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Earth Observing System

MISR

Multi-angle
Imaging
Spectro-
Radiometer

MISR Cloud Motion Vector Product Algorithm Theoretical Basis

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Multi-angle Imaging SpectroRadiometer (MISR)

Cloud Motion Vector Product Algorithm Theoretical Basis

Approval:

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MISR Principal Investigator

The MISR web site should be consulted to determine the latest released version of this document (http://www-misr.jpl.nasa.gov).
Approval signatures are on file with the MISR Project.

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GLOSSARY OF ACRONYMS

A

AGP (Ancillary Geographic Product)
ASDC (Atmospheric Sciences Data Center)
ATB (Algorithm Theoretical Basis)

C

CCD (Charge-Coupled Device)
CF (Climate and Forecast)
CMV (Cloud Motion Vector)
CMVP (Cloud Motion Vector Product)

E

ECI (Earth Centered Intertial)
ECR (Earth Centered Rotational)
EOS (Earth Observing System)

G

GDQI (Geometric Data Quality Indicator)
GOES (Geostationary Operational Environmental Satellite)

I

IFOV (Instantaneous Field of View)

L

L2TC (Level 2 Top-of-Atmosphere/Cloud)
LaRC (Langley Research Center)

M

MISR (Multi-angle Imaging SpectroRadiometer)
MODIS (Moderate Resolution Imaging Spectroradiometer)

N

NetCDF (Network Common Data Form)

P

PCMDI (Program for Climate Model Diagnosis and Intercomparison

PGS (Product Generator System)

S

SOM (Space Oblique Mercator)

W

WGS84 (World Geodetic System of 1984)

1 INTRODUCTION

1.1 PURPOSE

The Multi-angle Imaging SpectroRadiometer (MISR) Cloud Motion Vector Product (CMVP) contains retrievals of cloud motion determined by geometrically triangulating the position and motion of cloud features observed by MISR from multiple perspectives and times during the ~7 minute overpass of the Terra platform over each cloud scene. Estimates of cloud motion, here labeled cloud motion vectors (CMVs), are a valuable proxy observation of the horizontal atmospheric wind field at the retrieved altitude of the cloud. MISR CMVs have been and continue to be operationally produced as part of the publicly available Level 2 Top-of-Atmosphere/Cloud (L2TC) Stereo product, whose record dates from February 2000 to the present. The CMVP provides users a complete global list of the highest quality CMVs extracted from the standard L2TC product, distributed as monthly, seasonal, and annual NetCDF files that are neither gridded nor averaged. The annual files, the largest of these, are a manageable 160MB, facilitating scientific applications requiring CMV information spanning multiple months or years. The parameters encoded within each MISR CMV and recorded by the CMVP are summarized in Table 1. Distributed NetCDF files follow Climate and Forecast (CF) conventions established by the Program for Climate Model Diagnosis and Intercomparison (PCMDI).

The intent of this document is to identify and describe sources of CMVP input data required for parameter retrievals, provide the physical theory and mathematical background underlying parameter derivations, include implementation details, and describe key assumptions and limitations of the adopted approach. This document is used by the MISR Science Data System Team to establish requirements and functionality of the data processing software.

Table 1: CMV Parameters in the Cloud Motion Vector Product

CMV parameters		
Parameter name	**Units**	**Description**
Time	s	Specified as "seconds since 1970-01-01, 00:00:00 UTC"
Latitude	degrees	Latitude of center of 70.4 km SOM grid cell of retrieval
Longitude	degrees	Longitude of center of 70.4 km SOM grid cell of retrieval
CloudMotionEast	ms^{-1}	Apparent eastward motion of cloud features
CloudMotionNorth	ms^{-1}	Apparent northward motion of cloud features
CloudTopAltitude	m	Apparent altitude of cloud features relative to Earth ellipsoid
FwdAftDifferenceCloudMotionEast	ms^{-1}	Difference between redundant forward and aft elements of CMV component in the east-west direction

FwdAftDifferenceCloudMotionNorth	ms^{-1}	Difference between redundant forward and aft elements of CMV component in the north-south direction
FwdAftDifferenceCloudTopAltitude	m	Difference between redundant forward and aft determinations of cloud top altitude
QualityIndicator	-	Integer between 0 and 100 representing retrieval quality as estimated from forward-aft differences
InstrumentHeading	degrees	Earth-relative heading of Terra satellite at retrieval time, which influences retrieval error characteristics (degrees clockwise from North)
Orbit	-	Terra orbit in which retrieval occurred
Year	-	Year in which retrieval occurred (UTC)
DayOfYear	Days	Julian day of year when retrieval occurred (UTC)
HourOfDay	Hours	Hour of the day when retrieval occurred (UTC)
LandNearby	-	Specifies whether there is land in the vicinity of the retrieval (i.e., could terrain have influenced the retrieval)
LegacyQualityFlag	-	Integer between 0 and 4 representing retrieval quality estimated by Level 2 Stereo product

1.2 SCOPE

This document covers the algorithm theoretical basis for the CMVP that will be routinely generated at the Langley Research Center (LaRC) Atmospheric Sciences Data Center (ASDC).

Chapter 1 describes the purpose and scope of the document. Chapter 2 provides a brief overview. The processing concept and algorithm description are presented in Chapter 3. Chapter 4 summarizes assumptions and limitations. Literature references are indicated by a number in italicized square brackets, e.g.,*[1]*.

1.3 MISR DOCUMENTS

Reference to MISR Project Documents is indicated by a number in italicized square brackets as follows, e.g.,*[M-1]*. The MISR web site (http://www-misr.jpl.nasa.gov) should be consulted to determine the latest released version of each of these documents.

[M-1] Experiment Overview, JPL D-13407, Rev. A.

[M-2] Data Product Description, JPL D-11103.

[M-3] Level 1 Georectification and Registration Algorithm Theoretical Basis, JPL D-11532, Rev. D.

[M-4] Level 1 Ancillary Geographic Product Algorithm Theoretical Basis, JPL D-13400, Rev. A.

[M-5] Level 2 Cloud Detection and Classification Algorithm Theoretical Basis, JPL D-11399, Rev. D.

1.4 REVISIONS

This is the original version of the document.

2 EXPERIMENT OVERVIEW

2.1 OBJECTIVES OF MISR CLOUD MOTION VECTOR PRODUCT

The operational MISR L2TC Stereo product is available from February 2000 onward and provides altitude-resolved, cloud motion vectors representing proxy wind observations extending nearly pole to pole on the sunlit side of the Earth *[M-5]*. Unlike CMVs produced by other satellite systems, such as the Geostationary Operational Environmental Satellites (GOES) and the Moderate Resolution Imaging Spectroradiometer (MODIS), MISR's altitude assignments do not rely on knowledge of the temperature structure of the atmosphere, and the retrieved winds are controlled for quality through redundant checking, without reliance on forecast model guidance. The global performance of MISR's CMVs as wind proxies has been evaluated in a number of publications *[2] [3] [4]*. The CMVP is intended to facilitate the greater application of MISR CMV data by the research and operational meteorological communities.

2.2 INSTRUMENT CHARACTERISTICS

The MISR instrument consists of nine pushbroom cameras. It obtains global coverage every nine days, and flies in a 705-km descending polar orbit on the EOS-Terra platform. The cameras are arranged with one camera pointing toward the nadir (designated An), one bank of four cameras pointing in the forward direction (designated Af, Bf, Cf, and Df in order of increasing off-nadir angle), and one bank of four cameras pointing in the aftward direction (using the same convention but designated Aa, Ba, Ca, and Da). Images are acquired with nominal view zenith angles, relative to the Earth surface reference ellipsoid, of 0°, 26.1°, 45.6°, 60.0°, and 70.5° for An, Af/Aa, Bf/Ba, Cf/Ca, and Df/Da, respectively. Each camera uses four Charge-Coupled Device (CCD) line arrays in a single focal plane. The line arrays consist of 1504 photoactive pixels plus 16 light-shielded pixels per array. Each line array is filtered to provide one of four MISR spectral bands. The spectral band shapes are approximately Gaussian and centered at 446, 558, 672, and 866 nm.

MISR contains 36 parallel signal chains corresponding to the four spectral bands in each of the nine cameras. The zonal overlap swath width of the MISR imaging data (that is, the swath seen in common by all nine cameras along a line of constant latitude) is 380 km, which provides global multi-angle coverage of the entire Earth in 9 days at the equator, and 2 days near the poles. The cross-track instantaneous field of view (IFOV) and sample spacing of each pixel is 275 m for all of the off-nadir cameras, and 250 m for the nadir camera. Along-track IFOVs depend on view zenith angle, ranging from 214 m in the nadir to 707 m at the most oblique angle. Sample spacing in the along-track direction is 275 m in all cameras.

Additional background on the instrument design is provided in *[M-1]*.

2.3 MISR CLOUD MOTION VECTOR PRODUCT STRATEGY

The MISR CMVP is designed to provide conveniently organized, readily accessible, high quality retrievals of cloud motion due to advection. The CMVP does not contain any new retrievals of cloud motion, but instead reorganizes the information already available in the MISR L2TC Stereo product. The CMVP notably excludes retrievals from that product whose orbit or retrieval parameters suggest poor quality and whose altitude and speed are unlikely to be associated with true cloud advection, as described below. These exclusions allow CMVP users to more readily employ MISR CMV data as a source of proxy wind observations. They also allow the retrievals to be conveniently packaged and distributed as monthly, seasonal, and annual NetCDF files of manageable size.

A few CMVP parameters are not direct corollaries of parameters contained in the MISR Level 2 Stereo product. They have been included to provide more convenient geolocation and to allow more detailed analysis of cloud motion retrieval error characteristics:

- *Latitude*: the geographic latitude of the retrieval 70.4 km × 70.4 km SOM domain center
- *Longitude*: the geographic longitude of the retrieval 70.4 km × 70.4 km SOM domain center
- *LandNearby*: a Boolean parameter addressing whether the 70.4 km × 70.4 km stereo retrieval domain or its neighbors contain any terrain features
- *InstrumentHeading*: Heading of Terra spacecraft as returned by PGS Toolkit for time of CMV retrieval. Terra heading strongly influences MISR CMV error characteristics, as described in section 2.3.1
- *QualityIndicator*: Scalar indicator of expected CMV quality described in section 3.3.3.

Further details of the CMVP methodology are closely tied to the segmentation of CMVs into along-track and cross-track components as described in section 2.3.1 below.

2.3.1 Along-track motion, cross-track motion and instrument heading

The MISR L2TC Stereo algorithms *[M-5]* derive cloud position and motion from the apparent displacement of features in two pairs of Earth ellipsoid projected images from different cameras captured at different times and viewing zenith angles. Each apparent feature displacement associated with a real cloud is comprised of: (1) a parallax component roughly proportional to cloud altitude that is associated with the difference in view angle between MISR camera observations, and (2) a motion component associated with any movement of the cloud during the intervening time between observations. The parallax component is constrained by pseudo-epipolar geometry that limits its orientation to a curve closely approximated by the projection of MISR's trajectory onto the ellipsoid. Any feature displacement along this trajectory (i.e., *along-track* displacement) is composed of both cloud motion and parallax, whereas any displacement perpendicular to this trajectory (i.e., *cross-track* displacement) is predominately composed of cloud motion. As a result, the cloud motion estimate ultimately reconstructed from feature displacements associated with different camera pairings can be segmented into an along-track and a cross-track component, the latter of which exhibits greater accuracy due to not having to disentangle the contribution of both true motion and parallax. This finding is consistent with multiple studies *[2] [3]* that have found that the northward component of the MISR cloud motion retrieval (loosely associated with along-track) is less accurate than the eastward component (loosely associated with cross-track)[1].

[1] This is further demonstrated in Figure 5.

3 ALGORITHM DESCRIPTION

3.1 PROCESSING OUTLINE

Routine in-flight standard processing at the LaRC ASDC, to generate the MISR CMVP occurs in six stages, is described below.

(1) Reorganize daily L2TC Stereo input into a list of retrievals

(2) Remove retrievals not likely to be associated with true cloud motion

(3) Remove low quality retrievals

(4) Concatenate daily data into monthly CMVP product

(5) Concatenate monthly products into seasonal CMVP product

(6) Concatenate seasonal products into annual CMVP product

Processing flow concepts are shown diagrammatically throughout the document. The convention for the various elements displayed in these diagrams is shown in Figure 1.

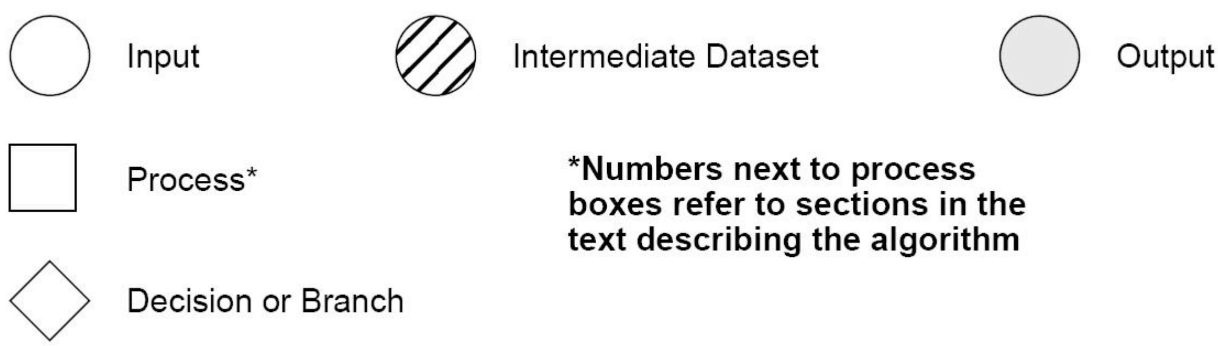

Figure 1. Conventions used in processing flow diagrams

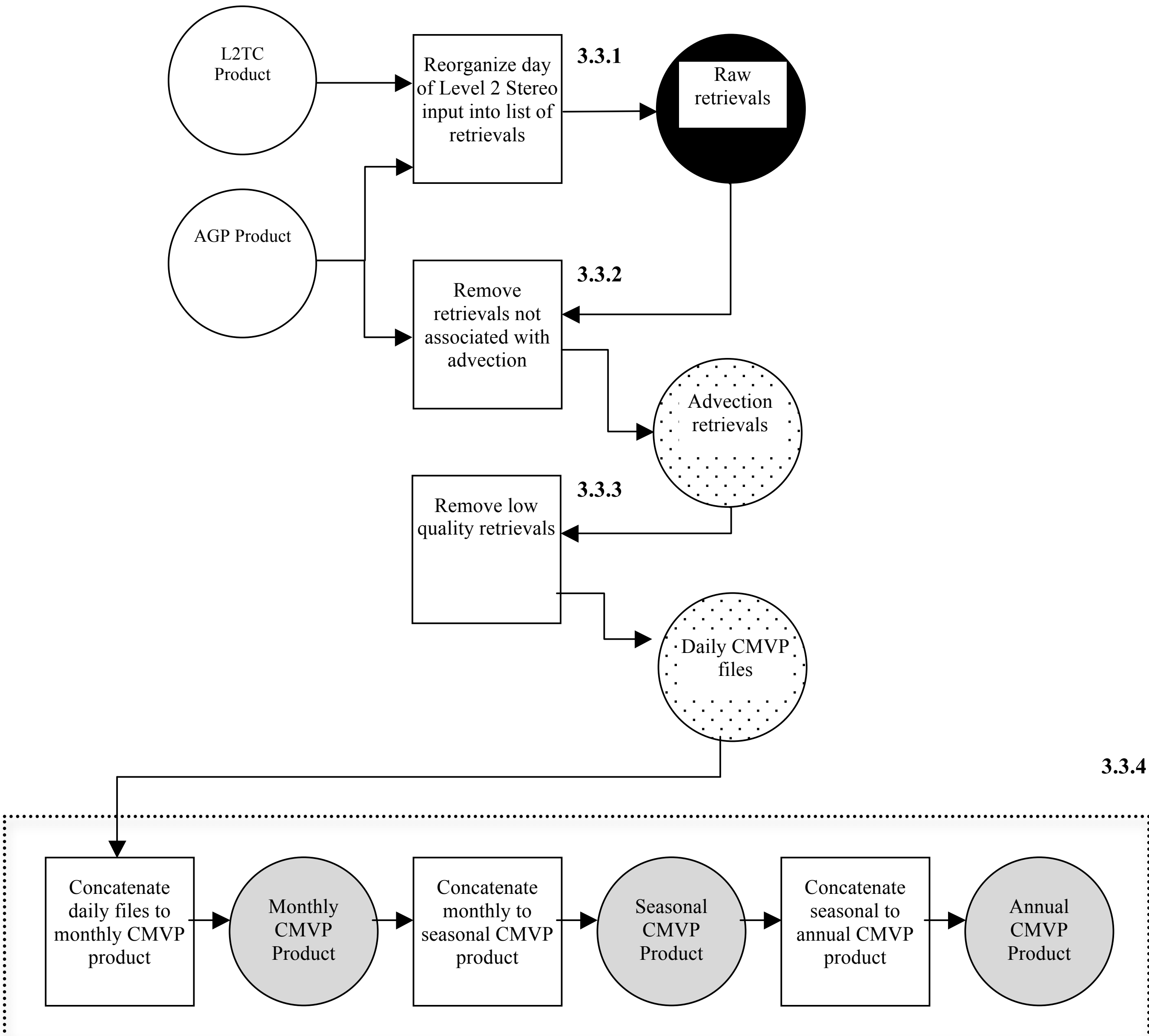

Figure 2. CMVP processing overview

3.2 ALGORITHM INPUT

The required inputs for the CMVP come from MISR and non-MISR sources and are summarized individually in the following paragraphs.

3.2.1 MISR data

Required inputs for the CMVP obtained from other MISR data products are summarized in Table 2. Further information on each of the inputs is provided below.

Table 2: CMVP inputs

Input data	Source of data	Reference
MedianHeightLowCloudBin	L2TC Stereo product	*[M-5]*
EWCloudMotionSpeedLowCloudBin	L2TC Stereo product	*[M-5]*
NSCloudMotionSpeedLowCloudBin	L2TC Stereo product	*[M-5]*
LowCloudBinIdentifier	L2TC Stereo product	*[M-5]*
WindQualityFlagLowCloudBin	L2TC Stereo product	*[M-5]*
MedianHeightHighCloudBin	L2TC Stereo product	*[M-5]*
EWCloudMotionSpeedHighCloudBin	L2TC Stereo product	*[M-5]*
NSCloudMotionSpeedHighCloudBin	L2TC Stereo product	*[M-5]*
HighCloudBinIdentifier	L2TC Stereo product	*[M-5]*
WindQualityFlagHighCloudBin	L2TC Stereo product	*[M-5]*
FwdAft_EWWind_Differences_MostPopBin	L2TC Stereo product	*[M-5]*
FwdAft_NSWind_Differences_MostPopBin	L2TC Stereo product	*[M-5]*
FwdAft_WHeight_Differences_MostPopBin	L2TC Stereo product	*[M-5]*
FwdAft_EWWind_Differences_NextMostPopBin	L2TC Stereo product	*[M-5]*
FwdAft_NSWind_Differences_NextMostPopBin	L2TC Stereo product	*[M-5]*
FwdAft_WHeight_Differences_NextMostPopBin	L2TC Stereo product	*[M-5]*
BlockCenterTime	L2TC Stereo product	*[M-5]*
Orbit_QA	L2TC Stereo product	*[M-5]*
Orbit_qa_winds	L2TC Stereo product	*[M-5]*
SurfaceFeatureID	Level 1 Ancillary Geographic Product	*[M-4]*

Input data	Source of data	Reference
RegAveSceneElev	Level 1 Ancillary Geographic Product	*[M-4]*
StdDevRegSceneElev	Level 1 Ancillary Geographic Product	*[M-4]*

3.2.1.1 TOA/Cloud Stereo inputs

L2TC Stereo inputs are derived for each 70.4 km SOM grid retrieval domain by triangulating the mean altitude and horizontal motion of clusters of identifiable features appearing in L1B2 ellipsoid projected 672 nm (red band) camera images captured at a nominal 275m resolution over a ~7 minute time span. Each parameter is then obtained from the average or difference of redundant determinations operating on the forward camera triplet (An, Bf, and Df) and the aft camera triplet (An, Ba, and Da). Two quirks of the L2TC Stereo retrieval are specifically relevant to CMVP processing. First, the retrieval does not distinguish between identifiable features associated with actual clouds and those potentially associated with terrain. As a consequence, retrievals over clear or partly cloudy scenes, or over scenes with thin clouds over land, generally reflect the position and motion (or lack thereof) of terrain rather than clouds. Second, identifiable features may be incorporated from adjacent domains during the determination of altitude and motion. As a result, the horizontal resolution of retrieval is marginally coarser than the nominal 70.4 km SOM grid sampling.

The *Orbit_QA* input is a flag calculated during MISR L1B2 processing and included within the L2TC Stereo product. Orbits for which the georectification and ellipsoid projection of raw MISR camera measurement have proceeded successfully report an *Orbit_QA* value of 0. Otherwise, the value of *Orbit_QA* is non-zero. See *[M-4]*.

The *Orbit_qa_winds* input is a flag intended to indicate potential georectification issues that may not have been captured by the *Orbit_QA* flag. It is set to a non-zero value when the northward component of the forward-aft differences is small for very few retrievals within the orbit, the absolute value of the mean northward difference is large, or the L1B2 reported geometric data quality indicator (GDQI) is generally poor. See *[M-5]*.

3.2.1.2 Ancillary Geographic Product inputs

Ancillary Geographic Product (AGP) inputs are static SOM gridded fields derived by projecting various map and digital elevation model parameters into SOM coordinate space. The *SurfaceFeatureID* flag categorizes 1.1 km × 1.1 km SOM grid domains into land identifiers, *Land* and *Coastline*, and multiple water identifiers such as *Deep Inland Water*. Surface elevation (*RegAveSceneElev*) and elevation standard deviation (*StdDevRegSceneElev*) relative to the WGS84 Earth ellipsoid are provided by the AGP at 17.6 km × 17.6 km grid resolution.

3.3 THEORETICAL DESCRIPTION:

CMVP processing reorganizes cloud motion vector information contained within per-orbit L2TC Stereo files into daily collections of CMV information (see 3.3.1), removes motion vectors not likely to be associated with advection (see 3.3.2), assigns quality indicator values to each motion vector, and removes low quality vectors (see 3.3.3). Daily datasets are then concatenated into monthly products that are subsequently concatenated into seasonal and annual products (see 3.3.4).

3.3.1 Reorganize a day of Level 2 Stereo input into a list of retrievals

The purpose of this stage is to read, reorganize, and accumulate raw CMVP parameters from the L2TC Stereo input data associated with a given day.

3.3.1.1 Detailed description of the algorithm

CMVP product parameters are determined for each per-orbit L2TC Stereo file and stored as a list of sets of parameter values transferred directly, without modification, from the L2TC Stereo inputs. Each set of parameter values constitutes a single "retrieval," and each day of data consists of a list of retrievals collected from multiple L2TC Stereo files. For orbits spanning a time period crossing a day boundary, only the retrievals whose calculated *Time* parameter is within the specific UTC day are included. No retrieval parameters are stored for orbits having a non-zero *Orbit_QA* or *Orbit_qa_winds* value because such retrievals are known to be of poor quality and unsuitable for scientific use *[2]*. All stored retrievals include their associated orbit number, recorded in the *Orbit* parameter, allowing users to relate the retrievals to the original L2TC Stereo file from which the retrievals were extracted.

Each L2TC Stereo orbit file provides data associated with two CMV retrieval attempts per 70.4 km SOM domain. These two retrievals are independently classified as *Low* and *High* and as *MostPopBin* and *NextMostPopBin.* The CMVP eliminates this arbitrary classification of retrievals, but must internally track whether the *Low* classified retrieval data corresponds with the *MostPopBin* or *NextMostPopBin* retrieval data using the *LowCloudBinIdentifier*. The same step is undertaken for the *High* classified retrieval data using the *HighCloudBinIdentifier*. For each L2TC Stereo 70.4 km SOM domain, two CMVP retrievals are initialized and altitude, eastward, and northward components are recorded from *Low* and *High* L2TC Stereo inputs listed in Table 3. CMVP fwd-aft difference parameters are recorded from the corresponding *MostPopBin* and *NextMostPopBin* L2TC inputs also listed in Table 3.

Table 3: Directly translated L2TC fields

CMV product parameter	L2TC Inputs
CloudMotionEast	EWCloudMotionSpeedLowCloudBin EWCloudMotionSpeedHighCloudBin
CloudMotionNorth	NSCloudMotionSpeedLowCloudBin NSCloudMotionSpeedHighCloudBin

CloudTopAltitude	MedianHeightLowCloudBin MedianHeightHighCloudBin
FwdAftDifferenceCloudMotionEast	FwdAft_EWWind_Differences_MostPopBin FwdAft_EWWind_Differences_NextMostPopBin
FwdAftDifferenceCloudMotionNorth	FwdAft_NSWind_Differences_MostPopBin FwdAft_NSWind_Differences_NextMostPopBin
FwdAftDifferenceCloudTopAltitude	FwdAft_Height_Differences_MostPopBin FwdAft_Height_Differences_NextMostPopBin
LegacyQualityFlag	WindQualityFlagLowCloudBin WindQualityFlagHighCloudBin

The *Time* parameter is derived from the *BlockCenterTime* input provided at block resolution (140.8 km × 563.2 km) within the L2TC Stereo product. Time values at 70.4 km domain centers are linearly interpolated in the SOM x-dimension (along track direction) from *BlockCenterTime* input values, yielding an effective precision of ~15 seconds. The *Year*, *DayOfYear*, and *HourOfDay* are readily determined from *Time*.

The *Latitude* and *Longitude* CMVP parameters are derived from the L2 SOM grid indices provided by the MISR Toolkit.

The *InstrumentHeading* CMVP parameter is determined using the PGS Toolkit call *PGS_EPH_EphemAttit*. Given the CMVP parameter *Time*, this returns the velocity vector for the Terra platform in ECI coordinates. Using CMVP parameters, *Latitude* and *Longitude*, this vector is transformed into geographic coordinates by transformations from ECI to ECR to geographic coordinates, following mathematics detailed in *[M-5]*. The *InstrumentHeading* value (λ) is then a simple function of the eastward (u_{Terra}) and northward (v_{Terra}) velocity vector components:

$$\lambda = 90 - \frac{360}{\pi}\arctan\left(\frac{v_{Terra}}{\left(\sqrt{u_{Terra}^{2} + v_{Terra}^{2}}\right) + u_{Terra}}\right) \qquad (1)$$

The *LandNearby* CMVP parameter is determined from values of the AGP input *SurfaceFeatureID* associated with the L2TC Stereo retrieval domain. *LandNearby* is set to *True* if any *SurfaceFeatureID* pixel at 1.1 km × 1.1 km resolution within the associated 70.4 km × 70.4 km domain or adjacent domains has a value of *Land* or *Coastline*, and is set to *False*, otherwise.

The remaining CMVP parameter, *QualityIndicator*, is described in section 3.3.2.

3.3.2 Remove retrievals that are not associated with cloud advection

The purpose of this stage is to screen retrievals not likely to be associated with actual cloud motion. The L2TC Stereo algorithm reports the position and motion of features discerned within MISR images, but does not differentiate between features associated with terrain or orographic clouds and features associated with advecting clouds. Retrievals of features associated with the former are characterized by near surface altitudes, negligible motion, and no expectation of correlation with the wind field. Thresholds calculated from analysis presented in 3.3.2.2 are applied as described in 3.3.2.1 to identify and remove these retrievals from the CMVP.

3.3.2.1 Mathematics of the problem

This screening of retrievals takes place in a series of steps. First, values of terrain altitude, $h_{terrain}$, and terrain altitude variance, $\sigma_{h,terrain}$, are assigned to each 70.4 km × 70.4 km resolution retrieval using collocated 17.6 km × 17.6 km values of *RegAveSceneElev* and *RegStdDevSceneElev* read from the AGP. These values are later compared with the value of the CMV retrieval altitude, *h*.

$$h_{terrain} = mean\left\{\text{RegAveSceneElev}\right\} \tag{2}$$

$$\sigma_{h,terrain} = \sqrt{\text{mean}\left\{\text{RegAveSceneElev}^2 + \text{RegStdDevSceneElev}^2 - h_{terrain}{}^2\right\}} \tag{3}$$

Next, CMVs and forward-aft differences are translated from eastward and northward components (u, v, u_Δ, and v_Δ) into along-track and cross-track components (at, ct, at_Δ, and ct_Δ) using the *InstrumentHeading* (λ).

$$\begin{aligned} at &= u\sin(\lambda) + v\cos(\lambda) \\ ct &= -u\cos(\lambda) + v\sin(\lambda) \end{aligned} \tag{4a}$$

$$\begin{aligned} at_\Delta &= u_\Delta \sin(\lambda) + v_\Delta \cos(\lambda) \\ ct_\Delta &= -u_\Delta \cos(\lambda) + v_\Delta \sin(\lambda) \end{aligned} \tag{4b}$$

For the next step, several additional variables are employed: the retrieval altitude and forward-aft altitude difference (h and h_Δ), the CMVP parameter *LandNearby*, and three constant thresholds ($H_{THRESHOLD}$= 330 m, $CT_{THRESHOLD}$= 1.0 ms^{-1}, and $AT_{THRESHOLD}$= 4.0 ms^{-1}) whose values are determined as described in section 3.3.2.2.

Retrievals are then labeled as being due to cloud advection if and only if at least one of the following conditions is true: the retrieval altitude is well above the terrain (Eq. 5a), the retrieval has significant cross-track cloud motion (Eq. 5b), or the retrieval is over ocean and has significant along-track motion (Eq. 5c). In each equation, half the forward/aft difference is subtracted prior to applying thresholds so that both the forward and aft contributions to the retrieval must fulfill the above criteria. The third criterion is applied only over ocean, due to the greater frequency of near surface CMVs associated with cloud advection, as opposed to over land, where the overwhelming majority of near surface CMVs appear to be associated with static terrain (see Figure 3).

$$|h| - \left|\frac{1}{2}h_{\Delta}\right| > H_{THRESHOLD} + h_{terrain} + 2\sigma_{h,terrain} \tag{5a}$$

$$|ct| - \frac{1}{2}|ct_{\Delta}| > CT_{THRESHOLD} \tag{5b}$$

$$|at| - \frac{1}{2}|at_{\Delta}| > AT_{THRESHOLD} \tag{5c}$$

Retrievals not meeting these criteria are not labeled as due to cloud advection and are subsequently removed from the CMVP.

3.3.2.2 Determining threshold values for use in screening non-advection retrievals

We seek to successfully identify at least 95% of L2TC Stereo retrievals that are not associated with cloud advection. To determine appropriate thresholds for accomplishing this, a set of retrievals was collected from all valid retrievals in the time span from December 2000 to November 2009 following the methodology of section 3.3.1.1. In order to focus only on the retrievals of at least moderate quality, this set was further screened to include only retrievals with a vector magnitude of forward-aft difference less than 12 ms^{-1}. Additionally, terrain altitudes and terrain altitude standard deviations were assigned to each retrieval as described in section 3.3.2.1.

To determine an appropriate value of threshold $H_{THRESHOLD}$ used in equation 5a, we review the distribution of retrieval altitude minus terrain altitude for retrievals over land and water shown in Figure 3. Over land there is a distinct mode of terrain surface retrievals that is well characterized as a normal distribution centered at 0 m, with standard deviation of ~200 m. The width of this near-surface mode is governed by the mean standard deviation of terrain altitude throughout the 70.4 km square domain, ~100 m, and by the standard deviation of retrieval altitude error. Over water, there is a less pronounced mode of surface retrievals. We assume this mode of retrievals to be spurious, although its source is presently unclear. Because surface altitude and variance are negligible over water, the standard deviation of this mode is governed only by altitude retrieval error, which appears to be ~165 m, consistent with mean fwd/aft differences determined in section 3.3.3.2. We therefore set $H_{THRESHOLD}$= 330 m, or twice the standard deviation of the distribution. By accounting for two standard deviations of uncertainty, this threshold should successfully identify 95% of non-advection retrievals.

To choose an appropriate value for $CT_{THRESHOLD}$ used in equation 5b, we review the distribution of retrieved cross-track motion for retrievals over land shown in Figure 4. There is a distinct mode of static retrievals that is well characterized as a normal distribution centered at 0 ms^{-1} with a standard deviation of 0.6 ms^{-1}. This standard deviation is greater than the value of 0.5 ms^{-1} expected from the standard deviation of fwd/aft difference determined in section 3.3.3.2.

Preferring to err on the side of mislabeling retrievals truly associated with advection as "not advection", we set $CT_{THRESHOLD}$=1.2 ms^{-1}, i.e. twice the greater of the two standard deviation values.

We set $AT_{THRESHOLD}$=4.0 ms^{-1}, i.e. the standard deviation of the difference between forward and aft along-track motion. The along track cloud motion distribution is not distinctly bimodal, requiring a threshold determined by the analysis presented in 3.3.3.2.

Figures 3 and 4 also show the distributions of retrievals labeled "advection" and those labeled "not advection," by the methodology of section 3.3.2.1. The mode of retrievals labeled "not advection" has a Gaussian shape for retrieval height above terrain (over land) and retrieval cross-track motion. The "not advection" retrieval altitude (over water) has a skewed distribution, suggesting a tendency to mislabel (and subsequently remove) a small fraction of low altitude, low speed retrievals of cloud advection over water.

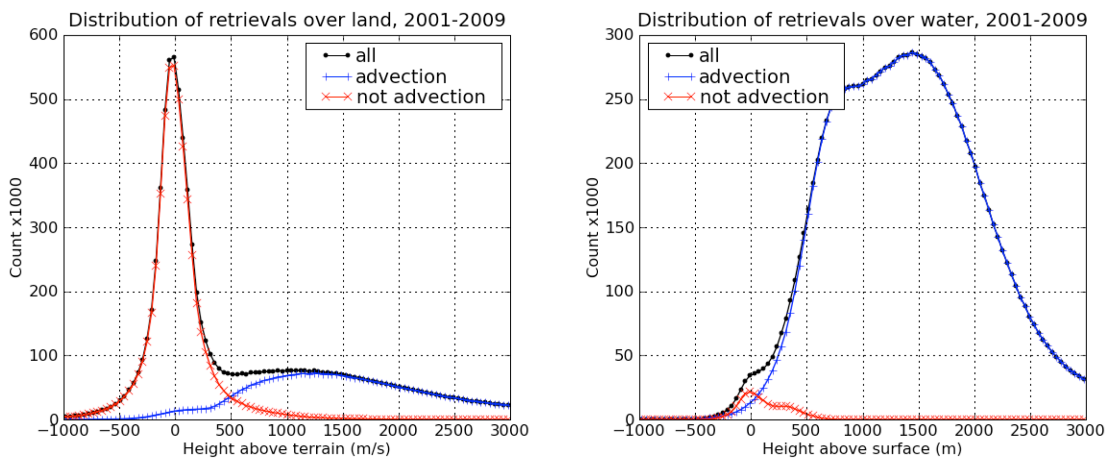

Figure 3. Bimodal retrieval altitude minus terrain altitude distribution

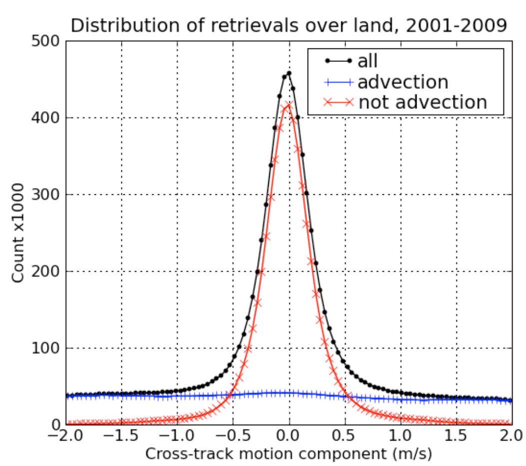

Figure 4. Bimodal retrieval cross-track motion distribution

3.3.3 Assign quality indicator to each retrieval and screen low quality retrievals

The purpose of this stage is to assign a quality indicator to each retrieval and then remove retrievals of low quality. MISR CMV quality control relies on the redundant determination of cloud motion altitude, eastward velocity, and northward velocity retrieved independently from the forward (An, Bf, and Df) and aft (An, Ba, and Da) camera triplets, as detailed in *[M-5]*. Each retrieval in the standard L2TC Stereo product consists of both the average of these forward and aft estimates and their difference. The differences dictate the value of the existing quality flag in L2TC Stereo product, which is retained in the *LegacyQualityFlag* CMVP parameter. Here we introduce a similar, but more refined approach, that grades each retrieval on the maximum number of standard deviations of the cloud altitude, along-track motion, or cross-track motion component differences from (approximately Gaussian) empirical difference distributions presented in section 3.3.3.2. This refinement is introduced to allow users to make more informed decisions regarding the quality of individual MISR CMV retrievals.

3.3.3.1 Mathematical description of the algorithm

For each retrieval, the CMV differences are first translated from eastward and northward components (u_Δ and v_Δ) into along-track and cross-track components (at_Δ and ct_Δ) using the *InstrumentHeading* (λ) as shown in equation 4b.

The final quality indicator (Q) is obtained from the maximum value of these and the cloud altitude differences (h_Δ), following normalization with respect to the respective standard deviations of each component ($\sigma_{at\Delta}$ = 4.0 ms^{-1}, $\sigma_{ct\Delta}$ = 1.0 ms^{-1}, and $\sigma_{h\Delta}$ = 330 m) as calculated in section 3.3.3.2. A hyperbolic tangent function is introduced to produce a more even distribution throughout the range of possible values[2], and the result is factored and discretized to yield a final quality indicator:

$$Q = \mathrm{int}\left(100 \cdot \left(1 - \tanh\left(\max\left\{\frac{at_\Delta}{3\sigma_{at\Delta}}, \frac{ct_\Delta}{3\sigma_{ct\Delta}}, \frac{h_\Delta}{3\sigma_{h\Delta}}\right\}\right)\right)\right) \quad (5)$$

Note that retrievals with one, two, and three standard deviations of maximal difference in forward-aft components correspond to Q values of 67, 41, and 23. Retrievals with a Q value less than $Q_{THRESHOLD}$=23 (more than three standard deviations) are removed. A retrieval with a Q value of 100 would indicate perfect agreement between forward camera and aft camera estimation of cloud position and motion.

3.3.3.2 Determination of forward-aft difference standard deviations

Following the analysis presented in section 3.3.2.2, statistical distributions of forward-aft

[2] An even distribution yields a desirable linear relationship between sampling and Q threshold, as shown in Figure 6.

differences were reviewed for L2TC Stereo retrievals from December 2000 to November 2009, including only cloud advection, and only retrievals whose forward-aft motion difference exists and has vector magnitude less than 12 ms^{-1}. The distribution of forward-aft differences for along-track and cross-track motion (*at* and *ct*), and cloud top altitude (*h*), normalized by the standard deviation of each distribution, is presented in Figure 5.

In order to derive the distribution presented in Figure 5, retrieval components were arranged into k =100 bins of size 0.4 ms^{-1} for *at*, 0.1 ms^{-1} for *ct*, and 25 m for *h*. For each component, the bins were counted to obtain n_i for each bin centered at value x_i. Then the population standard deviation, σ, of each component was calculated as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{k} x_i^2 \cdot n_i}{\sum_{i=1}^{k} n_i}} \tag{6}$$

This yields values of $\sigma_{at\Delta}$ = 4.0 ms^{-1}; $\sigma_{ct\Delta}$ = 1.0 ms^{-1}, and $\sigma_{h\Delta}$ = 330m. These values are then used to produce the final quality indicator as described in section 3.3.3.1.

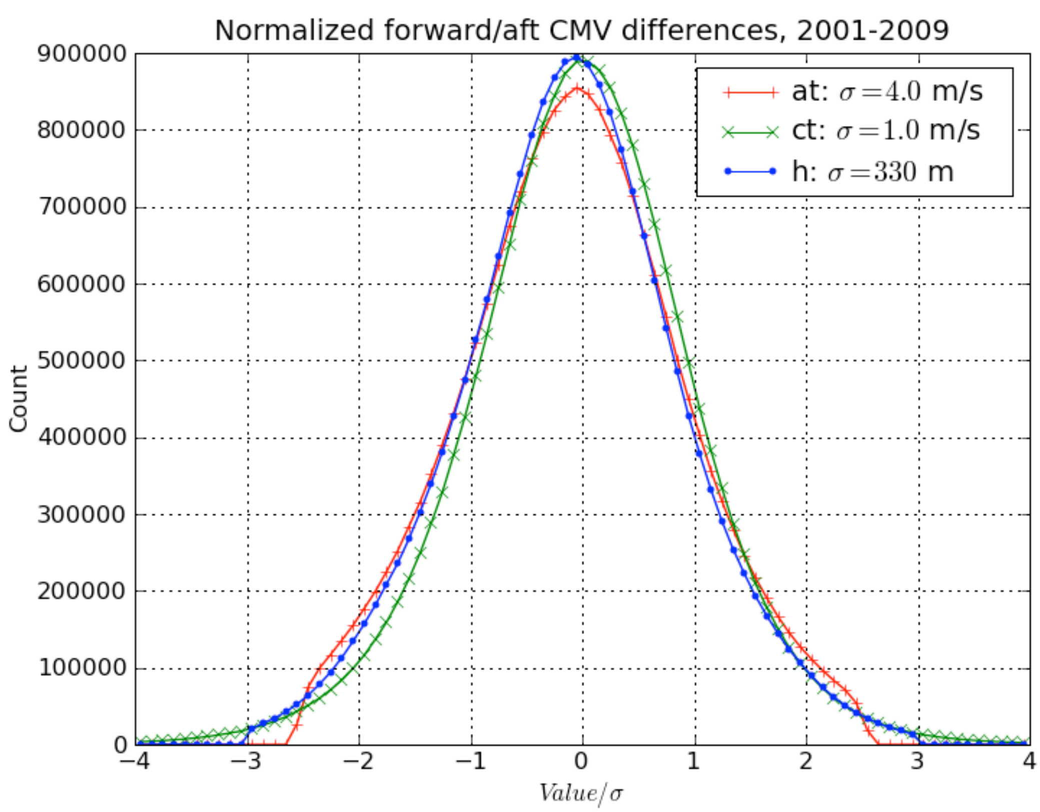

Figure 5. Normalized forward-aft distribution of retrieval components

Table 4 demonstrates the sampling and standard deviation of forward-aft component differences of sets of CMVP retrievals at or above various Quality Indicator threshold values in the time frame from December 2000 to November 2009. Of particular note is the desirable, generally linear relationship between sampling, mean component difference, and Q threshold for quality thresholds in the range from 50-90.

Table 4: Quality indicator threshold versus CMVP sampling

QI threshold	*Sampling x 10^6*	*Altitude std. dev.*	*Along-track motion std. dev.*	*Cross-track motion std. dev.*
23	20.7	328	4.0	1.0
30	20.3	316	3.9	0.9
40	18.6	279	3.5	0.9
50	16.1	238	3.0	0.8
60	12.6	195	2.5	0.6
70	8.4	149	1.9	0.5
80	4.2	102	1.3	0.3
90	1.0	52	0.6	0.2
95	0.2	27	0.3	0.1

3.3.4 Concatenate daily data into monthly, seasonal, and annual CMVP products

Monthly CMVP files contain CMV retrievals for all days within a given month. They are generated by concatenating lists of retrievals obtained for each day in the month into one larger list (in chronological order).

Seasonal CMVP files contain lists of CMV retrievals for three month periods: winter (December of previous year, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, and November). Seasonal CMVP files are generated by concatenating lists from three associated monthly CMVP files, into one larger list (in chronological order).

Annual CMVP files contain lists of cloud motion retrievals for twelve month periods extending from December of the previous year through November of the given year. Annual CMVP files are generated by concatenating lists from four associated seasonal CMVP files, into one larger list (in chronological order).

No averaging of retrievals is performed during this stage.

3.4 ALGORITHM VALIDATION

The AGP and stereo height products used to produce CFBA have been validated. The

evaluation of their performances can be found at http://eosweb.larc.nasa.gov/PRODOCS/misr/Quality_Summaries/misr_qual_stmts.html.
Analysis of cloud motion vectors is presented to a limited extent in sections 3.3.2.2 and 3.3.3.2.

4 ASSUMPTIONS AND LIMITATIONS

4.1 ASSUMPTIONS

The following assumptions are made when deriving CMV retrievals within the CMVP:

(1) Image features appearing to move or exist above the terrain altitude are labeled as clouds, but may represent various phenomena including, for example, optically thick aerosol plumes.

(2) Vertical cloud motions are ignored for the purposes of making wind displacement corrections. This may affect the accuracy of the along-track component of cloud motion estimates in situations where updraft speeds are very large.

(3) Horizontal wind is assumed constant for a given altitude over distances of 70.4 km. This may affect the accuracy of cloud motion estimates where the horizontal wind has significant variance at finer spatial scales.

(4) Standard nomenclature defines the altitude of each cloud motion retrieval as the "top" of the cloud, but retrieval altitude may be lower for optically thin, geometrically thick clouds.

(5) Collocated forward and aft cloud motion retrieval parameter estimates are assumed to constitute effectively independent measurements.

4.2 LIMITATIONS

The following limitations apply to the CMV retrievals within the CMVP:

(1) Despite screening, a number of CMV retrievals may be associated with terrain rather than cloud, yielding a low speed bias near the surface.

(2) Despite screening, a number of CMV retrievals may be associated with orographic clouds whose apparent motion is not due to advection. These cloud motion vectors are unlikely to be representative of the wind field.

(3) Cloud motion due to advection may have a low speed bias relative to wind and may therefore not represent an accurate proxy in certain situations. It is difficult to imagine a situation in which a cloud moves faster than the surrounding air. In contrast, the surrounding air can clearly move faster than the cloud.

(4) Motion associated with true advection of actual clouds, particularly near the surface, may be screened inappropriately, leading to a potential bias in the wind climatology in the opposite sense to (3) above. The relative contributions of these opposing effects have not been quantified.

(5) The position and motion of clouds, having optical depth nominally less than 0.3 or lacking distinguishable texture, may not be detected by the L2TC Stereo algorithm. See *[4]*.

5 REFERENCES

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6 APPENDIX

6.1 Constant thresholds

Table 5: Threshold values

Threshold name	Value	Description
$AT_{THRESHOLD}$	4.0 ms^{-1}	Along-track retrieval speed beyond which retrievals over ocean are unambiguously designated as advection
$CT_{THRESHOLD}$	1.2 ms^{-1}	Cross-track retrieval speed beyond which retrievals are unambiguously designated as advection
$H_{THRESHOLD}$	330m	Altitude above terrain or ocean surface beyond which retrievals are unambiguously designated as advection
$Q_{THRESHOLD}$	23	Minimum quality indicator value for retrievals included in CMVP
$\sigma_{at\Delta}$	4.0 ms^{-1}	Standard deviation of difference between forward and aft along-track cloud motion components
$\sigma_{ct\Delta}$	1.0 ms^{-1}	Standard deviation of difference between forward and aft cross-track cloud motion components
$\sigma_{h\Delta}$	330m	Standard deviation of difference between forward and aft cloud altitude components