CloudSat Project

A NASA Earth System Science Pathfinder Mission

Level 2-C Precipitation Column Algorithm
Product Process Description and Interface Control Document

Version: P2_R04

Internal Version: 002

Date: 24 January 2013

Approvals

________________________________Date_________
John M. Haynes
Data Product Algorithm Lead

________________________________Date_________
Tristan L'Ecuyer
Data Product Algorithm Lead

________________________________Date_________
Deborah Vane
Deputy Project Scientist

________________________________Date_________
Graeme Stephens
Project Scientist

________________________________Date_________
Donald Reinke
Data Processing Center Lead Engineer

Questions concerning the document and proposed changes shall be addressed to:

John M. Haynes
john.haynes@colostate.edu
+1 970 491 8535

Contents

1 Introduction

This document provides an overview of the 2C-PRECIP-COLUMN precipitation algorithm for CloudSat. The objective of the algorithm is to determine the presence of surface precipitation, and quantify the intensity, based on CloudSat Profiling Radar (CPR) observations. At this time only oceanic and inland water scenes are considered. The algorithm makes use of the radar reflectivity near the surface of the earth and an estimate of path integrated attenuation (PIA) determined from the surface reflection characteristics to determine rain occurrence and intensity. The remainder of this document describes the algorithm in greater detail. Section 2 provides an overview of the theoretical basis upon which the algorithm is built. Sections 3 and 4 describe inputs to the algorithm and detail its implementation. The output format for the product is summarized in Section 5, an example shown in Section 6, and instructions for the operator can be found in Section 7.

1.1 What's New: Revision History

Changes in version 2 include:

− AMSR-E based sea ice detection has been replaced with the daily sea ice product from SSM/I as found in the CloudSat CRYOSPHERE-AUX product (see Section 3.2.2). This provides a near-operational, 'bigger picture' of the sea ice coverage surrounding the CloudSat track, and therefore improves the precipitation retrievals. The variable $Surface\_type$ has changed accordingly (see page 10).
− Numerous data gaps in the 2C-PRECIP-COLUMN produced by AMSR-E data outages are now eliminated.
− Various bug fixes.

Changes in version 1 include:

− The precipitation incidence flag is now produced over land, ocean, and sea ice (although quantitative precipitation rate retrievals are only performed over ocean).
− A convective/stratiform flag has been added.
− For profiles that are determined to be convective, a new retrieval pathway is followed that considers supercooled water lofted above the melting level in convective cores.
− The clear-sky surface backscatter calculations have been improved, and a correction is now applied to this quantity by requiring CloudSat-identified cloud layers to be saturated with respect to liquid.
− Some variables have been renamed, in part to discourage their use except as diagnostics. In particular, $Retrieval\_info\_flag$ becomes $Diagnostic\_retrieval\_info$, $Phase\_flag$ becomes $Diagnostic\_retrieval\_type$, and SRT_flag becomes $Diagnostic\_SRT$.
− $Precip\_flag$ is now more clearly separated by precipitation type at the surface. In particular, profiles that may contain frozen precipitation are now segregated as snow or mixed. The snow profiles are highly likely to actually contain be entirely snow at the surface, whereas the mixed profiles may contain (or be) rain.
− The AMSR-E products are no longer passed through 2C-PRECIP-COLUMN. These products are now available in their own AMSR-AUX product.

2 Algorithm Theoretical Basis

2.1 Overview

The basis of the work is outlined in Haynes et al. [3], and all quantitative and mathematical details may be obtained from this source. An overview of the physical basis of the retrieval follows.

The algorithm makes use of path integrated attenuation (PIA) due to hydrometeors as a geophysical measurement. The method depends on the well-behaved relationship between the backscatter cross section of the ocean surface, σ_0, and the wind speed, V at the ocean surface. Higher wind speeds cause greater roughening of the ocean surface, resulting in increased scattering of microwave radiation away from the radar receiver and a lower resulting surface backscatter cross section. The sea surface temperature (SST) of the ocean surface also influences the backscatter cross section through variation of the index of refraction. A database of observations of the surface backscatter cross section under clear-sky conditions, σ_{clr}, provides a background reference for the state of the surface when hydrometeors are absent. When cloud or rain is present, the observed backscatter cross section is reduced by hydrometeor attenuation. This reduction allows calculation of PIA given knowledge of the wind speed at the ocean surface (derived from a numerical model) and, to a lesser extent, the SST [4].

The unattenuated radar reflectivity, Z_u, near the surface is closely related to the presence of rain; the higher Z_u the more likely precipitation is occurring. Z_u is the sum of the measured reflectivity, the PIA, and a component due to gaseous attenuation, G (determined from the ECMWF-AUX temperature and moisture profile). Multiple scattering within the precipitating column can be significant for rainfall exceeding a few millimeter per hour [1], so Monte Carlo modeling is used to simulate the relationship between rainfall and observed PIA for various vertical profiles of precipitation.

New to this version of the algorithm is a convective/stratiform flag. Each rain certain pixel is identified as being convective, stratiform, or shallow based on the vertical structure of reflectivity. The principle that liquid precipitation causes significant attenuation of the W-band radar reflectivity profile is central to the approach. Strong updrafts in convective precipitation lift significant amounts of liquid water above the 0°C freezing level while stratiform precipitation is characterized by primarily frozen hydrometeors above the freezing level, a well-defined melting layer approximately 500 m below the freezing level, and liquid precipitation below that.

Thus convective and stratiform precipitation can be distinguished by examining the height at which attenuation becomes evident in the reflectivity profiles. Convective profiles, like those shown in the top three rows of Figure 1, are characterized by reflectivity profiles that increase with height from the surface to well above the freezing level while stratiform reflectivity profiles (bottom 2 rows of figure) exhibit an inflection point near the freezing level corresponding to the melting layer. In 2C-PRECIP-COLUMN the height of this inflection point is assumed to represent the top of the liquid precipitation in the column. If this height is more than 500 m above the ECMWF 0°C level then the pixel is flagged as convective, otherwise it is identified as being stratiform. In the absence of a reflectivity value of 0 dBZ or greater above the freezing level, the pixel is classified as shallow. 2C-PRECIP-COLUMN reports both the rain type assigned to each pixel as well as the estimated top of the liquid precipitation column.

2.1.1 Stratiform/Shallow Retrieval

For stratiform profiles, a model of the melting layer is incorporated into the Monte Carlo calculations to better represent the transition from snow to rain. This melting layer model aims to treat the attenuating characteristics of melting snowflakes. The model follows snow (modeled through the discrete dipole approximation) falling through a melting layer and melting into rain, assuming a constant lapse rate, Γ_e, of 6 °C km^{-1}.

Liquid or mixed precipitation layers are considered to extend to the height of the lowest continuous cloud layer, H_{CTL}, as determined from the 2B-GEOPROF cloud mask, capped by the height of the freezing level, H_f, from ECMWF-AUX. The effects of purely frozen precipitation on PIA are only considered when a core of 10 dBZ of greater reflectivity extends through the freezing level, H_{sig}. When such a core is absent, melting is considered to start at the freezing level itself. The combination of H_{CTL}, H_f, and H_{sig} allow determination of the total depth of all precipitation, D_{tot}, and liquid precipitation, D_{liq}.

2.1.2 Convective Retrieval

For those cases determined to be convective, in addition to H_f and H_{sig}, the rain top height H_{RT} is also evaulated for the profile. Precipitation is considered completely frozen between H_{RT} and H_{sig}. It is taken to be a mix of frozen precipitation and supercooled water between H_f and H_{RT}, the fractional ice component being a linear function of distance between the two limits. Although this treatment neglects the preferrential growth of ice particles as dictated by the Bergeron-Findeisen process [6], it is likely to be a considerably better approximation than the gradual melting of ice particles considered by the stratiform portion of the retrieval. Precipitation below H_f is taken to be liquid.

2.2 Flow Diagram

A flow diagram showing the precipitation retrieval decision tree is shown in Figure 2.

3 Algorithm Inputs

3.1 CloudSat Level 2 Products

Time and location for each CloudSat pixel are supplied by the CloudSat geometric profile product (2B-GEOPROF). Table 1 summarizes the variables and their properties.

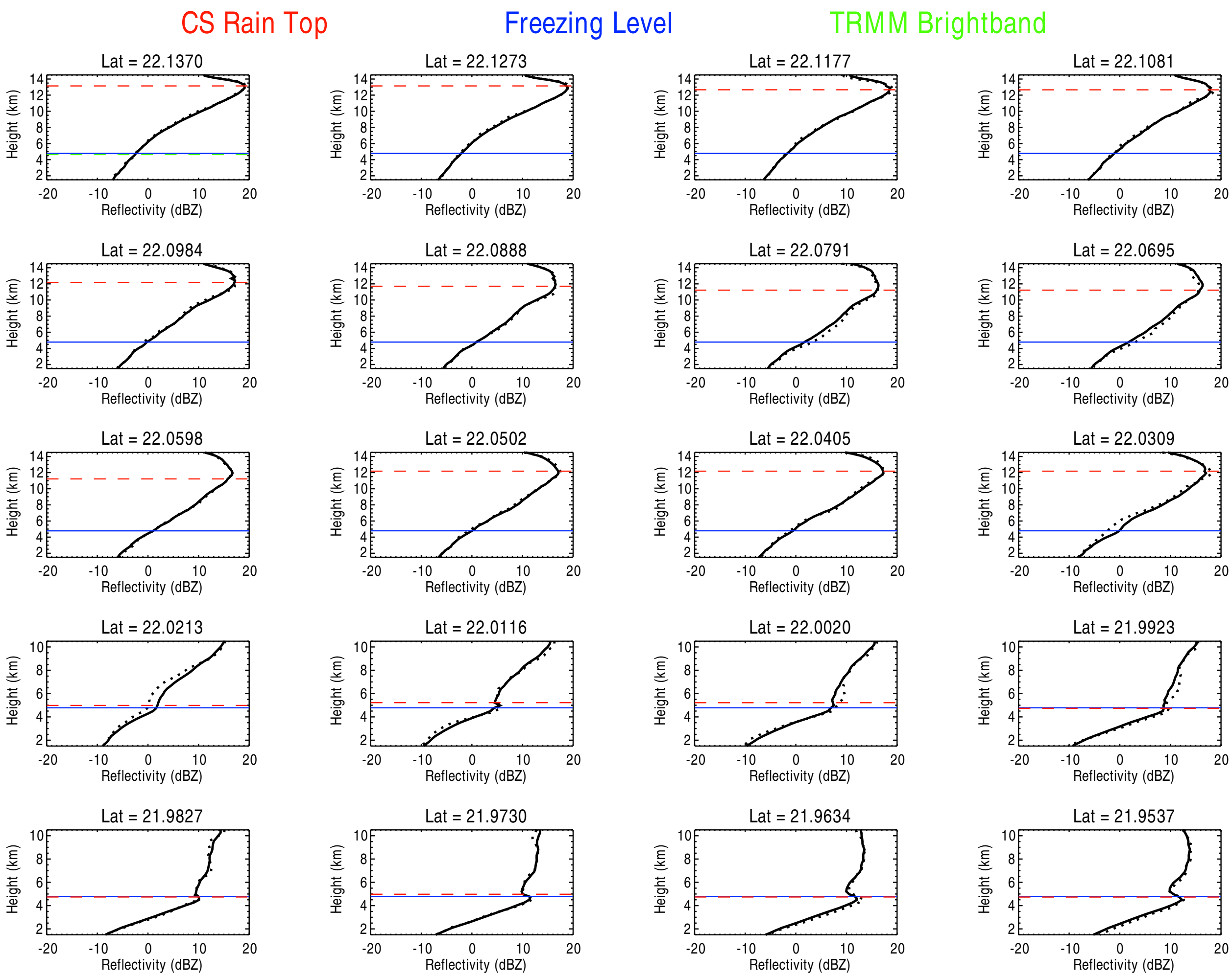

Figure 1: Example profiles demonstrating the convective/stratiform determination. The top three rows are convective profiles, while the bottom three are stratiform profiles. Blue lines indicate the freezing level, red lines the CloudSat rain top, and green lines the height of the TRMM bright band.

3.2 Auxiliary Data Sets

3.2.1 Numerical Model Variables

The current state of the atmosphere, including the atmospheric temperature, pressure, specific himidity, surface wind speed, and sea surface temperature are assessed from the ECMWF forecast model matched to the CPR track. Tables 2 and 3 summarize the variables and their properties.

3.2.2 Sea Ice Variables

The presence of sea ice (and inland lake ice) is determined from the daily sea ice product from SSM/I (Special Sensor Microwave Imager/Sounder) produced by the National Snow and Ice Data Center (Nolin et al. [5]). Table 4 summarizes the variables and their properties.

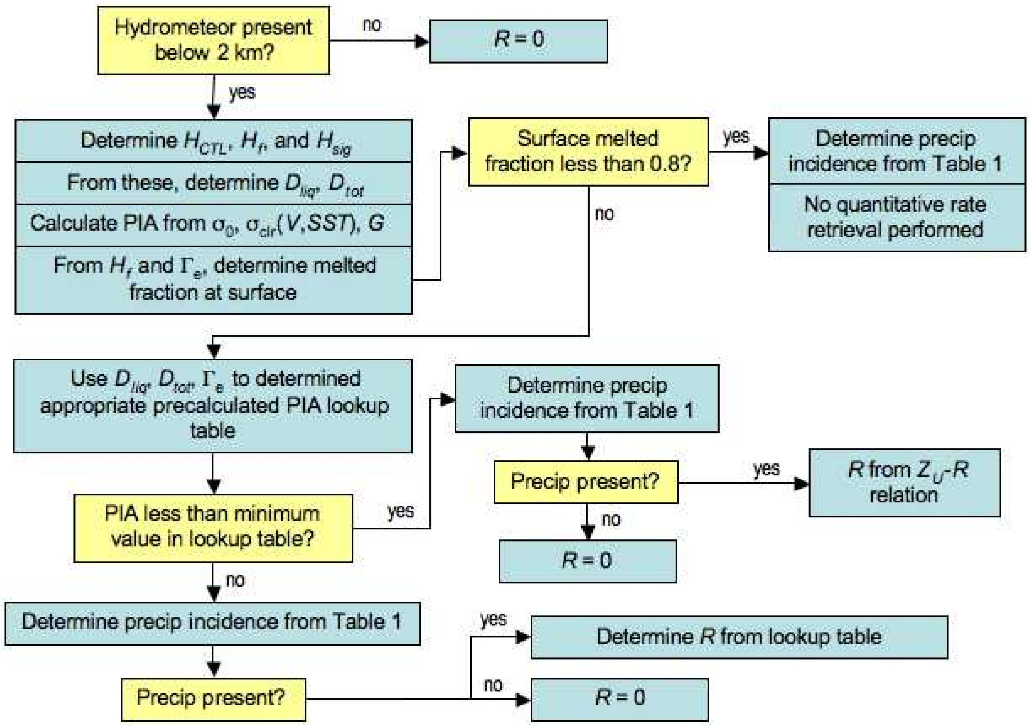

Figure 2: Flow diagram for the precipitation retrieval algorithm.

Table 1: Inputs from 2B-GEOPROF

Variable Name	Dimensions	Range	Units	Description
Per granule:				
TAI_start	scalar	0 - 6×10^8	s	International Atomic Time at granule start
UTC_start	scalar	0 - 86400	s	UTC seconds since 00:00 Z of the first profile
Per profile:				
Profile_time	scalar	0 - 6000	s	elapsed time since *TIA_start*
Latitude	scalar	-90 - +90	deg	Latitude
Longitude	scalar	-180 - +180	deg	Longitude
Height	vector (125)	-5000 - 30000	m	Height of each range bin
SurfaceHeightBin	scalar	1 - 125	-	Bin containing surface
SurfaceHeightBin_fraction	scalar	**	-	Fraction of bin to location of surface
Navigation_land_sea_flag	scalar	1 - 3	-	Surface type characterization
Gaseous_Attenuation	vector (125)	0 - 10	dBZe	Attenuation due to atmospheric gases
Sigma-zero	scalar	-10 - 40	dB	Normalized surface backscatter cross section
CPR_Cloud_mask	vector (125)	0 - 40	-	Cloud mask
Radar_reflectivity	vector (125)	-40 to 50	dBZe	Radar reflectivity

3.3 Ancillary Data Sets

3.3.1 AMSR-E Product Variables

The AMSR-E instrument aboard MODIS flies in formation with CloudSat, passing over the sub-satellite point of the CPR less than one minute before this point is observed by the radar. Although AMSR-E observations are used off-line for calibration of the σ_0 vs. V relationship, they are no longer used directly in the retrieval. Additional precipitation-related

Table 2: Inputs from ECMWF-AUX (per profile)

Variable Name	Dimensions	Range	Units	Description
$Temperature$	vector(125)	**	K	Air temperature
$Pressure$	vector(125)	**	Pa	Pressure
$Specific\_humidity$	vector(125)	**	kg/kg	Specific humidity
EC_height	vector(125)	-5000 - +30000	m	Gridbox height
$Temperature\_2m$	scalar	**	K	Two meter temperature

Table 3: Inputs from ECMWF2-AUX (per profile)

Variable Name	Dimensions	Range	Units	Description
$U10\_velocity$	scalar	**	m s^{-1}	Zonal component of surface wind
$V10\_velocity$	scalar	**	m s^{-1}	Meridional component of surface wind
$Sea\_surface\_temperature$	scalar	**	K	Sea surface temperature

Table 4: Inputs from CRYOSPHERE-AUX (per profile)

Variable Name	Dimensions	Range	Units	Description
$Extent$	vector(49)	**	%	Sea ice concentration

AMSR-E products are no longer passed through 2C-PRECIP-COLUMN, but may be found in the AMSR-AUX product.

3.4 Control and Calibration

At present no calibration of the 2C-PRECIP-COLUMN algorithm is planned. As a result, no ancillary control or calibration data is required. See Section 4.2.2 for details regarding planned validation activities for 2C-PRECIP-COLUMN products.

4 Algorithm Summary

4.1 Pseudo-code

The following provides a pseudo-code description outlining the details of the steps in the algorithm flow diagram in Figure 2:

start 2C-PRECIP-COLUMN

read wind speed / $sigma\_zero$ database

read IGBP surface type database

read multiple scattering apparent attenuation database

open 2B-GEOPROF

open ECMWF-AUX

open ECMWF2-AUX

open CRYOSPHERE-AUX

open 2C-PRECIP-COLUMN output file

for-each profile

  read 2B-GEOPROF variables

read ECMWF-AUX, ECMWF2-AUX variables
read CRYOSPHERE-AUX variables
get surface type from IGBP database, CRYOSPHERE-AUX
perform quality checks
perform stratiform/convective/shallow determination
adjust $sigma\_zero$, determine its reliability
get cloud base, freezing level height, height of 10 dBZ echo, rain top, significant echo height
compute PIA, near-surface PIA, and PIA uncertainty
compute precip incidence from near-surface unattenuated reflectivity
compute rain rate from lookup table (or Z-R relation, if needed)

end-for-each profile

write output variables

close 2C-PRECIP-COLUMN output file

close CRYOSPHERE-AUX

close ECMWF2-AUX

close ECMWF-AUX

close 2B-GEOPROF

stop 2C-PRECIP-COLUMN

4.2 Algorithm Performance

4.2.1 Timing Requirements and Performance

As retrievals are to be performed in real time, the requirement on the computational speed of the algorithm is estimated from the following considerations:

- satellite speed along ground track ∼7 km s^{-1}
- 3.5 km resolution along-track

Using a 2.33 GHz Intel Core 2 Duo processor set, one granule of CPR data (consisting of about 37000 rays) can be processed in approximately 8 to 12 seconds.

4.2.2 Uncertainty Requirements, Performance, and Validation

Validation of the rain incidence algorithm over ocean may be found in work by Ellis et al. [2]. This paper demonstrates that precipitation incidence from 2C-PRECIP-COLUMN is consistent with the ship-based observational climatology at lower-and-mid latitudes. At higher latitudes, 2C-PRECIP-COLUMN detects precipitation more often than other satellite based datasets [4], which may be the result of CloudSat's higher sensitivity to frozen precipitation than existing passive sensors.

Validation activity using the Canadian ground-based radar network, as well as results from the Light Precipitation Validation Experiment (LPVex) is underway.

Table 5: Values for $Precip\_flag$

Value	Meaning
0	No precip detected
9	Uncertain, see $Status\_flag$
Flags indicating surface rain	
1	Rain possible
2	Rain probable
3	Rain certain
Flags indicating surface snow	
4	Snow possible
5	Snow certain
Flags indicating surface mixed precipitation	
6	Mixed precipitation possible
7	Mixed precipitation certain

5 Data Product Output Format

5.1 Data Contents

To reiterate, the 2C-PRECIP-COLUMN algorithm estimates surface precipitation occurrence and intensity along the CPR track. A series of flags indicate the performance and reliability of the retrieval, and the presence of precipitation near the earth's surface.

$Precip\_flag$ (Table 5) indicates the probability precipitation is present in the profile using relative likelihood; these probabilities are segregated by the phase of the surface precipitation.

$Status\_flag$ (Table 6) indicates whether the retrieval contains only precipitation incidence information, or both incidence and intensity information. If an error condition occurred, the reason for the error is also given by this flag.

Table 6: Values for $Status\_flag$

Value	Meaning
0	Both the quantitative precip rate and occurrence retrievals were successful
1	Only the precip occurrence retrieval was successful; no precip rate was retrieved (see $Diagnostic\_retrieval\_info$)
8	No retrieval attempted (land, sea ice, unknown surface)
The following values indicate an error condition occurred:	
12	Reflectivity profile bad
13	Gaseous attenuation missing
14	SST missing
15	Surface wind speed missing
16	Sigma-zero could not be determined
17	Cloud base could not be determined
18	Near-surface reflectivity missing
19	Freezing level could not be determined

$Conv\_strat\_flag$ (Table 7) indicates the whether a precipitation-certain profile is convective, stratiform, or shallow, as described in Section 2.

$Cloud\_flag$ (Table 8) indicates whether it is likely the profile is cloudy based on information from the 2B-GEOPROF cloud mask.

$Surface\_type$ (Table 9) indicates the condition of the Earth's surface. The presence of sea ice (and inland lake ice) is determined from SSM/I (see Section 3.2.2). Since the precipitation algorithm aims to identify non-ice covered water with high confidence, the presence of ice in regions surrounding the CloudSat track can trigger an indication that sea ice or inland ice is possible. Retrievals over inland water (value of 1) should be considered experimental.

$Diagnostic\_retrieval\_info$ (Table 10) provides additional information about the retrieval, such as the reason no

Table 7: Values for $Conv\_strat\_flag$

Value	Meaning
-2	No determination possible due to shallow profile
-1	No determination possible due to bad input data
0	No certain precipitation present
1	Convective precipitation
2	Stratiform precpitation
3	Shallow precipitation

Table 8: Values for $Cloud\_flag$

Value	Meaning
0	No cloud or significant cloud not present
1	Significant cloud present with high certainty
9	Cloud presence unknown
Note: See $Lowest\_sig\_layer\_top$ in Section 5.3 for definition of what constitutes significant cloud.	

Table 9: Values for $Surface\_type$

Value	Meaning
0	Open ocean (no sea ice)
1	Inland water (no ice)
7	Sea ice (or inland ice) possible
8	Land

precipitation intensity retrieval was preformed, and whether the precipitation was intense enough to "saturate" the surface signal (i.e. the maximum retrievable precipitation rate was encountered).

Table 10: Values for $Diagnostic\_retrieval\_info$

Value	Meaning
0	No additional information to report
9	Uncertain, see $Status\_flag$
Reasons no quantitative precip retrieval was performed:	
1	Melted fraction of surface precipitation too small (< 85%)
2	Only snow was present
8	Land, sea ice, or unknown surface
Additional information:	
3	PIA was less than the lowest table value; revert to Z-R relation
50	Precipitation rate ceiling was encountered
51	Multiple solutions were found

$Diagnostic\_retrieval\_type$ (Table 11) describes the route followed in the retrieval pricess as determined by the assumed precipitation phase. It is recommended that users use $Precip\_flag$ to determine surface precipitation type.

$Diagnostic\_SRT$ (Table 12) indicates the reliability of the estimate of $Sigma\_zero$ and $PIA\_hydrometeor$.

All of these 2C-PRECIP-COLUMN data products are summarized in Table 13. The parameter "nz" is the total number of vertical intervals at which data are reported, typically 125, and "nray" is the total number of profiles in the data granule.

Table 11: Values for $Diagnostic\_retrieval\_type$

Value	Meaning
0	No precip detected
1	Rain only
2	Snow only
3	Rain and ice are present; significant stratiform precipitating ice
4	Rain and ice are present; however precipitating ice content is small and neglected in the retrieval process
5	Rain and ice are present; significant convective precipitating ice
6	The pixel is over land, sea ice, or an unknown surface, and the phase is specified exclusively in $Precip\_flag$
9	Uncertain, see $Status\_flag$

Table 12: Values for $Diagnostic\_SRT$

Value	Meaning
0,1	$Sigma\_zero$ and $PIA\_hydrometeor$ are reliable within their estimated uncertainty range
2,3,4	$Sigma\_zero$ is NO MORE than the given value; $PIA\_hydrometeor$ is NO LESS than the given value (within uncertainty)
8	No retrieval attempted (land, sea ice, unknown surface)
9	Uncertain, see $Status\_flag$

5.2 Data Format Overview

In addition to the data specific to the 2C-PRECIP-COLUMN algorithm results, the HDF-EOS data structure may incorporate granule data/metadata (describing the characteristics of the orbit or granule) and supplementary ray data/metadata. The data structure is described in Table 14. Only those data fields specifically required by the 2C-PRECIP-COLUMN algorithm are listed in the table and included in the descriptions in Section 5.3. The entries in the “Size” column of the table represent the array size where appropriate (*e.g.*, nray), the variable type (REAL, INTEGER, CHAR) and the size in bytes of each element (*e.g.*, (4)). The parameter “nray” is the total number of profiles in the granule.

5.3 Data Descriptions

2C-PRECIP-COLUMN data fields:

$Profile\_time$ (SDS, nray*REAL(4))
: Time since TAI_start.

UTC_start (SDS, REAL(8))
: UTC seconds since 00:00 Z of the first profile.

TAI_start (SDS, REAL(8))
: International Atomic Time of first profile in granule (seconds since January 1, 1993).

$Latitude$ (SDS, nray*REAL(4))
: CloudSat latitude.

$Longitude$ (SDS, nray*REAL(4))
: CloudSat longitude.

$DEM\_elevation$ (SDS, nray*REAL(4))
: Elevation of surface above mean sea level.

$Precip\_flag$ (SDS, nray*INTEGER(1))
: Indicates the probability precipitation is present in the profile using relative likelihood; these probabilities are segregated by the phase of the surface precipitation. (Values in Table 5)

$Status\_flag$ (SDS, nray*INTEGER(1))
: Indicates whether the retrieval contains only precipitation incidence information, or both incidence and intensity information. If an error condition occurred, the reason for the error is also given by this flag. (Values in Table 6)

Table 13: Algorithm Outputs (see Section 5.3 for detailed variable descriptions)

Variable Name	Dimensions	Range	Units	Description
$Profile\_time$	nray vector	0 - 6000	s	Elapsed time since TIA_start
UTC_start	scalar	0 - 86400	s	UTC seconds since 00:00 Z of the first profile
TAI_start	scalar	0 - 6×10^8	s	International Atomic Time at granule start
$Latitude$	nray vector	-90 - +90	deg	Latitude
$Longitude$	nray vector	-180 - +180	deg	Longitude
$DEM\_elevation$	nray vector	-9999 - +8850	m	Elevation of surface above mean sea level
$Precip\_flag$	nray vector	0 - 9	-	Precipitation incidence (Table 5)
$Status\_flag$	nray vector	0 - 19	-	Retrieval status (Table 6)
$Conv\_strat\_flag$	nray vector	-2 - +3	-	Convective/stratifom flag (Table 7)
$Precip\_rate$	nray vector	-40 - +40	mm h^{-1}	Surface precipitation rate
$Precip\_rate\_min$	nray vector	0 - 40	mm h^{-1}	Minimum surface precipitation rate
$Precip\_rate\_max$	nray vector	0 - 40	mm h^{-1}	Maximum surface precipitation rate
$Precip\_rate\_no\_ms$	nray vector	0 - 40	mm h^{-1}	Surface precipitation rate without M.S.
$PIA\_hydrometeor$	nray vector	-100 - +100	dB	PIA due to hydrometeors
PIA_near_sfc	nray vector	-100 - +100	dB	PIA to the near-surface bin
$PIA\_uncertainty$	nray vector	0 - 100	dB	PIA uncertainty
$Sigma\_zero$	nray vector	-100 - +100	dB	Surface attenuated backscatter cross section
$Near\_surface\_reflectivity$	nray vector	-100 - +100	dBZe	Attenuated radar reflectivity of the near-surface bin
$Frozen\_precip\_height$	nray vector	0 - 20	km	Maximum height reached by frozen precipitation
$Rain\_top\_height$	nray vector	0 - 18	km	Maximum height reached by liquid precipitation
$Melted\_fraction$	nray vector	0 - 1	-	Mass fraction of liquid water in surface precipitation
$Lowest\_sig\_layer\_top$	nray vector	0 - 20	km	Height of top of lowest significant cloud layer
$Highest\_sig\_layer\_top$	nray vector	0 - 20	km	Height of top of highest significant cloud layer
$Cloud\_flag$	nray vector	0 - 9	-	Cloud mask (Table 8)
$Surface\_type$	nray vector	0 - 8	-	Surface type characterization
$Freezing\_level$	nray vector	0 - 10	km	Height of the freezing level (ECMWF)
SST	nray vector	-100 - +100	deg C	Sea surface temperature (ECMWF)
$Surface\_wind$	nray vector	0 - 200	m s^{-1}	10 m wind speed (ECMWF)
$RLWP$	nray vector	0 - 50000	g m^{-2}	Column-integrated precipitation liquid water content
$CLWP$	nray vector	0 - 50000	g m^{-2}	Column-integrated cloud liquid water content
$Diagnostic\_retrieval\_info$	nray vector	0 - 51	-	Additional info (Table 10)
$Diagnostic\_retrieval\_type$	nray vector	0 - 9	-	Route followed by retrieval process (Table 11)
$Diagnostic\_SRT$	nray vector	0 - 9	-	Surface reliability (Table 12)

$Conv\_strat\_flag$ (SDS, nray*INTEGER(2))

Indicates whether convective, stratiform, or shallow precipitation is present. (Values in Table 7)

$Precip\_rate$ (SDS, nray*REAL(4))

Precipitation rate (mm/h).

If the maximum retrievable precipitation rate is encountered, $Precip\_rate$ is set to a negative number. The absolute value of this number is the minimum precipitation rate for the profile; the actual precipitation rate is probably higher (and may be much higher) but can not be resolved (see discussion of the maximum retrievable precipitation rate [MRP], Haynes et al. [3]). When $Precip\_rate$ is negative, $Diagnostic\_retrieval\_info$ is 50.

$Precip\_rate\_min$ (SDS, nray*REAL(4))

Lower bound on precipitation rate given instrument uncertainty (mm/h).

$Precip\_rate\_max$ (SDS, nray*REAL(4))

Upper bound on precipitation rate given instrument uncertainty (mm/h).

$Precip\_rate\_no\_ms$ (SDS, nray*REAL(4))

Precipitation rate that would be retrieved without considering multiple scattering effects; provided for informa-

Table 14: EOS-HDF File Structure

Structure/Data Name			Size
Swath	GEOFIELDS	$Profile\_time$	nray*REAL(4)
		UTC_start	REAL(4)
		TAI_start	REAL(8)
		$Latitude$	nray*REAL(4)
		$Longitude$	nray*REAL(4)
		$DEM\_elevation$	nray*REAL(4)
	DATAFIELDS	$Precip\_flag$	nray*INTEGER(1)
		$Status\_flag$	nray*INTEGER(1)
		$Conv\_strat\_flag$	nray*INTEGER(2)
		$Precip\_rate$	nray*REAL(4)
		$Precip\_rate\_min$	nray*REAL(4)
		$Precip\_rate\_max$	nray*REAL(4)
		$Precip\_rate\_no\_ms$	nray*REAL(4)
		$PIA\_hydrometeor$	nray*REAL(4)
		PIA_near_sfc	nray*REAL(4)
		$PIA\_uncertainty$	nray*REAL(4)
		$Sigma\_zero$	nray*REAL(4)
		$Near\_surface\_reflectivity$	nray*REAL(4)
		$Frozen\_precip\_height$	nray*REAL(4)
		$Rain\_top\_height$	nray*REAL(4)
		$Melted\_fraction$	nray*REAL(4)
		$Lowest\_sig\_layer\_top$	nray*REAL(4)
		$Highest\_sig\_layer\_top$	nray*REAL(4)
		$Cloud\_flag$	nray*INTEGER(1)
		$Surface\_type$	nray*INTEGER(1)
		$Freezing\_level$	nray*REAL(4)
		SST	nray*REAL(4)
		$Surface\_wind$	nray*REAL(4)
		$RLWP$	nray*REAL(8)
		$CLWP$	nray*REAL(8)
		$Diagnostic\_retrieval\_info$	nray*INTEGER(1)
		$Diagnostic\_retrieval\_type$	nray*INTEGER(1)
		$Diagnostic\_SRT$	nray*INTEGER(1)

tion only, do not use as a physical precipitation rate (mm/h).

$PIA\_hydrometeor$ (SDS, nray*REAL(4))
: Two-way path integrated attenuation due to hydrometeors between the satellite and the surface. See $Diagnostic\_SRT$ for quality information (dB).

$PIA\_near\_surface$ (SDS, nray*REAL(4))
: Two-way path integrated attenuation due to hydrometeors between the satellite and the lowest range bin the CPR can observe (dB).

$PIA\_uncertainty$ (SDS, nray*REAL(4))
: Uncertainty in path integrated attenuation estimate (dB).

$Sigma\_zero$ (SDS, nray*REAL(4))
: Surface attenuated backscatter cross section. See also $Diagnostic\_SRT$.

$Near\_surface\_reflectivity$ (SDS, nray*REAL(4))
: Attenuated reflectivity in the fourth bin (between 600 and 840 m) above the surface.

$Frozen\_precip\_height$ (SDS, nray*REAL(4))
: Estimated maximum height at which frozen precipitation is found in the column (km).

$Rain\_top\_height$ (SDS, nray*REAL(4))
Estimated maximum height at which liquid precipitation is found in the column (km).

$Melted\_fraction$ (SDS, nray*REAL(4))
The total mass fraction of liquid water contained in surface precipitation.

$Lowest\_sig\_layer\_top$ (SDS, nray*REAL(4))
The height of the top of the lowest significant cloud layer (km). A significant cloud layer is defined as one with a 2B-GEOPROF cloud mask of 30 or 40, and a reflectivity (corrected for gaseous attenuation) of at least -15 dBZ. Note that this is not necessarily a physical cloud top; use 2B-GEOPROF or 2B-GEOPROF-LIDAR to determine cloud boundaries.

$Highest\_sig\_layer\_top$ (SDS, nray*REAL(4))
The height of the top of the highest significant cloud layer (km). A significant cloud layer is defined as one with a 2B-GEOPROF cloud mask of 30 or 40, and a reflectivity (corrected for gaseous attenuation) of at least -15 dBZ. Note that this is not necessarily a physical cloud top; use 2B-GEOPROF or 2B-GEOPROF-LIDAR to determine cloud boundaries.

$Cloud\_flag$ (SDS, nray*INTEGER(1))
Indicates whether it is likely the profile is cloudy based on information from the 2B-GEOPROF cloud mask. (Values in Table 8)

$Surface\_type$ (SDS, nray*INTEGER(1))
Indicates the condition of the Earth's surface. (Values in Table 9)

$Freezing\_level$ (SDS, nray*REAL(4))
The height of the freezing level; from ECMWF (km).

SST (SDS, nray*REAL(4))
The sea surface temperature; from ECMWF (°C).

$Surface\_wind$ (SDS, nray*REAL(4))
The surface wind speed; from ECMWF (m/s).

$Diagnostic\_retrieval\_info$ (SDS, nray*INTEGER(1))
Provides additional information about the retrieval, such as the reason no precipitation intensity retrieval was preformed, and whether the precipitation was intense enough to "saturate" the surface signal (i.e. the maximum retrievable precipitation rate was encountered). (Values in Table 10)

$Diagnostic\_retrieval\_type$ (SDS, nray*INTEGER(1))
This flag describes the route followed in the retrieval process as determined by the assumed precipitation phase. It is recommended that users use $Rain\_flag$ to determine surface precipitation type. (Values in Table 11)

$Diagnostic\_SRT$ (SDS, nray*INTEGER(1))
Indicates the reliability of the estimate of $Sigma\_zero$ and $PIA\_hydrometeor$. Retrievals over inland water (value of 1) should be considered experimental. (Values in Table 12)

6 Example

An example of a rain retrieval over a 440 km swath of tropical convection observed by the CPR on 2006 October 20 is shown in Figure 3. The freezing level in this case is near 4.5 km. The middle panel demonstrates that σ_0 is correlated with the strength of the surface reflectivity. In the heavy raining core near profile 36500, for example, σ_0 drops to approximately -20 dB. The calculated PIA to the fourth bin above the surface peaks near 40 dB. Retrieved surface rain rates are shown in the bottom panel, with bars indicating the calculated uncertainties. While rain rates are generally a few mm/h or lighter, in the convective cores the MRP is reached and the upper bound on rain rate can not be determined. The colored dots correspond to varying likelihood that rain is actually occurring at the surface.

7 Operator Instructions

The 2C-PRECIP-COLUMN product processing software is part of the CloudSat Operational and Research Environment (CORE). Standard CORE modules for operating on data files are utilized.

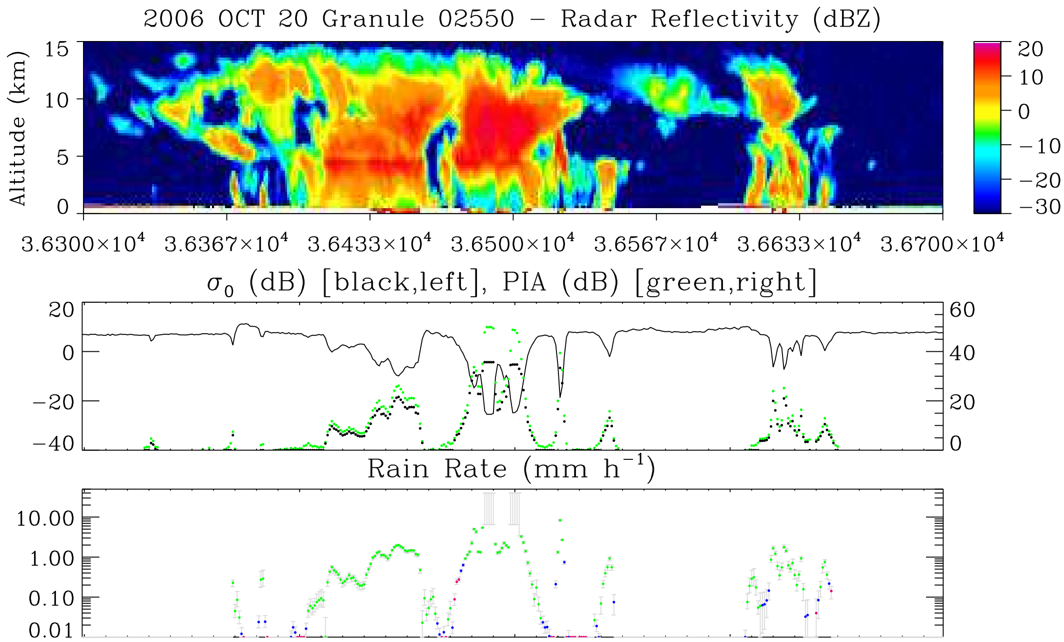

Figure 3: Sample retrieval for granule 2550, profiles 36300 through 36700. Top panel shows radar reflectivity profile. Middle panel shows σ_0 (black line, left scale), PIA to the surface (green dots, right scale) and PIA to the fourth bin above the surface (black dots, right scale). Bottom panel shows retrieved rain rate (colored dots) and uncertainties (bars). Green dots: "rain certain"; blue dots: "rain probable"; red dots: "rain possible."

8 Acronym List

AMSR-E Advanced Microwave Scanning Radiometer for EOS

CORE CloudSat Operational and Research Environment

CPR Cloud Profiling Radar

ECMWF European Centre for Medium-Range Weather Forecasts

EOS Earth Observing System

HDF Hierarchical Data Format

IGBP International Geosphere-Biosphere Programme

MRP Maximum Retrievable Precipitation Rate

PIA Path Integrated Attenuation

SST Sea Surface Temperature

References

[1] Battaglia, A., M. O. Ajewole, and C. Simmer, (2007), Evaluation of radar multiple scattering effects in cloudsat configuration. *Atmos. Chem. Phys.*, *7*, 1719-1730.

[2] Ellis, T. D., T. L'Ecuyer, J. M. Haynes, and G. L. Stephens (2009), How often does it rain over the global oceans? The perspective from CloudSat, *Geophys. Res. Lett.*, *36*, L03815, doi:10.1029/2008GL036728.

[3] Haynes, J. M., T. S. L'Ecuyer, G. L. Stephens, S. D. Miller, C. Mitrescu, N. B. Wood, and S. Tanelli (2009), Rainfall retrieval over the ocean with spaceborne W-band radar, *J. Geophys. Res.*, *114*, D00A22, doi:10.1029/2008JD009973.

[4] Li, L., G. M. Heymsfield, L. Tian, and P. E. Racette (2005), Measurements of ocean surface backscattering using an airborne 94-GHz cloud radar - Implication for calibration of airborne and spaceborne W-Band radars, *J. of Atmos. and Oceanic Technol.*, *22*, 1033-1045.

[5] Nolin, A., R. L. Armstrong, and J. Maslanik (1998), Near-Real-Time SSM/I-SSMIS EASE-Grid Daily Global Ice Concentration and Snow Extent, Version 2, Boulder, Colorado USA: National Snow and Ice Data Center.

[6] Wallace, J. M., and P. V. Hobbs (2006), *Atmospheric science: An introductory survey*, 2nd ed., Elsevier Academic Press, Amsterdam.