MCST Plan for the Level-1 Calibration Algorithm

Presented to

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Attachment 1

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Overview

The scientific background for the development of the MODIS Level-1 Calibration Product and the Cloud-Masking Utility Product can be found in Appendix A, which was originally written as possible input to a MODIS Land Discipline Product paper (Running, International Journal of Remote Sensing, 1993).

A top-level overview of the Level-1 Calibration Algorithm is presented graphically in Figure 1. The algorithm calculates the calibration coefficients for each new orbit based on the current orbit, the previous orbit, and the next orbit's data (if available). To minimize the effects of small, probably random fluctuations in the coefficient values, the new values, while retained, are used only if they differ from the pre-existing projected values by some minimum amount. The processing begins by creating an initial Level-1B calibrated dataset using the projected calibration coefficients. The next several processing steps calculate the new calibration coefficients.

Calculation of these new coefficients can be broken into two broad categories, non-image-based and image-based calculations, which are handled separately. The non-image-based calculations are performed first. These involve data from the MODIS on-board calibration systems and from lunar views. The calibration coefficients generated by these methods are temporarily stored while the next phase of processing occurs. The second phase begins with generating a cloud utility mask from the initial Level-1B calibrated dataset calculated earlier. As part of calculating the cloud mask, the utility masking algorithm will create a mask which identifies the radiometrically homogeneous pixels, i.e., the pixels which are composed of a single type of surface, be it vegetation, cloud or ocean, but which do not contain boundaries. Both of these masks are required by the image-based calibration routines, which must be able to identify cloud-free calibration sites to perform calibration-site-based coefficient calculation and be able to identify pure pixels to perform such relative image-based techniques as the modified histogram equalization routine. The calibration-site-based and the relative image-based routines each generate a new set of calibration coefficients.

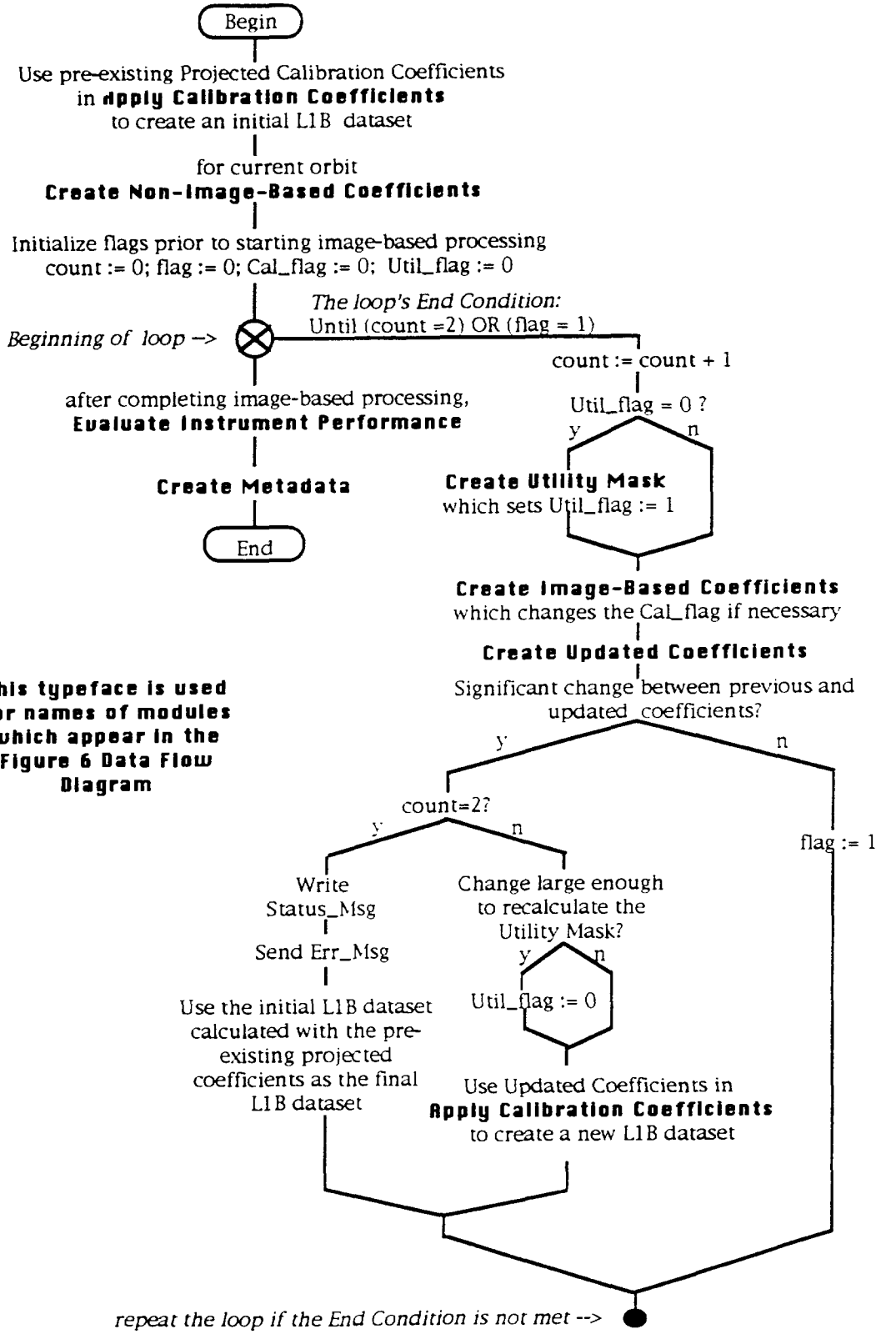
The three sets of new calibration coefficients are combined into a single new set, and this set is then compared to the previous values. If the difference is below some threshold, the previous values are used. If the difference is above the threshold then the new coefficients are used to calculate a new, presumably correctly calibrated Level-1B dataset. To verify that this new dataset is better calibrated than the older version, it is re-run through the image-based calibration processing and the resulting coefficients are combined into <u>another</u> new set, which is then compared with the previous 'new' set. If the difference is above the significance threshold, then there is probably a problem; an error message is generated indicating that the newly calculated coefficients are suspect and the pre-existing projected coefficients are used. The final steps in the Level-1 processing are the execution of a model to evaluate the instrument performance and the generation of metadata.

The remaining three Control Flow Diagrams, Figures 2 through 4, present the Level-1 Calibration Algorithm processing for programmers involved in implementing the system; specific data names are shown which refer to items in the Data Dictionary. Figures 5 through 11 present the Context Diagram and the Data Flow Diagrams for the Level-1 Calibration Algorithm System as it is currently envisioned; these are followed by the associated Data Dictionary and are also intended for the implementers of the Algorithm.

Control Flow Diagrams

Figure 1
Control Flow Diagram MODIS Level-1 Calibration Processing

Top-Level Overview of Level-1 Calibration Processing



This typeface is used for names of modules which appear in the Figure 6 Data Flow Diagram

Figure 2
Control Flow Diagram MODIS Level-1 Calibration Processing

Programmer's Overview of Level-1 Calibration Processing

Error checking and I/O processing are not shown

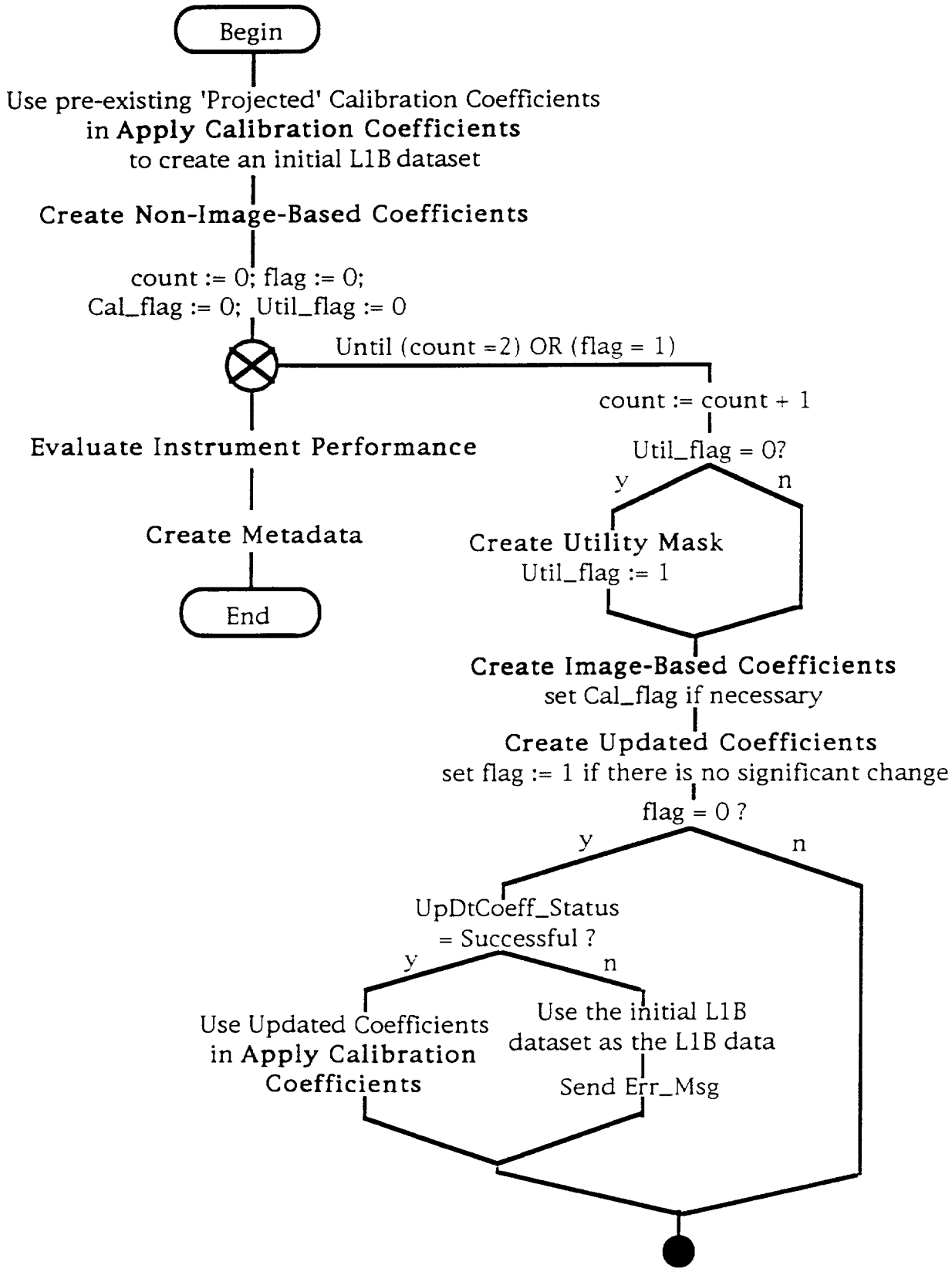


Figure 3

Control Flow Diagram MODIS Level-1 Calibration Processin

Create Image-Based Coefficients

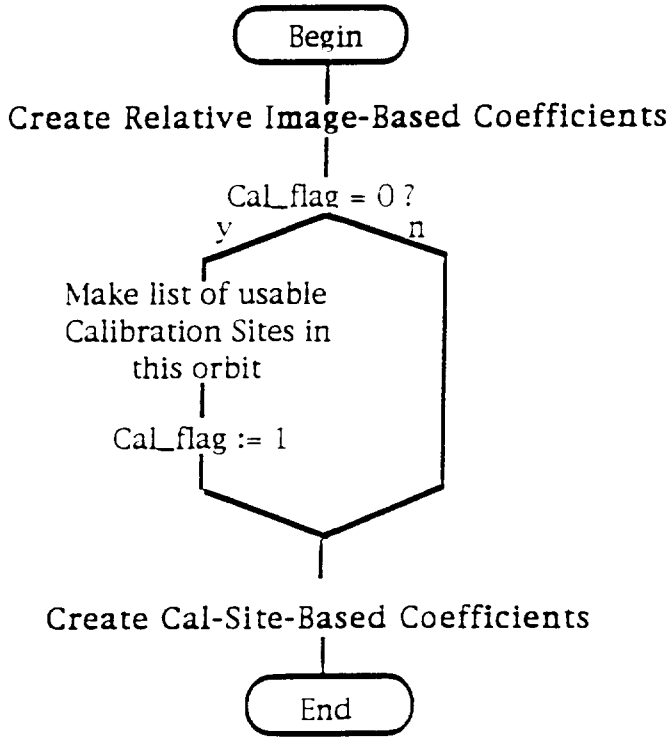
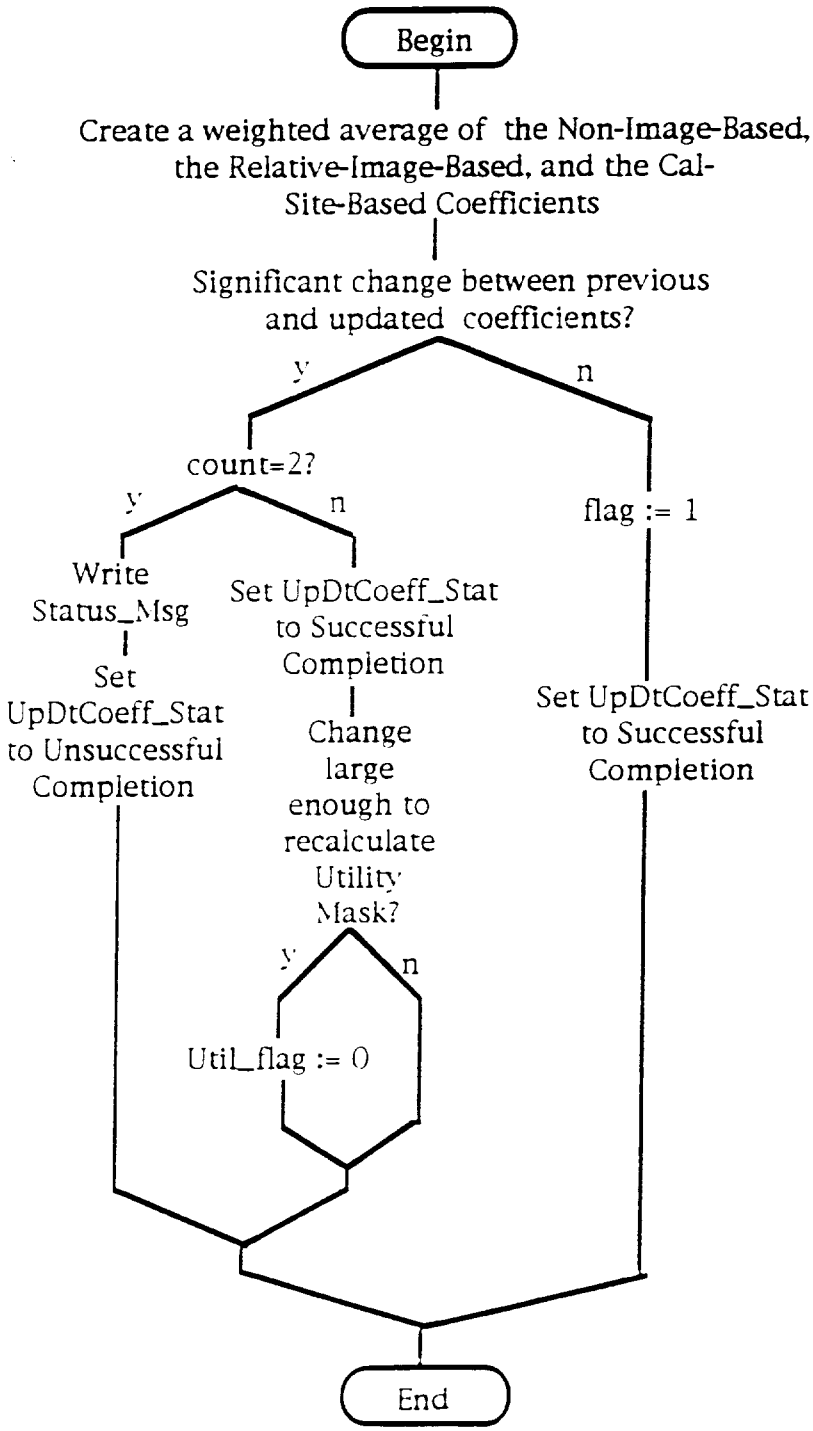


Figure 4

Control Flow Diagram MODIS Level-1 Calibration Processin

Create Updated Coefficients



Data Flow Diagrams

Figure 5

MODIS Level-1A to Level-1B Calibration Context Diagram

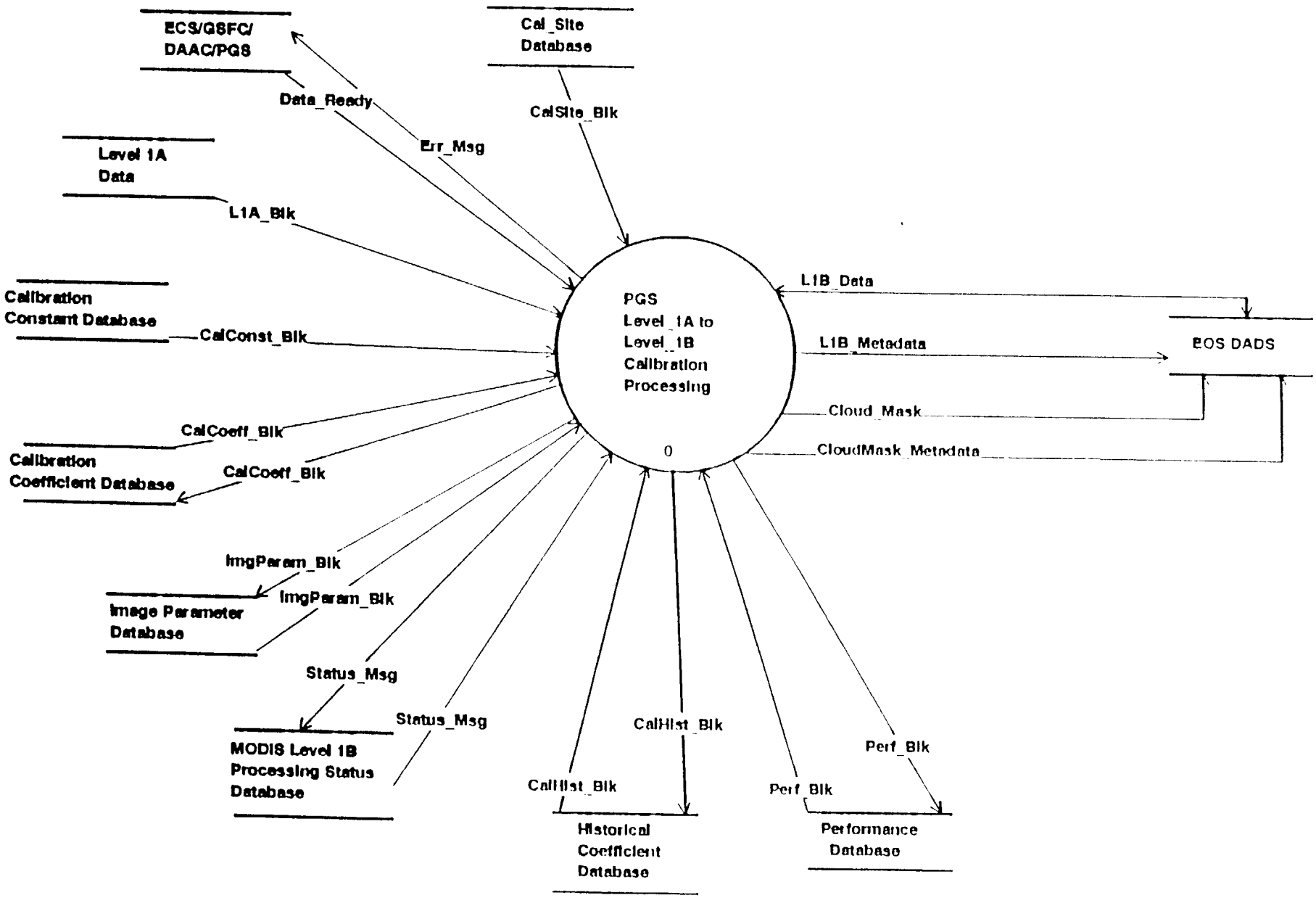


Figure 6
MODIS Calibration Algorithm Data Flow Diagram
Level 1.0

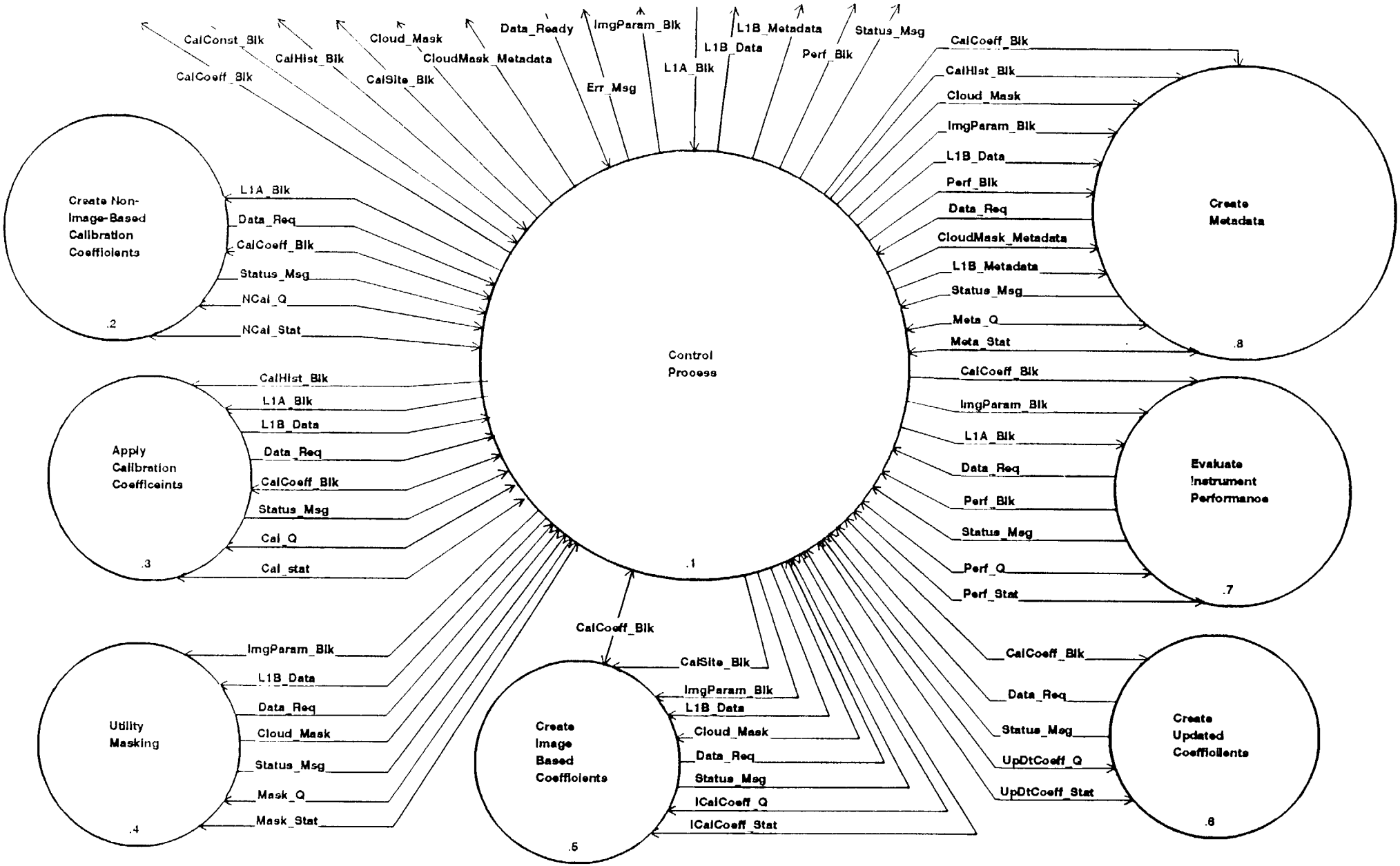


Figure 7
MODIS Calibration Algorithm Data Flow Diagram
Level 1.1

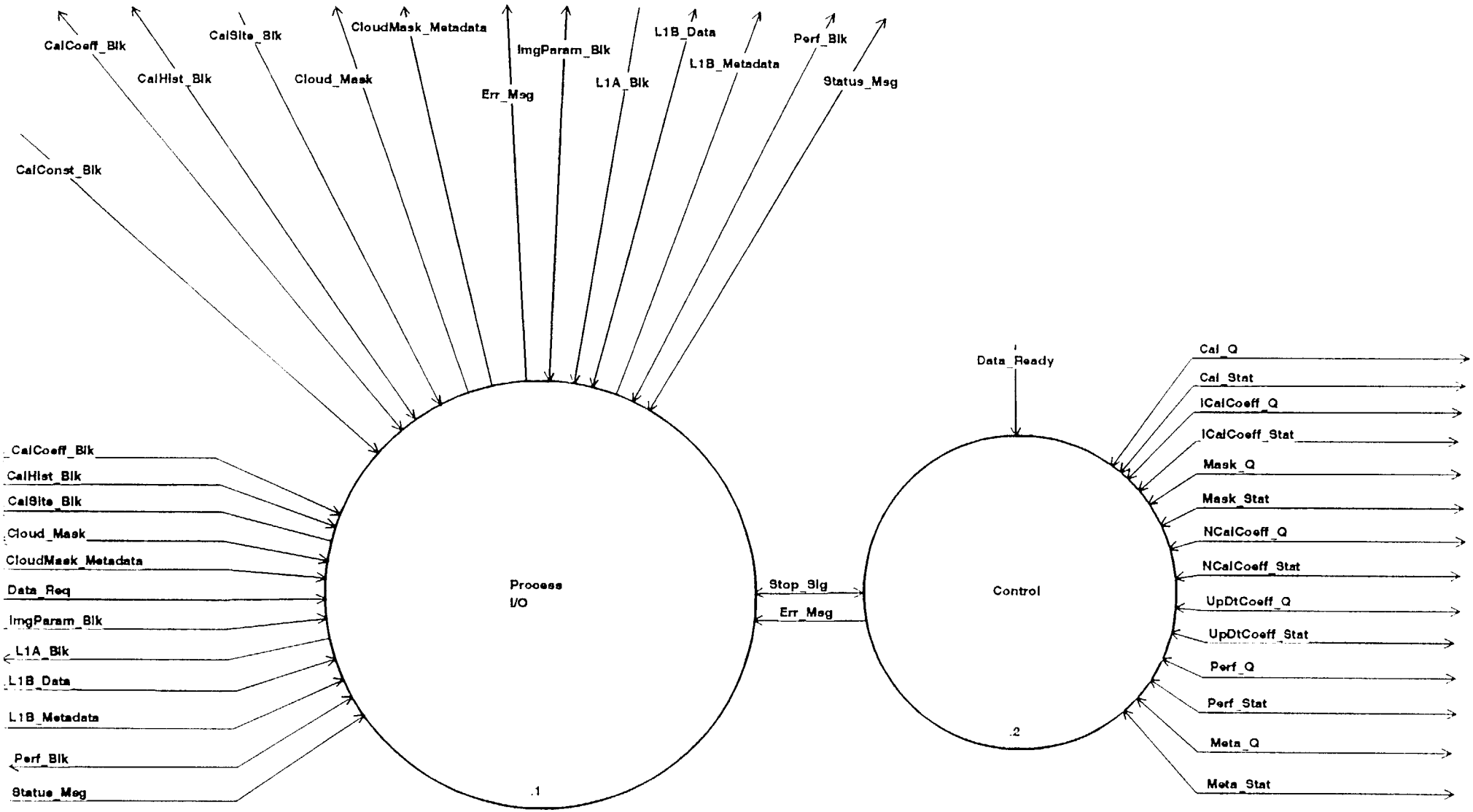


Figure 8

MODIS Level 1B Calibration Algorithm Data Flow Diagram Level 1.1.1

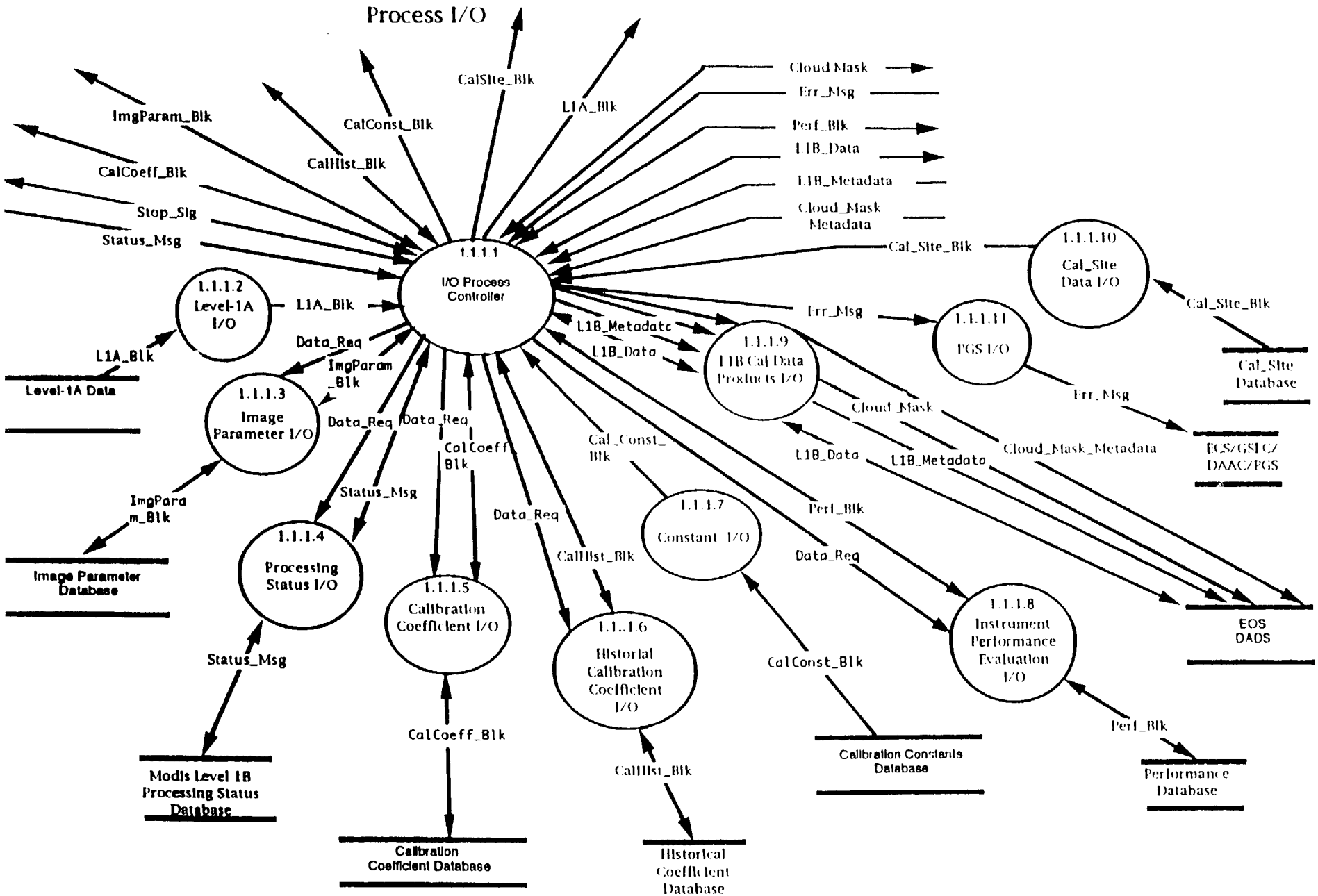


Figure 9

MODIS Level 1B Calibration Algorithm Data Flow Diagram Level 1.2

Perform Non Image-Based Calibration Checks

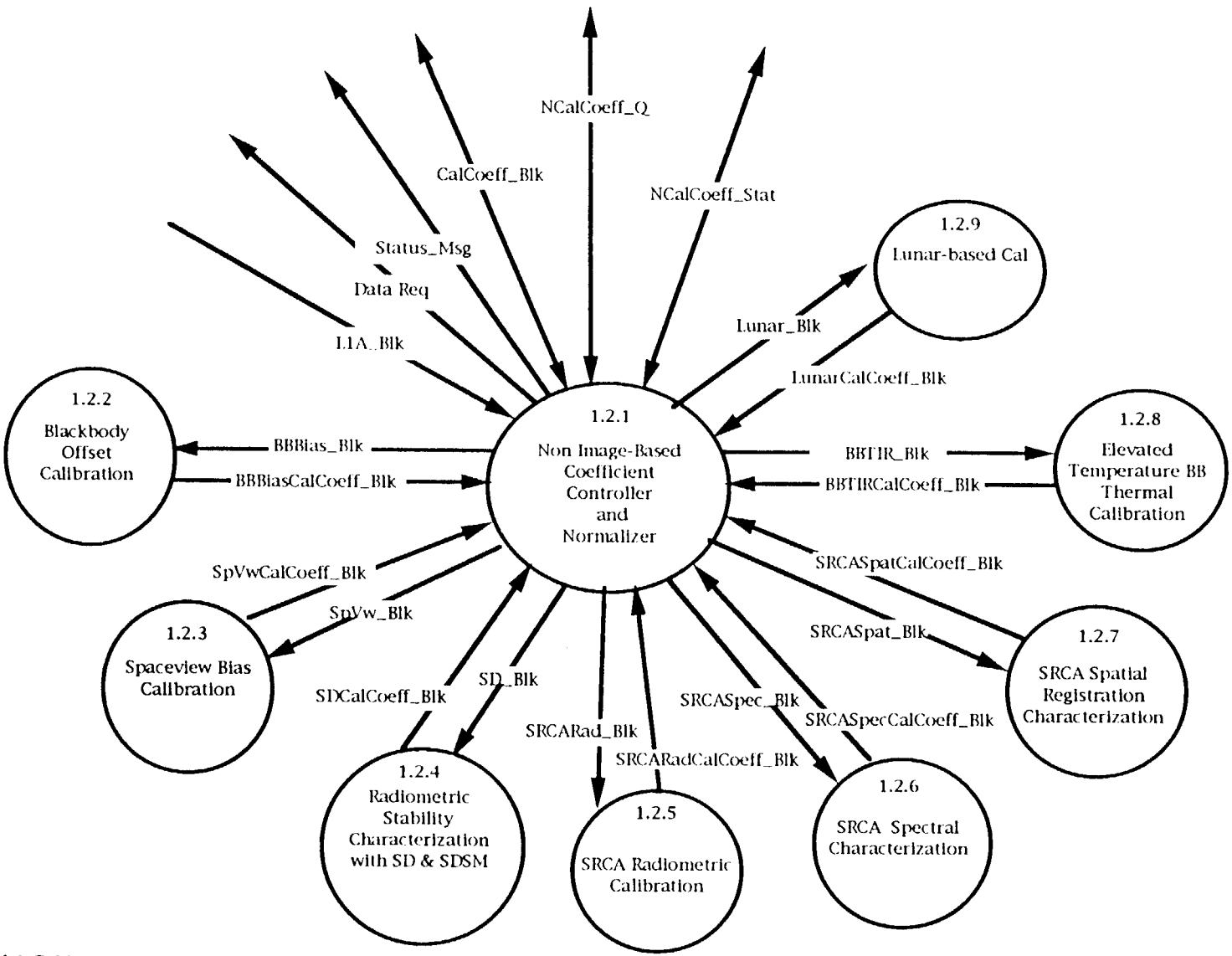


Figure 10

MODIS Level 1B Calibration Algorithm Data Flow Diagram Level 1.5

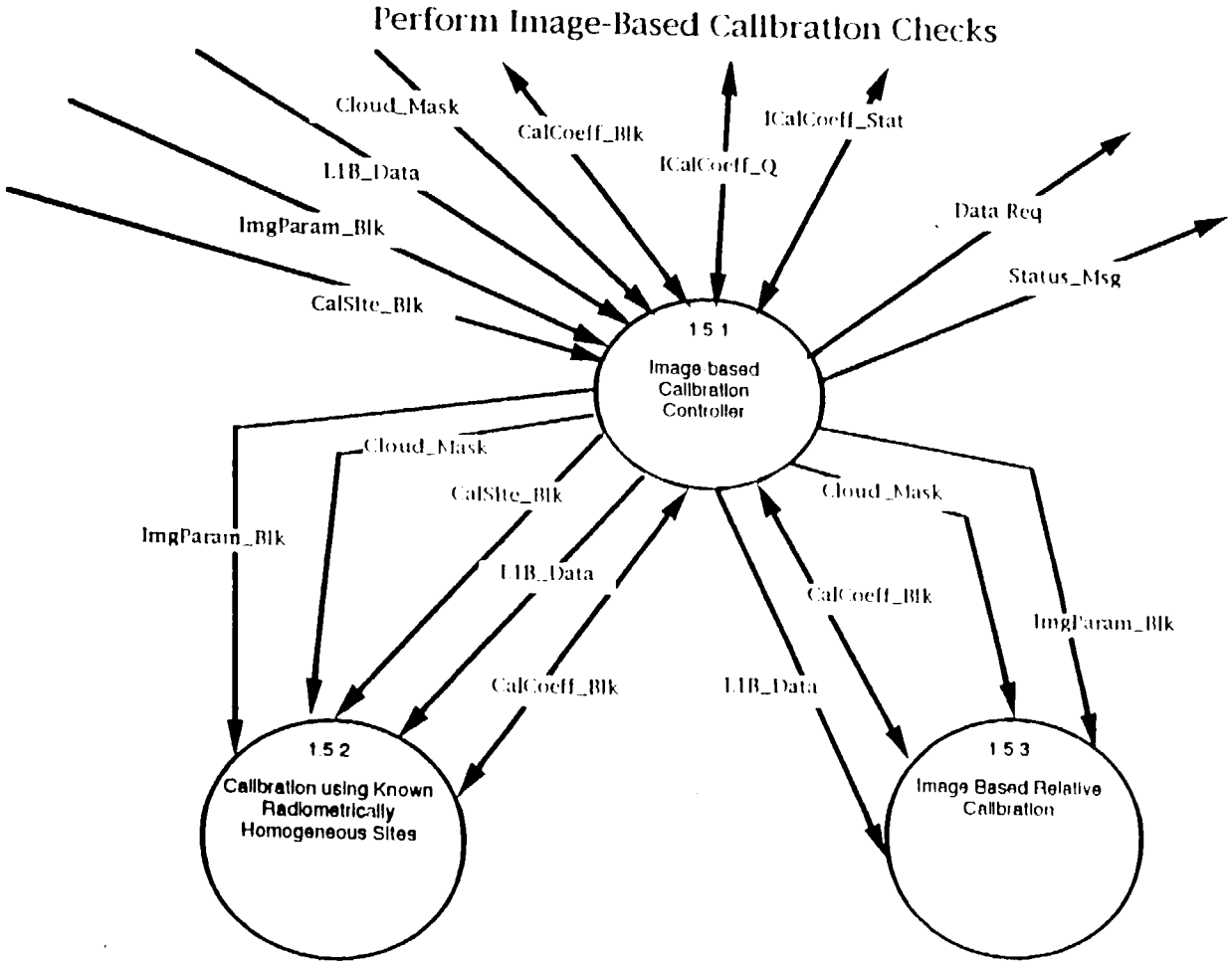
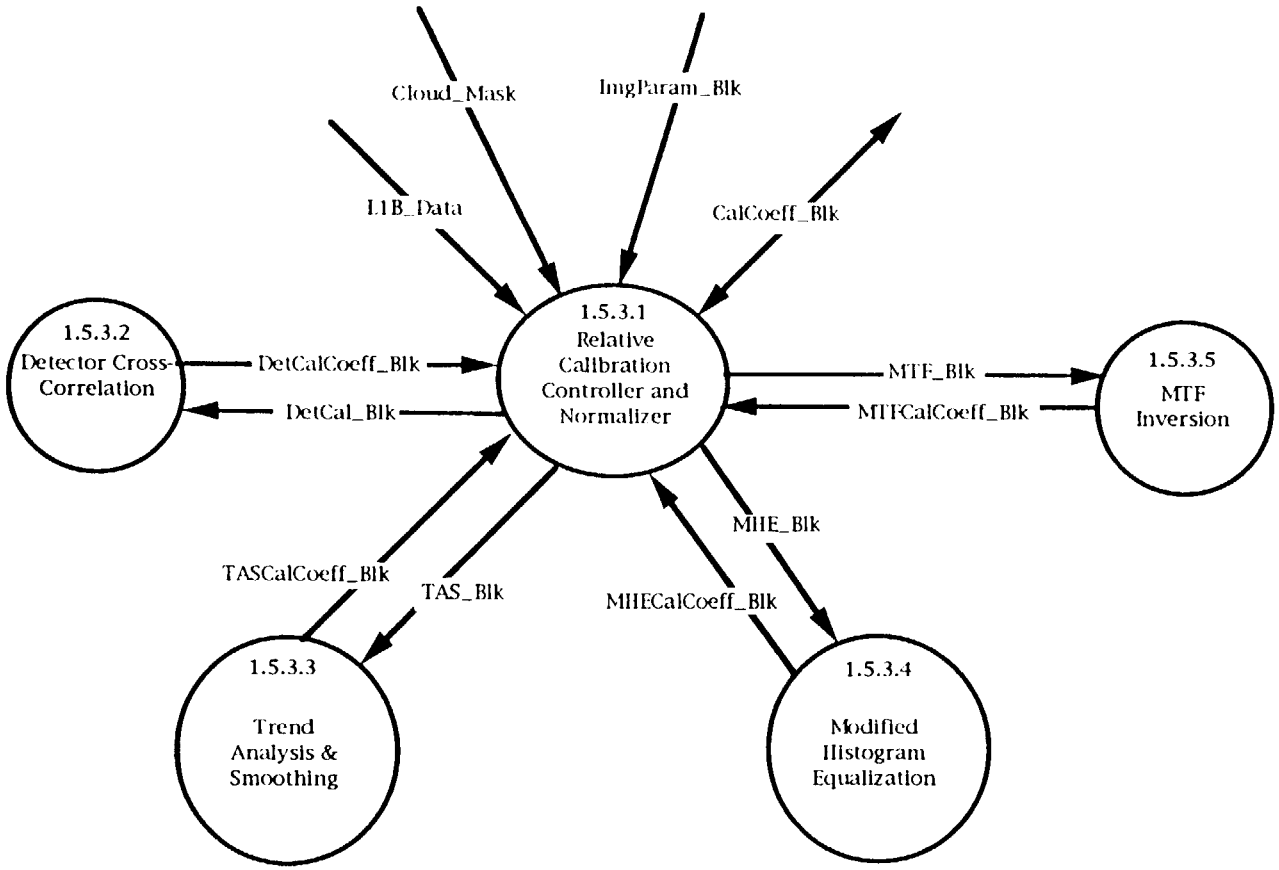


Figure 11

MODIS Level 1B Calibration Algorithm Data Flow Diagram Level 1.5.3

Perform Relative Calibration Checks



Data Dictionary

Level-1A to Level-1B Calibration Processing Data Dictionary

Name	Type	Primitives/Range	Description
BBBias_Blk	Structure	**TBD**	Data needed by the Blackbody Bias Calibration module.
BBBiasCalCoeff_Blk	Structure	**TBD**	Set of calibration coefficients produced by Blackbody Bias Calibration module.
BBTIR_Blk	Structure	**TBD**	Data needed by the Elevated Temperature Blackbody Thermal Calibration module.
BBTIRCalCoeff_Blk	Structure	**TBD**	Set of calibration coefficients produced by the Elevated Temperature Blackbody Thermal Calibration.module
CalCoeff_Blk	Structure	CalCoeff_Blk.Applied CalCoeff_Blk.CalSite1 CalCoeff_Blk.CalSite2 CalCoeff_Blk.Non Image CalCoeff_Blk.RelImg1 CalCoeff_Blk.RelImg2 CalCoeff_Blk.Date CalCoeff_Blk.Orbit CalCoeff_Blk.S/WVer	Coefficients are used by the equations which convert Level-1A data to Level-1B data.
CalCoeff_Blk.Applied	Floating Point array	**TBD**	Coefficients used to make the Level-1B data.
CalCoeff_Blk.CalSite1	Floating Point array	**TBD**	Calibration site coefficients generated by the first pass through the process.
CalCoeff_Blk.CalSite2	Floating Point array	**TBD**	The calibration site coefficients generated by the second pass through the process.
CalCoeff_Blk.Non Image	Floating Point array	**TBD**	The non image based calibration coefficients.

Name	Type	Primitives/Range	Description
CalCoeff_Blk.RelImg1	Floating Point array	TBD	The whole orbit based coefficients generated by the first pass through the process.
CalCoeff_Blk.RelImg2	Floating Point array	TBD	The whole orbit based coefficients generated by the first pass through the process.
CalCoeff_Blk.Date	32 bit Integer	TBD	The data on which the process was run.
CalCoeff_Blk.Orbit	32 bit Integer	0 - 900,000	The orbit number that the process was run on.
CalCoeff_Blk.S/WVer	32 bit Integer	TBD	The software version of the process used to generate the run.
CalConst_Blk	C header file of constants.	TBD	Calibration constant block from the Calibration Constant Database. Coefficients and Parameters used in the L1B Algorithm which do not change or which change very rarely. These will be part of a c header file to be included with the actual code. Changing these constants will require a code recompiliation.
CalHist_Blk	Structure	CalHist_Blk.Applied CalHist_Blk.CalSite1 CalHist_Blk.CalSite2 CalHist_Blk.Non Image CalHist_Blk.RelImg1 CalHist_Blk.RelImg2 CalHist_Blk.Date CalHist_Blk.Orbit CalHist_Blk.S/WVer	These Coefficients are copies of the CAlConst_Blk data which are stored to the Historical Coefficient Database for future reference.

Name	Type	Primitives/Range	Description
CalHist_Blk.Applied	Floating Point array	TBD	The coefficients used to make the Level-1B data.
CalHist_Blk.CalSite1	Floating Point array	TBD	The calibration site coefficients generated by the first pass through the process.
CalHist_Blk.CalSite2	Floating Point array	TBD	The calibration site coefficients generated by the second pass through the process.
CalHist_Blk.Non Image	Floating Point array	TBD	The non image based calibration coefficients.
CalHist_Blk.RelImg1	Floating Point array	TBD	The whole orbit based coefficients generated by the first pass through the process.
CalHist_Blk.RelImg2	Floating Point array	TBD	The whole orbit based coefficients generated by the first pass through the process.
CalHist_Blk.Date	32 bit Integer	TBD	The data on which the process was run.
CalHist_Blk.Orbit	32 bit Integer	0 - 900,000	The orbit number that the process was run on.
CalHist_Blk.S/WVer	32 bit Integer	TBD	The software version of the process used to generate the run.
Cal_Q	Structure	Orbit currently being processed Next orbit to be processed. ... Last orbit in queue.	Shows where the Apply Calibration Coefficients processing is.

Name	Type	Primitives/Range	Description
CalSite_Blk	Structure	CalSite_Blk.ID CalSite_Blk.Lat CalSite_Blk.Long CalSite_Blk.Type	Information about the type and location of the calibration sites in a given orbit.
CalSite_Blk.ID	Integer	**TBD**	The name of the Calibration Site.
CalSite_Blk.Lat	Floating Point	**TBD**	The latitude of the Calibration Site.
CalSite_Blk.Long	Floating Point	**TBD**	The longitude of the Calibration Site.
CalSite_Blk.Type	Integer	**TBD**	The classification of the site.
Cal_Stat	Integer	0=emergency shutdown 1=idle 2=running 3=successful completion 4=unsuccessful completion	Communicates module status to control process. This structure should make implementaion of asynchronous processing easier . Successful completion means that the L1B_Data just generated should be passed to the Make Performance Coefficients module for continued processing. Unsuccessful completion means that the Status_Msg should be written out to the Status file and this data remains uncalibrated in the absence of human intervention. No further processing is done at this time.
Cloud_Mask	Structure	**TBD**	This is the output of the Utility Mask Algorithm.
CloudMask_Metadata	**TBD**	**TBD**	This is the metadata generated by the Utility Mask Algorithm.

Name	Type	Primitives/Range	Description
Data_Ready	Structure	Data_Ready.Flag Data_Ready.OrbitNum Data_Ready.Loc Data_Ready.CalCoeff_Ver	Signal from the PGS to start processing. Assumed to be given whenever the next orbit's data is ready; includes orbit number of the data which is ready and the location of that data. This is added to the existing queue; if it already exists in that queue, it is assumed to be an update of the data location.
Data_Ready.CalCoeff_Ver	TBD	TBD	Allows the user to specify which calibration coefficient set to use for re-processing a run.
Data_Ready.Flag	Boolean	1=Data Ready, 0=Stop Processing	Signal from PGS to process; used to start processing if the L1B program isn't running, or to indicate the arrival of more data if it is in progress on earlier data. Usually will be 1. 'Stop Processing' signal is for PGS to shut us down gracefully if necessary.
Data_Ready.Loc	32 bit Integer	TBD	Code for file/memory location of this orbit's data; may change w/time since data could be swapped into longer-term stroage by PGS if L1B is back-logged...
Data_Ready.Orbit_Num	32 bit Integer	values from 1 to < 900,000	24 orbits/(instr*day)* 2 instr *365.25 days/yr * 50 yr = 876,600 orbits This should be an overestimate for a 15-yr program...
Data_Req	Structure	Data_Req.Type Data_Req.Dir Data_Req.Blk_ID	Record which mediates I/O requests.

Name	Type	Primitives/Range	Description
Data_Req.Blk_ID			Specifies what data is requested; default is last record in file.
Data_Req.Dir	Boolean	0=Output, 1=Input	Flag to specify whether request is for input or output (direction)
Data_Req.Type	Integer	1= L1A_Blk 2=CalHist_Blk 3=CalCoeff_Blk 4=CalHist_Blk 5=ImgParam_Blk 6=Perf_Blk 7=Status_Msg 8=Cloud_Mask 9=L1B_Data Other data sources TBD	Code for type of I/O data block.
DetCal_Blk	Structure	**TBD**	Data needed by the Detector Cross-Correlation module.
DetCalCoeff_blk	Structure	**TBD**	These are the calibration coefficients produced by the Detector Cross Correlation module.
Err_Msg	Structure	**TBD**	This indicates that a problem with the processing has occured. The severity of the problem and pointers to relevant data are included in the structure.
ICalCoeff_Q	Structure	Orbit currently being processed Next orbit to be processed. ... Last orbit in queue.	Shows where the Apply Calibration Coefficients processing is.

Name	Type	Primitives/Range	Description
ICalCoeff_Stat	Integer	0=emergency shutdown 1=idle 2=running 3=successful completion 4=unsuccessful completion	Communicates module status to control process. This structure should make implementaion of asynchronous processing easier. Successful completion means that the L1B_Data just generated should be passed to the next module for continued processing. Unsuccessful completion means that the Status_Msg should be written out to the Status file and the image based coefficients will not be used for this run. No further rins of this module are done during this run.
ImgParm_Blk	**TBD**	**TBD**	This is data used for calibration derived from old MODIS, AVHRR, Landsat TM and other sources.
L1A_Anchor_Pts	Structure	**TBD**	
L1A_Anchor_Pts_Index	Structure	**TBD**	
L1A_BandNum_to_DataChan	Structure	**TBD**	three tables which translate from logical along-track location, logical across-track location & band number to 3D Cube Data Channel Array indices. The logical locations of these data are TBD.
L1A_BandQual	Structure		
L1A_BB_Data	3-D Array Structure	**TBD**	Black Body Data referenced in 3 coordinates, Along-track, Across-track, and Band Number.

Name	Type	Primitives/Range	Description
L1A_Blk	Structure	L1A_Metadata L1A_Data_Prod	One Level-1A Data Product, per T.Geoff's DRAFT report 17 Dec 92 pp6 - 7
L1A_Calibration_Pointers	pointer array	**TBD**	Pointers which indicate where the coefficients and S/W used to process the 1A data to 1B are located.
L1A_DP.Header	Structure	TBD	per T.Geoff's DRAFT report 17 Dec 92 p 7
L1A_Engr_Mem_Dumps	Structure		
L1A_Metadata	Structure	Level-0 Accounting Data (from EDOS) Level-1A Derived Information (TBD)	per T.Geoff's DRAFT report 17 Dec 92 p6
L1A_Scan_Cube_*x*	Structure	L1A_Sci_Data L1A_SD_Data L1A_BB_Data L1A_SV_Data L1A_BandNum_to_DataChan L1A_Spatial_DataQual L1A_Time_Tag L1A_Anchor_Pts L1A_Anchor_Pts_Index L1A_SRCA_Data L1A_Engr_Mem_Dumps L1A_BandQual l1A_Calibration_Pointers	One Level-1A Scan Cube, per T.Geoff's DRAFT report 17 Dec 92 pp 7-9

Name	Type	Primitives/Range	Description
L1A_Sci_Data	3-D Array Structure	TBD	Science data, in 16-bit format. Data is accessed by band number & IFOV location, referenced in 3 coordinates, Along-track, Across-track, and Band Number.
L1A_SD_Data	3-D Array Structure	TBD	Solar Diffuser Data, referenced in 3 coordinates, Along-track, Across-track, and Band Number.
L1A_Spatial_DataQual	2-D Array Structure	TBD	code for data quality always at 1-km resolution in a 2 dimensional array, referenced by Along-track and Across-track.
L1A_SRCA_Data	Structure	TBD	Data collected when the SRCA is in operation.
L1A_SV_Data	3-D Array Structure	TBD	Space View Data, referenced in 3 coordinates, Along-track, Across-track, and Band Number.
L1A_Time_Tag	2-D Array Structure	TBD	2 time tags per frame in day mode, 1 in night mode
L1B_Data	Structure	TBD	Assumed similar to L1A_Blk.
L1B_Metadata	Structure	TBD	TBD
Lunar_Blk	Structure	TBD	This is the data needed by the Lunar-Based Calibration module.
LunarCalCoeff_Blk	Structure	TBD	These are the coefficients output by the Lunar-Based Calibration module.

Name	Type	Primitives/Range	Description
Mask_Q	Queue	Mask_Q.head Mask_Q.tail Mask_Q.full	FIFO Queue of orbits of data waiting to be processed.
Mask_Q.full	Boolean	0=queue OK 1=queue full	Flag; only necessary if queue is implemented as an array.
Mask_Q.head	Pointer	**TBD**	Points to head of queue.
Mask_Q.tail	Pointer	**TBD**	Points to tail of queue.
Mask_Stat	Integer	0=emergency shutdown 1=idle 2=running 3=successful completion 4=unsuccessful completion	Communicates module status to control process. This structure should make implementaion of asynchronous processing easier. Successful completion means that the data just generated is ready to be used by subsequent modules and should be saved. Unsuccessful completion means that the Status_Msg should be written out to the Status file and the data not used in further processing.
Meta_Q	Queue	Meta_Q.head Meta_Q.tail Meta_Q.full	FIFO Queue of orbits of data waiting to be processed.
Meta_Q.full	Boolean	0=queue OK 1=queue full	Flag; only necessary if queue is implemented as an array.
Meta_Q.head	Pointer	**TBD**	Points to head of queue.

Name	Type	Primitives/Range	Description
Meta_Q.tail	Pointer	TBD	Points to tail of queue.
Meta_Stat	Integer	0=emergency shutdown 1=idle 2=running 3=successful completion 4=unsuccessful completion	Communicates module status to control process. This structure should make implementation of asynchronous processing easier. Successful completion means that the metadata just generated should be saved and used in subsequent processing. Unsuccessful completion means that the Status_Msg should be written out to the Status file.
MHE_Blk	Structure	TBD	Data needed by the Modified Histogram Equalization module.
MHECalCoeff_Blk	Structure	TBD	Set of calibration coefficients produced by the Modified Histogram Equalization module.
MTFCal_Blk	Structure	TBD	Data needed by the Modulation Transfer Function (MTF) Inversion routine.
MTFCalCoeff_Blk	Structure	TBD	Set of calibration coefficients produced by the Modulation Transfer Function (MTF) Inversion routine.
NCalCoeff_Q	Queue	NCalCoeff_Q.head NCalCoeff_Q.tail NCalCoeff_Q.full	FIFO Queue of orbits of data waiting to be processed.
NCalCoeff_Q.full	Boolean	0=queue OK 1=queue full	Flag; only necessary if queue is implemented as an array.

Name	Type	Primitives/Range	Description
NCalCoeff_Q.head	Pointer	**TBD**	Points to head of queue.
NCalCoeff_Q.tail	Pointer	**TBD**	Points to tail of queue.
NCalCoeff_Stat	Integer	0=emergency shutdown 1=idle 2=running 3=successful completion 4=unsuccessful completion	Communicates module status to control process. This structure should make implementaion of asynchronous processing easier. Successful completion means that the Internal-calibration-based calibration coefficients just generated can be used in subsequent modules and should be saved. Unsuccessful completion means that the Status_Msg should be written out to the Status file and the calibration coefficients NCalCoeff just generated should not be used in further processing.
Perf_Blk	TBD	TBD	This is the data product of the Evauluate Instrument Performance module.
Perf_Q	Queue	Perf_Q.head Perf_Q.tail Perf_Q.full	FIFO Queue of orbits of data waiting to be processed
Perf_Q.full	Boolean	0=queue OK 1=queue full	flag; only necessary if queue is implemented as an array.
Perf_Q.head	Pointer	**TBD**	Points to head of queue

Name	Type	Primitives/Range	Description
Perf_Q.tail	Pointer	**TBD**	Points to tail of queue
Perf_Stat	Integer	0=emergency shutdown 1=idle 2=running 3=successful completion 4=unsuccessful completion	Communicates module status to control process. This structure should make implementaion of asynchronous processing easier . Successful completion means that the Performance Results just generated are within acceptable bounds. Unsuccessful completion means that the Status_Msg should be written out to the Alerts file.
SD_Blk	Structure	**TBD**	The data needed by the Radiometric Stability Characterization with SD & SDSM module.
SDCalCoeff_Blk	Structure	**TBD**	The calibration coefficients output by the Radiometric Stability Characterization with SD & SDSM module.
SpVw_Blk	Structure	**TBD**	The data needed by the Spaceview Bias Calibration module.
SpVwCalCoeff_Blk	Structure	**TBD**	The Calibration coefficients output by the Spaceview Bias Calibration module.

Name	Type	Primitives/Range	Description
SRCARad_Blk	Structure	**TBD**	The data needed by the SRCA Radiometric Calibration module.
SRCARadCalCoeff_Blk	Structure	**TBD**	The calibration coefficients output by the SRCA Radiometric Calibration module.
SRCASpec_Blk	Structure	**TBD**	The data needed by the SRCA Spectral Characterization module.
SRCASpecCalCoeff_Blk	Structure	**TBD**	The calibration coefficients output by the SRCA Spectral Characterization module.
SRCASpat_Blk	Structure	**TBD**	The data needed by the SRCA Spatial Registration module.
SRCASpatCalCoeff_Blk	Structure	**TBD**	The calibration coefficients output by the SRCA Spatial Registration module.

Name	Type	Primitives/Range	Description
Status_Msg	Structure	Status_Msg.Comment Status_Msg.Image_loc Status_Msg.Orbit Status_Msg.Signal Status_Msg.Source	The processing log. Interim results are stored here for future reference and problem resoulution. If anything goes wrong, write the details here for human perusal/action. This would include out-of-bounds coefficients, flawed data, or other such problem, as well as I/O errors. If there is a PGS-directed shutdown, the state of processing should be stored here for future recovery (major variables, etc)
Status_Msg.Comment	String	May be many pages long.	message giving best-guess on error type/cause, followed by any coefficients, data values, etc, which were bad. If there is a PGS-directed shutdown, the state of processing should be stored here for future recovery (major variables, etc)
Status_Msg.Image_loc	Pointer	**TBD**	Pointer to location of sample representative image which is typical of the problem. May point at image derived from the actual problem data. If NULL then no image exists.
Status_Msg.Orbit	32 bit Integer	values from 1 to < 900,000	24 orbits/(instr*day)* 2 instr *365.25 days/yr * 50 yr = 876,600 orbits This should be an overestimate for a 15-yr program...

Name	Type	Primitives/Range	Description
Status_Msg.Signal	Floating Point	TBD	This is a code for the type of error message which was generated during the run.
Status_Msg.Source	Integer	0=PGS-directed shutdown 1=Control Process 2=Make Non-Img Cal Coefficients 3=Calibrate 4=Utility Masking 5=Make Img Cal Coefficients. 6=UpDtalize Coefficients 7=Evaluate instrument performance. 8=Make Up dated Coefficient data.	Code for module in which the problem occurred
Stop_Sig	Integer	0=Run Status is OK; process as usual -1=Emergency shutdown. Save all major variables to the status file. 1=Preparing for shutdown. 2=Variables saved, OK to shut down.	Signals shutdowns and the state of the process during the shutdown.
TAS_Blk	Structure	TBD	Data needed by the Trend Analysis and Smoothing module.
TASCalCoeff_Blk	Structure	TBD	Calibration coefficients produced by the Trend Analysis and Smoothing module.
UpDtCoeff_Q	Queue	UpDtCoeff_Q.head UpDtCoeff_Q.tail UpDtCoeff_Q.full	FIFO Queue of orbits of data waiting to be processed.
UpDtCoeff_Q.full	Boolean	0=queue OK 1=queue full	Flag; only necessary if queue is implemented as an array.
UpDtCoeff_Q.head	Pointer		Points to head of queue.

Name	Type	Primitives/Range	Description
UpDtCoeff_Q.tail	Pointer	TBD	Points to tail of queue.
UpDtCoeff_Stat	Integer	0=emergency shutdown 1=idle 2=running 3=successful completion 4=unsuccessful completion	Communicates module status to control process. This structure should make implementaion of asynchronous processing easier. Successful completion means that the Internal-calibration-based calibration coefficients just generated can be used in subsequent modules and should be saved. Unsuccessful completion means that the Status_Msg should be written out to the Status file and the calibration coefficients UpDtCoeff just generated should not be used in further processing.

Appendix A

MCST Inputs to MODLand Paper
"Terrestrial Remote Sensing Science and Algorithms Planned for EOS/MODIS"

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30 January 1993

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MODIS Instruments on EOS Platforms

MODIS (Moderate Resolution Imaging Spectroradiometer) instruments for NASA's EOS (Earth Observing System) satellites for the international Mission-to-Planet-Earth (MPE) are designed to provide the scientific community and the public with 36 different spectral images of the whole Earth every two days for a period of fifteen years. This objective is to be reached by launching three EOS-AM platforms, as well as three EOS-PM platforms, with both being replaced in orbit every five years. The first, EOS-AM1, is scheduled for launch in 1998; EOS-PM1 is scheduled for launch in 2000.

Each EOS-AM and EOS-PM platform will have a MODIS instrument on it. Some of the scientifically significant MODIS instrument requirements are listed in Table 1. Most of these requirements are from the NASA/GSFC (Goddard Space Flight Center) MODIS specification (Weber, 1992). Some are derived or platform requirements. The geometric, spectral and radiometric requirements for MODIS were developed by scientists largely from the heritage of previous satellite missions (Barnes, 1986; Salomonson et al., 1989; King, 1991; and Salomonson and Barker, 1992). These previous missions included the following sensors and satellites (Manual of Remote Sensing, 1983):

6-band/1 Km CZCS (Coastal Zone Color Scanner) on Nimbus-7,
4-band/80m MSS (Multispectral Scanner) on Landsat-1/2/3/4/5 (1972-present),
7-band/30m-120m TM (Thematic Mapper) on Landsat-4/5 (1982-present),
5-band/1 Km AVHRR (Advanced Very High Resolution Radiometer) on NOAA-1-11 (1978-present), and
20-band/~15Km HIRS (High Resolution Infrared Sounder) on Nimbus 6 and NOAA-7.

Some of the scientific reasons for the exact spectral locations from 0.41 to 14.4 μm of the thirty six 250-1000m bands on the MODIS instruments are given in Table 2a (Reflective Solar Bands 1-19) and in Table 2b (Emissive Thermal Bands 20-36). The development of the spectral requirements for these MODIS bands has included considerations such as the avoidance of Fraunhofer lines in the solar irradiance spectrum, avoidance of atmospheric absorption lines and inclusion of key features in target spectra (Barker, et al., 1993a).

The sensor requirements were chosen for observing at-satellite radiances, cloud properties, atmospheric constituents, surface-leaving radiances and surface reflectance for inferring the type and state of various surfaces, and temperatures of the cloud, land and ocean surfaces. These requirements have been factored into the choice of the ground instantaneous field-of-view (GIFOV), spectral tolerances on center wavelength and band width, unsaturated radiometric dynamic range and the signal-to-noise ratios that led to the derived 10-12-bit radiometric sensitivity for MODIS bands (see Tables 3a and 3b). The scientific requirement for monitoring anthropogenic and natural environmental change on a global scale with optical instruments led to the requirement

for nearly daily coverage, which requires an along-scan ground field-of-view (GFOV) swath of 2300 Km for platforms in Sun-synchronous orbit.

The actual design of MODIS was derived from NASA's functional requirements by the MODIS contractor, Santa Barbara Research Center (SBRC). The layout of the detectors on the four focal planes is shown in Figure 1.

Calibration and Data Pre-Processing

The experience of Earth Scientists assembling multi-year data sets of satellite imagery for change detection, e. g. using AVHRR imagery to produce NDVI (Normalized Difference Vegetation Index) maps from even a single instrument, has led to the placing of a high requirement on the MODIS instruments being well calibrated and characterized over their entire operational lifetimes. Glint-free global coverage of the oceans has required that the MODIS instruments be on both the AM and PM platforms. Therefore, imagery from the sensors on these two platforms must be mergible into a single calibrated data set on a daily basis. In addition, the imagery collected from all six MODIS instruments in the EOS/MPE mission must be mergible into a single 15-year data set. Finally, MODIS data must be sufficiently well calibrated and characterized to be comparable to other EOS and non-EOS instruments in order to realize synergistic benefits of simultaneous observations and to extend the historical record for modeling long term global change.

Given the importance and difficulty of the calibration task, the MODIS Science Team has assumed that there will be multiple approaches, some of them discipline specific, to accomplish the required level of precision, accuracy and verification of the characterization and calibration, including both sensor-dependent and sensor-independent methodologies. The MODIS Science Team Leader, Vince Salomonson, has set up a separate organizational entity at Goddard Space Flight Center (GSFC), namely the MODIS Characterization Support Team (MCST), headed by John Barker. MCST has been assigned the primary responsibility for collecting input from these various sources, including the instrument vendor, SBRC, and for integrating the approaches where appropriate. In particular, MCST is to provide a single official Level-1 calibration/characterization algorithm. The calibration algorithm developed by MCST, and the changes made to it over time, are peer reviewed by the MODIS Calibration Review Team chaired by Phil Slater (U. AZ), who is also a member of the MODIS Science Team, with final approval coming from the Science Team and the Team Leader. The geolocation and spatial resampling algorithms will be developed by the MODIS Science Data Support Team (SDST) at GSFC with input from MCST. SDST is headed by Ed Masuoka, with consulting from Al Fleig (U. MD). These geolocation and resampling algorithms are subject to review by MCST and the MODIS Science Team. SDST receives the calibration algorithm from MCST and integrates it with the MODIS product

algorithms provided by the Team Members. SDST then provides the integrated software to the GSFC Distributed Active Archive Center (DAAC) at the ECS/ESDIS (EOS Core System of the Earth Science Data and Information System) ground processing facility. The objectives, approach and schedule of the various aspects of both the pre- and post-launch MODIS characterization and calibration efforts are maintained in a MCST document called the "MODIS Science Calibration Plan" (Barker et al., 1993, ver. 2.6) which is up-dated for meetings of the MODIS Science Team . It is anticipated that there will be the potential for value-added characterization and calibration as a result of on-orbit observations, in addition to the hardware related calibration algorithms supplied by the vendor. As each of these algorithms and characterizations are developed, MCST intends to produce and maintain through the GSFC/DAAC/DADS an electronically accessible "MODIS Science Calibration Handbook" containing and/or referencing the information the working scientist needs to know about the instrument in order to use MODIS imagery.

The primary function of the calibration algorithm is to convert uncalibrated (Level-0) data into spatially unresampled but radiometrically calibrated (Level-1) data. An illustrative flow diagram for generation of this MODIS Level-1 Calibration Product output is shown in Figure 2. EDOS (Earth Data Operations System) transmits the raw Level-0 imagery and accompanying ancillary data from the satellite as relayed to the White Sands, NM receiving station, and then to the West Virginia EDOS Relay/Packaging Station, and finally to the ECS. ECS provides these data to the GSFC/DAAC PGS (Product Generation System) for the production of the Level-1A uncalibrated MODIS imagery and the Level-1B calibrated imagery. The MCST-developed output of the standard Level-1 production process includes browse products/algorithms, and metadata files such as quality assessment products, modeled performance characteristics as a function of time, and calibration site imagery for the GSFC/DAAC DADS (Data Archive and Distribution System) databases. The Level-1 output can be used directly for production of MODIS products or be called up for access by scientists and other users at a later time through the DAAC IMC (Information Management Center). The ECS ICC/EOC (Instrument Control Center of the EOS Operations Center) also receives all the Level-1 output data for comparison with its summary of the condition of the MODIS detector channels based on analysis of all the raw Level-0 input. Error and quality assessment (QA) information on the characterization and calibration is generated automatically by the PGS from MCST-supplied algorithms; additional QA information may be appended through human intervention to the metadata files at a later time from PGS, ICC/EOC or MCST.

The functional calibration requirements on the instrument are explicitly stated in the GSFC MODIS specifications (Weber, 1992), or derived from them by SBRC. The MODIS specification requires absolute radiometric accuracy, A, on the observed spectral radiance, L_λ, of $\pm 5\%$ ($\pm 1\sigma$) for center wavelengths (λ_c) ≤ 3 micrometers, and $\pm$ 1% above 3 μm.

$$AL_\lambda \leq \pm 5\% \ (\pm 1\sigma) \qquad \text{for } \leq 3\ \mu m \qquad \text{Eq 1}$$

$$AL_\lambda \leq \pm 1\% \ (\pm 1\sigma) \qquad \text{for } \lambda_c > 3\ \mu m \qquad \text{Eq 2}$$

An additional on-orbit reflectance, R, requirement is for ± 2% radiometric precision, P, relative to the Sun.

$$PR \leq \pm 2\% \ (\pm 1\sigma) \qquad \text{for } \lambda_C \leq 3\ \mu m \qquad \text{Eq 3}$$

For a constant irradiance source, E, the combined band-to-band spectral and radiometric stability requirements are that the mean calibrated quantified response of each spectral band i, $QCal_i$, shall differ by not more than ± 1 % (± 3σ, with a ± 3σ goal of 0.5%) for any pair of reflectance bands and by ≤ ± 0.5% (± 3σ) for pairs of emissive bands for any time period of up to two weeks. For all time scales from two weeks to five years, the reflective pair differences, $\Delta QCal_{ij,E}$, shall be ≤ ± 2 % and the emissive pair differences ≤ ± 1 %.

$$\Delta QCal_{ij,E} \equiv QCal_{i,E} - QCal_{j,E} \qquad \text{Eq 4}$$

$$\Delta QCal_{ij,E} \leq \pm 1\ \% \ (\pm 3\sigma) \text{ req.} \qquad \text{for } \lambda_C \leq 3\ \mu m,\ \Delta t < 2\ w \qquad \text{Eq 5}$$

$$\Delta QCal_{ij,E} \leq \pm 0.5\ \% \ (\pm 3\sigma) \text{ goal.} \qquad \text{for } \lambda_C \leq 3\ \mu m,\ \Delta t < 2\ w \qquad \text{Eq 6}$$

$$\Delta QCal_{ij,E} \leq \pm 0.5\ \% \ (\pm 3\sigma) \text{ req.} \qquad \text{for } \lambda_C > 3\ \mu m,\ \Delta t < 2\ w \qquad \text{Eq 7}$$

$$\Delta QCal_{ij,E} \leq \pm 2\ \% \ (\pm 3\sigma) \text{ req.} \qquad \text{for } \lambda_C \leq 3\ \mu m,\ 2\ w \leq \Delta t < 5\ y \qquad \text{Eq 8}$$

$$\Delta QCal_{ij,E} \leq \pm 1\ \% \ (\pm 3\sigma) \text{ req.} \qquad \text{for } \lambda_C > 3\ \mu m,\ 2\ w \leq \Delta t < 5\ y \qquad \text{Eq 9}$$

Additional spectral stability requirements on center wavelength, λ_C (Tables 3a & 3b), and bandwidth, Δλ (Tables 3a & 3b), on each band for the duration of the mission are better than 2 nanometers (nm) in the visible and 1 % of the center wavelength elsewhere. This includes shifts caused by changes of humidity, temperature, pressure, vibrations, or time.

$$\Delta\lambda_C \leq \pm 1\ nm \ (\pm 3\sigma) \qquad \text{for } \lambda_C \leq 0.7\ \mu m,\ \Delta t < 5\ y \qquad \text{Eq 10}$$

$$\Delta\lambda_C \leq \pm 0.5\ \%\ \lambda_C \ (\pm 3\sigma) \qquad \text{for } \lambda_C > 0.7\ \mu m,\ \Delta t < 5\ y \qquad \text{Eq 11}$$

$$\Delta\Delta\lambda \leq \pm 1\ nm \ (\pm 3\sigma) \qquad \text{for } \lambda_C \leq 0.7\ \mu m,\ \Delta t < 5\ y \qquad \text{Eq 12}$$

$$\Delta\Delta\lambda \leq \pm 0.5\ \%\ \lambda_C (\pm 3\sigma) \qquad \text{for } \lambda_C > 0.7\ \mu m,\ \Delta t < 5\ y \qquad \text{Eq 13}$$

A critical requirement for the land community is that the pixels from each band be inherently registered to at least 0.2 pixel, with a goal of 0.1 pixel, so that 1) the instrument can function as a spectroradiometer, where data from the different bands can be compared directly because they correspond to the same area on the ground, and 2) multi-band geophysical information can be produced at Level-2 without the loss of resolution that would be associated with spatial resampling to Level-3 products in the ground processing. This inherent co-registration requirement for any two corresponding detector elements/channels, in spatially unresampled Level-1 and Level-2 xy (row x column) imagery is given by Eqs 14-19, where the x coordinate of a pixel in the imagery is in the along-scan direction and y is in the along-track direction:

$$\Delta x_{ij} \equiv x_{i,L1GIFOV} - x_{j,L1GIFOV} \qquad \text{for any pair or bands i,j} \qquad \text{Eq 14}$$

$$\Delta y_{ij} \equiv y_{i,L1GIFOV} - y_{j,L1GIFOV} \qquad \text{for any pair of bands i,j} \qquad \text{Eq 15}$$

$$\Delta x_{ij} \ \& \Delta y_{ij} \leq \pm 20\ \% \ (\pm 3\sigma) \text{ req.} \qquad \text{for } GIFOV_i = GIFOV_j \qquad \text{Eq 16}$$

$$\Delta x_{ij} \ \& \ \Delta y_{ij} \leq \pm 10\ \% \ (\pm 3\sigma) \text{ goal.} \qquad \text{for } GIFOV_i = GIFOV_j \qquad \text{Eq 17}$$

For 4 $GIFOV_i$ (500m pixels) overlaid on 1 $GIFOV_j$ (corresponding 1000m pixel)
and for 16 $GIFOV_i$ (250m) overlaid on 1 $GIFOV_j$ (1000m)

Δx_{ij} &$\Delta y_{ij} \leq 200$ m ($\pm$ 20 % ($\pm 3\sigma$) of the 1000 m pixel) req Eq 18

Δx_{ij} &$\Delta y_{ij} \leq 100$ m ($\pm$ 20 % ($\pm 3\sigma$) of the 1000 m pixel) goal Eq 19

Commandable adjustment of the cross-track (y-direction) registration between focal planes shall be better than 25 m. In order to increase the probability of success in meeting these calibration requirements, it is further required that "more than one approach shall be used to verify the calibration accuracy and provide additional confidence in the measurements" and that "all accuracy's shall be established relative to National Institute of Standards and Technology (NIST) standards and standard procedures." These and other requirements of the MODIS instrument specification reflect the scientific importance of calibration and characterization to assure the usefulness of a continuous 15-year dataset.

The MODIS instrument has been designed by SBRC to meet the functional and derived calibration requirements. In particular, the on-board calibrators (OBCs, Barker and Young, 1993) and sensor-based methods consist of the SRCA (Spectro-Radiometric Calibration Assembly), the Solar Diffuser (SD) Plate and associated Solar Diffuser Stability Monitor (SDSM), Blackbody (BB), and a view of space and the Moon (Figure 2).

SRCA: The SRCA is a 1/4 aperture calibration instrument on MODIS that provides for the first time on an Earth Science satellite an active on-orbit method that can characterize spectral ($0.4 \leq \lambda_C \leq 2.0$ µm) and spatial (all bands) changes in the instrument performance characteristics, in addition to providing both a pre-launch to on-orbit traceable absolute radiometric transfer standard for the solar diffuser ($0.4 \leq \lambda_C \leq 2.2$ µm) and a within-orbit radiometric calibration mechanism. The SRCA provides observations to verify the radiometric requirements in Eq 1 and the stability requirements in Eqs 5-13 & Eqs 16-17 for $\lambda_C \leq 2.2$ µm, for time scales of the order of minutes to weeks for the radiometry and to years for spectral and spatial changes.

SD/SDSM: The solar diffuser is designed to provide two ranges of radiances that differ by a factor of ten to cover the dynamic range of all the reflective bands whenever the SD door is open when passing over the North Pole. Since degradation of the full aperture diffuser plate is perceived to be a major concern, even with a pure Teflon-type diffuser, the SDSM is an instrument designed to alternately look at the Sun and the SD to provide a calibration of the SD. Given the presumed known irradiance from the Sun, the solar diffuser provides for radiometric calibration to meet the 2 % precision requirement (Eq 3) on a time scale of days to a few years, depending on the stability of the SDSM.

BB: The full-aperture blackbody is an aluminum plate with V-grooves cut at 25° half angles. The plate will be painted with a specular black paint to provide a high effective emissivity ($\geq$0.992). The blackbody will be allowed to float thermally and its temperature will be monitored to an accuracy of 0.1 K. The SRCA provides observations to calibrate the emissive bands, in order to meet the radiometric requirements in Eq 2 for the full five year+ mission of each MODIS instrument.

Space View: Space is viewed once per scan by all the bands through the space port. For the emissive bands, this will provide the second temperature calibration point for a linear calibration, as required with the BB to satisfy Eq 2. In addition, the possibility of a lunar radiometric calibration of the reflective bands on a time scale of 2-5 years in provided by the fact that the Moon passes through the view of the space port approximately two to six times per year at approximately 22.5 degrees beyond the first quarter, i.e. about 1/4th of full Moon. Even with the necessary spectral model of lunar reflectance of solar irradiance with time and viewing geometry over the full lunar cycle, this infrequent viewing of a partial Moon is probably not sufficient for radiometric calibration of the 1000 m MODIS bands without additional direct observations of the full Moon with near horizon viewing.

The required redundant approaches to calibration and the on-board MODIS calibration mechanisms represent the most significant committment to calibration in an Earth Science satellite instrument to date.

In addition to the on-board sources, the MODIS calibration efforts will include study of scene-based calibration processes, direct lunar observations, night-time imagery, and scene-dependent spectral, radiometric and spatial inversion algorithms. The routine scene-based methodologies include a modified version of histogram equalization for homogeneous targets and a radiometric rectification procedure using cloud-free daylight satellite observations of calibration sites on the ground. The histogram equalization procedure provides an at-launch within orbit de-stripping method for within-band relative radiometric calibration (Eqs 1-3). The radiometric rectification procedure (Hall et al., 1991) will require on-orbit verification of the slowly varying and predictable radiometric properties of perhaps 10-100 calibration sites per orbit, which may take several years and iterative removal of the atmosphere. Because of the stability of the atmosphere-free lunar surface and the knowability of solar irradiance, direct near-horizon viewing of the Moon at near zero phase on a monthly basis potentially provides the best chance of multi-year and cross-instrument calibration during the 15-year MODIS/EOS mission. Furthermore, the known spherical shape and sharp radiometric edge of the Moon provides an independent means of measuring changes in the spatial MTF (Modulation Transfer Function) of the MODIS bands as function of time in orbit. Observations at night throughout the life-time of the mission will be used to provide the basis for corrections for systematic errors such as coherent noise. For enhanced radiometry at the cost of reduced spatial resolution, scene-dependent MTF-inversion algorithms will be examined. With the SRCA spectral information it may be possible to provide spectral calibration for those investigators who would use a coarse spectral correction based on masking and known target spectra. Finally, traditional methods of aircraft (Abel et al., 1993) and ground observations(Slater et. al., 1990) of targets at the time of satellite overpass will be used to verify the radiometric methodologies. While none of these target- or scene-based sensor-independent methodologies offers the same short-term potential for enhanced precision and accuracy of the routine and repeated on-orbit use of the OBCs, they do substantially lower the risk of mission failure, due to OBC failure, by providing independent approaches to radiometric calibration.

The MODIS Level-1 calibration product (flow chart in Fig 2) is intended to be as accurate and stable as possible. While there will be adjustments in the calibration algorithm during the 3-6 month check out and on-orbit optimization phase, and in the early phases of operation, it is anticipated that a few months of observations will be sufficient to identify the best methodologies for each band and that changes in the algorithm itself will be less and less frequent with time in orbit. MODIS imagery will be made available to users without hold-up for changes in calibration methodology. The initial algorithm will depend heavily on the vendor supplied instrument based calibration algorithm. Other methods will be used on a band by band basis to the extent that they improve the calibration precision and accuracy. Fitting parameters for the algorithm will be calculated as a moving multi-orbit average. Calibration databases will be maintained and linked by pointer files in such a way that a user will have access to a quantitative measure of any difference between the calibration applied to a scene on a given date and the best current estimate of a calibration if it were reapplied with the benefit of the increased trending and modeling. It is the intention to have all significant information on the state of the instrument and the calibration, including independent calibration information from validation and verification experiments, available to users as an integral part of the ECS/DADS metadata information. One of the objectives of the MODIS math models is to take advantage of the inherently high precision and stability of the MODIS instrument to reduce the effect of systematic errors over time. The long-term objective for MODIS calibration is to provide "value-added" calibration capability from both empirical and predictive models based on in-orbit measurement of the model fitting parameters and observations of several instruments over periods of years.

Field observations are a part of both national and international efforts to assure the success of the MPE global change program. One international group in which these efforts are being coordinated is the Calibration and Validation Working Group (CVWG) of the Infrared and Visible Optical Sensors (IVOS) subgroup of the Committee on Earth Observation Satellites (CEOS). IVOS recommends that CEOS member agencies support the identification, characterization, and maintenance of ground test sites and their associated databases for the verification of on-board calibration systems, the in-orbit calibration, and subsequent cross-calibration of instruments. Another group which is known as the Calibration Test Site and Cross-Calibration Effort is the EOS Cal/Val Panel. MODIS team members are responsible for validating both the MODIS calibration and the MODIS data products. In pre-launch studies such as the one on MODIS spectral requirements (Barker et al., 1993a) the MODIS scientists are working with MCST to develop sensitivity curves quantitatively relating product accuracy to errors in calibration and characterization.

One of the standard MODIS products will be a generic cloud mask product. It will be developed by MCST in collaboration with members of the MODIS science team. The utility masks associated with this product will be produced as part of the Level-1 calibration process, therefore, they will be available, if desired, for use in the production of any other Level-2 or higher data products. Initially, this generic masking product will be three 32-bit Level-2A images, one for each of the different 250, 500 and 1000 m MODIS spatial resolutions. The bits in these images are each masks which will contain binary information on each pixel on the "definite" presence or absence of: clouds, snow/ice, water, land, glint, vegetation, shadow, spectral outlier, spatial center/edge, and day/night terminator lines. There will be different discipline-dependent masks for some of these classes. For some cases, there will be mixture information on the pixel. There will be different algorithms for daytime and nighttime imagery. This standard masking product will be available for all MODIS datasets. Some of the science team members will chose to develop their own masks as necessary for their specific products.

Cloud detection algorithm development efforts in the science community (Chou 1986) have evolved two categories of approaches: those using statistical methods and those using fixed thresholding. Statistical methods can respond to mixture pixels containing varying proportions of cloud and can respond to changes in cloud and background characteristics due to changing location and time. Threshold methods are less complex and can be tailored to work well on limited data. Rossow et. al. (1985) conducted an extensive comparison of six cloud algorithms and found that all performed similarly but none could be considered optimum. MCST is developing an approach to the masking utility algorithm which is statistically based and uses a multi-band texture pure pixel extraction step prior to clustering and classification of the mask categories. Both spectral and spatial clustering are used with database labeling of mask categories. An illustrative flow diagram for the MODIS cloud-masking utility product is given in Figure 3. The masking algorithm is being developed in the context of the needs of the MODIS science community with interaction with the groups identified in Figure 4 to insure that acceptable characteristics and performance levels are achieved for the products.

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MCST Figures and Tables For the MODLand Paper

Figures

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Figure 2: MODIS Level-1 Calibration Product: Illustrative Flow Diagram
Figure 3: MODIS Cloud Masking Utility Product: Illustrative Flow Diagram
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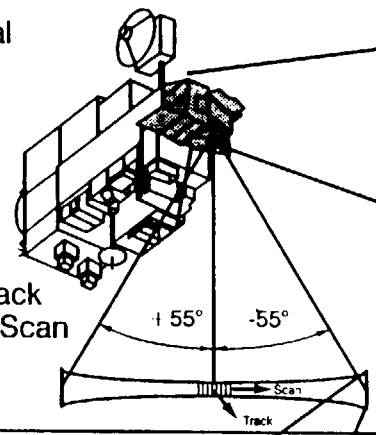
Table 2a: Reflective Bands Scientific Purposes
Table 2b: Emissive Bands Scientific Purposes
Table 3a: Reflective Band Requirements for MODIS Instruments
Table 3b: Emissive Band Requirements for MODIS Instruments

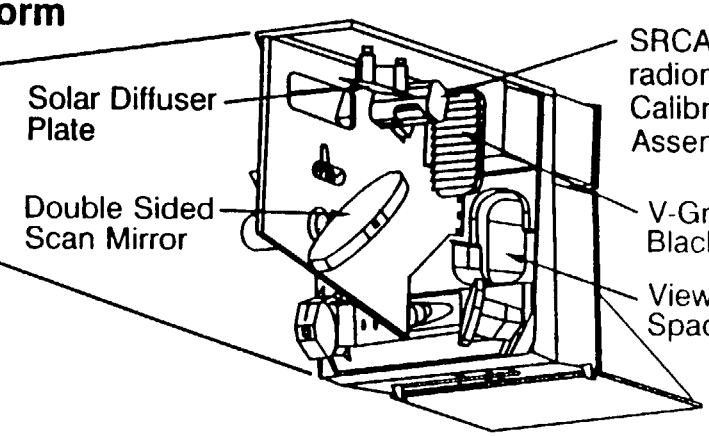
MODIS Earth-View and Cutaways

MODIS Instrument on EOS-AM Platform

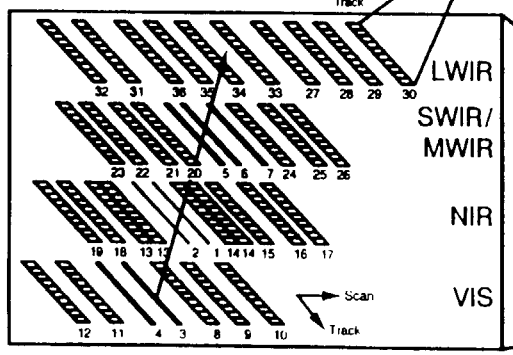
10:30 AM Equatorial Crossing Time in 705 Km Descending Polar Orbit

10-20 Km Along-Track by 2300 Km Along-Scan Ground Swath on the Earth





On-Board Calibrators (OBCs) in MODIS Scan Cavity



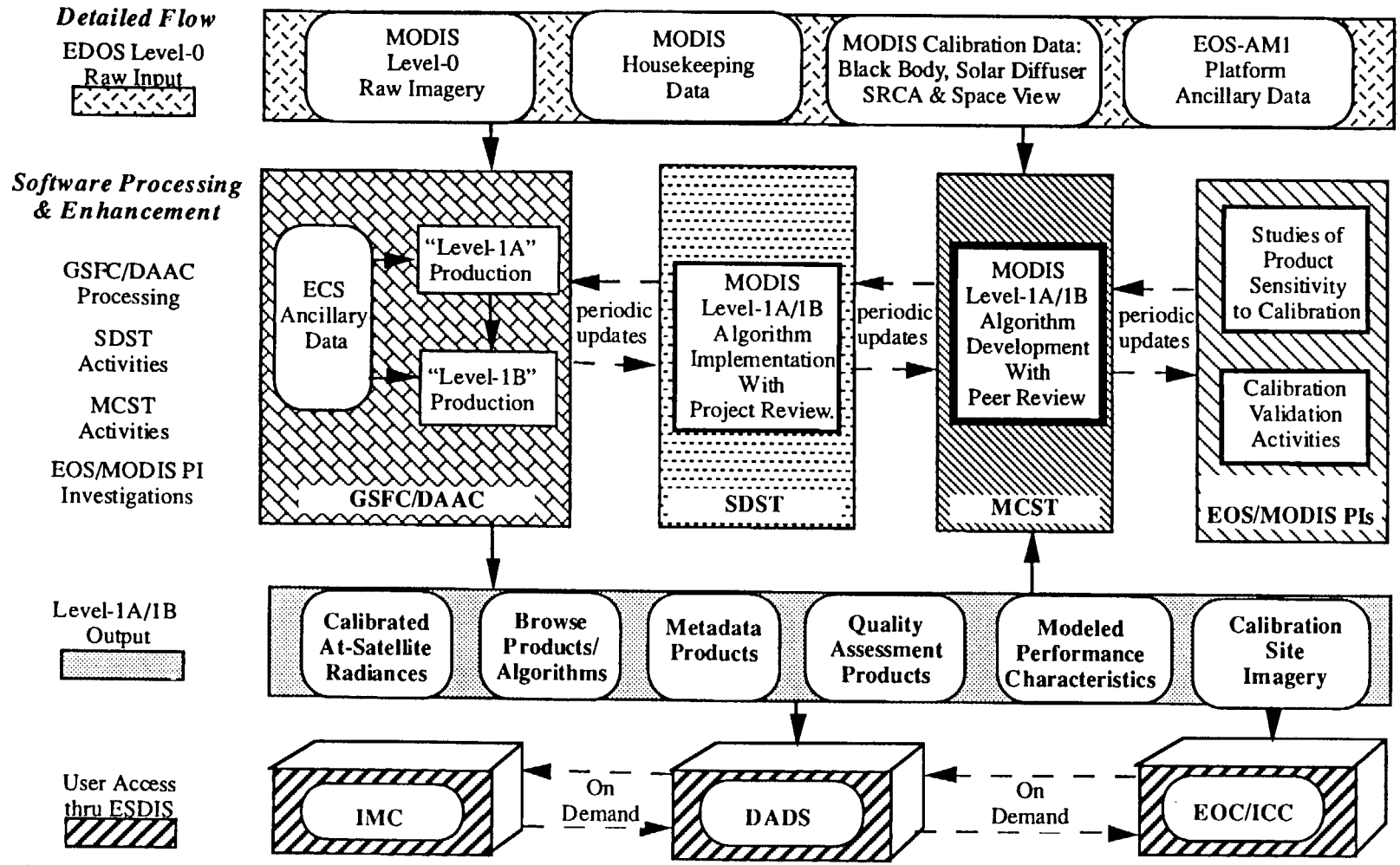
Four Co-Registered Focal Planes

- Long-Wave Infrared Emissive Bands
- Short and Mid-Wave Infrared Bands
- Near-Infrared and Sharpening Bands
- Visible Bands for Land and Ocean

36 MODIS Spectral Bands

MODIS Level-1 Calibration Product

Illustrative Flow Diagram



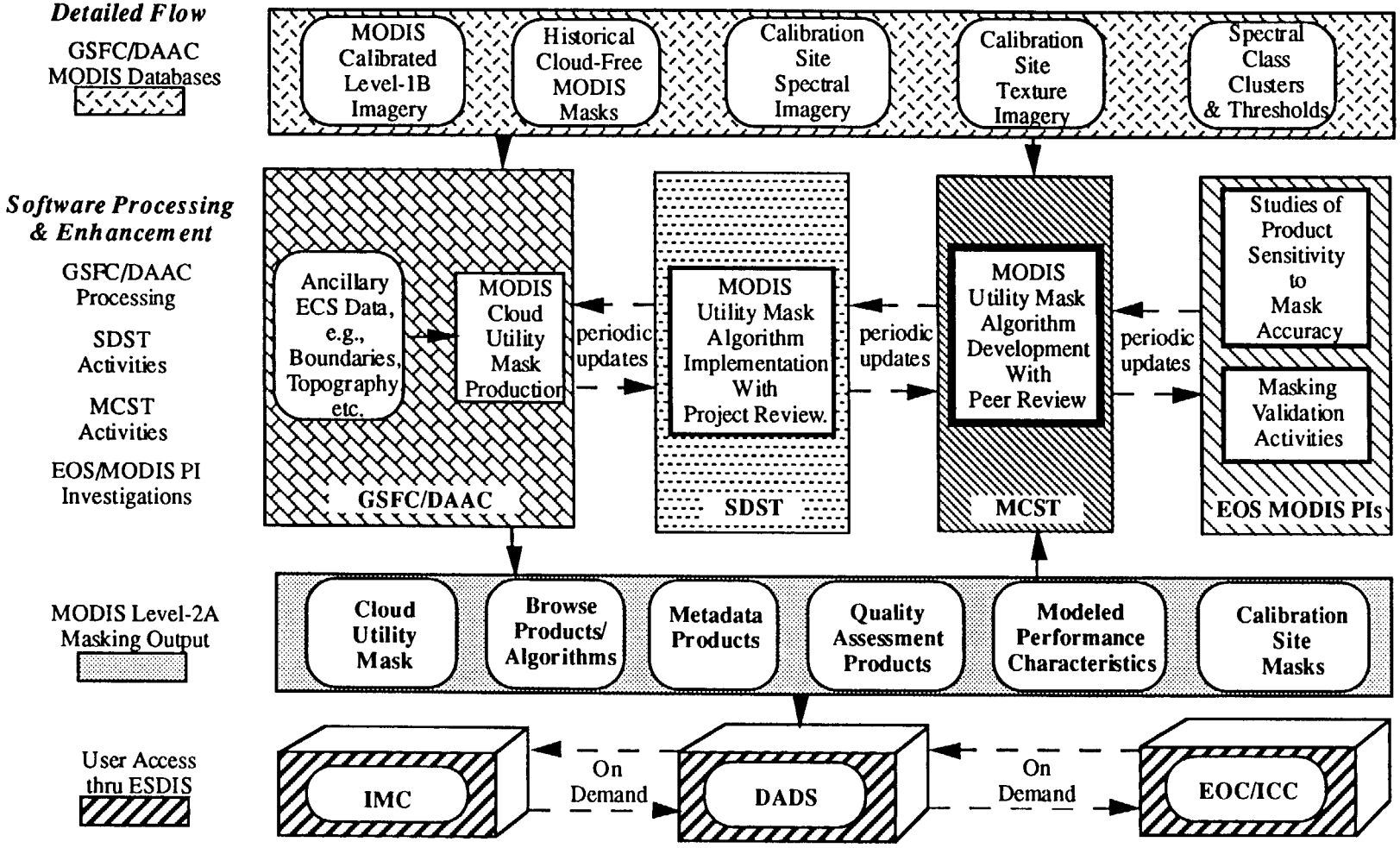
EOS MODIS Characterization Support Team (MCST)
Date: 12/31/92 Time: 3:05 p.m.

Figure 2

John L. Barker/NASA/GSFC/925/MCST
File: Fig2 L-1 Flow

MODIS Cloud-Masking Utility Product

Illustrative Flow Diagram



EOS MODIS Characterization Support Team (MCST)
Date: 12/31/92 Time: 3:05 p.m.

Figure 3

John L. Barker/NASA/GSFC/925/MCST
File: Fig3 Mask Flow

MODIS Cloud Masking Utility Interfaces (Context Diagram)

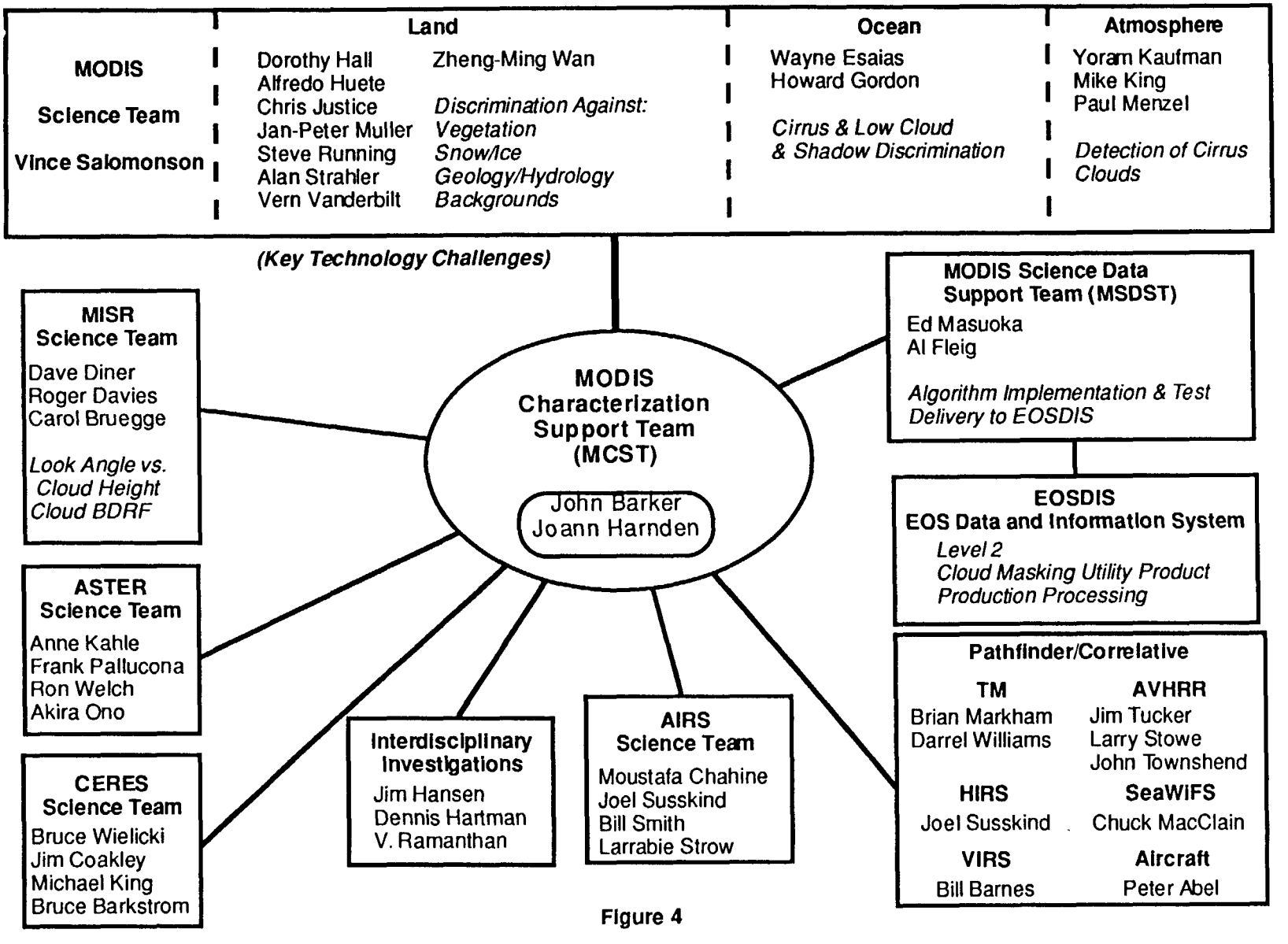


Figure 4

Table 1
MODIS Instrument Requirements

Variable/Parameter	Symbol	Requirement
Equatorial Crossing Time	t	10:30 AM Descending EOS-AM Orbit Platforms 1:30 PM Ascending EOS-PM Orbit Platforms
Platform Altitude	H	705 Km
Number of Spectral Bands	N	36 from 0.41 to 14.4 μm
Ground Swath	GFOV	2330 Km Along-Scan by 10-20 Km Along-Track
Angular Swath	FOV	$\pm$ 55° Along-Scan by 14 milliradians Along-Track
Ground Resolution	GIFOV	Band-Dependent 250m, 500m and 1000m @Nadir Band-Dep. 375m, 750m and 1500m at $\pm$ 45° Band-Dep. 500m, 1000m and 2000m at $\pm$ 55°
Angular Resolution	IFOV	0.354 mr, 0.709 mr, 1.418 mr (all $\pm$ 6%)
Band-to-Band Registration	BBR	< 0.1 IFOV goal, < 0.2 IFOV Requirement (3σ)
Quantization	n	10-12 Bit (to meet Signal-to-Noise (SNR) Spec)
Modulation Transfer Function	MTF	0.3 at Nyquist Frequency
Polarization Factor Insensitivity	PF	< 2%, 0.41 to 2.2 μm
Volume (Length x Width x Height)	V = l x w x h	< 1 x 1.6 x 1 m
Mass	M	< 250 Kg
Power	P	< 225 W average, < 275 W peak
Operating/Duty Cycle	OC	100%
Data Rates (with overhead)	DR	< 11 Mbps (Day Mode) < 3 Mbps (Night Mode)
Pointability Angle of Optical Axis	PA	$\pm$ 20° from Horizon (Full Phase of Moon)
Absolute Radiometric Accuracy	AL	$\pm$ 5% (1σ) $\leq$3 μm, $\pm$ 1% (1σ) > 3 μm
On-Orbit Reflectance Precision	PR	$\pm$ 2% (1σ) $\leq$ 3 μm relative to the Sun

Table 2a

Band N	Ground Resolution GIFOV [m]	FWHM Band Pass* Lower Bandpass λMin [nm]	FWHM Band Pass* Upper Bandpass λMax [nm]	Primary Scientific Purpose
1	250	620	670	Vegetation Chlorophyll Absorption Land Cover Transformations Cloud/Edge Detection/Masks
2	250	841	876	Cloud/Vegetation/Water/Edge Detection Land Cover Transformations/Masks
3	500	459	479	Soil & Vegetation Differences
4	500	545	565	Green Vegetation
5	500	1230	1250	Leaf & Canopy Properties
6	500	1628	1652	Snow & Cloud Differences/Masks
7	500	2105	2155	Land & Cloud Properties
8	1000	405	420	Water Color (Chlorophyll/Pigments/Sediments) Atmospheric Scattering/Cloud Mask
9	1000	438	448	Water Color
10	1000	483	493	Water Color
11	1000	526	536	Water Color
12	1000	546	556	Sediments
13	1000	662	672	Sediments, Atmosphere
14	1000	673	683	Chlorophyll Fluorescence
15	1000	743	753	Aerosol Properties
16	1000	862	877	Aerosol and Atmospheric Properties
17	1000	890	920	Water Vapor/Atmospheric Properties
18	1000	931	941	Water Vapor/Atmospheric Properties
19	1000	915	965	Water Vapor/Atmospheric Properties
26	1000	1360	1390	Cirrus Cloud/Cloud Mask

*** FWHM (Full Width at Half Maximum) = λMax-λMin, where $\lambda Max=\lambda_c+(BW/2)$ and $\lambda Min=\lambda_c-(BW/2)$**

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

Table 2b

Band N	Ground Resolution GIFOV [m]	FWHM Band Pass* Lower Bandpass λMin [nm]	FWHM Band Pass* Upper Bandpass λMax [nm]	Primary Scientific Purpose
20	1000	3660	3840	Sea Surface Temperature
21	1000	3931	3987	Forest Fires / Volcanoes
22	1000	3929	3989	Cloud
23	1000	4020	4080	Cloud / Surface Temperature/Cloud Mask
24	1000	4433	4498	Cloud / Surface Temperature/Cloud Mask
25	1000	4482	4549	Tropical Temperature / Cloud Fraction
26	**Moved to Table 2a**			
27	1000	6535	6895	Tropical Temperature / Cloud Fraction
28	1000	7175	7475	Mid-Tropical Humidity
29	1000	8400	8700	Upper-Tropical Humidity
30	1000	9580	9880	Surface Temperature/Cloud Mask
31	1000	10780	11280	Total Ozone
32	1000	11770	12270	Cloud / Surface Temperature
33	1000	13185	13485	Cloud / Surface Temperature
34	1000	13485	13785	Cloud Height & Fraction
35	1000	13785	14085	Cloud Height & Fraction
36	1000	14085	14385	Cloud Height & Fraction

*** FWHM (Full Width at Half Maximum) = λMax-λMin, where λMax=λ_c+(BW/2) and λMin=λ_c-(BW/2)**

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

Table 3a

Band N	Ground Resolution GIFOV [m]	Center Wavelength λ [nm]	Center Wavelength Tolerance TCW [nm,1σ]	Band Width Δλ [nm]	Band Width Tolerance TBW [nm,1σ]	Max Spectral Radiance LMax [W/m^2-μm)]	Noise Equiv. Spectral Radiance NEdL [W/m^2-μm)]	Signal to Noise Ratio SNR [unitless]	Max Reflectance * RMax [unitless]
1	250	645	4	50	4.0	685	0.169	128	1.43
2	250	858	2.2	35	4.3	285	0.123	201	0.96
3	500	469	4	20	2.8	593	0.145	243	1.01
4	500	555	4	20	3.3	518	0.127	228	0.93
5	500	1240	5	20	7.4	110	0.073	74	0.78
6	500	1640	7	** 25	9.8	70	0.027	275	1.02
7	500	2130	8	50	12.8	22	0.009	110	0.81
8	1000	412	2	15	1.5	175	0.051	880	0.33
9	1000	443	1.1	10	1.6	133	0.050	838	0.23
10	1000	488	1.2	10	1.7	101	0.040	802	0.18
11	1000	531	2	10	1.9	82	0.037	754	0.14
12	1000	551	5	10	1.4	64	0.028	750	0.12
13	1000	667	[+1, -2]	10	1.7	32	0.010	910	0.08
14	1000	678	1	10	1.7	31	0.008	1087	0.07
15	1000	748	2	10	1.9	26	0.017	586	0.07
16	1000	869	5	15	4.3	16	0.012	516	0.06
17	1000	905	2.3	30	5.4	185	0.060	167	0.67
18	1000	936	2.3	10	5.6	256	0.063	57	1.00
19	1000	940	2.4	50	5.6	189	0.060	250	0.74
26	1000	1375	6	30	8.0	** 90	0.040	150	1.00

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

* Used to derive MODIS Specification.
** Band Width = 24.6 and Max Spectral Radiance = 89.9 as stated in MODIS Specification.

Table 3b

N	Ground Resolution GIFOV [m]	Center Wavelength λ [nm]	CW Tolerance TCW [nm,1σ]	Band-width Δλ [nm]	BW Tolerance TBW [nm,1σ]	Max. Spectral Radiance LMAXλ [W/m^2-μm)]	Noise Equivalent Spectral Radiance NEdL [W/m^2-μm)]	Maximum Temperature * TMax [K]
20	1000	3750	19	180	22.5	1.71	0.001	335
21	1000	3959	20	59.4	23.8	86.00	0.150	500
22	1000	3959	20	59.4	23.8	1.89	0.002	328
23	1000	4050	20	60.8	24.3	2.16	0.002	328
24	1000	4465	22	65	26.8	0.34	0.002	264
25	1000	4515	22	67	27.1	0.88	0.006	285
26	**Moved to Table 3a**							
27	1000	6715	34	360	40.3	3.21	0.011	271
28	1000	7325	37	300	44.0	4.46	0.017	275
29	1000	8550	43	300	51.3	14.54	0.009	324
30	1000	9730	49	300	58.4	6.34	0.022	275
31	1000	11030	55	500	66.2	13.25	0.007	324
31-hi	1000	11030		500		29.08	0.247	400
32	1000	12020	60	500	72.1	12.10	0.006	324
32-hi	1000	12020		500		25.07	0.198	400
33	1000	13335	67	300	80	6.56	0.018	285
34	1000	13635	68	300	81.8	5.02	0.016	268
35	1000	13935	70	300	83.6	4.42	0.014	261
36	1000	14235	71	300	85.4	2.96	0.015	238

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

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

*Used to derive MODIS Specification.

Table C-12: Processing Load

Asrar Plus

Platform	Launch Date	Instrument	Processing Load (MFLOPS) L-1	L-2	L-3	Others *	Total
COLOR	Jan-1998	SeaWiFS	20.833	7.510	7.270		35.613
AM-1	Jun-1998	ASTER	N/A	18.016	0.018		18.033
		CERES	0.450	27.928	0.196	11.000	39.574
		MISR	16.523	22.204	8.930		47.657
		MODIS	36.407	33.052	1.070		70.530
		MOPITT	0.117	0.469	0.039		0.625
		Total	53.497	101.669	10.253	11.000	176.419
AERO	Jun-2000	SAGE III	0.162	0.029	0.006		0.196
PM-1	Dec-2000	AIRS	7.301	21.886	0.023	11.700	40.910
		AMSU-A	0.014				0.014
		CERES	0.450	27.928	0.196	11.000	39.574
		MHS	0.041				0.041
		MIMR	0.093	0.000	0.000		0.094
		MODIS	36.407	33.052	1.070		70.530
		Total	44.306	82.867	1.289	22.700	151.162
ALT	Jun-2002	ALT	0.000	0.002	0.000		0.002
		GGI	3.600	3.939			7.539
		GLRS-A	6.100	0.071	0.018		6.188
		Total	9.700	4.012	0.018		13.730
CHEM	Jun-2002	HIRDLS	12.731	3.160	0.632		16.524
		TES	30.000	50.768	5.077		85.845
		SAGE III	0.162	0.029	0.006		0.196
		STIKSCAT	0.100	0.350			0.450
		Total	42.994	54.307	5.714		103.015

* *Including those required for analysis*

Tech Team
2-11-93
Attachment 2

Table C-1: Daily Data Volume

Asrar Plus

Platform	Launch Date	Instrument	Avg. Data Rate (Kbps)	Daily Data Volume (GB/day)					Total (L0 - L3)
				L-0	L-1A	L-1B	L-2	L-3	
COLOR	Jan-1998	SeaWiFS	282.576	3.144	0.690		0.460	1.000	5.294
AM-1	Jun-1998	ASTER *	8300.000	89.640	131.472	131.472	0.798	0.010	353.393
		CERES	20.000	0.216	0.317	0.317	0.459	0.074	1.382
		MISR	3800.000	41.040	60.192	60.192	1.637	1.307	164.368
		MODIS	6200.000	66.960	98.208	98.208	19.474	11.714	294.564
		MOPITT	6.000	0.065	0.095	0.095	0.006	0.001	0.262
		Total	18326.000	197.921	290.284	290.284	22.374	13.107	813.969
AERO	Jun-2000	SAGE III	14.075	0.152	0.223	0.223	0.136	0.068	0.802
PM-1	Dec-2000	AIRS	1420.000	15.336	22.493	22.493	0.079	0.059	60.459
		AMSU-A	3.200	0.035	0.051	0.051			0.136
		CERES	20.000	0.216	0.317	0.317	0.459	0.074	1.382
		MHS	4.200	0.045	0.067	0.067			0.178
		MIMR	67.000	0.724	1.061	1.061	0.027	0.000	2.873
		MODIS	6200.000	66.960	98.208	98.208	19.474	11.714	294.564
		Total	7714.400	83.316	122.196	122.196	20.038	11.847	359.593
ALT	Jun-2002	ALT	85.000	0.918	1.346	1.346	0.001		3.612
		GGI	50.000	0.540	0.792	0.792	0.015	0.008	2.148
		GLRS-A	400.000	4.320	6.336	6.336	0.024	0.006	17.022
		Total	535.000	5.778	8.474	8.474	0.040	0.015	22.781
CHEM	Jun-2002	HIRDLS	40.000	0.432	0.634	0.634	0.014	0.003	1.717
		TES	406.000	4.385	6.431	6.431	0.006	0.003	17.256
		SAGE III	14.075	0.152	0.223	0.223	0.136	0.068	0.802
		STIKSCAT	5.200	0.056	0.082	0.082	0.004		0.224
		Total	465.275	5.025	7.370	7.370	0.160	0.075	19.999

* *Many of ASTER L2 products are on-demand products which will not be archived but will be regenerated each time as requested. Volume estimates for these data products are not included in the table.*

Note: Volume estimates are for standard data products only and do not include post-launch data products.