MODIS Mosaic of Antarctica 2003-2004 (MOA2004) Image Map, Version 2

USER GUIDE

How to Cite These Data

As a condition of using these data, you must include a citation:

Haran, T., J. Bohlander, T. Scambos, T. Painter, and M. Fahnestock. 2005, updated 2019. *MODIS Mosaic of Antarctica 2003-2004 (MOA2004) Image Map, Version 1*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/68TBT0CGJSOJ [Date Accessed].

Literature Citation:

As a condition of using these data, we request that you acknowledge the author(s) of this data set by referencing the following peer-reviewed publication.

Scambos, T., T. Haran, M. Fahnestock, T. Painter, and J. Bohlander. 2007. MODIS-based Mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size, *Remote Sensing of Environment*. 111. 242-257. https://doi.org/10.1016/j.rse.2006.12.020

FOR QUESTIONS ABOUT THESE DATA, CONTACT NSIDC@NSIDC.ORG

FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/NSIDC-0280

National Snow and Ice Data Center

TABLE OF CONTENTS

1 DATA DESCRIPTION

The MOA2004 mosaic is a composite of MODIS image swaths acquired over the 2003/2004 austral summer season. It provides a nearly perfect cloud-free view of the ice sheet, ice shelves, and land surfaces at two different grid scales of 125 m and 750 m. The underlying image resolution ranges between 150 m and 250 m, with a nominal resolution of 250 m at nadir. Three image maps were compiled from MODIS scenes: a surface morphology image map, derived from digitally smoothed red-light Band 1 MODIS data, and two snow grain size image maps, derived from the normalized difference of calibrated Band 1 and Band 2 MODIS data. The 260 image swaths used to create the 2003/2004 surface morphology image map and the 2003/2004 snow grain size image map were acquired from 20 November 2003 to 29 February 2004. The 122 image swaths used to create the 2003 snow grain size image map were acquired from 01 November to 17 December 2003. Land areas and islands larger than a few hundred meters south of 60° S are included in this mosaic, along with several persistent fast ice areas and some grounded icebergs. Vector data sets with the corresponding coastlines, ice sheet grounding lines, and islands are also provided. The image maps in this data set are complimentary to the MODIS Mosaic of Antarctica 2008-2009 (MOA2009) Image Map and the MODIS Mosaic of Antarctica 2013-2014 (MOA2014) Image Map data sets, and were generated using the same procedures as used for MOA2009 and MOA2014.

1.1 Parameters

The MOA images report two parameters: surface morphology and snow grain size.

1.1.1 Surface Morphology

The image provides a semiquantitative but highly consistent representation of the surface shape and approximate reflectivity, as illuminated by the sun across all surface types for the entire continent. The surface morphology mosaic required many processing steps as many images were combined to create the single grid cell values needed for a seamless and uniform mosaic. As such, the image values no longer have a clearly quantifiable relationship to the top-of-atmosphere, red light reflectances from which they were derived.

1.1.2 Snow Grain Size

Radiance ratios can be used to approximate mean snow grain size in areas with dust-free, non-shadowed snow, firn, and ice. Reduced pre-processing was used to produce a truer quantitative map of radiance ratios by sacrificing the seamlessness of the red-light image.

1.2 File Information

1.2.1 Format

The surface morphology image maps (labeled `hp1`) and snow grain size image maps (labeled `grn`) are available at two spatial grid scales, 125 m and 750 m, and are provided as a gzipped flat binary 16-bit or 8-bit unsigned-integer file (`.img.gz`) in little-endian byte order to preserve the radiometric content of the scenes. Each `.img` file has an equivalent ENVI header file (`.img.hdr`) in ASCII format and is also provided in GeoTiff (`.tif`) format. Map projection parameter and grid parameter definition files (`.mpp`, `.gpd`) are also available.

Coastlines, ice sheet grounding lines, and islands are available in the following formats: shapefiles (`.shp`, `.shx`, `.dbf`, `.prj`), ENVI vector files (`.evf`), Generic Mapping Tools (`.gmt`), Keyhole Markup Language (`.kml`), and ASCII text files of point locations, with the exception of islands, which are not provided as an ASCII text file of point locations.

1.2.2 File Description and Directory Structure

The image maps and ancillary files are located in the following directory:

https://daacdata.apps.nsidc.org/pub/DATASETS/nsidc0280_moa2004_v02/

Within this directory, there are three folders, `envi`, `geotiff`, and `coastlines`, and three ancillary files, `Moa0125.gpd`, `Moa0750.gpd`, and `Moa.mpp`. The `envi` folder contains the `.img` and `.img .hdr` files, and the `geotiff` folder contains the `.tif` image map files. The Antarctic coastlines, ice sheet grounding lines, and island files were derived from the MOA2004 surface morphology image and are located in the `coastlines` folder. This folder contains eight format file extensions for each file type, namely: `.shp, .shx, .dbf, .prj, .evf, .gmt, .kml`, and `.txt`. See Table 1 for more information.

1.2.3 Image Maps and Coastlines, Grounding Lines, and Islands Files

Table 1 gives an overview of the directory structure and lists the files and file extensions pertaining to this data set. Table 2 explains the different file types.

Table 1. File and Directory Structure

<table>
<tr><td>/root/</td><td>Moa_v02.0.mpp: Mapx map projection parameters file
Moa0125_v02.0.gpd: Map x grid parameter definition file for 125 m grid
Moa0750_v02.0.gpd: Map x grid parameter definition file for 750 m grid</td><td></td></tr>
<tr><td></td><td>coastlines/</td><td>moa2004_coastline_v02.0.ext
moa2004_grounding_line_v02.0.ext
moa2004_islands_v02.0.ext

Note: .ext denotes the file extension. Each coastlines, grounding lines, and islands file comes in the following eight formats:
<table>
<tr><td>.txt</td><td>ASCII text files containing WGS-84 latitude and longitude values.</td></tr>
<tr><td>.evf</td><td>ENVI Vector Files

Note: Visualizing the *.evf files requires the use of ENVI4.5+.</td></tr>
<tr><td>.gmt</td><td>Generic Mapping Tools Vector files</td></tr>
<tr><td>.kml</td><td>Keyhole Markup Language files</td></tr>
<tr><td>.prj, .shp, .shx, .dbf</td><td>Shapefiles</td></tr>
</table></td></tr>
<tr><td rowspan="2"></td><td rowspan="2">envi/</td><td>For 2003:
moa125_2003_grn_v02.0.img
moa125_2003_grn_v02.0.img.hdr
moa750_2003_xxx_v02.0.img
moa750_2003_xxx_v02.0.img.hdr

Note:
The 125 m .img files for 2003 are only provided as one file type, namely grn.
xxx denotes the file type for the 750 m .img files for 2003 and is one of the following: grn, gct, gsd, gwt.
File types are described in Table 2.</td></tr>
<tr><td>For 2004:</td></tr>
</table>

		moa125_2004_yyy_v02.0.img moa125_2004_yyy_v02.0.img.hdr moa750_2004_zzz_v02.0.img moa750_2004_zzz_v02.0.img.hdr **Note:** yyy denotes the file type for the 125 m .img files for 2004 and is one of the following: grn, hct, hp1, hwt. zzz denotes the file type for the 750 m .img files for 2004 and is one of the following: grn, gct, gsd, gwt, hct, hp1, hwt.
	geotiff/	For 2003: moa125_2003_grn_v02.0.tif moa750_2003_xxx_v02.0.tif **Note:** The 125 m .tif files for 2003 are only provided as one file type, namely grn. xxx denotes the file type for the 750 m .tif files for 2003 and is one of the following: grn, gct, gsd, gwt.
		For 2004: moa125_2004_yyy_v02.0.tif moa750_2004_zzz_v02.0.tif **Note:** yyy denotes the file type for the 125 m .tif files for 2004 and is one of the following: grn, hct, hp1, hwt. zzz denotes the file type for the 750 m .tif files for 2004 and is one of the following: grn, gct, gsd, gwt, hct, hp1, hwt.

Table 2. File Types and Descriptions

File Type	Description
grn	Weighted optical grain size image; 16-bit unsigned-integer little-endian flat binary
hp1	High-pass band 1 surface morphology image; 16-bit unsigned-integer little-endian flat binary
hct	Count of MODIS scenes contributing to each moa125_2004_hp1 grid cell; 8-bit unsigned-integer flat binary
hwt	Average weight applied to computed hp1 values to determine composited moa125_2004_hp1 values; 16-bit unsigned-integer little-endian flat binary; divide by 50000 to get true hwt decimal value.

File Type	Description
gct	Count of MODIS scenes contributing to each moa750_YYYY_grn grid cell; 8-bit unsigned-integer flat binary*
gsd	Standard deviation of unweighted optical grain size values contributing to each valid moa750_YYYY_grn cell; 16-bit unsigned-integer little-endian flat binary; a value of 1 indicates there were fewer than two valid contributing unweighted grain size values; otherwise divide by 10 to get true gsd decimal value.
gwt	Average weight applied to computed grain size values to determine composited moa750_YYYY_grn values; 16-bit unsigned-integer little-endian flat binary; divide by 50000 to get true gwt decimal value.

***Note:** YYYY denotes the 4-digit year of the acquisition period for a given grain size file, where:

- 2003 represents data collected from 01 November 2003 to 17 December 2003 (shortened spring-only season).
- 2004 represents data collected from 20 November 2003 to 29 February 2004 (full spring-summer season).

1.2.4 File Size

The total data volume is approximately 8 GB.

1.3 Spatial Information

1.3.1 Coverage

Southernmost Latitude: 90° S

Northernmost Latitude: 60° S

Westernmost Longitude: 180° W

Easternmost Longitude: 180° E

The mosaic includes all land areas and islands south of 60° S that are larger than a few hundred meters. Land areas north of 60° S and areas of ocean more than a few tens of kilometers from coastlines are masked with zero-fill.

1.3.2 Resolution

The individual MODIS scenes (i.e., the input swath data) from MODIS Bands 1 and 2 have a nominal resolution of 250 m at nadir. To increase the resolution of the final product beyond that of the individual MODIS scenes, MOA uses a data cumulation image stacking scheme. The estimated resolution of the final surface morphology composite ranges between 150 m and 250 m, depending on the number of images that were stacked and how the images were weighted. See Compositing the Image Swaths for more details. The higher-resolution 125 m files were created directly from the 250 m resolution swath data that were gridded to 125 m resolution. The lower-resolution 750 m files were then created by resampling the corresponding 125 m files.

1.3.3 Geolocation

The projection used is the Antarctic Polar Stereographic projection. Table 3 lists the geolocation details relevant to this particular projection.

Table 3. Geolocation Details

Geographic coordinate system	WGS 84
Projected coordinate system	Antarctic Polar Stereographic
Longitude of true origin	0°
Latitude of true origin	71° S
Scale factor at longitude of true origin	1
Datum	WGS 84
Ellipsoid/spheroid	WGS 84
Units	meters
False easting	0°
False northing	0°
EPSG code	3031
PROJ.4 string	+proj=stere +lat_0=-90 +lat_ts=-71 +lon_0=0 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs
Reference	https://epsg.io/3031

1.3.4 Grid Specifications

Table 4 lists the dimensions of the 125 m and 750 m product grids.

Table 4. Grid Details

	125 m grid	**750 m grid**
Grid dimensions (pixels)	x: 48333 y: 41779	x: 8056 y: 6964
Number of rows	48333	8056
Number of columns	41779	6964
Nominal gridded resolution	125 m x 125 m	750 m x 750 m

	125 m grid	750 m grid
Grid rotation	0° (i.e., 0° longitude at the top of the image)	0° (i.e., 0° longitude at the top of the image)
ulxmap – x-axis map coordinate of the center of the upper-left pixel (XLLCORNER for ASCII data)	-3,174,450 m	-3,174,450 m
ulymap – y-axis map coordinate of the center of the upper-left pixel (YLLCORNER for ASCII data)	2,406,325 m	2,406,325 m

Note: The South Pole is not at the center of either of these grids.

1.4 Temporal Information

1.4.1 Coverage

The total acquisition period is 01 November 2003 to 29 February 2004.

However, 260 image swaths were acquired between 20 November 2003 and 29 February 2004 for the full spring-summer season, and used to generate the surface morphology image map and one of the snow grain size image maps for each resolution. 122 image swaths were acquired between 01 November and 17 December 2003 for the shortened spring-only season, and used to generate the other snow grain size image map for each resolution.

Acquisition times were restricted to between 05:30 GMT and 13:30 GMT to ensure that the sun is positioned to the upper right of the projection grid in all scenes across the entire continent. To maintain a roughly uniform solar elevation angle across the composite, images acquired close to the austral summer solstice were selected for the region near the 135° W longitude coastline; for images near the 45° E longitude coastline, the majority of the scenes were acquired from late January through February.

2 DATA ACQUISITION AND PROCESSING

2.1 Background

The ability of Visible and Near-Infrared (VIS-NIR) satellite sensors, notably the Landsat series and the Advanced Very High Resolution Radiometer (AVHRR), to reveal previously unknown features of the Antarctic continent and coastlines was broadly recognized in the 1980s by glaciologists and cartographers. Later, a host of studies demonstrated how careful processing of image radiometry could provide unprecedented information about the structure of the ice sheet surface. Using

AVHRR, early studies revealed large-scale ice flow, sub-ice bedrock structure, and wind-related features in the interior of the ice sheet by portraying in detail the subtle surface morphology at approximately 1 km spatial resolution (Orheim and Lucchitta, 1988; Bindschadler and Vornberger, 1990; Scambos and Bindschadler, 1991; Seko et al., 1993). Subsequently, the U.S. Geological Survey created continent-wide mosaics using AVHRR (USGS 1991; USGS 1996). USGS and other groups then created regional ice feature image maps using Landsat (Ferrigno et al., 1994; Swithinbank et al., 1988).

Recognizing that a red-infrared band combination can provide grain size information, Winther et al. (2001) used the VIS-NIR data from the USGS/Ferrigno AVHRR mosaics to generate an approximate estimation of the total blue ice area for the Antarctic continent. This followed earlier experiments that mapped snow grain size and blue ice extent from space (Bourdelles and Fily, 1993; Orheim and Lucchitta, 1990).

The normalized difference band radiance ratio correlates with the surface grain size because snow reflectivity in the infrared decreases with increasing grain size (Warren, 1982; Fily et al., 1997; Painter and Dozier, 2004). Specifically, this change in reflectivity is caused by absorptive interactions between infrared light and the electronic structure of the ice crystals. Reflectivity changes in the infrared are thus one of the most important characteristics allowing snow grain size to be determined remotely. Reflectivity is also a function of the greater mean absorbing path length within a larger grain, i.e., increased absorption with a larger path length through the crystal structure. However, the optical path within the ice is also a function of grain shape. For example, complex, feathery grains will have a small optical grain size even though individual grains may have a much larger maximum dimension. Moreover, smaller grain sizes have a larger single-scattering component off of the crystal surface. For most albedo or energy balance investigations, optical grain size is the most important parameter, because the fundamental physics of the study concerns ice interacting with light.

2.2 Acquisition

The MOA2004 image maps were composited from MODIS swaths acquired over the 2003/2004 austral summer season. Images were selected from a specific time window (05:30 GMT to 13:30 GMT) to restrict solar illumination to a range of azimuths and to ensure that all scenes are illuminated from the upper right of the image projection; however, exceptions to this time window were made to gather Antarctic island data. Restricting the illumination in this manner results in a more seamless representation of mountains and topography across the continent. Unfortunately, the zone for which local noon is centered within the UTC time range for the Terra and Aqua satellite passes had a limited number of scenes available. The selected range of UTC times for image acquisition implies a broad range of local times across the continent. Over the northern West

Antarctic coastline, the UTC range occurs during local midnight. This means that VIS-NIR images must be acquired around the time of the austral summer solstice to provide an acceptable solar elevation ranging from 3° to 20°. Yet, at the opposite side of Antarctica in Enderby Land, a near-solstice image selection would result in a solar elevation of 35° to 45°. High solar elevation reduces the amount of topographic detail in the MODIS scenes. To moderate this, the chosen images were taken in late summer (late-January through February) for the regions near 45° E, reducing the solar elevation by about 10° in this area.

2.3 Processing

2.3.1 Geolocation and Processing

The scenes used to create the MOA2004 image maps were selected from Collection 4 MODIS/Aqua and MODIS/Terra Calibrated Radiances 5-Min Level-1B Swath 250 m data sets (MYD02QKM and MOD02QKM). Satellite image swaths of MODIS Band 1 and Band 2 Level-1B MYD02QKM and MOD02QKM files were geolocated and resampled onto the projection grid together with illumination and viewing angle data from Collection 4 MODIS Level-1A Geolocation Fields from EOS Aqua (MYD03) and EOS Terra (MOD03) files. This was done using NSIDC's MODIS Swath-to-Grid Toolbox (MS2GT) software which interpolates the 1 km resolution latitude and longitude data from the Level-1A files to 250 m resolution. It then resamples the Level-1B data to the grid using a forward elliptical weighted average (EWA) algorithm (Greene et al., 1986). The geolocation accuracy of the MODIS 250 m pixel centers is approximately 50 m (Wolfe et al., 2002).

Each `moa125_*` file was created directly from 250 m resolution swath data that were gridded to 125 m resolution. The `moa750_YYYY_g*` files were created by resampling the corresponding 125 m file using a nearest neighbor algorithm, and the `moa750_YYYY_h*` files were created by resampling the corresponding 125 m file using a drop-in-the-bucket averaging algorithm.

2.3.2 Destriping of MODIS Image Data

The MS2GT algorithm was modified to remove striping artifacts incurred by the 40-detector whiskbroom scanner and the two mirror sides of the MODIS Band 1 and Band 2 sensor (Haran et al., 2002). These artifacts are a known problem with all Terra and Aqua MODIS Level-1B data at 250 m (MOD02QKM and MOY02QKM data). Inter-detector variations are as large as 1% or 50 Digital Numbers (DN) in the 12-bit MODIS data, contributing to distinct horizontal striping in contrast-enhanced images. This primary striping pattern appears to be caused by poor inter-detector calibration among the 40 detectors that constitute a single scan of the 250 m data. A secondary variation in brightness occurs between successive 40-line scans due to mirror side effects in the double-sided MODIS scan mirror. A third artifact appears as an every-fourth-pixel brightness shift in detectors 28 and 29 (a stitching artifact in appearance). These three artifacts limit the usefulness of MODIS over ice sheet interior images, because they induce brightness variations as large or larger than the shading due to subtle topography. Corrections for these striping, stitching, and mirror-side effects were created by a statistical analysis of each image. To this end, large-region means were used to adjust DN numbers for stitching (relative to the dector 28 and 29 means for all those lines in a scene), mirror side (relating the side ‘a’ and side ‘b’ means for the 40 scanner swaths to the mean), and individual scan lines relative to the 40-scan mean for the entire swath. See Haran et al. (2002) for more details.

To correct the problems caused by other artifacts, investigators conducted a Lambertian solar zenith angle normalization on the swath data for both bands. Telemetry noise and line drops in the MODIS scenes, having the appearance of chads in the projected images, or gaps in the geolocated pixels, were reset to zero and treated as masked cloud areas. Though the mosaic composite is nearly cloud-free, some areas of thin cloud and small fog or cloud patches exist.

Two composite images were created from the geolocated Band 1 and Band 2 images: a high-pass filtered Band 1 image composite, which emphasizes the surface morphology; and a normalized-difference band-ratio image, which provides semi-quantitative information about mean surface grain size over snow and ice surfaces.

2.3.3 Cloud Masking

The geolocated swath images were manually masked to remove clouds, cloud shadows, fog, blowing snow, and heavy surface frost. To do this, the images were compared to the RAMP AMM-1 SAR mosaic image and to initial versions of the MOA composite to identify cloud, fog, and blowing snow areas. Investigators conducted cloud and surface artifact masking using the 750 m images. They then applied the same mask to the 125 m scenes. Some small cloud and fog features at less than 750 m scale were not masked; and in a few persistently cloudy areas, some thin cloud and cloud-shadow contaminated images had to be used to cover the entire continent with multiple scenes.

The mosaic composite is nearly perfectly cloud-cleared. Some areas of thin clouds, cirrus cloud shadows, and fog or low-lying small clouds are present in the northeastern Ronne Ice Shelf, which was persistently cloudy throughout the 2003-2004 austral summer. In numerous areas, there are small patchy clouds at spatial scales of less than 1 km as a result of using a 750 m resolution image for the cloud clearing. More regionally, some areas are partially impacted by blowing snow, particularly in the East Antarctic.

2.3.4 Compositing the Image Swaths

Investigators created two composite images from the geolocated Band 1 and Band 2 images: a high-pass filtered Band 1 image composite, emphasizing the surface morphology; and a normalized-difference band-ratio image that provides quantitative information about mean surface grain size over snow and ice surfaces. The processing and assembly steps of these two composites is discussed separately.

2.3.5 High-Pass Filtered Surface Feature Composite

After cloud masking, the geolocated, destriped Band 1 images were high-pass filtered to reduce non-Lambertian illumination and to reset the mean grayscale range to a common value for compositing. Investigators set the filter size for the images to 511 pixels x 511 pixels, or the ground equivalent of 64 km x 64 km. The mean brightness of these filtered images was set to the same value (the integer 16000) to match gray levels for compositing.

Investigators then applied a weighting scheme to the masked and filtered image swaths, creating a weight image for each gridded image that contains a scalar value for each non-masked pixel in the swaths. Weights for the pixels range from 0 to 50000. The weight was computed as the product of a fractional scan weight, a fractional mask weight, and a scale factor (50000). The scan weight was determined by the proximity to the nadir track, favoring near-nadir areas, and the mask weight by the proximity to an image edge or mask edge to feather the edges of the component images.

wscan, the scan weight image, is computed as follows:

Given:

R = 6371 km; radius of a spherical Earth
A = 725 km; altitude of circular satellite orbit
seze; sensor zenith angle image
seze_max = 66°; maximum sensor zenith angle

Computed:

scan = asin(R / (R + A) * sin(seze)); scan angle image
scan_max = asin(R / (R + A) * sin(seze_max)) = 55.1°; maximum scan angle
cos_scan_max_sq = cos(scan_max) * cos(scan_max)

Then:

wscan = [cos(scan) * cos(scan) - cos_scan_max_sq] / (1 - cos_scan_max_sq)
wmask, the mask weight image, is computed as follows:

Given:

landmask; land mask image
band1; cloud-masked Band 1 image
mask_smooth_width = 43 pixels; boxcar average smoothing width

Computed:

mask = band1;
where band1 > 0,
mask = 1
where landmask = 0,
mask = 0
mask = smooth(mask, mask_smooth_width); IDL function SMOOTH

Then:

wmask = (sqrt(mask) - sqrt(0.5)) / (1 - sqrt(0.5))
weight, the weight image, is then:
weight = wscan * wmask * 50000

The high-pass filtered Band 1 and weight images were then combined using stacking techniques, also called image super-resolution or data cumulation (Scambos et al., 1999), to improve spatial and radiometric detail beyond the 250 m and 12-bit characteristics of single Band 1 and Band 2 MODIS images. This improvement is in part due to reduction of random image noise by averaging and improvement of relative radiometric resolution by combining repeated measurements of the surface in the form of multiple digital images. The additional spatial resolution in the stacked image composite is a result of knowing the pixel center locations to a high precision (50 m), a precision that is smaller than the width of the pixel sample area (250 m).

Images were added to the mosaic with weighting applied according to the following scheme:

Given a set of n high-pass filtered Band 1 images (Bi) and a corresponding set of n weight images (Wi), compute the composited band image (Bc), composited weight image (Wc), and count image (Nc).

Bc, Wc, and Nc are initially all zero, and Ni is set to 1 for each pixel. Then, for each i from 1 to n, where Bi is not zero, and Wi is not zero:

Nc_old = Nc
Nc = Nc_old + Ni
Wc_0 = Nc_old * Wc / Nc
Wc_1 = Ni * Wi / Nc
Wc = Wc_0 + Wc_1
Bc = (Wc_0 * Bc + Wc_1 * Bi) / Wc

A set of n intermediate composites can themselves be composited into a single composite by setting the values of Bi, Wi, and Ni to the corresponding values of Bc, Wc, and Nc for each composite (in this case Ni is not set to 1), and then applying the given algorithm.

The image stacking allows multiple images to contribute to the representation of a single grid cell in the MOA composite. Image count ranges from 1 to 97 with a mean image count of 10.8; 93.3% of the imaged area is made up of six or more contributing images. Areas of low image count are the central West Antarctic ice sheet near the divide, the northeastern Ross Ice Shelf, and the Brunt, Riiser-Larsen, and Fimbul ice shelves. Using the equations and models developed in Scambos et al. (1999), investigators infer that regions with five or more contributing scenes have resolutions of approximately 200 m or more, reaching a best resolution value of approximately 150 m for images composed of 10 scenes or more. The mean weight of the image pixels for the MOA grid cells is 29250, ranging from 93 to 50000. A large region of lower weights (5000 - 9000) is centered on the South Pole, because all images are significantly off-nadir in this area.

In general, image quality is best in regions with high image counts and high composited weight.

2.3.6 Optical Mean Snow Grain Size

Two simple grain-size composite images were generated by applying a normalized difference algorithm to Band 1 and Band 2 of the composite scenes.

(Band1 - Band2)/(Band1 + Band 2)

This ratio takes advantage of the decreasing reflectivity of snow in the infrared range, creating an image that is sensitive to grain-size variations (Warren, 1982; Fily et al., 1997). To maintain a quantitative ratio, these images were not processed beyond geolocation, calibration, and destriping. Calibration is based on the information provided in the MOD02QKM and MYD02QKM files, as applied by the MS2GT software. The image is provided as a 16-bit unsigned-integer image of optical mean snow grain size in µm.

A composite image of optical surface grain size was generated by applying a model-derived lookup table to images of normalized difference MODIS Band 1 (red light; 620 nm - 670 nm) and MODIS Band 2 (near-infrared; 841 nm - 876 nm) radiances and solar zenith angle:

$G_{i,j} = (b1_{i,j} - b2_{i,j}) / (b1_{i,j} + b2_{i,j})$
$S_{i,j} = f(G_{i,j}, Z_{i,j})$

$G_{i,j}$ represents a normalized radiance ratio image, $b1_{i,j}$ and $b2_{i,j}$ are the calibrated band radiance values at grid location (i,j) for the respective MODIS bands, $Z_{i,j}$ is the solar zenith angle image for each MODIS pixel in the scene, $f(G_{i,j}, Z_{i,j})$ is the lookup table, and $S_{i,j}$ is the optical grain radius image. Calibration scale factors are provided in the MOD02QKM and MYDO2QKM data for the Terra and Aqua MODIS sensors, respectively.

Lookup table values for the grain size conversion were derived from runs of the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) software (Ricchiazzi et al., 1998). These lookup tables were then applied to the MODIS scenes to produce a corresponding set of grain size images. The grain size images were then composited together using the same weighting and compositing scheme as that used for the surface morphology image, except that in addition to masked areas, values of 5 µm or 1105 µm were treated as missing data. Values that led to unmodeled grain sizes, that is less than 10 µm or greater than 1100 µm, had the associated grain size value set to marker values of 5 µm and 1105 µm, respectively. Count and weight images for the grain size composites were slightly different from the corresponding surface morphology count and weight images because of these additional missing values. In cases where all images gave out-of-range grain size results, the grid cell value was set to either 5 µm or 1105 µm.

Runs of the SBDART software provided predictions of MODIS Top Of Atmosphere (TOA) Band 1 and Band 2 radiance values for a series of snow grain sizes (10 µm to 1100 µm in 10 µm increments) at a series of solar illumination solar zenith angles from 0° to 89° in 0.1° increments. Investigators provided SBDART with snow optical properties, that is, BRDF spectral reflectance information from a recent snow reflectance model (Painter and Dozier, 2004), and created files (one for every 10 µm of grain size) that used the data to represent the reflecting substrate in the atmospheric radiative transfer model. Investigators held the sensor viewing angle at nadir for all SBDART evaluations. The weighting scheme favoring nadir-viewing conditions was appropriate to reduce off-nadir BRDF effects in the final optical snow grain size composite.

To validate the optical grain size scheme, researchers with the Antarctic Remote Ice Sensing Experiment used a field spectrometer to collect six surface-snow spectral measurements during three locally clear-sky days in October 2003 (Massom et al., 2006). MOA investigators averaged 60 separate spectra of snow (spectral range 0.4 to 2.5 µm), normalized to 40 interspersed spectra of an Etalon calibration target and inverted the data to the optically equivalent grain-size radius using conversions developed by Nolin and Dozier (2000) with 50 µm - 100 µm grain radius uncertainties. The same sites were imaged by six MODIS scenes, five from the Terra platform and one from Aqua. In situ grain size radius ranged from 66 µm, for snow immediately following a storm accumulation, to 170 µm, for wet snow in warmer conditions. Comparing grain sizes predicted by the method used for these images with in situ measurements shows that, in general, the satellite algorithm underestimates grain size by 15 µm to 151 µm.

Validation data for the optical grain size measurement are shown in Table 5. Same-day sites are within 100 m of each other. SGS refers to Snow Grain Size.

Table 5. Validation Measurements of Normalized Difference Radiance Ratio and Optical Snow Grain Size

Site Locations	**In Situ Solar Zenith (°)[2]**	**In Situ Optical Snow Grain Size (μm)**	**Satellite Scene[3]**	**Satellite Solar Zenith (°)[4]**	**Satellite Sensor Zenith (°)[4]**	**Satellite-Sun Rel. Azimuth (°)[4]**	**Satellite NDRR[1]**	**MOA Optical SGS (μm)[4]**	**Corrected Optical SGS (μm)[4]**
04:48 3 Oct. 2003 Snow Site A 64° 36.55′ S, 117° 40.17 E	61.4	106 ± 50	Terra, 00:50 Terra, 02:30	69.2 62.6	30.7 50.6	66.5 109.2	0.264(2) 0.256(2)	87.4 ± 14 36.0 ± 5	85 70
05:26 3 Oct. 2003 Snow Site B 64° 36.55′ S, 117° 40.17 E	61.8	92 ± 50	Terra, 00:50 Terra, 02:30	69.2 62.6	30.7 50.6	66.5 109.2	0.264(2) 0.256(2)	87.4 ± 14 36.0 ± 5	85 70
04:00 7 Oct. 2003 Snow Site A (recent precip.) 64° 33.32′ S, 116° 34.90 E	60.3	66 ± 50	Terra, 00:25 Terra, 02:05	70.8 63.0	51.3 25.1	65.9 110.9	0.243(2) 0.258(3)	15 ± 5 34 ± 12	18.5 55
04:10 7 Oct. 2003 Snow Site B (recent precip.) 64° 33.32′ S, 116° 34.90 E	60.3		Terra, 00:25 Terra, 02:05	70.8 63.0	51.3 25.1	65.9 110.9	0.243(2) 0.258(3)	15 ± 5 34 ± 12	18.5 55

Site Locations	In Situ Solar Zenith (°)[2]	In Situ Optical Snow Grain Size (μm)	Satellite Scene[3]	Satellite Solar Zenith (°)[4]	Satellite Sensor Zenith (°)[4]	Satellite-Sun Rel. Azimuth (°)[4]	Satellite NDRR[1]	MOA Optical SGS (μm)[4]	Corrected Optical SGS (μm)[4]
03:10 20 Oct. 2003 Snow Site A (wet snow) 65° 16.26′ S, 109° 27.78′ E	56.3	170 ± 50	Terra, 01:35 Aqua, 07:10	62.2 61.7	18.4 14.9	66.1 112.3	0.282(4) 0.307(3)	151 ± 30 144 ± 25	160 172
03:20 20 Oct. 2003 Snow Site B (wet snow) 65° 16.26′ S, 109° 27.78′ E	56.3		Terra, 01:35 Aqua, 07:10	62.2 61.7	18.4 14.9	66.1 112.3	0.282(4) 0.307(3)	151 ± 30 144 ± 25	160 172

[1]Normalized Difference Radiance Ratio (NDRR).

[2]All in situ snow spectra-to-grain-size conversions run with 60 degree solar zenith angle.

[3]Acquisition start time for five-minute scene (UTC).

[4]Mean of five near-site pixel values

2.4 Quality, Errors, and Limitations

Wolfe et al. (2002) estimated the accuracy of the Level-1A geolocation data to be 50 m, considerably better than the Level-1B ground-equivalent nadir pixel size of 250 m.

The accuracy and precision of this geolocation was tested using known surface sites, such as South Pole Station, Vostok Station, Siple Dome camp and traverse trail, Megadunes Camp runway, and Dome Concordia camp, and areas of well-mapped coastline such as Ross Island and the northern Antarctic Peninsula. Investigators did not find discrepancies greater than 125 m in the projected location of a fixed object among the 260 scenes or relative to well-mapped coastline positions. Furthermore, identical features in areas where separate images overlap on the grid align to within one grid cell. As such, in areas where the position of mapped coast differs from the MOA image, the investigators believe that the MOA is more accurate relative to, for example, the CIA coastline database or the Antarctic Digital Database.

Discrepancies did not exceed 125 m in the projected location of a fixed object among the 260 scenes or relative to well-mapped coastline positions. Further, overlapped areas of separate images showed identical feature locations on the grid to within one grid cell.

The mean image weight and image count 750 m data products are provided as a means for users to assess image quality in various parts of the MOA. In general, the MOA quality is higher in areas of both high count and high weight.

Three sources of error are described below: geolocation error, surface obscurations, and snow grain size error.

The component MODIS scenes and the final MOA mosaic are geolocated to within an estimated 50 m, considerably less than the satellite image pixel size or the final grid spacing. This estimate was checked by comparisons with coastlines, field camps, mountain peaks, and other mosaics and maps. Coastline and grounding line files are estimated to be accurate, tracking the best estimate of these features, to within 250 m, or two grid cells. The coastline grounding-line interpretation may not be accurate in all areas.

The mosaic composite is almost perfectly cloud-cleared. Some areas of thin clouds, cirrus cloud shadows, and fog or low-lying small clouds are present in the northeastern Ronne Ice Shelf region, which was persistently cloudy throughout the 2003-2004 austral summer. Other known sites where clouds remain are the grounding line near Bailey Ice Stream (79.67° S, 33.1° W), the ice tongue of Jutulstraumen Glacier (70° S, 0° E), and the Mobiloil Inlet and adjacent Solberg Inlet (68.4° S, 66.5° W). In numerous areas, small patchy clouds and shadows, less than approximately 1 km in size, resulted from using the 750 m resolution images for cloud evaluation and masking. In addition, the investigators identified several areas with features that appear to be blowing snow on the scale of hundreds of square kilometers, particularly in East Antarctica over the upper slopes of the ice sheet. Blowing snow appears as low-contrast mottlings of the surface, often arranged in approximately linear bands oriented near the mean katabatic wind direction, as mapped by Parish and Bromwich (1991). Also, widespread, low-contrast artifacts from hoar frost patches can be seen in regions where fog or emerging vapor from the snowpack have formed frost crystals on the surface. In general, the artifacts appear as sharp-edged patches, often with a sawtooth or flame-like outline, that cross-cut undulations or other topography on the ice surface. Images from late spring or early summer were selected where possible to reduce the number of hoar patches, and then averaged over a sufficiently long period of time (frost patches change on a scale of days) to reduce the intensity of these features in the composite image.

Optical snow grain size error is approximately +/- 50 μm, estimated by compariing in situ spectra of varying snow grain sizes with near-simultaneous MODIS images that were processed in the same manner as the MOA grain size composite scenes. However, snow grain size varies greatly over the period of image acquisition for the MOA. As such, large ranges of snow grain sizes were averaged together in some areas, for example, in melting areas or warm but sub-freezing areas that experienced numerous snowfalls followed by snow diagenesis.

2.5 Instrumentation

The MODIS instruments collect 12-bit radiometric data in 36 spectral bands, ranging from 0.4 μm to 14.4 μm in wavelength. Bands 1 and 2 are imaged at a nominal resolution of 250 m at nadir, Bands 3 to 7 are sampled at 500 m, and Bands 8 to 36 are sampled at 1000 m.

The Terra satellite, launched on 18 December 1999, crosses the equator from north to south (descending node) at 10:30 A.M. local time; Aqua, launched on 04 May 2002, crosses from south to north (ascending node) at 1:30 P.M. local time. Both satellites occupy sun-synchronous, near-polar, circular orbits at an altitude of 705 km. The MODIS instruments' ±55° scanning pattern produces a 2330 km cross-track by 10 km along-track swath with nearly complete global coverage every one to two days.

3 SOFTWARE AND TOOLS

GeoTIFF files may be viewed with ESRI ArcGIS, QGIS, or similar Geographical Information System (GIS) software. ENVI vector files may be accessed using the ENVI software.

4 VERSION HISTORY

Version	Release Date	Description of Changes
1.0	14 December 2018	Initial release
2.0	16 February 2021	Data set version 1 retired; NSIDC DAAC designated as data owner/manager.

5 RELATED DATA SETS

MODIS Mosaic of Antarctica 2008-2009 (MOA2009) Image Map

MEaSUREs MODIS Mosaic of Antarctica 2013-2014 (MOA2014) Image Map

Images of Antarctic Ice Shelves

MODIS Data at NSIDC

RAMP AMM-1 SAR Image Mosaic of Antarctica, Version 2

Antarctic 1 km Digital Elevation Model (DEM) from Combined ERS-1 Radar and ICESat Laser Satellite Altimetry

6 RELATED WEBSITES

SCAR Antarctic Digital Database Version 6.0

MODIS Characterization Support Team

MS2GT Software at NSIDC

7 CONTACTS AND ACKNOWLEDGMENTS

Terry Haran

National Snow and Ice Data Center

449 UCB, University of Colorado

Boulder, CO 80309-0449 USA

Jennifer Bohlander

Polar Science Consulting

200 Merry Hill Drive

Cary, NC 27518 USA

Ted Scambos

National Snow and Ice Data Center

449 UCB, University of Colorado

Boulder, CO 80309-0449 USA

Thomas Painter
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Mark Fahnestock
Institute for the Study of Earth, Oceans, and Space
University of New Hampshire
Morse Hall
8 College Road
Durham, NH 03824-3525 USA

8 REFERENCES

Bindschadler, R. A. and P. L. Vornberger. 1990. AVHRR Imagery Reveals Antarctic Ice Dynamics. *EOS* 71(23), 741-742.

Bourdelles, B., and M. Fily. 1993. Snow Grain-size Determination from Landsat Imagery over Terre Adélie, Antarctica. *Annals of Glaciology*17, 86-92.

Greene, N. and P. S. Heckbert. 1986. Creating Raster Omnimax Images from Multiple Perspective Views Using the Elliptical Weighted Average Filter. *IEEE Computer Graphics and Applications* 6(6). 21-27.

Ferrigno, J. G., J. L. Mullins, J. A. Stapleton, R. A. Bindschadler, T. A. Scambos, L. B. Bellisime, J. A. Bowell, and A. V. Acosta. 1994. Landsat TM Image Maps of the Shirase and Siple Coast Ice Streams, West Antarctica. *Annals of Glaciology* 20, 407-412.

Fily, M, B. Bourdelles, J. P. Dedieu, and C. Sergent. 1997. Comparison of In Situ and Landsat Thematic Mapper Derived Snow Grain Characteristics in the Alps. *Remote Sensing of Environment* 59. 452-460.

Haran , T. M., M. A. Fahnestock, and T. A. Scambos. 2002. De-striping of MODIS Optical Bands for Ice Sheet Mapping and Topography. *EOS, Transactions, American Geophysical Union* 88(47). F317.

Massom, R., and 17 others (2006). ARISE (Antarctic Remote Ice Sensing Experiment) in the East 2003: Validation of Satellite-derived Sea-ice Data Products. *Annals of Glaciology*, 44, 288âˆ'296.

Nolin, A. W., and J. Dozier. 2000. A Hyperspectral Method for Remotely Sensing the Grain Size of Snow. *Remote Sensing of Environment*74(2), 207-216.

Orheim, O. and B. Lucchitta. 1988. Numerical Analysis of Landsat Thematic Mapper Images of Antarctica: Surface Temperatures and Physical Properties. *Annals of Glaciology* 11, 109.

Orheim, O., and B. Lucchitta. 1990. Investigating Climate Change by Digital Analysis of Blue Ice Extent on Satellite Images of Antarctica. *Annals of Glaciology* 14, 211-215.

Painter, T., and J. Dozier. 2004. Measurements of the Hemispherical-directional Reflectance of Snow at Fine Spectral and Angular Resolution. *Journal of Geophysical Research* 109, D18115, doi:10.1029/2003JD004458.

Parish, T. R. and D. H. Bromwich. 1991. Continental-scale Simulation of the Antarctic Katabatic Wind Regime. *Journal of Climate* 4(1), 135-146, doi: 10.1175/1520-0442(1991)004<0135:CSSOTA>2.0.CO;2

Ricchiazzi, P., S. Yang, C. Gautier, and D. Sowle. 1998. SBDART: A Research and Teaching Software Tool for Plane-parallel Radiative Transfer in the Earth's Atmosphere. Bulletin of American Meteorological Society 79(10), 2101-2114.

Scambos, T. A., and R. A. Bindschadler. 1991. Feature Map of Ice Streams C, D, and E, West Antarctica. *Antarctic Journal of the United States*26(5), 312-314.

Scambos, T., G. Kvaran, and M. Fahnestock. 1999. Improving AVHRR Resolution through Data Cumulating for Mapping Polar Ice Sheets. *Remote Sensing of Environment* 69. 56-66.

Seko, K., Furukawa, T., Nishio, F., and Watanabe, O. 1993. Undulating Topography on the Antarctic Ice Sheet Revealed by NOAA AVHRR Images. *Annals of Glaciology* 17, 55-62.

Swithinbank, C., K. Brunk, and J. Sievers. 1988. A Glaciological Map of Filchner-Ronne Ice Shelf, Antarctica. *Annals of Glaciology* 11, 150–155.

USGS. 1991. Satellite Image Map of Antarctica, 1:5,000,000. Miscellaneous Map Investigation Series I-2284.

USGS. 1996. Satellite Image Map of Antarctica, 1:5,000,000. Miscellaneous Map Investigation Series I-2560.

Warren, S. 1982. Optical Properties of Snow. *Reviews of Geophysics and Space Physics* 20(1), 67-89.

Winther, Jan-G., M. N. Jespersen and G. E. Liston. 2001. Blue-ice Areas in Antarctica Derived from NOAA AVHRR Satellite Data. *Journal of Glaciology* 47(157), 325–334.

Wolfe, R. E., M. Nishihama, A. J. Fleig, J. A. Kuyper, D. P. Roy, J. C. Storey and F. S. Patt. 2002. Achieving Sub-pixel Geolocation Accuracy in Support of MODIS Land Science. *Remote Sensing of the Environment* 83 (1-2), 31-49.

9 DOCUMENT INFORMATION

9.1 Publication Date

14 December 2018

9.2 Date Last Updated

06 April 2021