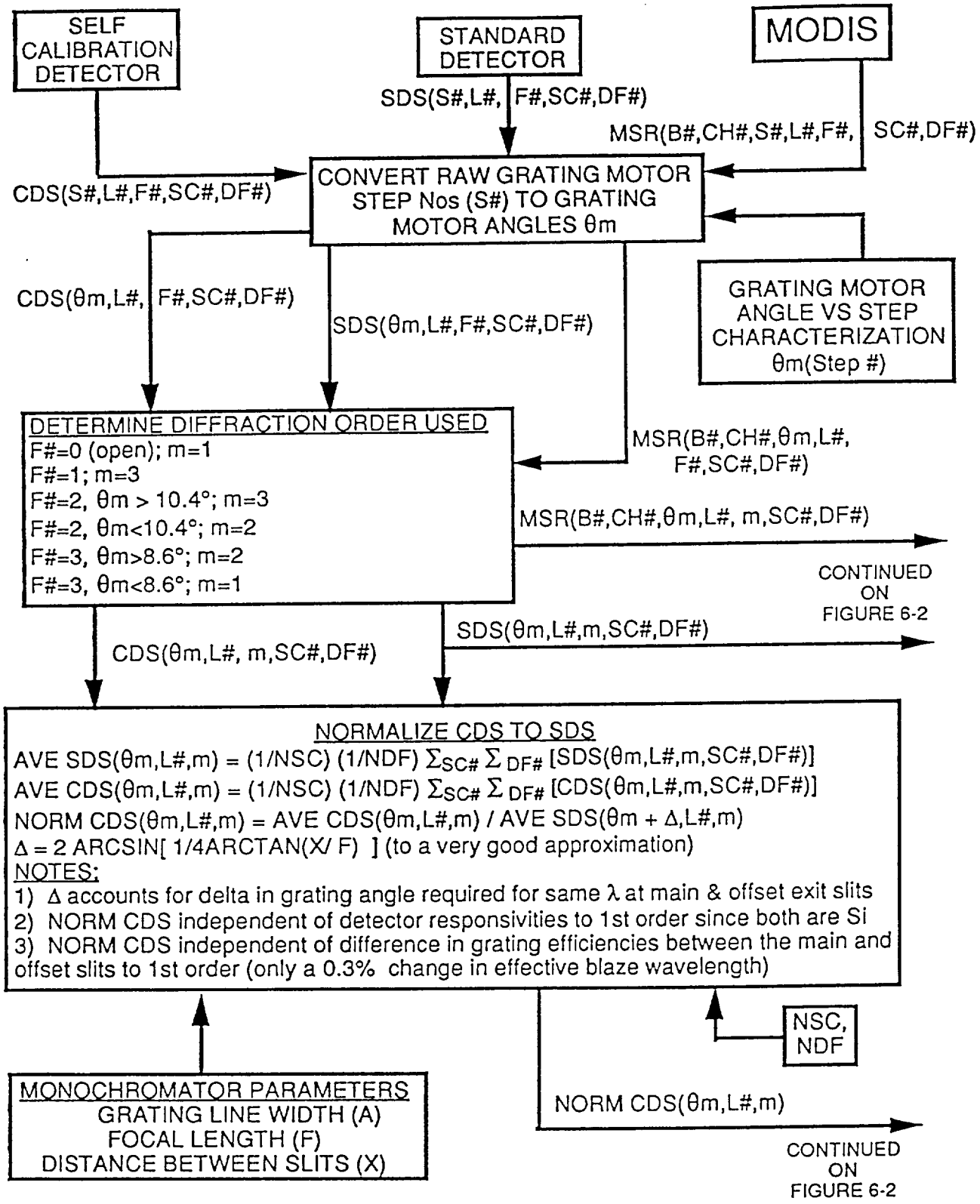


Figure 6.6a Spectral Calibration Algorithm

CALCULATE TOTAL AVERAGE MSR NORMALIZED TO SDS

$$\text{NORM MSR}(B\#,CH\#,\theta m,L\#,m,SC\#,DF\#) = \frac{\text{MSR}(B\#,CH\#,\theta m,L\#,m,SC\#,DF\#)}{\text{SDS}(\theta m,L\#,m,SC\#,DF\#)}$$

$$\text{TOTAL AVE MSR}(B\#,CH\#,\theta m,L\#,m,) = (1/NSC)(1/NDF)\,\Sigma_{SC\#}\Sigma_{DF\#}\,[\text{NORM MSR}(B\#,CH\#,\theta m,L\#,m,SC\#,DF\#)]$$

SDS(θm,L#,m,SC#,DF#)

CONTINUED FROM FIGURE 6-2

MSR(B#,CH#,θm,L#,F#,SC#,DF#)

NSC, NDF

TOTAL AVE MSR(B#,CH#,θm,L#, m)

CONTINUED ON FIGURE 6-3

β (L#); OFFSET (L#)

DETERMINE

1) GRATING MOTOR ANGULAR OFFSET, θ_{offset} (L#)
2) CZERNY TURNER HALF INCLUDED ANGLE, β (L#)

BY SIMULTANEOUSLY SOLVING FOLLOWING EQNS

Eqs 1-3: $\lambda c(D\#,m) = (A/m)\,\{\sin[\beta-\Omega m(L\#,m,D\#)-\theta_{offset}(L\#)]-\sin[\beta+\Omega m(L\#,m,D\#)+\theta_{offset}(L\#)+\delta]\}$, Where $\delta = \text{ARC TAN}(X/F)$

Eq 4: $\dfrac{\lambda c(D2,m=2) - \lambda c(D3,m=2)}{\Omega m(L\#,m=2,D2) - \Omega m(L\#,m=2,D3)} = \partial\lambda c/\partial\theta m|_{@\theta m=?}$

Eq 5: $\dfrac{(m=3) - (m=2)}{\Omega m(L\#,m=3,D3) - \Omega m(L\#,m=2,D3)} = \partial m/\partial\theta m|_{@\theta m=?}$

MONOCHROMATOR PARAMETERS
GRATING LINE WIDTH (A)
FOCAL LENGTH (F)
DISTANCE BETWEEN SLITS (X)

Ωm(L#,m,D#)

DIDYMIUM PASS BANDS CENTROID WAVELENGTHS λc(D#,m)

CONTINUED FROM FIGURE 6-1

NORM CDS(θm,L#,m)

DETERMINECENTROID GRATING MOTOR ANGLES Ωm FOR DIDYMIUM PASS BANDS

$$\Omega m\,(L\#,m,D\#) = \frac{\Sigma_{\theta m}\,[\text{Norm CDS}\,(\theta m,L\#,m) * (\theta m)]}{\Sigma_{\theta m}\,[\text{Norm CDS}\,(\theta m,L\#,m)]}$$

DIDYMIUM PASS BANDS	DIFFRACTION ORDER	θm RANGE
D2	3	9.5° - 10.2°
D3	2	6.8° - 7.4°
D3	3	10.6° - 11.4°

Figure 6.6b Spectral Calibration Algorithms

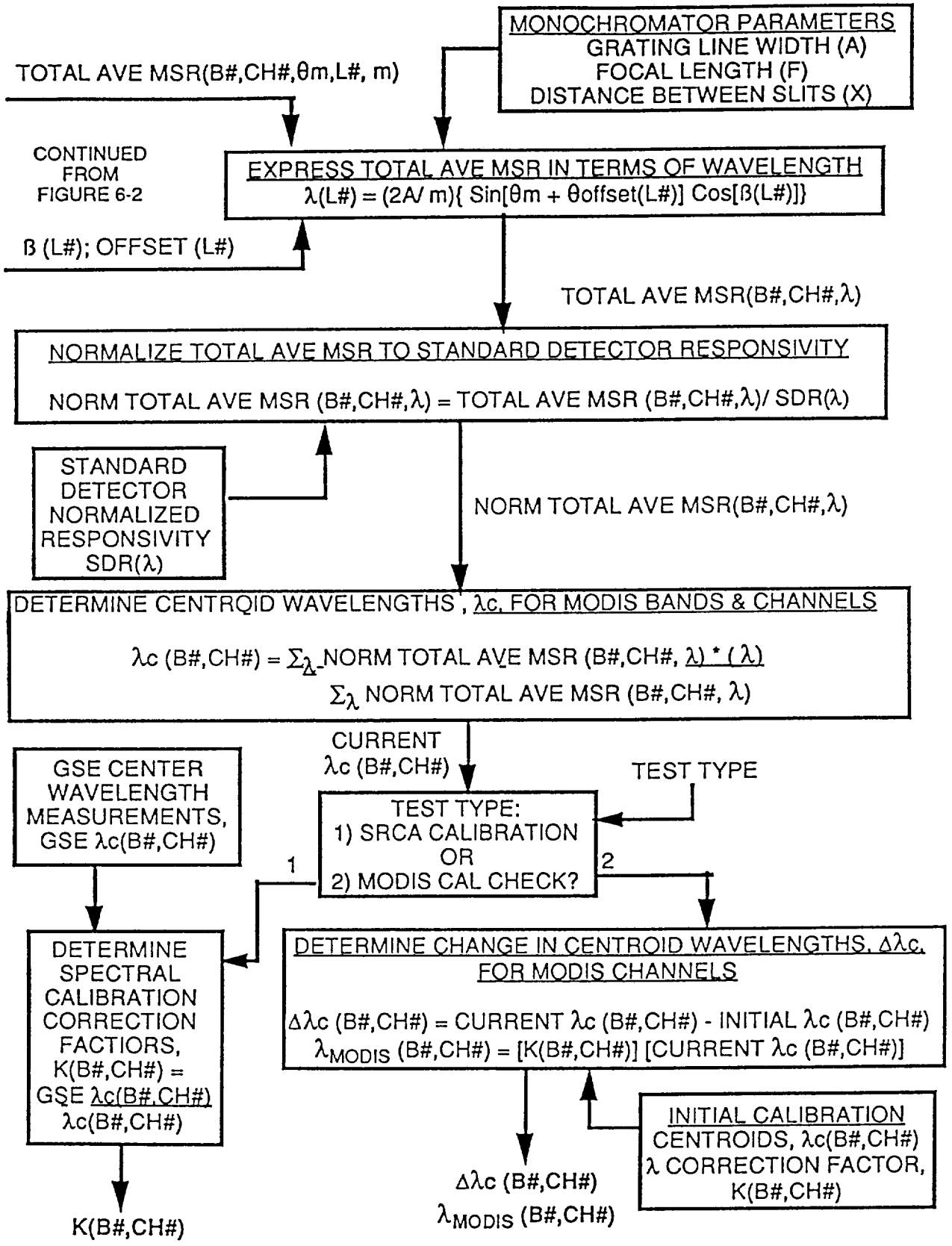


Figure 6.6c Spectral Calibration Algorithms

SBRC PRELIMINARY ALGORITHMS

SPATIAL

Pre-flight:

- Characterize MODIS with MGBC, then characterize SRCA
  Establish Correction Factor
- Characterize reticles

On-Orbit:

NO TRACK DIRECTION ALGORITHM YET

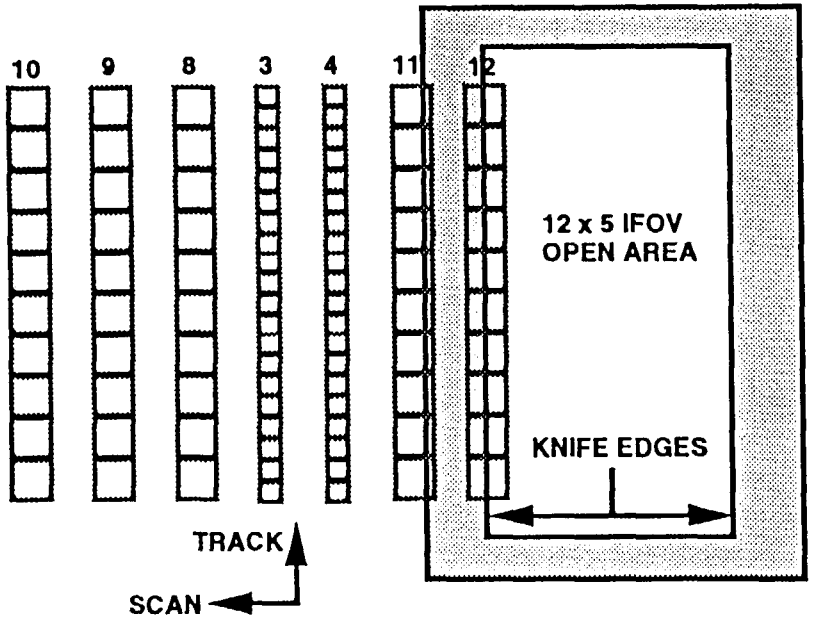
1. Determine number of scans, number of frames, amount of offset
2. Collect data.
3. Conduct appropriate averages.
4. Calculate Centroid (gives band to band registration).

IN-FLIGHT REGISTRATION MEASUREMENT CAN DETERMINE LAUNCH INDUCED ERRORS

HUGHES
SANTA BARBARA RESEARCH CENTER
a subsidiary

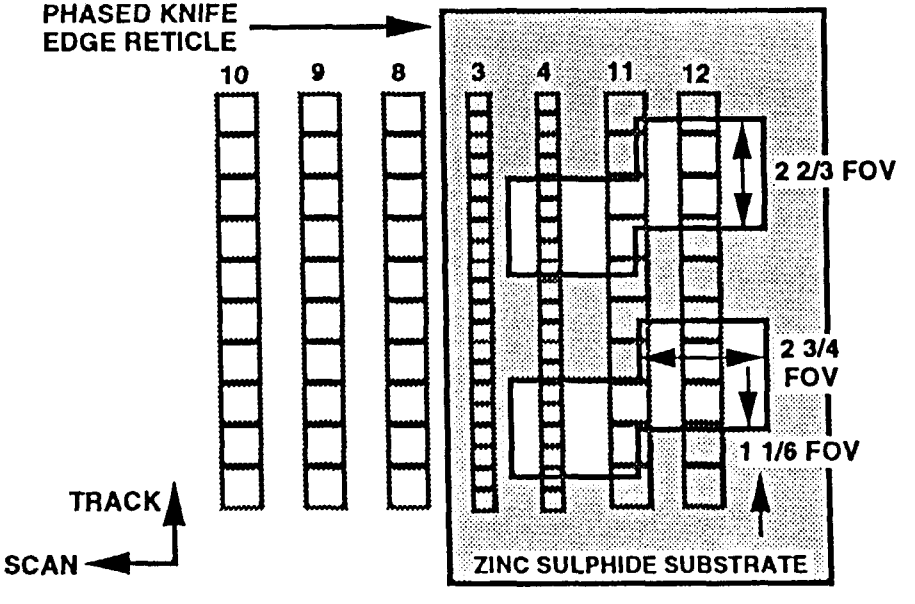
- MONOCHROMATOR EXIT WHEEL CONTAINS TWO SELECTABLE RETICLES

SCAN MEASUREMENT

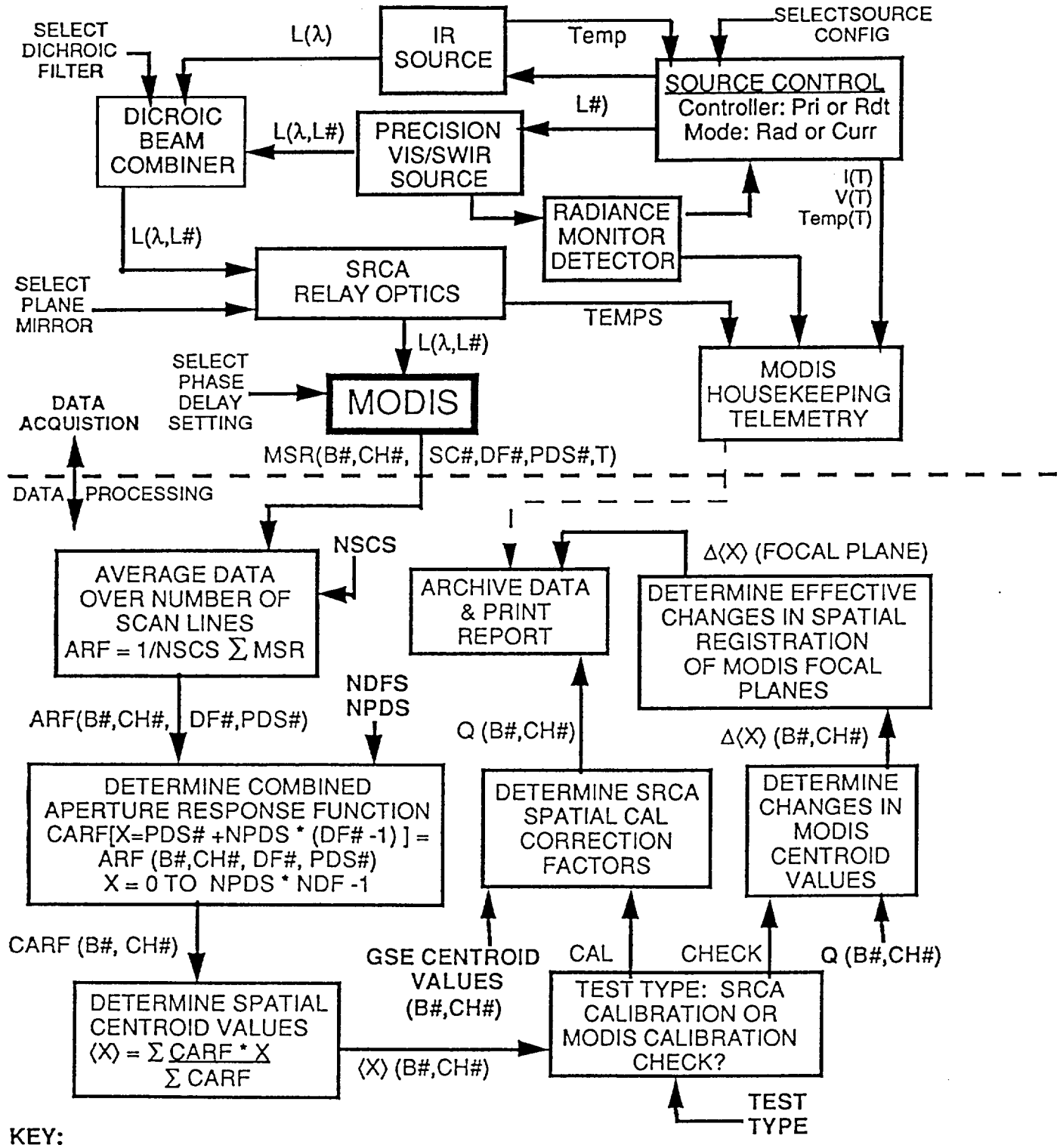


- ELECTRONIC PHASE DELAY STEPS ARRAY ACROSS KNIFE EDGES IN SCAN DIRECTION
  - Delay Step Range: ± 0.5 Pixel
  - No. of Positions: 5 - 10 per Radiance Level
- MEASURMENT REPEATABILITY: ≈ 0.05 Pixel

TRACK MEASUREMENT



- ELECTRONIC DELAY POSITIONS ARRAY IN RETICLE
- 8 DIFFERENT DETECTORS SAMPLED PER BAND
- PREDICTED PARTIAL APERTURE ALONG-TRACK KERs REQUIRED TO DETERMINE SHIFT
- MEASUREMENT REPEATABILITY: ≈ 0.1 Pixel



KEY:

T = Time & Date.	L = Radiance	SC# = Scan No.
L# = Lamp Config No.	V = Voltage	I = Current
Q = SRCA Spatial Cal Correction Factor		B# = MODIS Band No.
NPDS = No. of Phase Delay Settings Used		CH# = Detector Channel No.
NDFS = No. of Data Frames Collected		DF# = Data Frame No.
MSR = MODIS Spatial Response (Digital)		PDS# = Phase Delay Setting No.
Test Type = SRCA Calibration or MODIS Check		NSCS = No. of Scans Collected
ARF = Aperture Response Function		X = Spatial Coordinate

Figure 6.9 SRCA Spatial Calibration Flow Diagram

STATUS

- SBRC still developing/refining algorithms

- GSFC/SBRC still characterizing SRCA
  - STOP Analysis
  - Lifetime Considerations

- MCST has a steep learning curve to overcome

- Expanded characterizations yet to be investigated
  - Bandwidths
  - MTF

SPECIFICATION PACKET

This Packet Contains:

Appendix B of the ATBD, which describes the specification.
Select Sections of the Actual Specification.

Ed Knight maintains a current copy of the specification (22/C148, 6-2382).

Appendix B

Instrument Specification

B.1 Introduction

The MODIS Instrument Specification (Goddard Space Flight Center, 1993) sets forth the performance, testing, calibration and assurance requirements for MODIS. The instrument must meet these requirements upon delivery. The Specification therefore identifies the minimum characterization and calibration that must be done by the contractor.

This appendix presents a detailed discussion of the Specification as it relates to characterization and calibration. The intention is to be both comprehensive and sufficiently detailed enough so that the driving requirements for the calibration algorithm from the instrument become clear. To do so, it is divided into sections based on calibration requirements. Section B.2 presents a summary of the physical instrument requirements. The radiometric, spectral, and geometric requirements are presented in sections B.3, B.4, and B.5 respectively. Other important performance requirements are presented in section B.6. Finally, section B.7 summarizes the remaining Specification requirements.

It should be noted that other existing documents also cover MODIS operating requirements. These are cited in section ¶2.0 of the Specification (hereafter Specification references:¶ are denoted simply by section number). However, these do not directly relate to characterization and calibration and so are not discussed here.

B.2 Physical Instrument Requirements

The instrument must meet several basic physical requirements for operability. Table B-1 presents a summary of these parameters and cites the relevant Specification sections. Additionally, the lifetime and survivability requirements are addressed below.

One key requirement for the success of MODIS is that it be operable over its entire five year lifetime. The Specification (¶3.2.3) defines failure of the instrument to be the loss of 25% or more of the 36 spectral bands or more than 50% of the bands in any one spectral region (i.e., VIS, NIR, SWIR, MWIR, or LWIR). A band is considered as failed if the response in more than 25% of its detector elements falls 50% or more below the pre-launch response, or if its detector elements cannot be calibrated to perform within specification. Upon delivery, the instrument may have a maximum of one dead element per band and no more than two per focal plane (¶3.4.5.3.2).

While the lifetime of the MODIS instrument is intended to be five years in orbit, the Specification (¶3.2.3) requires it to be operable after delivery, without servicing, for six

Table B-1.Physical Requirements

Parameter	Requirement	Specification Section
Volume (Length x Width X Height)	1 x 1.6 x 1 m	3.6.2.2
Max. Appendage Length (external to Volume)	1 m	3.6.2.2
Mass	< 250 kg	3.6.2.2
Power	<225 W ave., <275 W peak	3.6.2.1
Ground View	120° cross-track 5° along-track	3.6.2.4.1
Sun View	allowed, no size requirement	3.6.2.4.2
Space View	allowed, no size requirement	3.6.2.4.3
Altitude	705.3 km	3.1.1
Equatorial Crossing Time		
AM Platform	10:30 AM +/- 15 min descending	3.2.1
PM Platform	1:30 PM +/- 15 min ascending	3.2.1
Lifetime	85% prob., 95% goal of being 5+ years	3.2.3
Radiation Recovery	unaffected by ambient	3.2.4.1
	< 5 km, < 5 data words for particles <20 MeV	3.2.4.2
Solar Recovery	< 10 orbits after 30 s direct view	3.4.10.4

months before launch as well as the five years in orbit. This follows a maximum period of eight years in storage plus two years of Integration and Test. If the storage period exceeds one year, the instrument will be thoroughly tested and recalibrated prior to integration on the spacecraft. The probability of meeting the five year lifetime is required to be 85% with a goal of 95% as determined by test experience and analytical assessment.

For survivability, the instrument is expected to operate within specification despite background radiation or unplanned scans through the sun. The instrument will pass through the South Atlantic Magnetic Anomaly; it may be unreasonable to expect to shield electronic parts from all possible particles. Therefore, the Specification (¶3.2.4.2) requires that a single event caused by particles having energy less than 20 MeV shall affect no more than 3 contiguous bands per focal plane, and 5 contiguous pixels per band. These pixels shall recover after 5 contiguous 1000 m pixel readout times (5 km) from the inception of the event. If the event affects the electronics following the focal planes, no more than 5 data words leaving the memory buffer may be degraded.

Under certain unplanned spacecraft attitudes, MODIS may scan through the sun. Therefore, the instrument shall be capable of scanning direct solar input in its 110-degree-wide FOV for 30 seconds per event, up to a total of 5 minutes in five years, without detectable performance degradation or lifetime reduction. Any radiative cooler must meet these same requirements for direct solar input. After any 30 second exposure, the instrument shall return to its calibrated condition within 10 orbits. Normal, expected solar inputs shall not degrade the instrument's performance for any portion of the orbit. Meeting these survivability and lifetime requirements is vital to the success of the MODIS mission.

B.3 Radiometric Requirements

One major goal of the MODIS program is to provide high radiometric accuracy for all of its spectral bands. Each of these bands is designed to address at least one specific scientific goal and thus has specific dynamic range requirements. Tables B-2a and B-2b summarize these requirements.

The instrument is expected to measure radiances from the noise equivalent differential spectral radiance (NEdL) up to the maximum spectral radiance (L_{max}) given for each band (¶3.4.1). L_{max} is the expected maximum value of Earth surface reflectance plus atmospheric effects for a solar zenith angle of 22.5 degrees (¶3.3.4.1). $L_{typical}$ (or L_{typ}), the expected spectral radiance needed for a given band for a solar zenith angle of 70 degrees (¶3.3.4.1), defines the reference radiance for many other specification requirements. Some specification requirements are concerned with the effects of radiance from clouds (L_{cloud}), which can be significantly different than L_{max}, so these values are also included in Tables B-2a and B-2b. L_{cloud} is defined as the spectral radiance of a 100% reflecting Lambertian surface illuminated at a solar zenith angle of 22.5 degrees (¶3.3.3.3). The given signal to noise ratio (SNR) must be met at $L_{typical}$ and exceeded for radiances above L_{typ} (¶3.4.1). Additionally, the sensitivity goal for each band shall surpass the tabulated requirements by 36% (¶3.3.4).

Table B-2a
Radiometric Requirements for MODIS Reflective Bands

Band	Center Wavelngth	Noise Equiv. Spectral Radiance	Spectral Radiance	Max Spectral Radiance	L_{cloud}	Signal to Noise Ratio
N	λ	NEdL	($L_{typical}$)	L_{Max}		SNR
	[nm]	(*)	(*)	(*)	(*)	[unitless]
1	645	0.169	21.8	685	457	128
2	858	0.123	24.7	285	293	201
3	469	0.145	35.3	593	570	243
4	555	0.127	29.0	518	559	228
5	1240	0.073	5.4	110	138	74
6	1640	0.027	7.3	70	68	275
7	2130	0.009	1.0	22	27	110
8	412	0.051	44.9	175	573	880
9	443	0.050	41.9	133	585	838
10	488	0.040	32.1	101	539	802
11	531	0.037	27.9	82	538	754
12	551	0.028	21.0	64	528	750
13	667	0.0104	9.5	32	471	910
14	678	0.008	8.7	31	440	1087
15	748	0.017	10.2	26	373	586
16	869	0.012	6.2	16	286	516
17	905	0.060	10.0	185	252	167
18	936	0.063	3.6	256	267	57
19	940	0.060	15.0	189	244	250
26	1375	0.04	6.0	89.9	113	150

* $\frac{W}{m^2 - sr - \mu m}$

Table B-2b
Radiometric Requirements for MODIS Emissive Bands

Band	Center Wavelength	Noise Equivalent Spectral Radiance	Spectral Radiance	Max. Spectral Radiance	L_{cloud}	Required NEdT	Typical Scene Temp	Max Temp
N	λ	NEdL	($L_{typical}$)	L_{Max}		(K)	T_{typ}	T_{Max}
	[nm]	(*)	(*)	(*)	(*)		(K)	[K]
20	3750	0.000957	0.45	1.71	0.45	0.05	300	335
21	3959	0.150	2.38	86.00	0.67	2.00	335	500
22	3959	0.00190	0.67	1.89	0.67	0.07	300	328
23	4050	0.00217	0.79	2.16	0.79	0.07	300	328
24	4465	0.00218	0.17	0.34	1.44	0.25	250	264
25	4515	0.00620	0.59	0.88	1.53	0.25	275	285
27	6715	0.0108	1.16	3.21	6.87	0.25	240	271
28	7325	0.0172	2.18	4.46	8.10	0.25	250	275
29	8550	0.00899	9.58	14.54	9.58	0.05	300	324
30	9730	0.0219	3.69	6.34	9.92	0.25	250	275
31	11030	0.00701	9.55	13.25	9.55	0.05	300	324
31-hi	11030	0.247	29.1	29.08	9.55	1.00	400	400
32	12020	0.00606	8.94	12.10	8.94	0.05	300	324
32-hi	12020	0.198	25.1	25.07	8.94	1.00	400	400
33	13335	0.0183	4.52	6.56	7.94	0.25	260	285
34	13635	0.0161	3.76	5.02	7.71	0.25	250	268
35	13935	0.0141	3.11	4.42	7.48	0.25	240	261
36	14235	0.0154	2.08	2.96	7.25	0.35	220	238

(*) $\frac{W}{m^2 - sr - \mu m}$

For the thermal bands, the primary concern is temperature. The corresponding noise equivalent temperatures (NEdT), typical scene temperature (T_{typ}), and maximum scene temperatures (T_{max}) are accordingly included in Table B-2b (¶3.3.4.2). Bands 31 and 32 are non-linear and the "high" segments (from 324 K to 400 K) do not carry the same calibration requirements as the lower segments.

The Specification requires that the MODIS band output be quantized (¶3.4.3). The quantization steps must be chosen both to preserve the required signal to noise requirements and so that the quantization is linear to better than 0.5 of the least significant bit.

Given these radiometric performance requirements, the next major specification concern is the radiometric accuracy. Table B-3 presents the absolute radiometric accuracy requirements (¶3.4.5.2).

Table B-3
Radiometric Accuracy Required in the MODIS Specification

Wavelength	Required Accuracy at L_{typ}[a] ($\pm 1\sigma$, %)	Minimum Required Accuracy from $0.3*L_{typ}$[a] to $0.9*L_{max}$[a] ($\pm 1\sigma$, %)
< 3 μm	5	6
> 3 μm	1[b]	2
Reflectance Calibration[c]	2	3

a. Based on use of multiple samples of a uniform, extended, non-polarized source.

b. At L_{typ} Band 20 shall have minimum required radiometric accuracy of 0.75% with a goal of 0.50% and Bands 31 and 32 shall have an accuracy of 0.50% with a goal of 0.25%. The "high" ranges of bands 31 and 32 shall have an accuracy of 10%.

c. Calibration relative to the Sun using the solar diffuser plate and solar diffuser stability monitor.

These requirements are based on the use of multiple samples of a uniform, extended, non-polarized source. Spectrally, for bands below 3000 nm, a tungsten lamp-based source may be used for ground tests. For bands above 3000 nm, the source shall have a black-body profile. The Specification mandates measurements at scan angles of 0, +45, and -45 degrees. However, the requirements must be met for all cross-track angles.

The Specification also cites relative radiometric accuracy requirements. When viewing a uniform calibration target, the RMS deviation from the mean of the radiance measurements shall not be greater than the NEdL values in Tables B-2a and B-2b

(¶3.4.5.3.1). For all live channels, the calibrated mean output of each channel shall match every other channel to within the NEdL (¶3.4.5.3.2). This matching requirement does not apply to the "high" segments of the nonlinear bands. For measurement purposes, this matching condition must be met when the instrument views a uniform radiance field at levels of $0.5L_{typ}$, L_{typ}, and $2L_{typ}$ (or L_{max} if $L_{max} < 2L_{typ}$).

Additionally, the Specification requires more than one approach be used to verify calibration accuracy (¶3.4.5.1). All accuracies must be established relative to NIST standards (¶3.4.5.2). Pre-launch, the contractor will conduct an end-to end analysis (¶3.4.5.1) and measure the SNR at a minimum of three equally spaced spectral radiance levels between 0.3 L_{typ} and 0.9 L_{max}, in order to characterize the signal dependence of the system noise (¶3.4.5.5).

B.4 Spectral Band Requirements

The MODIS instrument contains 36 spectral bands spanning regions from 0.4 μm to 14.4 μm. Table B-4 presents a summary of their requirements (¶3.3.3). The Center Wavelength (CW) is defined as the wavelength midway between the 50% response points (50% of the peak spectral response, also called the band edge). Since interference filters are difficult to construct precisely, the Specification allows some tolerance in the actual location of the center wavelength, which is expressed as Center Wavelength Tolerance (CWT) in Table B-4a/b.

The Specification defines the bandwidth (BW), or passband, as the wavelength interval between the 50% response points. It too has an allowed tolerance (BWT) for construction purposes.

Besides the CW and BW, the Specification requires the shape of the spectral bands to conform to certain requirements. The edge range, defined as the wavelength interval between the 5% and 80% response points on a given side, shall not exceed 50% of the bandwidth (¶3.3.3.2). The response between the 80% points shall always exceed 80% of the peak response (¶3.3.3.4). The 1% response points shall be within 1.5 times the bandwidth from the corresponding band edge (¶3.3.3.3). These 1% response points also define the extended bandpass, which is the wavelength interval between them. The out-of-band response is the ratio of the integrated spectral response beyond the extended bandpass to that within the extended bandpass. This ratio includes both the upper and lower response wings and cannot be greater than 0.05 (¶3.3.3.3). Compliance with this out-of-band response requirement shall be determined for a source spectrum equivalent to the sum of L_{cloud} (see B.3) and an extended 300 K blackbody.

Once constructed, the instrument is expected to meet additional characterization and spectral stability requirements. On the ground, all wavelength measurements shall be made with an absolute accuracy of 0.5 nm and a precision of 0.25 nm for wavelengths up to 1 μm, and shall scale linearly with wavelength above 1 μm (¶3.4.7.5). After launch, the center wavelength and bandwidth must be stable to better than 2 nm for the visible bands

Table B-4a
Spectral Requirements for the MODIS Reflective Bands

Band	Center Wavelength	Center Wavelength Tolerance	Bandwidth	Bandwidth Tolerance
N	λ	CWT	BW	BWT
	[nm]	[nm]	[nm]	[nm]
1	645	4	50	4.0
2	858	2.2	35	4.3
3	469	4	20	2.8
4	555	4	20	3.3
5	1240	5	20	7.4
6	1640	7	24.6	9.8
7	2130	8	50	12.8
8	412	2	15	1.5
9	443	1.1	10	1.6
10	488	1.2	10	1.7
11	531	2	10	1.9
12	551	5	10	1.4
13	667	[+1, -2]	10	1.7
14	678	1	10	1.7
15	748	2	10	1.9
16	869	5	15	4.3
17	905	2.3	30	5.4
18	936	2.3	10	5.6
19	940	2.4	50	5.6
26	1375	6	30	8.0

Table B-4b
Spectral Requirements for the MODIS Emissive Bands

Band	Center Wavelength	CW Tolerance	Bandwidth	BW Tolerance
N	λ	CWT	BW	BWT
	[nm]	[nm]	[nm]	[nm]
20	3750	19	180	22.5
21	3959	20	59.4	23.8
22	3959	20	59.4	23.8
23	4050	20	60.8	24.3
24	4465	22	65	26.8
25	4515	22	67	27.1
27	6715	34	360	40.3
28	7325	37	300	44.0
29	8550	43	300	51.3
30	9730	49	300	58.4
31	11030	55	500	66.2
31-hi	11030	55	500	66.2
32	12020	60	500	72.1
32-hi	12020	60	500	72.1
33	13335	67	300	80
34	13635	68	300	81.8
35	13935	70	300	83.6
36	14235	71	300	85.4

and better than 1% of the CW for the other bands (¶3.4.7.4). This includes shifts caused by changes of humidity, temperature, pressure, vibrations, and time.

B.5 Geometric Requirements

In addition to radiometric and spectral requirements, the MODIS Specification mandates specific requirements on the geometry of the earth view. These are primarily IFOV size requirements, coregistration requirements, and pointing knowledge requirements.

The primary geometric requirement is the instantaneous field of view (IFOV). IFOV is the combination of focal length and detector size which results in measuring a predetermined area on the Earth's surface at nadir from the nominal 705 km altitude. This area is measured at the 50% system response points and where the signal is sufficient to meet the SNR requirement (¶3.3.1). Table B-5 gives the along-track IFOV at nadir.

Table B-5
Geometric Requirements

Spectral Band	IFOV
1-2	250 m
3-7	500 m
8-36	1000 m

These are also the Ground Sample Distance (GSD) values, defined as the distance as measured on the ground between adjacent samples. The tolerance is +0/-6% in the along-track direction. In the cross-track direction, the distance traversed by the IFOV during sample integration must equal the GSD. Within a band, each detector must have an IFOV that does not differ from the mean by more than +/- 5% in either dimension (¶3.3.1). Within an , the response in the central 80% of each channel shall not vary by more than +/- 20% of the mean. The contractor is required to measure the system response in the along-track direction to a resolution of at least 10% of its width (¶3.4.5.4).

The Specification mandates close coregistration for corresponding detector elements from different spectral bands. For two elements with the same IFOV, the coregistration shall be within +/- 20% of an IFOV, with +/- 10% of an IFOV as a goal, in both the cross-track and along-track directions (¶3.4.6.3). For spectral bands having different IFOV's, four 500 m pixels and sixteen 250 m pixels shall overlay the corresponding 1000 m pixel at nadir to within 200 m (+/-20% of the 1000 m pixel), with 100 m as a goal. The contractor shall build in a commandable adjustment of the cross-track registration between focal planes, for both ground based and in-orbit registration corrections. The resolution of this adjustment shall be better than 25 meters (¶3.4.6.3). The relative alignment of all spectral bands shall remain within specification following any qualification level testing, launch, and in-orbit operation (¶3.4.6.2).

The instrument shall scan the IFOV +/- 55 degrees cross-track about nadir, using a method which does not introduce any image rotation (¶3.3.2).

To ensure geolocation accuracy (Appendix E), the Specification requires that an alignment reference cube be mounted on the MODIS instrument (¶3.4.6). The alignment of the instrument optical axis with respect to the instrument references and instrument mounting surfaces shall not change by more than 60 arc seconds (¶3.4.6.2). The knowledge of the angular location of each with respect to the reference cube shall be 30 arc seconds (each axis, ±1-sigma) at all scan angles. The contractor will supply an algorithm to relate this knowledge to a cube on the spacecraft mounting structure (¶3.4.6.1). Appendix E discusses pointing requirements and geolocation in greater depth.

B.6 Other Performance Requirements

While the radiometric, spectral, and geometric requirements are the primary concerns for MCST's characterization and calibration activities, several other performance requirements are also significant. Polarization and Modulation Transfer Function (MTF) spreading will both affect the radiometric accuracy. Crosstalk, Stray Light, and the Transient Response not only affect the radiometry, but degrade the imaging ability. This section addresses all five of these performance requirements.

If the instrument polarizes the light before it hits the detectors, uncertainties will be introduced in the radiance incident on the detectors. This is due to the optics' transmittance being a function of polarization. The Specification requires MODIS spectral bands 1 to 19 to be insensitive to linear polarization (¶3.3.5). The polarization factor, defined as

$$PF=(Imax - Imin) / (Imax + Imin)$$

shall be less than 0.02 for wavelengths from 0.43 μm to 2.2 μm and over scan angles of +/- 45 degrees. The contractor is required to provide an analytical end-to-end polarization model as part of the radiometric math model (see B-7). The contractor must map the magnitude and direction of the polarization sensitivity for bands 1 to 19 over the full range of angles. This mapping may combine measurements for at least 16 representative bands, including bands 9 through 17, with interpolation for the other bands. The polarization model must account for these measurements.

The Modulation Transfer Function (MTF) characterizes how the instrument resolves structured scenes. High spatial frequencies are attenuated or cut out, resulting in a blurring of the image. This blurring, or spreading, can have strong radiometric implications (light on one side of a bright edge bleeds into the other).

Therefore, the Specification requires the instrument system to satisfy or exceed the MTF requirements (¶3.4.2) presented in Table B-6.

Table B-6
Modulation Transfer Function (MTF) Requirements.

Frequency/Nyquist Frequency	MTF
0.00	1.0
0.25	0.9
0.50	0.7
0.75	0.5
1.00	0.3

The Nyquist frequency has a spatial period equal to two IFOV's on the ground. This MTF shall be met for both the along-track and cross-track directions for a sine wave input. It shall be met for modulations from dark to L_{typ} and dark to L_{max}, and shall be achieved for every channel of every band. The contractor is required to measure the MTF at representative points in the VIS, NIR, SWIR, MWIR, and LWIR regions.

Electronic crosstalk occurs when portions of the signal on one detector show up in the output of others. The Specification (¶3.4.5.3.3) requires that the response of a given detector element (the sender) shall not cause an apparent change in the response of any other detector element (the receiver) that is greater than one least significant bit (1-sigma), when the signal on the sender is equivalent to L_{typ} and the signal on the receiver is zero. This is based upon 12 bits for bands 1 to 32 and 10 bits for bands 33 to 36 (even though current design is 12 bits for all bands). This effect is measured as an increase above the crosstalk associated with photogenerated charge diffusing through the bulk of the detector material. Crosstalk requirements do not apply during transient radiation events. Additionally, other coherent noise mechanisms that lead to structured patterns in the output data (e.g., herringbone or diagonal bars) shall be imperceptible in data taken at the L_{typ} radiance levels for each spectral band. This will be verified by two-dimensional pictorial display tests used on representative bands.

The Specification requires MODIS to reject unwanted scattered and diffracted radiation which affects the radiometric accuracy (¶3.4.8.1). Stray light shall be restricted from entering any of the ports and from causing any degradation in the performance of a radiative cooler. In an operational, nadir-facing attitude, the instrument response to any stray light striking the instrument on any surface outside the FOV, from any angle, shall be less than $0.01L_{typ}$, when the incident radiance is L_{typ}. For compliance testing, the test sources shall have an intensity and view-factor sufficient to yield irradiance levels at any surface equal to the maximum solar irradiance for any spectral interval within the entire MODIS spectral range.

Additionally, the Specification mandates three specific stray light tests for cases within the instrument FOV. The first two, Bright Target (¶3.4.8.2) and Dark Target (¶3.4.8.3), apply to the VIS and NIR bands. The Bright Target test has MODIS viewing a 21 x 21 bright target,

which is surrounded by a dark background. The target is at L_{max} and the background is at L_{typ}. The background is then changed while the center pixel in the target is monitored. When the background is raised to L_{cloud}, the center pixel's radiance shall change by no more than $0.004L_{cloud}$. Figure B-1 demonstrates the geometry of this test.

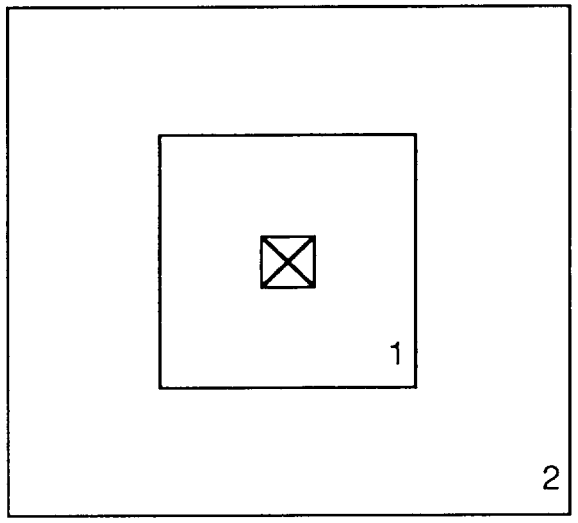


Figure B-1 Stray Light Tests

The target (region 1) is 21 x 21 IFOV for VIS/NIR and 5 x 5 for the Thermal regions. The background (region 2) is changed as the center pixel (the x) is monitored.

The Dark Target test uses the same geometry, with MODIS viewing a 21 x 21 IFOV dark target surrounded by a bright background. This time the target is at L_{typ} and the background is at L_{cloud}. Again, the background is then changed while the center pixel in the target is monitored. When the background is lowered to $0.2L_{max}$, the center pixel's radiance shall change by no more than $0.004L_{cloud}$.

For the thermal bands, the stray light test, Warm Target (¶3.4.8.4), is very similar to the Bright Target test. The test has MODIS view a 5 x 5 IFOV target at L_{typ}, which is surrounded by a background at $0.1L_{typ}$. The center pixel shall change by no more than 1% when the background radiance is increased to L_{typ}.

Finally, the transient response specification (¶3.4.4) sets the requirement for recovery after scanning across a bright target. When the instrument scans across a steep gradient from a maximum radiance of L_{cloud} (L_{max} for the thermal bands), to a minimum of $L_{typical}$, the output signal shall have less than a 1% overshoot and shall settle to within 0.5% of its final value within 2 km. Figure B-2 illustrates the allowed response envelope.

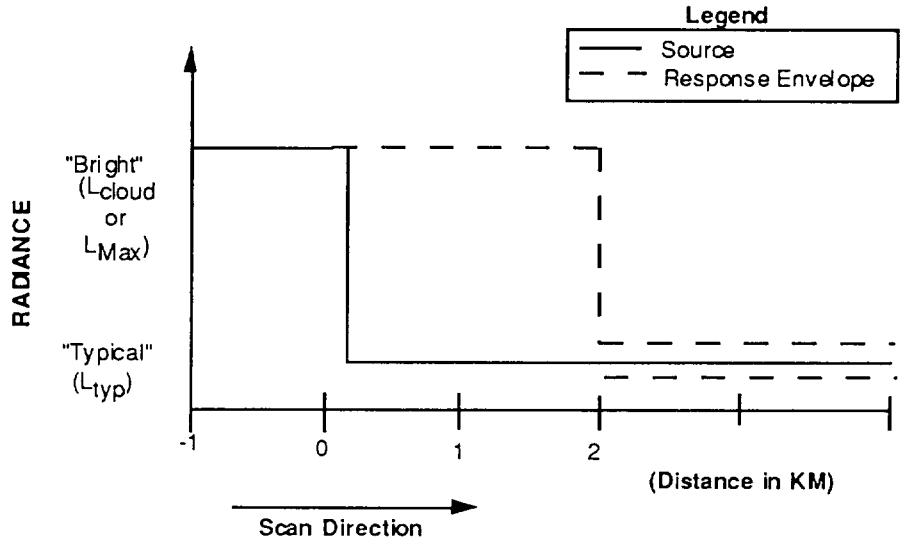


Figure B-2 Transient Response Requirement

The Transient Response Specification requires the instrument to be within +/- 0.005Ltyp of its final value after 2 km. The response envelope shows the allowed radiance values.

B.7 Remaining Specification Requirements

In the interests of completeness, this section presents a summary of the remaining specification requirements. Of relevance to MCST's activities are the In-Flight Calibration requirements, Model requirements, and Pre-Launch Verification and Calibration Requirements. Additionally, the Specification discusses operational modes, communication requirements, software requirements, Ground Support Equipment requirements, and several miscellaneous requirements. These are briefly summarized below--the reader is referred to the Specification if more detail is desired about these items.

The Specification (¶3.4.9) requires an in-flight calibration system, including necessary algorithms. This section therefore drives the design of the On-Board Calibrators. Specifically, the Specification mandates end-to-end calibration, with all absolute radiometric calibration sources filling the aperture. The instrument will provide in-flight radiometric calibration from $0.3L_{typ}$ to $0.9L_{max}$ for all bands (¶3.4.9.1). It shall include a solar diffuser and a solar diffuser monitor for reflectance calibration (¶3.4.9.3). MODIS will carry an in-flight wavelength calibration capability that shall be able to detect a 1 nm shift with a precision of 0.5 nm in its shortest wavelength band. For all wavelengths up to 1 μm, the detectable shifts and measurement precision shall scale with wavelength (¶3.4.9.2). Additionally, provisions shall be made for using the moon for a calibration source (¶3.4.9.4) and for calibrating the electronic response at appropriate points (¶3.4.9.5).

The contractor must deliver several instrument models to NASA (¶3.1.4). Three math models (radiometric, thermal, and structural), must all be maintained and updated (including experimental data when available) throughout the life of the contract. The

radiometric math model (RMM) (¶3.1.4.1) covers the end-to-end radiometric performance of the instrument including sensitivity analyses and error source identification. It will include all on-board and preflight ground laboratory calibration algorithms and data, which are deliverables to GSFC (¶3.1.4.1). The Thermal (¶3.1.4.2) and Structural Math Models (¶3.1.4.3) must similarly be verified before delivery to GSFC. The contractor is also required to build a Structural Model (¶3.1.4.4) and Engineering Model (¶3.1.4.5) for testing purposes. The Protoflight Model (¶3.1.4.6) and two Flight Models (¶3.1.4.7) shall be launched.

The Specification also contains several verification and calibration requirements to be fulfilled before the instrument is accepted (¶5.0). The contractor shall prepare and maintain a Verification Plan (¶5.1.1), Verification Specifications (¶5.1.2) and Verification Procedures (¶5.1.3). These are designed to demonstrate that the Specification requirements and all calibration accuracy requirements are being met (¶5.1). For calibration, a Calibration Management Plan (¶5.1.4) and Calibration Procedures (¶5.1.5) must be submitted for NASA review and approval. All Test and Calibration data (¶5.1.6) will be provided, and the Verification and Calibration Management Plans shall be controlled documents after acceptance (¶5.1.8). Finally, the contractor shall provide and maintain software to monitor critical functions, provide alarms as necessary, and shut down the instrument if the operator does not take corrective action (¶5.1.7).

The Specification provides more detail on specific environmental and calibration test requirements. Testing environments shall include both ambient and vacuum conditions (¶5.2) and shall be performed in accordance with all relevant NASA documents (¶5.3). The MODIS Technical Officer will appoint representatives to oversee all calibration procedures performed by the contractor (¶5.4.1). These calibration tests will include specified sources (¶5.4.2.1), temperature plateaus (¶5.4.2.2), linearity tests (¶5.4.2.3), diffuser spectral calibration (¶5.4.2.4), software (¶5.4.2.5), calibration fixtures (¶5.4.3), and temperature and voltage monitors (¶5.4.4). A history of all test data shall also be supplied (¶5.5).

Several operational modes are defined by the Specification (¶3.2.2). These are listed in Table B-7. The contractor shall recommend the instrument configuration for each of these modes.

The Specification also addresses several communication requirements. The instrument shall accept ground commands via the platform (¶3.5.1) and transmit data back in an appropriately formatted data stream (¶3.5.2). The data rate shall not exceed 10.8 Mbps (¶3.5.2.1). Telemetry data to monitor the instrument health and status will be included in the data stream (¶3.5.3).

The contractor shall provide all software necessary to operate, test, calibrate, design, and analyze the instrument (¶4.1). This includes data processing software (¶4.1.1), instrument-based software/firmware (¶4.1.2), software for operations analysis (¶4.1.3), a command list (¶4.1.4), and instrument ground software (¶4.2).

The Specification requires the contractor to provide and maintain all Ground Support Equipment (GSE) throughout the duration of the contract (¶6.1). This includes the System Test Equipment (STE), which shall be able to operate the instrument during all testing at the contractor's facility and record all received data (¶6.3), equipment for ambient operation (¶6.4) and ancillary equipment (drill template and handling fixtures) (¶6.5).

Finally, the Specification covers several miscellaneous instrument requirements. The contractor must include provisions to decontaminate the radiant cooler (¶3.4.10.1), identify and document sensitive parts and instrument limitations (¶3.4.10.2), and provide witness mirrors to check contamination (¶3.4.10.3). All desired details on these other specification requirements can be found in the Specification itself.

Table B-7
Operational Modes

Operational Mode	Instrument Status
Launch and Orbit Acquisition	monitor health and safety
Outgassing	protect vs. contamination
Activation	turn-on and warm-up
Mission	normal operation
Day Mode	full operating mode
Night Mode	thermal bands only
Solar Calibration	solar diffuser deployed
Lunar Calibration	view moon
Spectral Calibration	SRCA operates
Survival (Emergency Off)	minimum power

B.8 Summary

This Appendix discussed the Specification requirements in detail as they relate to characterization and calibration. Beyond the basic instrument requirements, the primary calibration concerns are radiometric, spectral, and geometric performance and accuracies. Additional performance requirements, such as MTF and stray light, will affect the calibration and so must be met as well. For completeness, this appendix also summarized the remaining specification requirements. These requirements serve as the starting point for MCST's calibration activities.

SPECIFICATION FOR THE MODERATE-RESOLUTION IMAGING SPECTRORADIOMETER (MODIS)

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APPENDIX A A-1

2.0 APPLICABLE DOCUMENTS

The following documents shall apply to the design, fabrication, and verification effort conducted in accordance with this specification, and shall be considered part of this specification. The version of the documents attached to the contract shall apply. In the event of conflict between this specification and any referenced document, this specification shall govern. The Unique Instrument Interface Document (UIID) will be the second document in precedence. Any contradictions between this specification and the UIID shall be brought to the immediate attention of the Technical Officer.

2.1 GSFC AND GENERAL GOVERNMENT SPECIFICATIONS AND STANDARDS

(1) Federal Standard 209D: Clean Room and Work Station Requirements, Controlled Environment

(2) NHB 5610.1: Handbook for Preparation of Work Breakdown Structures

(3) GSFC S-250-P-1C: Contractor Prepared Monthly, Periodic, and Final Reports

(4) GHB 5112.1: Performance Measurement System (PMS) Handbook

(5) NASA Ref. Publication 1124: Outgassing Data for Selecting Spacecraft Materials

(6) 420-05-01: EOS Performance Assurance Requirements for General Instruments

(7) 420-03-01: EOS Project Calibration Management Plan

(8) 420-02-02: EOS Project Configuration Management Plan

(9) 422-20-04: EOS MODIS-N Software Management Requirements

(10) GEVS-SE: General Environmental Verification Specification for STS and ELV Payloads, Subsystems, and Components, NASA Goddard

(11) GHB 7120.1: Work Breakdown Structure

(12) NHB 6000.1C: Requirements for Packaging, Handling and Transportation

2.2 MILITARY SPECIFICATIONS AND STANDARDS

(1) MIL-STD-130G: Identification Marking for U.S. Government Property

(2) DOD-D-1000B: Military Specification Drawings, Engineering and Associated Lists, for Categories, A, B, C, D, G, H, Using Form 2 Drawings

2.3 EOS POLAR SPACECRAFT INSTRUMENT INTERFACE SPECIFICATIONS

(1) 420-03-02: EOS General Instrument Interface Specification

(2) 422-21-05: EOS Unique Instrument Interface Document for MODIS

2.4 EOS REFERENCE DOCUMENTS

(1) Reserved

3.3 OPTICAL REQUIREMENTS

3.3.1 Instantaneous Field of View (IFOV)

The IFOV is defined as that combination of focal length and detector size which results in a predetermined area on the Earth's surface being measured from the nominal 705 kilometer altitude where the area is measured at the 50% system response points and the signal is sufficient to meet the required SNR. The along-track IFOV at nadir shall be as given in Table 3.3.3. The Ground Sample Distance (GSD) is defined as the distance as measured on the ground between adjacent samples. The nadir GSD shall be equal to the value listed in Table 3.3.3. The tolerance on the IFOV is +0/-6% in the along-track direction. The cross-track IFOV need not be equal to the values listed in Table 3.3.3, if the distance traversed by the IFOV during sample integration equals the GSD. For all other sections of this specification, the cross-track IFOV shall be equivalent to the GSD.

Each detector within a band shall have an IFOV that does not differ from the mean by more than +/-5% in either dimension.

3.3.2 Field of View

The instrument shall scan the IFOV +/-55 degrees cross-track about nadir, using a method which does not introduce any image rotation.

3.3.3 Spectral Bands

MODIS shall operate in the VIS, NIR, SWIR, MWIR and LWIR regions, and shall provide spectral band measurements as listed in Table 3.3.3.

Table 3.3.3: Spectral Band Optical Characteristics

BAND	CENTER WL (nm)	WL TOLERANCE (+/-nm)	BW (nm)	BW TOLERANCE (+/-nm)	IFOV
1	645	4	50	4.0	250
2	858	2.2	35	4.3	250
3	469	4	20	2.8	500
4	555	4	20	3.3	500
5	1240	5	20	7.4	500
6	1640	7	24.6	9.8	500
7	2130	8	50	12.8	500
8	412	2	15	1.5	1000
9	443	1.1	10	1.6	1000
10	488	1.2	10	1.7	1000
11	531	2	10	1.9	1000
12	551	5	10	1.4	1000
13	667	+1,-2	10	1.7	1000
14	678	1	10	1.7	1000
15	748	2	10	1.9	1000
16	869	5	15	4.3	1000
17	905	2.3	30	5.4	1000
18	936	2.3	10	5.6	1000
19	940	2.4	50	5.6	1000
20	3750	19	180	22.5	1000
21	3959	20	59.4	23.8	1000
22	3959	20	59.4	23.8	1000
23	4050	20	60.8	24.3	1000
24	4465	22	65	26.8	1000
25	4515	22	67	27.1	1000
26	1375	6	30	8.0	1000
27	6715	34	360	40.3	1000
28	7325	37	300	44.0	1000
29	8550	43	300	51.3	1000
30	9730	49	300	58.4	1000
31	11030	55	500	66.2	1000
32	12020	60	500	72.1	1000
33	13335	67	300	80.0	1000
34	13635	68	300	81.8	1000
35	13935	70	300	83.6	1000
36	14235	71	300	85.4	1000

The high ranges of bands 29, 31, and 32 (defined in Table 3.3.4.2) have the same wavelength requirements as the normal ranges of these bands.

3.3.3.1 Definitions

These parameters relate to performance of the complete instrument system. See Figure 3.3.3.1.

a. Band Edge - The wavelength at which the response is half of the peak response; there is a lower and an upper band edge.

b. Center Wavelength - The wavelength midway between the band edges.

c. Bandpass (or bandwidth) - The wavelength interval between the lower and upper band edges. This is also referred to as the FWHM response.

d. One-percent Response Point - the wavelength, nearest to the center wavelength, at which the response is one-percent of the peak response; there is a lower and an upper one-percent response point.

e. Extended Bandpass - The wavelength interval between the lower and upper one-percent response points.

f. Out-of-Band Response Regions - The spectral regions beyond the extended bandpass.

g. Out-of-Band Response - The ratio of integrated out-of-band spectral response to integrated extended bandpass spectral response. This ratio includes both the upper and lower wings of the response.

h. Out-of-Band Blocking - The inverse of the ratio defined as the out-of-band response.

i. Edge Range - The wavelength interval, in nanometers, between 5% of peak response and 80% of peak response.

```
                 100% --> --------
                         /        \
                        /          \
                       /            \
                      /              \
             50% --> +                +
                    /|                |\
                   / |                | \
                  -  |                |  -
                 -   |                |   -
   ___  - + <-- 1%   |                |      + -  ___
-------+------------+----------------+-------------+-------
OUT OF |            |<-- BANDPASS -->|             | OUT OF
 BAND  |<------------EXTENDED BANDPASS-------------| BAND
```

FIGURE 3.3.3.1

3.3.3.2 Edge Range

The edge range shall not exceed 50% of the bandwidth in any spectral band.

3.3.3.3 Out-of-Band Characteristics

The out-of-band response shall be less than 5%. Each one-percent response point shall be within 1.5 times the bandpass from the corresponding band edge. Compliance with this specification shall be determined for a source spectrum equivalent to the sum of Lcloud (the spectral radiance of a Lambertian surface of 100% reflectance, illuminated by the sun at a zenith angle of 22.5 degrees) plus an extended 300K blackbody. Lcloud is given in Table 3.3.4.1 for the VIS, NIR, and SWIR bands, and in Table 3.3.4.2 for the thermal bands.

3.3.3.4 Ripple

The response between the 80% of peak points of the bandpass shall always exceed 80% of the peak response.

3.3.4 Sensitivity Requirements

The sensitivity requirements for the MODIS spectral bands are given here. If the contractor determines that time delay and integration (TDI) is required for any band, this processing shall be done on board the instrument to minimize the data rate.

The instrument shall be capable of measuring spectral radiances from the Noise Equivalent Differential Spectral Radiance (NEdL) up to the Maximum Spectral Radiance at the entrance aperture of the instrument (Lmax). The instrument SNR shall be measured over this range of radiances.

As a consequence of increasing the IFOV areas 36% from Phase-B values, the sensitivity goal for each band shall surpass the requirements tabulated in Sections 3.3.4.1 and 3.3.4.2 by 36%.

3.3.4.1 Visible, Near IR and Short Wave IR Bands

Table 3.3.4.1 applies to the VIS, NIR and SWIR bands. It presents the requirements for NEdL and for SNR. It also presents Lmax, calculated for the expected maximum values of Earth surface reflectance plus atmospheric effects, for a solar zenith angle of 22.5 degrees. Additionally, the table contains the typical spectral radiance, Ltypical, at the instrument entrance aperture, for a solar zenith angle of 70 degrees. The required NEdL and SNR shall be achieved for Ltypical. The SNR is the ratio of Ltypical to the required NEdL. Lcloud is included in the table.

TABLE 3.3.4.1
MODIS VIS, NIR and SWIR Bands

BAND	CENTER WAVELENGTH (nm)	REQUIRED NEdL (*)	TYPICAL SPECTRAL RADIANCE (Ltypical) (*)	REQUIRED SNR	MAXIMUM SPECTRAL RADIANCE (Lmax) (*)	Lcloud (*)
1	645	0.169	21.8	128	685	457
2	858	0.123	24.7	201	285	293
3	469	0.145	35.3	243	593	570
4	555	0.127	29.0	228	518	559
5	1240	0.073	5.4	74	110	138
6	1640	0.027	7.3	275	70	68
7	2130	0.009	1.0	110	22	27
8	412	0.051	44.9	880	175	573
9	443	0.050	41.9	838	133	585
10	488	0.040	32.1	802	101	539
11	531	0.037	27.9	754	82	538
12	551	0.028	21.0	750	64	528
13	667	0.0104	9.5	910	32	471
14	678	0.008	8.7	1087	31	440
15	748	0.017	10.2	586	26	373
16	869	0.012	6.2	516	16	286
17	905	0.060	10.0	167	185	252
18	936	0.063	3.6	57	256	267
19	940	0.060	15.0	250	189	244
26	1375	0.04	6.0	150	89.9	113

* = Watts/m^2/um/sr

3.3.4.2 Thermal Emittance Bands

Table 3.3.4.2 presents requirements for the thermal emittance (MWIR and LWIR) bands. The table shows required NEdT and NEdL for typical scene temperatures and spectral radiances, Ltypical, of extended scenes. The table also gives the maximum scene temperatures, Tmax, and equivalent Lmax values which the instrument shall measure. The NEdT shall be met at the typical scene temperatures. Lcloud in included in the table.

3.3.5 Instrument Polarization Insensitivity

MODIS spectral bands 1 to 19 shall be insensitive to linear polarization as defined here. An analytical end-to-end polarization model shall be provided as part of the radiometric math model.

Table 3.3.4.2
MODIS Thermal Bands

BAND	CENTER WAVELNTH (nm)	TYPICAL SCENE TEMP Ttyp (K)	TYPICAL SPECTRAL RADIANCE Ltyp (*)	REQD NEdT (K)	NEdL (*)	MAX SCENE TEMP Tmax (K)	MAX SPECTRAL RADIANCE Lmax (*)	Lcloud
20	3750	300	0.45	0.05	0.000957	335	1.71	0.45
21	3959	335	2.38	2.00	0.015	500	86.00	0.67
22	3959	300	0.67	0.07	0.00190	328	1.89	0.67
23	4050	300	0.79	0.07	0.00217	328	2.16	0.79
24	4465	250	0.17	0.25	0.00218	264	0.34	1.44
25	4515	275	0.59	0.25	0.00620	285	0.88	1.53
26	(moved to Table 3.3.4.1)							
27	6715	240	1.16	0.25	0.0108	271	3.21	6.87
28	7325	250	2.18	0.25	0.0172	275	4.46	8.10
29	8550	300	9.58	0.05	0.00899	324	14.54	9.58
30	9730	250	3.69	0.25	0.0219	275	6.34	9.92
31	11030	300	9.55	0.05	0.00701	324	13.25	9.55
31hi	11030	400	29.1	1.00	0.247	400	29.08	9.55
32	12020	300	8.94	0.05	0.00606	324	12.10	8.94
32hi	12020	400	25.1	1.00	0.198	400	25.07	8.94
33	13335	260	4.52	0.25	0.0183	285	6.56	7.94
34	13635	250	3.76	0.25	0.0161	268	5.02	7.71
35	13935	240	3.11	0.25	0.0141	261	4.42	7.48
36	14235	220	2.08	0.35	0.0154	238	2.96	7.25

* = Watts/m^2/um/sr

Note: The high range of nonlinear bands 31 & 32 is 324K to 400K.

The polarization factor, as defined below, shall be no greater than 0.02 over scan angles of +/-45 degrees and wavelengths from 0.43 to 2.2um.

$$PF = (Imax - Imin)/(Imax + Imin) < 0.02$$

The contractor shall map the magnitude and direction of the polarization sensitivity of bands 1 to 19 over the full range of scan angles. This mapping may combine measurements for at least sixteen representative bands, including bands 9 through 17, with interpolation for the other bands.

The polarization model shall be adjusted to account for these data.

3.4 SYSTEM PERFORMANCE REQUIREMENTS

Performance and ground calibration data shall be analyzed and displayed in real time and in a quickly understandable form. This form shall generally be plots in engineering units.

3.4.1 Dynamic Range

MODIS shall be designed to operate over a dynamic range that extends from the noise floor (NEdL) in each spectral band to the maximum levels (Lmax) given in Tables 3.3.4.1 and 3.3.4.2. Instrument signal to noise ratio for radiances above Ltyp shall exceed the requirements at Ltyp.

3.4.2 Modulation Transfer Function

The MTF of the instrument system shall satisfy or exceed the values tabulated below. This MTF shall apply to both along-track and cross-track directions for a sine wave input. The Nyquist frequency has a spatial period equal to two IFOV's on the ground.

Frequency/Nyquist Frequency	MTF
0.00	1.0
0.25	0.9
0.50	0.7
0.75	0.5
1.00	0.3

The MTF requirements shall be satisfied for modulations of dark to Ltypical and for dark to Lmax, and shall be achieved for every channel of the different spectral bands in the instrument. The MTF's shall be measured at representative points of the VIS, NIR, SWIR, MWIR and LWIR regions.

3.4.3 Minimum Quantizing Resolution

A quantizer shall be included in the MODIS instrument to generate a digital data stream. The quantization steps shall be sized so that the signal-to-noise requirements for the typical spectral radiances and temperatures given in Tables 3.3.4.1 and 3.3.4.2 are met. Differential linearity of any signal quantizer shall be better than 0.5 of the least significant bit (LSB).

3.4.4 Transient Response (Bright Target Recovery)

The instrument shall be designed to minimize overshoot and ringing when the IFOV scans across a steep gradient in spectral radiance, from a maximum of Lcloud (Lmax for thermal bands) to a minimum of Ltypical. For this radiance step change the output signal shall have less than 1% overshoot and the output signal shall settle to within 0.5% of its final value within 2km.

3.4.5 Radiometric Performance

3.4.5.1 Radiometric Accuracy (Spectral and Amplitude)

The MODIS digitized and calibrated spectral radiances shall meet, in orbit, the accuracy requirements delineated below. More than one approach shall be used to verify the calibration accuracy and provide additional confidence in the measurements.

An end-to-end analysis of the total system shall be conducted to show that the system will meet the specified accuracy requirements over the full dynamic range.

The contractor shall consider internal heaters on key elements, or other instrument features which would aid in the post-launch verification of instrument calibration.

The frequency of calibration updates required in orbit for the instrument shall be recommended by the contractor. Operational procedures for routine, periodic calibration in orbit shall be developed.

3.4.5.2 Absolute Radiometric Accuracy

The MODIS absolute radiometric accuracy requirements are given in Table 3.4.5.2, and shall be established at the typical spectral radiance levels given in Tables 3.3.4.1 and 3.3.4.2. At any other radiance between 0.3Ltypical and 0.9Lmax the absolute accuracy of the radiance shall not exceed the values in Table 3.4.5.2 by more than 1%. These measurements shall be made at scan angles centered at 0, -45, and +45 degrees of the cross-track swath. Accuracies for the "hi" ranges (Table 3.3.4.2) of the nonlinear bands

shall be 10%. All accuracies shall be established relative to National Institute of Standards and Technology (NIST) standards and standard procedures. These calibration accuracy requirements shall be satisfied for all cross-track angles.

Table 3.4.5.2
ABSOLUTE RADIOMETRIC ACCURACY REQUIREMENTS *

	REQT (ONE-SIGMA)
BELOW 3000 nm	5%
ABOVE 3000 nm	1% **
REFLECTANCE CALIBRATION	2%

* Based on use of multiple samples of a uniform, extended, non-polarized source. For bands below 3000nm, a tungsten lamp based source may be used for ground tests. For bands above 3000nm, the source shall have a black-body profile.

** Band 20 shall be 0.75% with a goal of 0.50%. Bands 31 and 32 shall be 0.50% with a goal of 0.25%.

3.4.5.3 Relative Radiometric Accuracy

3.4.5.3.1 Root Mean Square Deviation

The RMS deviation from the mean of the calibrated spectral radiance measurements within any spectral band when viewing a uniform calibration target shall be no greater than the NEdL values given in Table 3.3.4.1 and 3.3.4.2. This applies over the full range of spectral radiance levels.

3.4.5.3.2 Channel to Channel Uniformity

If multiple detector elements are used within a spectral band, then one dead element per band and no more than two dead elements per focal plane are acceptable. For all live channels, the calibrated mean output of each channel with respect to every other channel shall be matched to within the values of NEdL given in Table 3.3.4.1 for bands 1-19 and to within the values of NEdL given in Table 3.3.4.2 for bands 20-36. This matching condition shall be met when the instrument views a uniform constant spectral radiance field at levels of approximately 0.5Ltypical, Ltypical and 2Ltypical (or Lmax, if Lmax < 2Ltypical). This requirement does not apply in the high temperature ranges of the nonlinear (fire) bands.

3.4.5.3.3 System Electronic Crosstalk and Pattern Noise

The response of a detector element in a given spectral band (the sender) shall not cause an apparent change in either the response of another detector element in any band (the receiver) that is greater than one least significant bit (1-sigma) in response to a signal placed on the sender that is equivalent to the Ltypical for the sender and the receiver with zero incident radiance. This shall be based upon 12 bits for bands 1 to 32 and 10 bits for bands 33 to 36. This effect excludes those crosstalk effects associated with photogenerated charge diffusing through the bulk of the detector material and is measured as an increase above the diffusion crosstalk. With respect to the sender/ receiver in the same spectral band, the effect may be detected as information is read off the focal plane as a memory effect residual from the sender into the receiver's expected zero signal level. This paragraph does not apply during transient radiation events.

There are other coherent noise mechanisms that lead to structured patterns in the output data (e.g., herringbone or diagonal bars). These extraneous noise sources shall be imperceptible in data taken at the Ltypical radiance levels for each spectral band. This shall be verified by two-dimensional pictorial display tests used on representative bands.

3.4.5.4 Uniformity of Response Across an IFOV

The system response across each IFOV of each channel, in the along-track direction, shall be measured to a resolution at least as fine as 10% of its width. Within the central 80% of the width of the IFOV this response shall not vary by more than +/-20% of the mean.

3.4.5.5 System Noise Measurements

The signal-to-noise ratio shall be determined for all bands at a minimum of three equally spaced spectral radiance levels between 0.3 Ltypical and 0.9 Lmax to characterize the signal dependence of the system noise.

3.4.6 Geometric Performance Requirements

An alignment reference cube shall be mounted on the MODIS instrument to allow transfer of alignment from the instrument to the spacecraft mounting structure or to another reference on the spacecraft. The contractor may also use this cube during performance testing.

3.4.6.1 Pointing Knowledge

The angular location of each IFOV with respect to the MODIS alignment reference cube shall be known to within 30 arc sec (each axis, 1-sigma) at all scan angles. The contractor shall develop an algorithm to relate this knowledge to a cube on the spacecraft mounting structure.

3.4.6.2 Alignment Changes

The alignment of the instrument optical axis with respect to the instrument references and to the instrument mounting surface shall not change by more than 60 arc seconds and the relative alignment of all spectral bands shall remain within specification following any qualification level testing, launch, and in-orbit operation.

3.4.6.3 Spectral Band Registration

Coregistration of any two corresponding detector elements from different spectral bands having the same IFOV shall be within +/-20% of an IFOV in the cross-track and along-track directions, with +/-10% of an IFOV as a goal.

For spectral bands having different IFOV's, four 500m pixels and sixteen 250m pixels shall overlay the corresponding 1000m pixel at nadir. The tolerance on this coregistration requirement is 200m (+/-20% of the 1000m pixel), both cross-track and along-track with 100m as a goal.

Commandable adjustment of the crosstrack registration between focal planes shall be available to facilitate ground based and in orbit registration corrections in the crosstrack direction. The resolution of this adjustment shall be better than 25 meters.

3.4.7 Radiometric Amplitude Stability and Repeatability

Bias errors will be removed from the data during ground processing in order to improve radiometric accuracy. To accomplish this the instrument shall be stable over temperature and time as defined below.

3.4.7.1 Short-Term Stability

Short-term stability as defined here applies to all time scales less than two weeks. The mean radiometric response of each spectral band, corrected on the ground using in-flight calibration data, shall not differ by more than +/-1% (goal +/-0.5%) in the reflectance bands, and +/-0.5% in the emittance bands, from another response measurement made while viewing the same source operating at equal intensity, but separated by any time up to two weeks,

including the effects of perturbations at the orbital period. These stability requirements shall also be met for short-term temperature excursions that may be expected to occur in the MODIS instrument.

3.4.7.2 Long-Term Stability

Long-term stability as defined here applies to all time scales between two weeks and five years. The mean calibrated radiometric response, as defined in the previous paragraph, of each band shall not change by more than +/-2% (+/-1% longer than 3000nm). Because of the impracticability of demonstrating compliance by actual measurement before instrument delivery, compliance can be demonstrated by an estimate of long-term stability based upon short-term tests plus analysis. This analysis shall use measured instrument rates of change as well as vendor supplied component/subsystem test data.

3.4.7.3 Spectral Band to Band Stability

The relative amplitude stability between all pairs of spectral bands shall be better than +/-0.5% measured at full-scale and +/-1% at half-scale. Each band shall be exposed to a source and the mean responses determined. To compare outputs between bands, the ratio of the means shall be calculated for each band with respect to a common band. In addition, ratios shall be calculated for selected (approximately ten) pairs of bands which will be used in common retrieval algorithms, e.g., ocean science pairs and land science pairs. These ratios shall remain constant within +/-0.5% at full-scale and +/-1% at half-scale over times separated by any interval up to two weeks, including orbital variations.

3.4.7.4 Wavelength Stability

The stability of both the center wavelength and the bandwidth shall be better than 2nm for the VIS bands, and better than 1% of the center wavelength for the other MODIS spectral bands. This includes shifts caused by changes of humidity, temperature, pressure, vibrations, or time.

3.4.7.5 Wavelength Accuracy and Precision

Wavelength measurements of the entire system shall be made on the ground, with an absolute accuracy of 0.5nm and a precision of 0.25nm, for wavelengths up to 1 um. The measurement accuracy and precision for all other spectral bands shall scale linearly with wavelength from 1um.

3.4.9 In-Flight Calibration Requirements

An in-flight calibration system, including necessary algorithms, is required. This system shall be capable of calibrating the entire instrument from radiometric input to digital data stream output. Sources for amplitude calibration include the sun, the moon, and on-board visible and thermal sources. An in-flight solar calibration for the VIS and NIR bands is required; spectral calibration is also required for these bands. All absolute radiometric calibration sources shall fill the aperture.

3.4.9.1 In-Flight Radiometric Calibration

The MODIS shall provide for in-flight radiometric calibrations of all spectral bands, providing measurement of changes in gain of the optical, focal plane, and analog electronics subsystems. In-flight radiometric characterization, i.e., output digital value versus input spectral radiance, shall be made with sufficient accuracy to assure that the calibration requirements delineated in this specification are achieved over the dynamic range of 0.3Ltypical to 0.9Lmax.

3.4.9.2 In-Flight Wavelength Calibration

The MODIS shall provide for in-flight wavelength calibration of wavelengths up to 1um. The flight calibration shall be sensitive enough to detect a 1.0nm shift in the shortest wavelength band with a precision of 0.5nm. The detectable shifts and measurement precision for the other spectral bands below 1um shall scale with wavelength.

3.4.9.3 In-Flight Reflectance Calibration

The MODIS shall provide for in-flight reflectance calibration, using the sun to illuminate a solar diffuser surface which is viewed through the complete instrument optical system.

An on-board capability to monitor the solar diffuser characteristics shall be provided. Knowledge of the diffuser characteristics shall be adequate, when combined with other on-board calibrations, to maintain the calibration and stability requirements of this specification throughout the five year lifetime of the MODIS instrument.

The contractor shall demonstrate by test that the system provided to monitor the solar diffuser characteristics is sensitive enough and has the stability required to detect changes in the diffuser spectral reflectance in orbit, with a precision and accuracy sufficient to meet the calibration

Geometric Correction of MODIS data

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27 September 1993

Introduction

Geometric distortion has historically been a limiting factor in the use of remotely sensed satellite data. There are numerous sources for this distortion, but the most noticeable effects for imagery from the MODIS instrument arise from the maximum off nadir scan angle of +/- 55 degrees during a scan, and the simultaneous clocking of 10 lines per scan. These characteristics result in unequal IFOVs as projected onto the Earth's surface and overlap between scan cubes as a function of scan angle. Level 1A processing will compute geolocated coordinates at each pixel which will compensate for all significant error sources to approximately .1 km. We advocate an intermediate data product which will use this highly accurate geolocation information to produce a geometrically corrected data array which has been resampled into a gridded, or equally spaced, alignment. Our objective is to present the user with an easily accessible data set which maintains most of the original radiometric integrity while eliminating geometric distortion. We have done a computer simulation to mimic MODIS data collection. The difference between the original scan cube image and a rectified image is illustrated in the attached raster images.

It is important to emphasize that the purpose of this short exposition is to spark discussion on this topic and to solicit input from the expected scientific users of MODIS data.

Definitions

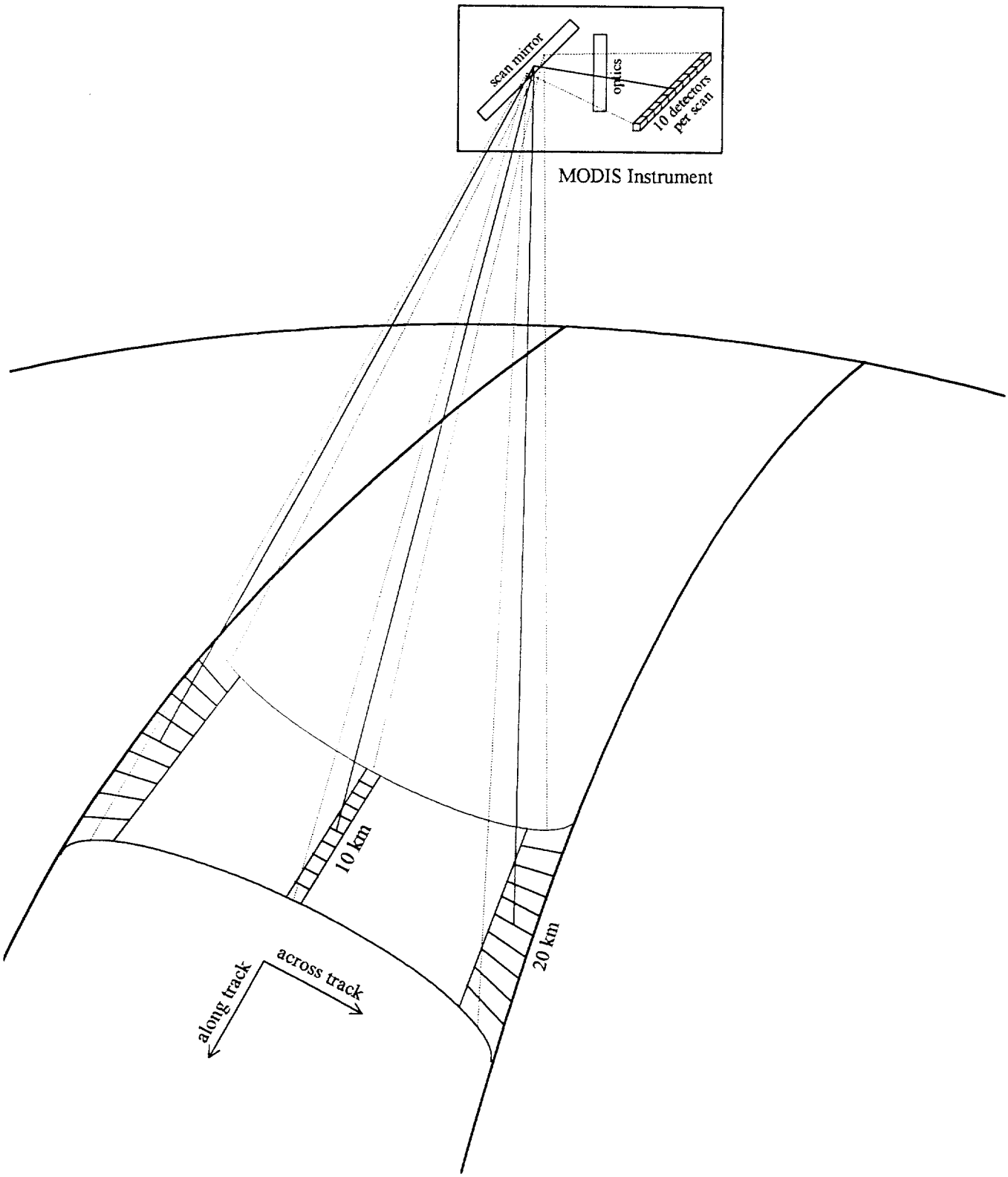
Data from the MODIS instrument can be represented by a three dimensional "scan cube". The axes of this scan cube correspond to the across track scan (mirror rotation), the along track ten detectors (simultaneous readout), and the 36 bands. The calibration sources and the engineering data are added to this scan representation containing the instrument Earth views.

The use of the term "gridding" is somewhat context dependent, but generally is interpreted as the spatial aggregation of multiple data values into equally spaced bins. Since we want to maintain maximum data precision and resolution, we do not want to aggregate pixels. Therefore, to avoid confusion, we use the term "rectification" to describe the proposed, non-aggregated data product.

For our purposes, "rectification" is defined as a process which aligns data in an orthogonal coordinate system, and resamples the original data values to produce equally spaced data. In particular, we advocate using the natural scan geometry axes corresponding to the nadir ground track (y axis) and the nominal along scan line (x axis) as our orthogonal coordinate system. The unit spacing along the nadir ground track will be precisely 1 km, as will the unit spacing along each "parallel" to the nominal along scan line. However, since it is impossible to place a rectangle onto a sphere without any distortion, there must be a slight scale change in the y direction as we move off nadir. This scale change induces a distortion that is less than 2 percent at the maximum off nadir scan angle. This effect is summarized in the attached graph.

The term "mapping" is generally used to indicate a transformation from the oblate Earth to a flat plane which typically preserves at least one, but not all, of the following properties: equal area, equal distances, and equal angles. Experience has shown that scientists can rarely agree on a common map projection, much less the parameters (such as center latitude and longitude) which completely specify it. Several popular mapping projections produce huge spatial distortion at the poles and are therefore inappropriate for the scientific analysis of global data sets.

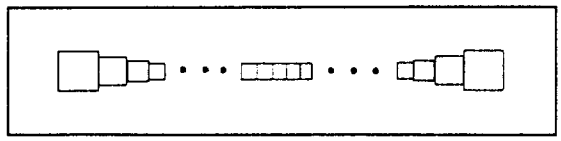
MODIS Scanning Geometry



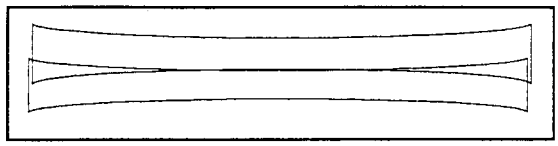
Sources of Geometric Distortion in MODIS Data

➢ "Bowtie" effect:

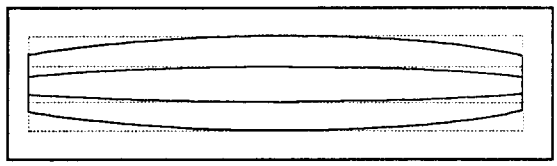
- varying IFOV ground footprint along scan, increasing with scan angle



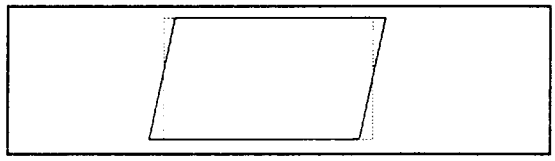
- scan cube overlap off nadir, also increasing with scan angle



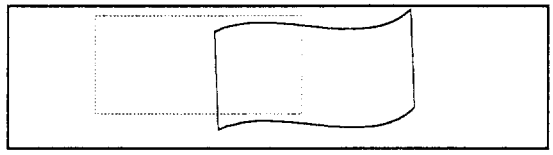
➢ Earth's curvature, including the departures from a perfect sphere. (Successive scan cubes do not have the same spacing along track at nadir as they do off nadir.)



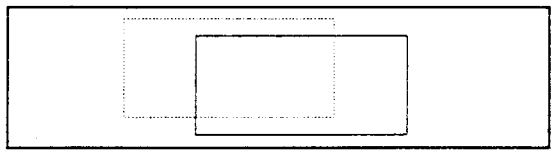
➢ Earth's rotation



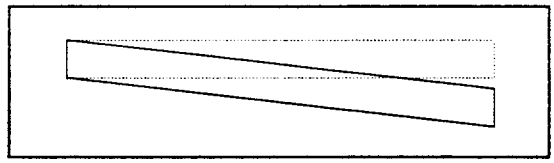
➢ Spacecraft's speed, position, and attitude (including uncompensated momentum from other instruments)



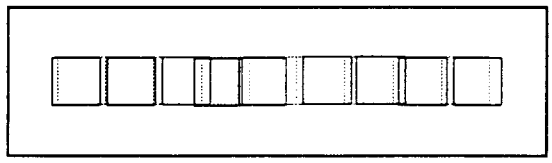
➢ Instrument pointing error (e.g., mounting point offsets, thermal deformations, scan mirror velocity)



➢ Scan skew (movement of the satellite along track during mirror rotation)



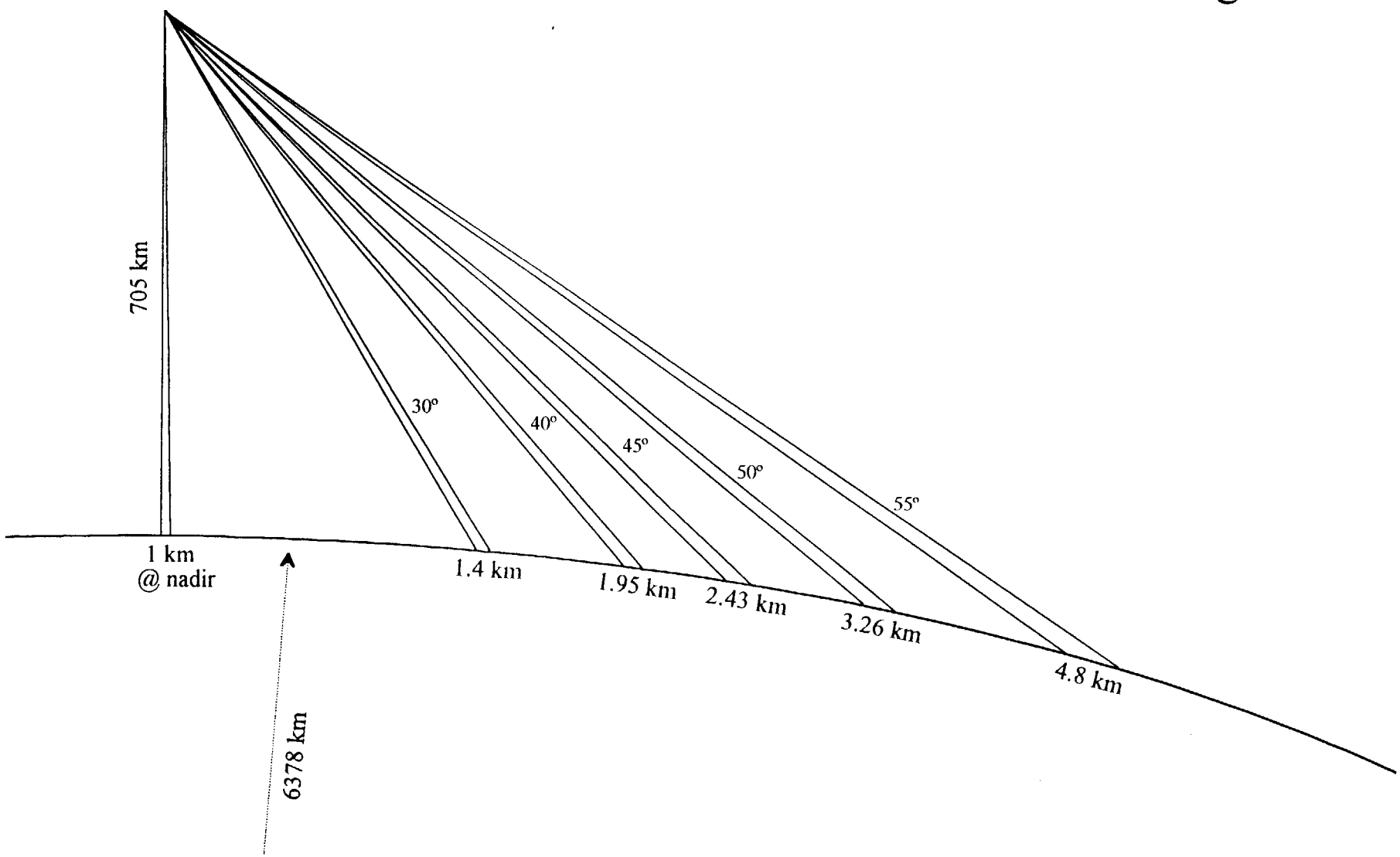
➢ Terrain effects (elevation and slope)



Not illustrated is the refraction of the atmosphere at large scan angles. This error is a weak function of wave length, but is always less than 20 meters. All of these error sources are incorporated into the geolocation calculation at every pixel which is part of the Level 1A processing, but the radiance values are <u>not</u> corrected for these effects.

It is important to note that when scan cube pixels are geolocated, they do not "line up" in any sense. They are actually irregularly spaced in all directions, primarily due to terrain effects, bowtie effect, and spacecraft related errors. Even more confusing, subsequent scan cubes overlap each other by as much as 50% (5 pixels) at maximum scan angle (+/- 55 deg).

Illustration of increasing IFOV as a function of scan angle



Rationale Behind Gridding / Rectification

The primary reason for either gridding or rectifying MODIS data is for the removal of geometric distortion and scan overlap. If it is done as part of the ground processing, then it can be done once instead of numerous times at the user level, and can be done in a consistent manner.

Points in favor of gridding or rectification:

- The scan cube data is absolutely unusable for science algorithms with spatial dependencies (e.g., neighborhood operations, scene statistics, or correlation of features within an orbit such as cloud and cloud shadow). Some preprocessing must be done if support for such algorithms is desired at the project level.

- The scene based imagery resulting from gridding / rectification is in a format which is familiar to the Earth scientist, and consistent with raster based image processing packages.

- The resultant gridded data type is easy to import into a GIS system (e.g., ArcInfo's GRID package) for powerful image analysis capability.

Points opposing gridding or rectification:

- Either process requires resampling of the data.

- Subsequent mapping from this data set will entail a further resampling.

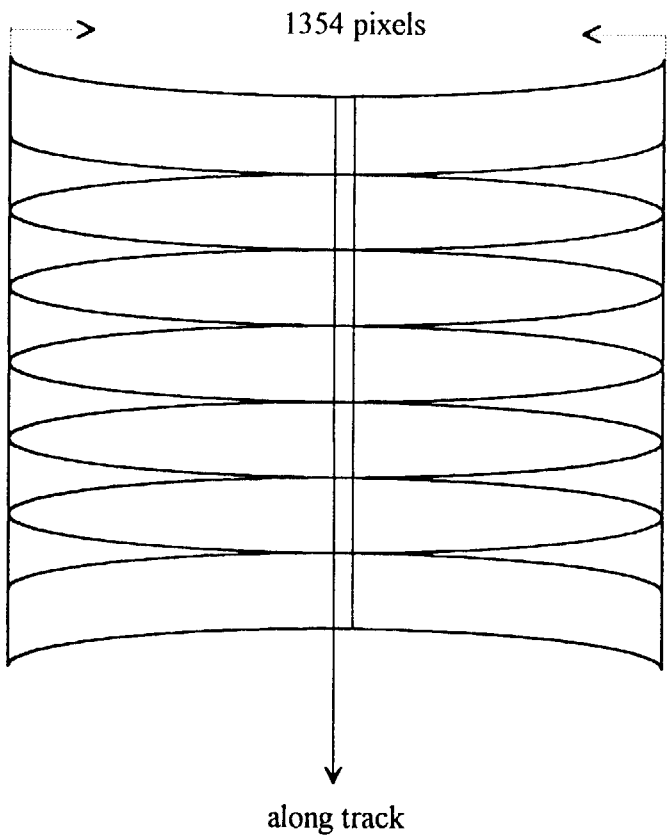
- Nonuniform spatial resampling is compute intensive.

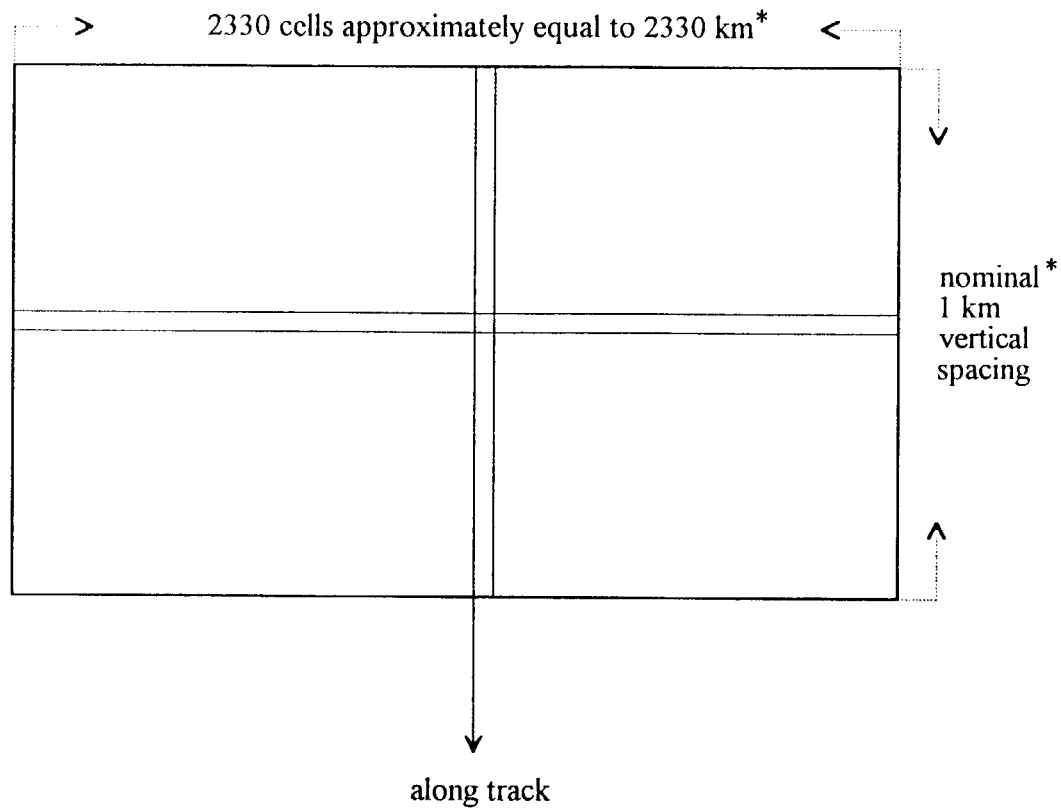
Counterpoints to the opposition:

- The geometric distortion problem must be addressed at some level before any quantitative science can be done with MODIS data.

- Mapping of MODIS data will likewise have to compensate for the inherent geometric distortion; i.e. the work must be done whether at a gridding or rectification step, or at the mapping stage. Moreover, most of the computation required to get a gridded or rectified data set saves an equivalent amount of computation in the mapping step.

Comparison of uncorrected MODIS scans with rectified scans





*Cells will be exactly 1 km by 1 km along axes and deviate from that by Earth's curvature.

Advantages of 1 km x 1 km Rectification

There are distinct advantages to the proposed rectification scheme. These are:

- This scheme is equally applicable to all Earth locations (i.e. not mapped, and does not use lat-long coordinates)

- It does not aggregate pixels, hence provides maximum data precision and resolution.

- Rectification incorporates the highly accurate geolocation data with terrain height at every pixel into the resampling process via a weighted two dimensional interpolation process for irregularly spaced data (specific algorithm TBD).

- MODIS data meet the criteria for successful two dimensional interpolation:

  - The number of sample points is representative of the spatial distribution.

  - Spatial autocorrelation: e.g., places closer together in space tend to be more similar than different.

- This technique defers the mapping question for specific user needs, since the choice of mapping parameters and projection is highly subjective.

- Mapping will be easy to do from the rectified data since the geometric distortion has been removed, and the geolocation accuracy has been maintained.

- The geolocation information is now implicit in the data structure, so it is not necessary to carry along the geolocation coordinates at every pixel.

- Scan geometry rectification provides a common coordinate system for all channels of MODIS data, and is applicable to other instruments on the same platform.

- Orbit repeatability for every 233 orbits should result in registered data sets in the time domain for a given ground track.

- The proposed rectification is very close to an equal area representation of the data, since the x scale is true 1 km spacing and the y scale errs from that by less than 2% in the worst case at maximum scan angle.

Summary

The georeferencing information at every pixel provided by MODIS Level 1A processing provides the ancillary information needed for a high precision geolocated data product. The need for quantitative scientific analysis of MODIS data motivates the application of this precision to the removal of the geometric distortion inherent in remotely sensed, scanned data. This paper presents ideas from a preliminary investigation into this matter, and one of many possible scenarios for the correction of the MODIS instrument scan geometry nonuniformities. Only the first order effects have been incorporated into the numbers and MODIS image simulation presented here. The results of further analysis will be presented in future papers.

We expect this exposition to generate interest and debate regarding this issue. We welcome any responses and comments via E-mail, U.S. mail or phone to:

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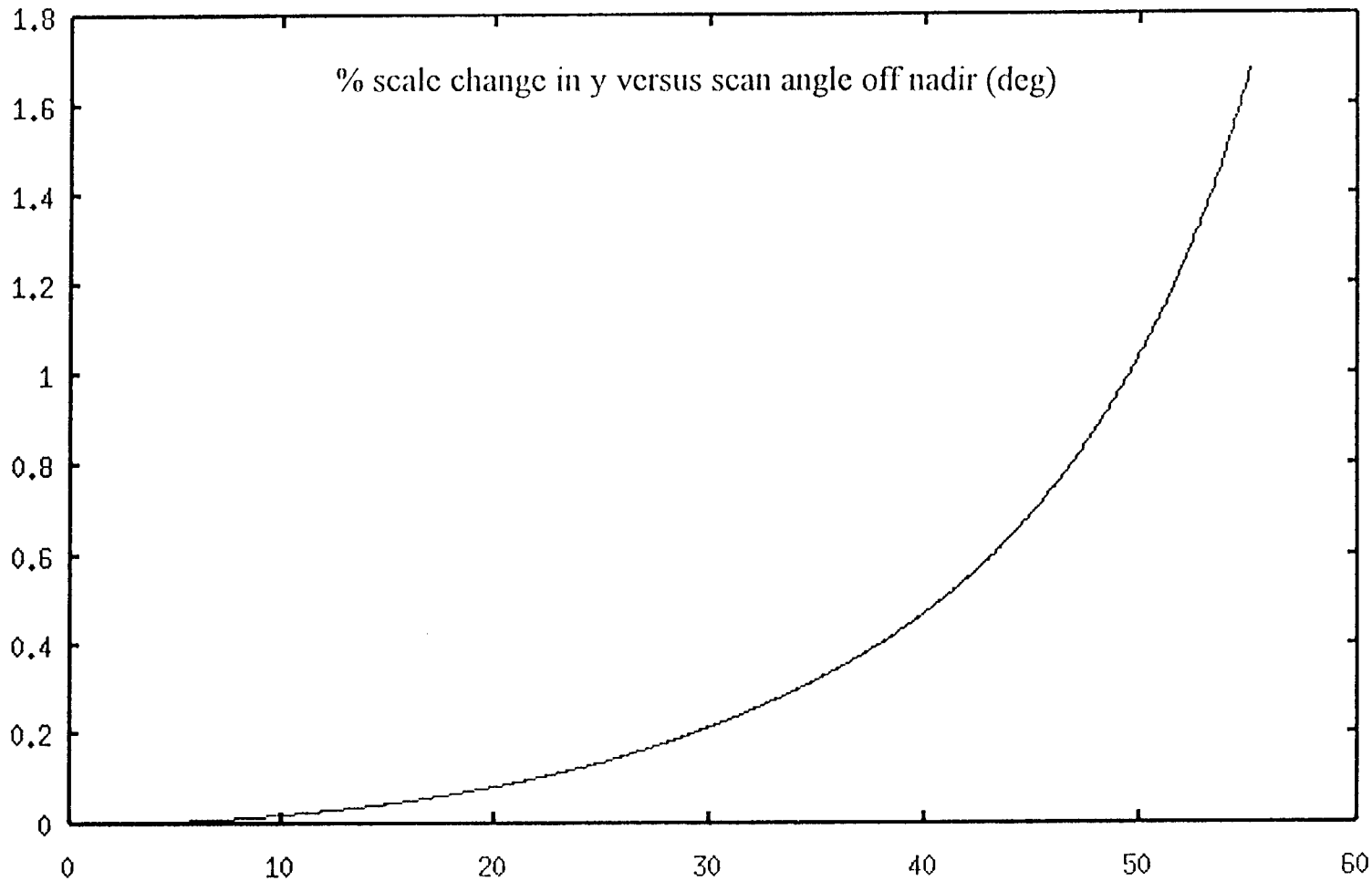
or

Thomas E. Goff: E-mail: teg@cheshire.gsfc.nasa.gov
7855 Walker Drive, Suite 460, Greenbelt, Md. 20770
phone: (301) 982-3704

Scale change in y axis of rectified coordinate system due to Earth's curvature



V.L.Kalb and T.E.Goff, SDST

Simulated MODIS Scan Cubes

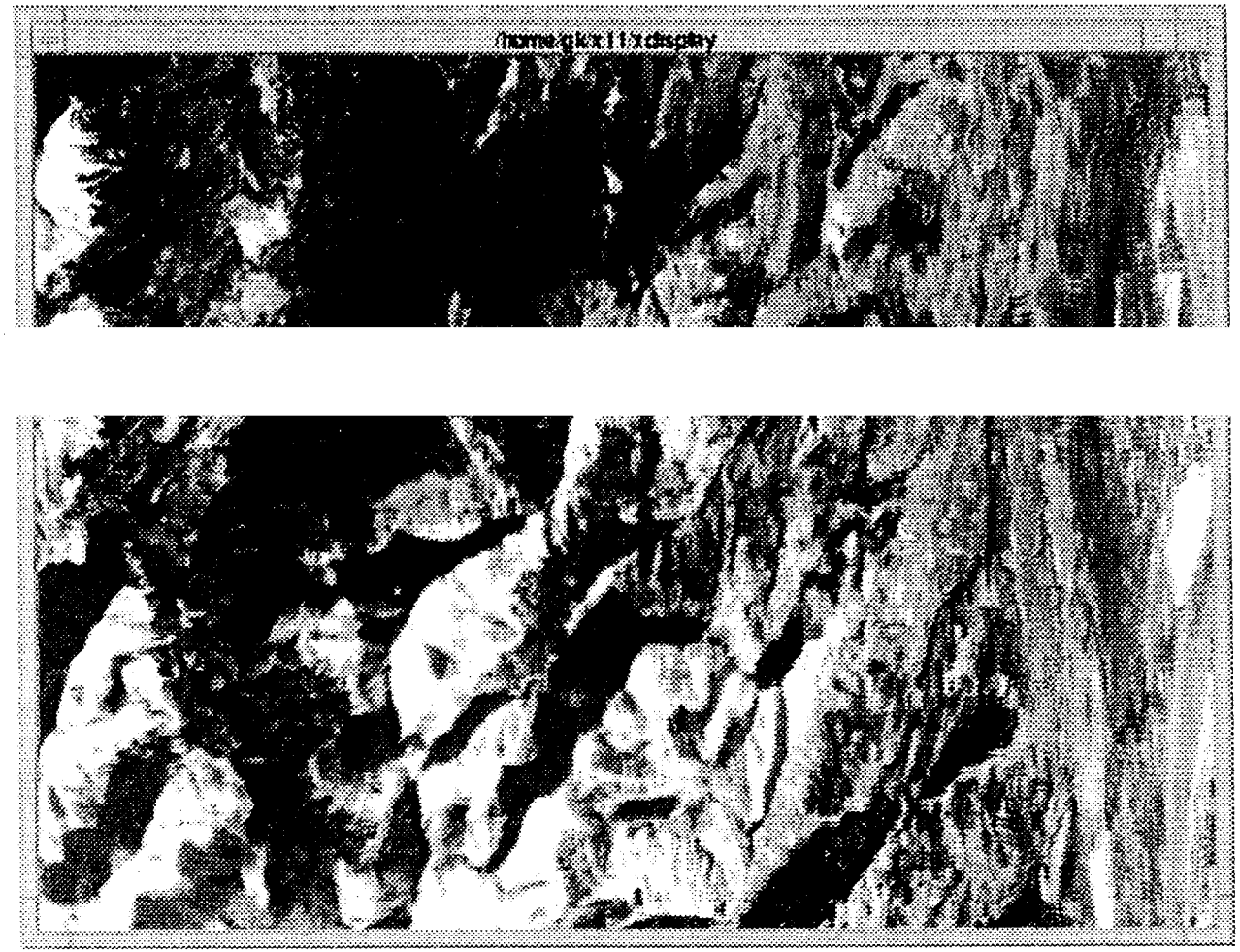
from nadir to 55 degree scan angle

V.L.Kalb and T.E.Goff, SDST

(maximum resolution; 677 x 500 pixels)

Simulated MODIS Scan Cubes

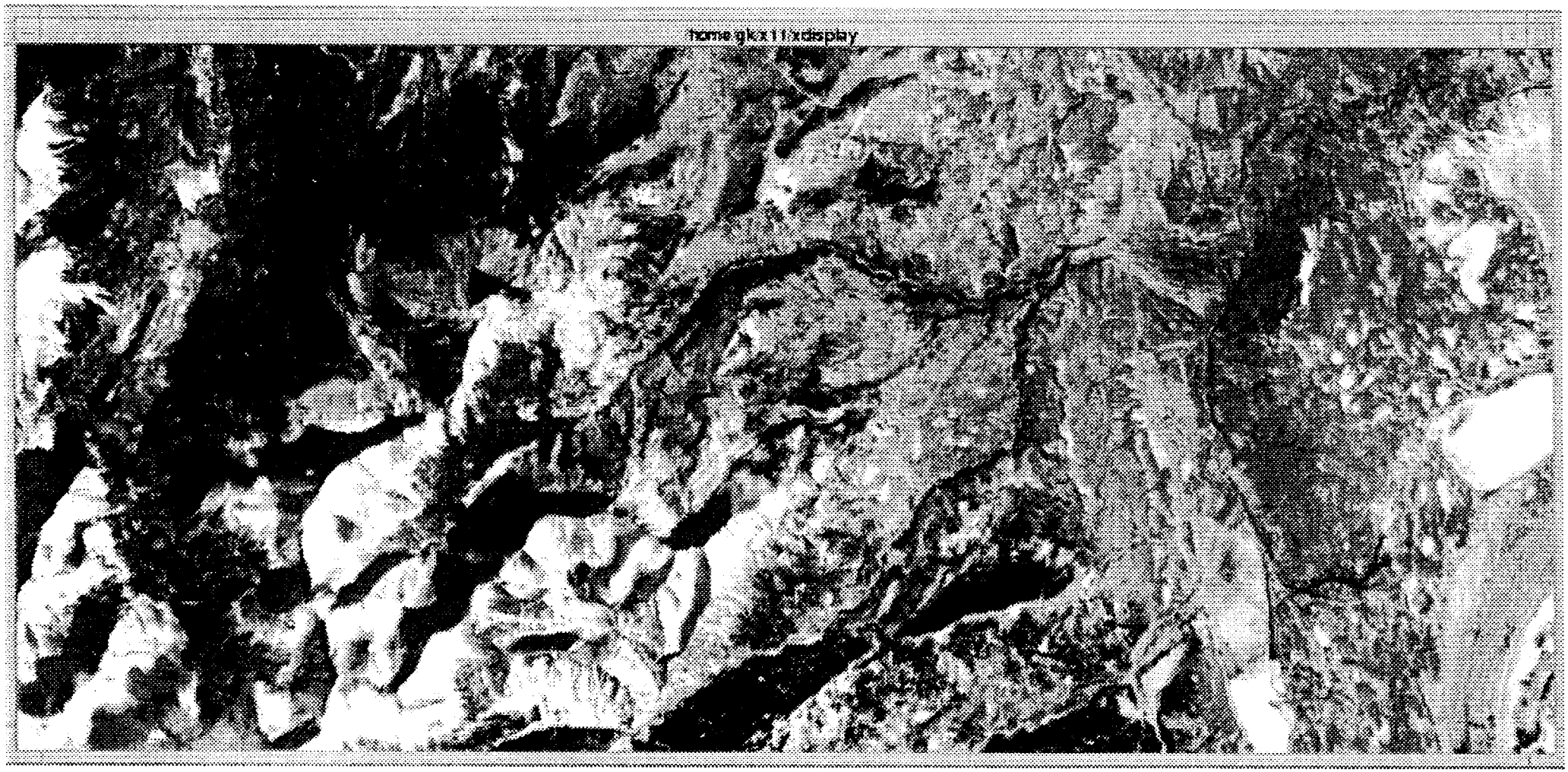
from nadir to 55 degree scan angle



V.L.Kalb and T.E.Goff, SDST

(70% photo reduction)

Rectified Satellite Image

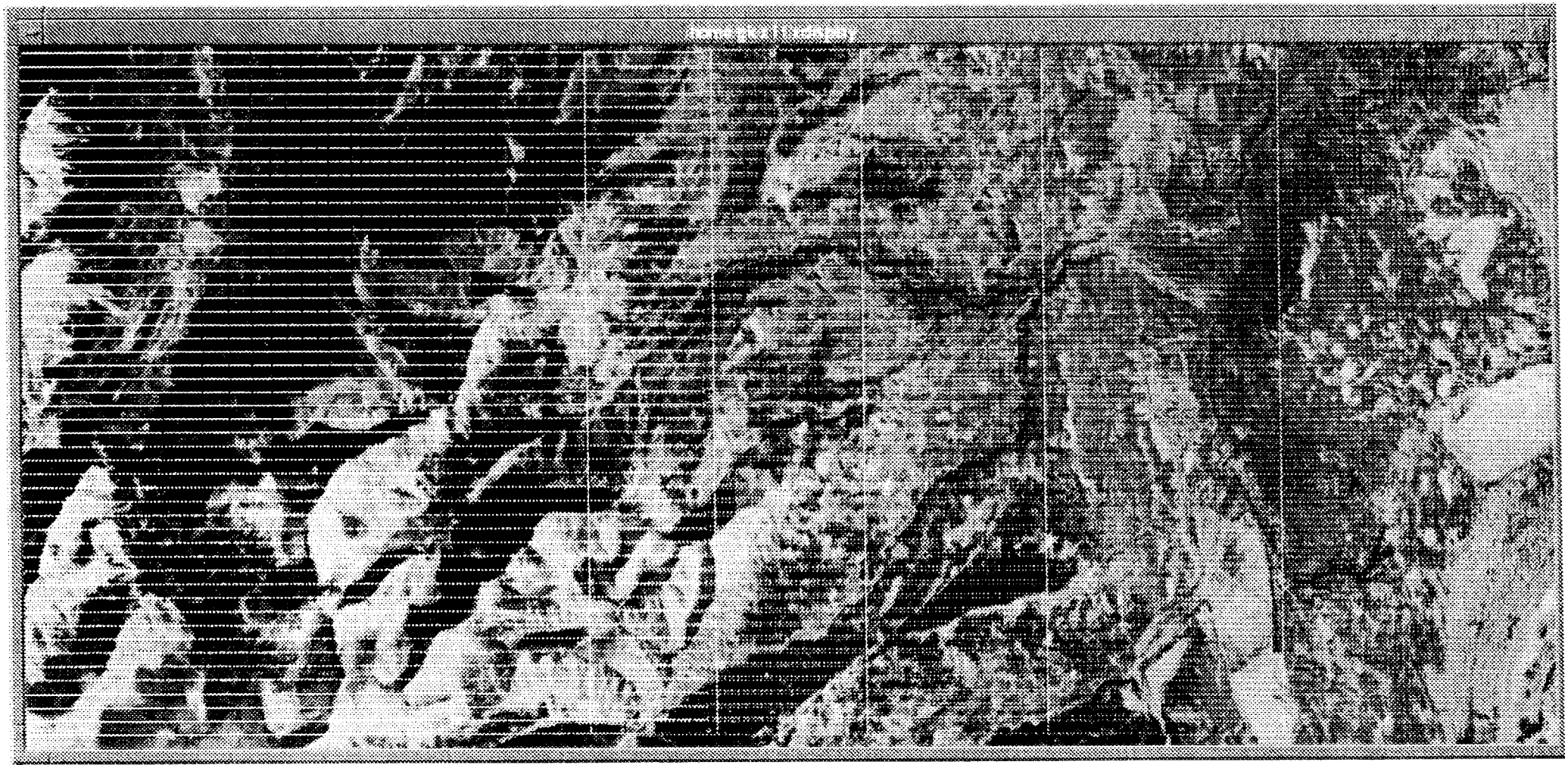


V.L.Kalb and T.E.Goff, SDST

(70% photo reduction)

Rectified Satellite Image

with reference lines showing the ground track of the centers of detectors 1 and 10 of each scan cube, and an indication of changing scan angle (vertical bars)



0° 30° 35° 40° 45° 50° 55

(70% photo reduction)

V.L.Kalb and T.E.Goff, SDST

MODIS Data Rates, Volumes, and Processing Performance with the proposed Computerized Data Structures

Thomas E. Goff
NASA/GSFC/MODIS/SDST/RDC
last revision date: 8 February 1994

This is document is an evolving master list of the MODIS data rates and volumes expected from the MODIS instrument. Several assumptions have been made in order to provide these estimates and these are noted at the point the estimate is presented. An indication of the variance of these estimates is included as notes within each section. See the glossary at the end of this document for the definitions of MODIS instrument related item descriptions

The Data Products will be archived in the Hierarchical Data Format (HDF) which will require an agreed upon list of formal names for all parameters and dimension indices. These formal names will be presented in a spreadsheet format in future editions of this document, or as separate documents for each Data Product.

Assumed, currently accepted constants

- Scan Period: 1.47717 seconds per scan (not the mirror rate) (SBRC 9/92).
- Orbital Period: 98.9 minutes = 5934 seconds = 14.575 orbits per day (EOS-AM1).
- Satellite altitude of 705 kilometers.
- for an Earth equatorial radius of 6378 kilometers (6356 polar) the nadir ground velocity is 6.75 kilometers per second.
- adding 705 kilometers for the spacecraft altitude gives an orbital velocity of 7.5 kilometers per second
- The Earth surface is 510.1 million square kilometers of which 149.9 square kilometers are land area. (Rand McNally Atlas of the World)
- Equatorial separation of each MODIS orbit is 2753 kilometers (6378*2*pi / 14.575 orbits per day).

The MODIS instrument has:

- 2 - 250 meter bands.
- 5 - 500 meter bands.
- 29 - 1 kilometer bands. These sizes are the nominal at nadir ground pixel sizes.
- 2 - alternate gain / dual detector channels (for bands 13 + 14) - These results give (2*16+5*4+29+2=) **83 channels of science data per 1 km spatial element**.
- 490 separate detectors on 4 focal planes (2 bands * 40 detectors/band + 5 bands * 20 detectors/band + 29 bands * 10 detectors/band = 470 detectors, the additional 2 alternate bands * 10 detectors/band give a total of 490 detector readouts).
- 10 detectors (for the 1km bands, 20 for 500m bands, 40 for 250m bands) in the along track direction form a frame of data (simultaneous readout)

- 1354 science frames per scan (± 55° scan angle)
- 50 solar diffuser (SD) frames per scan.
- 5 spectroradiometric calibrator (SRCA) frames per scan.
- 30 black body (BB) frames per scan.
- 15 space view frames per scan.

(NOTE: the above four numbers of onboard calibration (OBC) frames are commandable from the ground and will vary! This will slightly affect the number of bits per scan cube and dataset sizes derived below.)

- 2 engineering data frame equivalents (1 engineering and 1 memory dump) - These results give 50+5+30+15+1354+2=1456 data frames per scan (SBRC 3/93).
- 12 bits per pixel for all science, SD, SRCA, BB, and space view detector readout data (SBRC 3/93).
- 14,956,032 bits per day mode scan (SBRC 9/92) - This number includes all science, calibration, engineering, and CCSDS header/trailer bits.
- 2,733,170 bits per night mode scan (SBRC 9/92).
- day/night mode mix = 50% day, 50% night (60% day, 40% night would be a 60% duty cycle). (Day mode includes all 36 bands, night mode is limited to bands 20 through 36.)

MODIS Scan Frame and Telemetry Packet Sizes (day and night mode):

- 4980 data bits per frame segment (one segment per packet), two segments per day mode frame (83 channels * 10 detectors along track * 12 bits per detector / 2 segments per frame).
- 2040 data bits per night mode frame (17 channels * 10 detectors * 12 bits per detector), unsegmented packets.
- 108 bits for secondary header and check sum.
- 48 bits for CCSDS header.
- 5136 day mode bits or 2196 night mode bits per CCSDS packet.

Derived Packet Transfer Rates:

- 14,956,032 bits per day mode scan (2 day mode packets per frame * 1456 frames per scan * 5136 bits per packet)
- 4,021,128 bits per night mode scan (1 packet per frame * 1354 frames per scan * 2196 bits per packet + 2 packets per framer * 102 frames per scan * 5136 bits per packet)
- 10.124787 megabits per second, day mode (14,956,032 bits per scan / 1.47717 scans per second)
- 2.722183 megabits per second, night mode (4,021,128 bits per scan / 1.47717 scans per second)
- (Note that the budgeted EOS-AM1 platform rates for MODIS are 11,000 kilobits per second peak rate and 6,200 kilobits per second average rate. The average rate assumed a 40% day mode rate that is no longer valid! The average rate should be 6,423.485 kilobits per second.)

Basic Derived Scan Cube Results (day and night mode):

- 4017.14 scans per orbit (98.9 minutes per orbit * 60 seconds per minute / 1.47717 scans per second)
- 14.56 orbits per day (24 hours per day * 60 minutes per hour / 98.9 minutes per orbit)

- 58,490.22 scans per day (24 hours per day * 60 minutes per hour * 60 seconds per minute / 1.47717 scans per orbit)

Level-0 Data Volume and Rates: MODIS will be in one of two major modes: day or night. (A mode which schedules solar diffuser data deletion is mentioned in the references. This may affect the number of data frames in a scan cube)

- Peak Level 0 rate is 1.2656 kilobytes per second and the average rate is .803 kilobytes per second (10.124787 megabits per second / 8 bits per byte, 10.124787*50% + 2.722183*50% / 8 bits per byte)
- 1456 data frames per scan * 2 long (5136 bits) packets per frame = 2912 packets per scan (day mode)
- 1456 data frames * 1 short (2196 bits) packet per frame = 1456 packets per scan (night mode)
- 1354 data frames * 1 short (2196 bits) packet per frame plus 102 (full) frames (times 2 packet segments per frame) = 1550 packets per scan (night mode). All bands (long segmented packets) for non-science data at night is an assumption.
- for a 50/50 day/night orbital mix, 2912 packets/scan, day mode * 5136 bits/packet + 204 long packets/scan * 5136 bits/packet + 1354 short packets/scan * 2196 bits/packet) * 4017 scans/orbit / 2 (50/50% mix) / 8 bits/byte = 4.76445 gigabytes per orbit
- for 14.56 orbits per day = **69.37 gigabytes per day**, assuming the night mode non-science frames are of the long packet type. This does not include any EDOS accounting information.
- 7.5101e9 bytes per orbit = 7.51 gigabytes per orbit, 100% day rate (5136 bits per packet * 2912 packets per scan * 4017.14 scans per orbit / 8 bits per byte)
- 1.0937e11 bytes per day = 109.37 gigabytes per day, 100% day rate (7.51 gigabytes per orbit * 14.56 orbits per day)
- 1.6055e9 bytes per orbit = 1.61 gigabytes per orbit, 100% night rate, assuming all non-science frames are of the short type (2196 bits per packet * 1456 packets per scan * 4017.14 scans per orbit / 8 bits per byte)
- 2.3377e10 bytes per day = 23.38 gigabytes per day, 100% night rate (short non-science frames)
- 66.38 gigabytes per day, 50/50% day/night mix (if the short non-science night mode frames are constrained to 17 data channels) (109.37 + 23.38 / 2)
- Level-0 ancillary (accounting, metadata) are to be determined (TBD) and supplied by the EDOS design team.

These data estimates can be considered to be fully accurate with essentially no variance, assuming that all frames of data are continuously sampled. It is assumed that the solar diffuser (SD) frame data will be enabled for all orbits or the major part of a selected orbit and will be a normal component of the scan cube. If the SD data is scheduled to be deleted from the scan data, the data rate will reduce by 3.4% (50 divided by 1456 frames) of the full data rate by disabling the SD frame data. This may occur for a small fraction of an orbit at a TBD interval (monthly perhaps). Other data frames are assumed to be always present (not selectively scheduled).

Structure of the Level-0 Data Product

The structure of the Level-0 Data Product and the Level-0 accounting (metadata) product will be determined by the MODIS instrument builder (Hughes SBRC) and EDOS respectively. The sizing information within this document is based on the best available information available to the MODIS SDST at the time this document is updated.

Level-1A Data description:

The Level-1A data Product Generator is expected to produce two data products: the Level-1A Data Product and the Level-1A Metadata. These products will be produced for both standard and quick look data transmission modes. The Level-1A Data Product consists of three components: the science data (ground looking), the calibration data (solar diffuser, black body, space view port, etc.), and the engineering data (housekeeping, memory dumps). Data volumes are presented as scan cube estimates with orbital and daily volumes summarized at the end of this section. A visualization of a scan cube is conceptualized in Figure 1.

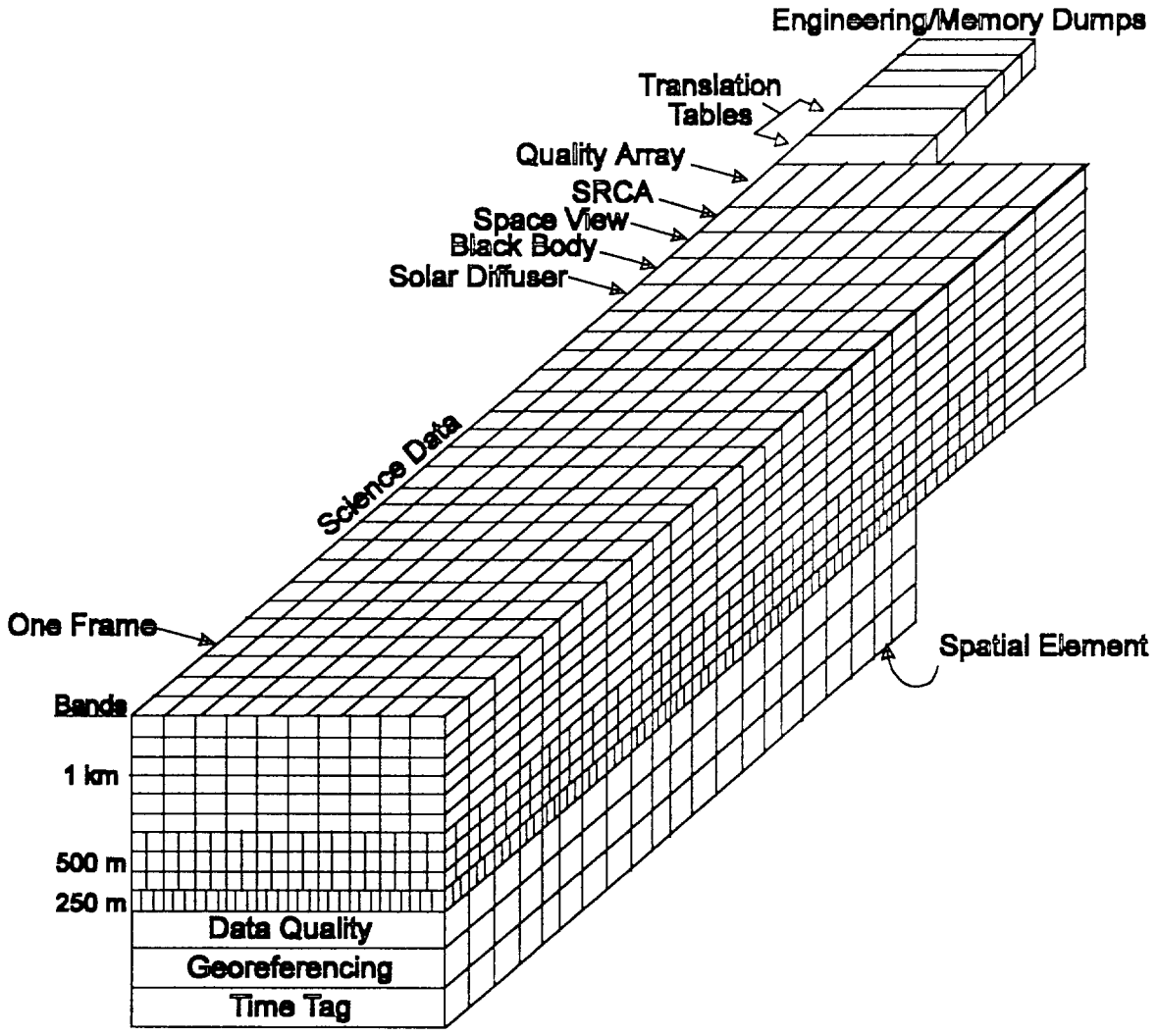


Figure 1. Level-1A Scan Cube

An important concept: *Science data are obtained from 36 frequency bands, but is organized into 83 data channels as follows:* One kilometer spatial views are designated as spatial elements and consist of 16 - 250 meter IFOVs for each of bands 1 and 2, 4 - 500 meter IFOVs for each of bands 3 through 7, and 1 - 1 kilometer IFOV for each of bands 8 through 36. Bands 13 and 14 have two data channel values (high/low gains at separate detectors) per band. This results in 83 data channels per 1 km spatial view. Data is assumed to be taken for all channels during the calibration phase even if the data is inapplicable (for example: solar diffuser data during MODIS night mode).

A frame of data consists of the above mentioned 83 data channels multiplied by the 10 (or 20 or 40) along track detectors. Visualizing the scan cube as a loaf of store bought bread, a frame of data would be equivalent to a slice of bread, and a loaf would contain 1456 slices. This loaf of bread would be flying through space sideways (laterally), which is also how the MODIS instrument will travel in orbit (see Figure 2).

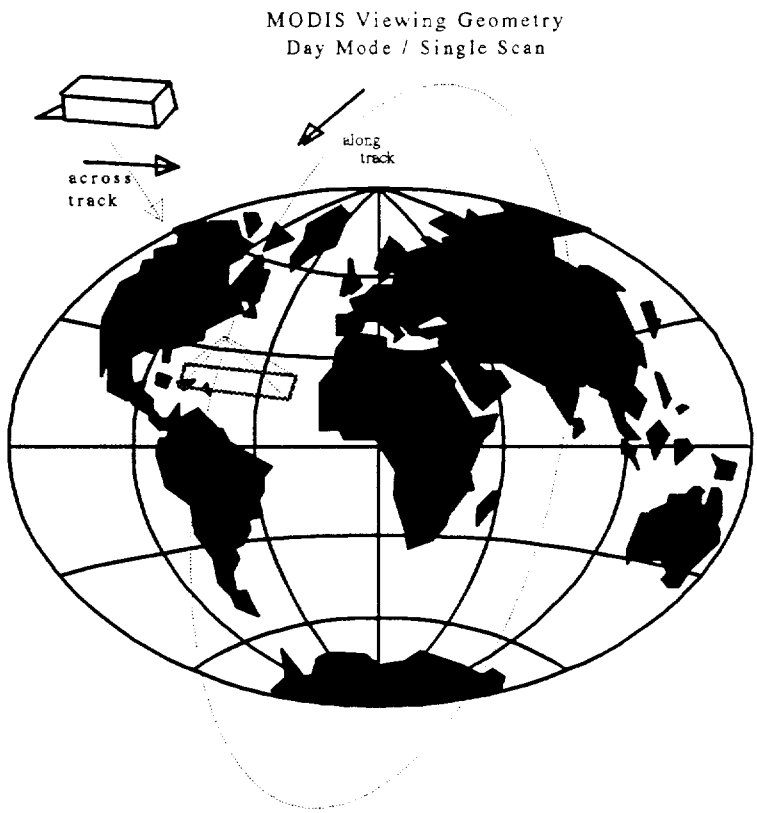


Fig-2 MODIS AM1 Orbital Geometry

Science Data - day mode

- 12 bits per science data value (pixel) unpacked and byte aligned into 2 byte (16 bit) words. This is the current assumption for the Level-1A Data Product.
- 2*16 + 5*4 + 29 + (2 dual gain) = 83 data channels (IFOV data values) per spatial element
- 10 along track spatial elements per frame
- 1354 across track frames per swath (half mirror rotation, one scan)

- 1,123,820 day mode science data values per scan cube. (83 channels * 10 spatial elements per frame * 1354 frames per scan)

Science Data - night mode

- 12 bits per science data value (pixel) unpacked and byte aligned into 2 byte (16 bit) words (assumed)
- 17 bands (IFOV data values) per spatial element (bands 20 through 36)
- 10 along track spatial elements per frame
- 1354 across track frames per swath
- 230,180 night mode science data values per scan cube (17 channels * 10 spatial elements per frame * 1354 frames per scan)

Calibration Data - solar diffuser (SD)

- 83 channels per 1 km spatial element
- 50 frames of data values
- 10 elements per frame
- 41,500 solar diffuser data values per scan cube (= 83 * 50 * 10) (when scheduled)

Calibration Data - spectroradiometric calibrator (SRCA)

- 83 data channels per 1km spatial element
- 5 frames of data values
- 10 elements per frame
- 4150 SRCA data values per scan cube

Calibration Data - black body (BB)

- 83 bands per element
- 30 frames of data values
- 10 elements per frame
- 24,900 black body data values per scan cube (= 83 * 30 * 10)

Calibration Data - space view

- 83 bands per element
- 15 frames of data values
- 10 elements per frame
- 12,450 space view data values per scan cube (= 83 * 15 * 10)

Engineering & Memory Dump Data

- low rate housekeeping data (This is a guess based on data available in 1991)

69 Boolean values
48 analog values
Rumor suggests that 430 values is a closer answer (Jan 1994)

- spacecraft ancillary data (?). Note that the original concept for obtaining the spacecraft position and attitude information assumed that this information would be contained within a separate packet stream, not a part of the MODIS data. However, the spacecraft will have the TONS system onboard which will provide this data on the spacecraft data bus. Detailed specifications (values and first derivatives) and data update rates are TBD.

The engineering data that is listed in the following items is currently assumed to be sampled at the MODIS 12 bit precision. These values will be used to measure the references to be used in the calibration techniques. A case can be made to improve the precision of these measurements (possible to 16 bits) because the precision of the measuring device should be greater that the precision of the item under measurement.

- raw black body temperature data
  12 sensors with 12 (or more) bits per sensor
- solar diffuser stability monitor (SDSM) sensor data (?). The spectral emissions of the solar diffuser plate.
- SRCA self calibrate and reference diode data (?)
- scan mirror linearity time data (?). Perhaps a time based encoder readout of the mirror position at selected scan frame clock times?
- status information (?). Will this include a repeat back of the MODIS Commands and/or instrument states?
- DC restore offset data (?). Assumed to be for each data channel! What about the data channels that have more than one detector?
- memory used for functional control (?)
- format processor memory as scheduled (?). A computer memory dump.
- test and control processor memory as scheduled (?). A computer memory dump.
- *Engineering & memory Summary* - (not representative of the final values) (Any decommutation, conversion, or formatting is TBD. Note that the low rate data will be submultiplexed and carried in the data set header rather than the scan cubes)
  2 frames * 2 segments per frame * 5136 bits per segment = 20544 bits per scan
- 13540 georeferencing ground locations (one for each spatial element of 1354 frames * 10 elements per frame)

Level-1A Data volume and rates:

- 1456 frames per scan cube
- 83 channels (data values) per spatial element for day mode, 17 channels for night mode
- 10 spatial elements per frame
- 2 bytes per data value
- These result in <u>2,416,960</u> bytes of instrument data values per scan cube for day mode (1456 frames per scan * 83 data channels * 10 detectors along track * 2 bytes per data value)

- 629,680 bytes of instrument data values for night mode (1354 frames per scan * 17 data channels * 10 detectors along track * 2 bytes per data value + 102 frames * 83 data channels * 10 detectors along track * 2 bytes per data value)
- 8 georeferencing data values (real, floating point numbers) per spatial element. (geodetic latitude, longitude and height; solar zenith and azimuth angles; and instrument zenith and azimuth angles and slant range). This adds 433,280 bytes to both the day mode and the night scan cubes (13540 spatial elements* 8 data values * 4 bytes per data value).
- 13540 bytes for data quality (13540 spatial elements * 8 bits per element)

Possible decommutation and formatting of engineering data and reformatting of the SRCA data and the addition of an 8 bit index into the data quality array may increase these scan cube sizes.

The total computed summary for the **scan cube sizes** are : **2,863,780 bytes for day mode and 1,076,500 bytes for night mode**. (2,416,960 + 433,280 + 13540, and 629,680 + 433,280 + 13540) Note that the spatial element georeferencing consumes 15.1 percent of the day mode scan cube and 40.2 percent of the night mode scan cube.

- 4017.14 scans per orbit gives a 100% day mode orbital data set size of 11.5042 gigabytes, including the header information, and 4.3245 gigabytes for night mode.
- For a 50/50 day/night split, (11.5042 + 4.3245) * 50%, **7.916 gigabytes per orbital data set, 50/50% day/night split**.
- 14.56 orbits per day will produce 167.5 gigabytes of Level-1A Data Product per day for 100% day mode, 64.964 gigabytes per day for 100% night mode, **115.233 gigabytes per day for a 50/50% day/night split**.

These data sizes can be considered to be accurate to ± 3 percent. They include all detector, data quality, and georeferencing data but do not include the demultiplexing of any engineering, house keeping, or memory dump data.

Note that data compression is not a consideration at the present time. If data compression will be employed, then a fixed length scan cube for both day and night mode would simplify the logical organization of the data structure by allowing bands 1 to 19 to be included in the night mode scan cube without a storage penalty.

Structure of the Level-1A Data Product

The Level-1A Data Product will be generated as two data sets: the Metadata and the Data Product. The Metadata will consist of the Level-0 accounting data (an early type of metadata) with any MODIS Level-1A derived information appended. This value added data is expected to be a synopsis of the Data Product, indications of the completeness and quality of the data, and any outside user comments on the data. Any structure for this metadata will be determined by the EOS project, CCSDS recommendations, and Science Team member input.

The Level-1A Data Product will consist of a header and multiple occurrences of the scan cubes. The header information will contain free field (ASCII) information, completeness and quality information in both ASCII and binary forms, instrument anomalies, spatial coverage, geolocation parametric data, memory dump data, and all other data set related information. The quality information in the header will apply to the complete collection of scan cubes. Detailed quality about an individual scan cube will be included with each scan cube and summarized in the header. Header information (other than the geolocation parametric data) is repeated in the metadata.

Each scan cube, as illustrated in Figure 1, will contain all the data obtained from the instrument frames, segmented spacecraft time (MODIS and platform) at each frame, mirror side, source identification, and configuration indications. This will apply to the solar diffuser, spectroradiometric calibration array, black body, space view, and science view (Earth) data portions of the scan. Adjacent to the science data portion of the cube will be the Earth georeferencing location and geometry array for each spatial element and a data quality array for each spatial element. Following the scan cube will be the Engineering Frames (data representations, decommutations, and formatting are TBD), and a detector quality, two dimensional array for each data channel (83 channels by 10 along track 1 km spatial elements).

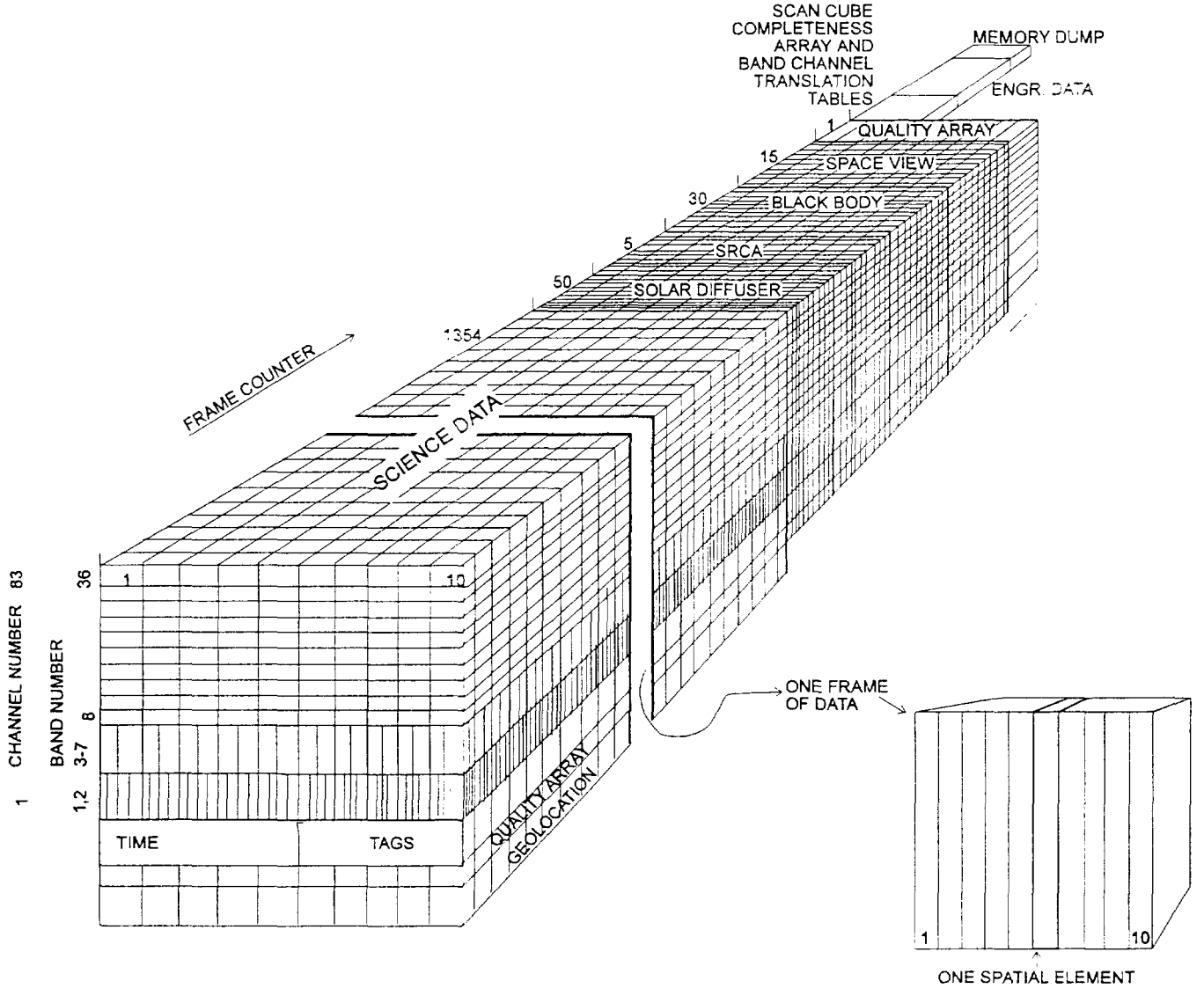


Figure 1 - MODIS Level 1A Scan Cube

Most of the data processing to be performed in the following Level-2 processes will be performed on a pixel by pixel basis. This suggests that the internal scan cube structure should be stored with all bands of data for one spatial element in adjacent memory locations. Unfortunately, this could only be accomplished with a complicated variable length indexed data structure which could not be implemented or accessed in FORTRAN. Also, computer systems that are currently available and will be enhanced in the future, can handle the direct addressing of three megabyte arrays with no penalties. Plus, the data quality array further complicates any direct easy access to the data structure. Therefore, the internal data structure will be principally based on the concept of the 1 km spatial element with 83 channels of data, in place of a logical 36 band based structure. Data can be accessed by a band and IFOV location which will be translated into the internal channel and spatial element location via included translation tables. This allows the science data to be accessed via the logical spatial index while the internal data cube representation retains the square indices.

The data set will be placed into the HDF representation which is in the process of being upgraded for use by the NASA DAACS. Facilities within the HDF technique in the future may allow for indexing, that could simplify the data structure as presented here. The VSET capability in HDF will allow the georeferencing to be applied to the Level 1A, 1B, and 2 data sets concurrently without a storage penality. Georeferencing can be extracted and appended to distributed data sets as needed.

The major components of the Level-1A output Data Product structure with descriptors are listed in the following item list.

MODIS Level 1A Data Product Header

- Source of the data set
- spatial extent -coverage at nadir and selected latitudes
- temporal extent - date, time, and ephemeris
- georeferencing parameters - a set of coefficients that will allow the data set to be geolocated to less accuracy than the georeferenced spatial element points. The SDST will supply a software function that will allow MODIS data product users to determine the ground location, given these parameters.
- pointers to all related data sets - metadata, calibration measurements, DEM, etc

MODIS Level 1A Data Product Scan Cubes

- Raw Science Data - three dimensional array - along track, across track (= scanwise), band number
- Raw Solar Diffuser Data - three dimensional array - along track, scanwise, band number
- SRCA Data - three dimensional array - along track, scanwise, band number
- Raw Black Body Data - three dimensional array - along track, scanwise, band number
- Raw Space View Data - three dimensional array - along track, scanwise, band number
- Band Number to Data Channel translation tables - three tables that translate the logical along track index, the logical across track index, and the band number into the three dimensional cube data channel array indices. Note that the logical cube indices have differing ranges as a function of the band number.
- Spatial Data Quality - two dimensions - along track, across track at 1 km indices. Eight bits will allow 255 possible quality specifications to be determined on a per spatial element basis.
- Time Tag - array with two tags per frame for day mode, one tag for night mode. This will be subdivided into the various time elements when they have been further specified by EOS and SBRC.

- Geolocation - a set of real (floating point) values that specify the latitude, longitude, solar zenith, solar azimuth, instrument zentith, instrument azimuth, and instrument range for each 1km spatial element. These are not the parametric coefficients included in the data set header that are used for less accurate geolocation.
- SDSM - The view direction and integrating sphere data readouts.
- Engineering / Memory Dumps - these are a set of sequential variables or linear arrays, the format and contents of which are (TBD). Note that the memory dumps and many engineering readings are sampled at a much lower rate that the scan cube rate. These data will be submultiplexed within this data area.
- Band Quality - array - the data quality specified for all IFOVs combined, one index per data channel.

A parametric software routine giving the ground location of any science data value will be provided as part of the Data Product header data structure specifications. An array of data quality descriptors in ASCII form, given the data quality index number, will also be included in the scan cube specification. These items will be derived at a future date.

Bands 13 and 14 have both a high gain and a low gain data channel, corresponding to the two detectors for each of these bands. For the purposes of the Level 1A Data Product, which contains the raw instrument counts, the high gain channels will be accessed as logical bands 37 and 38.

Coordinate System

The scan cube coordinate system, illustrated in figure 2 and further defined in figure 3, follows the SBRC detector numbering scheme with 40 detectors for bands 1 and 2, 20 detectors for bands 3 to 7, and 10 detectors for the remaining bands in the along track direction and 5416, 2708, and 1354 frames of detector readouts, respectively, in the across track (along scan) direction. This coordinate system will follow through (using the same scheme) for the solar diffuser, SRCA, black body, and space view data.

The illustration in figure 2 shows a view of the Earth, looking from the Sun, during a day mode, descending orbital pass. The EOS-AM orbit plane will be inclined 8 degrees from vertical as shown. This corresponds to an orbital inclination of 98 degrees. The satellite will pass over the equator at 10:30 am local time. This corresponds to a 22.5 degree rotation about the Earth vertical axis in the westerly direction. A scan cube at the equator during the day mode, will be 'tilted' 8 degrees clockwise as viewed from above. The MODIS instrument will scan from left to right, and generate successive scan cubes from top (north) to bottom (south). The nightime pass will 'tilt' 8 degrees at the equator in the counterclockwise direction, create scan cubes south to north and scan right to left as viewed from a point opposite the Sun.

The current pixel numbering scheme uses increasing numbers in the scan direction, but decreasing numbers in the along track dimension. Numbers in parentheses in the included diagram represent the limits of the pixel numbering for the 500 meter and 250 meter bands respectively. Pixel numbering for the solar diffuser, black body, and space view will follow the same along track system but will have across track limits to match the number of data frames.

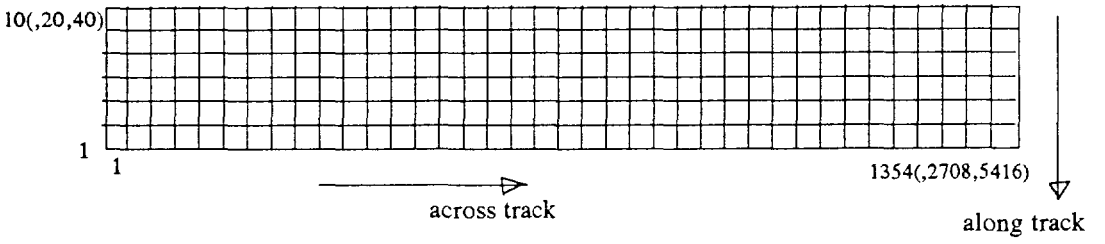


Figure 3 - Pixel Numbering Scheme

Level 1A Profiling and Computing Resources

Input / Output Rates

Note that any data staging by the DADS or other facilities in the data transmission chain are not included in this discussion.

- One long packet of 5136 bits = 642 bytes, short packet of 2196 bits = 275 bytes.
- 2912 packets per day mode scan, 1354 short and 102 long packets per night mode scan, 4017.14 scans per orbit, and an orbital period of 98.9 minutes give an input channel rate of 1510.32 packets per second orbital average.
- The maximum input packet size (day mode) gives a real time maximum Level-0 input rate of .9696 megabytes per second.
- A day mode scan cube size of 2.9 megabytes every 1.47717 seconds gives a maximum Level 1A output rate of 1.963 megabytes per second.
- A night mode scan cube size of 1.1 megabytes every 1.47747 seconds gives a maximum Level 1A output rate of .75 megabytes per second.

Processing Power

The following numbers represent a best guess and do not represent any detailed dasign or prototyping efforts at the present time.

- Incoming packet validation - (2 mips estimated)
- Placement of instrument data from packets into scan cubes - 1.208 million detector values (1456*10*83) per scan cube with <20 operations (2 loads, 1 store, 1 and, 12 shifts, 1 or) = 24,160,000 operations per scan cube
- Georeferencing for each of the 13540 spatial elements (from the "MODIS Level 1A Geolocation Processing Estimate" internal document. A total of 41.4 mflops, with the following breakdown:
  - geolocation to the ellipsiodal Earth - 1,519,188 operations per scan cube (657 multiplies, 373 adds, 70 trigometric, and 22 square roots per frame * 1354 frames per scan cube)

- Digital Terrain Model (DTM) correction - 1,632,924 operations per scan cube (686 multiplies, 438 adds, 56 trigometric, and 26 square roots per spatial element * 1354 frames per scan cube * 10 spatial elements per frame)
- ancillary angle (zenith and azimuth) determination - 1,221,308 operations per scan cube (512 multiplies, 268 adds, 82 trigometric, and 40 square roots per frame * 1354 frames per scan cube)

- Allowing for data quality testing, message passing, possible packet ordering, engineering data organization and validation, etc. an initial guess of ~20 mips multiplied by suitable scaling factor (TBD) would be appropriate.
- Scan cube handling overhead - 1 mips estimated.
- TOTAL Processing Power (assuming mips = flops) = 88.5 mflops, minimum.

These results can be considered accurate for the I/O (input/output) rates, but highly speculative for the processing power estimates. Note that the I/O rates use relatively small data transfer sizes, resulting in a high I/O channel overhead. Blocking these packets into larger entities would produce a more efficient system from an I/O view point.

Important note: Possible future requirements that need to be kept in mind for the level 1A processing may include the determination of a land / water / cloud mask, the separation of ground truth data, or a volcanology algorithm with location information to be passed to the ASTER team for rapid pointing to targets of opportunity.

Level-1B Data Description

The Level-1B data product contains the same type of information as the Level 1A Data Product. This consists of a Metadata product that contains all of the Level 1A Metadata with additional Level-1B metadata appended. The format of the data products is expected to remain basically the same. The scan cube data product contains the same components as the Level 1A: science data, calibration data (solar diffuser, SCRA, black body, space view port) and the engineering data. Data volumes are presented as scan cube estimates with orbital and daily volumes summarized at the end of this section. One kilometer spatial views are designated as spatial elements and consist of 16 - 250 meter IFOVs for bands 1 and 2, 5 - 500 meter IFOVs for bands 3-7, and 1 - 1 kilometer IFOV for the remainder. Bands 13 and 14 have two data channel values (high/low gains for the two detectors per band) per band. This results in 83 data channels per 1 km spatial view.

The science and calibration scan frame data are calibrated to at-satellite radiances and are assumed to be represented as floating point (real) numbers with 4 bytes per data value. An alternate representation would be scaled integers, a data type which is handled by HDF as an auto-scaling capability (built-in units conversion). Engineering and Memory Dump data will be represented in numerical formats appropriate to each parameter or array.

They georeferencing data values for each spatial element for the Level 1B Data Product are identical to the georeferencing in the Level 1A Data Product. If the Level 1A and Level 1B data were in the same HDF data set, the VSET facility could be used to avoid the duplication of the georeferencing in each Data Product. There is currently no facility for applying the VSET capabilities across data sets. This is design item that should be considered for future HDF enhancements.

Science Data - day mode

- 4 bytes per data value
- 1,123,820 science values per scan cube

Science Data - night mode

- 4 bytes per data value
- 230,180 data values per scan cube

Calibration Data - Solar Diffuser

- 4 bytes per data value
- 41,500 data values per scan cube (when scheduled)

Calibration Data - Spectroradiometric Calibrator

- unknown format, 4150 equivalent values per scan cube

Calibration Data - Black Body

- 4 bytes per data value
- 24,900 data values per scan cube

Calibration Data - Space View

- 4 bytes per data value
- 12,450 data values per scan cube

Engineering and Memory Dumps

- These formats are TBD

Level-1B Data Volume and Rates

The data volume for the Level-1B Data Product follows the same thinking as the Level 1A Data Product volume, with floating point data values in place of raw data values.

- 1456 frames per scan cube
- 81 day mode channels, 17 night mode channels of data per spatial element. The two high/low gain raw data values are expected (assumed) to yield one calibrated value.
- 10 spatial elements per frame
- 4 bytes per data value
- These result in 4,717,440 bytes of data values per scan cube for day mode (= 1456 * 81 * 10 * 4), or 990,080 bytes for night mode.
- All Level 1A georeferencing arrays are assumed to be retained in the Level-1B scan cubes

Allowing for engineering and memory dump data formatting and any SDSM formatting, a day mode scan cube size of 6 megabytes may safely be assumed. The corresponding night mode scan cube size would be 2.4 megabytes.

- orbital sizes are 20.1 gigabytes for day mode, and 4.66 megabytes for night mode.
- daily sizes for a 50/50% day/night split are 180.26 gigabytes.

These data sizes can be considered to be accurate to ± 5 percent. Note that data compression is not a consideration at the present time, but has the potential to decrease these volumes by one half.

Structure of the Level-1B Data Product

The Level-1B Data Product will be generated as two data sets: the Metadata and the Data Product. The Metadata will consist of the Level 1A accounting data with any MODIS Level-1B derived information appended. This value added data is expected to be a further synopsis of the Data Product, indications of the quality of the data, and any outside user comments on the data. Any structure for this metadata will be determined by the EOS project, CCSDS recommendations, and Science Team member input.

The Level-1B Data Product will consist of a header and multiple occurrences of the scan cubes. The header information will contain free field (ASCII) information, completeness and quality information in both ASCII and binary forms, selected science observation summaries, and all other data set related information. The quality information in the header will apply to the complete collection of scan cubes. Detailed quality about an individual scan cube will be included with each scan cube and summarized in the header. Header information is repeated in the metadata.

Each scan cube, as illustrated in Figure 4, will contain all the calibrated data derived from the level 1A Data Product, its accompanying calibration parameters and algorithm, segmented spacecraft time (MODIS and platform) at each frame, mirror side, source identification, and configuration indications. This will apply to the solar diffuser, black body, space view, and science view (Earth) data portions of the scan. Adjacent to the science data portion of the cube will be multiple occurrences of the Earth location arrays for each spatial element, and the retained Level 1A Earth location anchor point arrays for selected spatial elements. Following the scan cube will be the SRCA and Engineering Frames (data representations, decommutations, and formatting are TBD), and a detector and calibration quality, two dimensional array for each data channel (81 channels by 10 along track 1 km spatial elements).

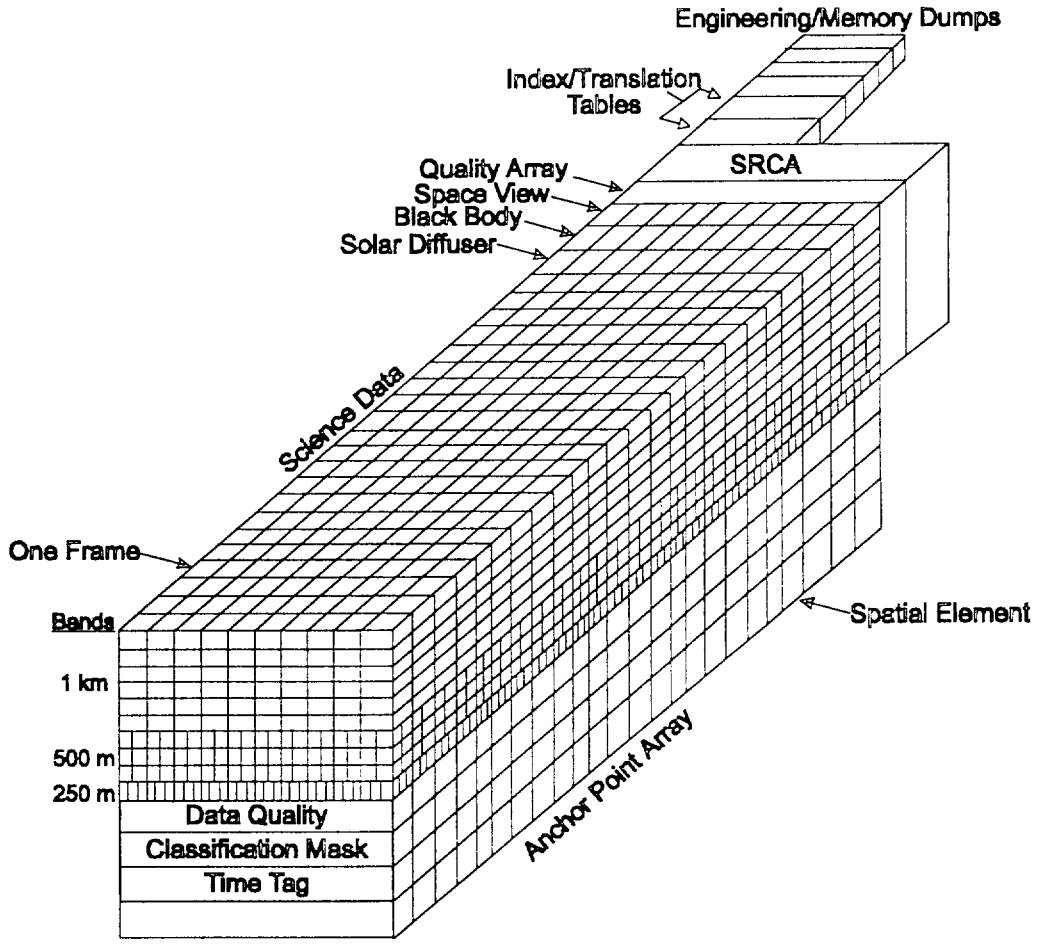


Figure 4. Level-1B Scan Cube

The internal data structure will be principally based on the concept of the 1 km spatial element with 81 channels of data, in place of a logical 36 band based structure. This is the same philosophy as the Level 1A internal data structure. Data can be accessed by a band and IFOV location which will be translated into the internal channel and spatial element location via included translation tables. This allows the science data to be accessed via the logical spatial index while the internal data cube representation retains the square indices.

The major components of the Level 1A output Data Product structure with descriptors are listed in the following item list.

- Calibrated Science Data - three dimensional array - along track, across track, band number
- Calibrated Solar Diffuser Data - three dimensional array - along track, across track, band number
- Calibrated Black Body Data - three dimensional array - along track, across track, band number

- Calibrated Space View Data - three dimensional array - along track, across track, band number

Calibrated views of the calibration source targets can be used to verify the calibration techniques, retained in their raw counts form, or omitted from the data set.

- Band Number to Data Channel translation tables - three tables that translate the logical along track index, the logical across track index, and the band number into the three dimensional cube data channel array indices. Note that the logical cube indices have differing ranges as a function of the band number.
- Spatial Data Quality - two dimensions - along track, across track at 1 km indices. Eight bits will allow 255 possible quality specifications to be determined on a per spatial element basis. This quality is a combination of the calibration and raw instrument data quality.
- Time Tag - array with two tags per frame for day mode, one tag for night mode. This will be subdivided into the various time elements when they have been specified by EOS and SBRC.
- Ground Location Arrays - two dimensional arrays - along track and across track. Each spatial element will have a corresponding ground location point with Earth location via WGS84, Earth location via a digital elevation model (DEM), Earth location via an updated digital terrain model (DTM), and satellite and solar, azimuth and elevation angles at a minimum. Additional location data may be appended to reflect updated instrument position, attitude, and other knowledge.
- Anchor Point Array - two dimensional arrays - along track, across track. Two arrays if latitude and longitude are desired, three arrays for a Cartesian or added elevation coordinate system. Multiple occurrences of this table can be added which would allow the location information to be updated if more precise instrument positioning and/or attitude become available.
- Anchor Point Index Array - two arrays containing the locations within the scan cube of the across track and along track spatial elements that have anchor point values. This allows the translation to / from the logical scan cube coordinates and the anchor point array.

The anchor point array data may be deleted in favor of a full spatial element array with more accurate versions of the ground location data.

- SRCA Data - (TBD)
- Engineering / Memory Dumps - these are a set of sequential variables or linear arrays, the format and contents of which are (TBD). Note that the memory dumps and many engineering readings are sampled at a much lower rate that the scan cube rate. These data will be submultiplexed within this data area.
- Calibration Quality - array - the data calibration quality specified for all IFOVs combined, one index per data channel.

Level-1B Profiling and Computing Resources

Input / Output Rates

- Each scan cube of Level 1A data is 2.5 megabytes in length, and occurs every 1.47717 seconds.
- 4017.14 scans per orbit, and an orbital period of 98.9 minutes give an input channel rate of .677 scan cubes per second, orbital average.
- The output channel rate is also .677 scan cubes per second, orbital average.
- A Level 1A scan cube size of 2.5 megabytes every 1.47717 seconds gives a maximum Level 1A input rate of 1.6924 megabytes per second.

- A Level-1B scan cube size of 5.0 megabytes every 1.47717 seconds gives a maximum Level-1B output rate of 3.385 megabytes per second.

Processing Power

The following numbers represent a best guess and do not represent any prototyping efforts at the present time.

- 1.208 million raw detector values per scan cube with <15 operations (a polynomial expansion perhaps?) = 18.12 million flops (floating point operations per second).
- Ground location determination would involve the determination of instrument scan angles, and earth location function calls which would be performed 13540 (1354 * 10) times per 1.47717 seconds = 9106 computing exceptions per second. (? operations per second for internal function and external setup ?)
- allowing for data quality testing, message passing, data characterization, engineering data translation, etc. a guess of ~50 mips would be appropriate.
- These operation should be able to be performed on a 100+ specmark machine.

These results can be considered accurate for the I/O (input/output) rates, but highly speculative for the processing power estimates. Note that the I/O rates use relatively large data transfer sizes. This may be a problem for channel controllers that are limited to 64kbyte transfers. Deblocking these scan cubes into smaller entities may be required at the operating system level.

Possible future requirements that need to be kept in mind for the level-1B processing that may have not been incorporated into the Level 1A processing may include the determination of a land / water / ice / cloud mask, or a volcanology algorithm with location information to be passed to the ASTER team for rapid pointing to targets of opportunity. The possible future inclusion of algorithms for classification masking, volcanology, and/or similar requirements will impact these processing estimates.

GLOSSARY

- Pixel -The smallest decomposed unique science data value. One pixel represents the data from one spatial position and one channel of data.
- Anchor Point Array - a spatial array of Earth located positional values (latitude, longitude, and possibly elevation) that determines the location of a selected subset of the science data pixels.
- Spatial Element - all channels of data corresponding to a 1 kilometer ground equivalent field of view. This means that 16 - 250 meter detectors, 4 -500 meter detectors, and 1 - 1 km detector reside within one spatial element.
- Channel - the data derived from an instrument data gathering electronic channel. Channels of data may be obtained in parallel. Contrast this with a band of data.
- Band - A center frequency and filter function width combination that are referenced by an arbitrary number. One channel usually measures data from one band, but MODIS has two channels of data for each of bands 13 and 14.
- Scan Cube - The three dimensions of the science data: along track, across track, and band number with ground locations, engineering data (per scan), and quality indications attached.

- Frame - A set of data representing one instance of: all bands of science data and 10 along track spatial elements (day or night mode), or all bands & 10 spatial elements of solar diffuser, black body, or space view data, or specialized data from the SRCA or Engineering / Memory dumps.
- Swath - Engineering term for a half mirror rotation. This is equivalent to a scan cube.
- Metadata - Information describing the content, format, and utility of a data set.

MODERATE RESOLUTION IMAGING SPECTRORADIOMETER
(MODIS) PROGRAM

OPERATIONAL IN-FLIGHT CALIBRATION PROCEDURES

(PRELIMINARY REPORT)

CDRL 404

PREPARED FOR
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT ROAD
GREENBELT, MARYLAND 20771

Contract No. NAS5-30800

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Section 1

1.0 INTRODUCTION

This is a preliminary draft of CDRL #404 entitled "OPERATIONAL IN-FLIGHT CALIBRATION PROCEDURES". The preparation information given for this CDRL is:

> "These procedures shall describe the equipment, methods, accuracies, and command sequences for in-flight calibration. Fail-safe methods shall be used for conducting in-flight calibration."

Related documents include the following:

- CDRL #016 Preliminary Design Review (PDR)
- CDRL #018 Calibration Management Plan (CMP)
- CDRL #019 Calibration Peer Review (CPR)
- CDRL #025 In Flight Check Out Plan
- CDRL #032 Preship Review (PSR) Package
- CDRL #101 Radiometric Math Model (RMM)
- CDRL #303 Command List and Description
- CDRL #405 General Operating Command Procedures
- CDRL #410 Detailed Ground Calibration Procedures
- 420-30-01 EOS Calibration Calibration Management Plan

This CDRL shall cover all of the MODIS On-Board Calibrator mechanisms, namely:

- 2.x.x.x.x Space View Source (SVS)
- 3.x.x.x.x Blackbody Assembly (BBA)
- 4.x.x.x.x Solar Diffuser Assembly (SDA)
- 5.x.x.x.x Solar Diffuser Stability Monitor (SDSM)
- 6.x.x.x.x Spectroradiometric Calibration Assembly (SRCA)
- 7.x.x.x.x Electronic Gain Calibration

The document is organized to treat each of the mechanisms / functions separately. To the extent applicable each area is further broken down into:

- x.1.x.x Description Summary
- x.2.x.x Preflight Calibration
- x.3.x.x Calibration / Characterization Algorithms
- x.4.x.x Required Data
- x.5.x.x Command Implementation

This coverage exceeds our interpretation of CDRL #404 requirements. However at this time it seems that this format will enhance necessary communication between SBRC and NASA personnel. However, since this CDRL submittal is the preliminary one if after review by SBRC

and NASA the format used herein is deemed inappropriate it will be altered in subsequent submittals.

Furthermore it is to be noted that some calibrator mechanisms are treated in much more detail than others. This is indicative of two factors: First, there is a large disparity in the complexity among the On-Board Calibrators and secondly some areas are more mature.

Table 1.1 is a listing of the MODIS on board calibration mechanisms. These mechanisms shall be covered in this CDRL.

TABLE 1.1 MODIS IN-FLIGHT CALIBRATION SUMMARY

Section	Type of Calibration	Source	Mechanism	Aperture	Spectral Bands	Usage Frequency (Max)	Other Comments
2	Radiometric	Space		Full	MWIR / LWIR	Once per scan line	
3	DC Restore	Blackbody	Blackbody	Full	All	Once per scan line	
3	Radiometric	Blackbody	Blackbody	Full	Bands 20-25 & 27-36	Once per scan line	
4	Radiometric	Sun	Solar illuminated diffuser	Full	VIS / NIR / SWIR less Bands 8-16	Once per orbit	Eff albedo 0.45 to 0.59
4	Radiometric	Sun	Solar illuminated diffuser	Full	VIS / NIR / SWIR	Once per orbit	Eff albedo 0.038 to 0.050
5	Diffuser Stability Monitor	Sun	Spherical integrator with filtered detectors	Full	VIS / NIR / SWIR	Available once per orbit	Both high and low albedo levels
6	Radiometric	Incandescent source with spectral shaping	SRCA collimator	Partial	VIS / NIR / SWIR	Available any time during orbit	
6	Spectral (MODIS)	Incandescent source	SRCA grating monochromator with collimator	Partial	VIS / NIR / SWIR	Available any time during orbit	Grating rotated
6	Spectral (Monochro-mator)	Incandescent source	Didymium filtered photodiode	Full	VIS / NIR / SWIR	Available any time during orbit	Grating rotated
6	Spatial Registration	Incandescent and IR sources	SRCA collimator with spatial reticles	Partial	All	Available any time during orbit	
7	Electronic gain	voltage source		NA	All	Available any time during orbit	injected at FPA

1.1 Calibration Accuracy

Achieving total sensor accuracy is not simply a matter of obtaining good calibration standards, but one of identifying and controlling the numerous physical and environmental factors that ultimately limit measurement accuracy. Our experience in sensor calibration has taught us as much about identifying sources of uncertainty as in learning how to control them. For most bands, sufficiently accurate standards exist but calibration of a total sensor, on the ground and on orbit, include multiple transfer standards, auxiliary optics, and test instabilities that individually can contribute sources of error many times larger than the standard itself.

Blackbody sources are used for calibration in the MWIR and LWIR, and there are no equivalent standards to reflectance standards to use. The driving parameters in blackbody calibration accuracy are emissivity and temperature. There are no emissivity standards available through NIST, however NIST is receptive to calibrating blackbodies, if they are compatible with their calibration facility. Temperature standards do exist through NIST and have reported accuracies of ≤0.01K, more than sufficient to meet MODIS requirements. In addition, cross calibration will be accomplished in conjunction with University of Arizona.

An estimate of the preflight and in flight calibration accuracies for reflectance and thermal bands are given in Table II and III.

Figure 1.1 indicates the preflight calibration / characterization that will be performed on the MODIS On-Board Calibrators. A summary of this data will be covered under preflight characterization of each of the OBC.

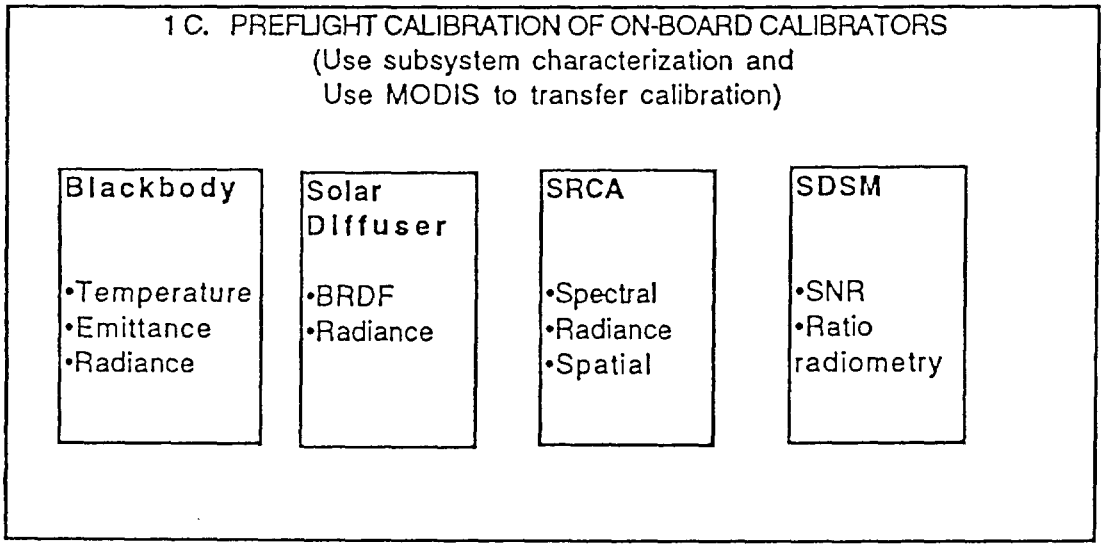


Figure 1.1. MODIS PREFLIGHT CALIBRATION PLAN

2.1 Space View Source

The space view provides a zero scene radiance. This radiance level in conjunction with the Blackbody Assembly are used to accomplish the inflight MWIR/LWIR calibration.

SECTION 3

BLACKBODY ASSEMBLY (BBA)

3.1 Blackbody Assembly Description

The blackbody cavity design utilizes an aluminum plate with V-grooves cut at a 40.5 -degree included angle. The V-groove surfaces will be polished and anodized. The resultant cavity shall have an emittance ≥0.992. Twelve temperature sensors shall be embedded in the blackbody source for monitoring/controlling the blackbody temperature. The blackbody source shall normally float at MODIS ambient temperature but the capability to heat and control the temperature to 315K upon command shall be provided. The blackbody temperature uniformity is expected to be ≤ 0.03 K and 0.3 for ambient and 315 K operation respectively. Preliminary thermal modeling indicates that the time required to heat the BB from 285 to 315 is 130 minutes. The cool down time constant is 100 minutes. Effective temperature knowledge shall be known (TBR) to within 0.1 K during these heating and cooling phases.

The Blackbody Assembly shall provide full aperture radiometric calibration of the MWIR and LWIR bands, (bands 20 to 36; 3.6 μm ≤ λ ≤ 14.4 μm) with an absolute accuracy of 1%. The required radiometric calibration is achieved with 15 samples whereas 45 samples are available through scan mirror travel. A second function of the blackbody is to provide dc restoration of all spectral bands.

3.2 Blackbody Assembly (BBA) Preflight Calibration

The BBA shall be calibrated in thermal vacuum. Figure 3.1 block diagram indicates the setup. The MODIS sensor shall be used as a transfer radiometer for this calibration. With the variable temperature blackbody calibration source (BCS) a spectral radiance versus MODIS signal output set of data is generated. This data will calibrate the MODIS instrument and then this calibration is transferred to the BBA. This calibration will be accomplished for different instrument temperatures.

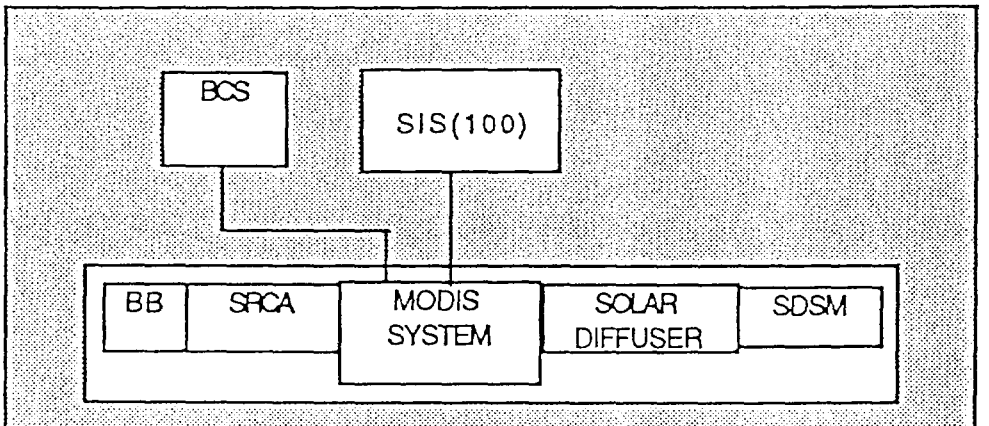
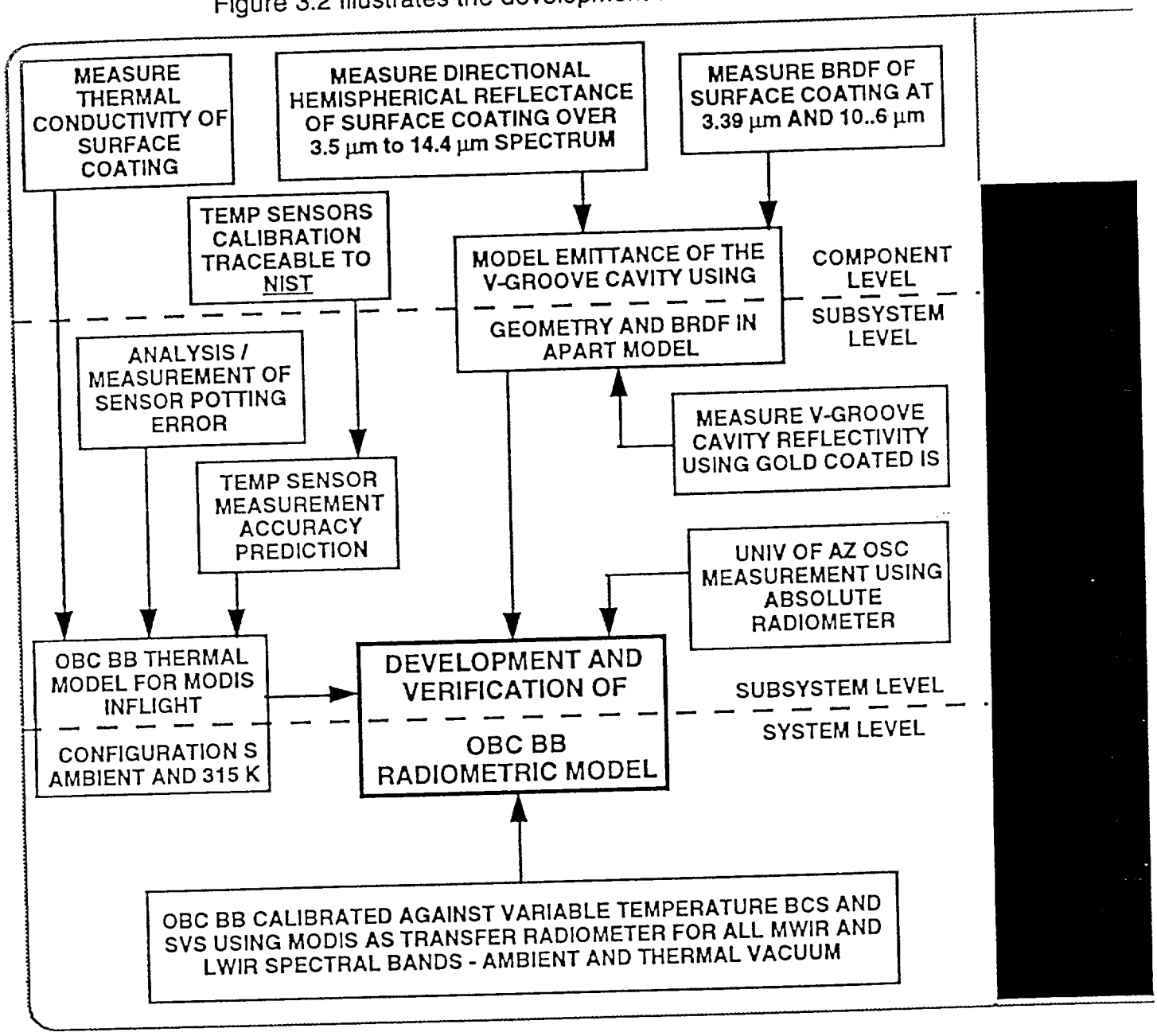


FIGURE 3.1 PREFLIGHT SYSTEM CALIBRATION

Figure 3.2 illustrates the development and verification flow of the BBA.



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.

3.4 Required Data

Data required to accomplish the in-flight calibration include:

1. Blackbody temperature - 12 sensors
2. Scan mirror / BB cavity temperature
3. MODIS Band (B#), Channel (Ch#), Data frame (FD#)
4. MODIS detector background

3.5 Command Implementation TBD

This section shall address the command sequences required to:

- OBC subsystem configuration setup
- OBC subsystem preparation sequence
- OBC execution sequence
- OBC shut down sequence

Section 4

SOLAR DIFFUSER ASSEMBLY (SDA)

4.1 Solar Diffuser Assembly (SDA) Description

The Solar Diffuser Assembly (SDA) is one of four MODIS on-board calibrator assemblies. When illuminated by the sun it is a full aperture source used for in-flight reflectance and radiometric calibration of MODIS. The Solar Diffuser design utilizes a fixed single sided, near lambertian diffuser plate tilted at a known angle with respect to the incident solar irradiance. The diffuser material is Spectralon (available from Labsphere). The Solar Diffuser Assembly provides two known radiometric levels suitable for calibration of MODIS VIS, NIR, and SWIR spectral bands (bands 1-19 and 26; 0.4 μm - 2.2 μm). A selectable, partially transmitting screen, placed in front of the solar diffuser, provides the second (lower) calibration level. The high level albedo range is 0.45 to 0.59. The low level albedo range is 0.038 to 0.050. These albedo levels are consistent with a solar illumination angle of incidence (AOI) range of 63.0° to 53.5°.

Figure 4.1 illustrates the interrelationships between solar diffuser door and attenuation screen actuators with the built in calibration redundancy. The solar diffuser / door philosophy is illustrated in Figure 1. The following are aspects of this philosophy. There will be one fixed diffuser with nearly unity diffuse reflectance. The diffuser door will have an actuator to open and close the door. There will be a 8.5 % transmitting screen. With the diffuser door operational there will be a latching mechanism that will permit the 8.5 % screen to open with the diffuser door or remain closed when diffuser door is opened. If and when the diffuser door actuator fails the diffuser door will fail in the open position. In addition the latching mechanism is to be made inoperable at that time. Furthermore upon this failure there will be a back-up actuator made operational to open and close the 8.5% transmitting screen. If and when this secondary screen door actuator fails it will fail with the screen door closed.

4.2 Solar Diffuser Assembly (SDA) Preflight Calibration

The preflight calibration is a combination of component and subsystem characterization / calibration. These tests are illustrated by Figures 4.2, 4.3, and 4.4. Figure 4.2 represents the solar diffuser spectral BRDF(Øi, Øs, λ) characterization, where:

- Øi-covers solar illumination angular region
- Øs-covers MODIS angular viewing region
- λ - selected wavelengths in the 0.4 to 2.2 μm region

To the extent possible these measurements will be traceable to NIST diffuse reflectance standards and correlated with NASA GSFC measurements.

Figure 4.3 is a laboratory calibration of the solar diffuser and the solar diffuser stability monitor (SDSM). Figure 4.4 is a subsystem measurement that uses the sun as a source. Atmospheric effects have to be removed from these data. It is expected that Univ. of Arizona Remote Sensing Group will participate in this calibration.

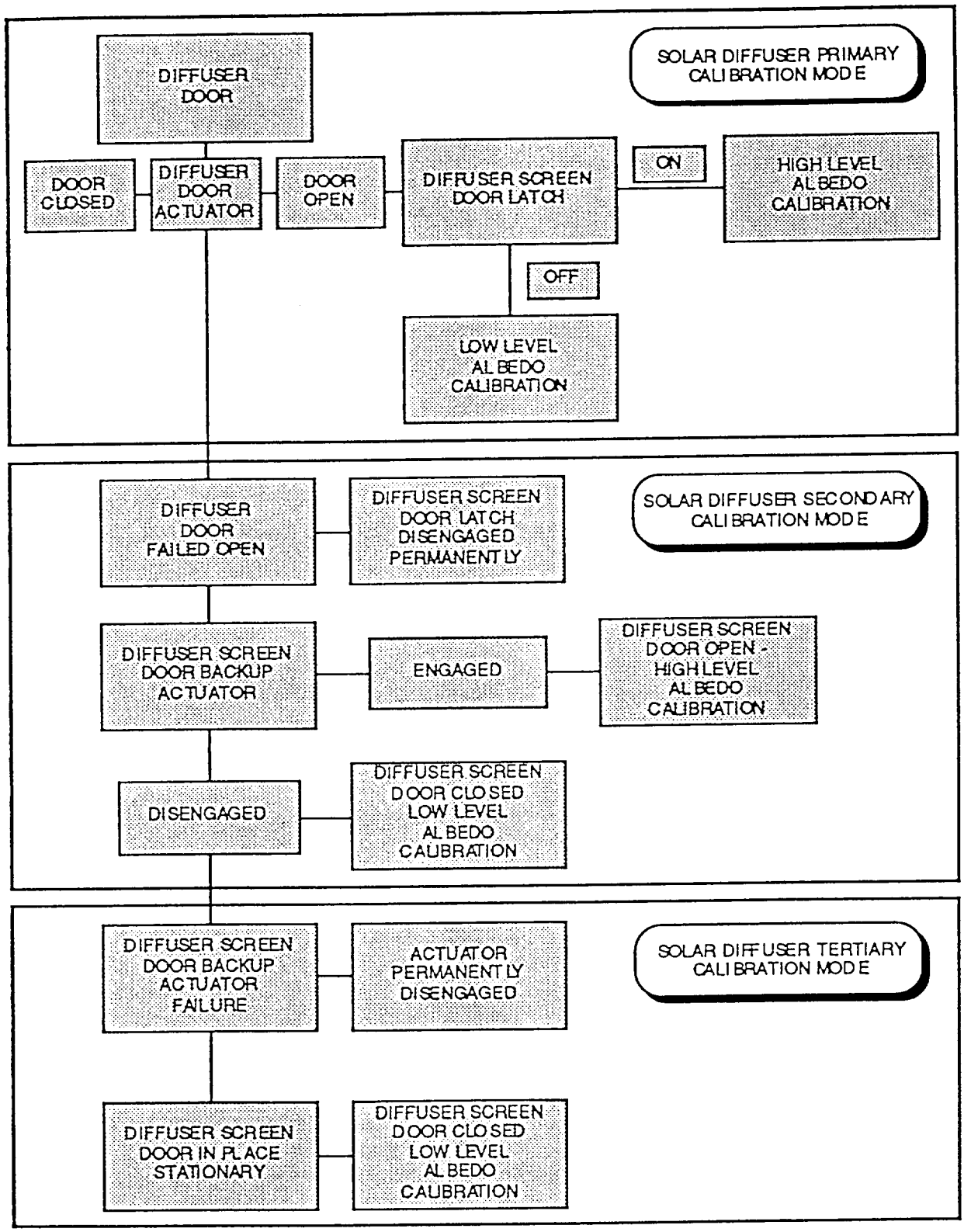


Figure 4.1. Solar Diffuser/Diffuser Door Operational Modes.

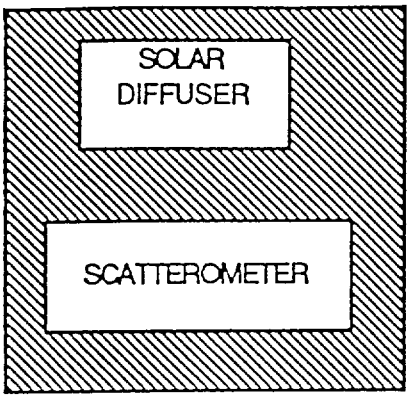


FIGURE 4.2 SOLAR DIFFUSER - BRDF

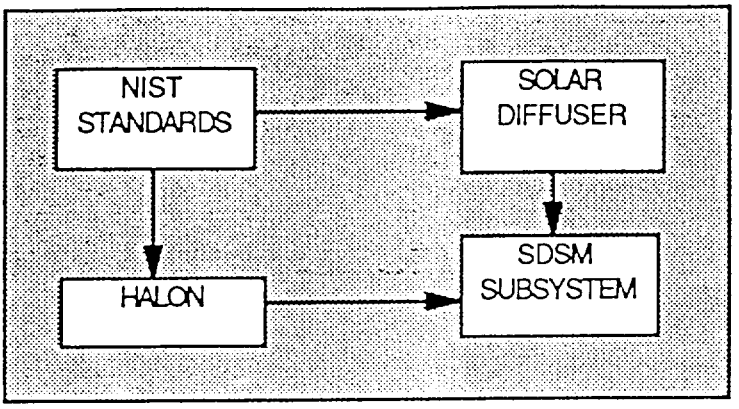


FIGURE 4.3 SDSM SUBSYSTEM CALIBRATION

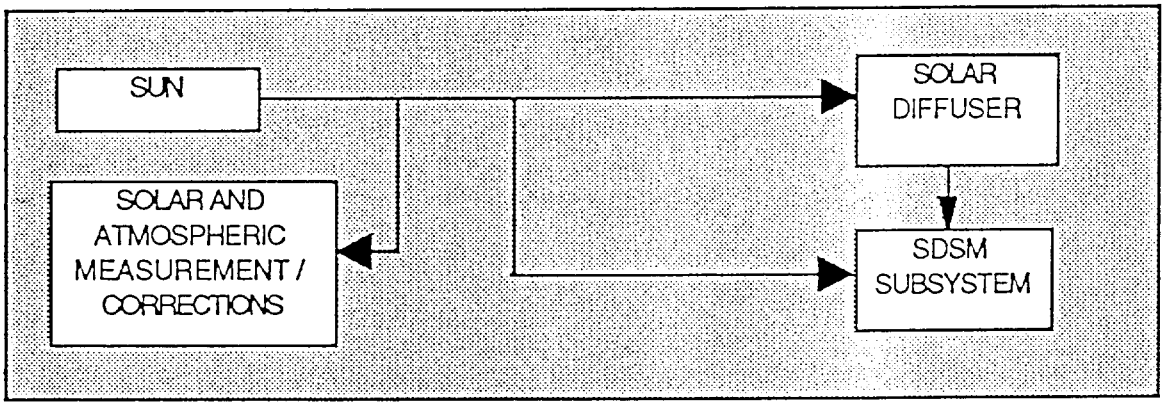


FIGURE 4.4 SOLAR DIFFUSER / SDSM SUBSYSTEM CALIBRATION (SOLAR SOURCE)

4.3 Solar Diffuser Radiometric Calibration (VIS/NIR/SWIR) In-Flight Algorithms

The solar-illuminated diffuser is used to calibrate all VIS, NIR, and SWIR bands and channels. All bands are calibrated at the low albedo level , namely, with the 8.5 % transmitting screen. All bands that are not saturated at the high albedo level will be calibrated without the 8.5 % transmitting screen. Only one calibration level will be accomplished in any one orbit. Visualize the calibration will be accomplished with or without the screen in any one orbit.

- Select reflectance or radiance calibration mode: same data collected but data reduction differs.
- Select calibration level: high - without screen; low - with screen
- Time of year: TOY
- Sun-to-diffuser angle of incidence: $\varnothing$inc(FD#, αhor)
- Record MODIS signals when viewing solar diffuser: DN_sd(B#, Ch#, FD#)
- Record MODIS signals when viewing space port: DN_sp(B#, Ch#, FD#)
- Calculate average space signal: $DN_sp_avg(B\#, Ch\#) = \frac{DN_sp(B\#,Ch\#,FD\#)}{\sum F\#}$

- Calculate responsivity - radiance mode

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

- Calculate responsivity - reflectance mode

$$R_\rho(B\#, Ch\#, F\#) = \frac{DN_sd(B\#, Ch\#, F\#) - DN_sp_avg(B\#, Ch\#)}{\Delta \rho}$$

where $\Delta L(B\#, Ch\#, \emptyset inc) = BRDF(\emptyset inc, \emptyset modis) * Esun(B\#) * \cos(\emptyset sun_sd)$

$\Delta \rho(B\#, Ch\#, \emptyset inc) = BRDF(\emptyset inc, \emptyset modis) * \cos(\emptyset sun_sd)$

- Calculate average radiance responsivity:

$$R_L_avg(B\#, Ch\#) = \frac{\Sigma R_L(B\#, Ch\#, FD\#)}{\Sigma\ FD\#}$$

- Calculate average reflectance responsivity:

$$R_\rho_avg(B\#, Ch\#) = \frac{\Sigma R_\rho(B\#, Ch\#, FD\#)}{\Sigma\ FD\#}$$

- Scene radiance algorithm:

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

- Scene reflectance algorithm:

$$\rho(B\#, Ch\#) = \frac{DN_scene(B\#, Ch\#, FD\#) - DN_sp_avg(B\#, Ch\#, FD\#)}{R_\rho_avg(B\#, Ch\#)}$$

The required data reduction algorithms for the configuration with the transmitting screen will be more complex. The added complexity involves the projections of the screen and MODIS entrance aperture. The screen is comprised of small apertures that are uniformly spaced. The incident sunlight illuminates this aperture pattern and thus the diffuser is illuminated via this projected aperture pattern. This pattern will translate on the diffuser as a function of time because of the spacecraft orbital motion. The other aspect is associated with the MODIS entrance aperture projected onto the diffuser. The MODIS entrance aperture will be scanned across the diffuser via scan mirror action. The useful calibration energies is given by the convolution of these two functions. Preliminary computer modeling indicates that all of the data needed to achieve an unambiguous calibration is available. However a detailed computer model is needed to determine the appropriate on-orbit calibration algorithms.

4.4 SDA Required Data (TBD)

The required data includes the following variables:

- The spectral BRDF over the region used.
- Is the attenuation screen in or out?
- The attenuation screen transmissio
- Solar spectral irradiance

- Angular relationship of sun and solar diffuser normal
- MODIS relative spectral response functions
- SDSM data to be used to correct solar diffuser BRDF, if needed

4.5 SDA Command Implementation (TBD)

This section shall address the command sequences required to:

- OBC subsystem configuration setup
- OBC subsystem preparation sequence
- OBC execution sequence
- OBC shut down sequence

Section 5

SOLAR DIFFUSER STABILITY MONITOR (SDSM)

5.1 Solar Diffuser Stability Monitor (SDSM) DESCRIPTION

The material used for the solar diffuser is expected to degrade as a function of time in orbit. A device is needed to quantitatively track this degradation, so that, the change in solar diffuser performance can be corrected. The SDSM is such a device and is schematically shown in Figure 5.1. Nominally a 5 cm diameter spherical integrating cavity is used. A three position fold mirror permits the integrating cavity to sequentially view MODIS illuminated solar diffuser, internal housing (DC restoration), and direct sunlight. The integrating cavity has a common square entrance port for direct sunlight and solar diffuser illumination. A positive lens located at the integrating cavity entrance port causes the direct sunlight and solar diffuser paths to approximately illuminate the same portion of the integrating cavity wall. The integrating cavity will be formed from molded Halon. There will be filtered detectors (9 SiPD and 2 Ge) located in the integrating cavity wall. The optical filtering permit monitoring of the solar diffuser performance relative to the sun over the 400 to 1700 nm spectral range.

5.2 Solar Diffuser Stability Monitor (SDSM) preflight calibration

At the SDSM subsystem level, the spectral response will be characterized for the integrating sphere, filter, and detector assembly. The 2% solar attenuation screen will be measured. In Figure 5.2 the SDSM is calibrated in terms of spectral irradiance and radiance. In Figure 5.3 the SDSM is used in the subsystem calibration of the solar diffuser and SDSM. NIST spectral irradiance standards are used in both of these tests as radiometric reference sources. In Figure 5.4 the SDSM and solar diffuser shall be calibrated using the sun as a source. It is necessary for atmospheric effects be removed from these measurement results. It is expected by the University of Arizona Remote Sensing Group shall participate in these tests.

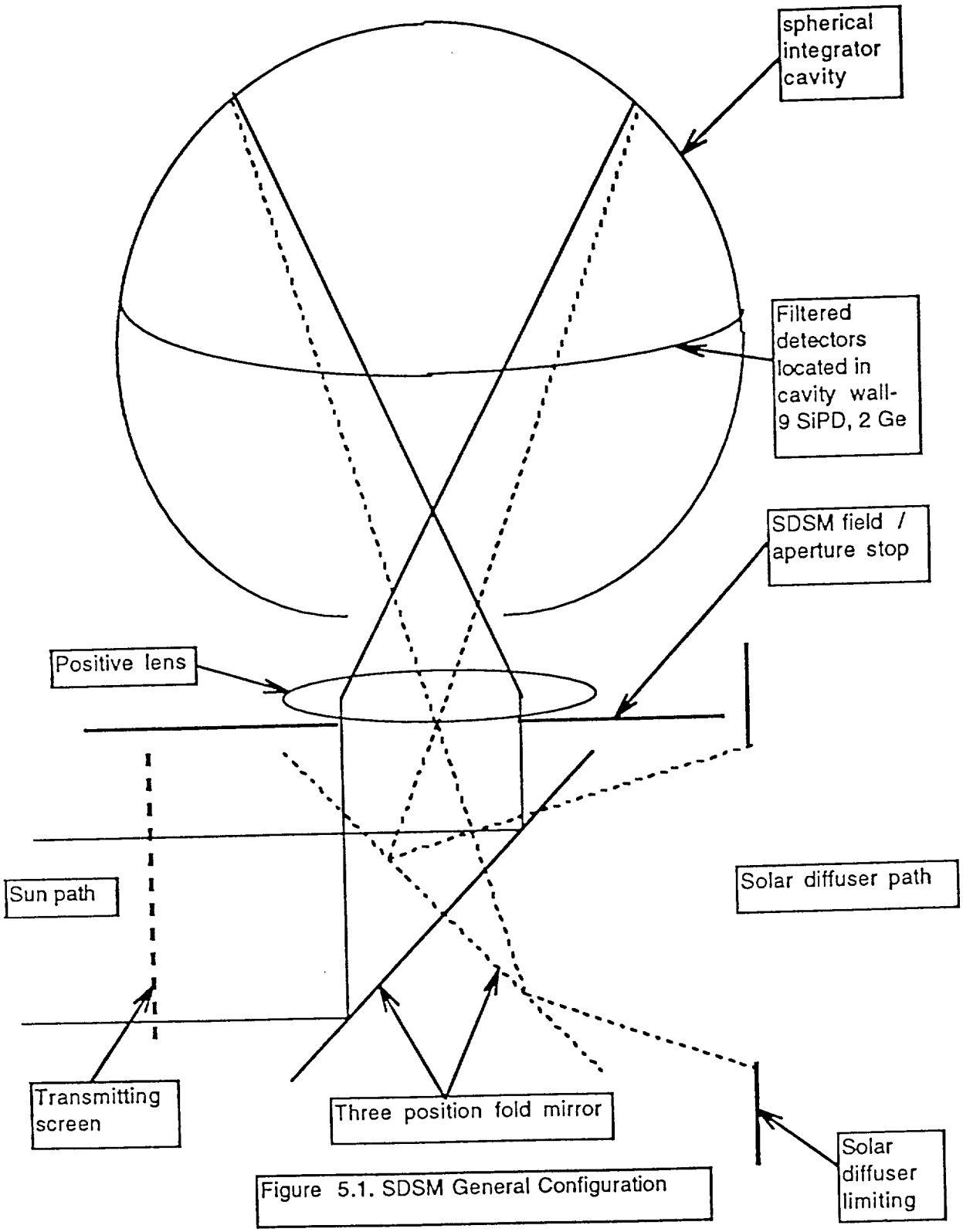


Figure 5.1. SDSM General Configuration

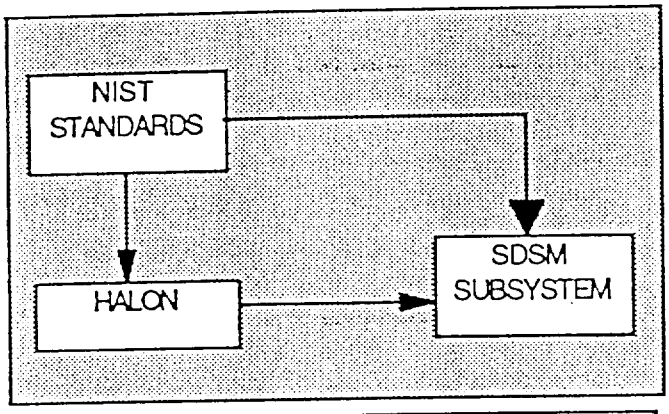


FIGURE 5.2 SDSM SUBSYSTEM CALIBRATION

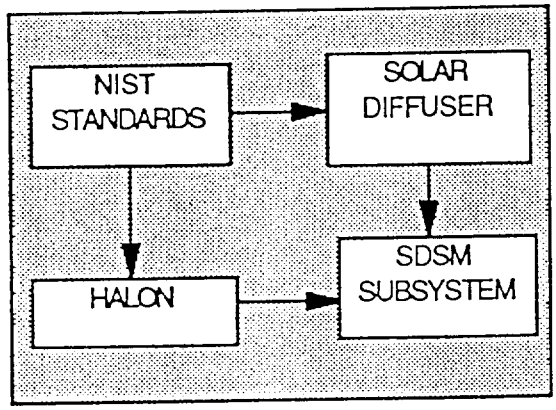


FIGURE 5.3 SDSM SUBSYSTEM CALIBRATION

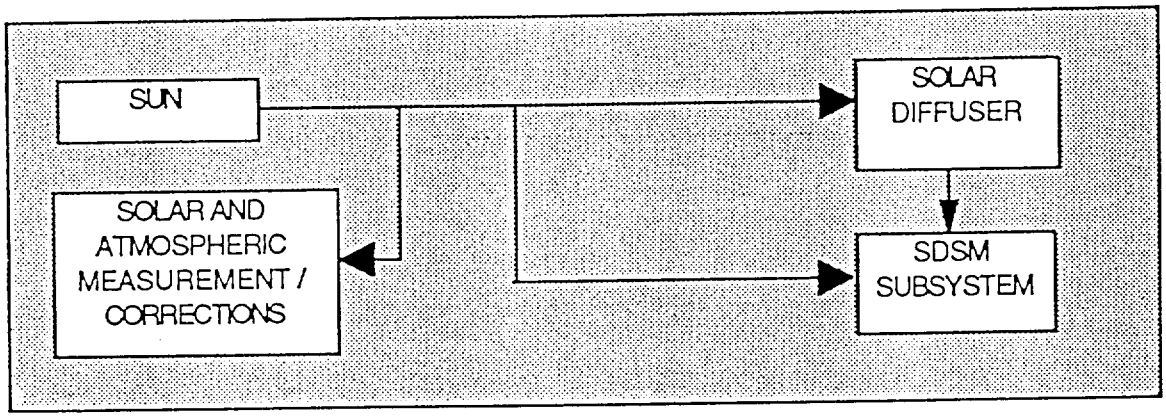


FIGURE 5.4 SOLAR DIFFUSER / SDSM SUBSYSTEM CALIBRATION (SOLAR SOURCE)

5.3 Solar Diffuser Stability Monitor In-Flight Algorithms

The primary function of the SDSM is to track any changes in the solar-diffuser reflectance and provide means to correct its reflectance so that an accurate on-orbit radiometric calibration is maintained for Bands 1 through 19 and 26. Each time the solar diffuser is used for calibration of the MODIS, the SDSM is also used. A brief outline of data collection and data reduction is given below:

- Last update value of solar diffuser BRDF - BRDF_prev(BB#)
- Last update value for SDSM correction factor - Fcorr_prev(BB#)
- Select calibration level: High - without screen; low - with screen
- Time of year - TOY
- Sun to diffuser angle of incidence: $\emptyset$inc(F#, αhor, SL#)
- SDSM detector signals all bands dc restore function - DN_dcr(SL#, BB#)
- SDSM detector signals all bands direct sunlight - DN_sun(SL#, BB#)

- SDSM detector signals all bands solar diffuser - DN_sd(SL#, BB#)

  NOTE: DC restore signal and either direct sun or solar diffuser signals are obtained each scan line throughout the one minute used to obtain solar diffuser calibration and SDSM data.

- Calculate SDSM correction factor for each scan line set and SDSM bands:

$$Fcorr(SL\#, BB\#) = \frac{DN_sd(SL\#, BB\#) - DN_dcr(SL\#, BB\#)}{COS(\emptyset sun_sd)} * \frac{COS(\emptyset sun_att\ scr)}{DN_sun(SL\#, BB\#) - DN_dcr(SL\#, BB\#)}$$

- Calculate current average SDSM correction factor for each SDSM band:

$$Fcorr_current(BB\#) = \frac{\Sigma\ Fcorr(SL\#, BB\#)}{\Sigma\ SL\#}$$

- As this correction factor changes it needs to be applied as a correction to the solar diffuser BRDF. In principle, the following ratio will be used:

$$\frac{BRDF_current(BB\#)}{Fcorr_current(BB\#)} = \frac{BRDF_prev(BB\#)}{Fcorr_prev(BB\#)}$$

- The BRDF as given above would be at the SDSM spectral regions. BRDF for the MODIS spectral bands would be derived from these.

5.4 SDSM Required Data (TBD)

The required data includes the following variables:

- File of previous SDSM outputs
- Attenuation screen in / out
- SDSM detector signals for solar diffuser, dc restore, and direct sun viewing
- Special test wherein SDSM is used to support transfer of preflight calibration to inflight includes numerous preflight calibration files

5.5 SDSM Command Implementation (TBD)

This section shall address the command sequences required to:

- OBC subsystem configuration setup
- OBC subsystem preparation sequence
- OBC execution sequence
- OBC shut down sequence

Section 6

SPECTRORADIOMETRIC CALIBRATION ASSEMBLY (SRCA)

6.0.1 SRCA DESCRIPTION.

6.0.1.1 TOP LEVEL DESCRIPTION.

The SRCA is a compact instrument that provides multimode calibration capability (spectral, spatial and radiometric calibration) of the MODIS instrument on-orbit; as well as, a self calibration of the SRCA's spectral output. The SRCA, no doubt, will also provide secondary calibration and periodic health checks of the MODIS instrument during pre-launch integration and test as well. The SRCA provides only partial aperture illumination of the MODIS instrument; approximately 1/5 the MODIS entrance aperture area is illuminated by the SRCA. This partial aperture illumination results in small but significant differences in the spectral and spatial responses of the MODIS instrument when compared to full aperture illumination. As a result, the SRCA is not capable of providing the primary absolute calibration for MODIS. Its primary purpose is to detect changes in MODIS (spectral, spatial and radiometric) which can then be used to update MODIS calibration values obtained from primary, full-aperture calibration sources (such as the Ground Base Calibrator, On-Board Blackbody, Spaceview and Solar Diffuser). Therefore, the calibration of the SRCA is not only dependent upon its own performance characteristics, but is also dependent upon how the MODIS instrument responds to the SRCA's partial aperture illumination. This being the case, the calibration of the SRCA (spectrally, spatially and radiometrically) will be performed using the MODIS instrument itself as a transfer vehicle once its own calibration has been established using the Ground-based, full aperture calibration sources. After the MODIS has had its Gain, Offset and DC Restore values set, the SRCA will be calibrated by measuring the response of MODIS (each band, channel) at the same or very near in time and under similar conditions as the MODIS itself is calibrated using the primary ground-based calibration sources. The SRCA will be calibrated in this manner for all three modes of operation (radiometric, spatial and spectral calibration). Once calibrated, the SRCA will become a calibration standard, able to measure and track changes in the MODIS instrument over its life (pre-launch, pre-launch to on-orbit and on-orbit).

6.0.1.2 OPERATIONAL CONFIGURATIONS.

Upon command, the SRCA is uniquely configured for each of the three calibration modes of operation as specified below. A graphical representation of the following operational configurations is shown in Figure 6.1.

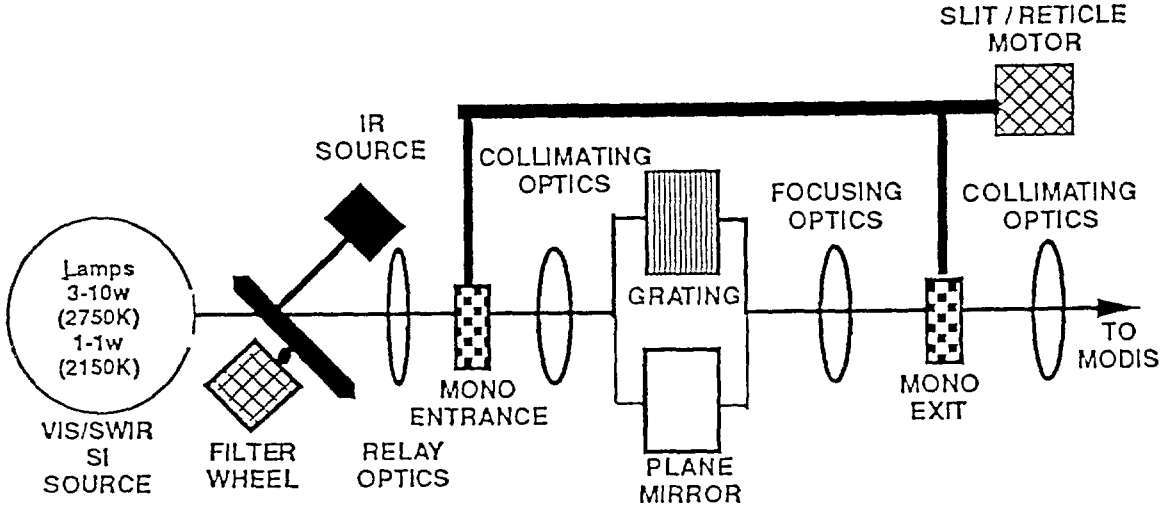
a. Radiometric calibration mode: VIS, NIR and SWIR source radiance level selected; open or ND filter position selected at filter wheel; monochromator entrance and exit ports open; and plane mirror surface selected on rotatable mount.

b Spatial calibration mode: VIS, NIR, and SWIR source radiance level selected; IR source at ~ 390K; dichroic beamcombiner selected at filter wheel; monochromator entrance port open; and one of two reticle patterns placed at exit port; and plane mirror surface selected on rotatable mount.

c. Spectral calibration mode: VIS, NIR and SWIR source radiance level selected; slits placed at monochromator entrance and exit ports; one of the three order filters selected to eliminate unwanted diffracted orders; grating selected on rotatable mount; and didymium glass filtered photodiode behind offset exit slit sensing monochromator spectral output.

Redundant incandescent sources provide illumination for the VIS, NIR and SWIR bands. During spatial calibration, an IR source is combined with the incandescent source beam via a dichroic beamcombiner. The beamcombiner, located on the source filter wheel, is rotated into place during spatial calibration only. The source energy is focused at the entrance plane of a modified Czerny-Turner monochromator with a rotatable mount containing one grating and a plane mirror. With the

grating in place, the SRCA becomes a monochromator used for spectral calibration. With the grating/mirror mount rotated to the plane mirror position, the "monochromator optics" then relays the source radiance to the exit plane of the monochromator/relay optics. The output of the monochromator/relay optics is collected by a two-mirror Cassegrain telescope that collimates the light and directs it, through a fixed fold mirror, to the MODIS scan mirror. In the radiometric calibration mode, the entrance and exit planes of the monochromator are open and the plane mirror position selected at the grating/mirror mount. In the spatial registration mode, the entrance plane of the monochromator is open and one of two reticle patterns is placed at the exit port of the monochromator; the reticle image is relayed by the SRCA collimating optics onto the MODIS focal planes. The SRCA also has capability to perform self-calibration of the spectral output of the monochromator by sampling the spectral profile of didymium absorption glass using a photodiode located at the exit plane of the monochromator.



CALIBRATION MODE	SOURCE	FILTER WHEEL	MONO ENTRANCE	GRATING / MIRROR	MONO EXIT
RADIOMETRIC	VIS/SWIR	CLEAR & ND	OPEN	MIRROR	OPEN
SPECTRAL	VIS/SWIR	ORDER (3)	SLIT	GRATING	SLIT / SiPDs
SPATIAL	VIS/SWIR & IR	DICHROIC	OPEN	MIRROR	RETICLES

FIGURE 6.1. SRCA SELECTABLE CONFIGURATIONS

6.0.1.3 DETAILED COMPONENT DESCRIPTION.

6.0.1.3.1 VIS/NIR/SWIR Source: The VIS/NIR/SWIR source consists of a 1.75 inch diameter Spectralon Spherical Integrating Source (SIS) containing four 10.4 watt tungsten halogen lamps operating at a 2750K filament temperature and two 1 watt tungsten vacuum lamps operating at a 2150K filament temperature. For reliability, one lamp of each type shall serve as redundant, backup lamps. Also, the control electronics for the source is redundantly configured. Individual On/Off control for each of the lamps provides the ability of to adjust the radiant output of the SIS; thus, simplifying the filtering requirements for the source to satisfy all calibration modes of the SRCA (Radiometric, Spectral and Spatial). Four different lamp operating configurations are utilized in achieving the various radiance levels required (3-10 Watt; 2-10 Watt; 1-10 Watt; and 1-1 Watt).

There are two modes of operation for controlling the SRCA VIS/SWIR source itself: SiPD Feedback; and Constant current.

1) SiPD Feedback Control Mode: The primary mode of source control utilizes a temperature controlled SiPD in a radiant output feedback loop. By monitoring and controlling the radiant output of the SRCA source, changes due to Spectralon reflectance degradation, lamp output degradation, air/vacuum temperature shifts and zero gravity effects on halogen lamp

operation should be minimized. Two SiPDs are used for the source control circuitry, one for each set of redundant control electronics.

2) Constant Current Control Mode: The secondary mode of source control is to provide the SRCA lamps with a constant current. Both sets of redundant source control electronics are capable of controlling in the constant current mode.

6.0.1.3.2 IR Source: The Design for the IR Source is simply a block of resistive material coated with high emissivity paint whose temperature can be uniformly controlled to 390K ± 5 K through resistive heating. The IR source will only be operated during the spatial calibration mode of the SRCA.

6.0.1.3.3 Filter Wheel: The source filter wheel design has six positions each of which is selectable upon command. Three of the positions are occupied by order filters, one position is dedicated to the IR/SW dichroic beamcombiner, another is occupied by a neutral density (ND) attenuation filter and the final position is an open position.

1) IR/SW Dichroic Beamcombiner: Consists of a single layer of tin-doped indium oxide (ITO) which reflects the IR and transmits the short waves, combining the two into a single optical beam. The dichroic filter is selected only during spatial calibration.

2) Order Filters: The MODIS spectral bands each have their own bandpass filters and therefore would not normally require order filtering. However, order filters are required by the intrinsic silicon detectors (standard or reference detector and the didymium filtered) used for spectral calibration mounted near the exit plane of the monochromator. For each spectral band the diffraction grating will be positioned so that wavelength λ will be passed through the exit slit of the monochromator; however additional wavelengths corresponding to higher orders ($\lambda/2$, $\lambda 3$, $\lambda/4$ and etc.) will also be passed through the monochromator. If these additional wavelengths happen to fall within the response bandpass of the silicon reference detectors then the reference signals will be corrupted. Three order filters will be required to cover the MODIS spectral bands between 0.4 µm and 1.0 µm, the response band pass for typical intrinsic silicon detectors. The reflective bands operating beyond 1.0 µm (Bands 5,6,7 & 26) do not require order filtering since intrinsic silicon detectors have no response at these wavelengths.

3) Neutral Density Filter: In order to optimize the radiance levels for all bands and for all modes of calibration, an approximately 50% transmitting neutral density filter is used in conjunction with the varying lamp configurations.

6.0.1.3.4 Monochromator Entrance: The Monochromator Assembly's entrance wheel has three positions each of which is selectable upon command. One position is dedicated to the monochromator's entrance slit which is selected during spectral calibration. The remaining two positions are identical and provide an open path used during radiometric and spatial calibration.

6.0.1.3.5 Monochromator Exit / Reference Detectors: The Monochromator Assembly's exit wheel design also has three positions each of which is selectable upon command. The spectral calibration position is dedicated to the monochromator's exit slits consisting of the main exit slit which is view by MODIS and an offset slit behind which the didymium filtered detector is located. This detector will be used for spectral calibration of the monochromator itself; correlating grating orientation with spectral output by sensing the spectral profile of the didymium glass over the 0.4 µm to 1.0 µm region. A second unfiltered detector located in the Collimator optics (behind the main exit slit) will serve as a reference during spectral calibration of the MODIS VIS and NIR bands to remove the inherent spectral shape of the monochromator due to the source spectral shape, grating efficiency , and etc. from the spectral response measurements of the MODIS bands. An open position will be selected during radiometric calibration. The knife edges of this open position will also be used to obtain along-scan spatial registration information. The final wheel position is for the along-track spatial registration reticle.

6.0.1.3.6 Collimator Assembly: A two-mirror Cassegrain telescope design is used to collect the radiant output of the Monochromator/Relay Assembly, collimate and direct the radiance onto the MODIS scan mirror via a fold mirror. The exit slit and spatial reticle patterns located at the exit plane of the Monochromator Assembly are imaged onto the MODIS focal planes. The diameter of the collimated output is 3.5 inches (one-half the diameter of the MODIS entrance aperture).

6.0.1.4 PERFORMANCE REQUIREMENTS.

The performance requirements for each calibration mode of the SRCA are as specified below.

a .Radiometric calibration mode. The SRCA shall provide radiometric calibration for all the VIS, NIR and SWIR bands to within 5% (1σ) accuracy. Primary roles are: 1) provide transfer of MODIS radiometric calibration, preflight to on-orbit; and 2) provide intra-orbital, relative calibration with absolute calibration being provided by the Solar Illuminated Diffuser Assembly.

b. Spatial calibration mode. The SRCA shall determine spatial band-to-band registration to within 0.15 IFOV (goal of 0.1 IFOV) for all spectral bands. However, in-flight spatial registration is only required between focal planes and not between every band combination since the required measurement accuracy may be achieved using correlation with prelaunch, along-track and along-scan band-to band registration data.

c. Spectral calibration and self-calibration mode. The SRCA shall determine the shift of spectral band center for all VIS, NIR and SWIR bands. The measurement shall be accurate within 1.0 nm (1σ) and repeatable within 0.5 nm (1σ) for the shortest wavelength spectral band. The accuracy and repeatability requirements shall scale linearlywith wavelength for other spectral bands below 1.0 μm; there are no NASA system requirements specified for measurements of spectral bands greater than 1.0 μm. Correlation with prelaunch, spectral calibration data shall be used to achieve the required measurement accuracy. The SRCA shall be spectrally self-calibratable to the degree of accuracy required to achieve the requirements specified for the spectral calibration mode.

6.1.2 SRCA PREFLIGHT RADIOMETRIC CALIBRATION

6.1.2.1 TOP LEVEL DESCRIPTION. After the MODIS has had its Gain, Offset and DC Restore values set, each MODIS reflective band, channel (Bands 1-19, & 26) is radiometrically calibrated using the 100 cm Spherical Integrating Sphere (SIS). At the same or very near in time and under similar conditions (same focal plane temperatures, etc.) as the MODIS radiometric calibration, the SRCA will be radiometrically calibrated by measuring the response of MODIS (each reflective band, channel) to the SRCA's radiant output. This calibration of the SRCA using the MODIS as a transfer vehicle will be performed for all the different SRCA radiance levels. For each SRCA radiance level, a corresponding effective spectral radiance will be determined from the inverse of the MODIS Calibration Function and the MODIS Digital Response Value.

6.1.2.2 CALIBRATED MODES OF THE SRCA SOURCE. The radiometric calibration of the SRCA, as described above, will be performed for different modes of SRCA operation (primary and redundant SRCA source electronic controller; and radiance feedback and constant current modes of source lamp control). In addition, the spare lamps within the SRCA's Spherical Integrating Source must be calibrated as well. Normally, the SRCA source will operated using the Primary Electronic Source Controller in the radiance feedback lamp control mode with a fixed sequence of lamp configurations which does not include the redundant lamps. However, the redundant modes of SRCA source operation and spare lamps must be exercised and even calibrated to some degree. If all possible modes of source operation were to be considered, the task would be enormous; without going into all the details there are 88 different combinations of lamp configurations (spares included), attenuation filters (clear or ND for two of the levels), control electronics, and lamp control modes. Table 1 lists the various SRCA source configurations which, as a minimum, must be radiometrically calibrated and periodically exercised.

Table 6.1 lists only 20 of the possible 88 combinations of SRCA source configurations. The 20 configurations listed are felt to represent the minimum number of configurations required to adequately calibrate and exercise the SRCA source assembly. A number of assumptions and insights were used to determine the 20 source configurations; these are:

a. The desired hierarchy of Controller and Mode configurations are respectively: Primary Controller in Radiance Feedback Mode; Redundant Controller in Radiance Feedback Mode; Primary Controller in Constant Current Mode; and Redundant Controller in Constant Current Mode. There is no difference between primary and redundant controllers.

b. The Neutral Density (ND) filter is only required with the single 10 Watt and single 1 Watt lamp configurations to provide adequate radiance levels without saturating particular MODIS spectral bands.

c. The #1 10 Watt lamp will be operated the most and therefore, is most likely to be the first lamp to fail. It is this assumption that drives the calibration of the spare 10 watt lamp as a replacement for the #1 10 watt lamp. If either the #2 or #3 10 watt lamps are actually the first to fail, then the lamp configurations using the spare lamp will not be calibrated on the ground. However, the SRCA calibration can be updated at that time using the MODIS response to the SRCA and the Solar Illuminated Diffuser as will routinely be done anyway. Remember, after the SRCA transfers MODIS calibration pre-launch to on-orbit, its primary function is to track changes in MODIS calibration on an intra-orbit time scale.

6.1.2.3 PRELIMINARY ALIGNMENT DISPLAY REQUIREMENTS. Prior to performing a radiometric calibration of the SRCA radiant output levels or simply performing a check of MODIS calibration using the already calibrated SRCA, a simple check should be performed to verify the SRCA is functioning, the MODIS detector channels are responding and the MODIS Digital Response Signal is properly centered in the Data Frame collect window to be used by the data collection software. These checks can be accomplished by performing the following tasks.

a. Turn on a single 10 watt lamp in the SRCA source

b. Verify via telemetry that the SRCA is properly configured for radiometric calibration with a single 10 watt lamp operating nominally (check lamp current, voltage and radiance detector signal).

c. Display the digital response of various MODIS bands, channels as a function of Data Frames. Verify proper signal levels and data frame location.

6.1.2.4 DATA COLLECTION. For a given SRCA source configuration, digital data will be collected over the 12 data frames allocated to the SRCA for each detector channel for MODIS bands 1-19 & 26 for a total of N scan lines (data base parameter, currently assumed to be 50). The data will be tagged with the following information:

a. MODIS Band and Channel numbers

b. Test type: SRCA calibration or MODIS calibration check

c. Date and time

d. SRCA lamp configuration

e. SRCA attenuation filter: clear or ND

f. SRCA source controller: Primary or Redundant

g. Source control mode: Radiance or Current

TABLE 6.1. SRCA SOURCE CONFIGURATIONS

Lamp Configuration						Attenuation Filter	Electronic Controller	Control Mode
10 Watt				1 Watt				
#3	#2	#1	S	#1	S			
X	X	X				CLEAR	PRI	RAD
	X	X				CLEAR	PRI	RAD
		X				CLEAR	PRI	RAD
		X				ND	PRI	RAD
				X		CLEAR	PRI	RAD
				X		ND	PRI	RAD
X	X		X			CLEAR	RDT	RAD
	X		X			CLEAR	RDT	RAD
			X			CLEAR	RDT	RAD
			X			ND	RDT	RAD
					X	CLEAR	RDT	RAD
					X	ND	RDT	RAD
X	X	X				CLEAR	PRI	CUR
	X	X				CLEAR	PRI	CUR
		X				CLEAR	PRI	CUR
				X		CLEAR	PRI	CUR
X	X		X			CLEAR	RDT	CUR
	X		X			CLEAR	RDT	CUR
			X			CLEAR	RDT	CUR
					X	CLEAR	RDT	CUR

6.1.3 RADIOMETRIC CALIBRATION ALGORITHM.

The calibration algorithm is quite simple. In the radiometric calibration mode, the SRCA illuminated field covers 5 1Km FOV in the scan direction. Therefore, the response of each unsaturated MODIS detector channel will look like a rounded hump or pulse spread over up to 7 data frames (see Figure 6.2).

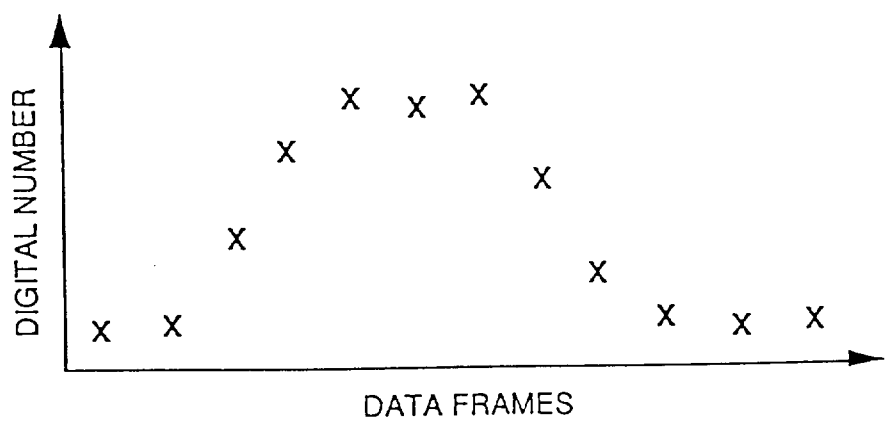


Figure 6.2 Typical Response to SRCA Calibration Source.

The top of this MODIS calibration response pulse will not be flat due to detector channel noise, SRCA source instability, SRCA source illumination non-uniformities, and translation of the SRCA aperture projection at the MODIS entrance aperture causing slight spectral response changes in MODIS. To determine a single digital value for each channel's calibration response pulse, the measured digital values will be averaged for X data frames (data base parameter, assume 3) about the mid data frame centered between the Y% response points (data base parameter, assume 30). This pulse averaging will be done for each of the N scans (data base parameter, assume 50) of data collected for each detector channel. From the N averaged pulse values, statistics will be determined (average and standard deviation). The statistics determined for each detector channel will be tagged with the following and logged into a history file:

a. Date and time

b. SRCA lamp configuration

c. SRCA attenuation filter: clear or ND

d. SRCA source controller: Primary or Redundant

e. Source control mode: Radiance or Current

If the test type is "SRCA Calibration", the corresponding effective radiance for a particular SRCA source configuration is determined for each detector channel using the inverse of the MODIS calibration function determined using 100 cm SIS data and the averaged MODIS digital response values to the SRCA source configuration just obtained. This effective radiance calibration values are then placed in a "standard" calibration file. Figure 3. illustrates the data collection and algorithm reduction for the SRCA radiometric calibration.

6.1.4 REQUIRED DATA

6.1.4.1 DATA BASE PARAMETERS. The required data base parameters are included in the SRCA Radiometric Calibration Flow illustrated in Figure 3 (shown in bold). The data base parameters are described below:

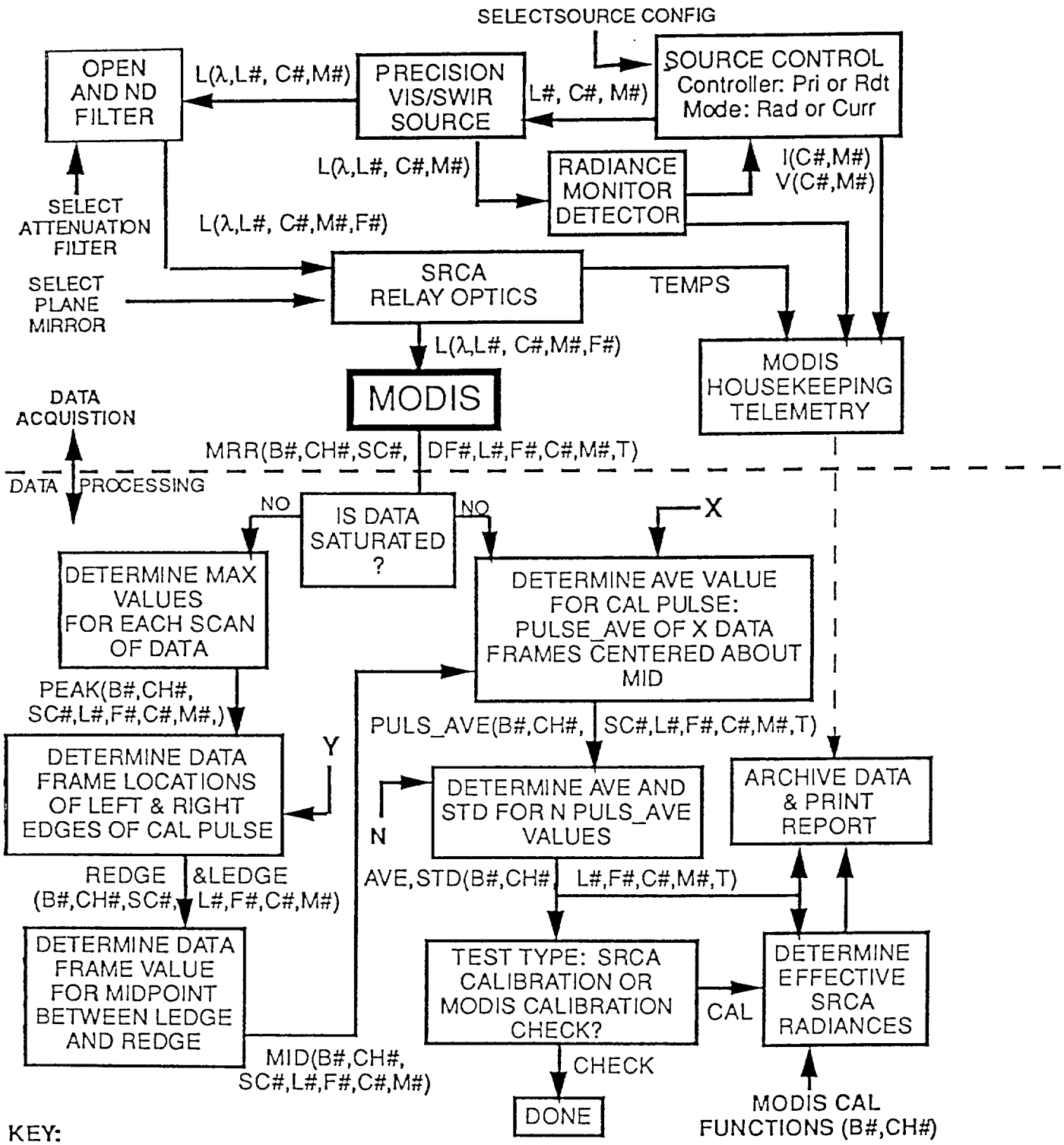
a. N is the number of scans for which the MODIS response to the SRCA radiant output is collected for each SRCA source configuration. N is currently assumed to be equal to 50

b. Y is the fraction of peak response value which will be used to define the left and right edges of the Calibration Response pulse for each band and channel. Y is currently assumed to be equal to 0.30.

c. X is the number of data frames about the midpoint of the Calibration Response pulse which is be used in the calculation of an average Calibration Response pulse value for each scan of data collected for each band and channel. X is currently assumed to be equal to 3.

d. MODIS Calibration Functions for each Band and channel are determined from calibration data obtained using the 100 cm SIS. These calibration functions are required to determine the effective radiance values for each of the SRCA radiance level and source configuration. Using the average (AVE) digital response for each band and channel and the inverse of the MODIS Calibration Functions, the effective radiances for each SRCA radiance level are determined.

e. Test type: Test type can either be a SRCA Radiometric calibration or a MODIS Calibration Check. If a SRCA Calibration, then effective radiances are calculated for the SRCA radiance levels. If a MODIS calibration check then the MODIS digital response values to the SRCA radiance levels are averaged and compared to previous measurements.



KEY:

B# = MODIS Band No.	SC# = Scan No.	
CH# = Detector Channel No.	L = Radiance	T = Time & Date
DF# = Data Frame No.	V = Voltage	I = Current
L# = Lamp Config No.	N = No. of Scans Collected	
M# = Source Control Mode	Y = Fraction of Peak Value Defining Pulse Edges	
C# = Source Controller Type	X = No. of Data Frames used in Puls_AVE	
MRR = MODIS Radiometric Response (Digital)		

Figure 6.3 Typical SRCA Radiometric Calibration Flow

6.1.5 COMMAND IMPLEMENTATION (TBD)

This section shall address the command sequences required to:

- OBC subsystem configuration setup
- OBC subsystem preparation sequence
- OBC execution sequence
- OBC shut down sequence

6.2.2 SRCA SPECTRAL CALIBRATION

6.2.2.1 TOP LEVEL DESCRIPTION. After MODIS has had is Gain, Offset and DC Restore values set, each MODIS spectral band and channel shall have its spectral bandpass characterized (center wavelength, bandwidth and shape) using the Ground Support Equipment (GSE) double-monochromator. At the same or very near in time and under similar conditions, the SRCA will be used to measure the center wavelength for each detector channel of the reflective bands (bands 1-19 & 26). Since the SRCA only provides partial aperture illumination of MODIS, it is expected the center wavelength values measured using the GSE monochromator and the SRCA monochromator will differ slightly. The center wavelength values measured with the GSE monochromator will used as absolute measured values. The SRCA measured values will be used to determine relative changes in the center wavelengths of MODIS Bands 1-19 & 26. The values measure using the SRCA monochromator will have a correction factor applied in order to equate with the GSE measured values. There will be a unique SRCA correction or spectral calibration factor determined for each detector channel for Bands 1-19 & 26. This SRCA spectral correction will then be applied to subsequent center wavelength measurements using the SRCA.

6.2.2.2 PRELIMINARY ALIGNMENT DISPLAY REQUIREMENTS. Prior to performing a spectral calibration (center wavelength) calibration of MODIS using the SRCA, a simple check should be performed to verify: the SRCA is functioning; the MODIS detector channels are responding; and the MODIS Digital Response Signal is properly centered in the Data Frame collect window to be used by the data collection software. These checks can be accomplished by performing the following tasks.

a. Turn on a single 10 watt lamp in the SRCA source and verify proper operation (lamp current, voltage and radiance detector signal).

b. Command the slit reticles to be positioned at the entrance and exit of the monochromator. Verify via telemetry that the slits have been positioned and the filter wheel and grating/mirror mount remain at their home positions (open position and plane mirror position, respectively).

c. Display the digital response of various MODIS bands and channels as a function of Data Frames. Verify proper signal levels and data frame location. Note, the exit slit of the SRCA monochromator fills approximately 1/2 of a 1Km FOV in the along scan direction.

6.2.2.3 DATA COLLECTION. The SRCA will be configured for spectral calibration: slit reticles positioned at both entrance and exit of monochromator; diffraction grating selected; and one of three different order filters selected at source filter wheel. The SRCA source will be stepped through the following four lamp configurations in order: 3 - 10 watt lamps; 2 - 10 watt lamps; 1 - 10 watt lamp; and 1 - 1watt lamp. Radiance levels will always be changed in a descending order by turning lamps off. In general, each of the MODIS bands 1-19 & 26 will required a different SRCA configuration (lamp configuration, order filter and set of grating angles) during the spectral calibration data collects. For a single SRCA lamp configuration, only a subset of Bands 1-19 & 26 will have the proper signal levels during the spectral calibration and each band requires a unique combination of order filter selection and range of grating angles. Therefore, in general, the digital data for only a single band will be collected at any one time (Note, there may be one or two exceptions where two bands require the same source and filter configurations and the required range of grating angles overlap slightly).

With the SRCA properly configured for spectral calibration (center wavelength) of a particular MODIS band, the diffraction grating shall be rotated in small steps to change the spectral output of the SRCA in small wavelength increments. At a particular grating step position (SRCA wavelength output), digital data for all channels of the particular band shall be collected for NDF data frames over NSC scan lines. NDF and NSC are data base parameters: NDF can be assumed to be equal to 3 since the monochromator slit width only fills 1/2 of a single 1Km FOV and NSC will be function of the MODIS spectral band being calibrated in order to optimize signal to noise.

In addition to the MODIS digital response data collected, digital data will be collected from two silicon photodiodes during spectral calibration (data will be part of science and engineering telemetry packets). The Didymium Filtered, Self-Calibration Diode data will be used to calibrate the SRCA monochromator itself, correlating spectral output with diffraction grating angle. The diode resides behind an offset slit at the monochromator exit and is used to measure the center wavelength of the Didymium absorption filter's pass bands in an analogous manner to a MODIS detector channels and its own passband filter. Just like the MODIS spectral bands, the Didymium passbands require a unique SRCA configuration during spectral calibration (Lamp configuration, order filter selection and range of grating angles). The measurement of three Didymium pass bands will be made for each SRCA lamp configuration. The Standard or Reference Diode data will be collected when ever a MODIS or Didymium band data is being collected. The Standard diode data is used to normalize the MODIS and Didymium signals to eliminate the inherent spectral shape of the SRCA source and monochromator itself. The Standard diode is located in the SRCA collimator assembly behind the main exit slit of the monochromator.

The digital data collected will be tagged with the following information:

a. Band and Channel numbers

b. Test Type: SRCA calibration (determination of spectral correction factors) or MODIS calibration check

c. Date and Time

d. SRCA lamp configuration

e. SRCA filter selection: order filter 1, 2 or 3

f. Grating Angle

6.2.3 SRCA SPECTRAL CALIBRATION IN-FLIGHT (PREFLIGHT) ALGORITHMS

6.2.3.1 Basic Equations.

The following basic grating equations will prove useful in the understanding the discussion on the Spectral Calibration algorithm.

The full grating equation written in terms of wavelength (λ) is given by:

$$m\lambda = A \cos(\phi) (\sin \theta i \pm \sin\theta d) \qquad \text{(Eqn. 1)}$$

Equation 1 can be expressed in slightly different forms when applied to the two specific configurations used within the SRCA monochromator.

1.) SRCA Main Exit Slit view by MODIS spectral bands (incident and diffracted rays symmetric about the optical axis):

$$m\lambda = A \cos(\phi)[\sin(\beta-\theta g) \pm \sin(\beta+\theta g)] = 2A \cos(\phi) \sin(\theta g) \cos(\beta) \qquad \text{(Eqn. 2)}$$

2.) SRCA Offset Exit Slit viewed by Didymium pass bands (diffracted ray offset angularly with respect to the symmetric position; $\theta d = \beta+\theta g +\Delta$):

$$m\lambda = A \cos(\phi)[\sin(\beta-\theta g) \pm \sin(\beta+\theta g+\Delta)] \qquad \text{(Eqn. 3)}$$

where

(-) sign is used for SRCA configuration, $\beta > \theta g$

m = grating order

A = grating groove spacing

ϕ = out of plane angle of incidence about grating normal

θi = angle of incidence about grating normal in the plane of diffraction $=|\beta-\theta g|$

θd = angle of diffraction about grating normal in the plane of diffraction $=\beta+\theta g$

θg = angle between grating normal & bisector between incident & diffracted rays in diffraction plane

β = 1/2 the included angle between the incident and diffracted rays in the plane of diffraction

Δ = Angular offset between Didymium offset and main exit slits

Figure 6.4 will aid in the definition of terms.

6.2.3.2 Self Calibration. Upon inspection of Eqn. 2, it is apparent that the variables β, A, θg and φ are all subject to change due to thermal expansion/contraction, vibration, zero gravity release, and etc. which will result in changes in the SRCA spectral output, $\Delta\lambda srca$. Two of these parameters, A, and φ will be held to tight tolerances by design. θg is really equal to $\theta motor + \theta offset$, the sum of the grating motor angle and any rotational offset of the motor with respect to the monochromator assembly. $\theta motor$, as a function of number of motor steps, will be characterized very accurately and will be highly repeatable. Therefore, there remains two variables, β and $\theta offset$, which must be accurately determined in order to relate the spectral output of the SRCA to the grating motor's angular position. This is where the self-calibration capability of the SRCA monochromator comes into play.

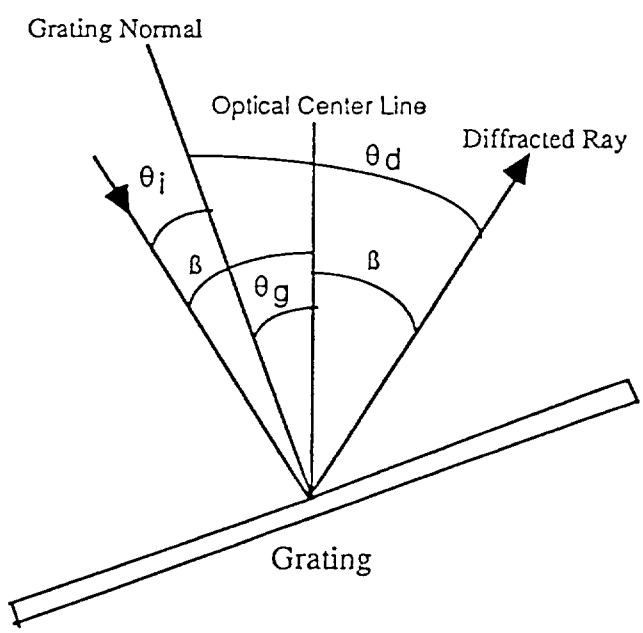


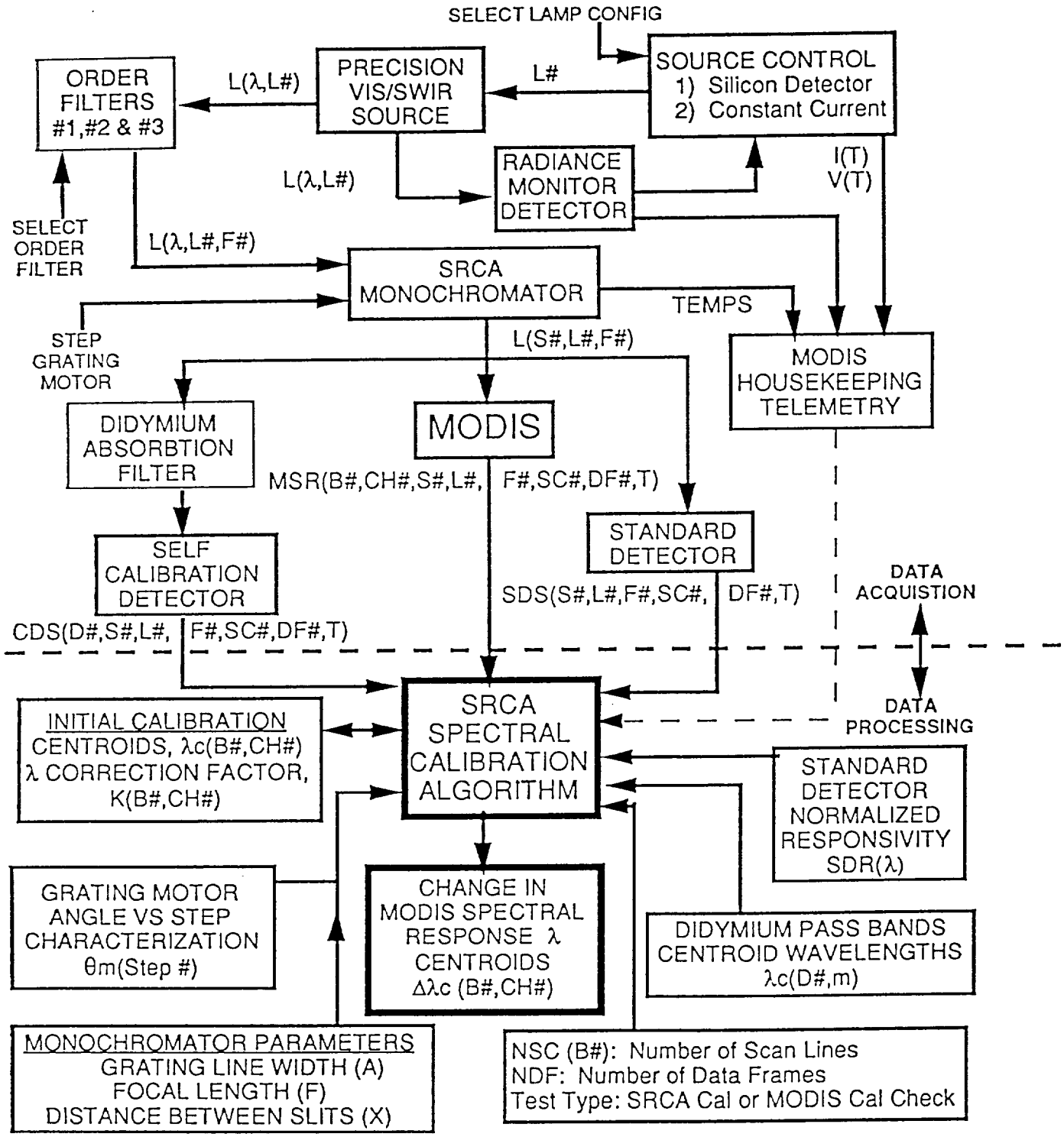
Figure 6.4 Definition of grating terms

Self-calibration of the SRCA's spectral output plays an important role in meeting the requirements for in-flight spectral calibration of the MODIS instrument. A SiPD placed behind a didymium glass filter which has distinct and sharp transmission bands will be used for spectral calibration of the SRCA monochromator itself; correlating grating orientation with spectral output by sensing the spectral profile of the didymium glass over the 0.4 to 1.0 μm region. The center wavelength measurements of the didymium transmission passbands will be done in the same manner as the measurements for the MODIS bands. That is, computing the centroid of the spectral bandpass based on data samples exceeding a specified amplitude threshold. The bandpass centroid approach is the least sensitive to the measurement noise introduced by the grating's positional uncertainty which is greatest on the slopes of spectral bandpass being measured. Only two of the didymium transmission bands are utilized (Didymium Bands D2 and D3, with D3 being used in both the 2 and 3 diffraction order). To minimize spectral measurement uncertainties introduced due to thermal changes of the SRCA over time of operation, the center wavelength measurements of the Didymium bands are repeated for each SRCA source configuration used.

The offset distance between the Didymium diode exit slit and the main exit slit which intersects the optical axis is 6 mm. To maintain image quality, it is desirable to minimize the offset distance. A minimum offset of 6 mm was determined for the didymium/diode exit slit, taking into account the size of the diode's package, width of the main exit slit, and adequate margin. Both exit slits will be cut into the same reticle pattern to prevent any physical shifts and thus spectral errors in the SRCA's self-calibration after initial calibration preflight.

6.2.3.3 Spectral Calibration Algorithm. The spectral calibration algorithm is quite involved. A brief verbal description is given below. However, the algorithm is probably best understood by referring to Figures 5 and 6. The top level flow for spectral calibration using the SRCA is shown in Figure 5. Illustrated is the flow of various parameters required (both collected data and data base parameters) into the Algorithm for SRCA Spectral Calibration. Figures 6-1, 6-2 & 6-3 provide a more detailed look at the Spectral Calibration Algorithm.

Through a complex sequence of SRCA configurations and step rotation of the diffraction grating, spectral profiles of the MODIS and Didymium bands (for self calibration) are measured as a function of grating steps. A reference signal is also collected from the Standard Detector which will be used to normalize the spectral profiles. Next the spectral profiles are converted to be a function of grating motor angle using data base information correlating grating motor angle with step number. The diffraction order used during the measurements of the spectral profiles is next determined from the order filter and grating angle information with which the data is descriptively tagged. The Calibration Detector Signal (Didymium) is normalized using the Standard Detector Signal after both signals have been averaged over the Number of Data Frames (NDF) and the Number of Scan Lines (NSC). This normalization is complicated somewhat by the fact that each of the detectors measures the same wavelength spectrum at different grating motor angles due to the offset between the two. If the monochromator self calibration was already completed, then it would be easy to derive an expression for the difference in grating angle which provides the same wavelength spectrum at each detector. Since the calibration of the monochromator can not be done until after the Calibration Detector Signal is normalized, the difference in grating angle has been approximated with expression written in terms of physical offset between the detectors only. If this approximated expression is found to be inadequate, the process of approximation, normalization, & self-calibration of the monochromator will be done iteratively until the approximation converges. Note, the detector responsivities and the difference in grating efficiencies are not included in the normalization of the Calibration Detector Signal since these errors should not only be small but should also be constant; therefore, will not significantly effect the repeatability of the spectral measurement. Remember, the SRCA is only used to measure change. Once the Calibration Detector Signal has been normalized, the centroid grating motor angles are determined for each of the three Didymium pass bands at each lamp configuration used. Using these Didymium centroid grating motor angles, it is possible to solve for β and θoffset to a high degree of accuracy. Once β and θoffset have been determine, then it is now possible to relate grating motor angle to spectral (wavelength) output of the SRCA. The validity



KEY:

B# = MODIS Band No.	D# = Didymium Band No.	F# = Filter No.
CH# = Detector Channel No.	m = Diffraction Order	SC# = Scan No.
S# = Grating Motor Step No.	L = Radiance	V = Voltage
DF# = Data Frame No.	L# = Lamp Config No.	I = Current
λc = Centroid Wavelength	CDS = Calibration Detector Signal	
SDS = Standard Detector Signal	MSR = MODIS Spectral Response (Digital)	
NDF = No. of Data Frames	NSC = No. of Scan Lines	T = Time & Date

Figure 6.5 Spectral Calibration Plan

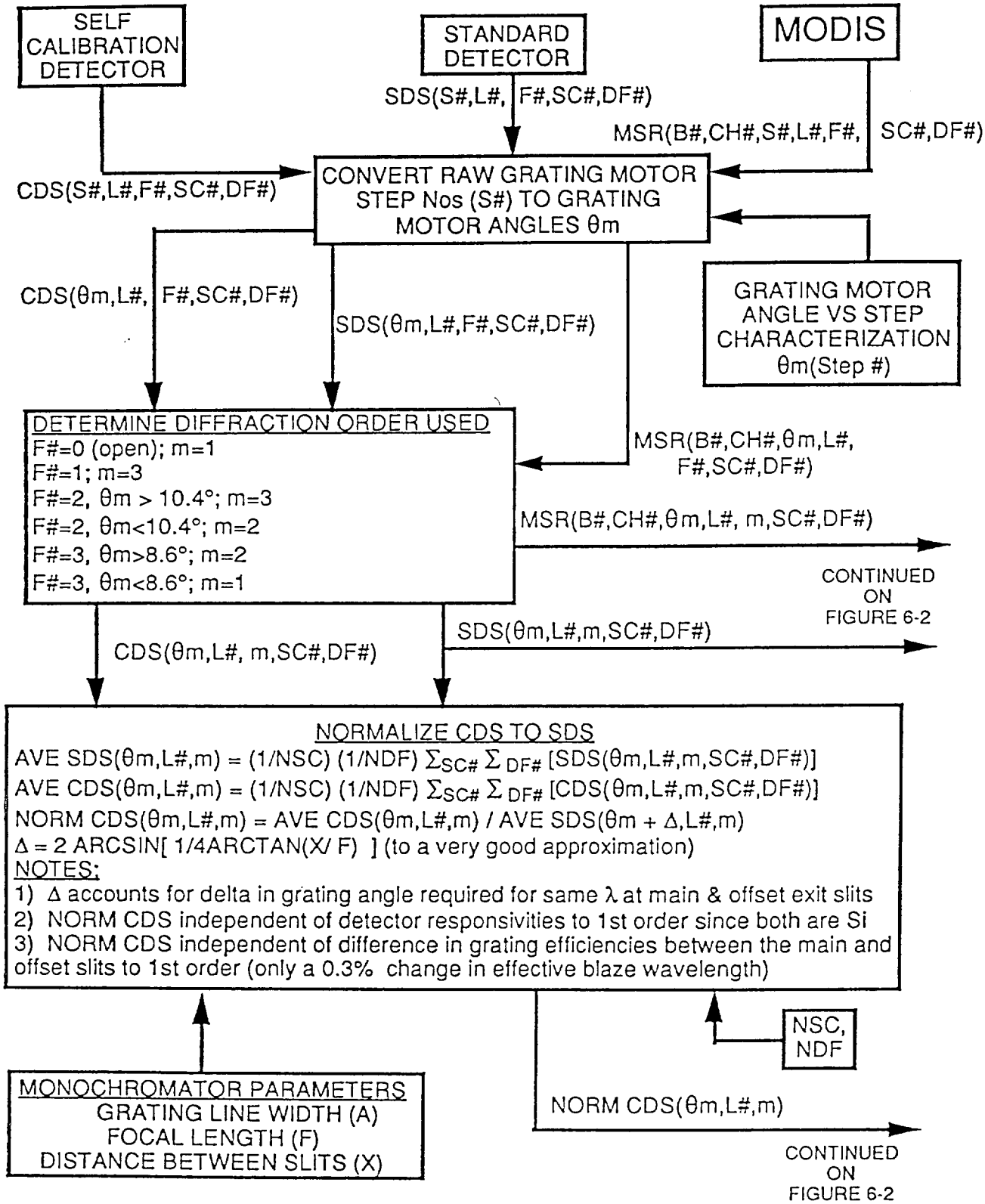


Figure 6.6a Spectral Calibration Algorithm

CALCULATE TOTAL AVERAGE MSR NORMALIZED TO SDS

$$\text{NORM MSR}(B\#,CH\#,\theta m,L\#,m,SC\#,DF\#) = \frac{\text{MSR}(B\#,CH\#,\theta m,L\#,m,SC\#,DF\#)}{\text{SDS}(\theta m,L\#,m,SC\#,DF\#)}$$

$$\text{TOTAL AVE MSR}(B\#,CH\#,\theta m,L\#,m,) = (1/NSC)(1/NDF)\,\Sigma_{SC\#}\Sigma_{DF\#}\,[\text{NORM MSR}(B\#,CH\#,\theta m,L\#,m,SC\#,DF\#)]$$

SDS(θm,L#,m,SC#,DF#)

CONTINUED FROM FIGURE 6-2

MSR(B#,CH#,θm,L#,F#,SC#,DF#)

NSC, NDF

TOTAL AVE MSR(B#,CH#,θm,L#, m)

CONTINUED ON FIGURE 6-3

ß (L#); OFFSET (L#)

DETERMINE

1) GRATING MOTOR ANGULAR OFFSET, θ_{offset} (L#)

2) CZERNY TURNER HALF INCLUDED ANGLE, ß (L#)

BY SIMULTANEOUSLY SOLVING FOLLOWING EQNS

Eqs 1-3: $\lambda c(D\#,m) = (A/m)\,\{\sin[\beta-\Omega m(L\#,m,D\#)-\theta_{offset}(L\#)]-\sin[\beta+\Omega m(L\#,m,D\#)+\theta_{offset}(L\#)+\delta]\}$, Where $\delta = \text{ARC TAN}(X/F)$

Eq 4: $\dfrac{\lambda c(D2,m=2) - \lambda c(D3,m=2)}{\Omega m(L\#,m=2,D2) - \Omega m(L\#,m=2,D3)} = \partial\lambda c/\partial\theta m|_{@\theta m=?}$

Eq 5: $\dfrac{(m=3) - (m=2)}{\Omega m(L\#,m=3,D3) - \Omega m(L\#,m=2,D3)} = \partial m/\partial\theta m|_{@\theta m=?}$

MONOCHROMATOR PARAMETERS
GRATING LINE WIDTH (A)
FOCAL LENGTH (F)
DISTANCE BETWEEN SLITS (X)

Ωm(L#,m,D#)

DIDYMIUM PASS BANDS CENTROID WAVELENGTHS λc(D#,m)

CONTINUED FROM FIGURE 6-1

NORM CDS(θm,L#,m)

DETERMINECENTROID GRATING MOTOR ANGLES Ωm FOR DIDYMIUM PASS BANDS

$$\Omega m\,(L\#,m,D\#) = \frac{\Sigma_{\theta m}\,[\text{Norm CDS}\,(\theta m,L\#,m)\,*\,(\theta m)\,]}{\Sigma_{\theta m}\,[\text{Norm CDS}\,(\theta m,L\#,m)\,]}$$

DIDYMIUM PASS BANDS	DIFFRACTION ORDER	θm RANGE
D2	3	9.5° - 10.2°
D3	2	6.8° - 7.4°
D3	3	10.6° - 11.4°

Figure 6.6b Spectral Calibration Algorithms

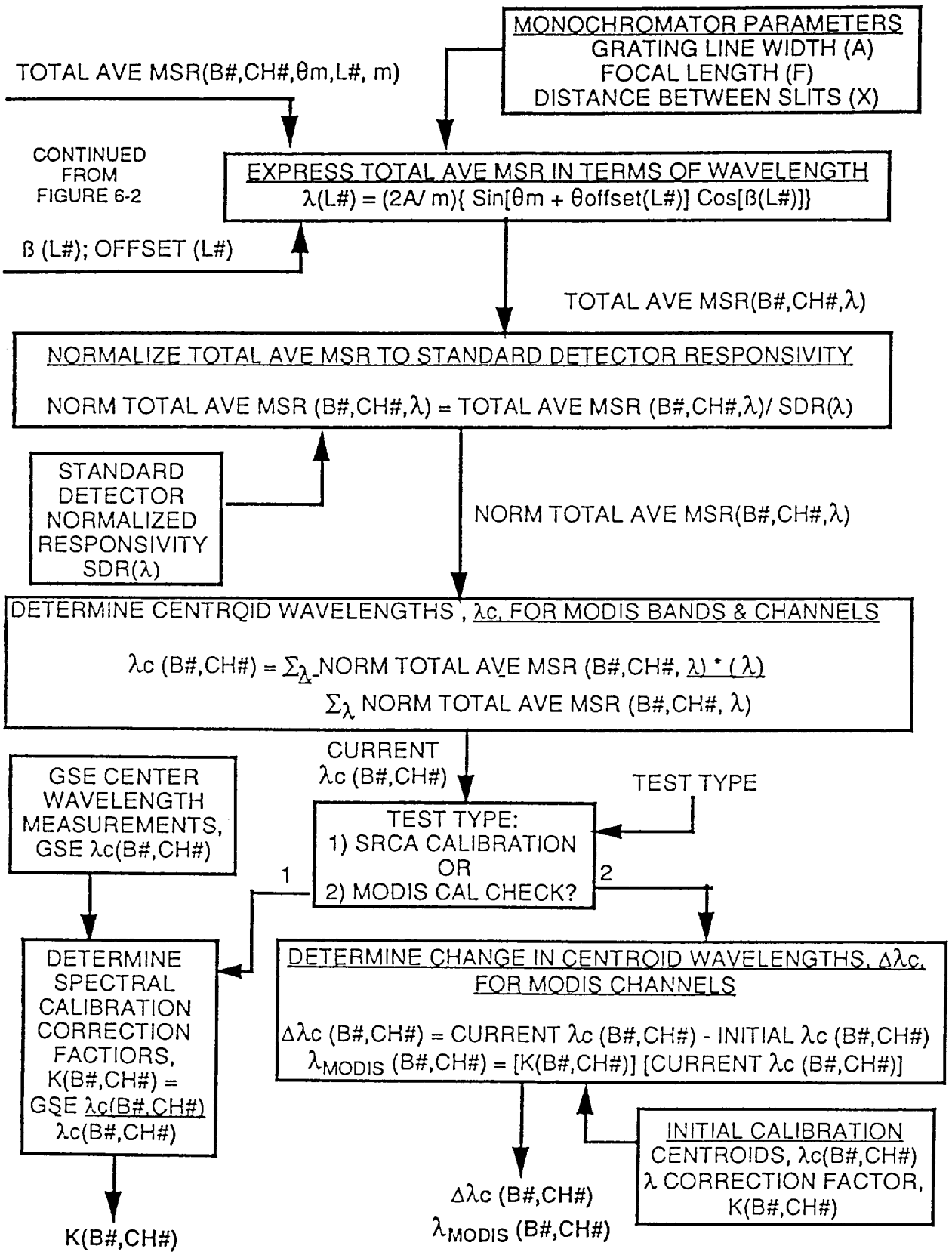


Figure 6.6c Spectral Calibration Algorithms

of the approximation made in normalizing the Calibration Detector Signal should now be checked. With the self-calibration portion of the algorithm complete, the measured digital response for each of the MODIS bands and channels can be normalized using the Standard Detector Signal and its spectral responsivity (data base parameter) and averaged over the number of scan lines collected (NSC). Using these normalized and averaged MODIS response values, the centroid wavelengths for each MODIS band and channel are determined. If the test type is an SRCA calibration, a spectral correction or calibration factor (K) is determined which equates the SRCA measured centroid wavelengths with the GSE measured center wavelengths for each MODIS band and channel. If the test type is a MODIS calibration check, the change in SRCA measured centroid wavelengths are determined for each MODIS band and channel.

6.2.4 REQUIRED DATA

6.2.4.1 DATA BASE PARAMETERS. The required data base parameters are included in the SRCA Spectral Calibration Flow illustrated in Figure 6.5 as well as the pictorial outline of the Spectral Calibration Algorithm shown in Figure 6.6. The data base parameters are described below:

a. NSC is the number of scans for which the MODIS Spectral Band Response to the SRCA monochromator output is collected for each grating position (or wavelength). NSC will be a function of MODIS spectral band and will be chosen to optimize the signal to noise of the spectral measurement.

b. NDF is the number of data frames collected of the 12 data frames allotted for the SRCA for each scan line during spectral calibration. Since the exit slit of the SRCA monochromator only fills approximately 1/2 of a single 1Km FOV, no more than 3 data frames should be required.

c. Normalized spectral responsivity of the Standard Detector will be used for normalization of the MODIS spectral response signals and the Calibration Detector (Didymium) signals.

d. Monochromator parameters: Grating Line Width (A); SRCA monochromator focal length (F); physical distance between monochromator's main and offset (didymium) exit slits (X)

e. Centroid wavelengths for the Didymium pass bands measured during subassembly testing of the SRCA.

f. Grating motor characterization relating motor steps to motor angle.

g. GSE measured center wavelengths for detector channels of MODIS bands 1-19 & 26. These values will be used to determine spectral correction factors to be used equate SRCA and GSE measured values.

h. Spectral Correction Factors: factors used to equate SRCA and GSE center wave-length measurements. Used to correct SRCA center wavelength measurements (due to its partial aperture illumination).

i. Test type: either SRCA calibration or MODIS calibration check. If SRCA calibration, the spectral correction factors equating SRCA and GSE center wavelength measurements for each SRCA detector channel will be determined. If MODIS calibration check, the spectral change in the center wavelengths of the measured MODIS bands will be determined.

6.2.4.2 REPORT FORMAT REQUIREMENTS. The report should provide the center wavelengths for each band, channel measured during a particular calibration run. Band statistics (averages and standard deviations) of the individual detector channel values should also be provided. Also the values of β and θoffset computed for the SRCA monochromator using the self-calibration data obtained using the Didymium filter detector (calibration detector) shall be reported for each lamp level. If the test type is an initial spectral calibration of the SRCA, the computed spectral correction factors used to equate the GSE and SRCA center wavelength measurements should be reported. If the test type is a calibration check of MODIS, then the change in the measured center wavelengths compared to the previous and initial SRCA spectral calibration runs

for each band and channel should be reported. Again band statistics on the change in center wavelength values should also be provided. All reported data should be tagged with the time and date of the collect.

6.2.5 COMMAND IMPLEMENTATION

This section shall address the command sequences required to:

- OBC subsystem configuration setup
- OBC subsystem preparation sequence
- OBC execution sequence
- OBC shut down sequence

6.3.2 SPATIAL CALIBRATION

6.3.2.1 TOP LEVEL DESCRIPTION. After MODIS has had is Gain, Offset and DC Restore values set, each MODIS spectral band and channel shall have its relative geometric registration characterized (along scan and track spatial response centroid values measured relative to all other bands, channels) using the Ground Support Equipment (GSE). At the same or very near in time and under similar conditions, the SRCA will be used to measure the relative geometric registration for each detector channel of the MODIS spectral bands (most bands will be measured using the SRCA, but not all). Since the SRCA only provides partial aperture illumination of MODIS, it is expected the spatial registration values measured using the GSE monochromator and the SRCA monochromator will differ slightly. However, there are additional differences between the SRCA and GSE spatial measurements. The SRCA measures centroid values for the along scan direction only; In the along track direction, a composite knife edge response function using several different detectors within a band is measured and will result in additional differences between the GSE and SRCA spatial registration measurements. The spatial registration values for each MODIS band and channel measured with the GSE monochromator will used as absolute measured values. The SRCA measured values will be used to determine changes in the relative spatial registration of entire focal planes only since it is extremely unlikely for intra-focal plane spatial changes to occur. The values measured using the SRCA will have a correction factor applied in order to equate with the GSE measured values. In the along scan direction, there will be a unique SRCA correction or spatial calibration factor determined for each detector channel of the spectral bands measured using the SRCA. In the along track direction, there will only be a unique SRCA correction or spatial calibration factor determined for each MODIS band measured since the SRCA is only capable of measuring a band composite function in this direction. These SRCA spatial corrections will then be applied to subsequent geometric registration measurements using the SRCA.

6.3.2.2 PRELIMINARY ALIGNMENT DISPLAY REQUIREMENTS. Prior to performing a spatial calibration of the SRCA or simply performing a check of MODIS spatial registration using the already calibrated SRCA, a simple check should be performed to verify the SRCA is functioning, the MODIS detector channels are responding and the MODIS Digital Response Signal is properly centered in the Data Frame collect window to be used by the data collection software. The detector sampling phase delay may have to be adjusted in order to adequately position the detector's FOV within the along-track reticle. These checks can be accomplished by performing the following tasks.

a. Turn on a single 10 watt lamp in the SRCA VIS/SWIR source and the SRCA IR source.

b. Verify via telemetry that the SRCA is properly configured for along-scan spatial calibration with the single 10 watt lamp and IR source operating nominally (check lamp current, voltage and radiance detector signal and the IR source current and temperature).

c. Display the digital response of various MODIS bands, channels as a function of Data Frames. Verify proper signal levels and data frame location.

d. Select the along-track reticle within the SRCA; verify via telemetry.

e. Display the digital response of various MODIS bands, channels as a function of Data Frames. Verify proper signal levels and data frame location. Vary MODIS detector sampling phase delay as required to properly position the detector's FOV within the along-track reticle.

6.3.2.3 DATA COLLECTION. The SRCA will be configured for spatial calibration: open position at monochromator entrance, one of two spatial registration reticles (along scan and along track) positioned at the exit of monochromator; plane mirror selected; and dichroic beamcombining filter selected at source filter wheel. The SRCA IR source will be heated to 390 ± 5K and the SRCA VIS/SWIR source will be stepped through the following four lamp configurations in order: 3 - 10 watt lamps; 2 - 10 watt lamps; 1 - 10 watt lamp; and 1 - 1watt lamp. VIS/SWIR source radiance levels will always be changed in a descending order by turning lamps off. In general, each of the MODIS VIS/SWIR bands (Bands 1-19 & 26) will required a different SRCA VIS/SWIR source lamp configuration during the spatial calibration data collects. For a single SRCA lamp configuration, only a subset of Bands 1-19 & 26 will have the proper signal levels during the spatial calibration

6.3.2.4 Along-Scan Calibration. With the SRCA properly configured for along-scan spatial calibration (centroid measurements), the reticle shown in Figure 6.7 is placed at the focus of the SRCA and uniformly illuminated with both the IR and VIS/SWIR source.

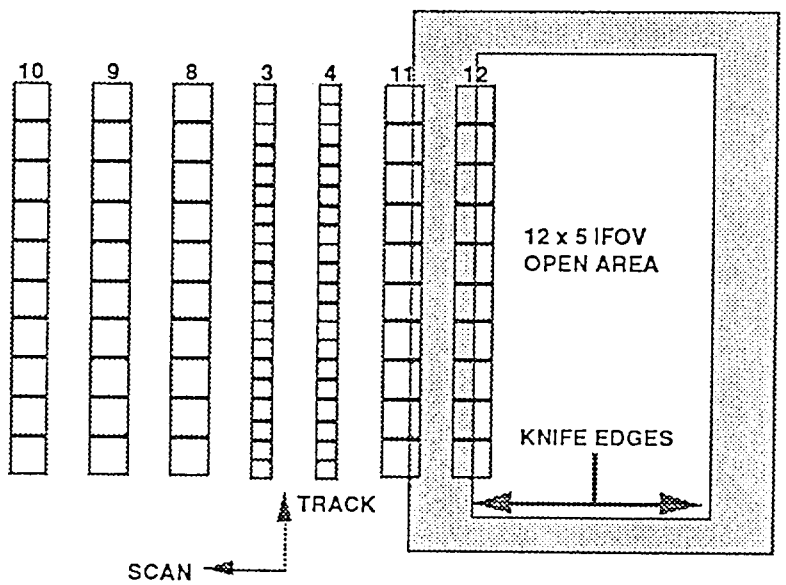


Figure 6-7. SRCA Along-Scan/Open Reticle

This is the same reticle used for the radiometric calibration mode of the SRCA. The reticle completely fills the along-track field of view for the MODIS bands and fills 5 - 1Km FOV in the along-scan direction. The leading and trailing edges of the reticle in the scan direction are knife edges. Once the proper radiance levels are established for a given set of MODIS bands, digital data is collected for all channels NDFS data frames over NSCS scan lines. NDFS and NSCS are data base parameters: NDFS can be assumed to be equal to 7 since the along scan reticle width fills 5 single 1Km FOV and NSCS will be function of the MODIS spectral bands being calibrated in order to optimize signal to noise. The MODIS detector sampling shall be delayed in a series of small equal increments in order to step the MODIS detector's field of view across the SRCA along-scan reticle. There shall be NPDS phase delay settings used in the along-scan spatial calibration measurement. NPDS is the number of phase delay settings, a data base parameter, and can be assumed equal to 10; thus resulting in 0.1 FOV size phase delay steps. At a particular detector sampling phase delay,

digital data for all channels of the particular bands being calibrated shall be collected for NDFS data frames over NSCS scan lines.

The digital data collected will be tagged with the following information:

a. Band and Channel numbers

b. Test Type: SRCA calibration (determination of spatial correction factors) or MODIS calibration check

c. Calibration Type: Along-scan or Along-track

d. MODIS detector sampling phase delay (for along scan data only)

e. Date and Time

6.3.2.5 Along-Track Calibration. With the SRCA properly configured for along-scan spatial calibration (centroid measurements), the reticle shown in Figure 6.8 is place at the focus of the SRCA and uniformly illuminated with both the IR and VIS/SWIR source.

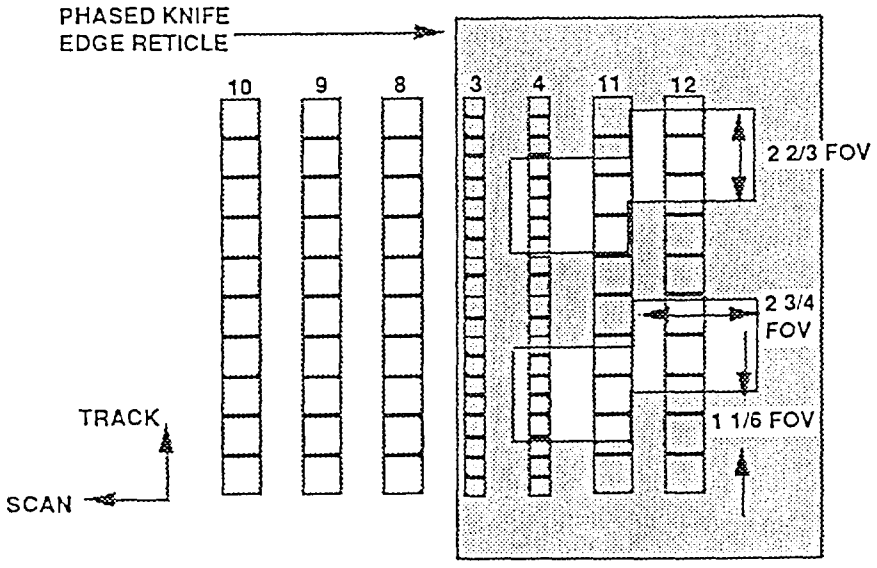


Figure 6-8. SRCA Along-Track Spatial Reticle

The reticle fills 5.5 - 1Km FOV in the along-scan direction. There are 8 knife edges located at different phased location along the track direction; each phased knife edge will intersect a different detector channel within a particular band. Once the proper radiance levels are established for a given set of MODIS bands, digital data is collected for all channels NDFT data frames over NSCT scan lines. NDFT and NSCT are data base parameters: NDFT can be assumed to be equal to 8 since the along scan reticle width fills 5.5 single 1Km FOVs and NSCT will be a function of the MODIS spectral bands being calibrated in order to optimize signal to noise. The detector sampling phase delay may have to be adjusted in order to adequately position the detector's FOV within the along-track reticle.

6.3.3 SPATIAL CALIBRATION ALGORITHM.

6.3.3.1 Along-Scan Calibration. The along-scan spatial calibration algorithm is quite simple. The algorithm is illustrated in Figure 9 which will prove helpful in understanding the following brief discussion. For all channels of each MODIS band spatially calibrated using the SRCA, NDFS data frames over NSCS scan lines will be collected. This will be repeated for NPDS different phase delay settings. The data is then averaged over the number of scan lines for each combination of detector channel, data frame sample and phase delay setting. This results in NPDS Aperture Response Functions (ARF); ARF is consistent with terminology used by Jim Young in describing spatial response centroid measurements. Next, the data for the different phase delay settings are combined into a single set of data for each detector channel called the Combined Aperture Response Function (CARF). The CARF is created by interlacing the data values from the NPDS individual ARFs according to spatial dimension for which they were collected. For example the first CARF data point is equal to the first data frame sample from the 0 FOV phase delayed ARF and corresponds to spatial dimension, X=0 FOV. The second CARF data point is equal to the first data frame sample from the 1/NPDS FOV phase delayed ARF and corresponds to spatial dimension, X=1/NPDS FOV. The third through the NPDS data points for the CARF are determined in a like manner. The NPDS+1 CARF data point is equal to the second data frame sample from the 0 FOV phase delayed ARF. The remaining data points for the CARF are determined in a similar manner until all data samples from the individual phase delayed ARFs have been combined. The spatial response centroid for that detector channel is then computed from the CARF for each detector channel.

If the test type is an SRCA calibration, a spatial correction or calibration factor (Q) is determined which equates the SRCA and GSE measured spatial centroid values for each MODIS band and channel measured using the SRCA. If the test type is a MODIS calibration check, the previously determined spatial correction factors (Q) are applied to the measured centroid values and the change in spatial centroid values determined for each MODIS band and channel measured. From the changes in spatial centroid values for each detector channel measured, an effective change in spatial registration is determined for each MODIS focal plane (VIS, NIR, SWIR, MWIR and LWIR).

6.3.4 REQUIRED DATA

6.3.4.1 Along-Scan Calibration. The required data base parameters are included in the SRCA Radiometric Calibration Flow illustrated in Figure 9 (shown in bold). The data base parameters are described below:

a. NSCS is the number of scans for which the MODIS Digital Response during along-scan spatial calibration is collected for each detector sampling phase delay setting. NSCS will be a function of MODIS the spectral band and will be chosen to optimize the signal to noise of the spectral measurement.

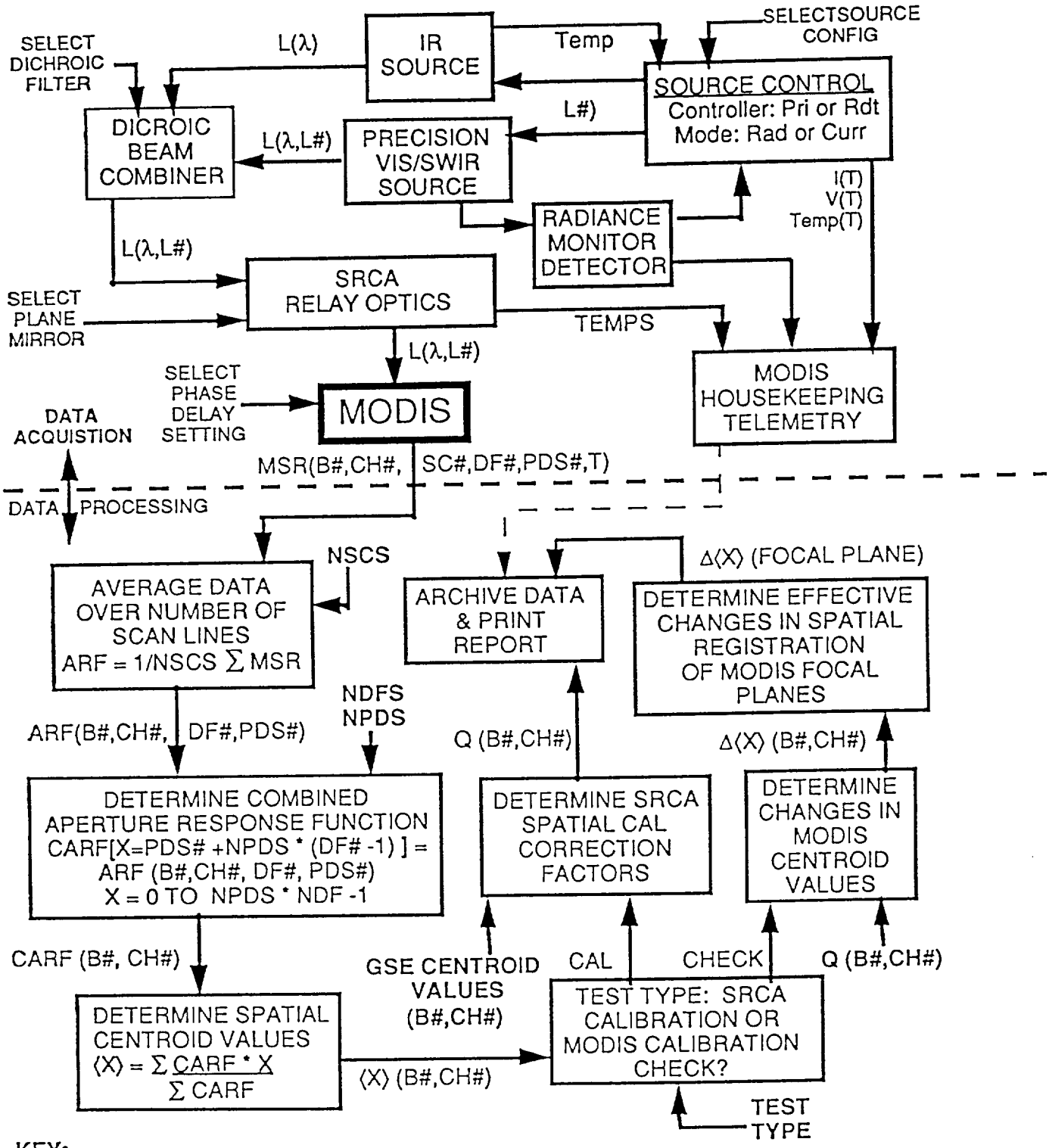
b. NDFS is the number of data frames collected of the 12 data frames allotted for the SRCA for each scan line during along-scan spatial calibration. Since the SRCA along-scan reticle fills 5 - 1Km FOVs, no more than 7 data frames should be required.

c. NPDS is the number of different phase delayed settings used for the detector sampling during the along-scan spatial calibration.

d. GSE measured centroid values for MODIS bands and channels These values will be used to determine SRCA spatial calibration correction factors to equate SRCA and GSE measured values.

e. Spatial Correction Factors: factors used to equate SRCA and GSE centroid measurements. Used to correct SRCA spatial centroid measurements (due to its partial aperture illumination).

f. Test type: either SRCA calibration or MODIS calibration check. If SRCA calibration, the spatial correction factors equating SRCA and GSE centroid measurements for each SRCA detector channel will be determined. If MODIS calibration check, the change in the measured centroid values for each detector channel will be determined. Also, the effective spatial registration change for each MODIS focal plane array will be determined.



KEY:

T = Time & Date.	L = Radiance	SC# = Scan No.
L# = Lamp Config No.	V = Voltage	I = Current
Q = SRCA Spatial Cal Correction Factor		B# = MODIS Band No.
NPDS = No. of Phase Delay Settings Used		CH# = Detector Channel No.
NDFS = No. of Data Frames Collected		DF# = Data Frame No.
MSR = MODIS Spatial Response (Digital)		PDS# = Phase Delay Setting No.
Test Type = SRCA Calibration or MODIS Check		NSCS = No. of Scans Collected
ARF = Aperture Response Function		X = Spatial Coordinate

Figure 6.9 SRCA Spatial Calibration Flow Diagram

6.3.4.2 REPORT FORMAT REQUIREMENTS.

6.3.4.3 Along-Scan Calibration. The report should provide the spatial response centroid values for each band, channel measured in the particular calibration run. Band statistics (averages and standard deviations) of the individual detector channel values should also be provided. If the test type is an initial spatial calibration of the SRCA, the computed spatial correction factors used to equate the GSE and SRCA centroid measurements should be reported. If the test type is a calibration check of MODIS, then the change in the measured centroid values compared to the previous and initial SRCA spatial calibration runs for each band and channel should be reported. Again band statistics on the change in centroid values should also be provided. In addition, the effective spatial registration change for each of the MODIS focal planes should be provided. All reported data should be tagged with the time and date of the collect.

6.3.5 COMMAND IMPLEMENTATION

This section shall address the command sequences required to:

- OBC subsystem configuration setup
- OBC subsystem preparation sequence
- OBC execution sequence
- OBC shut down sequence

Section 7
ELECTRONIC CALIBRATION

7.1 Electronic Calibration, Offset, and Linearity, Bands 1-30

The signal processing of the output for each channel in the photovoltaic (PV) bands 1-30 consists of a detector on the focal plane (FPA) feeding into a capacitance transimpedance amplifier (CTIA), a multiplexer selecting the channel, an integrator on the input to the Analog Electronics Module (AEM) to remove the multiplexer transient effects, a programmable gain and offset, and a 12-bit A/D. The CTIA is normally reset after each multiplexer readout to prepare for the next instantaneous field of view (IFOV). The MODIS bands are separated from each other along-scan to facilitate FPA construction. However, the Format Engine of the Main Electronics Module (MEM) stores the data from the AEM A/D, then reorders the data to down-link the data in packets with the bands spatially aligned as if they were all viewing the same features in object-space.

The electronic calibration consists of electronically inserting a programmed amount of charge into the CTIA rather than reading the detector input. At the end of the multiplexer readout interval, the CTIA is not reset, so the next IFOV time results in an increase of charge, thus forming a stair-step of output. This stair-step process continues for a programmed number of steps.

The electronic calibration data are inserted into data packets taken in the Solar Diffuser (SD) data sector for times when MODIS is not over the North Pole. During that time, the SD data would not have been valid. The reordering of data by the MEM mentioned above serves to "dis-order" the electronic calibration data. The electronic calibration process is turned on and off for all 30 bands at one time, but the spatial reorientation delays the data. The full set of electronic calibration data is saved by taking 50 Frames of Data (FD) for the SD sector, rather than 30 FD which are required to store the SD data. This assures that 25 steps can be recorded. The data can easily be reordered during ground processing.

The 25 electronic calibration steps allow measurement of any departure from linearity of the electronic system exclusive of the detectors in increments of 4% of full scale. Any linearity error can be determined by linear interpolation between the expected value and the actual values recorded for these steps.

7.2 Electronic Calibration, Offset, and Linearity, Bands 31-36

Bands 31-36 use photoconductive detectors, and it is not possible to disconnect these detectors without using a relay device. Such a device would not provide the five-year reliability, and would impose other problems. The electronic calibration for these bands has been implemented by inserting charge in addition to the detector output. This procedure is only performed when the channels are looking at the low signals from the space view port, thus allowing the full range of the electronic calibration to be exercised. The space view consists of 15 FD. Since this data is also reordered by the MEM, some compensation must be made. However, it is not possible to take more FD since the low signal space view only consists of 15 FD. The procedure followed is to use 10 steps (10% increments), but to turn on the electronic calibration for each band independently. The bands are all contained spatially within 16 IFOV of each other.

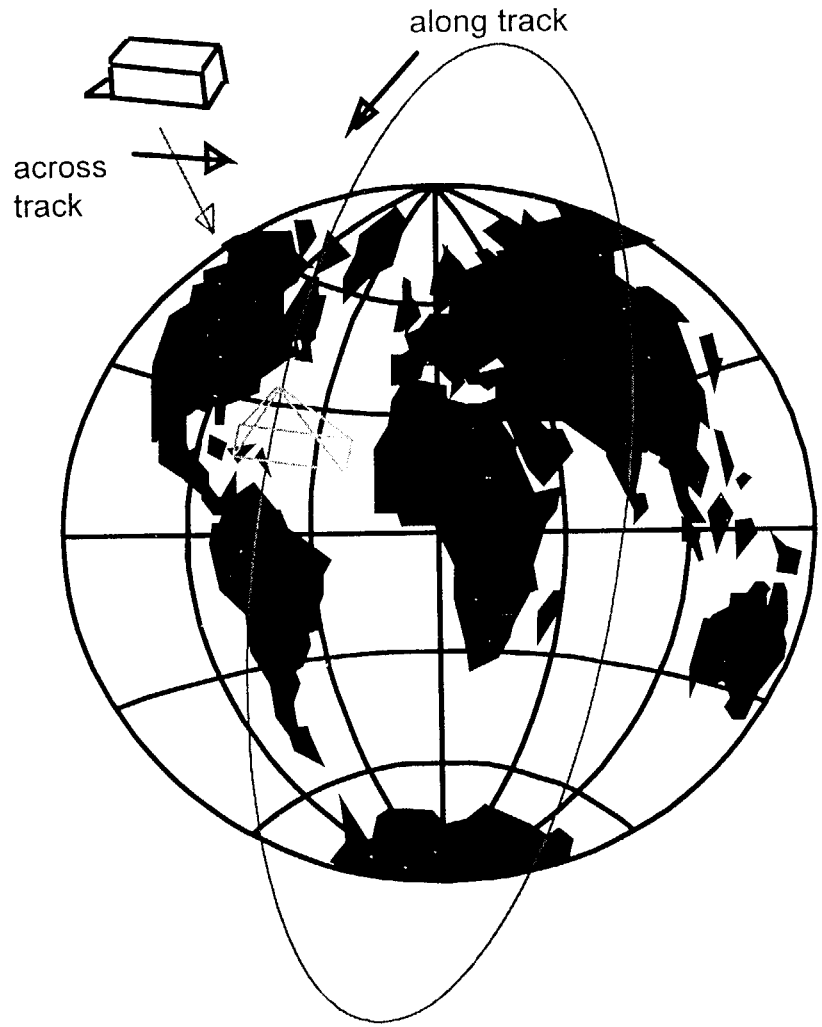
The 10 electronic calibration steps allow measurement of any departure from linearity of the electronic system exclusive of the detectors in increments of 10% of full scale. Any linearity error can be determined by linear interpolation between the expected value and the actual values recorded for these steps.

Acronyms and Abbreviations:

amb lab - ambient laboratory
BB - blackbody
BCS - Blackbody Calibration Source
BRDF - Bidirectional Reflectance Distribution Function
Ch - channel
cm - centimeter
FS - full scale
FWHM - full width half maximum
Ge - Germanium
GSE - ground support equipment
GSFC Goddard Space Flight Center
HS - half scale
IAC - Integration and Alignment Collimator
IFOV - instantaneous field of view
IGFOV - instantaneous geometrical field of view
IR - infrared
Irrad - irradiance
ITO - indium tin oxide
K - degree absolute temperature scale
KER - knife edge response
LSF - line spread function
LWIR - Bands 27 through 36
m - meter
MGBC - MODIS Ground Based Calibrator
MODIS - Moderate Resolution Imaging Spectroradiometer
mr - milliradian
MTF - Modulation Transfer Function
MWIR - Bands 20 through 25
NASA - National Aeronautics and Space Administration
NEΔL - noise equivalent radiance
NIR - Bands 1,2,13 through 19
NIST - National Institute of Standards and Technology
nm - nanometer
OBC - On Board Calibrators / ON Board Calibration
OOB - out of band transmittance
Para - paragraph
Rad - Radiance
RSS - root sum square
SBR - Spectral Band Registration
SD - solar diffuser
SiPD - Silicon photodiode
SIS - Spherical Integrating Source
SIS(100) - Spherical Integrating Source 100 cm diameter

MODIS VIEWING GEOMETRY

Day Mode / Single Scan



2/8/94
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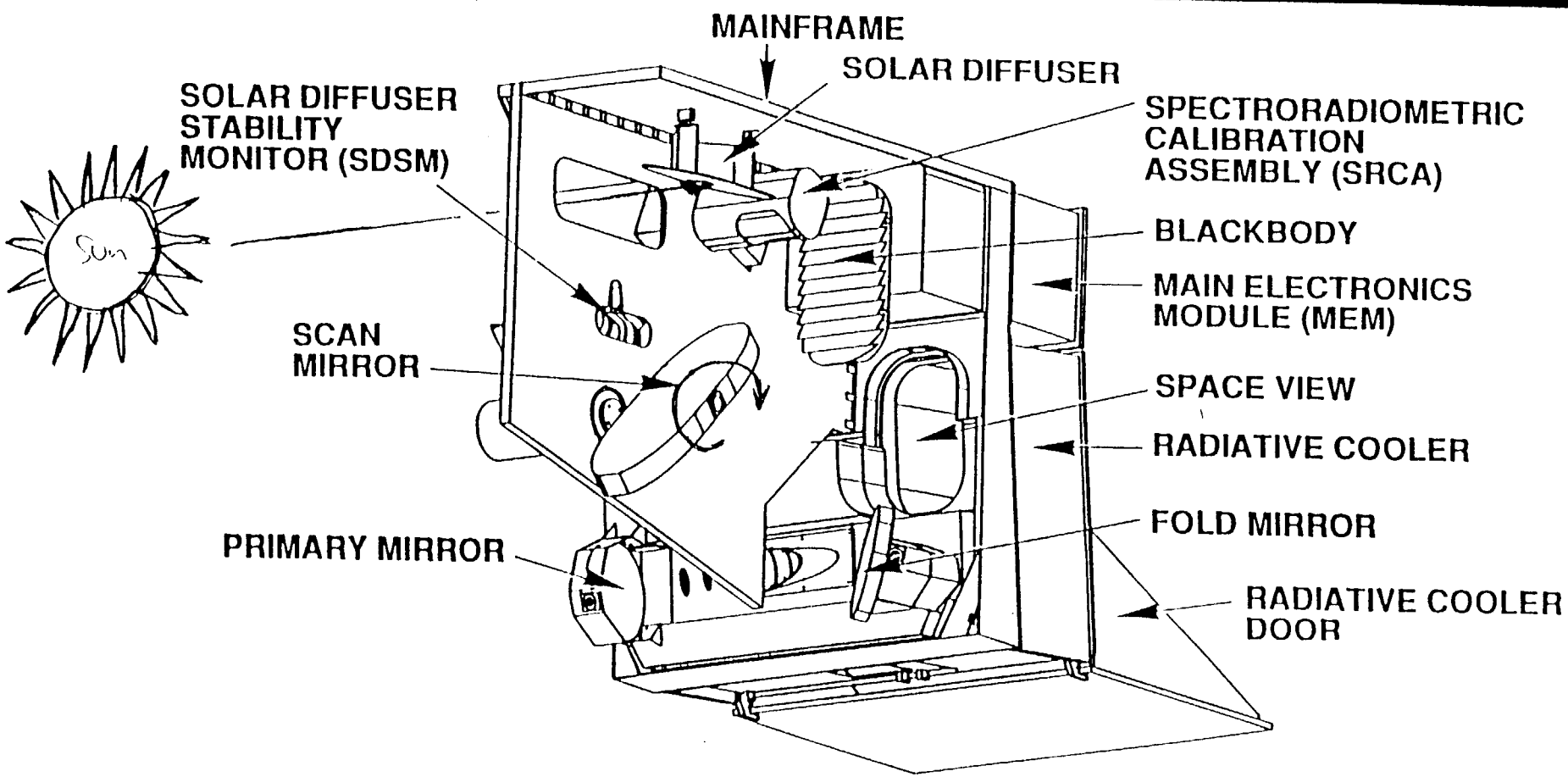
MODIS SCAN CAVITY VIEW

HUGHES

SANTA BARBARA RESEARCH CENTER
a subsidiary



- ENTIRE MAINFRAME NOT SHOWN IN CUT-AWAY FOR CLARITY

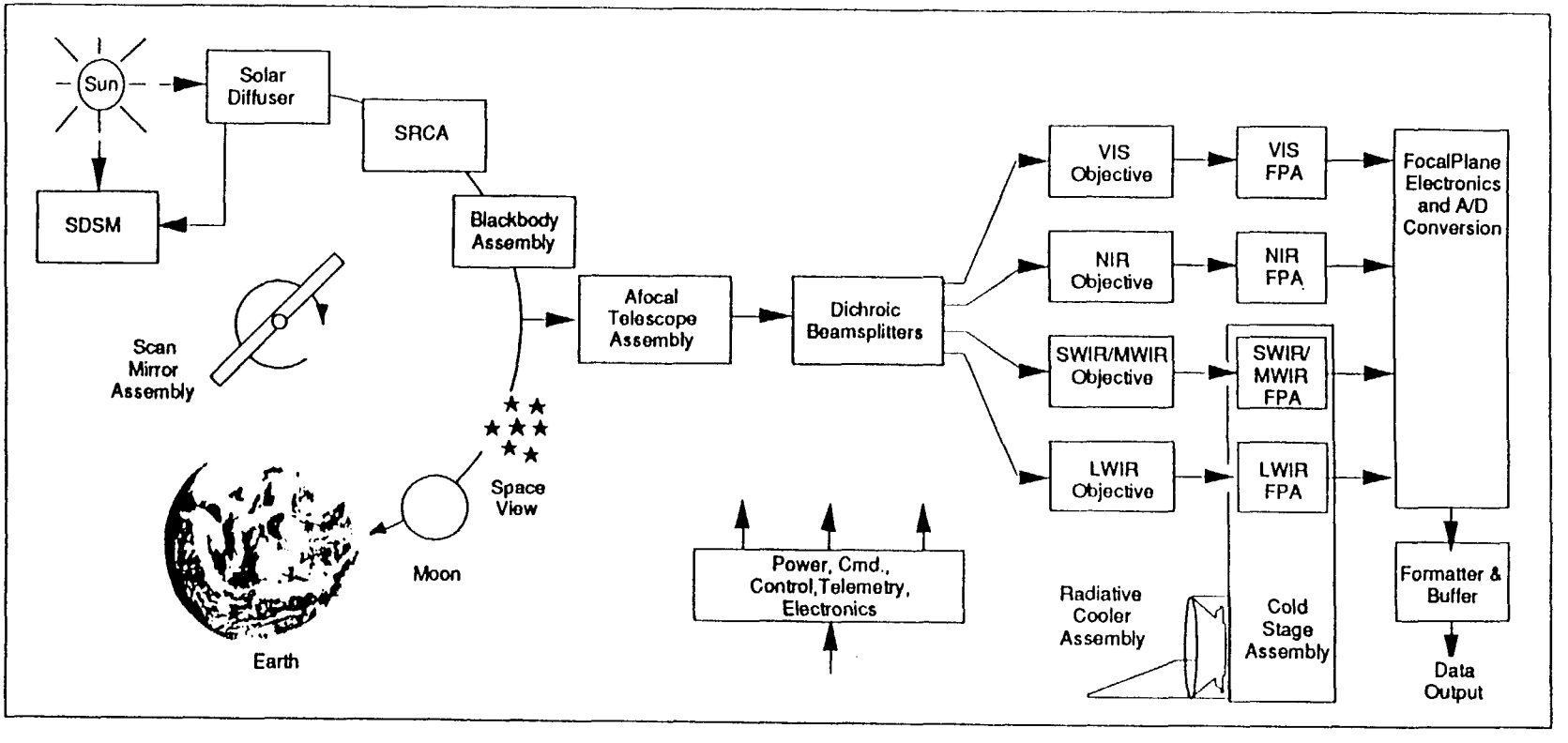
Earth

3/93
93-0204-5

MODIS DESIGN FROM PHOTONS TO DATA

HUGHES

SANTA BARBARA RESEARCH CENTER
a subsidiary



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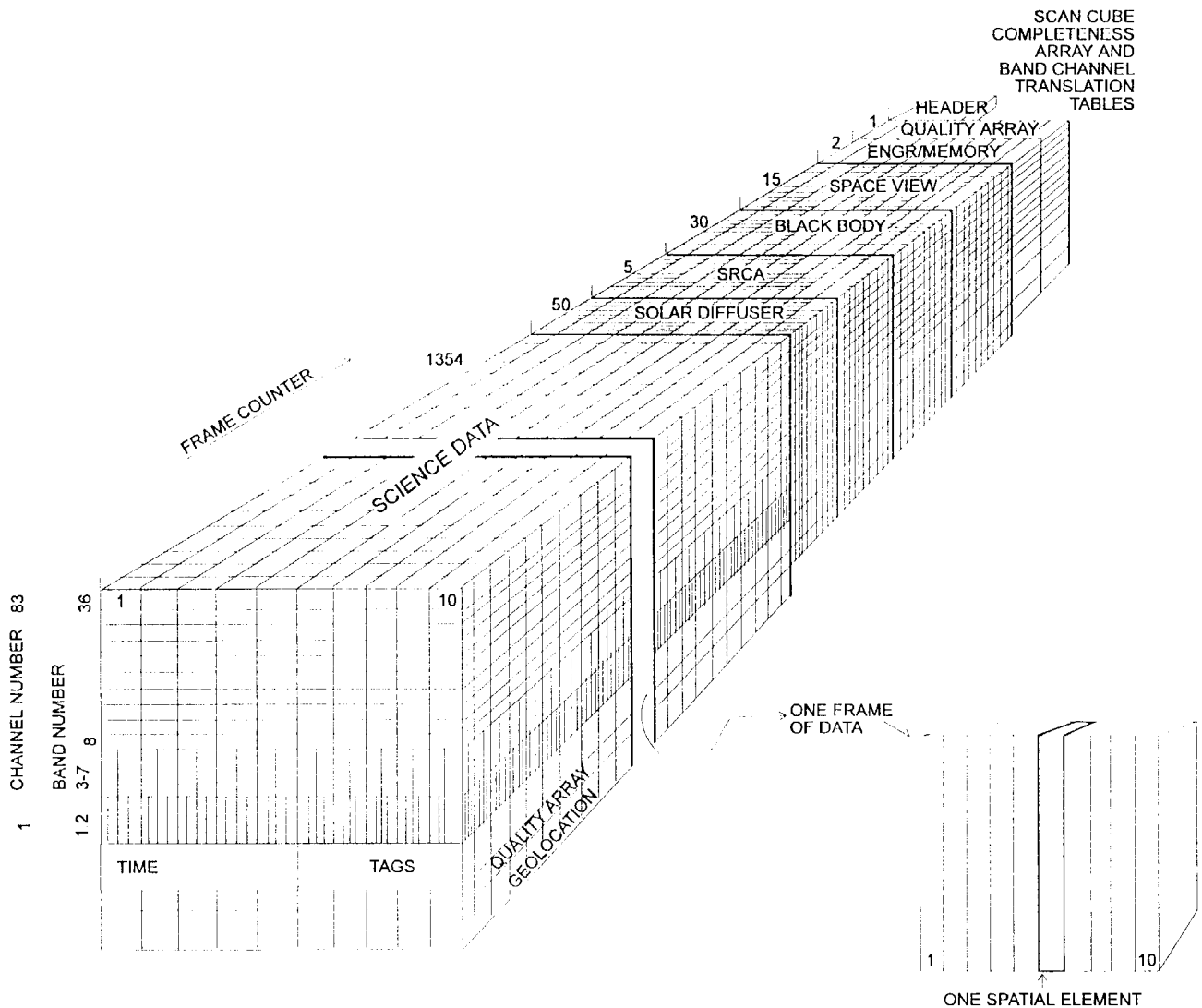
MODIS SCAN CUBE



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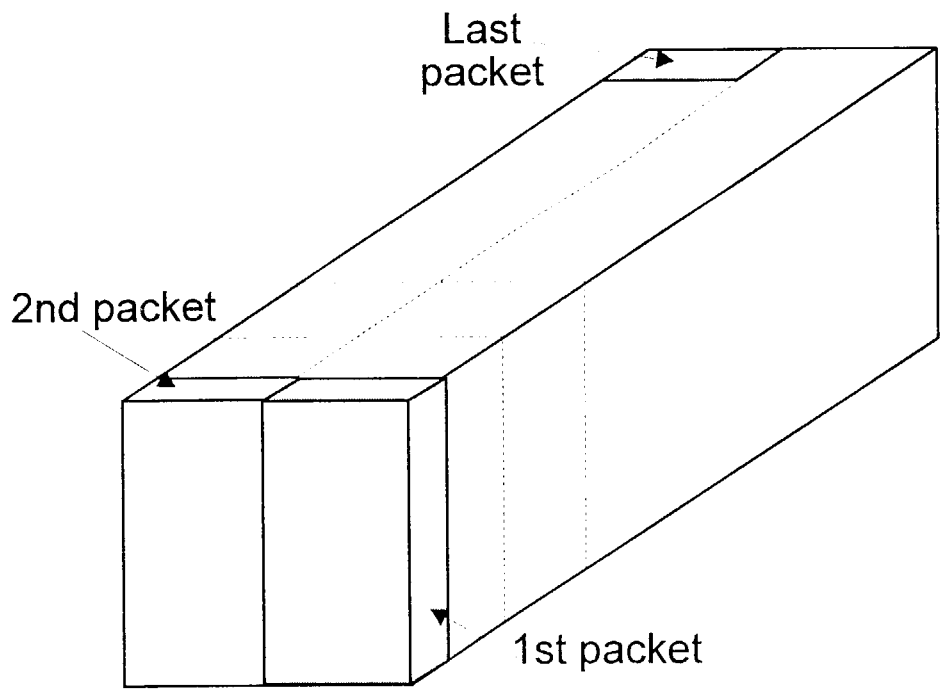
PACKETS TO SCAN CUBES



Counts [*i*] [*j*] [*k*]

- *i* → across tracks along scan
- *j* → along track
- *k* → channel (band)

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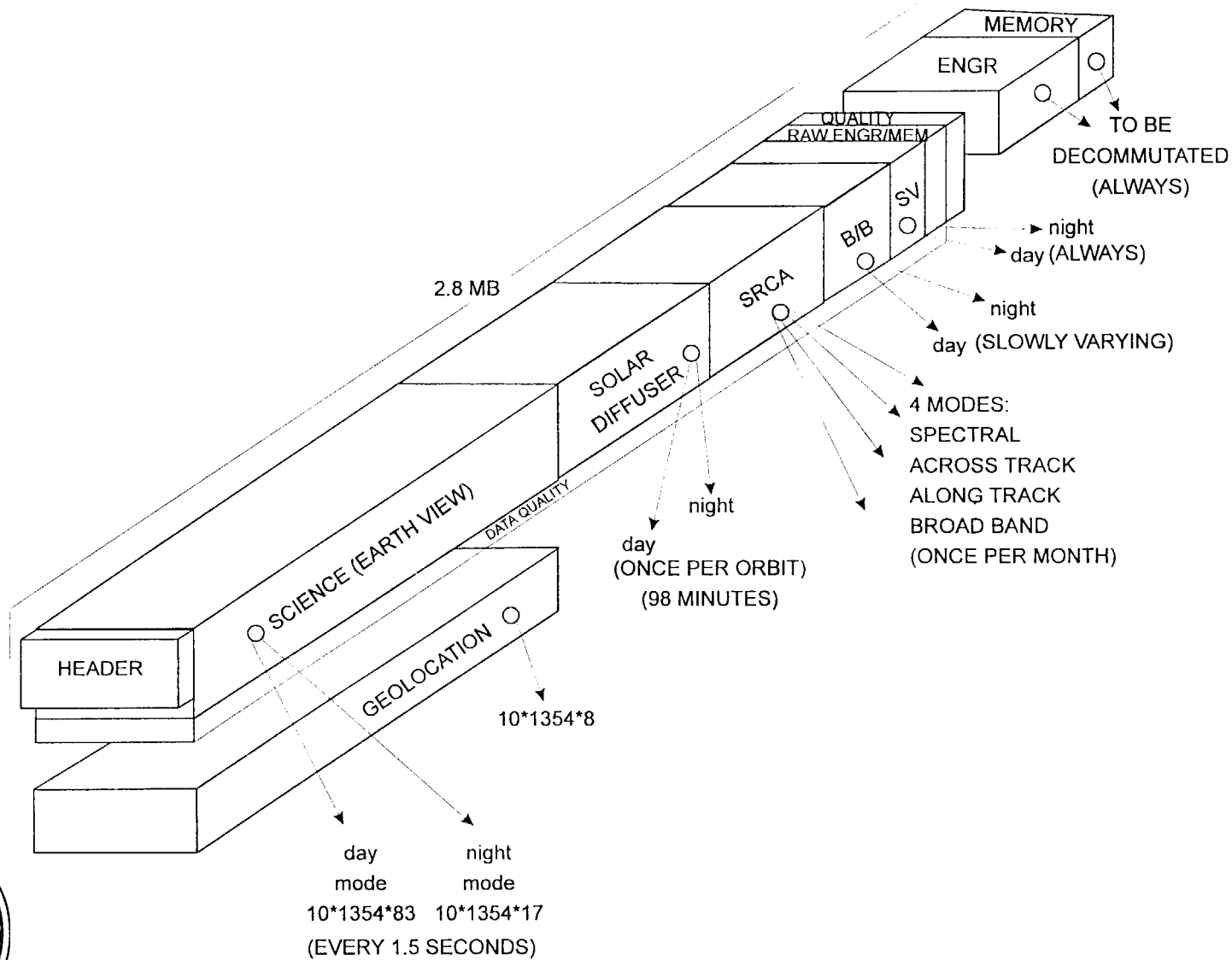
MODIS SCAN CUBE CONTENTS



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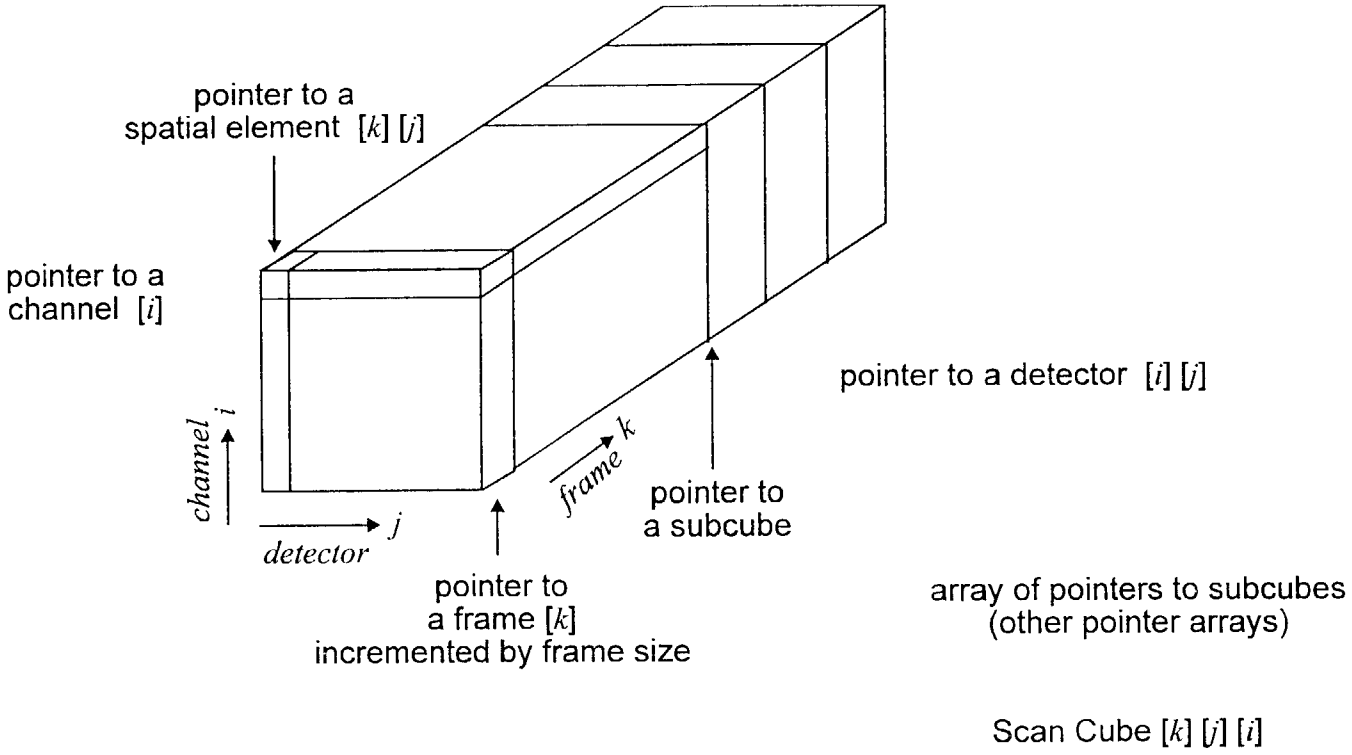
POINTER VISUALIZATION



POINTER USAGE

2-D array of pointers to each spatial element

* counts [*i*] [*j*]

1-D array of pointers to each frame of data

* pF[frame]

1-D array of pointers to each band of data

* pB[channel]

HDF representation → unknown

FTN 90 pointer equivalency → unknown

MISCELLANEOUS

Caviots:

- 32 bit addressing limitations = 4 GByte
- 16 bit I/O channel limitations = 64 KByte
- 32 bit registers

MODIS sizes:

Orbit	8 GBytes
Scan Cube	3 MBytes

Data Staging: Code and data separation, internal CPU cache, virtual memory, file buffers, external cache, associated memory (~1 KBytes)

Compiler Optimization:

Very Long Instruction Words (microcode) - eliminates the instruction decoding - do it in software.

QUESTIONS

Will all limitations due to 32 bit addressing be removed from the PGS and all other EOSDIS specified machines – e.g., SCFs and DAACs?

These limitations occur in:

- Memory segments <4 GBytes
- Double precision integers and long int are defined by ANSI to be 32 bits
- I/O channel controllers have even smaller bit field limitations
- HDF can not handle greater than 32 bit addressing.

CONCLUSIONS

- Using pointers to address elements within a scan cube eliminates any preferred ordering of indices in multidimensional arrays.
- The L1A scan cube will have no ragged arrays in the baseline processing design. Ragged arrays will be potentially useful for the engineering and memory dump scan portions such as thermistor arrays.
- Channel to/from band index arrays need to be implemented and incorporated into the HDF structure.

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