T-GE/29/1//36102

The Moderate Resolution Imaging Spectrometer (MODIS) Science and Data System Requirements

Philip E. Ardanuy
Daesoo Han
Vincent V. Salomonson

Reprinted from
IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING
Vol. 29, No. 1, January 1991

The Moderate Resolution Imaging Spectrometer (MODIS) Science and Data System Requirements

Philip E. Ardanuy, Daesoo Han, and Vincent V. Salomonson

Abstract—**The Moderate Resolution Imaging Spectrometer (MODIS) has been designated as a facility instrument on the first NASA polar orbiting platform as part of the Earth Observing System (EOS), and is scheduled for launch in the late 1990's. The near global daily coverage of MODIS, combined with its continuous operation, broad spectral coverage, and relatively high spatial resolution, makes it central to the objectives of EOS. The mission requirements of the EOS and the MODIS instruments may be traced through the MODIS science team members to the proposed set of core MODIS data products. The development, implementation, production, and validation of these core data products define a set of functional, performance, and operational requirements on the data system that operate between the sensor measurements and the data products supplied to the user community. In this paper, we review the science requirements guiding the processing of MODIS data, and we discuss some aspects of an operations concept for the production of data products from MODIS for use by the scientific community.**

I. Introduction

THE goal of the Earth Observing System (EOS) Mission is to understand changes of the Earth, viewed as a completely integrated system, by examining the Earth's hydrological, geophysical, and climatic processes coupled with the biogeochemical cycles [1]. To achieve this goal, long-term multidisciplinary Earth observations must be made. One of the instruments proposed to measure oceanographic, terrestrial, and atmospheric parameters is the Moderate Resolution Imaging Spectrometer (MODIS) [2], [3]. MODIS will observe nearly the whole Earth twice a day—once during daytime and once during nighttime. Current plans call for the collection of data for at least 15 years, thus providing long-term global data sets to the scientific community for the study of global change. MODIS will be composed of two cross-track scanning components: nadir-viewing MODIS-N [4] and tiltable MODIS-T [5]. As currently envisioned, MODIS-N will have 36 spectral channels, and MODIS-T will have 32 channels. MODIS-N channels will observe the visible, near-infrared, and thermal-infrared (Table I) spectral regions. Observations will be taken at spatial resolutions ranging from 250 m to 1 km at nadir. MODIS-T channels each have a nadir resolution of 1.1 km, and extend from 410 to 875 nm in 32 bands, each between 10 and 15 nm in width (full width, half maximum). The capabilities of the MODIS instrument expand upon the achievements of a number of earlier sensors: the Advanced Very High Resolution Radiometer (AVHRR), the High Resolution Infrared Sounder (HIRS), and the Coastal Zone Color Scanner (CZCS). Additional spectral bands common to the Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS) have also been included.

MODIS data products are being required not only by the members of the MODIS science team, but also by members of the other EOS facility instrument teams, the EOS interdisciplinary investigators, and the scientific community at large. The diverse observing capabilities of the MODIS-N and MODIS-T instruments allow MODIS observations and data products to be applied to many of the key areas in the study of global surface dynamics, change, and the interrelationships of Earth processes [6], [7].

The mission requirements of the EOS and the MODIS instruments may be traced through the MODIS science team members (Fig. 1) selected through peer review by NASA. The development, implementation, production, and validation of data products from MODIS in turn define a set of functional, performance, and operational requirements to be placed on a data system that operates between the sensor measurements and the data products supplied to the user community. The primary data systems include the MODIS Instrument and its processor (from sensor signals to data packets), the EOS Platform (data transmission from the instrument through the platform to the ground), and the ground processing system including the EOS Data and Information System (EOSDIS). A set of definitions defining the processing stages for instrument data from sensor signal through data product are given in Table II.

Processing requirements for MODIS data are being studied [8]–[10]. The most important feature is the amount of data collected by the MODIS instrument. Operating with 12-b quantization on a 100% duty cycle, the MODIS instrument will have an orbital average data rate near 8 Mb/s. Each day, just under 1 Tb of raw data will be acquired. A large number of multidisciplinary geophysical parameters will be produced for each observation. The EOS ground data system is being sized and designed to handle the data efficiently in order to effectively meet stated functional, performance, and operational requirements [11], [12].

Remote sensing science begins with a definition of science requirements, i.e., what scientific questions can be addressed using spaceborne platforms and sensors, and what geophysical features can be detected. These requirements drive the instrument design. The instrument design defines acceptable radiance noise levels (the radiometric sensitivity), which impose an absolute limitation on the ability of the instrument to potentially meet the science requirements. Science requirements also drive the formulation and refinement of an operations concept, which

Manuscript received December 30, 1989; revised March 7, 1990.

P. E. Ardanuy is with Research and Data Systems Corporation, Greenbelt, MD 20771.

D. Han and V. V. Salomonson are with the Earth Sciences Directorate, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

IEEE Log Number 9036102.

TABLE I

BAND CENTER (nm FOR BANDS 1–19, μm FOR BANDS 20–36), NADIR IFOV (m), FULL-WIDTH HALF-MAXIMUM BANDWIDTH (nm FOR BANDS 1–19, μm FOR BANDS 20–36), AND PRIMARY PURPOSE OF THE MODIS-N VISIBLE, NEAR-INFRARED, AND THERMAL BANDS. (THE SPECTRAL PARAMETERS FOR THE MODIS-N DETECTORS (AND TO A LESSER EXTENT MODIS-T) WILL CONTINUE TO BE REFINED TO OPTIMIZE THE POTENTIAL INFORMATION CONTENT AND STABILITY OF THE MEASUREMENTS)

Band	Center	IFOV	Width	Primary Purpose
Land, Aerosol, and Cloud Properties Bands				
1	659	250	50.0	Chlorophyll Absorption and Land Cover
2	865	250	40.0	Atmospheric Correction and Land Cover
3	470	500	20.0	Soil-Vegetation Differentiation
4	555	500	20.0	Green Peak
5	1240	500	20.0	Leaf Canopy Properties
6	1640	500	20.0	Snow/Cloud Differentiation, Volcanoes
7	2130	500	50.0	Land Surface and Cloud Properties, Volcanoes
Ocean Color Bands				
8	415	1000	15.0	Chlorophyll
9	443	1000	10.0	Chlorophyll
10	490	1000	10.0	Chlorophyll
11	531	1000	10.0	Chlorophyll
12	565	1000	10.0	Chlorophyll and Sediments
13	653	1000	15.0	Aerosol Properties and Sediments
14	681	1000	10.0	Chlorophyll Fluorescence/Aerosol
15	750	1000	10.0	Aerosol Properties
16	865	1000	15.0	Aerosol and Atmosphere Properties
Atmosphere/Cloud Bands				
17	905	1000	30.0	Total Precipitable Water and Cloud Properties
18	936	1000	10.0	Total Precipitable Water and Cloud Properties
19	940	1000	50.0	Total Precipitable Water and Cloud Properties
Thermal Bands				
20	3.75	1000	0.18	Sea Surface Temperature
21	3.75	1000	0.05	Forest Fires/Volcanoes
22	3.96	1000	0.05	Clouds and Surface Temperature
23	4.05	1000	0.05	Clouds and Surface Temperature
24	4.47	1000	0.05	Tropospheric Temperature and Cloud Fraction
25	4.52	1000	0.05	Tropospheric Temperature and Cloud Fraction
26	4.57	1000	0.05	Tropospheric Temperature and Cloud Fraction
27	6.72	1000	0.36	Mid-Tropospheric Humidity
28	7.33	1000	0.30	Upper-Tropospheric Humidity
29	8.55	1000	0.30	Silicate Emissivity; Surface Temperature
30	9.73	1000	0.30	Total Ozone
31	11.03	1000	0.50	Clouds/Surface Temperature; Split Window
32	12.02	1000	0.50	Clouds/Surface Temperature; Split Window
33	13.34	1000	0.30	Cloud Height and Fraction/CO_2 Slicing
34	13.64	1000	0.30	Cloud Height and Fraction/CO_2 Slicing
35	13.94	1000	0.30	Cloud Height and Fraction/CO_2 Slicing
36	14.24	1000	0.30	Cloud Height and Fraction/CO_2 Slicing

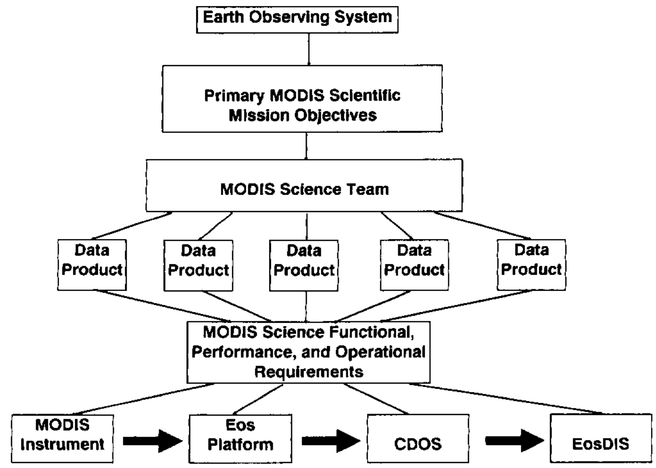

Fig. 1. A conceptual illustration of the flow of requirements from the EOS science objectives to the data system (top to bottom) along with the flow of instrument data from MODIS to the end users (left to right).

TABLE II

DATA DICTIONARY DEFINING SIX LEVELS OF EVOLUTION IN THE PROCESSING OF THE MODIS INSTRUMENT DATA

Data Level	Data Definition
Level-0	Instrument-Data at original resolution, time order restored, with duplicates removed.
Level-1A	Level-0 data which are reformatted, with earth location, calibration data, and other ancillary data appended.
Level-1B	Level-1A data to which the radiometric calibration algorithms have been applied, to produce radiances or irradiances and to which the Earth-location and navigation algorithms have been applied.
Level-2	Geophysical parameter data retrieved from the Level-1B data by application of geophysical parameter algorithms.
Level-3	Earth-gridded geophysical parameter data (including Level-1 and Level-2 radiances), which have been averaged or composited in time and space.
Level-4	Analyses of the lower levels of instrument data, generally involving detailed model calculations.

include items such as the choice of orbit, duty cycle, and scheduling for the various operating modes of the instrument. Conversion of the radiances detected by the sensor into meaningful geophysical data products then requires a geophysical algorithm. Given the operations concept, there is an inherent error from three sources: 1) the instrument radiometric sensitivity; 2) the accuracy of ancillary, external data that may be required by the algorithm; and 3) the accuracy of the algorithm in converting radiances to geophysical data products.

The following sections present the current science requirements. In Section II, we review the oceanic, atmospheric, and terrestrial "core" data products to be produced by the MODIS science team. Radiances at the top and bottom of the atmosphere are considered. Required utility algorithms and their role in the MODIS data processing are reviewed in Section III. Section IV presents operational requirements on the current design of the platform and the EOS Data and Information System (EOSDIS). Timeliness requirements for data processing to monitor instrument performance and support field experiments are given. In Section V, issues affecting other elements of the EOS are discussed.

II. MODIS Core Data Products

A. Definition of Core Products

The MODIS science team is making an effort to have in place, and implemented on an EOS Distributed Active Archic Center (DAAC) by launch of the first polar platform (EOS-A), a set of algorithms which will produce a complete set of "core" MODIS data products. A MODIS data product may be defined as a core, or "at launch," product if it meets the following criteria.

- It is of interest to the scientific community, particularly to members of the MODIS science team, other EOS instrument science teams, and the interdisciplinary investigations.
- There is some experience with previously flown spaceborne or aircraft instruments that indicates it is feasible to produce the geophysical data product at, or shortly after, launch.
- The availability and accuracy of the data product will provide an important contribution toward meeting the scientific objectives of EOS.
- The product can be generated using primarily, although not exclusively, MODIS data.

B. Types of Core Products

Four ~~For~~ types of core MODIS data products have been identified: 1) Level-1 radiances at the top of the atmosphere and Level-2 radiances at the bottom of the atmosphere; 2) core terrestrial data products; 3) core oceanic data products; and 4) core atmospheric data products, which include the core cloud data products. Table III lists Level-2 to Level-4 core MODIS data products that have been identified by the MODIS science team.

It is envisioned that the MODIS sensor data, MODIS ancillary data, and platform ancillary data will be combined with calibration and Earth-location data sets to create MODIS Level-1 radiance products In addition to the primary MODIS Level-1 products used for processing to higher data levels, Level-1 processing should create routine radiometric calibration support products and instrument response histories (Fig. 2). The latter product would then be combined with command histories and event and anomaly analyses, and archived as a comprehensive MODIS instrument mission history. The Level-1 radiances may be converted into Level-2 and higher-level (3 and 4) MODIS data products. Cloud identification, snow/ice discrimination, and atmospheric corrections would be applied early in processing since these procedures are required for the generation of most Level-2 and higher products. The cloud identification algorithms to be used at the beginning of Level-2 processing would be, for the most part, unrelated to the algorithms that will create core Level-2 cloud products. However, the atmospheric correction algorithms would incorporate features and elements of algorithms proposed for the generation of core Level-2 atmospheric products.

TABLE III
Preliminary List of MODIS Core Data Products, to be Available at Launch

MODIS Ocean Data Products
Water-Leaving Radiances
Single-Scattering Aerosol Radiances
Angstrom Exponents
Chlorophyll-a Concentrations (Case 1)
Chlorophyll-a Concentrations (Case 2)
Chlorophyll-a Fluorescence
CZCS Pigment Concentrations
Sea-Surface Temperature
Sea-Ice Cover
Surface Incident Photosynthetically Active Radiation
Attenuation at 490 nm
Detached Coccolith Concentration
Phycoerythrin Concentrations
Dissolved Organic Matter
Seston
Primary Production
Calibration Adjustment Data Sets
MODIS Land Data Products
Cloud Mask, Cloud Shadow
Land-Leaving Radiances
Vegetation Index
Surface Temperature
Thermal Anomalies
Snow Cover
Land-Cover Type
Bidirectional Reflectance, BRDF
MODIS Atmospheric Data Products
Cloud Fractional Area
Cloud Effective Emissivity
Cloud-Top Temperature
Cloud-Top Pressure
Cloud Optical Thickness (0.66 μm)
Cloud Particle Effective Radius
Cloud Particle Thermodynamic Phase
Aerosol Optical Depth (0.41 to 2.13 μm)
Aerosol Size Distribution
Aerosol Mass Loading
Atmospheric Stability
Total Precipitable Water
Total Ozone

C. Core (Level-1 and Level-2) Radiance Data Products

The general science community appears to have an interest in both the radiances at the top of the atmosphere (Level-1) and the radiances at the bottom of the atmosphere (Level-2). The EOS-wide requirement for MODIS radiances is presumed to extend over most of the spectral bands (particularly in the reflected wavelengths). The requirement will include upwelling radiation at both the top and bottom of the atmosphere, and will be for a range of spatial resolutions.

Several MODIS-N water-leaving radiance bands may be required for general oceanographic use; however, water-leaving radiances from most of the MODIS-T spectral regions will be required for algorithm development work. Also, additional longer wavelengths not required for open ocean may be required for this product for coastal regions. These bands are divided into those requiring atmospheric correction to produce water-leaving radiances (e.g., bands 8 to 16) and those requiring water vapor correction to produce sea surface temperatures (e.g., bands 20, 31, and 32). The snow and sea-ice cover algorithms should require no atmospheric correction, and utilize bands used for other ocean products.

MODIS-T radiances are not relevant to the production of sea surface temperatures or sea ice estimates, but only water-leaving radiances and products derived therefrom. However, all bands in the visible wavelengths will probably be used for research, even if they are not required for core data products. Thus, MODIS-T may require atmospheric correction for all bands between 400 and 700 nm, and perhaps to 875 nm.

In research involving the remote sensing of terrestrial vegetation, many results have been presented in a qualitative way

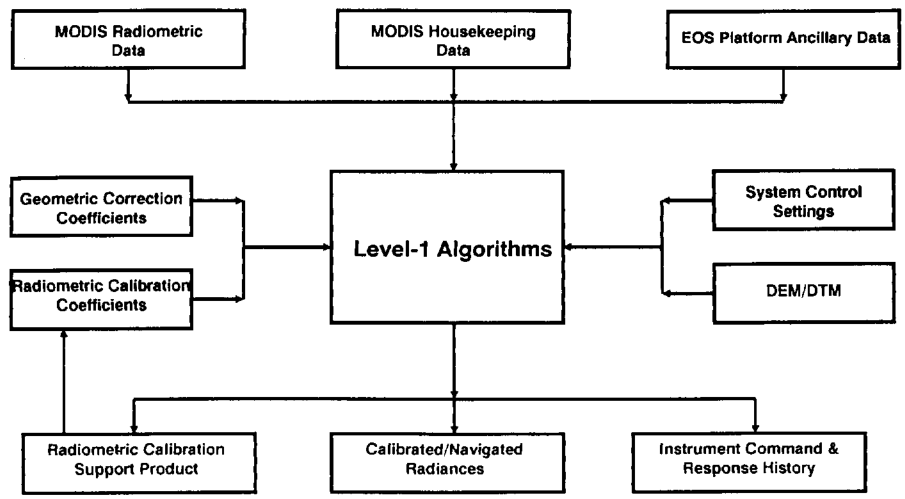

Fig. 2. Conceptual data flows through the MODIS Level-1 processing, illustrating the earth location and calibration steps and the merging of MODIS sensor data, MODIS ancillary (engineering) data, and platform ancillary data.

(e.g., ratios of reflectance and correlations of the ratios with ground data). The most popular vegetation ratio is the Normalized Difference Vegetation Index (NDVI), which has been found to be strongly related to vegetation parameters such as Absorbed Photosynthetically Active Radiation (APAR), green-leaf biomass, leaf-area index, net primary productivity of natural vegetation, and seasonal green-leaf dynamics at a continental scale. This qualitative presentation of remote sensing data has been prevalent in the literature on remote sensing since the beginning. Using the greater multispectral capabilities and higher bit quantization of MODIS, it will be possible to advance to the quantitative analysis of remotely sensed vegetation dynamics using radiance values for the bottom of the atmosphere.

It appears that the major obstacles to obtaining land-leaving radiances from satellite data in the past have been either a lack of good radiometric calibration of the sensor or an absence of standardized atmospheric corrections; both are required to retrieve land-leaving radiances. With MODIS, the requisite radiometric data and the ability to generate the atmospheric corrections should be available. Thus, land-leaving radiances may become a standard Level-2 MODIS data product. For the terrestrial sciences, a number of the MODIS-N bands may be routinely corrected for atmospheric effects.

These atmospherically corrected Level-2 ''land-leaving'' radiances would be useful for: 1) the direct comparison of ground-based in situ data with MODIS observations; 2) the calculation of physiological processes and energy balances in ecological modeling studies; 3) the computation of energy balances for several disciplines; and 4) analysis in studies employing multitemporal data sets. Atmospherically corrected data may also enhance our ability to discern among surface features. By accounting for atmospheric scattering and absorption, the use of land-leaving radiances may make it possible to discriminate and detect smaller differences among features, especially at the higher bit quantizations of MODIS.

The MODIS Level-1 data product will contain substantial information in addition to the calibrated spectral radiances. Earth locations (latitude, longitude, and elevation) will be provided for a subset of the detector IFOV's (and, due to storage considerations, not for all spectral bands). Angles describing the Earth–Sun–satellite viewing geometry (e.g., solar zenith angle, satellite zenith angle, relative azimuth, and the satellite's viewing azimuth from due north) must be provided for use in bidirectional-reflectance and digital-elevation model determination and application, and for use in comparison to other instrument observations. Comprehensive platform and MODIS ancillary data will also have to be included. Derived ancillary data will include calibrated MODIS temperatures, scan position, and status words.

D. Core Ocean Data Products Overview

Fig. 3 describes a candidate data flow scenario for obtaining ocean core data products proposed for MODIS. Its primary purpose is to show the interrelations among the products. The overview is compatible with the MODIS ocean core data products algorithms; however, expected changes that may result form improved algorithms are not reflected. The flight of the Sea Wide Field of View Sensor (SeaWiFS) instrument [13], for example, may result in some changes.

Derivation of MODIS ocean data products begins with Level-1B calibrated radiances. A cloud filter may then be applied, diverting the data stream from ocean products to cloud products. However, cloud products may then be used to make determinations of surface incident Photosynthetically Available Radiation (PAR). If pixels pass the cloud test (if they are sufficiently clear), they should then be used, uncorrected for atmosphere, to determine sea ice extent. They can also be corrected for water vapor to determine the sea surface temperature. These products can only be generated by MODIS-N because they require observations in thermal-infrared wavelengths. Otherwise, the pixels will be atmospherically corrected to produce water-leaving radiances. At this time, it is expected that both MODIS-N and MODIS-T will generate water-leaving radiances and products derived therefrom. Although this scenario involves some duplication, it also maximizes global coverage by allowing MODIS-N to fill gaps in MODIS-T observations at Level-3, and vice versa.

The atmospheric correction involves determining the Rayleigh scattering and aerosol absorption; and scattering contributions to the total radiances, and removing them. Angstrom exponents, an indicator of the wavelength dependence of aerosol attenuation, come out directly in this process. Atmospheric correction will directly generate two ocean core products: water-

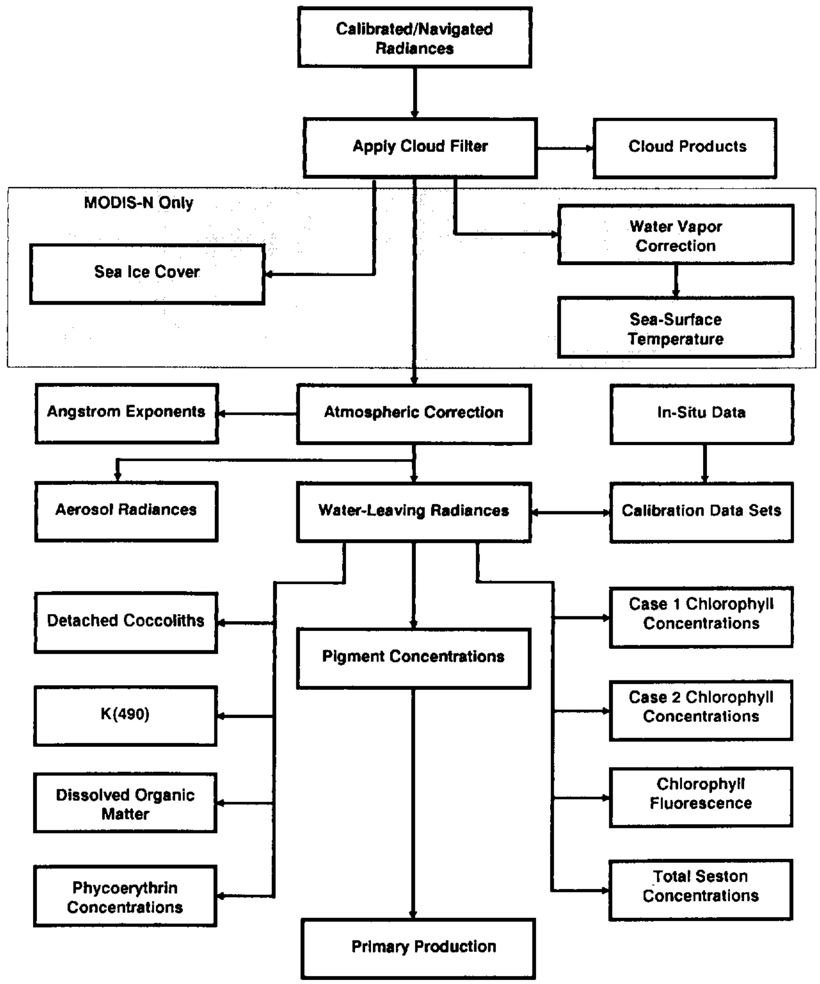

Fig. 3. A conceptual overview of the core MODIS ocean data processing scenario, including the primary data flows.

leaving radiances and aerosol radiances. Water-leaving radiances form the foundation for the remaining products. They would be used to directly obtain pigment concentrations and chlorophyll-a pigment concentrations for Case-1 and Case-2 waters. In the generation of Case-2 pigment concentrations, a flag differentiating Case-1 from Case-2 areas will be used to determine whether to employ the Case-2 algorithm. Also derived from the water-leaving radiances are chlorophyll fluorescence, total seston (suspended particulate matter) concentrations, detached coccolith concentrations, K(490), dissolved organic matter, and phycoerythrin concentration. Phycoerythrin is an accessory light-harvesting pigment present in specialized types of phytoplankton.

For the oceanic primary production, an empirical approach relates MODIS-generated pigment concentrations to measured in situ primary production. Surface incident PAR and the diffuse attenuation coefficient for PAR, as well as Case-1 and Case-2 chlorophyll-a concentrations, may also be involved in this algorithm. Chlorophyll fluorescence is also envisioned as a possible method to obtain primary production in the future

When MODIS data product software prototyping is considered, each of these algorithms and their related code may be visualized and realized as a separate subroutine. The calling sequence for the subroutines is identical to the scenario illustrated in Fig. 3, with a single exception. The calibration adjustments generated through a comparison of the water-leaving radiances and the *in situ* data will likely require human intervention. The improved calibration could then be applied to adjust the water-leaving radiances, either for future processing or for reprocessing. The time scale for this step could be from weeks to months initially, and then from months to annual well after launch.

E. Core Atmospheric Data Products Overview

An overview of the suggested processing structure for the atmospheric core data products is provided in Fig. 4. One of the first steps in the Level-2 processing will be the setting of cloud cover flags. We anticipate that cloud flags will be set in a two-step process. First, a series of tests will be performed to identify clear fields of view. Second, a series of tests will be applied to separate homogeneous clouds from partly cloudy and mixed IFOV's. Snow and ice cover discrimination will also be performed at this stage of the processing. A cloud fractional area product can be produced directly from the cloud flags.

A series of tests for cloud cover can be performed, and the result of each test would be stored by setting flags. Every test could be applied to each pixel, and the result of up to eight tests can be carried as a single byte. This technique allows MODIS data users flexibility in selecting data for further processing. This procedure is viewed as necessary since there is no single definition of a cloud, and certain types of cloud cover may not prevent the determination of surface properties. For example, NDVI may be useful even under thin cirrus. Cloud flags will

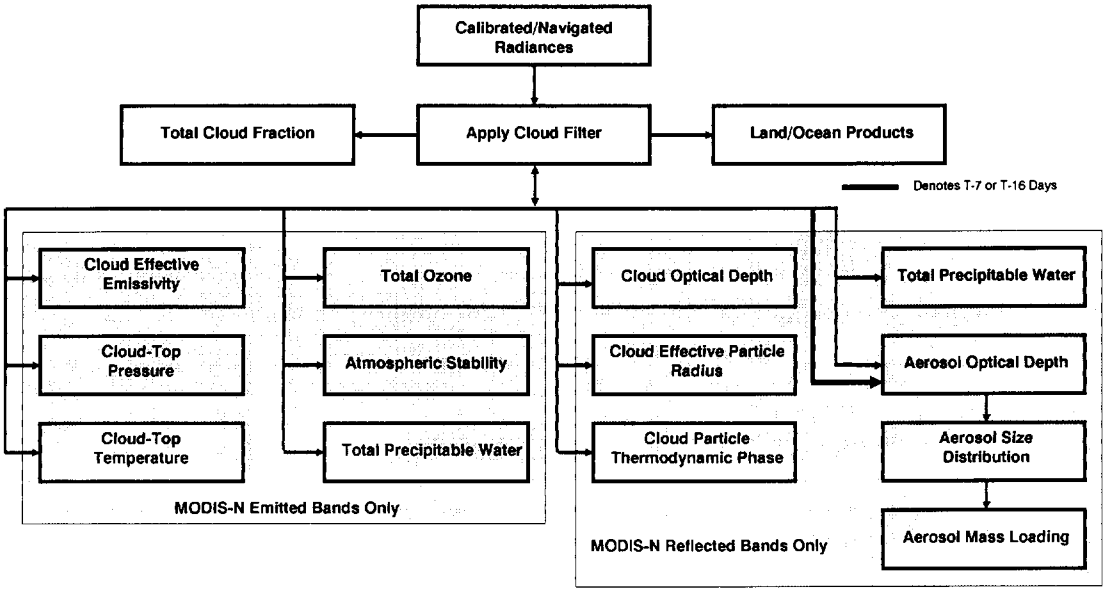

Fig. 4. A conceptual overview of the core MODIS atmospheric data processing scenario, including the primary data flows.

be useful for users of either MODIS-N or MODIS-T radiances. However, radiances from MODIS-N only will be required to generate atmospheric core data products.

Those observations for which cloud flags have been set will be processed to retrieve cloud data products. Infrared radiances may be used to determine cloud-top pressure and temperature by means of a CO_2 slicing algorithm and effective cloud emissivity. Radiances from up to five MODIS-N reflected bands will be used to retrieve cloud optical depth at 0.66 μm, effective cloud particle radius, and cloud particle thermodynamic phase. Surface reflectances for these bands will be required as ancillary data.

The infrared radiances from as many as 16 bands will also be used for all scenes to compute the total ozone, atmospheric stability (e.g., lifted index), and total precipitable water. Layer-mean temperatures and water vapor amounts will be by-products in the generation of these core products. Observed or forecast (AIRS or NMC) surface and atmospheric temperatures will be required as ancillary data.

All of the processing to this point can be done for a single swath of MODIS-N data (one scan). Some of the products may require the combination of scan swaths so that the analysis can be applied over larger areas. In particular, the algorithms which would be developed to determine cloud area and perimeter, fractional cloud coverage, and aerosol parameters may work most efficiently with scenes with dimensions of 200 km or larger (alternatively, these products may only be generated at Level-3).

Required inputs to the aerosol core data product processing (Fig. 4) include Level-1B radiances over approximately eight spectral bands, previously observed radiances for scenes with the same viewing geometry (perhaps 7 to 16 days earlier), NDVI values, land-cover-type maps, total column ozone amounts, total precipitable water, and surface relative humidity. The radiances will first be screened to remove clouds. Depending upon the surface type, aerosol optical depth (0.41 to 2.13 μm) could be calculated by as many as three different algorithms. Surface spectral reflectances or albedos would also be required by some of these algorithms. Given aerosol optical depths, the aerosol size distribution and aerosol mass loading then become derivative data products.

F. Core Land Data Products Overview

Except for aerosol optical depth and spectral surface albedo, the land core data product processing scheme shown in Fig. 5 assumes that all atmospheric computations required to support land product processing are done as a part of atmospheric processing. Since aerosol optical depth and surface spectral albedo both affect the radiance observed by the MODIS instruments, they appear as simultaneous unknowns in the solution process, and surface spectral albedo is obtained automatically as a coproduct of atmospheric correction. Surface spectral albedo might be computed in the final stage of atmospheric processing just before dedicated land processing begins.

The atmospherically corrected radiances serve as inputs for the determination of land surface temperatures, thermal anomalies, snow/ice cover, vegetation indexes, land-cover type, spatial heterogeneity measures, and the development of bidirectional reflectance distribution functions. Since thermal anomalies, such as fires and volcanic eruptions, may affect the apparent value of the land surface temperature, thermal anomaly events may need to be tagged in the listings of land surface temperature. Similarly, extraordinary values of land surface temperatures may help to corroborate thermal anomaly events, so that the land surface temperature may be examined as a part of the thermal anomaly identification process. The snow/ice identification makes use of land temperature determinations, as well as reflected visible and near-infrared radiance observations.

The vegetation indexes (e.g., NDVI) may be obtained using either atmospherically corrected or uncorrected radiances. Atmospherically corrected indexes are best for identifying long-term trends, and these may be desired for MODIS use. Since the computation of vegetation indexes may be made to depend on the presence or absence of snow cover, the snow cover flag may serve as possible input for the computation of vegetation indices.

G. MODIS Data Processing Scenario

An overview of a candidate MODIS core data product processing scenario is illustrated in Fig. 6. Initially, Level-0 data are acquired (Table II) and used to generate Level-1A and Level-

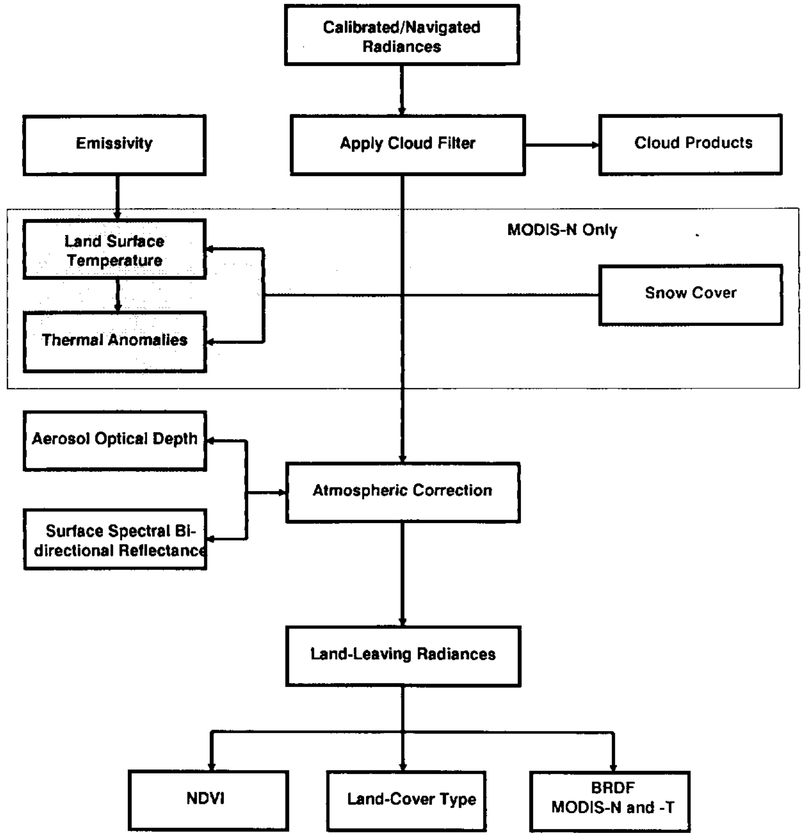

Fig. 5. A conceptual overview of the core MODIS land data processing scenario, including the primary data flows.

1B radiances at the top of the atmosphere. A set of masks are generated at the bit or word level to indicate scene-type information (e.g., land, ocean, cloud, snow/sea ice) georeferenced to the particular scan of data being processed. Based on the status of the cloud flags, cloud or other atmospheric, oceanic, or terrestrial MODIS core products are produced. During the generation of the Level-2 products, many of the MODIS bands should be atmospherically corrected. The Level-2 data are then available for the generation of higher-level products. Within this scenario, it may be possible to efficiently process an entire scan of MODIS-N or MODIS-T data from Level-0 through Level-2 and into Level-3, for all data products, without the need for I/O interruptions.

This concept is expanded in Fig. 7 for the Level-1 processing. In the illustration, a Level-0 scan "cube," with dimensions of a single or small number of scans along and across-track by the number of spectral bands, is first processed through Level-1A and then Level-1B, perhaps without leaving the main memory of the processor. Still in main memory, the Level-1B data could then be made available for Level-2 processing as the Level-1 components are routed to archive.

In a similar manner, the Level-1B data cube is then processed through Level-2 (Fig. 8) before being routed to Level-3. Within the Level-2 processing, a candidate set of processing and analysis masks are first appended before the core products are generated. The scan data cube could then be routed to Level-3 processing, as the Level-2 components are sent to archive.

III. Core Modis "Utility" Algorithms

The algorithms for the core geophysical data products will be provided by the MODIS science team members. There are a number of algorithms, other than the core geophysical algorithms, which appear essential to the reduction of the Level-0 MODIS data and the successful generation of higher-level products, including standard:

- calibration algorithms
- earth location algorithms
- topographic correction algorithms
- cloud identification (flagging) algorithms
- cloud and snow/ice discrimination algorithms
- atmospheric correction algorithms
- time and space averaging and rectifying/overlaying algorithms
- display and processing algorithms.

A. Calibration Algorithms

To support the scientific goals of EOS and the MODIS science team members, the maintenance of the MODIS calibration over the planned 15-year period will be an area of substantial emphasis for the science team. Calibration may be performed by a MODIS Characterization Support Team (MOST), which would be composed of MODIS science team members and supporting staff. The MOST should fully characterize the MODIS-N and MODIS-T instruments, and also consider the absolute MODIS calibration and, perhaps, most importantly from a perspective of global change, the relative calibration stability of MODIS over time. Preflight calibration data, instrument models and simulated data, on-board calibration data, routine data, data taken over ground-truth sites, and supporting ancillary and *in situ* data would be used by the MOST. The ICT is to be responsible for the delivery of sensor calibration algorithms and

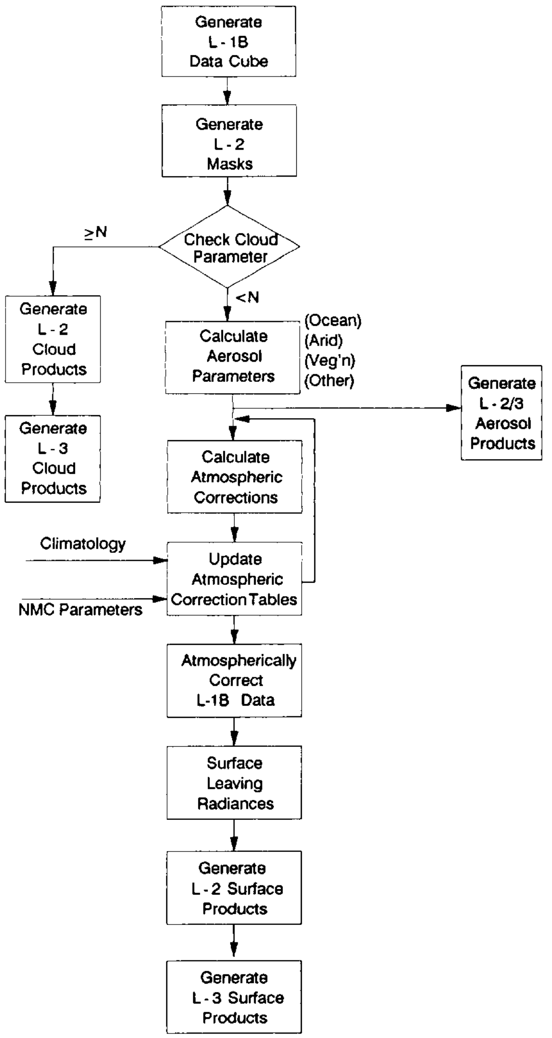

Fig. 6. General processing scenario overview for the generation of MODIS core data products.

coefficients to the DAAC so that MODIS data products may be generated. For this purpose, the calibration algorithms would include:

- instrument data monitoring algorithms
- analysis of internal calibration data; potential sources include blackbodies, lamps, space, the sun, and the moon
- analysis of instrument models
- comparison to *in situ* and ground-truth data
- comparisons to other EOS and non-EOS instrument date
- Assignment of the MODIS calibration coefficients for production
- intercomparisons of MODIS-N and MODIS-T collocated, coincident, and co-angular data sets.

B. Earth Location Algorithms

The navigation of MODIS observations to the Earth's surface is required. At nadir, positioning accuracies of at least 500 m (i.e., about one-half pixel) are estimated to be necessary to meet the science requirements. To accomplish this task, the Earth location algorithms will include:

- determination of the sensor IFOV line of sight, given platform attitude, platform thermal or dynamic distortion data, and sensor tilt and scan angles
- navigation of the IFOV centers to the Earth geoid
- correction for the effects of atmospheric refraction (a small but systematic effect)
- interpolation of the Earth locations from a sparse array of anchor points to each IFOV
- correction for surface topography.

C. Topographic Corrections for MODIS

A global Digital Elevation or Terrain Model (DEM/DTM) is highly desirable for the generation of standard data products. Applications of the DEM include (J.-P. Muller, personal communication, 1990):

- the correction of geometric distortion (pixel shifts during navigation to Level-1; orthographic resampling)
- radiometric correction for terrain slope and aspect, as well as shadowing from subpixel scale features
- atmospheric correction for path radiance and thermal profiles
- surface roughness.

Present analyses indicate that a global DEM, with a spatial resolution and vertical accuracy approaching 100 and 10 m, respectively, is necessary. The DEM might be routinely applied to all pixels located in regions of the Earth for which the terrain elevation exceeds 1 km.

D. Cloud Identification Algorithms

For the analysis and retrieval of data products at the Earth's surface, it will be necessary to identify the presence of clouds. The core cloud product algorithms should be more sophisticated than those required to make a yes/no decision regarding cloud cover. There are a substantial number of techniques available that could possibly be used for the identification of cloud cover. The MODIS instruments, and particularly MODIS-N, offer a wide spectral capability for cloud detection. Because many of the Level-2 data product algorithms will have a heritage that is distinct and unique from the other product algorithms, it will probably be appropriate to employ multiple (parallel) cloud detection algorithms. A set of flags (from six to ten) could be set based on the detection technique (e.g., IR threshold, VIS reflectance, spectral flatness, spatial coherence, bispectral, maximum likelihood, etc.). This processing will occur at the very beginning of the Level-2 processing. Each higher-level algorithm would then be free to accept or reject observations based on consistent definitions of cloud contamination appropriate to that algorithm. In addition to cloud identification and cloud versus snow/ice discrimination algorithms, it may be desirable to delineate cloud shadows where possible.

E. Atmospheric Correction Algorithms

For the analysis and retrieval of data products at the Earth's surface, and particularly for oceanic product retrievals, which provide only a small contribution to the total reflected radiance signal, it is essential that the atmospheric "contamination" be removed. Atmospheric correction over land surfaces is also critical. The development, refinement, and implementation of atmospheric correction algorithms may be a major research activity, particularly for aerosol estimation and correction. Furthermore, maximum commonality in the atmospheric correction procedures over land and ocean surfaces should be considered, so that artificial discontinuities at coastlines are not introduced.

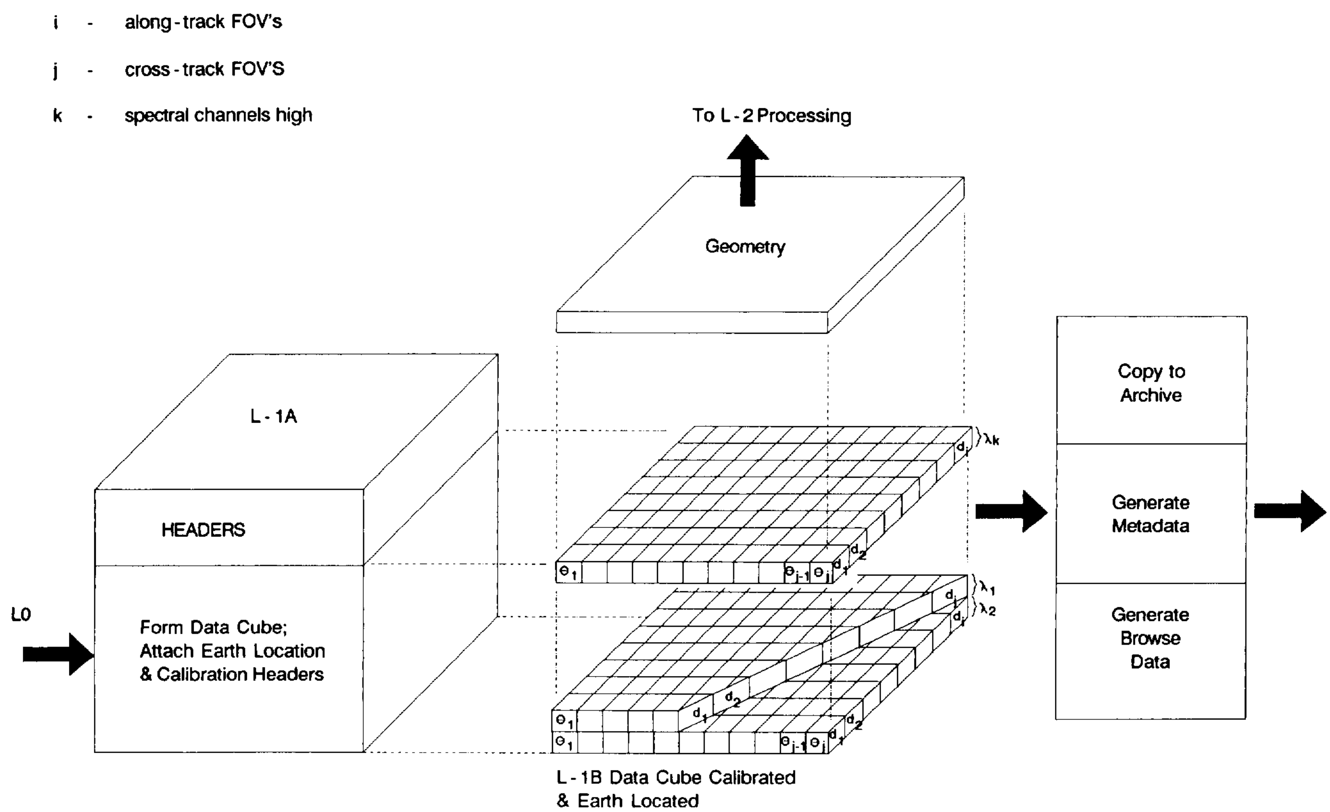

Fig. 7. Evolution of a data cube during Level-1 processing.

Contamination sources (for clear skies) include:

- Rayleigh scattering
- aerosols
- ozone
- total precipitable water.

F. Time and Space Averaging Algorithms

Standard algorithms averaging product data to standard MODIS grids may be required. Several different compositing methods may be employed depending on the particular product. These might include averages of densely or sparsely sampled parameters, selection of a single or several pixels within a region to represent the whole, pixel intervals (e.g., every second, third, or fourth pixel in time or space), empirical orthogonal functions (EOF's), or low/high/band-pass filters. The different techniques (which will produce such diverse products as NDVI, sea surface temperature, ocean biooptical constituents, and cloud parameters) must be self-consistent to enable the study of the Earth as a system.

Other algorithms will be required to remove the effects of bidirectional anisotropy in the measured radiance field, limb darkening, and the dependence of albedo on solar zenith angle. The development of algorithms that can overlay observations taken from different viewing angles (side-to-side and fore-to-aft) with varying footprint sizes is required. Many Level-3 products will require weekly, monthly, seasonal, and annual averages.

G. Display and Processing Algorithms

Display algorithms that are envisioned would include land and land-cover type, coastal, and Case 1/Case 2 oceanic region overlays, which can be used to identify regions for a specific type of processing. An example of this is the generation of a product at 1 km resolution for costal regions, and 4 km for open oceanic regions.

With the advent of the EOS and the generation of global data products, it is asserted that it is important to move away from a scene-oriented processing system to a global mapping system. A wide range of map projection options should be available for all products with topographic, political, and physiographic ancillary data. A suggested map projection for atmospheric and some other global data products is the Hammer projection of latitude and longitude. These global grids are equal area, thereby representing the area of the Earth's ocean and land surface without distortion. Atmospheric data products which go into this mapped product could be produced as averages on a 1° by 1°, or 0.5° by 0.5°, latitude–longitude grid. Alternatively, a 1024 by 2048 global grid has been suggested for the primary Level-3 MODIS grid resolution for ocean products. For snow and ice mapping, an equal-area 10-km mesh is desired.

IV. Operations and Other Requirements on EOSDIS

A. External Data Acquisition and Ancillary Data Set Requirements

Ancillary data sets will be required to generate both core and research and development MODIS data products. These data sets must be acquired, supplied, or otherwise made available by the EOSDIS. For example, National Meteorological Center (NMC) global gridded fields of surface pressure and 1000 mb winds must be supplied within 24 h of MODIS observations. *In situ* data, including optical and other buoy measurements, sur-

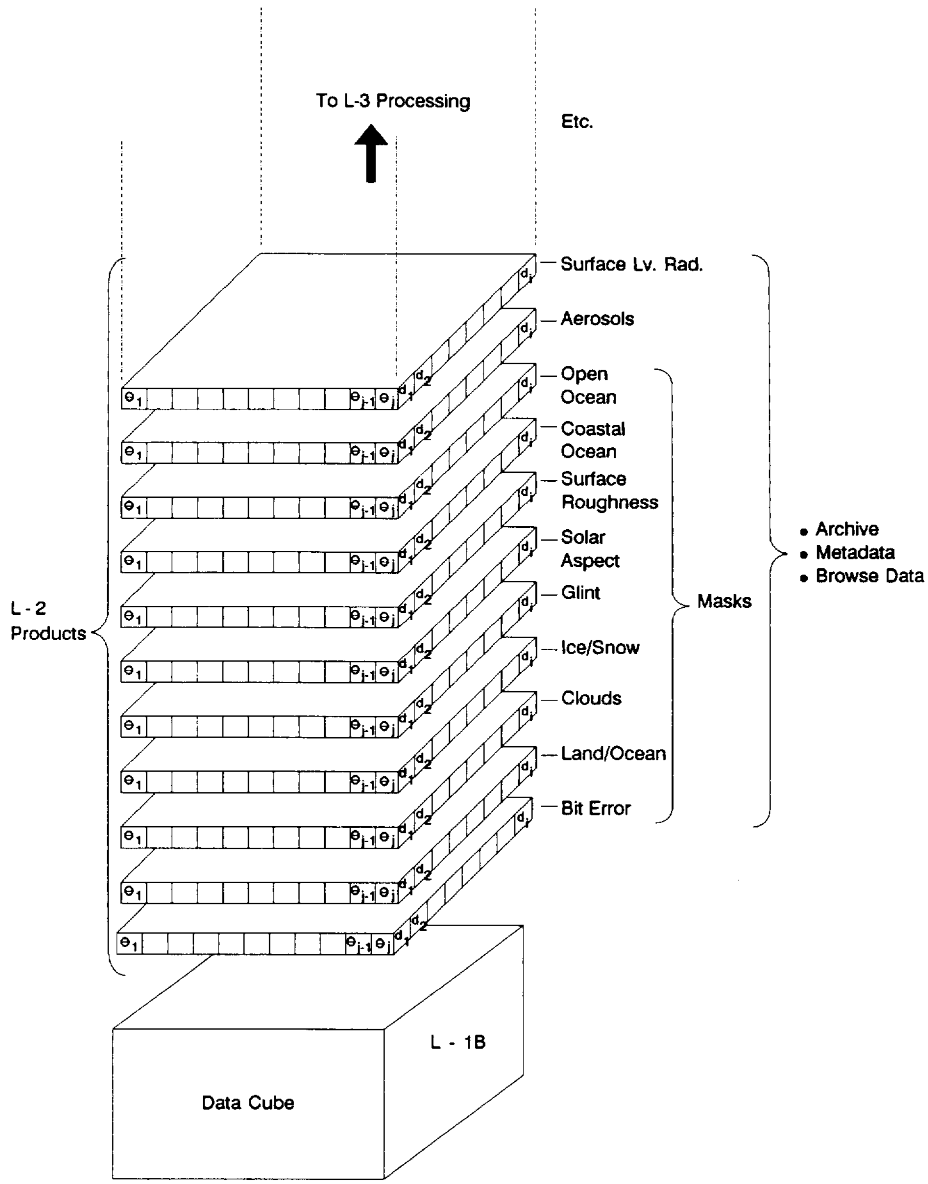

Fig. 8. Evolution of a data cube during Level-2 processing.

face and upper-air meteorological observations, and other data types, must be made available within 48 h for the quality assessment or validation of data products prior to archival and distribution. A substantial number of other correlative data sets will also be required for the development and validation of future MODIS data products. These will include, for example, data from SPOT, aircraft measurements, and other U.S., Japanese, and ESA instruments.

Global observations of ocean color have been identified as one of the key contributions of MODIS to EOS. Three data sets external to the MODIS processing environment have been identified as required in order to produce MODIS ocean color data products. These are: 1) total ozone to determine the absorption of ozone, 2) atmospheric pressure to determine the Rayleigh scattering contribution to the total radiance received by the sensor, and 3) wind speeds to determine the sun glitter and sea foam contributions to the total radiance. These data sets are required for the calculation of water-leaving radiances, which in turn are required to obtain all ocean data products based on ocean color. Our analyses are based on the premise that the high radiometric sensitivity of MODIS be maximized. By this premise, errors in normalized water-leaving radiance induced by sunglint or nonstandard total ozone or Raleigh scattering (atmospheric pressure) should be kept at or below the MODIS noise-equivalent radiance difference (NEdL) in order to prevent an effect on ocean color.

The specific details of the analyses defining these requirements is outside the scope of this paper, and will be made available in report form in the near future (W. Gregg, personal communication).

B. Product Implementation—A Turnkey System

MODIS data product implementation will occur both prior to launch and on an as-needed basis during the mission. At launch, the ground data system will be in place with data product generating software implemented and validated with simulated MODIS data and/or data from analogous instruments and platforms. Perhaps the first three to six months of MODIS observations (Table IV) will provide actual data for the final adjustment of algorithms.

TABLE IV
HYPOTHETICAL TIMETABLE FOR THE PROTOTYPING AND IMPLEMENTATION OF MODIS DATA PRODUCTS ALGORITHMS

T − 5 years:	Investigator-Specific Simulated MODIS Data Available (Version A; e.g., CZCS, AVHRR, HIRS, TM, GOES, etc.)
T − 3 years:	Prototype Core Product Software Delivery (Version 1) Standard Simulated MODIS Data Available (Version B)
T − 2 years:	Complete Core Product Software Delivery (Version 2) Standard Simulated MODIS Data Available (Version C)
T − 1 year:	Flight-Ready Core Product Software Delivery (Version 3)
T:	Launch of EOS-A (Second Quarter, 1998)
T + 1 month:	Actual (Prototype) Level-1 MODIS Data Available Actual (Prototype) MODIS Products Available
T + 4 months:	Final Core Product Software Delivery (Version 4)
T + 6 months:	End of Post-Launch Period Actual Level-1 MODIS Data Available Actual MODIS Products Available
T':	(T + 5 years) Launch of EOS-C
MODIS-A (MODIS on EOS-A) and MODIS-C (MODIS on EOS-C) will have minor differences in spectral coverage. Some channels may have significant changes. Algorithm changes may be required. New standard product algorithms may be introduced. Some standard products may be dropped.	
T' + 1 month:	Actual Level-1 MODIS-A Data Available Actual (Prototype) Level-1 MODIS-C Data Available Actual MODIS-A Products Available Actual (Prototype) MODIS-C Products Available
T' + 6 months:	End of MODIS-A/MODIS-C Overlap Period Actual Level-1 MODIS-C Data Available Actual MODIS-C Products Available

During the 15-year MODIS lifetime, new algorithms are expected to be developed. They will support new data products or serve as refinements and corrections to existing data products. Prior to being certified for regular production, new software and algorithms will be fully tested in the DAAC in a fully operational environment. This certification process may initially involve the conversion of the software for differences in language, architectures, operating systems, or compiler implementations. Once certified and documented, the new software will be integrated with the existing MODIS processing, and the new or modified data products will become part of the MODIS product set. This process is expected to be repeated many times during MODIS's lifetime.

This concept for the implementation of MODIS data products and their retrieval algorithms calls for the equivalent of a turnkey system. Under this concept, fully tested code in a high-level language will be delivered by the investigators to EOSDIS where it will be implemented. The concept assumes that the code will execute as delivered; nonworking code would be returned to the investigators for revision. However, there is clearly the need for an intermediary that might: 1) provide software shells containing the required common blocks and I/O and other utility algorithms; 2) assist with optimization of the code, both prior to implementation and in a continuing sense; 3) provide coding support for the investigators if required; and 4) make the software system efficient. The importance for code and the whole processing system optimization cannot be overemphasized. Mathematically complex geophysical parameter retrieval algorithms, operating on even relatively small subsets of the observations, have the potential to be major processing system drivers.

As with other operational satellite data processing system, new releases of algorithms may be developed, implemented in advanced prototype form, and tested off-line on "parallel" (duplicate) facilities prior to full-scale operational implementation. The same procedure could be advocated for MODIS. Furthermore, we advocate the development of an implementation scenario (Table IV) utilizing several releases of simulated data and implementations of the prototype core product algorithms (e.g., preliminary (rough), prototype (full complexity), flight-ready (best as possible before launch; implemented one year before launch), and actual (based on the first several months of MODIS data; implemented three to six months after launch)).

C. *Product Reprocessing*

Clearly, as with all recent satellite data sets, some reprocessing of MODIS data products must be expected. The motivations for such reprocessing efforts may include the release of an improved set of instrument calibration coefficients, the development of an improved parameter retrieval algorithm, or the implementation of a new data product algorithm. In each of these examples, there may be a demand for the reprocessing of perhaps years of previously generated data sets, or the retrospective processing of new products. The extent and complexity of reprocessing will depend on factors that include the number of affected archived data sets, the interdependencies among MODIS data products, and the quantity of data necessary for generating the new products. The reprocessing requirements must be defined. The parent/child relationships between data sets must be consulted to identify impacts and sensitivities associated with planned reprocessing efforts. Furthermore, consideration needs to be given to the retention of outdated, but not invalid, duplicate data products so that traceability to research studies is not lost.

D. *Product Dependencies and Processing Control*

Given that a number of MODIS data products require other MODIS or EOS products as input for their computation, the sequence in which MODIS and other products are generated must be carefully coordinated and controlled. The scheduling and planning problems are not unlike that facing researchers experimenting with parallel computer architectures where output from one processor may be required as input to complete processing at another processor. In fact, many of the techniques developed for parallel computer architectures may be directly applicable to MODIS and other EOS products. While some potentially applicable techniques have been developed, other implementation techniques for parallel systems are currently research topics, and results may not be available for MODIS use within the required timeframe. Automated processing concepts utilizing multiple relational database management system layers will likely be required to smoothly cope with the volume and complexity of the MODIS data.

E. Processing Redundancy/Product Integration

It appears that each MODIS science team member may be individually responsible for only one or a few core data products. Since these products have, in many cases, been developed and validated independent of other MODIS team member efforts, many researchers may initially prefer to implement a complete set of algorithms that generate required data products beginning with MODIS Level-1 data. Since the intermediate products required to generate the required final product may resemble (or be identical to) final core products generated by other team members, processing redundancy may arise. For example, the atmospheric corrections currently used for ocean products include aerosol corrections and cloud filters similar to those produced as core products by atmospheric researchers.

The alternative to redundant processing is product integration which, at least in the case of currently existing products, may require substantial negotiation, algorithm revision, and product revalidation. The basic issues are as follows. How much redundant processing is tolerable? What data system structures would best support the creation of a integrated product set? In the case of cloud products, how much redundancy between the MODIS and the efforts of other instrument teams is desirable?

F. Data Processing Prioritization

MODIS data processing will probably require data at four levels of processing priority (see Table V). MODIS product generation and data processing will generally use the routine data stream. The timeliness goals of this data type define the requirements for externally supplied data as well as the general pace for standard data product availability to end users.

The near-real-time data would be composed of two types: data supporting field experiments and targets of opportunity (TOO); and data supporting background science monitoring. Each data type is equivalent to approximately 5% of the daily MODIS data volume, and is processed in addition to the routine data stream. The nominal requirements for field experiment/TOO data are for processing over 15 (five terrestrial, five meteorological, and five oceanic) 2000 × 2000 km scenes per day. The data requirement is estimated to be 100% of the MODIS data over a daily total of 75 min (≈5% of the time).

The nominal requirement for background science monitoring (e.g., volcano and forest fire detection and monitoring) is for a subset of the MODIS bands to be processed in near real time, perhaps globally. The data requirement is for ≈5% of the data (on the order of five of the 1000 or 1100 m bands) 100% of the time.

G. Processing Growth

At the time of the launch of EOS-A, on the order of 40 MODIS core data product algorithms may be implemented and resident at an EOS DAAC for the generation of terrestrial, atmospheric, and oceanic geophysical parameters. However, the MODIS instrument will provide the Earth science community with advanced capabilities for spectral and spatial coverage at a full 12-b quantization. The global observing capabilities of MODIS should be made available to the science community through the archival of calibrated and navigated Level-1 visible, near-infrared, middle-infrared, and thermal-infrared radiances (Table I), as well as atmospherically corrected radiances over a large subset of the spectral bands. There exist at present many additional proposed data product algorithms which have been identified as candidates for possible future MODIS standard products. These algorithms have been termed "research and development (R&D)" efforts, as their refinement will require the observing capabilities that perhaps only MODIS is capable of providing.

TABLE V
DATA DICTIONARY DEFINING FOUR LEVELS OF PRIORITY IN THE PROCESSING OF MODIS DATA

Data Priority	Data Definition
Routine	MODIS instrument (science and ancillary) and platform ancillary data initially stored on the platform tape recorder, played back after up to two orbits (3 h), fully processed through Level-0 within 24 h (99.7% complete), Level-1 within 48 h, and Level-2 within 72 h.
Near-Real-Time	MODIS instrument and platform ancillary data initially stored on the platform tape recorder, played back after up to two orbits (3 h), partially Level-0 processed (priority processed, Reed–Solomon error corrected, but no completeness guarantee), processed through Level-3, and made available to users (archived) within 3 to 8 h after real time.
Quick-Look	MODIS instrument and platform ancillary data, real-time or platform-recorded, minimally Level-0 processed (passed through CDOS within 10 s), and used primarily for instrument monitoring purposes.
Real-Time	MODIS instrument data, only propagation delayed (possible during scheduled TDRSS contact), subsequently treated as quick-look data.

For example, the CZCS provides water-leaving radiances in four spectral bands at 8-b quantization. the proposed SeaWiFS instrument will provide water-leaving radiances at 10-b accuracy over six spectral bands. MODIS-T will make available a full 32 bands of measurements at the more accurate 12-b resolution (13 b when alternate gain selections are considered). If SeaWiFS is launched prior to EOS, then a number of these R&D algorithms will be further developed and may evolve into new MODIS core data products.

We estimate that the number of data products generated by MODIS could grow at a rate of 40% per year following launch. Of course, the load on the data system would also increase, potentially doubling every two years. After 15 years of operations, MODIS might require a data product processing system that is 10 to 100 times more powerful than the baseline system sized as adequate at launch.

V. REQUIREMENTS FOR OTHER ELEMENTS OF EOS

A. MODIS Instrument

To facilitate the near-real-time and instrument monitoring functions of the ground data system, data packetization by spectral band could reduce the MODIS ground data processing effort. In this approach, individual data packets would be built within the MODIS-N and MODIS-T instruments for each spectral band, as well as for the instrument ancillary data. The source data packets might be constructed for an entire scan of data and segmented into convenient lengths. Packet headers would then identify the spectral band and provide other information to facilitate the sorting of individual data packets without the need to first unpack the entire datastream. However, the loss of even a single data packet (for an essential spectral band) could have a disproportionately large effect (albeit for only a fraction of a scan) for geophysical products requiring multiple bands. The tradeoffs are improved handling convenience versus increased impact from lost packets.

B. *EOS Platform*

To meet the EOS science objectives, the creation and analysis of long-term (15 years) data sets is required. The stability of the orbit plane, particularly the local time of the ascending node, will be critical in determining the validity of trends observed during this period. Present plans indicate that this data record will be provided through the use of similar or identical instruments on three platforms, each with a nominal lifetime of five years. Under this scenario, overlap periods of six months to one year will be required to maintain the calibration and continuity of the measurement time series.

C. *Level-0 Processing*

The Data Handling Center (DHC) will perform Level-0 processing. MODIS requirements call for the provision of three data streams, each with specific completeness, timeliness, and processing requirements. The routine data will consist of all MODIS data and will be fully restored (Table V) into the original form of the MODIS source data packets. Separate data packet types might be desirable for each spectral band, as well as for the ancillary data. Although Level-0 processing is required to be completed within 21 h after reception at the DHC (about 24 h after observation), data completeness is considerably more important than a precise adherence to time cutoffs.

Data requiring near-real-time handling should be appropriately identified in the header of each packet. For this data stream, timeliness will be more important than completeness, and the Level-0 processing should be completed in less than an hour after data are received at the ground station and transmitted to the DHC. Up to 100% of the MODIS data may be required for monitoring the performance and status of the MODIS instrument at the Instrument Control Center (ICC). These quick-look data will be minimally processed, and should be passed through the DHC with 10 s.

For routine and near-real-time data, platform ancillary data (position, attitude, and relevant engineering data) will be required with the same timeliness. A platform attitude sampling frequency of no less than 10 Hz is required to accurately navigate the MODIS observations when uncompensated instrument angular momentum is considered.

VI. Summary

We have presented concepts for producing data products from MODIS. The MODIS science team has reviewed the set of core MODIS data products that have been presented here. Because of the team's experience with other instruments that form the MODIS heritage (AVHRR, CZCS, HIRS, TM, etc.), we feel reasonably comfortable that these core products can be produced at launch. Between now and launch, there will be continued studies as to how to optimally implement these core data product algorithms within EOSDIS. As such, this paper is an interim statement of progress; concepts are still undergoing evolution and refinement. Further interactions among members of the Earth science and data communities will have to occur before a definitive set of procedures are developed.

Acknowledgment

Over the course of three formal MODIS Science Team meetings, much of the guidance in shaping these requirements has been received from the team members, whom the authors wish to acknowledge here: M. Abbott, W. Barnes, I. Barton, O. Brown, K. Carder, D. Clark, W. Esaias, R. Evans, H. Gordon, F. Hoge, A. Huete, C. Justice, Y. Kaufman, M. King, P. Menzel, J.-P. Muller, J. Parslow, S. Running, P. Slater, A. Strahler, J. Susskind, D. Tanre, V. Vanderbilt, and Z. Wan. Other members of the MODIS Data Study Team played an active role in collecting the information presented in this paper. They are: M. Andrews, W. Gregg, D. Hoyt, L. Kyle, A. McKay, J. Ormsby, G. Riggs, B. Sharts, and T. Wolford. The efforts of B. Vallette in preparing this manuscript are also acknowledged.

References

[1] J. P. Ormsby, and G. A. Soffen, "Foreword" to IEEE Special Issue on the Earth Observing System (Eos), *IEEE Trans. Geosci. Remote Sensing*, vol. 27, pp. 107–108, 1989.

[2] V. Salomonson, B. Barnes, H. Montgomery, and H. Ostrow, "MODIS: Advanced facility instrument for studies of the earth as a system," in *Proc. IGARRS'87*, 1987, vol. 1, pp. 361–366.

[3] V. Salomonson, B. Barnes, P. W. Maymon, H. Montgomery, and H. Ostrow, "MODIS: Advanced facility instrument for the study of the earth as a system," *IEEE Trans. Geosci. Remote Sensing*, vol. 27, pp. 145–153, 1989.

[4] P. Maymon, S. Neeck, and J. C. Moody, "Optical system design alternatives for the Moderate Resolution Imaging Spectrometer-Tilt (MODIS-T) for the earth observing system," *Proc. SPIE*, vol. 924, pp. 10–22, 1988.

[5] V. Salomonson, B. Barnes, H. Montgomery, and H. Ostrow, "Moderate Resolution Imaging Spectrometer-Nadir (MODIS-N): Progress 1988," *Proc. SPIE*, vol. 924, pp. 2–9, 1988.

[6] F. Bretherton, "Earth system science: A close view," Rep. Earth Syst. Sci. Committee to NASA Advisory Council, NASA, Washington, DC, 1988 (available from Code EPM-20, NASA Headquarters, Washington, DC 20546).

[7] Committee on Earth Sciences, *Our Changing Planet: The FY 1990 Research Plan*, U.S. Global Change Plan, Office Sci. Technol. Policy, Executive Office of the President.

[8] D. Han and P. Ardanuy, "The Moderate Resolution Imaging Spectrometer Data System," *Tech. Papers ASPRS/ACM 1989 Ann. Convention/Agenda for the 90's*, vol. 3, pp. 91–100, 1989.

[9] B. Anderson *et al.*, *HIRIS and MODIS Ground Data Systems: Functional Requirements, Level-I*, GSFC Doc. D-8802, 1988.

[10] D. Han *et al.*, *The MODIS Information, Data, and Control System (MIDACS) Level-II Functional Requirements*, GSFC TM 100719, 1988.

[11] ——, *The MODIS Information, Data, and Control System (MIDACS): Operations Concepts*, GSFC TM 100721, 1988.

[12] ——, *The MODIS Information, Data, and Control System (MIDACS): System Specifications and Conceptual Design*, GSFC TM 100720, 1988.

[13] J. Baker, "System concept for wide-field-of-view observations of ocean phenomena from space," Rep. Joint EOSAT/NASA SeaWiFS Working Group, NASA Earth Sci. Appl. Division/Earth Observation Satellite Co., 91 pp, 1987.

Philip E. Ardanuy received the Ph.D. degree in meteorology from the Florida State University, where he specialized in tropical meteorology and modeling, and the study of the Earth's radiation budget.

He is the Vice President for Atmospheric Science and Global Change at Research and Data Systems Corporation, Greenbelt, MD. He has over 12 years of atmospheric science and remote sensing experience, and has conducted research into many diverse areas of atmo-

spheric modeling, satellite remote sensing, and climate change, including numerical weather prediction in the tropics, the El Niño/southern oscillation, low-frequency tropical oscillations, cloud-radiative forcing, the morphology of the Antarctic Ozone Hole, and the design of EOS instrument data systems. Recently he has examined the observability of interannual climate variability from a decadal radiation budget data set. He is a member of the Science Team for the Earth Radiation Budget (ERB) experiment, which is taking its 11th year of observations on board the Nimbus-7 satellite. He has over 40 publications to his credit. He is the Project Manager of the contractor team supporting the MODIS Data Study Team.

Dr. Ardanuy, as a member of the Airborne Antarctic Ozone Experiment Team, was recipient of the NASA Group Achievement Award.

Daesoo Han received the Bachelor's degree in physics from the Seoul National University, and the Master's and Ph.D. degrees in physics from Yeshiva University.

He is the Manager of the MODIS Data System Study Team at the NASA/Goddard Space Flight Center, Greenbelt, MD. He is also leading the LAWS Data Study Team. He is responsible for the data system study of the Tropical Rainfall Measuring Mission. He is the Nimbus-7 Manager and is responsible especially for scientific aspects of the Nimbus Project. He has been working on remote sensing areas for the past 12 years. Formerly he was Program Manager at the STX Corp., supporting scientific analyses of Nimbus-7 data for the Nimbus project.

Vincent V. Salomonson received the B.S. degree in agricultural engineering from Colorado State University in 1959, the B.S. degree in meteorology from the University of Utah in 1960, the M.S. degree in agricultural engineering from Cornell University in 1964, and the Ph.D. degree in atmospheric science from Colorado State University in 1968.

He is the Director of the Earth Sciences Directorate at Goddard Space Flight Center, NASA. In that capacity he is responsible for overseeing and coordinating the activities of approximately 440 scientists and engineers in the Directorate who are actively involved in research of the Earth-Atmosphere system using advanced technology. Prior to assuming his present position, he served at Goddard as the Deputy Director for Earth Sciences in the Space and Earth Sciences Directorate (1988-1990), Chief of the Laboratory for Terrestrial Physics (1980-1988), Project Scientist for Landsat 4 and 5 (1977-1989), the Head of the Hydrospheric Sciences Branch (1973-1980), and as a Research Meteorologist (1968-1973). Prior to coming to Goddard, he spent three years as Weather Officer in the United States Air Force (1959-1962). His publication record shows over 100 publications in scientific journals, conference proceedings, and NASA reports.

Dr. Salomonson was awarded the 1986 Distinguished Achievement Award from the IEEE Geoscience and Remote Sensing Society for his significant technical contributions to satellite remote sensing. In 1987 he was also awarded the William T. Pecora Award for his involvement in satellite remote sensing. He serves as a member of the Executive Administrative Committee (AD-Com) for the IEEE Geoscience and Remote Sensing Society, and was the General Chairman of the International Geoscience and Remote Sensing Symposium (IGARSS-90) held in Washington, DC.