MODIS DATA STUDY
TEAM PRESENTATION

December 15, 1989

AGENDA

1. Compatibility of MODIS and HIRIS for Ocean Color (Comments of Ken Carder)
2. Atmospheric Correction in Terrestrial Studies (Comments of Yoram Kaufman)
3. High-Level Flows for Routine Level-1 MODIS Data Processing
4. MODIS Browse Data Generation and Storage
5. Sub-Sampling for Time and Space Representations
6. Calibration Utility Requirements
7. Atmospheric Corrections Needed for Producing Level-2 Land-Leaving Radiances [Preliminary]
8. MODIS Data Navigation Algorithm Requirements

Compatibility of MODIS and HIRIS for Ocean Color

The compatibility of MODIS and HIRIS ocean color observations was discussed with Dr. Ken Carder, who serves on the Science Team for both sensors. This report derives from the discussion, on December 14, 1989.

Generally, Dr. Carder felt that it was too early to quantitatively define how MODIS and HIRIS might be used together, but that observations from each should be complementary. MODIS is an operational sensor, while HIRIS will only be turned on by demand, such that HIRIS will probably operate mostly in conjunction with field experiments. This will allow HIRIS to be fine-tuned to observations, and, coupled with its already very high signal-to-noise ratio (SNR), should allow it to obtain higher accuracies than MODIS. But its coverage is extremely limited, allowing it to observe only sporadic, regional events as opposed to MODIS, which is capable of providing insights into global change questions.

However, rather than use HIRIS as a potential data validation source for MODIS, Dr. Carder saw MODIS as providing better aerosol determinations (due to its wider field-of-view and better Earth coverage) to improve HIRIS accuracies. HIRIS would most likely complement MODIS by providing observations of sub-MODIS-pixel scale chlorophyll/cloud patches.

Dr. Carder envisions using MODIS as the primary ocean color sensor, particularly in the open ocean. As one approaches the land/ocean boundary, the high spatial resolution (24 m) of HIRIS will allow observations of coastal features, such as the Mississippi River plume. HIRIS will also provide better coverage of estuarine and inland lake regions, thus allowing extension of the MODIS global coverage into these areas, which have significant anthropogenic importance and influence.

Estimated accuracies for HIRIS were due in part to its high SNR, but also to expected improvement due to averaging procedures to be used with the observations. In addition, HIRIS can achieve very high accuracy when in stare mode, by virtue of further reduction in SNR. However, stare mode can provide only very limited coverage and is likely not going to be used except in exceptional circumstances. In the real ocean, however, it is probably in-water optical constituents (e.g., dissolved organic matter, suspended sediments, etc.) and aerosol estimations that will limit the accuracy of both HIRIS and MODIS in determining water-leaving radiances and hence chlorophyll.

ATMOSPHERIC CORRECTION IN TERRESTRIAL STUDIES

On Monday, December 11, George Riggs, Doug Hoyt, and Watson Gregg met with Yoram Kaufman to discuss the subject of atmospheric correction in terrestrial studies.

Dr. Kaufman explained that the atmospheric correction process could be divided into two steps:

1. Derivation of the physical composition of the atmosphere, from data collection and theory

2. Use of an appropriate radiative transfer code to make the atmospheric corrections.

Dr. Kaufman thought that the need for atmospheric correction depends on what the data product will be used for and that for some data products some atmospheric effects may be taken as negligible.

There is yet much developmental work that needs to be done in some areas, especially regarding corrections for aerosols. Most of the discussion focused on Dr. Kaufman's work with correcting for aerosol scattering. Aerosols are the major component in the estimation and correction of the atmospheric effect. If enough is known about the aerosol climatology and/or surface features of an area then it may be possible to correct for some of the aerosol effect. One problem with aerosols is that knowledge of their temporal and spatial variability is required to make an accurate correction for their effect. In Kaufman and Sendra[1] an algorithm for atmospheric correction of the aerosols (aerosol optical thickness) in the visible and near-IR for satellite imagery is presented; it is dependent on the presence of a dense, dark vegetation target in the image. From this discussion, it would appear that a atmospheric correction for aerosols, over land, that could be routinely applied to MODIS data is in need of development.

Rayleigh scattering is generally small and stable and only starts to get significant in the blue region. The optical air mass is required for this correction and can be determined from surface pressures. The effect of optical air mass may be important at higher altitudes.

Dr. Kaufman thought that both ozone and precipitable water were negligible in their effects on reflected radiation. The biggest requirement he felt was the need for developments in aerosol climatology before atmospheric corrections can be further developed for aerosols.

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[1]Kaufman, Y.K. and Sendra, C. 1988. Algorithm for automatic atmospheric corrections to visible and near-IR satellite imagery. Int. J. Remote Sens. 9:1357-1381.

HIGH-LEVEL DATA FLOWS FOR ROUTINE LEVEL-1 MODIS DATA PROCESSING

1. INTRODUCTION

The routine processing of MODIS Level-0 data into MODIS Level-1 data has been separated into five types of operations (Figure 1):

- **Manage Level-1 Processing**, where the MODIS Level-0 and platform ancillary data are received from the Data Handling Center (DHC), the source packets are assembled, and ultimately the scan cubes of data are assembled and submitted for Level-1 processing.

- **Navigate Observations**, where the spacecraft attitude and ephemeris data are interpolated and matched to the MODIS observations, the anchor points Earth located, the solar ephemeris computed, and the solar and satellite viewing geometry determined.

- **Calibrate Observations**, where new calibration-relevant and verification-relevant data are extracted and Instrument Characterization Team (ICT) recommended calibration coefficients and equations are applied to convert the 12-bit digital counts to radiances.

- **Develop Geophysical Ancillary Data**[1], where the anchor-point Earth locations and geophysical data are interpolated to each observation, processing-control masks are assigned, and digital elevation model (DEM) corrections are produced.

- **Format and Output Level-1 Data**, where the Instrument Response History, ICT Support Product, and Level-1 MODIS records are formatted, assembled, and distributed.

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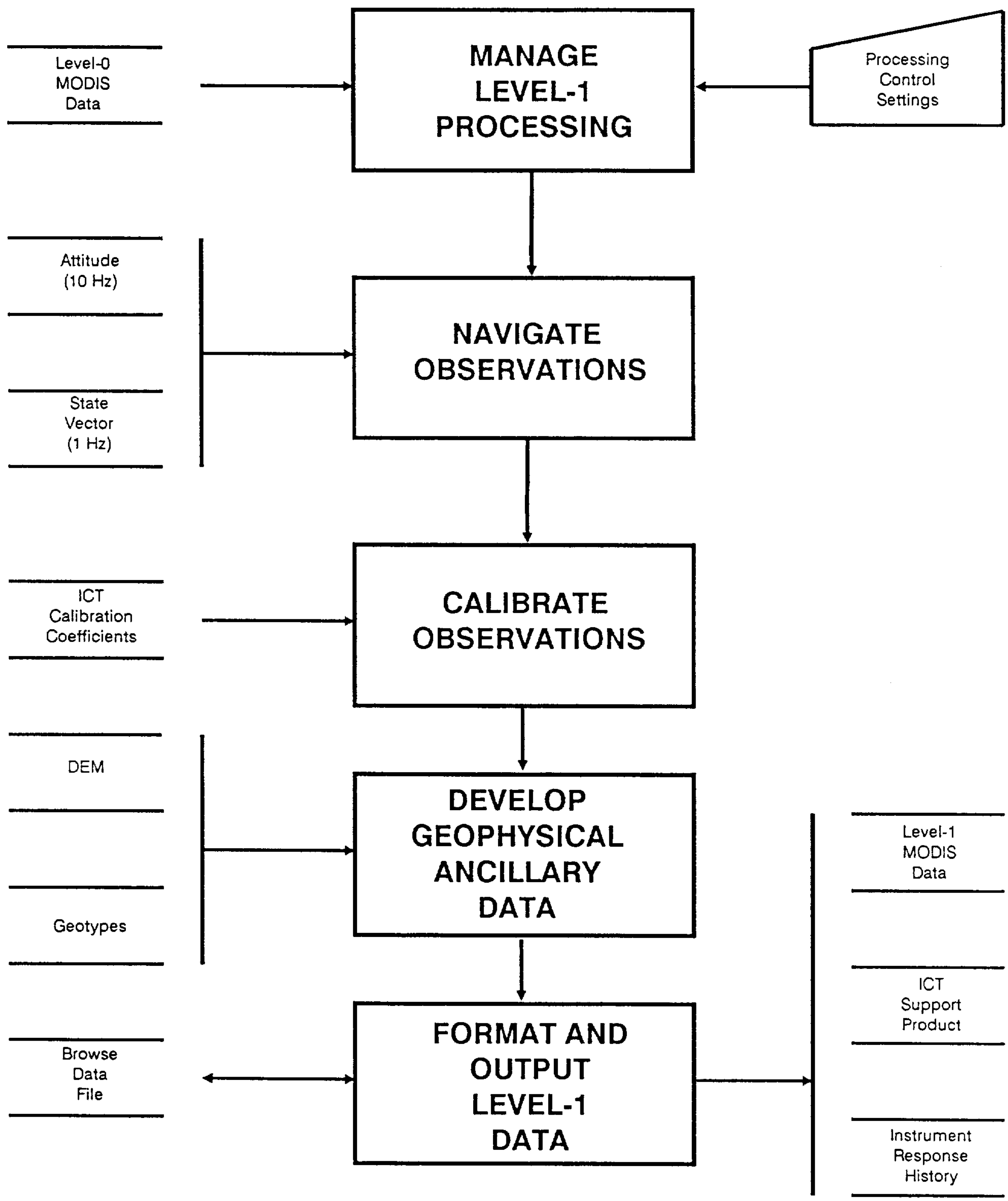
[1]This processing step is required either prior to or in the early stages of the Level-2 processing, and thus might not be ultimately retained as a Level-1 processing step.

HIGH-LEVEL DATA FLOWS FOR ROUTINE LEVEL-1 MODIS DATA PROCESSING



2. MANAGE LEVEL-1 PROCESSING

The Manage Level-1 Processing function has been separated into six types of operations:

- **Receive Processing Control Settings**, where the directives governing the production of Level-1 data are incorporated into the processing.

- **Receive MODIS Level-0 Data**, where the MODIS Level-0 data packet segments are received from the Data Handling Center (DHC) and combined into complete source packets.

- **Receive Platform Ancillary Data**, where the platform's ephereris (e.g., position and velocity) and attitude as a function of time are received from the Data Handling Center (DHC).

- **Receive ICT Calibration Coefficients**, where the updated gain and offset data sets are received from the ICT.

- **Assemble Scan Cubes**, where the individual MODIS source data packets and corresponding platform ancillary data are assembled into complete scan cubes of data.

- **Submit Level-1 Processing**, where the complete scan cubes of MODIS and platform ancillary data are submitted for the remaining Level-1 processing once complete cubes are produced.

3. NAVIGATE OBSERVATIONS

The Navigate Observations function has been separated into four types of operations:

Merge MODIS and Platform Data, where the spacecraft attitude and ephemeris data are interpolated and matched to the MODIS observations.

Extract MODIS Sensor Alignment Data, where the scan mirror positions and the inter-band, inter-pixel, and detector-array alignment differences are prepared for use.

Anchor Point Earth Location, where the right ascension, declination, Greenwich hour angle, latitude, and longitude of the anchor points are identified for an Earth geoid.

Solar Ephemeris Computation, where the solar right ascension, declination, and the Earth-Sun distance are identified.

Viewing Geometry Determination, where the solar and satellite zenith angles, relative azimuth, and satellite true azimuth from north are computed for each anchor point.

4. CALIBRATE OBSERVATIONS

The Calibrate Observations function has been separated into four types of operations:

- **Extract New Calibration/Verification Data**, where all requested internal calibration or Earth-viewing observations are pulled for dissemination to the ICT.
- **Interpolate/Merge Calibration Coefficients**, where the ICT-provided calibration coefficients are interpolated and matched to the MODIS observations.
- **Generate Within-Scan Calibration Coefficients**, where all calibration coefficients deduced from observations within a MODIS scan (e.g., space-look) are computed.
- **Apply ICT/Within-Scan Calibration**, where the ICT-provided and within-scan generated calibration coefficients are used to perform the counts-to-radiance conversion.

5. DEVELOP GEOPHYSICAL ANCILLARY DATA

The Develop Geophysical Ancillary Data function has been separated into four types of operations:

- **Interpolate Earth Locations**, where the navigations are interpolated from the anchor points to all MODIS fields of view.

- **Interpolate Geophysical Data**, where the DEM, geotype, and other (e.g., snow/ice) maps are interpolated from their base resolution to all MODIS fields of view.

- **Assign Processing Masks**, where processing masks (e.g., land/ocean, overcast, cloud-free, Case-I/Case-II waters, etc) are computed for higher-level processing control.

- **Obtain DEM Corrections**, where correction terms accounting for illumination changes (due to DEM slopes) and Earth location errors (due to topography) are computed.

6. FORMAT AND OUTPUT LEVEL-1 DATA

The Format and Output Level-1 Data function has been separated into six types of operations:

- **Generate Metadata**, where all required catalog and descriptive information regarding the scan cube is generated.

- **Generate Browse Data**, where reduced resolution (spectral, spatial, word length) images of a subset of the MODIS bands are prepared for subsequent incorporation into the MODIS browse data sets.[2]

- **Produce Header**, where all descriptive information (the beginnings of "a complete pedigree") concerning the algorithm and coefficient versions and processing are appended to the MODIS data.

- **Build MODIS Instrument Response History Record**, where all data relevant to compiling a comprehensive history of MODIS commands and responses are formatted and packed into a physical record.

- **Build ICT Support Product Record**, where all data destined for the ICT are formatted and packed into a physical record.

- **Build MODIS Level-1 Data Record**, where the calibrated and Earth-located Level-1 scan cube of data, including appropriate ancillary data, are formatted and packed into a physical record.

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[2]The browse data set, possibly a global 1,024 X 2,048 (18 km) grid, will reside external to each scan cube. However, as each scan cube of MODIS data is processed, the browse data grid will be updated.

MODIS BROWSE DATA GENERATION AND STORAGE

In the broadest meaning of the term, browse data is data that can be used to select other data having desired characteristics. By this definition, samples of products and metadata describing available products would qualify as browse data. However, to avoid confusion with products and services otherwise available from the data system, we shall use the term browse data here in a restricted sense to mean specially produced data products that serve primarily to allow a data user to select data with desired characteristics. Such products may also incidentally be useful for data quality verification and for scientific purposes - certainly such use is allowed - but the primary purpose of a browse product is to give a user an overview of available data so he can select data that meets his need.

As the term is used here, browse data consists of high-level reduced-resolution displays of observed radiances and derived MODIS products. Browse data will be available on-line, and if demand is sufficient, in optical disc or other storage medium formats. The projected requirements for MODIS browse data are as follows:

1. Reduced Spatial Resolution

MODIS browse products will be available on a global 1,024 by 2,048 grid, with an equatorial resolution of approximately 20 km. The global grid will also decompose into eight regional images, each with 512 by 512 elements, with image edges at the equator, the dateline, the Greenwich meridian, and $\pm 90°$ longitude. For special interest applications, regional images with boundaries adjusted to include a specific continent or ocean may also be produced. Boundaries for such special interest regional images have not yet been defined.

2. Reduced Dynamic Resolution

For efficiency in on-line transmission or other distribution, MODIS browse products will be reduced in dynamic resolution to single-byte integers (0 to 255). Though this is a substantial decrease in information from the full MODIS capability, it equals the capabilities of previous sensors such as the CZCS.

3. Types of Browse Products

Three types of browse products have been identified: (1) basic MODIS radiances as observed at the top of the atmosphere; (2) atmospherically corrected water-leaving radiances over oceans; and (3) derived Level-3 MODIS products. Candidate browse products are displayed in Table 1. Browse product are produced from both MODIS-T and MODIS-N data; however, because of the multidisciplinary capabilities of the MODIS-N, observations from this instrument result in more browse data products (17 from MODIS-N, as opposed to seven for MODIS-T).

4. Enhancements to Browse Products

Options include additional 512 x 512 browse images centered over the arctic and antarctic regions (and other regions of particular interest), the incorporation of coastlines, political boundaries, and latitude/longitude annotation.

5. Generation of the Browse Products

We anticipate that MODIS data processing at Levels-1 and -2 will operate on "image cubes" containing the data for a single scan. The axes of the cube are along track dimension, across track dimension, and spectral channel number. Level-2 products may be visualized as additional planes added to this cube as the various Level-2 products are generated (e.g., atmospherically corrected water-leaving radiances). Level-3 and Level-4 products will be generated on Earth-referenced grids, often at a reduced resolution relative to the initial MODIS fields of view. We expect that browse products will be created both for observed radiances and for derived geophysical parameters.

The process that generates reduced-resolution browse images is similar to the one that creates Level-3 products from Level-1 or -2 inputs. However, delivery of browse data is expected simultaneously with the delivery of Level-1 or Level-2 data products and their corresponding metadata. Therefore, the generation of the browse images might occur either just prior to the delivery of products to the archive, or in portions as each scan cube is processed.

The MODIS Level-1/2 granule[1] will most likely be either a scan cube or an image cube (a set of scan cubes containing approximately the same number of across-track and along-track measurements). If an image cube is chosen, data may be partitioned spectrally, so that a user could order specific bands of MODIS data. Metadata will be required at the archive for each data granule. Metadata will be updated to reflect the availability of browse data as it is delivered for the granule.

6. Storage Requirements for the Browse Products

The basic browse images will occupy on the order of 50 megabytes of storage on a daily basis, with each global browse image taking up just over two megabytes. The resultant annual storage requirement would be 18 gigabytes.[2]

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[1]A granule of MODIS data will be the minimum logical unit of data that can be selected and ordered by a user.

[2]With present technology, a Sony 12" platter at double density will store 6.4 gigabytes of digital data.

Table 1. MODIS Browse "Data Products"

MODIS-N LEVEL-1 CALIBRATED RADIANCES AT THE TOP OF THE ATMOSPHERE

BAND	CENTER	DISCIPLINE	SPECTRAL REGION	PRIMARY PURPOSE
9	443 nm	ocean	blue	aerosols/clouds/glint QC
12	565 nm	ocean	yellow	aerosols/clouds/glint QC
15	745 nm	ocean	near-IR	aerosols/clouds/location I.D.
4	555 nm	terrestrial	green	green peak
1	659 nm	terrestrial	red	Chlorophyll Absorption
2	865 nm	terrestrial	near-IR	Vegetation/Land Cover
6	1.64 μm	terrestrial	medium-IR	Snow/Ice Discrimination
20/21	3.75 μm	terrestrial	medium/thermal-IR	Surface Temp./Volcanology
31	11.0 μm	multi-disc.	thermal-IR	Surface/Cloud Temperature

MODIS-N LEVEL-2 ATMOSPHERICALLY CORRECTED WATER-LEAVING RADIANCES

BAND	CENTER	DISCIPLINE	SPECTRAL REGION	PRIMARY PURPOSE
9	443 nm	ocean	blue	chlorophyll
12	565 nm	ocean	yellow	susp. sediments/coccoliths

MODIS-N LEVEL-2/3 DATA PRODUCTS

Chlorophyll
NDVI
Surface Temperature
Cloud Fraction
Total Ozone
Surface Type (Snow/Ice, Case-I/Case-II, Land/Ocean, etc.)

MODIS-T LEVEL-1 CALIBRATED RADIANCES AT THE TOP OF THE ATMOSPHERE

BAND	CENTER	DISCIPLINE	SPECTRAL REGION	PRIMARY PURPOSE
3	440 nm	ocean	blue	aerosols/clouds/glint QC
11	560 nm	ocean	yellow	aerosols/clouds/glint QC
25	755 nm	ocean	near-IR	aerosols/clouds/location I.D.

MODIS-T LEVEL-2 ATMOSPHERICALLY CORRECTED WATER-LEAVING RADIANCES

BAND	CENTER	DISCIPLINE	SPECTRAL REGION	PRIMARY PURPOSE
3	440 nm	ocean	blue	chlorophyll
11	560 nm	ocean	yellow	susp. sediments/coccoliths

MODIS-T LEVEL-2/3 DATA PRODUCTS

Chlorophyll
Surface Type (Snow/Ice, Case-I/Case-II, Land/Ocean, etc.)

Sub-Sampling for
Time and Space Representations

A. Purpose

1. To identify global trends in geophysical variables, the primary scientific purpose of MODIS. Global trends in geophysical variables may be obscured by full spatial resolution, daily observations. Furthermore, cloud cover prevents full global views on a given day. Thus to obtain a global representation, observations from several orbits may be required.

2. To identify other large scale, low frequency trends in geophysical variables, i.e., on regional scales. Again, due to cloud cover and internal variability, trends in geophysical variables may be obscured by full spatial resolution, daily observations. Analysis of such trends is important for management considerations and because these regional scale trends aid in the analysis of global scale trends.

3. To facilitate the widespread use of MODIS data by the general public, which may not possess high capacity computer facilities, by reducing the spatial and temporal variability of data. This is a critical issue; unless subsets of the MODIS data products are generally available, use of these products by the scientific and even non-scientific community may be hindered.

4. To allow synoptic views of data products on standard CRT display devices. The CRT displays used with data systems are normally capable of displaying only a very limited number of pixels. Since the resolution of the MODIS instruments is about 1 km, the number of pixels generated for a regional or global scene will exceed the display capabilities of a terminal.

B. Level-3 Product Generation

Before any sub-sampling may take place, MODIS data products must be Earth-gridded, i.e., taken out of the satellite coordinate system (scan, along-track) and placed into an Earth-referenced system. Thus sub-sampling occurs after Level-3 processing. Although a number of Earth-gridding options are available, an equal-area projection has many benefits: subsequent averaging procedures require no areal weighting, polar regions are equally represented with equatorial regions, areal representation of the data is simplified. On the other hand, a Mercator projection has the advantage of easy recognition. EosDIS may provide the option of many different projections for Level-3 products. It has been suggested that a standard Earth grid be utilized for all products. This is an issue that must be presented to the MODIS Science Team.

C. Method of Sub-Sampling

There are many possible options for sub-sampling in time and space in order to produce reduced resolution data sets with reduced variability. Optimal options should be directly related to the product itself, taking into account desired spatial coverage, spatial and temporal variability, historical methods for sub-sampling, and spatial and temporal coherence. Thus it is likely that products will be sub-sampled by different methods, but some guidelines may be developed for the three MODIS disciplines: atmospheric, ocean, and terrestrial. A list of potential spatial and temporal sub-sampling methods are listed below.

1. Averages
2. Selection of a single pixel within a region/period to represent the whole
3. Pixel intervals, i.e., using every second, third or fourth pixel in time or space, etc.
4. Empirical Orthogonal Functions (EOF's)
5. Low/high/bandpass filters

1. Averages

Time and space averages are perhaps the most natural and common manner to present reduced resolution data. Averages suppress the individual variability of data and allow the identification of trends not apparent from an examination of the discrete data items. Averages computed to identify trends may sometimes be presented in a conventional "map" type presentation where each pixel represents an average value for a region and time period. For some types of analysis, the data reduction associated with high-level spatial and temporal averaging may be the only means to allow data analysis.

However, averaging to identify trends may also include the generation of a single number that represents the summation of all activity for a domain under investigation. An example of such a single-number average might be the Normalized Difference Vegetation Index (NDVI) averaged over a particular terrestrial biome, say Coniferous Forests of the Pacific Northwest. The average NDVI for such a region might be displayed as a single number superimposed on an outline map showing the boundaries of the defined region.

Suggested averaging methods proposed by the MODIS Science Team are listed in Tables 1-3. These form a basis for selecting a limited set of time and space averaging intervals for other data products. In general, we may suggest that atmospheric products be produced on very coarse time and space resolution (50-100 km in space; weekly-monthly in time), and ocean and land products at high spatial resolution (1-4 km) and a variety of temporal resolutions (daily to annually).

Dr. Robert Evans suggests that the sum of the variable in question, the sum of the squares of the variable, and other intermediate statistical variables should be preserved for each averaging process completed. With these data, one can evaluate the variance as well as the mean of the data, and averages and variances for larger regions can be computed from the data for subregions within the larger region when these data are available.

To support the generation of single or few-number averages for terrestrial biomes, the averaging algorithm will need to allow the specification of irregular regions over which the appropriate quantities are to be averaged. Potential methods of defining regions for the computation of averages include the specification of geodetic coordinates, mouse-drawn outlines on suitable "map" displays, threshold filters working on the parameter to be averaged or other geophysical parameters, and all unions, intersections, and complements of the above-defined regions.

The averaging process may need to support the generation of weighted averages, i.e. certain values may "count" more heavily in determining desired averages than others. Certainly the system should support the weighting of observations by the size of the area to which the observation or observations applies. Other potential weighting schemes might be based on assessed data quality, such as position within the scan (satellite zenith angle dependence), sun zenith angle dependence, proximity to clouds, etc.

2. Selection of a Single Pixel to Represent the Whole Region/Time

The Sea-WIFS Science Team decided that spatial averages were the least preferred method of sub-sampling, and suggested the use of a single pixel to represent a region. The pixel chosen would be cloud-free, presumably located near the center of a scan, with limited aerosol and sun glitter contamination. Such a procedure is simple and contains an internal and inherent quality control mechanism. However, it loses the variability of the data, unlike averages with which are retained the sum of squares. The procedure also invites bias and alias when assessing long term trends.

NDVI (Normalized Difference Vegetation Index) analyses often require selection of the "greenest" pixel in a given region to perform comparative anaylses. This method of selecting maxima or minima might be used for other products and yield important information not obtainable from averages. It also provides upper and/or lower bounds from which trends may easily be discerned.

Furthermore, the method is simple and objective. However, trends residing within these upper and lower bounds may be lost in this procedure, along with the variability of the data.

3. Pixel Intervals

Dr. Michael King suggested using pixels at intervals (every other pixel) to sub-sample his series of atmospheric products. The advantages of this method are simplicity and flexibility to provide a variety of spatial coverages. It is also representative of the data and unbiased in its depiction. However, a disadvantage is the loss of some of the variability of the data.

4. Empirical Orthogonal Function Analysis

Empirical Orthogonal Function (EOF) analyses are useful as a sub-sampling method because they explain most of the variability of the data. A modified method that takes into account images with missing data (spatially and temporally) has been developed and tested for CZCS imagery (Eslinger et al., 1989), and should be applicable to MODIS. However, the method is computationally expensive and, since it is a statistical model, might better be defined as a Level-4 product.

5. Low/High/Bandpass Filters

Finally, high/low/bandpass filters may be applied to the data to reduce variability and provide lower resolution data sets. These methods are well-defined, and may be used as a quality control of the data.

D. Ocean Issues Pertaining to Sub-Sampling (MODIS-T Tilt Strategy)

An interesting situation occurs with respect to the ocean products, in that both MODIS-N and T are capable of obtaining ocean color products (those derived from water-leaving radiances). However, observations from MODIS-N, which does not possess a tilt capability, will be severely contaminated by sun glitter at times, while MODIS-T will not. On the other hand, MODIS-T may suffer from a lack of Earth coverage while changing its tilt mode. Ideally, one should be able to obtain composites of MODIS-N and T observations using the best of data from each. In such a manner one can produce full (except for clouds) global coverage of ocean color products such as chlorophyll. However, the success of this compositing technique will depend on the tilt strategy of MODIS-T.

Ordinarily, MODIS-N will encounter the greatest sun glitter contamination near the latitude of the solar declination. At the same time, the best avoidance of sun glitter by MODIS-T is effected by tilting away from the solar declination (to the south when approaching, to the north after passing). This tilt strategy implies that MODIS-T will be changing tilt from back to forward at the solar declination latitude, where MODIS-N is most severely contaminated. Thus one will obtain no Earth coverage at the solar declination latitude, and the compositing method described above will not work. How serious this issue is depends on the time required for MODIS-T to change its tilt, which is not yet known. However, to maximize coverage a different tilt strategy may be required.

Reference

Eslinger, D.L., J.J. O'Brien, and R.L. Iverson, 1989. Empirical orthogonal function analysis of cloud-containing Coastal Zone Color Scanner images of northeastern North American coastal waters. Journal of Geophysical Research 94: 10884-10890.

Table 1. Examples of time and space averages proposed by MODIS Science Team members for global products.

Space	Daily	Weekly	Monthly
1 km	Coastal Water-Leaving Radiance Chlorophyll (Evans)		
4km	Open Ocean Water-Leaving Radiance Chlorophyll (Evans) Cloud Top Pressure Temp./Moisture Profiles Cloud Emissivity (Menzel, Susskind)	SST (Brown)	
10 km		Snow Cover (Salomonson)	
50 km		SST (Barton) Cloud Emissivity Cloud Top Pressure	Cloud Fractional Area (Menzel) Cloud Emissivity

		(Menzel, Susskind)	Cloud Top Pressure (Menzel, Susskind)

Table 1 continued.

		Time	
Space	Daily	Weekly	Monthly
1° x 1°		Aerosol Optical Depth Aerosol Size Dist. Single Scattering Albedo (Tanre)	Aerosol Optical Depth Aerosol Size Dist. Single Scattering Albedo (Tanre) Cloud Droplet Radius Cloud Thermo. Phase Cloud Optical Thickness (King)

Table 2. Time averages proposed by the MODIS Science Team with no spatial requirement stated.

5-Day	Oceanic Primary Production (Esaias)
Weekly	Oceanic Primary Production, Fluorescence Yield (Abbott) Evapotranspiration, Net Photosynthesis (Running) (North America Only)
Monthly	Oceanic Primary Production (Esaias, Abbott), Fluorescence Yield (Abbott)
Seasonal	Oceanic Primary Production, Fluorescence Yield (Abbott), Vegetation Index (Justice)
Annual	Oceanic Primary Production (Esaias) Vegetation Index (Justice) Net Terrestrial Primary Production (Running) (North America Only)

Table 3. Spatial averages proposed by MODIS Science Team with no temporal average stated.

$0.5^\circ \times 0.5^\circ$	Aerosol Mass Loading, Single Scattering Albedo (Kaufman)

CALIBRATION UTILITY REQUIREMENTS

6. Appendices

6.1 Traceability to NIST Standards
6.2 References

MODIS CALIBRATION SOFTWARE

Executive Summary:

For MODIS calibration there are requirements for the development of algorithms to monitor the instrument and its components during assembly, in the pre-flight check out and testing phase, in the activation period after launch, during normal operations, and during Eos or other satellite comparisons. The algorithms for these processes are identified and, where known, their required capabilities are described. Only the algorithms used for calibration (i.e., conversion of Level 1A data to Level 1B) will be used routinely every day. The other software will be employed either periodically or on occasion as diagnostic tools. The amount of computer coding involved for calibration may prove to be extensive and will probably continue to grow as scientists become experienced with the MODIS operations.

1. INTRODUCTION

Software required for the MODIS calibration can be divided into five major categories: 1) Ground support software, 2) radiometric math model software, 3) in-flight calibration software, 4) verification software, and 5) command and control software associated with calibration. Most of the calibration software can be defined as utility software, which means it used on sub-sets of the data rather than routinely and that the utilities are of general interest to many or all team members. If a utility is of general interest, it may be developed by the Instrument Characterization Team (ICT) and/or by the Science Data Support Team (SDST). Utilities will also be developed by the instrument builders and by individual team members, who are also members of the ICT.

Ground support software and the mathematical model of the instruments is discussed in section 2. Section 3 is devoted to the calibration software used in-flight during the activation period and normal operations. Command and control software are also mentioned in this section where many of the command modes of the instruments are listed. Section 4 is devoted to verification software, which establishes the calibration by comparing MODIS measurements to previous MODIS measurements, by comparing MODIS-N and -T to each other, by comparing MODIS measurements to other satellite measurements, and by comparing MODIS to in-situ observations using theoretical radiative transfer models. The interests of the science team members in calibration and verification are described in section 5. Section 6 consists of appendices giving acronyms, references, and a discussion of traceability of MODIS measurements to NIST standards.

2. GROUND SUPPORT SOFTWARE

2.1 Statement of Pre-launch Calibration Goals

The goal for MODIS is to identify the absolute incident energy falling on the system aperture to within the required accuracy based on physical standards maintained by NIST during the entire mission. Since MODIS is not a self-calibrating instrument, the calibration will be developed through the use of extended sources such as an integrating sphere similar to those used for MSS or AVHRR, a diffuser plate with the sun incident on it, and calibrated blackbodies (NASA, 1986). Some sources will be part of instrument package and will provide a measure of the long-term stability of the instruments.

After launch the satellite has the opportunity to observe well-known external sources such as the sun, space, moon, and the dark side of the Earth. Other potential sources are ocean and desert regions of the Earth which are less well known, but through measurements and modelling can provide traceability to NIST standards.

The MODIS-N required accuracies are $\pm$ 5% in the visible below 3000 nm, $\pm$ 1% above 3000 nm, and $\pm$ 2% for reflectance calibrations. Relative accuracy requirements are even greater with a 0.5% consistency from spectral band to spectral band at all wavelengths and therefore each detector and its associated optics. The detector to detector uniformity is required to be less than the noise equivalent spectral radiance (NESR) for all wavelengths. The instrument is required to be stable to better than 1.0% over any two week period or in the presence of a 10 degree C. temperature excursion. The calibration must be maintained for the mission lifetime which may be as long as five years.

2.2 Ground Support Software for Components

2.2.1 Introduction

Prior to launch the MODIS instrument will be well characterized so that the calibration will meet its accuracy and traceability requirements. The first step in this procedure requires that components of the MODIS instruments be well documented. The next five sub-sections outline material that can be included in this type of documentation. Utilities to derive the data products will be supplied by the manufacturer of the instrument.

2.2.2 Detector Characterization

MODIS-T consists of a 32 by 34 CCD silicon array. The 81 detectors in MODIS-N are photodiodes and photovoltaic HgTeCd detectors. The ground calibration should characterize these detectors so that a complete instrument error analysis can be performed and a radiometric mathematical model of the instrument can be constructed. The builders of the MODIS instruments are responsible for providing mathematical models of the instrument.

The Calibration Plan will provide procedures with expected accuracies and precision, an explanation of the physical principles involved, the equipment and fixtures required, the software utilities required, and the frequency and number of times of measurements are repeated for the detector characteristics, of which the following is a sample list:

- Radiometric sensitivity (S/N ratio)
- Temperature dependence of radiometric sensitivity
- Linearity vs. radiance level
- Detector to detector differences
- Individual detector uniformity (point spread function)
- Response time and transient response including overshoot
- Long-term stability
- Polarization sensitivity
- NESR or dark current noise levels.
- Quantum efficiency vs. wavelength (spectral bandpass)
- Detectors used to monitor lamp or blackbody output

2.2.3 Optical Components Characterization

The Calibration Plan will provide procedures with expected accuracies and precision, an explanation of the physical principles involved, the equipment and fixtures required, the software utilities required, and the frequency and number of times of measurements are repeated for the optical components, such as the following:

- Interference filter transmission vs. wavelength (MODIS-N)
- Solar diffuser plate properties
- Dichroic beamsplitter properties
- Mirror reflectivities

In addition, the alignment and spectral band separation will be measured which can be best done for the assembled instrument.

For the interference filters, measurements of their transmission as a function of wavelength is required both in the region on maximum transmission and in all regions from 0.4 to 1.0 microns, to search for potential out-of-band light leakage. The sensitivity of the transmission to temperature variations is required, particularly if there is no control over the filter temperature in space. If these measurements are repeated on the ground over the course of several months, a better idea of their long-term stability will be available prior to launch.

The other optical components will probably have similar series of tests prior to launch.

2.2.4 Standard Radiance Sources Characterization

The Calibration Plan will provide procedures with expected accuracies and precision, an explanation of the physical principles involved, the equipment and fixtures required, the software utilities required, and the frequency and number of times of measurements are repeated for standard radiance sources characteristics such as:

- Calibration lamp and blackbody stability
- Lamp currents and voltages
- Blackbody temperatures (accuracy and uniformity)
- Blackbody emissivity
- On-board spectral response calibrator
- Uniformity of integrating sphere (if one exists)
- Spectral dependence of integrating sphere output
- Characteristics of integrating sphere irradiance monitors

2.2.5 Electronics Characterization

The Calibration Plan will provide procedures with expected accuracies and precision, an explanation of the physical principles involved, the equipment and fixtures required, the software utilities required, and the frequency and number of times measurements are repeated for the electronics characteristics such as:

- Linearity
- Accuracy
- Temperature dependence
- Response time
- Stability of standard voltage sources
- Electronic noise
- Crosstalk

2.3 Ground Support Software for the Assembled Instrument

2.3.1 Introduction

Several software models will be developed to characterize the assembled MODIS instruments. These models are:

- Radiometric Math Model
- Thermal Math Model
- Structural Math Model

The Radiometric Math Model is most germane to the calibration of MODIS and is discussed in the next section. Plans are also part of the documentation associated with calibration. There is the Calibration Plan which covers all aspects of calibration and there is the Survival Mode Plan which describes instrument operations and software when the MODIS instrument is placed in its survival mode. This later plan, as it affects calibration, is discussed in a section below. Neither plan is yet written.

2.3.2 Radiometric Math Model

Prior to launch, a Radiometric Math Model of the instrument will be developed. This model will aid in the evaluation of the calibration of the instrument. A Thermal Math Model and a Structural Math Model will also be developed and will aid in the understanding of the instrument's behavior. Some of the instrument parameters that may be modelled using the Radiometric Math Model are:

- Radiometric sensitivity (S/N ratio)
- Temperature dependence of radiometric sensitivity
- Linearity vs. radiance level
- Detector to detector differences
- Individual detector uniformity (point spread function)
- Response time and transient response including overshoot
- Modulation transfer function
- Long-term stability
- Polarization sensitivity
- Alignment sensitivity
- Spectral bandpass and stray light rejection
- NESR or dark current noise levels.
- Quantum efficiency vs. wavelength (spectral bandpass)
- Field of view uniformity
- Vacuum-air differences
- Instrument hysteresis
- Properties of detectors used to monitor lamp or blackbody outputs

The above list should not be taken as exhaustive and there may be omissions which can be added. Summary information on these topics may be provided in a User's Guide to the MODIS Pre-launch Calibration, although this is yet to be determined.

Prior to launch, standard level 1A data products will be generated in an identical format and storage media as those generated from in-flight data, except that the headers will have different information, such as dummy values for the satellite location. These data products will be archived. Following this procedure will assure continuity in the calibration between the pre-launch and in-flight periods and make comparisons of pre-launch and in-flight data easier. Since the lamps and internal blackbodies are the only sources that the instrument will view in both the pre-launch and in-flight periods, it is important that the standard Level 1A data products have counts data from these sources.

Implicit in the generation of these Level 1A and 1B data products is the data acquired when MODIS-N and MODIS-T, each independently calibrated, are compared. Several such comparisons are likely.

A summary and information on access to this data may be included in a User's Guide to the MODIS Pre-launch Calibration, although this is yet to be determined. This user's manual would also be expected to provide source code to any utilities used for the generation of calibration data products, as well as information on their use. It is planned that the instrument maker will provide these utilities and their associated data products.

2.3.3 Survival Mode Software

The MODIS instrument during its mission lifetime may undergo a failure or failures which could effect how the calibration data products are analyzed and handled. The failure may be a partial failure, such as a loss of one or more lamps, the loss of one or more detectors, the increased noise level in one or more detectors, the contamination of the optics and so forth. Failures of this type may effect the calibration algorithms, the method of storing calibration data, or the routine data processing. Typically, if a partial failure occurs, there is a period of time when routine processing ceases while the problem is studied. In the MODIS experiment however there is a requirement for quick turn around and the delay in processing of several weeks while the problem is resolved must be avoided. Therefore, a Survival Mode Plan will anticipate potential failures and provide a ready made procedure for dealing with them, with a minimum of delay and down time. For example if one detector becomes excessively noisy, the plan may call for the substitution of a new calibration algorithm for the old algorithm, with data from the noisy detector not used. Accompanying the plan would be diagnostic software which could be used to pinpoint the cause of the problem or to provide a solution for the problem.

The other type of failure for MODIS is a full failure. The Phase A documentation states that if the sensitivity of the MODIS instruments is reduced to 60% of its original sensitivity, the instrument will have failed. Even in this case it is likely some useful scientific data can still be acquired, so a decision as to whether to cease measuring will have to be made. With a 5% decrease in sensitivity every year (a not unreasonable expectation), the MODIS instrument will have failed by this definition in 10 years. The most likely other mode of full failure is a scanner failure, which will considerably decrease the amount of useful data acquired.

2.4 Summary of Software, Models, Guides, and Data Products

Prior to launch, a series of documents, data sets, data products, and software utilities will be generated. Candidate data products identified in this plan, sorted according to storage media, include:

Ground Support Software

- Radiometric Math Model of the MODIS Instruments
- Structural Math Model
- Thermal Math Model
- Survival mode software
- Component analysis software
- CAD/CAM model of instruments
- Database of instrument properties

Plans and Users' Guides

- Calibration Plan
- Verification Plan
- Survival Mode Plan
- User's Guide to MODIS Pre-launch Calibration
- User's Guide to MODIS In-flight Calibration

MODIS Ground Support Calibration Data Products

- Standard Level 1A/1B radiances using simulated targets
- Standard Level 1A/1B radiances for comparisons of MODIS-N and MODIS-T
- Pre-launch calibration coefficients
- Component characterization data

- Assembled instrument characterization data

All the data products above will also be made available as browse files, in the sense that they can be assessed by an on-line database, which are available to the DADS and the TMCF. A database and processing program will be made available so the users can assess the most recent version of the documents and data and review earlier versions. Any instrument blueprints must be CAD/CAM generated and the program to read these data files must be provided. If some of the component or other characterization data is acquired graphically such as filter transmission, the graphs and digitized files will be provided.

The standard Level 1A/1B data products identified above will be compatible with the standard Level 1A/1B data products generated in the in-flight period. The data format standards, which these data products comply with, must meet the agreed upon international data format standards. As a consequence of this requirement, the Phase C instrument development and the Phase C calibration procedures development must be closely coordinated.

3. IN-FLIGHT CALIBRATION SOFTWARE

3.1 Operational Modes for MODIS

MODIS-N will have several operational modes, which are:

- Launch phase and orbital acquisition mode
- Outgassing mode
- Activation mode
- Mission mode (with day and night modes)
- Solar calibration mode (solar diffuser plate deployed)
- Yaw roll mode (scan of solar diffuser plate)
- Lunar calibration mode (moon observed through aperture)
- Spectral calibration mode (spectral calibrator on)
- Survival mode (instrument in safe state)

Possible additional operational modes for MODIS-T are:

- Any constant tilt angle mode
- Sun glint avoidance mode
- Stereo view mode
- Stare mode

During calibrations using internal sources, some additional operational modes are:

- Internal lamps on/off (MODIS-N only)
- Blackbody mode fixed temperature/floating temperature
- Various gain setting modes
- Electronic instrumentation check modes

3.2 Activation Period Software

Prior to initiating the long-term routine data processing for MODIS, a check out period of a to be determined duration will occur. This time is called the activation period. The instrument will be in the outgassing mode, activation mode, launch phase and orbital acquisition mode, and the early stages of the mission mode during this period. The calibration modes and other modes will also be checked during this period. The MODIS instrument may be placed in some modes of operation which it may not normally encounter during the rest of the mission, the pre-launch and in-flight calibrations will be compared, and all levels of data will be generated to see if reasonable and expected results are being generated. This section discusses the data products generated during the activation period. Special software will be required to handle the interpretation of data acquired during the activation period, which may then not be used for the rest of the mission.

Assuming MODIS is a linear instrument, gains and offsets for each detector will be measured. For the visible channels, space and the darkside of the Earth will be used to measure the offsets. Lamps on MODIS-N (perhaps) and the solar diffuser plate will be used for gain determinations. For the thermal channels space and blackbodies will be used to measure the gains and offsets.

The gains and offsets can be compared to the pre-launch values. If there are differences in the calibrations, the reason must be identified and the appropriate action taken.

In addition to a check of the instrument, the lamp outputs and the sensitivity of the detector used to monitor lamp outputs also require measurements and comparison to the pre-launch measurements. Blackbody temperatures are also require monitoring in the same manner.

Pre-selected Earth targets will be examined which will be used throughout the instrument life to monitor the stability of the measurements.

Most of these measurements will be continuations of quality control charts or other procedures started prior to launch.

In summary then, the following tests will be done in the activation period:

- o All calibration modes tested and compared
- o Sources checked
- o Spectral calibrator checked
- o Calibration algorithms checked
- o Initial Level 1B data generated
- o Initial measurements of pre-selected Earth targets performed

All these calibration procedures will be performed routinely during the operational phase of the instrument. It is likely that the calibration software will have options within it that can handle the tests listed above since they will be performed throughout the satellite mission.

The Phase A report on the Level 1A data processing (SAR, 1987) states that, since the solar diffuser output may depend on the beta angle (i.e., the solar azimuth angle) which can vary by about 8 degrees during the course of the year, the Eos platform should be offset from its nominal zero yaw angle to simulate these beta angle variations. This will be a special mode of operation which normally will not be allowed. It allows the angular dependence of the solar diffuser plate to be measured. It is likely that special software will be written to analyze this mode of operation and the instrument output.

3.3 Operational Calibration Software

3.3.1 Calibration software requirements within the CDHF

In the normal operation of the MODIS instrument, the calibration will be monitored using the imbedded calibration sources and the gains and offsets determined by these sources will be automatically calculated. If there are no unexplainable shifts in instrument calibration, this method will provide the proper calibration coefficients. More likely the ICT will use several calibrations of the instrument in any one day to look for calibration changes. This avoids the problem of potentially having different gains for each scan and also allows changes in instrument gain to be monitored over long periods of time as required to detect trends in the instrument sensitivity.

Suppose we consider MODIS-N in the following modes: 1) Lamp on with set and measured electrical current, 2) Blackbody at a fixed temperature, 3) Fixed gain setting, 4) Linear A/D conversion, and 5) routine day mode. The Central Data Handling Facility (CDHF) can generate the Level 1A data associated with these measurements. The ICT can have a standing request to receive a subset of this data, perhaps some measurements once every hour. In Figure 1, the calibration data product flows within the ICT during routine processing is illustrated. First the ICT derives the calibration coefficients which then are used to update a control chart. The question is then posed as to whether the calibration of the instrument is unchanged (i.e., in control) or if it has changed (i.e., not in control). If the calibration is in control, the calibration coefficients are cataloged and stored, and then transferred to the CDHF for routine processing. The Data Archive and Distribution System (DADS) can receive these same coefficients a little later. If the instrument is not in control, then it is determined if there has been an instrument failure. Instrument failures are covered in a Survival Mode Plan. If there is no failure or if that cannot be decided based on the available information, then it is decided if more data is required to resolve the problem. If more data is not required, the revised or unchanged coefficients, can be cataloged and stored as before. If more data is required, then it must be determined if the data is available or not. If available, then a special data request is sent to the CDHF and the procedure outlined above is repeated. If the required data is not available, then the ICT will formulate an observation request for MODIS to acquire the data.

Sample subsets of Level 1A data which may follow identical pathways within the ICT are:

- Lamp on mode
- Fixed temperature blackbody mode
- Earth calibration target mode
- Lunar calibration mode
- Spectral calibrator on mode

Each of these operational modes can be expected to reveal something about the instrument calibration, such as its stability or alternate calibration coefficients. The ICT will develop techniques (i.e., software utilities) to resolve differences in calibration given by different calibration techniques. If different calibration techniques give different calibration coefficients, the control chart procedure will resolve whether the differences are sufficiently large to indicate if a partial instrument failure has occurred or if more data is required to resolve the discrepancy.

The data products above are all standard Level 1A data products and can all be treated the same as standard scenes. Some Level 1A data products may not be formatted this way or may require a different procedure for processing. Candidate data products are:

1. Spectral calibrator on/off: A spectral radiation source may be incorporated within the instrument. When it is on, the instrument may not be taking Earth data, so this data will probably be separated for special processing concerned with the wavelength calibration of the spectrometers.

2. Solar diffuser deployed/stowed: If the solar diffuser plate is deployed, then the Earth may not be viewed, so this data set will also have to be separated from the standard Level 1A data products.

Finally Level 1B data products may be used for verification by using a subset of the available data to look for anomalies attributable to calibration changes. Sample verification data products in this category are:

1. Calibration scenes: A calibration scene is defined as a calibrated Level 1B data product using a predetermined target which it is anticipated will remain stable over long time periods. The calibration scenes must be co-located so that each scene of a given type can be compared with earlier and later scenes. The purpose of this procedure is to see if secular trends are occurring in these selected scenes. Candidate calibration scenes are: 1) Earth targets: White Sands, New Mexico is a potential target which has been used by ERBE and Landsat satellites. Other potential targets are desert areas in Saudi Arabia or the Sahara, ocean "desert" regions, or clear arctic regions such as Greenland. 2) Moon: It is planned that the moon will be visible to the MODIS-N instrument. Special software may be required to extract and analyze this data.

2. Visible channels on at night: Another shortwave calibration target may be the Earth at night. This verification data product is listed since it may require the MODIS instrument to be put in a special operation mode to acquire this data. The extracted data may be analyzed using a special set of software utilities.

3.3.2 Calibration software requirements within the ICC

In addition to the routine operational calibration activities within the CDHF, there will be software and hardware at the ICC to monitor the instrument health, including calibration. This will consist of an image processing workstation that can view any one of four pre-selected MODIS channels delivered in near-real-time from CDOS. The software at this location will ingest Level 0 data and generate Level 1B data products. The accuracy of the calibrations will be determined using some as yet to be defined diagnostic software. The schedule and frequency of this type of operations is also yet to be determined. Any data products generated also require software and hardware to store the results for more analysis later.

3.4 Summary of Software, Models, Guides, and Data Products

Each mode of MODIS-N operation will probably transfer data in the same fixed format, but the ancillary data associated with each mode will differ. Thus, the following normal transmissions can be expected:

- Day or night mode (Earth viewed)
- Solar calibration mode (diffuser plate deployed and viewed)
- Lunar calibration mode (full moon seen through aperture)
- Spectral calibration mode (spectral calibrator on)

Each of these modes will require special software utilities to extract and interpret the data streams. The following ancillary data is associated with the calibration modes:

- Lamp(s) output, voltages, and currents
- Lamp detector outputs and temperatures
- Active cavity radiometer outputs and temperatures when solar diffuser plate is deployed
- Spectral calibrator output and temperatures

It is not clear if these outputs will always be downlinked or will be downlinked only when MODIS-N is in one of its calibration modes. In either case, special software to extract and analyze the ancillary data will be required.

Earth calibration scenes will be part of the normal day and night modes of the instrument. Data will simply have to extracted for further analysis, which requires software to obtain data by location such as longitude and latitude.

In addition to the above, MODIS-T will have several modes of operation unique to itself. These are:

- o Tilt modes (any angle from 0 to ± 50 degrees)
- o Stare mode (one location on Earth is viewed continuously as the satellite passes over for SBDRF studies)
- o Sun glint avoidance mode (the tilt changes to avoid the sun-glint and missing data is filled with MODIS-N data)
- o Stereo mode (for stereo images of single Earth region)

In each of these modes, the normal data stream is probably transmitted (except the sun-glint avoidance mode), so software will be required to extract the data and properly analyze it.

Both MODIS instruments will have the normal compliment of user's guides to the software.

4. Verification Software using other Satellites and Observations

4.1 Introduction

This section illustrates various verification software using examples from other satellite missions. Sections 4.2 to 4.7 describe some of the potential verification software may be required by MODIS.

4.2 Sample Calibration Issues requiring Software Development

The next few paragraphs briefly describe some problems that have been encountered in the calibration of satellites similar to the MODIS instruments. These same problems may show up during the MODIS lifetime. These problems are selected based upon the fact that the detectors or optical components are identical to those in the MODIS experiment. For each potential problem, software will required to detect the problem and possibly to correct it. If the problems are anticipated prior to launch, then much of the software development can be done then. Since not all potential problems can be identified, additional software development will be an on-going project.

1. Cosmic ray bombardment and decreasing detector sensitivity and measurements of lamp output.

The MODIS calibration depends upon using known sources. For the MODIS-N visible channels, a lamp or group of lamps reflecting off an integrating sphere may be one standard source. To assure constant output, the lamps are given fixed measured electrical currents and separate silicon photodiodes are used to measure the lamp radiant output. Thus the repeatability and accuracy of the lamps may be no better than the repeatability of the silicon photodiodes.

The ERBE experiment took a similar approach, using lamps with silicon photodiodes to measure their output. Fortunately the ERBE experiment also measured the lamp radiant output using Active Cavity Radiometers (ACR's) which are stable to within a few tenths of percent over many years (e.g., Willson, 1971). The time history of the lamp output in the ERBE satellite showed a nearly constant output over two year when measured using the ACR's (Hoyt,1987). The simultaneous measurement of the same lamps with the silicon photodiodes showed an apparent decrease in lamp output of about 3% per year. In this case the silicon photodiodes apparently lose sensitivity as they are bombarded by cosmic rays, even if, as was the case here, the detectors are protected and only used intermittently. Similar long-term decreases in silicon photodiode sensitivities have been noted in the Landsat satellite measurements.

2. Filter deterioration and contamination of optical components

Most satellite radiometers undergo changes in sensitivity while in orbit. Often these changes can be attributed to changes in the optical components rather than the detector itself. For example, Jacobowitz et al. (1984) show the narrowband interference filters on the Nimbus-7 ERB experiment initially decreased rapidly in transmittance followed by a recovery over the next several months. Apparently these changes were caused by contamination which boiled off after its initial deposition. The interference filters in subsequent years have continued to show long-term, generally downward, changes in transmittance.

The Coastal Zone Color Scanner (CZCS) on the same satellite also showed decreases in sensitivity attributable to changes in the optical components rather than the detector (Gordon, 1987). The lamp output seemed to be constant for this experiment.

The Landsat MSS instruments have also undergone long-term decreases in sensitivity, which may be a combination of filter deterioration and detector degradation due to cosmic ray bombardment, although the exact causes cannot be unambiguously identified (see e.g., Markham and Barker, 1987).

3. Striping

If the calibration of the MODIS scanners has been properly performed and there are no detector to detector inconsistencies, then no striping will appear in the images. It is likely however that striping will appear either within a scan or from scan to scan and it is the responsibility of the Instrument Characterization Team to remove the stripes. Poros and Peterson (1985) review some techniques used to de-stripe Landsat images. Their method is computer intensive and in the design of the data processing system, this requirement must be carefully considered.

In summary, the three illustrative problems given above will have an impact on the software development and the data products produced by MODIS. If they are not considered in the design of the data processing system, either the processing after launch will be slowed or the data products generated will not meet the scientific goals.

4.3 Software for Comparing MODIS-N and MODIS-T

A verification study is defined as one in which the results of presumably correctly calibrated MODIS instruments are compared to the presumably correctly calibrated measurements by other satellite instruments or in-situ observations. The purpose of these studies is to verify the calibration of the MODIS measurements. Differences between measurements can arise from calibration errors in the MODIS instruments, calibration errors in the other measurements, errors in the data reduction algorithms, or failure to examine the same co-located scenes. The ICT's interest in these studies is identifying problems with the MODIS instrument radiometric or geometric calibration. Sample verification studies are discussed in this section and the next two sections. Figure 2 provides a guide for the data flow that can be expected in a verification study. Each verification study will probably require a set of special utility programs.

The most straightforward way to verify the MODIS measurements is the comparison of radiance measurements at the top of the atmosphere made by MODIS-N to MODIS-T. Using the same wavelengths when both are viewing nadir and making adjustments for differences in bandwidth and field-of-views, software can be developed to compare the two instruments.

4.4 Software for Comparing MODIS to Other Satellite Instruments

Both MODIS instruments may also be compared to HIRIS, if the HIRIS spatial resolution is reduced to match the MODIS resolution. A special filter will be required for this resolution reduction, which will adjust for the point spread functions of MODIS and other differences. These intercomparisons can be performed looking at nadir or for MODIS-T at some specified tilt angle. AIRS, CERES, ITIR, and MOPITT are other NPOP-1 instruments for which radiance comparisons may be possible. It is anticipated that special software will be required for each of these comparisons.

It is more difficult to perform radiance intercomparisons to other satellite since they are in different orbits and may only infrequently have simultaneous measurements of the same region. Even in these cases, they may view the same scene at different angles requiring the use of bidirectional models which have their own uncertainties. Further complications arise from the use of different spectral bandpasses in different satellite instruments. The more such differences there are the more difficult it becomes to state that the observed differences in measured radiance values arise from calibration errors. Possible intercomparison satellites may be future variants of GOES/VAS or AVHRR.

4.5 Software using In-situ Observations and Theoretical Radiative Transfer Models

The next step removed from comparing radiance measurements at the top of the atmosphere is using the MODIS radiance measurements and radiance values predicted by a theoretical radiative transfer model using a known surface reflectance or surface radiance. Fraser and Kaufman (1986) show how, using clear regions in the Atlantic Ocean, the VISSR instrument on GOES can be calibrated in the visible.

Still one more step removed is a comparison of MODIS radiances with in-situ measurements. An accurate theoretical radiative transfer model and an atmosphere with known properties is required for this type of intercomparison.

The ICT will develop verification methods such as the ones outlined above and will maintain separate data products for each verification method thus developed.

A study of the sensitivity of the differently derived quantities to calibration errors must be performed prior to launch to see if the calibration stability and perhaps accuracy can be monitored through the derivation of these scientific parameters.

4.6 Software for Calibration Independent and Calibration Dependent Measurements of the Same Parameters

There are certain calibration independent methods of deriving some parameters which can be compared to calibration dependent derived values of the same parameters. One such parameter is cloud height. Using MODIS-T stereo images of clouds can be made under some conditions and cloud top heights derived. Similarly the MODIS instruments can derive cloud top heights which are dependent upon the calibration of the instruments. If the calibration is correct, both techniques will give the same cloud top heights. Stereo imaging provides a method of checking the MODIS calibration.

Using the thermal channels of MODIS-T, the day-night differences can be calculated. If the instrument sensitivity is stable, the mean day-night differences should remain essentially unchanged over time. The day-night method provides another check of the thermal channel stability.

Other techniques may be developed which will provide checks on the calibration accuracy and stability.

4.7 Software for Non-MODIS Calibrations

Team members or users in the scientific community may develop their own calibration techniques. The ICT is a resource which can aid users in evaluating and/or using the newly developed calibration techniques. If these calibration techniques present advantages to the scientific community as a whole, the ICT may recommend to the Science Team Members that they be adopted in the data processing or reprocessing.

4.8 Summary of Software, Models, Guides, and Data Products

For verification studies, the normal data is transmitted, calibrated, and stored. When a verification study is performed, software to extract the data, given the locations and times desired, is required. The extracted data can then be compared to the data from other satellites by an interactive image processing station which allows overlays, spatial filtering, spectral manipulations, and so forth. Alternatively, if a type of comparison is performed frequently, the process can be automated and done in a batch mode. Therefore, two categories of verification software can be anticipated:

- Interactive image processing
- Batch radiance comparisons

The following types of software must be available:

- Mapping software to overlay, rectify, and filter radiances from other satellite instruments such as GOES, AVHRR, Landsat, and HIRIS.
- Mapping software to convert point surface measurements to a MODIS compatible coordinate system
- Radiative transfer codes (analytic, Monte Carlo, etc.) to convert measured surface leaving radiances from field experiments to satellite level radiances
- Modulation transfer function codes
- De-striping software (possibly)
- Day-night difference software
- Stereo cloud height vs. thermal cloud height comparison software
- Sun-glint and desert target software

5. Team Member Proposed Calibration Software Development

The following seven sub-sections describe the specific interests of seven team members as they apply to calibration. The team members are treated in an alphabetical order.

5.1 Dr. Brown

Dr. Brown is interested in the in-flight calibration of seven channels of MODIS-N. He did not specify if he were interested in calibration algorithm development.

5.2 Dr. Evans

Dr. Evans is interested in the in-flight calibration of the visible channels of MODIS-N and all the channels of MODIS-T. He did not specify if he were interested in calibration algorithm development.

5.3 Dr. Kaufman

Dr. Kaufman is interested in the calibration of MODIS-N using sunglint and desert observations. It appears Dr. Kaufman would develop the software for these verification studies.

5.4 Dr. Menzel

Dr. Menzel is interested in the calibration of the thermal channels of MODIS-N. It is not clear if this interest includes algorithm development.

5.5 Dr. Parslow

Dr. Parslow is interested in hourly calibrations of the MODIS-T selected channels. It would appear that this calibration effort would involve some algorithm development. He is also interested in using the moon as part of verification studies.

5.6 Dr. Salomonson

Dr. Salomonson is interested in all aspects of the MODIS-T and MODIS-N calibration and verification studies. This covers all the software development and use previously described in this report.

5.7 Dr. Slater

Dr. Slater is also interested in all aspects of the MODIS-T and MODIS-N calibration and verification studies. This covers all the software development and use previously described in this report.

6. APPENDICES

6.1 Traceability to NIST Standards

The basic goal of calibration is to maintain traceability to NIST standards with an accuracy of 2% in the visible and 1% in the thermal infrared. This goal must be achieved without the use of laboratory standard sources in the in-flight period.

In Figures 3 and 4 a schematic diagram of the various paths of tracing the calibration to NIST standards is shown for the visible and thermal channels. The discussion below is based upon these two figures. During the pre-launch period, the measurements of the properties of the components of the instrument can all be traced to NIST standards, but to provide traceability of the assembled instrument using this approach, a reliable mathematical model of the instrument with a detailed error budget is required. This approach to NIST traceability is a difficult one. The builders of the MODIS instruments will be required to supply a radiometric math model of their instruments.

For the visible channels, secondary standard lamps used in the ground calibration can provide the required accuracy.

The only sources that MODIS will examine in both the pre-launch and in-flight periods are the in-flight lamps and blackbody. It is important that their traceability be carefully documented and that any detector used to monitor their output (see Section 4.2) be stable and provide this traceability.

For the visible channels it is important to note that the only source that the instrument views in both the pre-launch and in-flight period is the lamp or lamps. It is important then that this source be stable or if not stable that its output be accurately monitored with a suitable detector (Section 4.2 emphasizes this point). If this traceability path is lost then less reliable paths of traceability must be used. The next most reliable method of traceability is the use of known space sources, such as space to provide a reliable zero for the instrument, the darkside of the Earth to provide another higher temperature zero for the visible channels, the sun viewed through a diffuser plate, and the moon. The moon itself is valuable check on the stability of the instrument and will be visible for MODIS-N through a special aperture. The sun is not as a reliable source as one might expect since the diffuser plate may change its properties over time, as it has on other satellites. There is a plan to monitor the diffuser plate using an active cavity radiometer which should provide better long-term stability. Next in order of accuracy in providing traceability to NIST standards is the use of secondary space sources, primarily Earth targets coupled with in-situ measurements and radiative transfer models. Uncertainties in the composition of the atmosphere, the accuracy and representativeness of the in-situ observations, and the accuracy of the radiative transfer calculations all combine to reduce the certainty that traceability to NIST standards has occurred. Nonetheless this method provides at the very least a check on the stability of the sensitivity of the instrument. Finally there is traceability to NIST standards through the comparison of the MODIS instrument to other satellite instruments, which have calibrations traceable to NIST. The problem in this approach is that it is difficult to get comparable wavelength bands, comparable fields of view, and simultaneous measurements. These limitations make the comparisons less certain and less frequent.

All the comments above apply to the visible channels specifically, but they are also valid for the thermal infrared channels as well. The thermal channels have fewer standard or secondary standards available, so the paths for traceability to NIST standards are reduced. If the in-flight blackbody remains stable, as from experience with previous satellites one expects them to, then the traceability to NIST standards is a straightforward problem. The question of linearity of the proposed HgCdTe detectors compels further consideration however, which implies that a second blackbody held at a different temperature may be required.

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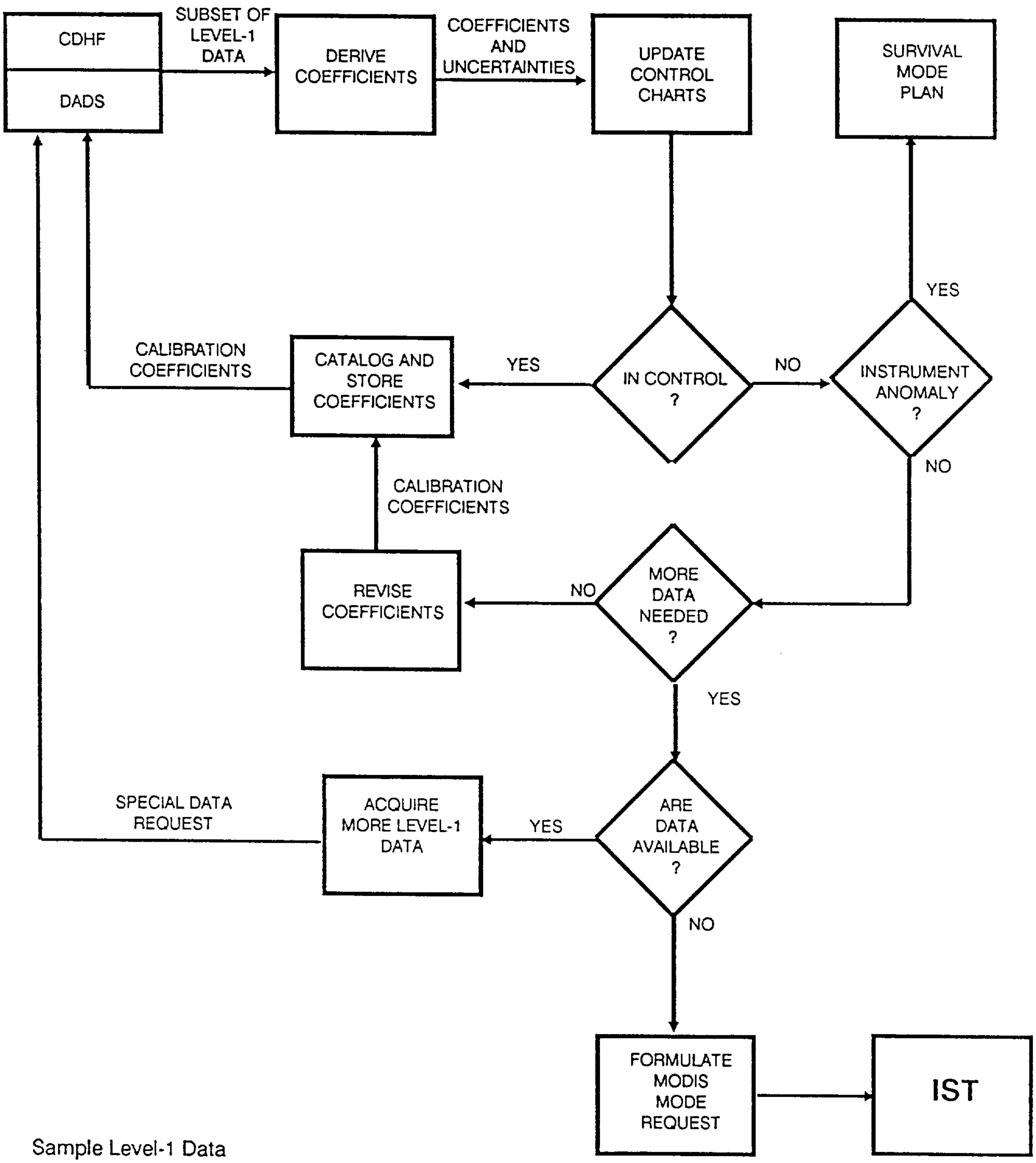
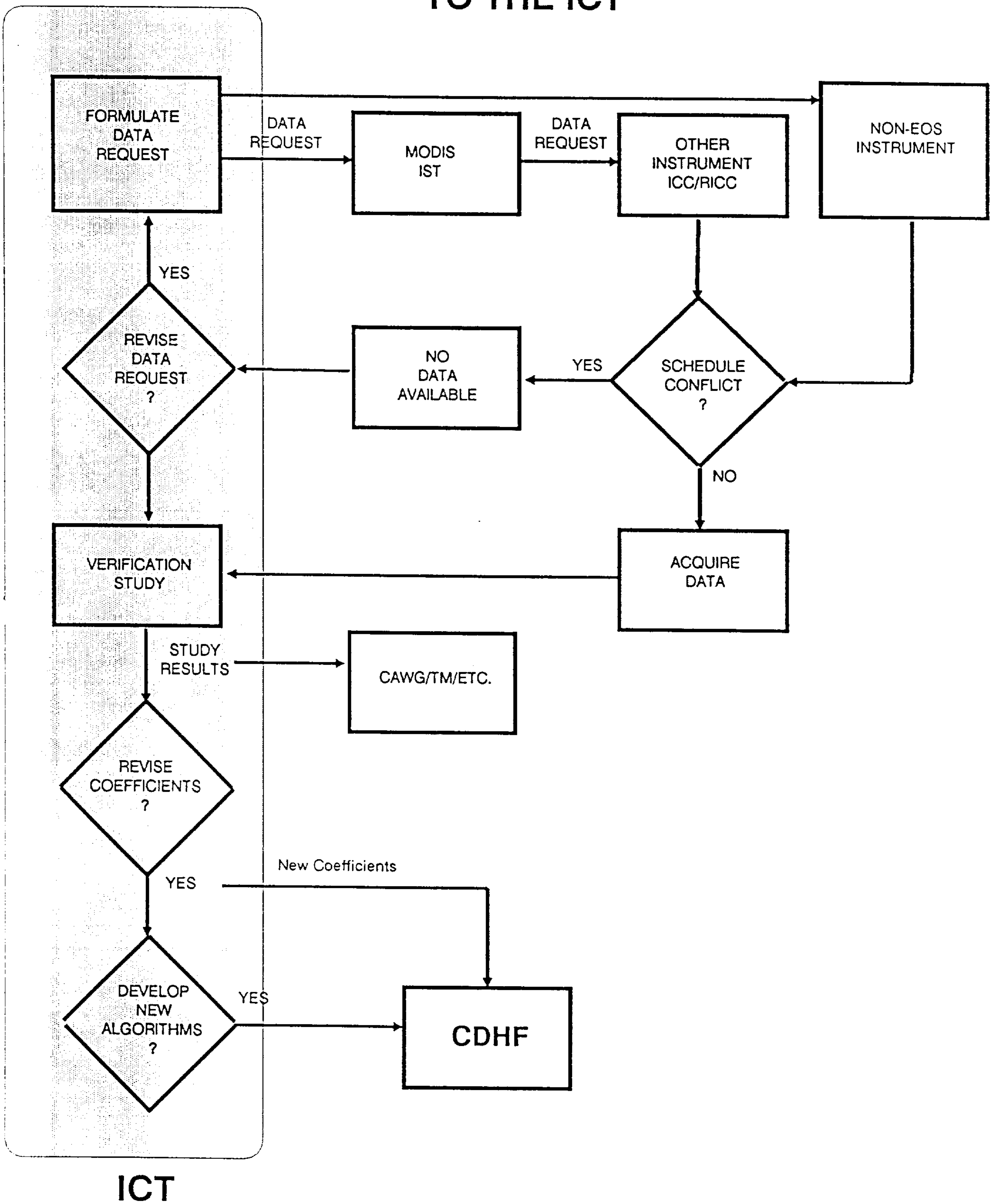
CALIBRATION DATA PRODUCT FLOWS WITHIN ICT DURING ROUTINE PROCESSING



Sample Level-1 Data

- Evenly Spaced in Time
- Lamp On
- Solar Diffuser Plate Deployed
- Moon
- Spectral Calibrator On

VERIFICATION STUDIES DATA FLOWS FROM AND TO THE ICT



UTILITY/SUPPORT ALGORITHMS

ATMOSPHERIC CORRECTIONS PRELIMINARY
Atmospheric Corrections Needed for Producing Level-2 Land-Leaving Radiances

Land-Leaving Radiances have been identified as a potential MODIS Core Data Product, based on expectations that the atmospheric correction algorithms required for producing land-leaving radiances are to be developed during pre-launch phases. At present these atmospheric correction algorithms, and the requirements for them, have not been specified, nor has any MODIS Science Team Member(s) committed to developing them. This section of the document outlines a proposed atmospheric correction algorithm that attempts to provide a reasonable land-leaving radiance product useful to members of the MODIS Science Team. This is a preliminary atmospheric correction algorithm and it is expected to evolve as science team members review its form and usefulness in producing other data products. Much of the logic of the proposed algorithm is derived from remote sensing research of terrestrial vegetation.

To produce land-leaving radiances the effects of a variable atmosphere need to be corrected for. What is outlined here is a correction to account for Rayleigh scattering, aerosol scattering and ozone absorption of the direct beam and add to it a path radiance. Radiance measured at the sensor is a function of irradiance, surface reflectance, atmospheric transmittance, absorption, radiance, and wavelength. The approach here is to treat the atmosphere as a single layer through which radiation passes to the surface, is reflected by the surface, passing back through the atmosphere to the sensor. Transmission and absorption of radiation along these two paths, that of incident and reflected radiation, are considered. Two geometries, sun-surface and surface-sensor, are used in calculating the incident irradiance and reflected radiation, respectively.

Atmospheric correction will need to be done for each pixel because of differences in geometries and differing optical path lengths through the atmosphere across a scan. Required accuracies for input data needed to calculate some of the atmospheric corrections are not specified at this time; they most likely will be determined as the correction algorithm is developed.

The general equations for atmospheric correction:

$$L_m = L_s\ e^{-\tau x/\cos\phi} + L_a \quad (1)$$

$$L_s = \rho\ L_o\ e^{-\tau x/\cos\theta} + L_a \quad (2)$$

where,

L_m = radiance at sensor
L_s = radiance reflected from surface
L_o = extraterrestrial irradiance
L_a = path radiance
ϕ = surface-sensor angle
θ = sun-surface angle
τ_x = optical thickness
  τ_R = Rayleigh optical thickness
  τ_A = aerosol optical thickness
  τ_O = ozone optical thickness
ρ = surface reflectance

These equations provide a starting point for correcting for atmospheric effects on incoming and reflected radiation. Solving for these effects may be considered as a two step problem; 1) determine the physical characteristics of the atmosphere, then 2) correcting for their effect.

Physical characteristics of the atmosphere that need to be determined are the optical thickness for, Rayleigh, aerosol, and ozone. Rayleigh and aerosols have different characteristics and are both wavelength dependent in their scattering effects. Ozone absorbs radiation and is wavelength dependent. There are various ways available for determining the amount of each present in the atmosphere and correcting for their effect. The method of correction does in large part depend on physical measurements available and the intended use of the product.

Rayleigh scattering

Rayleigh (or molecular) scattering is inversely related to the fourth power of the wavelength. Rayleigh scattering is often assumed to be relatively invariant in time and space. Rayleigh optical thickness can either be assumed for a standard atmosphere, or determined from surface pressure measurements. τ_R may be calculated as:

$$\tau_A = P/P_o\ \tau_{Ao} \quad (3)$$

where;

P = surface pressure (mb)
P_o = standard atmospheric pressure, 1013.25 mb
τ_{Ao} = optical thickness at standard atmospheric pressure
(From, Gordon, et al., 1988).

Rayleigh scattering should be calculated for every pixel to account for varying optical path lengths, cos ϕ, and cos θ , across a scan. Surface pressure measurements could come for the National Meteorological Center (NMC). Accuracies required for pressure data need to be defined.

Aerosols

Though the radiative transfer characteristics of aerosols are rather well defined, a major difficulty in correcting for their effects, is determining their physical amounts in the atmosphere (Y. Kaufman). Aerosols are variable in both temporally and spatially, making them difficult to correct for. It appears that τ_A may be calculated if some assumption is made of the aerosol climatology of a region, or may be determined from the imagery and climatology, e.g. Kaufman and Sendra (1988). The results of two methods of calculating τ_A that employ assumptions about the aerosol climatology are shown in Figure 1. The Angstrom formula was used to calculate τ_A for a clear and hazy atmosphere.

$$\tau_A = \beta\lambda^{-\alpha} \qquad (4)$$

where,
α = 1.0, a value typical of continental aerosols
β = turbidity coefficient related to turbidity
β =0.102 for clear, 25 km visibility
β =0.43 for hazy, 5 km visibility

Singh and Saull (1988) calculated aerosol optical thickness for an average continental type as:

$$\tau_{A\lambda} = 0.1\lambda^{-1.3} \qquad (5)$$

and this equation produced a curve that was in close agrement with the Angstrom formula for a clear atmosphere (Fig. 1).

The apparent need for an aerosol correction is demonstrated by the relatively large difference in aerosol optical thickness between clear and hazy conditions.

A technique for determine τ_A that will yield reasonable measurements and provide for acceptable data products will need to be determined. It may be possible to obtain τ_A from the Atmospheric Core Data Product analysis as it has been listed as a core data product, as well as other characteristics of aerosols.

Ozone

The determination of τ_0 is not well researched at the present time, but in general it appears that τ_0 may be measured directly or estimated, based upon some assumptions or predictions. A measure of O_3 concentration appears to be required. Could the Total Column Ozone identified as a Atmosphere Core Data Product be used?

Path radiance

Common to both equations 1 and 2 is the path radiance term L_a. Path radiance is radiance scattered in the atmosphere and contributes a diffuse component to the surface, and a diffuse component to the radiation sensed by the sensor. The contribution of path radiance to the total radiance sensed depends on atmospheric characteristics. The calculation of path radiance may be handled in various ways and its determination requires more discussion. Suffice for the present to identify that it has a contribution to reflectance.

Surface reflectance

A knowledge of surface reflectance ρ is required for determining the amount of reflected radiance. It seems that at this time surface reflectances could be obtained from a look up table containing values of ρ for different surface features that could be compiled from a variety of sources and geographically referenced.

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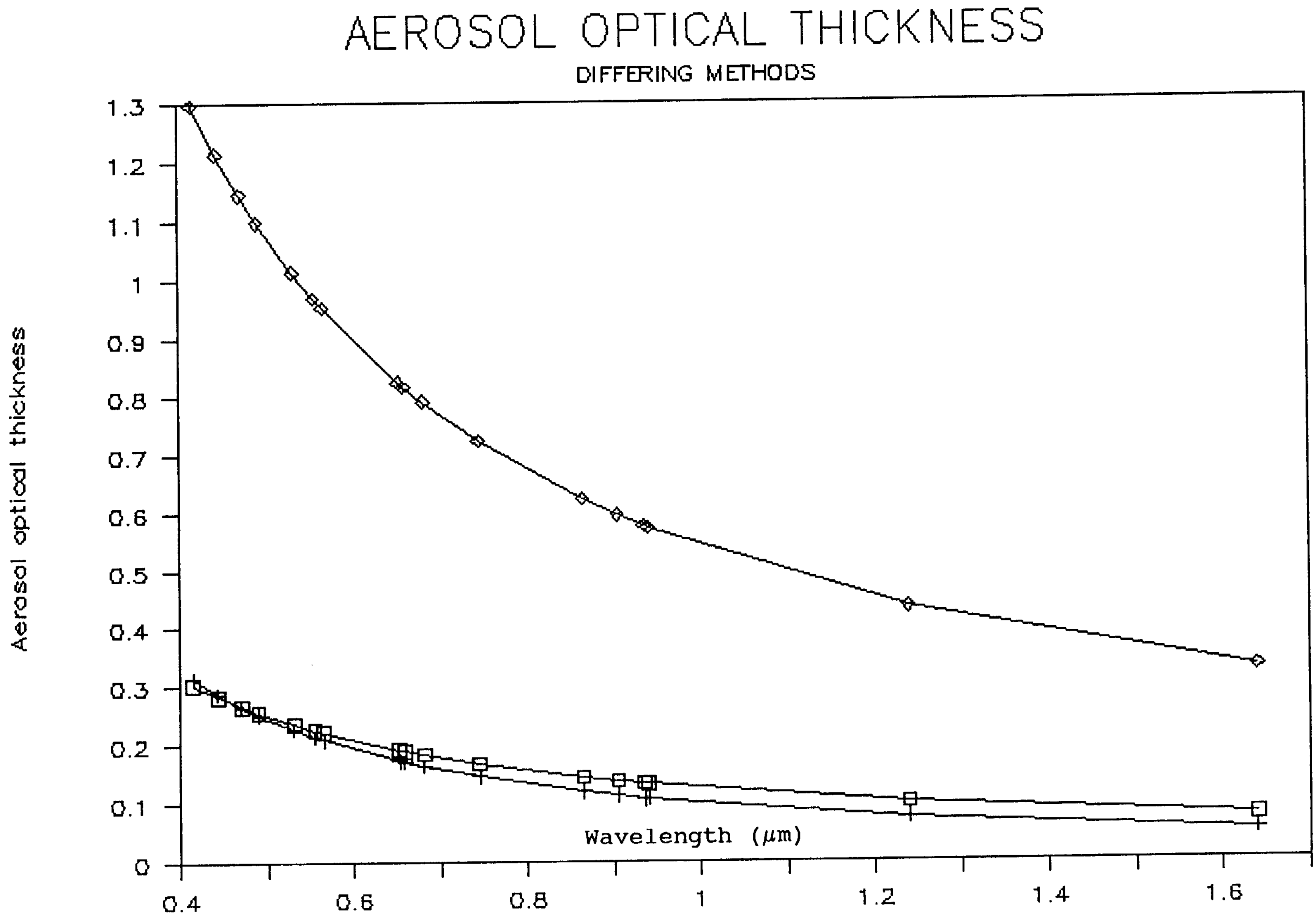

Figure 1. Differing methods of calculating aerosol optical thickness. Angstrom formula; clear atmosphere (□), hazy atmosphere (◇), and by Eq. 5 (+).

MODIS Data Navigation Algorithm Requirements

Products requiring earth location.

The MODIS instruments support three broad categories of data products: atmospheric, oceanic, and terrestrial (land). In general, earth location requirements depend on the product type.

Atmospheric features are properly located by the coordinates of the point on the Earth's surface directly underneath the feature. However, since the scan angle of the MODIS instruments can exceed 45 degrees, toward the edges of the scan an error in apparent position can occur that is about equal to the height of an observed atmospheric object above the surface of the Earth. An elevation correction could be applied to atmospheric products to account for the apparent shift in position due the oblique viewing angle of the sensor and the height of the object. However, such correction would require knowledge of the height of the object (not usually available), and in fact, in the case of layered atmospheric structures with transparent upper layers, several corrections might be appropriate depending on the height of the particular atmospheric feature being examined. Moreover, the atmospheric scientists involved have not yet expressed an interest in receiving such elevation corrected atmospheric products as routine MODIS output, and until such interest is identified, it will be presumed that elevation corrections are not essential for atmospheric products.

Atmospheric products may be referenced by the coordinates of the surface observation associated with the instrument scan geometry. The uncertainty in true position thus introduced for atmospheric products is roughly equal to the height of the features being examined (referenced to mean sea level).

Ocean products require no elevation correction (sea level changes due to tides are considered negligible). The model of the earth appropriate for use with ocean products is the Earth geoid (gravitational equipotential of the Earth corresponding to Mean Sea Level).

Errors in apparent location due to oblique scanning and elevation also occur for terrestrial products. Elevation correction of terrestrial products requires high-resolution terrain elevation data for the land regions of the Earth. Worldwide elevation data at five minute resolution has been located; data at higher resolution may be used where it is available. To achieve stated location accuracy goals, elevation correction is required for MODIS land products.

General processing features and algorithm requirements for Earth location.

To avoid the necessity of detailed Earth location computations for each MODIS pixel, detailed computations will be done for selected pixels called "anchor points" and results will be obtained for the remaining pixels by interpolating between these anchor points. When elevation correction is required (terrestrial data), individual elevation corrections will be applied to each observed pixel, i.e. elevation corrections will not be interpolated between anchor points.

Ephemeris data for the MODIS platform will include Global Positioning System (GPS) position data and platform attitude data from an on-board star-tracker. Earth location of the selected anchor pixels can begin with the interpolation of ephemeris data and platform attitude data (expected at perhaps 1 second and 0.1 second intervals, respectively) to the time at which the anchor pixel was observed. Using an EOS recommended geoid model for the earth, location coordinates for each anchor pixel can be determined. The computations involve determining the celestial coordinates of the path between the observed object and the sensor (right ascension, Greenwich hour angle, and declination) and the conversion of these coordinates to latitude and longitude on the earth geoid.

Anchor point computations are applied using nominal instrument scan angles to determine pixel locations. Experience has shown that slight registration errors may occur between nominally corresponding pixels at different spectral wavelengths and between geographically neighboring pixels in a single wavelength image. Pixel registration errors may be accounted for if the interpolation between anchor points is done using non-uniform increments between pixels, i.e. if the interpolation increments reflect the actual positions of the detectors involved without assuming that the pixels are uniformly spaced within a single-wavelength image or consistently spaced across different wavelengths. In the most general case, registration corrections will be required for each along track pixel at each sensor wavelength, i.e. 2 x 4 x 32 = 256 214 m detectors, 5 x 2 x 16 = 160 428 m detectors, and 29 x 8 = 232 856 m MODIS-N detectors (648 total) [This computation assumes that the detector sample frequency is maintained for the high-resolution detectors]. MODIS-T will require 30 x 64 = 1,920 correction constants.

When elevation corrections are required, they should be individually applied to the interpolated pixel locations on the Earth geoid. Since high-resolution corrections for elevation effects are desired, this procedure will accommodate accurate elevation correction without forcing an unwarranted increase in the number of anchor points computed. Since elevation data will be specified at points randomly located with respect to MODIS pixels, interpolation will be required to generate elevation estimates at