Key Characteristics of MODIS Data Products

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***Abstract*— Forty science products totaling 600 GB of storage volume per day will be produced from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). Eighty-five percent of this data volume is in products that are in the instrument's scan geometry (processing Levels 1 and 2) that are not earth located. Before ordering MODIS data products, users should consider processing level, data formats, product size, and the unique characteristics of MODIS products. Given the data volumes associated with the MODIS Levels 1 and 2 products, the resources required to process them and the issues associated with the scanning geometry of the instrument, users are encouraged to order data products that are earth located. These include Level 3 products, which are produced on fixed global grids and Level 2G products, in which observations and their earth location have been stored in bins of the MODIS global grids.**

***Index Terms*—Data processing, image sensors, remote sensing, satellites.**

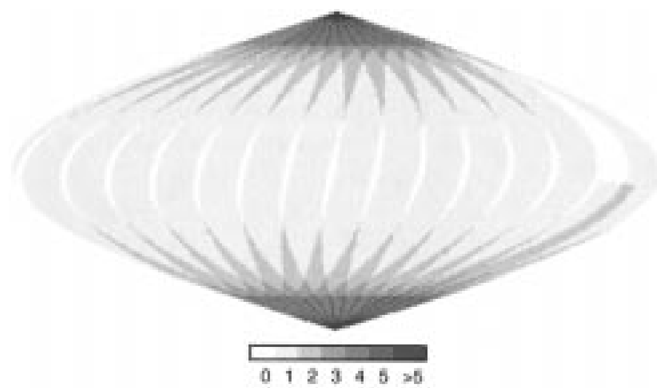

Fig. 1. Coverage of the earth by a single MODIS instrument over a 24-h period. Portions of the earth without coverage are shown as white space, and overlapping swaths are shown in increasingly darker shades of gray as the number of overlapping swaths increases near the poles.

I. Introduction

THIS PAPER provides an overview of science data products from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). Topics include data formats, data volumes, and unique characteristics of MODIS products. Important features to consider before ordering MODIS data products, such as processing level and product size, are discussed, and recommendations are made regarding which form of data product is the easiest to use.

II. MODIS Instrument

The MODIS instrument will be carried onboard the Earth Observing System morning (EOS-AM1) and evening (EOS-PM1) spacecraft, which are scheduled for launch in 1998 and December 2000, respectively. Both spacecraft will be placed in 705-km polar, sun-synchronous orbits. EOS-AM1 will be launched in a descending orbit with an equatorial crossing time of 10:30 a.m., when there is generally less cloud cover over land, while EOS-PM1 will be placed in an ascending orbit with a 1:30 p.m. equatorial crossing time to maximize information on clouds, precipitation, and other meteorological phenomena. The two MODIS instruments in complementary orbits will enable scientists to collect information on diurnal variations in observed characteristics of land, ocean, and the atmosphere and obtain complete global ocean color measurements. In a day, a single MODIS instrument will image almost every point on the earth, with small gaps in coverage from the equator to 50° latitude and overlapping coverage from 50° latitude to the poles, as illustrated in Fig. 1. The repeat cycle for the EOS-AM1 orbit is 16 days, with a near repeat every eight days. Complete coverage of the earth is achieved every two days when one MODIS instrument is in orbit and every day when both an a.m. and p.m. MODIS are in operation. In the latter case, data from one satellite will differ from that collected by the other, due to time of acquisition as well as differences in the two MODIS sensors.

MODIS is a cross-track scanning radiometer with 36 spectral bands covering visible, near, and shortwave infrared from 0.4 to 14.5 μm. Each half rotation of the MODIS scan mirror collects a swath of data covering an area 2330-km across track and 10-km along track (at nadir). As described in an accompanying paper [3], measurements are made at nominal 1-km resolution for 29 of the bands, 500–m resolution for five bands, and 250-m resolution for two bands. Most land data products, which are made directly from the calibrated radiances (Level 1B) data product, use finer spatial resolution (250 and 500 m) bands, while ocean and atmosphere data products are made from bands with 1-km spatial resolution.

MODIS data are collected in two modes, typically with half the time spent in each mode. In the first mode, data are collected from all 36 bands, while in the second mode, data are collected only in bands 20–36. This reduction in data collection saves spacecraft power, storage, and telemetry bandwidth as well as ground processing and storage. These two modes of operation are referred to as day and night modes since the primary source of information in the visible channels, which are only present in the first mode, is reflected sunlight. Some scans will contain both day and night pixels because the MODIS swath is over 2300-km wide. When the nadir (centermost) pixel is in darkness, the instrument is generally run in night mode. However, on occasion, the instrument may be operated in day mode at night for calibration purposes.

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TABLE I
MODIS PRODUCTS THAT CAN BE ORDERED FROM THE DAAC'S

File ID	Description	Resolution	Software that produces file	Level	Discipline	Archive Site	Temporal Coverage	File Size (MB)	Files Created per Day	Volume of Data Archived per Day (GB)
MOD_L0	2 hours of Instrument Packets	250 m - 1 km	EDOS	0	Level 1	GSFC	2 hours	5850	12	70.20
MOD01_L1A	Level 1A Raw Counts	250 m - 1 km	PGE01	1	Level 1	GSFC	5 minutes	329	288	94.75
MOD03_L1A	Level 1A Geolocation Fields	250 m - 1 km	PGE01	1	Level 1	GSFC	5 minutes	57	288	16.33
MOD02_1KM	Level 1B Calibrated Radiances 1 km	1 km	PGE02	1	Level 1	GSFC	5 minutes	221	288	63.50
MOD02_QKM	Level 1B Calibrated Radiances 250 m bands	250 m	PGE02	1	Level 1	GSFC	5 minutes	65	288	18.72
MOD02_HKM	Level 1B Calibrated Radiances 500 m bands	500 m	PGE02	1	Level 1	GSFC	5 minutes	57	288	16.42
MOD02_OBC	Calibrated Radiances Onboard Calibrator	250 m - 1 km	PGE02	1	Level 1	GSFC	5 minutes	18	288	5.24
									Total Levels 0,1	**285**
MOD35_L2	Level 2 Cloud and Surface Classification Masks	250 m - 1 km	PGE03	2	atmosphere	GSFC	5 minutes	48	288	13.71
MOD07_L2	Atmospheric Profiles	5 km	PGE03	2	atmosphere	GSFC	5 minutes	28	288	8.18
MOD04_L2	Aerosol Product	10 km	PGE04	2	atmosphere	GSFC	5 minutes	10	144	1.44
MOD05_L2	Precipitable Water	1-5 km	PGE04	2	atmosphere	GSFC	5 minutes	8	288	2.19
MOD04LA_L2	Level 2 Land Aerosol Product	18 km	PGE05	2	atmosphere	GSFC	5 minutes	28	14.6	0.41
MOD06_L2	Cloud Product	1-5 km	PGE06	2	atmosphere	GSFC	5 minutes	35	288	10.18
MOD08_Zonal	Atmospheric Tiling	1 degree	PGE69	3	atmosphere	GSFC	daily/5 degree	interim	36	interim
MOD08_D	Daily Gridded Atmospheric Product, Climate Modelling Grid 1 degree	1 degree	PGE56	3	atmosphere	GSFC	1 day	450	1	0.45
MOD08_M	Monthly Gridded Atmospheric Product, Climate Modelling Grid 1 degree	1 degree	PGE57	3	atmosphere	GSFC	1 month	500	1 per month	0.02
									Atmosphere Totals	**37**
MOD09_L3_REFL_8DY	8 Day Gridded Surface Reflectance	250 m and 500 m	PGE21	3	land	EDC	8 days	289	289 per 8 days	9.00
PRAGG	L3 Aggregation	1 km	PGE22	3	land	EDC	5.00	interim	289.00	interim
MOD43_BRDF_L3_16DY	Gridded BRDF/Albedo	1 km	PGE23	3	land	EDC	16 day	166	289 per 16 days	3.00
/OD43_BRDF_CMG_16DY	16 day BRDF/Albedo, Climate Modelling Grid 0.25 degree	28 km	PGE24	3	land	EDC	16 day	16	1 per 16 days	0.00
MOD13_VI_16DY	16 day Gridded Vegetation Indices	250 m	PGE25	3	land	EDC	16 day	111	289 per 16 days	2.00
MOD13_VI_1M	Monthly Gridded Vegetation Indices	250 m	PGE26	3	land	EDC	1 month	111	289 per month	1.00
MOD13_VI_CMG_16DY	16 day Vegetation Indices - Climate Modelling Grid 0.25 degree	28 km	PGE27	3	land	EDC	16 days	16	1 per 16 days	0.00
MOD13_VI_CMG_1M	Monthly Vegetation Indices- Climate Modelling Grid 0.25 degree	28 km	PGE28	3	land	EDC	1 month	16	1 per month	0.00
MODIS Thermal Anomalies_L3_8DY	8 Day Gridded Thermal Anomalies	1 km	PGE29	3	land	EDC	8 days	145	289 per 8 days	6.00
MODIS Thermal Anomalies_L3_1M	Monthly Gridded Thermal Anomalies	1 km	PGE30	3	land	EDC	1 month	221	289 per month	2.00
MODIS Land Surface Temperature_L3_8DY	Weekly Land Surface Temperature	1 km	PGE31	3	land	EDC	8 days	27	1 per 8 days	1.00
MODIS Land Surface Temperature_CMG_DY	Daily Land Surface Temperature- Climate Modelling Grid 0.5 degree	56 km	PGE32	3	land	EDC	1 day	4	1	0.00
MODIS Leaf Area Index_L3_DY	Leaf Area Index Daily Product	1 km	PGE33	3	land	EDC	1 day	28	289	8.09
MODIS Leaf Area Index_L4_8DY	8-day Leaf Area Index & FPAR	1 km	PGE34	4	land	EDC	8 days	28	289 per 8 days	1.00
MODIS Leaf Area Index_CMG_L4_8DY	8 Day Leaf Area Index-Climate Modelling Grid 0.25 degree	1 km	PGE35	4	land	EDC	8 days	16	1 per 8 days	0.00
MODIS_NPP_DY	NPP Daily	1 km	PGE36	4	land	EDC	1 day			
MODIS_NPP_8DY	8 Day Net Primary Productivity	1 km	PGE37	4	land	EDC	8 days	28	289 per 8 days	1.00
MODIS_NPP_YR	Yearly Net Primary Productivity	1 km	PGE38	4	land	EDC	1 year	28	289 per year	0.00
MODIS_NPP_CMG_8DY	Net Primary Productivity - Climate Modelling Grid 0.5 degree	56 km	PGE39	4	land	EDC	8 days	4	1 per 8 days	0.00
MODIS Land Cover_L3_32DY	Monthly Gridded Land Cover Database	1 km	PGE40	3	land	EDC	1 month	443	289 per month	4.00
MODIS Land Cover_L3_96DY	Quarterly Gridded Land Cover Type	1 km	PGE41	3	land	EDC	3 months	16	289 per 3 months	0.05
MODIS Land Cover_CMG_96DY	96 day Land Cover -CMG 0.5 degree	56 km	PGE42	3	land	EDC	3 months	4	1 per 3 months	0.00
MODIS Land Surface Temperature_CMG_8DY	8 Day Land Surface Temperature - Climate Modelling Grid 0.5 degrees	56 km	PGE58	3	land	EDC	8 days	4	1 per 8 days	0.00
MODIS Land Surface Temperature_CMG_1M	Monthly Land Surface Temperature- Climate Modelling Grid 0.5 degrees	56 km	PGE59	3	land	EDC	1 month	4	1 per month	0.00
MODIS Leaf Area Index_CMG_L4_1M	Monthly Leaf Area Index-Climate Modelling Grid 0.5 degree	56 km	PGE63	3	land	EDC	1 month	4	1 per month	0.00
MODIS Leaf Area Index_CMG_L4_32DY	Monthly Leaf Area Index-Climate Modelling Grid 0.25 degree	28 km	PGE63	4	land	EDC	1 month	16	1 per 32 days	0.00
MODIS Net Primary Productivity_NPP_CMG_YR	Yearly Net Primary Productivity- Climate Modelling Grid 0.5 degree	56 km	PGE64	4	land	EDC	1 year	4	1 per year	0.00
MOD43_BRDF_CMG_Month	Monthly BRDF/Albedo, Climate Modelling Grid 0.25 degree	28 km	PGE65	3	land	EDC	1 month	16	1 per month	0.00
MOD_44_L4_1M	Monthly Land Cover Change	250 m	PGE66	3	land	EDC	1 month	221	289 per month	2.00
MOD10_L2	Snow Cover	500 m	PGE07	2	land	NSIDC	5 minutes	11	144	1.56
MOD29_L2	Sea Ice Max Extent	1 km	PGE08	2	land	NSIDC	5 minutes	11	144	1.56
MOD09	Surface Reflectance/Fire	250 m, 500 m and 1 km	PGE11	2	land	GSFC	5 minutes	24	288	7.00
PRMGR	L2G Geolocation Angles	1 km	PGE12	2	land	EDC	5 minutes	66	289.00	19

III. MODIS PRODUCTS

Over 40 data products will be produced from the raw MODIS data for distribution to the public, which are listed in Table I. A given geophysical parameter, such as sea surface temperature, may be available in more than one format, including products in instrument scan geometry (Levels 1 and 2) and products whose values are on fixed earth grids (Levels 3 and 4). Most Level 1 and all Level 2 products are stored

TABLE I (*Continued.*)
MODIS PRODUCTS THAT CAN BE ORDERED FROM THE DAAC'S

File ID	Description	Resolution	Software that produces file	Level	Discipline	Archive Site	Temporal Coverage	File Size (MB)	Files Created per Day	Volume of Data Archived per Day (GB)
PRMGPNYR	L2G Pointers	250 m, 500 m and 1 km	PGE12	2	land	EDC	5 minutes	42	289.00	12
PRMGR	2G Surface Reflectance	250 m, 500 m and 1 km	PGE13	2	land	EDC	1 day	422	289	121.96
PRMGR	Level 2G Thermal Anomalies	1 km	PGE13	2	land	EDC	1 day	21	578	12.27
PRMGR	Level 2G Snow	500 m	PGE14	2	land	EDC	5 minutes	31	289	interim
PRMGR	Level 2G Sea Ice	1 km	PGE15	2	land	EDC	5 minutes	21	289	interim
MOD11	Land Surface Temperature	1 km	PGE16	2	land	EDC	5 minutes	24	288	7.00
MOD10_L3_DY	Daily Gridded Snow Cover	500 m	PGE43	3	land	NSIDC	1 day	11	354	4.00
MOD29_L3_DY	Daily Gridded Sea Ice	1 km	PGE44	3	land	NSIDC	1 day	8	130	1.00
MOD10_L3_8DY	Weekly Gridded Snow Cover	500 m	PGE45	3	land	NSIDC	8 days	23	354 per 8 days	1.00
MOD10_CMG_DY	Snow_CMG-Daily	28 km	PGE46	3	land	NSIDC	1 day	2	1	2.00
MOD29_L3_8DY	Weekly Gridded Sea Ice Cover	1 km	PGE47	3	land	NSIDC	8 days	2	130 per 8 days	0.20
MOD29_CMG_DY	Weekly Gridded Sea Ice Cover	28 km	PGE48	3	land	NSIDC	daily	2	130 per 8 days	0.20
MOD10_CMG_8DY	Weekly Snow Cover-Climate Modelling Grid 0.25 degree	28 km	PGE67	3	land	NSIDC	8 days	16	1 per 8 days	0.00
MOD29_CMG_8DY	Weekly Sea Ice-Climate Modelling Grid 0.25 degree	28 km	PGE68	3	land	NSIDC	8 days	16	1 per 8 days	0.00
									Land Totals	**231**
ocncolorlw	Level 2 Ocean Color	1 km	PGE09	2	ocean	GSFC	5 minutes	149	144	21.48
ocncolordr2	Level 2 Ocean Color	1 km	PGE09	2	ocean	GSFC	5 minutes	139	144	19.97
ocncolordr1	Level 2 Ocean Color	1 km	PGE09	2	ocean	GSFC	5 minutes	160	144	22.98
ocncolor_sb	Ocean Color Space Binning	4.65 km	PGE09	2	ocean	GSFC	5 minutes	interim	144	interim
sst	Level 2 Sea Surface Temperature	1 km	PGE10	2	ocean	GSFC	5 minutes	42	288	12.06
sst_sb	Sea Surface Temp. Space Binning	4.65 km	PGE10	2	ocean	GSFC	5 minutes	interim	288	interim
MOD27_L3_WK	Weekly Gridded Ocean Productivity	4.65 km	PGE18	4	ocean	GSFC	8 days	1620	1 per 8 days	0.20
MOD27_L3_YR	Yearly Gridded Ocean Productivity	4.65 km	PGE18	4	ocean	GSFC	1 year	3280	1 per 8 days	0.41
mtbin	L3 interim daily	4.65 km	PGE20	3	ocean	GSFC	1 day	interim	1 per day	interim
mtbin	L3 interim weekly time binner	4.65 km	PGE49	3	ocean	GSFC	8 days	interim	1 per 8 days	interim
mtbin	Time Binner 3 week Reference File	4.65 km	PGE50	3	ocean	GSFC	24 day	interim	1 per 8 days	interim
mfill	Fill Bins in 3 week Reference File	4.65 km	PGE50	3	ocean	GSFC	24 day	interim	1 per 8 days	interim
[p1..p12]_oclw_dy	Daily Ocean Color	4.65 km	PGE53	3	ocean	GSFC	1 day	620	12	7.44
[p13..p23]_ocdr2_dy	Daily Ocean Color	4.65 km	PGE53	3	ocean	GSFC	1 day	620	11	6.82
[p24..p36]_ocdr1_dy	Daily Ocean Color	4.65 km	PGE53	3	ocean	GSFC	1 day	680	13	8.84
sst_[d1...n2]_dy	Daily Sea Surface Temperature - 2 day and 2 night products	4.65 km	PGE53	3	ocean	GSFC	1 day	620	4	2.48
[p1..p12]_oclw_wk	Weekly Ocean Color	4.65 km	PGE54	3	ocean	GSFC	8 days	620	12 per 8 days	0.93
[p13..p23]_ocdr2_wk	Weekly Ocean Color	4.65 km	PGE54	3	ocean	GSFC	8 days	620	11 per 8 days	0.85
[p24..p36]_ocdr1_wk	Weekly Ocean Color	4.65 km	PGE54	3	ocean	GSFC	8 days	680	13 per 8 days	1.11
sst_[d1...n2]_wk	Weekly Sea Surface Temperature- 2 day and 2 night products	4.65 km	PGE54	3	ocean	GSFC	8 days	620	4 per 8 days	0.31
									Ocean Totals	**105.88**
									Total Archived Volume (GBper day)	**659**
					Key		Single estimate for combined products			

in granules that are derived from approximately 5 min of continuous instrument data. These granules contain data from approximately 200 swaths and cover approximately 2330-km across track × 2000-km along track. File sizes of individual MODIS products range in sizes from 1.6 MB for a vegetation indexes product to 680 MB for an ocean color product.

The production of MODIS data products from the receipt of the raw instrument data to Levels 3 and 4 gridded products is a complex undertaking. More than 70 separate MODIS unique computer programs, which comprise more than 1-million lines of Fortran and C code, have been integrated into processing packages called Product Generation Executives (PGE's) from software provided by individual scientists. These PGE's will run in three EOSDIS processing centers know as Distributed Active Archive Centers (DAAC's). These DAAC's, which process MODIS data sets, are located at NASA's Goddard Space Flight Center, Greenbelt, MD, which archives and distributes all MODIS Level 1, atmosphere and ocean products; the United States Geological Survey's (USGS's) EROS Data Center, Sioux Falls, SD, which archives and distributes all land products, with the exception of snow and sea ice products, and NOAA's National Snow and Ice Data Center (NSIDC), Boulder, CO, which archives and distributes snow and sea ice products. To produce all MODIS products requires that the computer systems at the DAAC's maintain a combined processing rate of six billion floating point operations per second and support I/O rates over 100 million bytes per second. During an average day at the DAAC's, over 4000 MODIS jobs will run and process over 17 000 files to produce data products that require a storage volume of 600 billion bytes in the data archive. These DAAC's will be capable of distributing more than 1 trillion bytes of MODIS data products to the scientific community each day once full production capability is reached.

All MODIS data products are written in HDF-EOS, a superset of NCSA's Hierarchical Data Format, which was developed to support the storage and display of data in an instrument swath or in global grids. While the at-launch version of EOSDIS will only support subsetting for the MODIS Level 1B (calibrated radiances) product by band, the additional capability to subset MODIS products based on geographic coordinates and geophysical parameters will be available in

EOSDIS in late 1999. Until this additional subsetting capability is available, it is important to realize that, when we order a MODIS data product for a specific area of the earth, the entire file comprising a 5-min Level 2 granule or a $1 \times 1^{\circ}$ Level 3 tile will be shipped even if only a small portion of the file overlaps the user's area of interest. The size in millions of bytes (MB) of a file for each product is presented in Table I. It is also important to note that data sets for a product are not mosaicked together at the processing site, and ordering a day's worth of products for the entire globe can result in as many as 288 separate files at Level 2 and 354 separate files at Level 3 for each product ordered.

In addition to ordering MODIS products, we may also obtain the MODIS software that runs in the EOSDIS production system to produce them. Potential users of the operational MODIS software should be aware that a Science Data Processing (SDP) Toolkit and HDF libraries have been incorporated into the MODIS software to isolate it from the underlying operating system to make it portable across different computing platforms. The use of these libraries has altered the MODIS software such that it will not run in a UNIX system without the additional libraries and their configuration files. Furthermore, in the software's current form, modifying input or output files or I/O routines requires a knowledge of HDF and an understanding of the SDP Toolkit.

A. Level 1 Products

Level 1 products are instrument counts, calibrated reflectances, and geolocation data. These data are presented at full instrument resolution and arranged in time order as the detector samples are collected.

Generation of MODIS products begins with the receipt of the spacecraft telemetry data by the EOS Data and Operations System (EDOS), where it is processed to remove telemetry artifacts, place packets in correct time order, and remove duplicate packets. EDOS then assembles and transmits the spacecraft data in 2-h blocks to the GSFC DAAC. At the DAAC, this 6-GB Level 0 instrument data file is read by the MODIS Level 1A software, which unpacks the binary data containing 12-bit MODIS observations and formats each observation as a 16-bit integer and breaks the 2-h instrument data file into 5-min granules. Each 5-min granule of the Level 1A product contains over 200 million individual radiance measurements and requires 330 million bytes of storage.

Earth location and related spatial information are generated as part of the initial processing for each granule of data. This information is needed to understand the location and viewing geometry for the individual elements of every Levels 1 and 2 product. Rather than duplicate and store this information as part of every product, it is provided as a single, stand alone data set. This means that to accurately earth-locate the pixels of a Levels 1 or 2 data product, we must also obtain the geolocation file for each granule. For some uses, we may not need to determine the earth location of each pixel to within a few hundred meters. In these instances, a parametric fit based on the corner coordinates of the granule, which are carried in the metadata for the granule, is all that is needed to located individual samples to within several kilometers (usually within 2 km over ocean and 2–10 km over land, depending on terrain and scan angle).

The earth location algorithm uses earth ellipsoid and terrain surface information in conjunction with spacecraft ephemeris and attitude data, and knowledge of the MODIS instrument and EOS satellite geometry to compute the geodetic position (latitude, longitude, and height above the earth ellipsoid), surface-to-satellite direction (zenith angle and azimuth) and range, and solar zenith angle and azimuth for each MODIS spatial element. Spatial element means the ground field-of-view of a nominal 1-km nadir resolution MODIS detector. MODIS actually makes one measurement for each of 29 1-km resolution bands, four measurements for each of five 500-m bands, and sixteen measurements for the two 250-m resolution bands for each spatial element. These individual measurements are nominally aligned to the individual spatial element. However, since the alignment is not perfect, a set of parametric equations and a table of subpixel corrections for each detector in each wavelength band is included in the geolocation data product to capture the effects of detector-to-detector offsets and permit calculation of the locations of the centers of the 250- and 500-m picture elements. A complete description of the geolocation process is provided in the MODIS Level 1A Earth Location theoretical basis document [10].

The accuracy of the geolocation process is dependent on the following four inputs:

1) knowledge about the location of the EOS spacecraft;
2) knowledge about the attitude of the EOS spacecraft;
3) knowledge of the pointing position of the MODIS instrument relative to the EOS spacecraft; and
4) knowledge of the earth surface at the point of observation.

There are both time constant biases and variable terms associated with each of these inputs. Operational MODIS geolocation processing will include collecting ground control point matching data for a limited set of the overall data set. These ground control points will be analyzed in an off-line statistical process to determine the bias terms in the ongoing geolocation process. Once these analyses are completed, the operational geolocation algorithm will be adjusted to eliminate the bias terms. Prelaunch expectations are that the initial bias component of the error may be on the order of 1–2 pixels and that this will be identified and reduced to an insignificant level within the first several months of processing. Once this is done, current estimates [6] are that there will be approximately a 0.1 pixel (100 m at nadir) two-sigma error in locating individual spatial elements. This level of accuracy is a requirement from MODIS land science team members who need it in to make accurate comparisons between multiple dates for the purpose of mapping land cover and identifying land cover change.

As described above, MODIS generates a simple rectangular array of pixels generated in time sequence by the scan mirror rotation and spacecraft along-track motion. At first blush, it would seem as if this data could be laid down directly on an

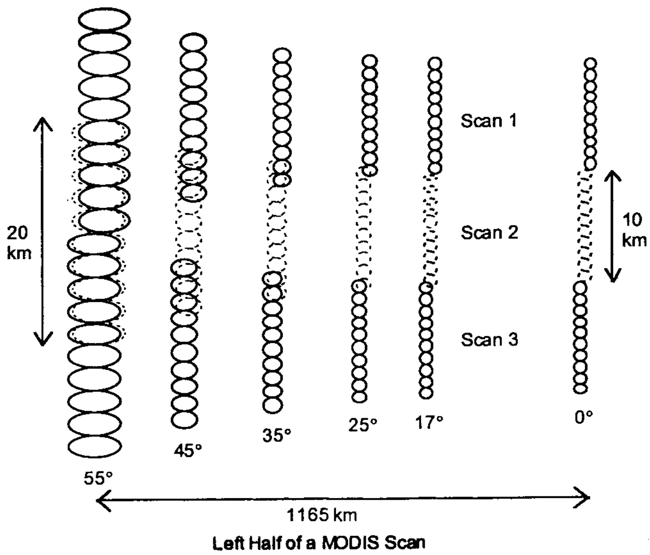

Fig. 2. Pixel growth and overlap between adjacent MODIS scans is illustrated. At 55°, the first and third scans completely overlap the second scan and pixel size has grown from 1 × 1 km (at nadir) to 4 × 2 km.

image screen to provide a simple visual display of the data. However, the actual viewing geometry is substantially more complex than this. At nadir, a nominal 1-km pixel has dimensions of 1 × 1 km, but as the scan angle increases from nadir, the pixel dimension grows until at either end of the scan a pixel is approximately 4.8-km across track × 2-km along track. (The 500- and 250-m nominal pixel sizes increase proportionally to 2.4 × 1-km and 1.2 × 0.5-km across and along track.) Because pixel size increases with swath angle, a single swath covers 10-km along track at nadir but expands to cover 20-km along track at the end of the scan. This bowtie-shaped area on the ground overlaps the swath above and below it, as shown in Fig. 2. In fact, at scan angles greater than 25° a pixel in the first row of the second swath is not as far down track as those in the last row of the preceding swath. This overlap increases rapidly, and at the edge of a scan pixels in the first row of the second swath are adjacent to pixels in the sixth row of the preceding scan and above pixels in the seventh through tenth rows of the preceding scan. Because of this overlap, the same feature on the earth may appear in several scan lines of a MODIS scene if it occurs in a region seen near either edge of the MODIS swath. This is not a flaw in the data, it is the way the instrument was designed. However, it does mean that great care must be taken in interpreting data that are presented in time order of observation. The cross-scan compression due to pixel growth can be seen in Fig. 3, a synthetic MODIS image of an orbit crossing over the eastern United States and Canada. Most users will find that either Level 2G data, which have been reorganized to be presented on a spatial grid basis [15], or Level 3 data, which have been resampled in space and or time, will be much more convenient for their use. It is recommended that users order samples of Levels 2, 2G, and 3 data and come to a full understanding of this issue before ordering large volumes of Level 2 data products.

Level 1B calibrated radiances data products are produced from the unpacked but uncalibrated instrument observations in the Level 1A product. The Level 1B software produces the following five separate products:

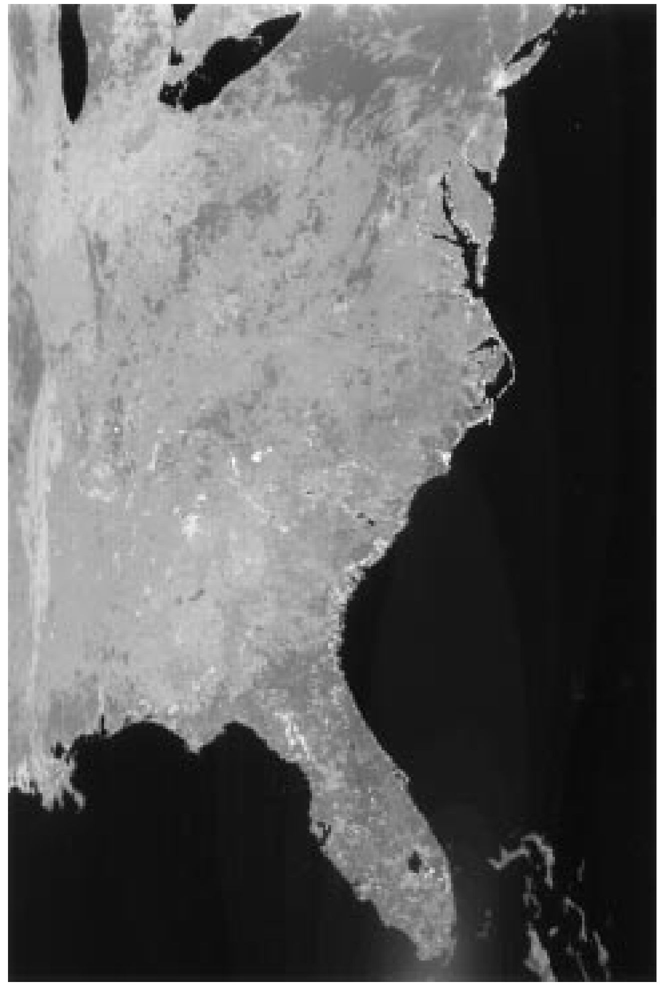

Fig. 3. Across-scan compression (most easily seen in the shape of the Great Lakes) and sun glint (off the coast of Florida) are illustrated in this synthetic image of MODIS band 5.

1) calibrated radiances from 250-m bands;
2) calibrated radiances from 500-m bands;
3) calibrated radiances from 1-km bands in day mode (this product also contains radiances from the 250- and 500-m bands that have been aggregated to 1 km);
4) calibrated radiances from 1-km bands in night mode; and
5) data from the onboard calibrators.

The day-mode calibrated radiances were split into three products to reduce unnecessary data staging during production in the EOSDIS and enable users to select a collection of bands rather than the full 36. Since many ocean and atmosphere products use only the 1-km bands and the first seven MODIS bands of 250- and 500-m resolution data account for more than half of the data volume of day-mode calibrated radiances, the option to order a subset of the total bands can significantly reduce the data volume that we will receive when ordering MODIS calibrated radiances.

B. Levels 2 and 3 Data Products

A brief overview of the production process for producing MODIS Levels 2 and 3 products follows. Level 2 products are

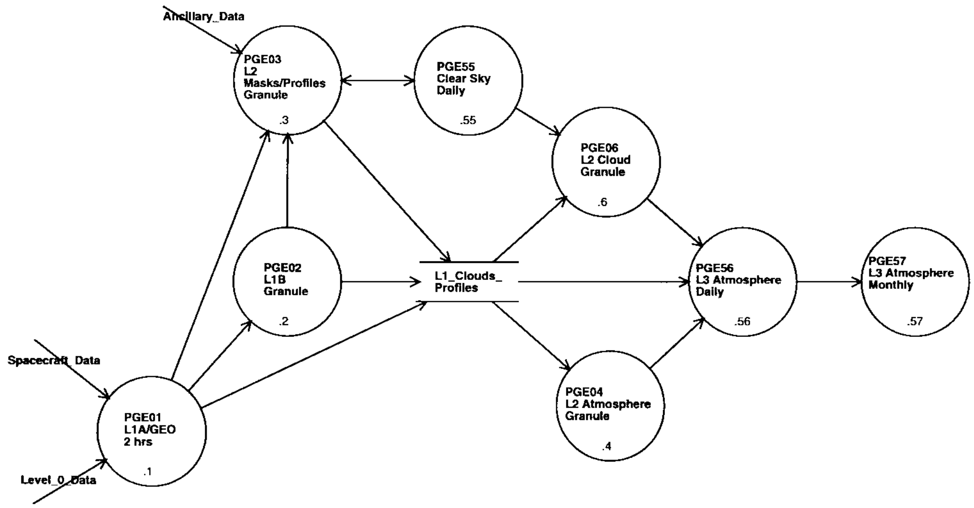

Fig. 4. Processing flow at the GSFC DAAC for Level 1 and atmosphere products.

derived directly from the Level 1 products and have observations at the same locations and resolutions as the Level 1 data products. Level 3 ocean and atmosphere products are produced from Level 2 products by mapping Level 2 observations into global grids of 1, 5, and 18-km resolution. Land data products go through an intermediate step that involves storing all values from Level 2 land product in bins that correspond to the Level 3 global grid cells [15] to produce a family of intermediate products known as Level 2G data products. The Level 2G products are used in turn by land Level 3 processing software to make global-gridded land data products.

1) Atmosphere Processing: MODIS atmosphere products are produced by a series of Levels 2 and 3 processes, all run at the GSFC DAAC. The processing flow for the atmosphere products is presented in Fig. 4. The first step in producing Level 2 MODIS products is to determine the locations of clouds and cloud shadows. This is done in the MODIS cloud mask process, which inputs Level 1B calibrated radiances and geolocation and uses spectral tests in the visible, near-infrared, and infrared channels to flag each pixel as cloudy or clear. The mask product provides a 6-byte set of flags for every 1-km field of view. The flags indicate whether a pixel is cloudy or clear, and if marked as clear, the probability ($>$66, $>$95, or $>$99%) that it is clear. Additionally, the cloud mask has flags that indicate whether the radiance data suggests that a pixel is over water, land, mixed (on the coast), or desert, contains snow or ice, is in cloud shadow, or has sun glint. (Note that the cloud mask deals only with the presence or absence of clouds. Information about cloud properties is generated in a subsequent cloud properties processing step described below.)

MODIS atmospheric profiles are produced from Level 1B calibrated radiances and the cloud mask. These profiles are produced globally for clear sky only and include an estimate of total column tropospheric and stratospheric ozone, atmosphere profiles of moisture and temperature, atmospheric stability indexes, and total tropospheric column water vapor. The atmospheric profiles product provides subsequent MODIS land and ocean algorithms with critical inputs for atmospheric correction of observed radiances.

The two remaining Level 2 atmospheric products provide information about aerosols and cloud properties. The MODIS aerosol product contains atmospheric aerosol optical thickness and size distribution globally over oceans and land and is first produced using 250-m, 500-m, and 1-km MODIS bands. The MODIS cloud product algorithms use infrared and visible bands to determine cloud properties, including cloud optical thickness, cloud particle size, cloud top temperature and emissivity, cloud top height, and cloud particle phase (ice versus water.)

Cloud properties from the Level 2 products are aggregated into 10-km pixels on two different Level 3 grids, which are described in a subsequent section of this paper. The Level 3 daily aerosol over land is produced on an 18-km POLDER grid, while the Level 3 daily gridded atmospheric product is produced on a 1° Climate Modeling Grid. The monthly Level 3 gridded atmospheric product is produced by taking the average of the observations in each cell of the gridded daily products weighted by the number of observations in each cell.

2) Land Processing: Almost 50 separate processing steps are required to produce the MODIS land products and aggregate them into various gridded and resampled forms in which they can be ordered [7]. The Level 2 and 2G land processes run at the GSFC DAAC, and their processing flow is shown in Fig. 5. Level 3 snow and sea ice products are produced at the NSIDC DAAC (Fig. 6) and the remaining land products are produced at the EDC DAAC (Figs. 7 and 8).

Level 2 land products include surface reflectance, thermal anomalies, snow cover, and sea ice distribution. These products are input to Level 2G PGE's, which produce gridded Level 2G products from each Level 2 input [15]. Subsequent Level 3 software selects the "best" pixel or set of pixels (based on criteria optimized for the particular Level 3 parameter) from which to derive the value for each grid cell. Having all values for a Level 2 land product already placed in the appropriate cell of the Level 3 global grid enables other researchers interested in creating new Level 3 land products to focus on algorithms to processing these observations rather than collecting and organizing them into the correct grid cells. Of the four products

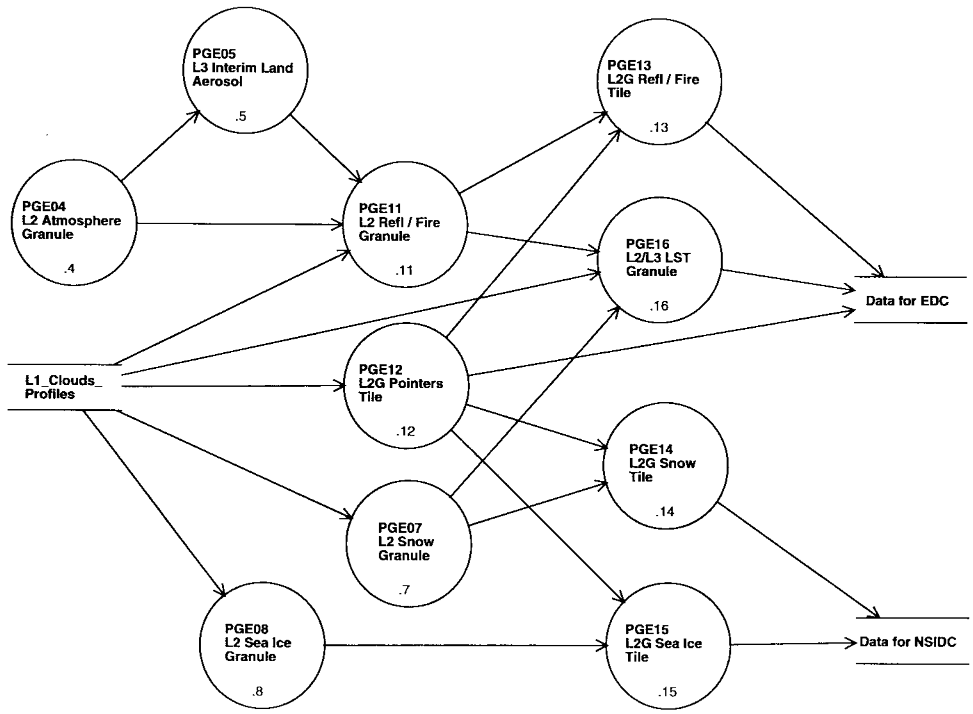

Fig. 5. Processing flow at the GSFC DAAC for land products.

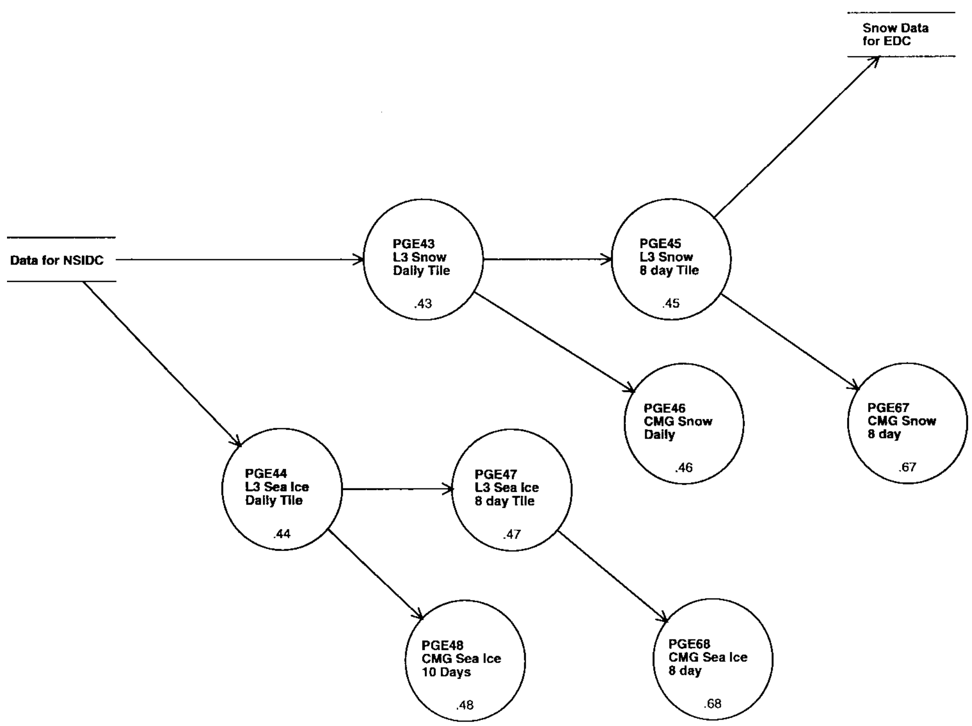

Fig. 6. Processing flow for snow and ice products the NSIDC DAAC.

above, surface reflectance and thermal anomalies will be archived and distributed in the Level 2G format as will two supplemental data sets that contain information about the intersection of each sensor observation and the Level 3 grid cells. The Level 2G product format is unique to land processing and was adopted because it is more efficient to compute the intersection of sensors observations and grids cells for several products at once and use this information to organize the Level 2 observations into grid cells than it would be to compute the intersection of sensor and grid cell for each product in the individual PGE's. MODIS atmosphere and ocean processing software does not use intermediate Level 2G products because there is only one atmosphere and one ocean Level 3 PGE that reads the Level 2 products.

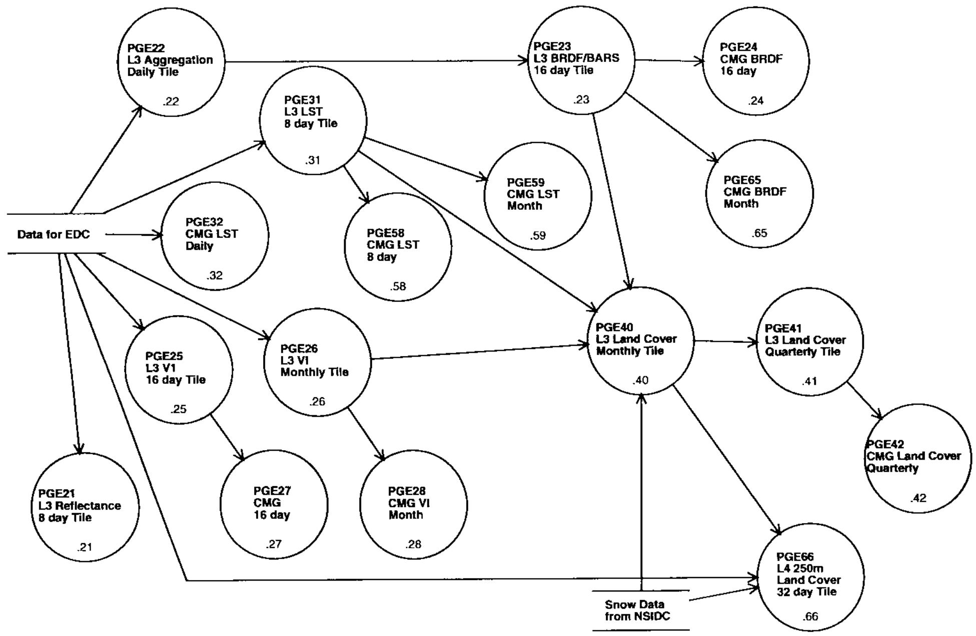

Fig. 7. Processing flow for land products at the EDC DAAC.

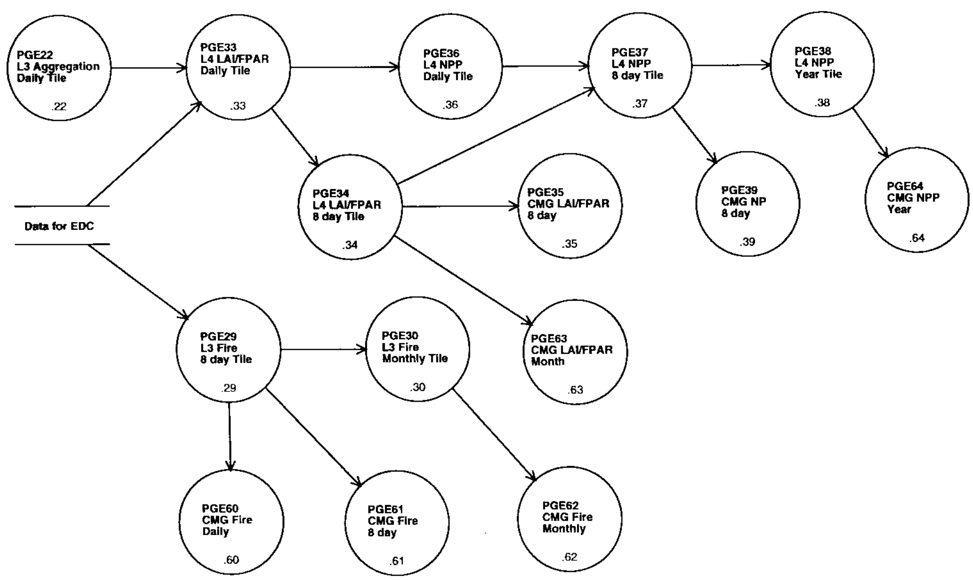

Fig. 8. Processing flow for land products at the EDC DAAC.

Two Level 2 and 4 Level 2G products produced at the GSFC DAAC are transferred to the EDC DAAC for archival and distribution to the public and/or as inputs in Level 3 data production. The Level 2G surface reflectance product is used to produce Level 3 surface reflectance, which is an important input to leaf area index (LAI) and photosynthetically active radiation (FPAR), net primary productivity, and vegetation indexes. Daily Level 3 land surface temperature from the GSFC DAAC is used to generate a weekly Level 3 land surface temperature product, which is utilized with a variety of other land products (snow, albedo, and vegetation indexes) to produce the Level 3 land-cover product. Two global-gridded MODIS products record land cover change. The first is 250-m land cover conversion, which will detect abrupt land cover change due to forest clearing and urbanization through differences in local spatial texture, sudden appearance of linear features, and differences in red and infrared reflectance between successive dates. The second product, land-cover change at 1-km spatial resolution, will identify changes in the 17 classes of land-cover in the Level 3 land-cover product using a multitemporal and multispectral change vector approach to identify those changes that result primarily from interannual variation in climate. The magnitude and direction of the change vector indicate the type and intensity of the land-cover change [8], [9]. The complex product dependencies in the land data production are illustrated in Figs. 7 and 8.

3) Ocean Processing: Level 2 MODIS ocean products are produced from sea surface temperature and ocean color PGE's

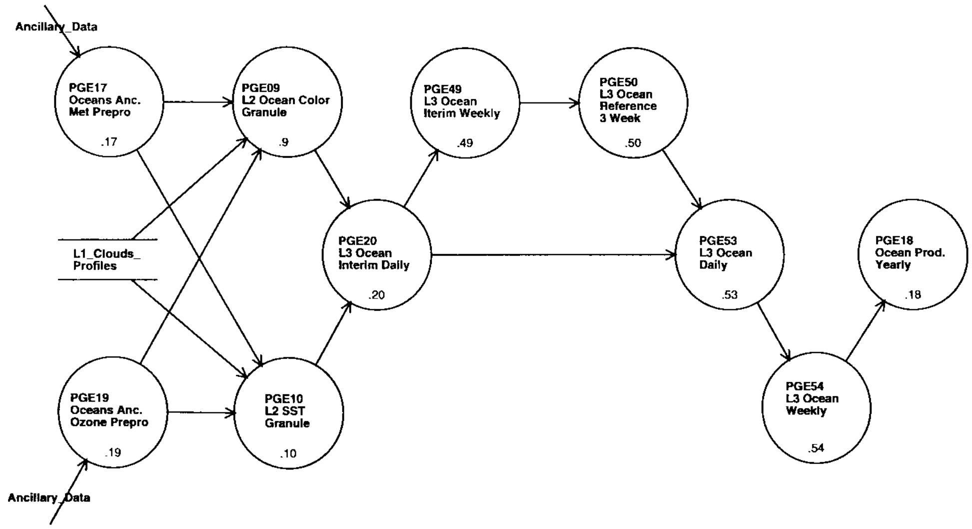

Fig. 9. Processing flow of ocean products the GSFC DAAC.

at the GSFC DAAC [4]. The separate Level 2 products are then processed by common gridding and compositing routines to produce the Level 3 gridded ocean color and sea surface temperature product suites. The ocean processing flow is depicted in Fig. 9.

The Level 2 sea surface temperature (SST) process produces two sea surface temperature products, each with day and night files. The Level 2 ocean color process produces 36 separate geophysical parameters grouped into three files, which can be ordered separately. These parameters include chlorophyll concentration, suspended solids and water leaving radiance. The output from these processes are mapped into global grids during subsequent Level 3 processing.

Level 3 processing takes Level 2 product files for a day and composites them into a global grid to produce an interim daily product. The interim product has missing values where clouds obscure the surface and at the equator where scans do not overlap. In the next processing step, missing values are filled by computing a value for them based upon the last three Level 3 weekly files. The resulting file is the Level 3 daily product. Each week statistics are computed for the observations in the Level 3 daily files and stored in the Level 3 weekly products for sea surface temperature and ocean color. At the end of the ocean processing chain, a weekly ocean productivity product is produced from the weekly sea surface temperature product and the chlorophyll a fields in the weekly ocean color product.

C. Level 3 Product Formats

Level 3 products have been resampled in space and/or time and are projected onto an earth-referenced grid. The value of a geophysical parameter is calculated for each cell in the grid for a specified time period, and that time period varies from a single day to an entire year. The period of the ground track of the MODIS satellite is 16 days, with a near repeat every eight days. As a result, many MODIS products are produced on eight- and 16-day cycles rather than weekly and semimonthly.

Selection of a gridding scheme for MODIS products was influenced by several factors. A common gridding system would simplify processing and comparison between geophysical parameters. However, each of the major discipline groups supported by MODIS (atmosphere, land, and oceans) have fundamentally different spatial resolutions and substantial heritage with unique processing grids. In addition, the products for use in climate models and polar studies have unique, inconsistent, gridding requirements.

An integerized sinusoidal projection, storing data at or near the instrument's spatial resolution, was selected to satisfy most of the MODIS user community's diverse needs. MODIS also produces parameters requested by the climate modeling community in a coarse resolution, equal-angle geographic map projection. Two products, snow and sea ice cover, will be produced in the EASE-Grid to address the needs of the scientists studying high latitudes and the poles. Land software is written so that it could also produce products in the Goodes Homolosine projection [12] to allow comparisons to heritage products produced by the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder program, although this will not be produced on an operational basis at the time of launch.

The spatial resolution of the MODIS Level 3 products varies with the highest resolution for land products, an intermediate resolution for ocean products, and a coarser resolution for atmospheric products. MODIS used integer multiples of resolutions when possible to allow the possibility of using simple algorithms for comparing quantities at different resolutions.

1) Integerized Sinusoidal Grid: The Integerized Sinusoidal Grid is the primary grid used for MODIS. Except for the climate modeling grid products, all MODIS products are produced in this grid. It was first recommended for use by Rossow [11]. It is used by the International Satellite Cloud Climatology Project (ISCCP), by the Oceans Pathfinder and SeaWiFS projects [5], and by the POLDER community.

The integerized grid begins with a sinusoidal map projection, and at each latitudinal row of the grid, calculates a small adjustment to the cell's angular width so that there are an integral number of cells covering the entire 360° in that latitude band. Grid cells within a row in the new grid all have the same area, but there is a small difference (up to 0.5%) in area between any two rows. Each row is like a row of bricks, in which each cell may be offset from the cell below it by up to 1/2 a cell width.

Oceans data are stored in this grid at a resolution of 4.6 km (2.5 arc-min at the equator). This grid is nested with the SeaWiFS 9.2-km (5 arc-min at the equator) grid. The oceans' parameters are stored in a single dimension array. This is done storing only those grid cells that contain ocean data, adjusting for row length differences and storing each row end-to-end, from west to east starting at the south pole. Storing ocean data as a one-dimensional (1-D) array with land cells removed does not easily lead itself to displaying global images of MODIS ocean products. Therefore, the user ordering Level 3 MODIS ocean products will need to obtain a mapping utility as well to display them. A utility developed by the MODIS ocean team, map, which projects a Level 3 ocean product into any of 30 map projections and produces images of a user-specified size, will be available from the GSFC DAAC. Since the data volume of the Level 3 daily and weekly ocean product is as much as 680 MB per file and the volume of a 1024 $\times$ 1024 image for a single parameter produced by map is only 1 MB, users may wish to request that images for parameters of interest be produced at the GSFC DAAC and the resulting files be shipped to them via the Internet rather than obtaining the entire Level 3 product.

The land products are stored at three different resolutions, 230 m (7.5 arcsec at the equator), 460 m (15 arcsec), and 920 m (30 arcsec). These grids are commonly referred to as the 250-m, 500-m, and 1-km grids, respectively, since they are fairly close to these resolutions. The grid cells are nested starting from the 920-m resolution. They are stored in a regular array by centering the rows of grid cells around the central meridian and adding fill values at the end of each row.

The daily land aerosol product is stored in this grid at a resolution of 18.5 km (10 arc-min at the equator). This grid is also used by the POLDER community at a finer resolution. The POLDER grid has an even number of grid cells per row, unlike the land product grid, where a row may contain an even or odd number of grid cells.

For atmosphere and ocean products, a single file covers the entire earth and contains one or more geophysical parameters, such as cloud top temperature, cloud particle size, and cloud particle phase. These files range from 8 to 1600 MB in size. MODIS land products, however, are presented at much finer spatial scale and are much larger than the ocean and atmosphere products. To keep them under 2 GB per file and reduce the resources required to generate an individual product file, land products are produced and archived as tiles that cover a 1100 $\times$ 1100 km (10 $\times$ 10° at the equator) portion of the earth's surface. Fig. 10 shows the distribution and size of the 354 land tiles on the globe. Since the EOSDIS system at-launch does not support subsetting or merging of product files, the tile is the basic unit we will order for Level 3 land products. Individual tiles range in size from 2 to 420 MB, depending on the product and the number of tiles for a product depends on the area it covers. Initially, most land products are made within a limited band of latitude between 80° N and 60° S and cover

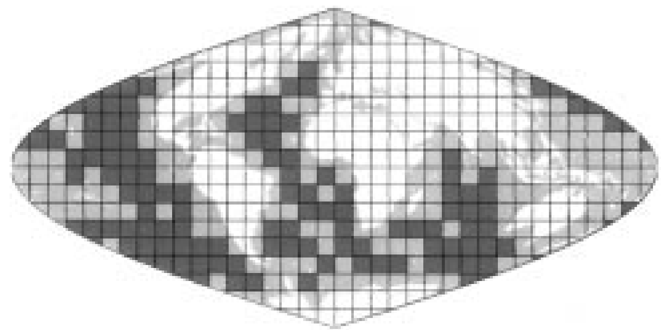

Fig. 10. Distribution of land tiles used for processing Level 3 products is shown. Each gray or white tile is a cell of a 10 $\times$ 10° integerized sinusoidal grid, which contains land or at high latitudes, sea ice.

289 tiles. However, there are two exceptions, snow, which is made for all 354 land tiles and sea ice, which is made for 109 tiles over frozen ocean from 50° latitude to the poles.

2) Polar Grids: The snow and sea ice cover products are also stored in Lambert Azimuthal Equal Area grids, centered at each pole. These grids are based upon the EASE Grid [1], a grid commonly used by the polar community. The snow and sea ice products are also produced in the integerized sinusoidal projection for easy comparison with other land and ocean products.

Snow cover products are stored at 500-m resolution, and the sea ice cover products are stored at 1-km resolution. The products are also divided into 10° square tiles. Snow cover products in the polar grid will extend down from either pole to 40° latitude. Sea ice cover products only extend down to 50° latitude.

3) Climate Modeling Grid: Gridded data that are useful to the climate models are also produced at a coarse resolution (0.25, 0.5, and 1°), equal-angle geographic projection. This grid is one that was proposed to be used by the EOS community for standard production of these "climate modeling grid" products [13].

IV. Where to Find Additional Information

Additional information about MODIS products and software can be found on the World Wide Web (WWW) at several sites. The MODIS site at http://modarch.gsfc.nasa.gov/MODIS/ provides an overview of the MODIS sensor, an annotated directory of the MODIS Science Team, and links to other relevant MODIS sites. A detailed description of the theoretical basis of each MODIS algorithm is available at the EOS Project Science Office WWW site http://eospso.gsfc.nasa.gov/. The DAAC, which will process, archive, and distribute MODIS data sets, each have sites from which we will be able to order both data products and the science software that produced them. The URL for each DAAC is as follows:

GSFC DAAC
http://daac.gsfc.nasa.gov/DAAC_DOCS/gdaac_home.html

EDC DAAC
http://edcwww.cr.usgs.gov/landdaac/landdaac.html

NSIDC DAAC
http://www-nsidc.colorado.edu/NASA/PODAG/.

Finally, to learn more about the EOSDIS system, begin with the EOSDIS Core System site at: http://ecsinfo.hitc.com/.

Other sources for information about the MODIS instrument and its data products include the 1995 MTPE/EOS Reference Handbook [2], which describes the instruments that will fly on spacecraft of the EOS, and the 1997 MTPE/EOS Data Products Handbook [14], which describes the data products that will be produced by the EOS instruments.

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Robert E. Wolfe, for a photograph and biography, see this issue, p. 1249.

F. Patt, photograph and biography not available at the time of publication.