MODIS Multi-Angle Implementation of Atmospheric Correct (MAIAC) Data User's Guide

Collection 6 (ver. of June 2017)

Version 2.0

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TABLE OF CONTENTS

1. Introduction

MAIAC is a new advanced algorithm which uses time series analysis and a combination of pixel- and image-based processing to improve accuracy of cloud detection, aerosol retrievals and atmospheric correction (*Lyapustin et al*., 2011a,b; 2012; publication on current MAIAC is under preparation). The underlying physical idea behind MAIAC is simple: because surface changes slowly in time compared to aerosols and clouds given the daily rate of global MODIS observations, we focus on extensive characterization of the surface background in order to improve all stages of MAIAC processing. MAIAC starts with gridding MODIS measurements (L1B data) to a fixed grid at 1km resolution in order to observe the same grid cell over time and work with polar-orbiting observations as if they were "geostationary". In this regard, this approach is fundamentally different from the conventional swath-based processing where the footprint changes with orbit and view geometry (scan angle) making it difficult to characterize always changing surface background.

To enable the time series analysis, MAIAC implements the sliding window technique by storing from 4 (at poles) to 16 (at equator) days of past observations in operational memory. This helps us retrieve surface BRDF from accumulated multi-angle set of observations, and detect seasonal (slow) and rapid surface change. A detailed knowledge of the previous surface state also helps MAIAC's internal dynamic land-water-snow classification including snow detection and characterization.

Consistently with the entire C6 MODIS land processing, the top-of-atmosphere (TOA) L1B reflectance includes standard C6 calibration (*Toller et al*., 2014) augmented with polarization correction for MODIS Terra (*Meister et al*., 2012), residual de-trending and MODIS Terra-to-Aqua cross-calibration (*Lyapustin et.al*, 2014). The L1B data are first gridded into 1km MODIS sinusoid grid using area-weighted method (*Wolf et al*., 1998). Due to cross-calibration, MAIAC processes MODIS Terra and Aqua jointly as a single sensor.

2. Overview of MAIAC products

MAIAC provides a suite of atmospheric and surface products in three HDF4 files: *daily* MAIAC[TA]BRF (spectral BRF, or surface reflectance), *daily* MAIAC[TA]AOT (atmospheric properties), and *8-day* MAIACRTLS (spectral BRDF/albedo).

2.1 Tiled File Structure and Naming Convention

Products are by default reported on 1km sinusoidal grid. The sinusoidal projection is not optimal due to distortions at high latitudes and off the grid-center, but it is a tradeoff made by the MODIS land team for the global data processing. The gridded data are divided into 1200x1200km^2 standard MODIS tiles shown in Figure 1.
Users can also define their own projections to minimize map distortions by changing the run time parameters before the data is processed. We have currently predefined five local projections for users' convenience: AlaskaCananda, Asia, Australia, NA (North America), SouthAmerica.

The current dataset presents data per orbit (we do not provide a daily composite image as in standard MODIS surface reflectance product MOD09). Each daily file name follows name convention below, for instance:
MAIAC[TA]AOT.TileNumber.TimeOfObservation.hdf
T stands for Terra and A stands for Aqua
TileNumber has the standard format, e.g. h11v05 for the east coast USA.
TimeOfObservation has the format "YYYYDDDHHMM", where YYYY is year, DDD is Julian day, HH is hour MM is minute.
TileNumber has the standard format, e.g. h11v05 for the east coast USA.

Figure 1. Illustration of MODIS Sinusoidal Tiles.

2.2 MAIAC Products: General Description

In C6 Collection, MAIAC reports spectral BRF, BRDF, snow fraction, snow grain size, column water vapor, and aerosol optical depth (AOD) for both land and water. Over

water, MAIAC also reports fine mode fraction, and spectral reflectance of underlight (or equivalent reflectance of water-leaving radiance).

2.2.1 Atmospheric Properties File (MAIAC[TA]AOT)

For each orbit, MAIAC atmospheric properties file includes:

Over land:

- *column water vapor* (CWV) retrieved from MODIS near-IR bands B17-B19 at 0.94m (in cm). CWV is reported for both clear and cloudy pixels. In the latter case, it represents water vapor above the cloud;
- *aerosol optical depth and type* (background, biomass burning or dust). The AOD is originally retrieved (and reported) in MODIS Blue band B3 (0.47m). Because the common input for the chemical transport models and GCMs as well as AOD validation and AOD product intercomparison are standardized to 0.55m, we also provide the "Green" band (B4) AOD. It is computed from 0.47m based on spectral properties of regional aerosol model used in retrievals. Validation shows that quality of AOD at 0.55m is generally close though slightly worse than the original retrieval at 0.47m. Currently, AOD is not retrieved at high altitudes >3.5km, except when Smoke/Dust aerosol is detected. Rather, we report static "climatology" value of 0.01 which is used for atmospheric correction. Our study showed that in conditions of very low AOD, non-flat terrain and generally bright surface, MAIAC aerosol retrievals at high altitudes are unreliable.
- *AOD uncertainty:* This parameter is evaluated based on the Blue-band B3 surface brightness (reflectance) only, and thus gives only a general indication of possible increase of error over brighter surfaces;
- *Injection Height* of Smoke plume (in m above ground): Reported near detected fire hot spots when smoke plume is optically thick and exhibits brightness temperature contrast with the previous clear observation or with unobscured neighbor land surface. A limited validation against MISR MINX plume height for the case of Idaho-Wyoming fires of 2014 showed a reasonable accuracy within ~500m (publication in preparation). This product is experimental and requires thorough investigation.

Over water:

- *AOD* outside of glint area (glint angle 40). When MAIAC detects dust, AOD is also reported for smaller glint angles if the retrieved value is above zero.
- *Fine Mode Fraction (FMF)* is reported along with AOD over open ocean and large in-land lakes (like Great Lakes of North America). It is not retrieved over small in-land water bodies.

View Geometry over land and water *at 5km*:

- *Cosines of Solar and View zenith angles, relative azimuth, scattering angle and glint* *angle*.

2.2.2 Surface Reflectance File (MAIAC[TA]BRF)

For each orbit, MAIAC *daily* surface reflectance file includes:

Over land (for solar zenith angles below 80):

- *1km BRF (surface reflectance)* in MODIS land and unsaturated ocean bands B1-B12. It is produced in cloud-free and clear-to-moderately turbid ($AOD_{0.47}$<1.5) conditions;
- *500m BRF,* nested in 1km grid, in MODIS land bands B1-B7;
- *1km BRF uncertainty (Sigma_BRFn)* in MODIS Red (B1) and NIR (B2) bands. BRF uncertainty is required for higher level land algorithms, such as LAI/FPAR (*Chen, Knyazikhin et al.*, 2017), global model assimilation etc. We define it as a standard deviation of the geometrically normalized BRFn over 16-day period under assumption that surface is stable or changes linearly in time. As such, this is the most conservative estimate of uncertainty which includes contribution from gridding, undetected clouds, errors of atmospheric correction including those from aerosol retrievals, and of surface change when reflectance change is non-linear over time. As one can see, this definition of uncertainty is much broader than the one that may come from "theoretical" considerations, but it is also much more realistic. Sigma_BRFn in the Red band can serve as a proxy of uncertainty at shorter wavelengths, where the surface is generally darker, and the NIR value can be a proxy for the longer wavelengths with high surface reflectance.

When snow is detected, we also compute snow grain size (diameter, in mm) which governs spectral snow albedo for pure snow, and sub-pixel snow fraction. The algorithm is based on a linear mixture model of spectral snow reflectance (*Lyapustin et al.*, 2010) and pure land spectral BRDF for every land grid cell. Processing uses minimization of MODIS reflectance in bands B1, B5, B7. The residual between the best fit and MODIS observations in B1,B5,B7 is reported in parameter Snow_Fit:

- *Snow grain size* (diameter, in mm) at 1km;
- *Sub-pixel snow fraction* (range 0-1) at 1km;
- *Snow Fit* (rmse for the best fit and MODIS observations in B1,B5,B7) at 1km.

View Geometry and Kernels of RTLS BRDF model *at 5km*:

- *Cosines of Solar and View zenith angles, relative azimuth, Sun azimuth (SAZ), sensor view azimuth (VAZ), scattering angle and glint angle.*
- *Volumetric* (F_{0v}) *and geometric-optics* (F_{0g}) *kernels of RTLS model* for the observation geometry. Kernels are provided for geometric- (or BRDF-) normalization of spectral BRFs, which is needed in many tasks, such as change detection, geophysical and calibration trend analysis (e.g., *Lyapustin et al.*, 2012; 2014) etc. Then, the BRDF (or geometry)-normalization can be done using spectral BRDF kernel weights $\{k_L, k_V, k_G\}$ from file MCD19A3 based on the following formula (see Eqs. (6) and (8) from *Lyapustin*

et al., 2012):

$$BRF_n = BRF * (k_L - 0.0458621*k_V - 1.1068192*k_G)/(k_L + F_{0V}*k_V + F_{0G}*k_G).$$

This equation normalizes BRF from a given view geometry to the fixed geometry of nadir view and 45 sun zenith angle ($F_V(45)$=-0.0458621, $F_g(45)$=-1.1068192). One can easily modify normalization to a preferable Sun angle according to latitude or season, by replacing coefficients in the numerator with values from the following table 1 built for different solar zenith angles and nadir view.

The 5km reporting scale for geometry and volumetric and geometric-optics kernels is sufficient as geometry changes slowly.

SZA	Fv(SZA)	Fg(SZA)
0	0	0
1	-0.0000589	-0.0222231
2	-0.0002322	-0.0444532
3	-0.0005146	-0.0666974
4	-0.000901	-0.0889604
5	-0.0013863	-0.1112519
6	-0.0019654	-0.1335773
7	-0.0026334	-0.1559435
8	-0.0033854	-0.1783573
9	-0.0042163	-0.2008253
10	-0.0051215	-0.2233558
11	-0.006096	-0.2459545
12	-0.0071349	-0.2686286
13	-0.0082336	-0.2913864
14	-0.0093873	-0.3142342
15	-0.0105912	-0.3371795
16	-0.0118406	-0.3602294
17	-0.0131308	-0.3833919
18	-0.0144569	-0.4066738
19	-0.0158144	-0.4300835
20	-0.0171985	-0.4536282
21	-0.0186043	-0.4773155
22	-0.0200272	-0.5011534
23	-0.0214623	-0.5251498
24	-0.0229049	-0.5493125
25	-0.0243501	-0.5736493
26	-0.025793	-0.5981684
27	-0.0272287	-0.6228774
28	-0.0286523	-0.6477844
29	-0.0300587	-0.6728968
30	-0.0314429	-0.6982225

31	-0.0327997	-0.7237687
32	-0.0341241	-0.7495425
33	-0.0354105	-0.7755507
34	-0.036654	-0.8017994
35	-0.0378488	-0.8282937
36	-0.0389896	-0.8550386
37	-0.0400707	-0.8820373
38	-0.0410865	-0.9092915
39	-0.042031	-0.9368016
40	-0.0428984	-0.964565
41	-0.0436827	-0.9925762
42	-0.0443776	-1.0208257
43	-0.0449768	-1.0492985
44	-0.0454738	-1.0779734
45	-0.0458621	-1.1068192
46	-0.0461346	-1.1357927
47	-0.0462846	-1.1648338
48	-0.0463049	-1.1938568
49	-0.0461881	-1.2227401
50	-0.0459265	-1.2513024
51	-0.0455125	-1.2792587
52	-0.044938	-1.3061037
53	-0.0441948	-1.3305788
54	-0.0432743	-1.3506508
55	-0.0421677	-1.3717234
56	-0.040866	-1.3941458
57	-0.0393597	-1.4180392
58	-0.0376392	-1.44354
59	-0.0356944	-1.4708021
60	-0.033515	-1.5
61	-0.0310901	-1.5313327
62	-0.0284086	-1.5650272
63	-0.0254589	-1.6013447
64	-0.022229	-1.640586
65	-0.0187063	-1.6831008
66	-0.014878	-1.7292967
67	-0.0107305	-1.7796524
68	-0.0062498	-1.8347336
69	-0.0014212	-1.8952141
70	0.0037704	-1.9619021

Table 1. Values of V and G kernels for different SZA and nadir view (VZA=0).

2.2.3 Surface BRDF File (MAIACRTLS)

The *8-day* BRDF/albedo file includes:

- *Three parameters of RTLS BRDF model* k_{iso}, k_v, k_G (here $k_{iso} = k_L$) in MODIS bands B1-B8 at *1km*. The retrievals represent cloud-free and low aerosol ($AOD_{0.47}$<0.6) conditions;
- *Spectral surface albedo* in MODIS land bands B1-B8 at 1km. It represents instantaneous albedo defined as a ratio of reflected and incident narrowband radiative fluxes at the surface. Albedo is related to BRDF retrieval and also represents cloud-free and low aerosol conditions.

Please, keep in mind that the current Terra L1B data (based on current C6 re-processed MODIS data) still contain small residual calibration artifacts which sometimes become visible as stripes in both aerosol and surface products on the right part of the scan from about middle to the edge of scan.

3. QA-related Comments (please read)

In *daily* output files, the QA bit contains cloud mask, adjacency mask, surface type (the result of MAIAC dynamic Land-Water-Snow classification), and a surface change mask.

3.1 Change in reported AOD for MAIAC AOT users:

The current C6 MAIAC AOD is reported for two values of Cloud Mask in QA bit - Clear and Possibly_Cloudy.

- Most applications should use AOD ONLY when QA.CloudMask = Clear, which guarantees high product quality.

The Possibly_Cloudy value mostly originates from spatial analysis of retrieved AOD which assumes a certain degree of aerosol spatial homogeneity (this does not apply when MAIAC detects absorbing aerosols (smoke/dust)). This filter detects residual clouds and significantly improves aerosol product quality. However:

- The work from air quality community (Allan Just and Itai Kloog et al.) showed that in some locations with high spatial aerosol variability such as Mexico City, this filter may systematically erase AOD retrievals in cloud-free conditions over certain urban areas.
- This filter will also erase AOD for parts of spatially variable smoke or dust plumes where MAIAC Smoke/Dust detection failed.

For such user-specific applications (e.g., urban air quality analysis; fire smoke monitoring), we retain and report AOT when QA.CloudMask = Possibly_Cloudy.

3.2 Use of Adjacency Mask:

This mask gives information about detected neighbor clouds or snow (in the 2-pixel vicinity). For general applications, we recommend to only use data with QA.AdjacencyMask=Normal. The value AdjacentToASingle CloudyPixel can also be used as it often represents false cloud detection. The other categories of AdjacencyMask are not recommended when using AOD. In land analysis, we do not recommend using values AdjacentToCloud and SurroundedByMoreThan6CloudyPixels.

3.3 Selecting Best Quality BRF and AOD

To select best quality BRF, one should apply the following QA filter:

QA.AOTLevel=low (0), QA.AdjacencyMask=Clear, and QA.AlgorithmInitializeStatus= initialized (0).
To select the best quality AOD, one should apply the following QA filter:
Over land: QA.CloudMask = Clear and QA.AdjacencyMask=Clear.
Over water: QA.QA_AOD_WATER=Best_Quality.

4. MAIAC Data Specification

4.1. Surface Reflectance (MAIAC[TA]BRF)

SDS name	Data Type	Scale	Description
Sur_refl	INT16	0.0001	Surface reflectance at 1km for bands 1-12
Sigma_BRFn	INT16	0.0001	BRFn uncertainty over time, for bands 1-2
Snow_Fraction	INT16	0.0001	Snow fraction
Snow_Grain_Size	INT16	0.0001	Snow grain diameter
Snow_Fit	INT16	0.0001	Snow reflectance RMSE in band 1,5,7
Status_QA	UINT16	n/a	QA bits
Sur_refl_500m	INT16	0.0001	Surface reflectance 500m for band 1-7 (500m)
cosSZA	INT16	0.0001	Cosine of Solar zenith angle (5km)
cosVZA	INT16	0.0001	Cosine View zenith angle (5km)
RelAZ	INT16	0.01	Relative azimuth angle (5km)
Scattering_Angle	INT16	0.01	Scattering Angle (5km)
SAZ	INT16	0.01	Solar Azimuth Angle (5km)
VAZ	INT16	0.01	View Azimuth Angle (5km)
Glint_Angle	INT16	0.01	Glint Angle (5km)
F_0v	FLOAT32	n/a	RTLS volumetric kernel (5km)
F_0g	FLOAT32	n/a	RTLS geometric kernel (5km)

4.2 Status QA definition for MAIAC[TA]BRF (16-bit unsigned integer)

Bits	Definition

0-2	**Cloud Mask** 000 --- Undefined 001--- Clear 010 --- Possibly Cloudy (detected by AOT filter) 011 --- Cloudy (detected by cloud mask algorithm) 101 -- - Cloud Shadow 110 --- Fire hot spot 111 --- Water Sediments
3-4	**Land Water Snow/Ice Mask** 00 --- Land 01 --- Water 10--- Snow 11 --- Ice
5-7	**Adjacency Mask** 000 --- Normal condition/Clear 001 --- Adjacent to cloud 010 --- Surrounded by more than 8 cloudy pixels 011 --- Adjacent to a single cloudy pixel 100 --- Adjacent to snow 101 --- snow was previously detected for this pixel
8	**AOD level** 0 --- AOD is low (<=0.6) 1 ---- AOD is high (> 0.6) or undefined
9	**Algorithm Initialize Status** 0 --- Algorithm is initialized 1 --- Algorithm is not initialized
10	**BRF retrieved over snow assuming AOD = 0.05** 0 --- no 1 --- yes
11	**Altitude >3.5km, BRF is retrieved using climatology AOD =0.02** 0 --- no 1 --- yes

12-15	**Surface Change Mask** 0000 --- no change 0001 --- Regular change Green up 0010 -- Big change green up 0011 --- Regular change Senescence 0100 --- Big change senescence 0101 --- Flooding **Regular Change**: Relative change in Red and NIR nadir-normalized BRF is more than 5% but less than 15% **Big Change** : Relative change in Red and NIR nadir-normalized BRF is more than 15%

4.3 Aerosol Optical Depth (MAIAC[TA]AOT)

SDS name	Data Type	Scale	Description
Optical_Depth_047	INT16	0.001	Blue band aerosol optical depth
Optical_Depth_055	INT16	0.001	Green band aerosol optical depth
AOT_Uncertainty	INT16	0.0001	AOD uncertainty
FineModeFraction	INT16	0.0001	Fine mode fraction for ocean
Column_WV	INT16	0.001	Column Water Vapor (cm)
Injection_Height	FLOAT32	n/a	Smoke injection height (m above ground)
AOT_QA	UINT16	n/a	AOD QA
AOT_MODEL	UINT8	n/a	AOD model used in retrieval
cosSZA	INT16	0.0001	Cosine of Solar zenith angle (5km)
cosVZA	INT16	0.0001	Cosine of View zenith angle (5km)
RelAZ	INT16	0.01	Relative azimuth angle (5km)
Scattering_Angle	INT16	0.01	Scattering Angle (5km)
Glint_Angle	INT16	0.01	Glint Angle (5km)

4.4 AOT QA definition for MAIAC[TA]AOT (16-bit unsigned integer)

Bits	Definition
0-2	**Cloud Mask** 000 --- Undefined 001--- Clear 010 --- Possibly Cloudy (detected by AOD filter) 011 --- Cloudy (detected by cloud mask algorithm) 101 -- - Cloud Shadow 110 --- hot spot of fire 111 --- Water Sediments
3-4	**Land Water Snow/ice Mask** 00 --- Land 01 --- Water 10--- Snow 11 --- Ice
5-7	**Adjacency Mask** 000 --- Normal condition/Clear 001 --- Adjacent to cloud 010 --- Surrounded by more than 8 cloudy pixels 011 --- Single cloudy pixel 100 --- Adjacent to snow 101 --- snow was previously detected on this pixel

8-11	**QA for AOT retrieval over Water** 0000 --- Best quality 0001 --- Water Sediments are detected 0010 --- AC over water done, but AOT>0.5 0011 --- There is 1 neighbor cloud 0100 --- There is >1 neighbor clouds 0101 --- no retrieval (cloudy, or whatever) 0110 --- no retrievals near detected or previously detected snow 0111 --- Climatology AOT: altitude above 3.5km(water) and 4.2km(land) 1000 --- no retrieval due to sun glint 1001 --- retrieved AOT is very low (<0.05) due to glint 1010 --- AOT within +-2km from the coastline is replaced by nearby AOD 1011 --- Land, research quality: AOT retrieved but CM is possibly cloudy
12	**Glint Mask** 0 --- no glint 1 --- glint (glint angle < 40)
13-14	**Aerosol Model** 00 --- Background model (regional) 01 --- Smoke model (regional) 10 --- Dust model
15	**Reserved**

4.5 8-day BRDF model parameters (MAIACRTLS)

SDS name	Data Type	Scale	Description
Kiso	INT16	0.0001	RTLS isotropic kernel parameter for band 1-8
Kvol	INT16	0.0001	RTLS volumetric kernel parameter for band 1-8
Kgeo	INT16	0.0001	RTLS geometric kernel parameter for band 1-8
Sur_albedo	INT16	0.0001	Surface albedo for band 1-8

UpdateDay	UINT8	n/a	Number of days since last update to the current day

5. Caveats and Known Problems

- The maximum AOD in the current look-up tables (LUT) is 4.0.
- Current MAIAC LUTs are built assuming pseudo-spherical correction in single scattering which has reduced accuracy for high sun/view zenith angles. A reduced MAIAC performance is expected at solar zenith angles > 70°.
- Current MAIAC may be missing several bright salt pans in the Sahara desert and Ethiopia/Somali regions. In such cases, it generates a persistent high AOD resulting in missing surface retrievals.
- Because of inherent uncertainties of gridding on the coastline, the area of 1-3 pixels from the coastline may contain frequent artifacts in cloud mask (over-detection), AOD (higher values) and surface BRF. Users should exercise caution in this case.

We are working to resolve these issues.

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We are looking forward to your comments, suggestions etc. which you may forward either to myself (Alexei.I.Lyapustin @nasa.gov) or to Yujie (Yujie.Wang@nasa.gov).
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