Tropical Rainfall Measuring Mission (TRMM)
Precipitation Radar Algorithm

Instruction Manual
For Version 7

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National Aeronautics and Space Administration (NASA)

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0. Introduction

This instruction manual of TRMM PR algorithm is for PR version 7 algorithms and products that were released to the public on July 1st, 2011. They are summarized in Table 0-1.

0-1. TRMM precipitation radar system description

The TRMM precipitation radar (PR) is the first spaceborne rain radar and the only instrument on TRMM that can directly observe vertical distributions of rain. The frequency of TRMM PR is 13.8 GHz. The PR can achieve quantitative rainfall estimation over land as well as ocean. The PR can also provide rain height information which is useful for the radiometer-based rain rate retrieval algorithms. The footprint size of PR is small enough to allow for the study of inhomogeneous rainfall effects upon the comparatively coarse footprints of the low frequency microwave radiometer channels.

Major design and performance parameters of the PR are shown in Table 0-2 [Kozu et al.,2001]. Observation geometry of PR is shown in Fig 0-1. During the normal observation mode, PR antenna beam scans in the cross-track direction over ±17° to results 220 km swath width from end to end. The antenna beam width of the PR is 0.71° and there are 49 observation angle bins within the scanning angle of ±17°. The horizontal resolution (footprint size) is 4.3 km at nadir and about 5 km at the scan edge when TRMM takes the nominal altitude of 350 km. The range resolution of TRMM PR is 250 m which is equal to the vertical resolution at nadir.

The radar echo sampling is performed over the range gates between the sea surface and the altitude of 15 km for each observation angle bin. For nadir incidence, the “mirror image” is also collected up to the altitude of 5 km. In addition, “oversample ” echo data are partially collected for surface return echoes (for scan angle within ±9.94°) and for rain echoes (for scan angles within ±3.55° up to the height of 7.5 km). These oversampled data will be used for precise measurements of surface return echo level and melting layer structure.

The minimum detectable Z (corresponding to the noise-equivalent received power) improved from 23.3 dBZ (based upon the specifications requirement) to 20.8 dBZ as determined from the pre-launch ground test and from the orbit test. This is mainly due to the increased transmit power and the decrease of the receiver noise figure.

Actually the rain echo power is measured from the subtraction of the system noise power from the total receiver power (rain echo power + system noise power). The accuracy of rain echo power can be characterized by the effective signal-to-noise ratio (S/N), that is the ratio of mean to standard deviation of rain echo power.
By considering these facts, the actual minimum detectable Z can be considered to be about 16-18 dBZ after the detailed statistical calculation. The effective signal-to-noise ratio (S/N) of 3 dB is obtained when Z -factor is 17 dBZ.

0-2. TRMM precipitation radar algorithms

The TRMM PR standard algorithms are developed by the TRMM science team. They are classified into Level 1 (1B21, 1C21), Level 2 (2A21, 2A23, 2A25) and Level 3 (3A25, 3A26). Level 1 and Level 2 products are data in the IFOV. Level 3 data give the monthly statistical values of rain parameters mainly in 5° x 5° grid boxes required by the TRMM mission. The characteristics of TRMM PR algorithms are summarized in Table 0-3 where numbers and the names of the algorithms, contact persons, products, and brief descriptions of algorithms are shown. Also the mutual relation of the algorithms are shown in Fig. 0-2.

The algorithm 1B21 produces engineering values of radar received power (signal + noise) and noise levels. It decides whether there exists rain or not in the IFOV. It also estimates the effective storm height from the minimum detectable power value. Algorithm 1C21 gives the radar reflectivity factor, Z, including rain attenuation effects.

The algorithm 2A21 computes the spatial and temporal statistics of the surface scattering coefficient $\sigma0$ over ocean or land when no rain is present in the IFOV. Then, when it rains in the IFOV, it estimates the path attenuation of the surface scattering coefficient $\sigma0$ by rain using no rain surface scattering coefficient $\sigma0$ as a reference [Meneghini, 2000]. The algorithm 2A23 tests whether a bright band exists in rain echoes and determines the bright band height when it exists [Awaka, 1997] .The rain type is classified into the stratiform type, convective type and others by the 2A23. It also detects shallow isolated rain whose height is below the melting level height (zero degree Celsius). The algorithm 2A25 retrieves profiles of the radar reflectivity factor, Z, with rain attenuation correction and rain rate for each radar beam by the combination of Hitschfeld-Bordan and surface reference methods[Iguchi,2000].

As the 13.8 GHz frequency band selected for the TRMM PR is fairly heavily attenuated by rain, the compensation of this rain attenuation becomes the major subject in the rain retrieval algorithms.

Algorithm 3A25 gives the space-time averages of accumulations of 1C21, 2A21, 2A23 and 2A25 products. The most important output products are monthly averaged rain rates over 0.5° x 0.5° and 5° x 5° grid boxes. It also outputs the monthly averaged bright band height over 0.5° x 0.5° and 5° x 5°grid boxes. Algorithm 3A26 gives monthly averaged rain rates over the 5° x 5° grid boxes using the multiple threshold method.

0-3. Altitude change of the satellite and modification of algorithms

The TRMM satellite changed its altitude from 350 km to 402.5 km in August 2001 in order to save the fuel for altitude maintenance. Major impacts of the attitude change (hereafter boost) on the PR are 1) degradation of sensitivity by about 1.2 dB and 2) occurrence of mismatch between transmission and reception angles for one pulse among 32 onboard averaging pulses. The correction algorithm for the latter was added in 1B21 algorithm (please see Chapter 1 for detail). Other than the 1B21, algorithms were not changed according to the altitude change of the satellite.

0-4. PR hardware switch from A-side to B-side

The PR experienced a major anomaly on May 29, 2009, resulting in a loss of data. JAXA and NASA inferred that the FCIF/SCDP (Frequency Converter and IF/System Control Data Processor) units were not working normally. JAXA and NASA successfully switched the FCIF/SCDP units from the original A-side (FCIF/SCDP-A) to the backup B-side (FCIF/SCDP-B) and restarted the PR to resume observation on June 17, 2009. The first granule of the B-side standard products was acquired just after the PR panel temperatures were stabilized on June 19, 2009. A PR B-side Task Force including JAXA carried out internal / external calibrations and carefully investigated the best way to calibrate the PR so as to maintain continuity of PR products between the A-side and B-side.

0-5. References

J. Awaka, T. Iguchi, H, Kumagai and K. Okamoto [1997], “Rain type classification algorithm for TRMM precipitation radar,” Proceedings of the IEEE 1997 International Geoscience and Remote Sensing Symposium, August 3-8, Singapore, pp. 1636-1638.

R. Meneghini, T. Iguchi, T. Kozu, L. Liao, K. Okamoto, J. A. Jones and J. Kwiatkowski [2000], “Use of the surface reference technique for path attenuation estimates from the TRMM precipitation radar,” J. Appl. Meteor., 39, 2053-2070.

K. Okamoto, T. Iguchi, T. Kozu, H. Kumagai, J. Awaka, and R. Meneghini [1998], “Early results from the precipitation radar on the Tropical Rainfall Measuring Mission,” Proc. CLIMPARA’98, April 27-29, Ottawa, pp. 45-52.

T. Iguchi, T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto [2000], Rain-profiling algorithm for the TRMM precipitation radar, J. Appl. Meteor., 39, 2038-2052.

T. Kozu, T. Kawanishi, H. Kuroiwa, M. Kojima, K. Oikawa, H. Kumagai, K. Okamoto, M. Okumura, H. Nakatuka, and K. Nishikawa[2001], “Development of Precipitation Radar Onboard the Tropical Rainfall Measuring Mission (TRMM) Satellite,” Proceedings of the IEEE 2001 trans. Geoscience and Remote Sensing, 39, 102-116.

Table 0-1. Major changes of PR algorithm from version 6 to version 7

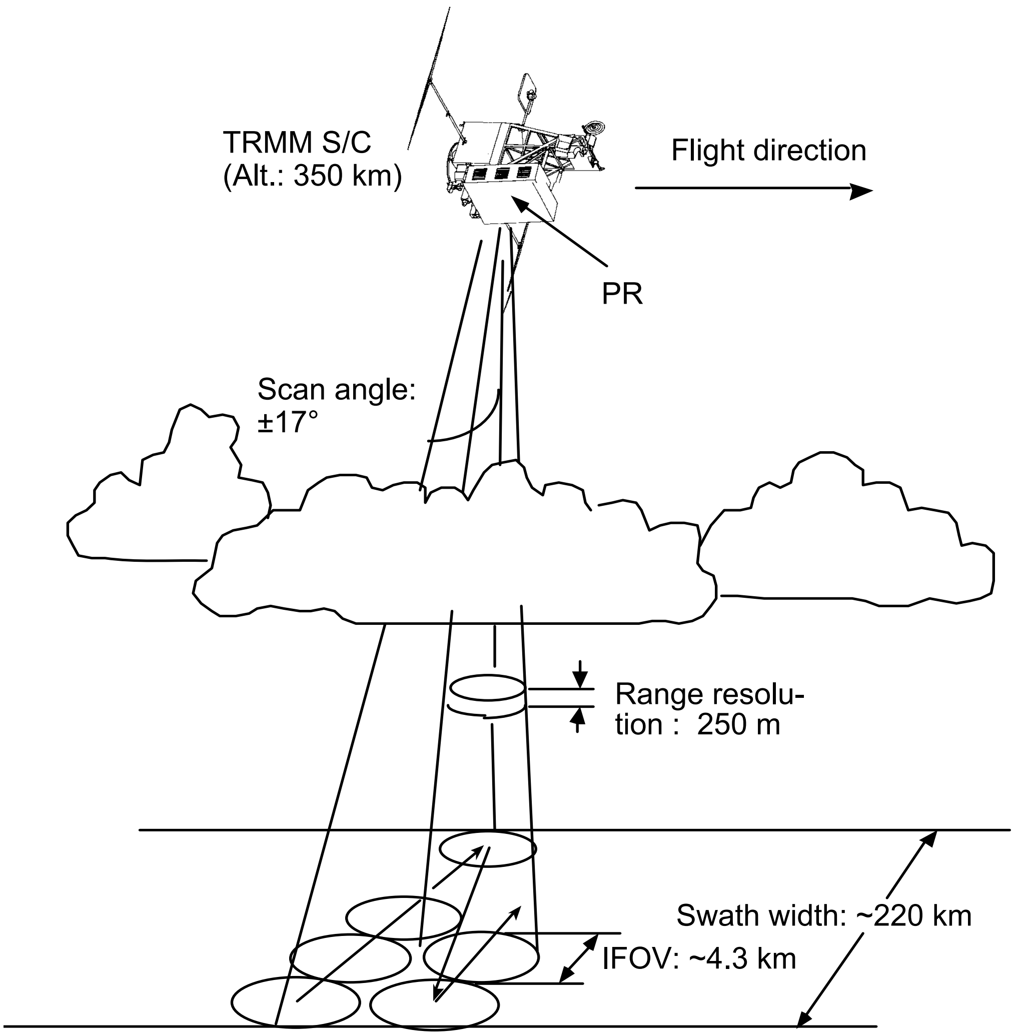
Product No	Major Changes
1B21: PR calibration	a. Improve clutter routine module. b. Improve elevation data with SRTM30 over India, Tibet and South America. c. Change “landOceanFlag” and “scOrientation”. d. Change general data structure using PPS I/O toolkit. e. Modification of calibration coefficients for B-side period.
1C21: PR reflectivities	a. Change general data structure using PPS I/O toolkit.
2A21: Sigma-zero	a. Introduction of 5 types of PIA Temporal reference: increased spatial resolution introduction of the reference data base with 0.1 deg. grid Spatial reference: introduction of backward reference b. Reference curve is determined piecewise in the hybrid method c. Introduction of the concept of distance from the reference point in the spatial reference method d. Introduction of effective PIA (PIA_{eff}) and its error estimate
2A23: PR qualitative	a. Introduced a concept of small rain cell, which is convective. (Effect appreciable.) b. About 40% of shallow non-isolated is classified as convective. (Effect appreciable.) c. GANAL data (Global analysis data by JMA) is used for estimating 0C height. d. When BB is detected, rain type is basically stratiform. But an exception is introduced so that rain type can be convective even when BB is detected, (Very infrequent occurrence.) e. When storm top>15 km and without BB, rain type is convective. (Low frequency of occurrence.) f. Increased rain-type sub-categories.
2A25: PR profile	a. Expected value to maximum likelihood value in estimating α b. Adding 0.5 dB to PIA estimates over land from 2A21 to compensate the wetting effect c. Changed the assumed vertical profile of specific attenuation k (α in $k = \alpha Z_e^{\,b}$) (Changed the vertical profile of the mixing ratio of water to ice) d. Introduction of a new DSD model (Z-R relation) e. Changed the uncertainty of ζ (α and Z_m) in the Hitschfeld-Bordan attenuation correction method f. Introduction of NUBF correction g. Correcting the smearing of BB in off-nadir beams

3A25: Space-time average of PR products	a. New products: Epsilon fit: statistics to characterize the slope of a regression line between zeta and a function of the path-integrated attenuation derived from the SRT - PIA and zeta
3A26: Statistical method	a. Only minor changes

Table 0-2. Major parameters of TRMM PR

Item	Specification
Frequency	13.796, 13.802 GHz
Sensitivity	≤ ≈ 0.7 mm/h (S/N /pulse ≈ 0 dB)
Swath width	220 km (from end to end)
Observable range	Surface to 15 km altitude
Horizontal resolution Vertical resolution	4.3 km (nadir) 0.25 km (nadir)
Antenna	
Type	128-element WG Planar array
Beam width	0.71° x 0.71°
Aperture	2.0 m x 2.0 m
Scan angle	± 17° (Cross track scan)
Transmitter/receiver	
Type	SSPA & LNA (128 channels)
Peak power	≥ 500 W (at antenna input)
Pulse width	1.6 μs x 2 ch. (Transmitted pulse)
PRF	2776 Hz
Dynamic range	≥ 70 dB
Number of indep. samples	64
Data rate	93.2 kbps
Mass	465 kg
Power	250 W

Figure 0-1. Observation concept of the PR.

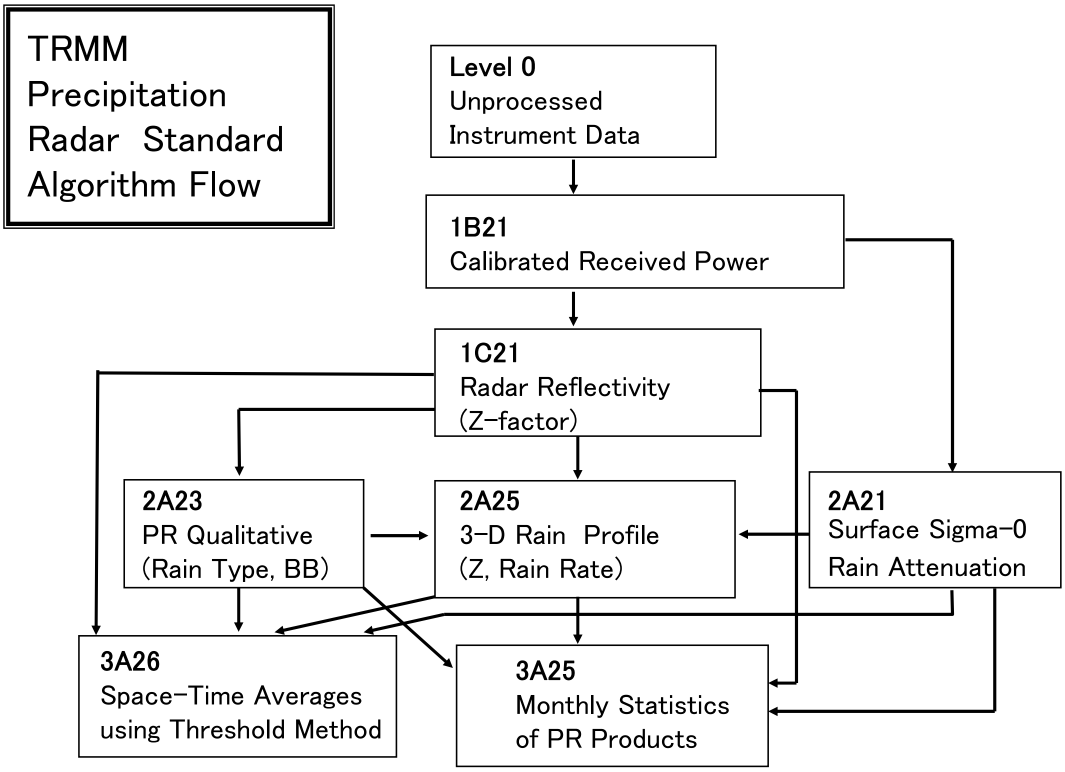


The IFOV is about 5.0 km and the swath width is about 250 km after the boost of the orbit.

Table 0-3. TRMM Standard PR Algorithms

Product No.	Name	Contact Person	Products	Algorithm Description
1B21	PR calibration Rain/No rain	JAXA/EORC (Japan) J. Awaka (Japan) T. Iguchi (Japan)	Total received power, Noise Level Clutter contamination flag.	Conversion of the count value of radar echoes and noise level into engineering value. Decision of rain/no rain. Determination of effective storm height from minimum detectable power value. Rejection of mainlobe and sidelobe clutter.
1C21	PR reflectivities	JAXA/EORC (Japan)	Profiled Z_m (radar reflectivity factors without rain attenuation correction).	Conversion of the power and noise value to radar reflectivity factors Z_m without rain attenuation correction.
2A21	Surface scattering coefficient σ^0	R. Meneghini (USA)	Path integrated attenuation (PIA) of σ^0 (in case of rain) and its reliability. Data base of σ^0 (ocean/ land, in case of no rain)	Estimation of path integrated attenuation and its reliability using the surface as a reference target. Spatial and temporal statistics of surface σ^0 and classification of σ^0 into land/ocean, rain/no rain.
2A23	PR qualitative	J. Awaka (Japan)	Detection of bright band, Bright band height, strength, width, Rain type classification, Detection of shallow isolated rain. Output of rain/no rain flag, height of storm top.	Whether a bright band exists in rain echoes or not, and determination of bright band height when it exists. The rain type is classified into stratiform type, convective type or others. Shallow isolated rain, the height of which is below the 0 deg., is detected.
2A25	PR profile	T. Iguchi (Japan)	Range profiles of attenuation-corrected radar reflectivity factors, rainfall rate. Estimated near surface, and surface rainfall rates, and average rainfall rates between the two predefined altitude (2,4 km).	The rainfall rate estimate is given at each resolution cell. This algorithm employs a hybrid method of the surface reference method and the Hitschfeld-Bordan method. Precipitation water content at 5 altitudes, and vertically integrated precipitation water content are also calculated.
3A25	Space-time average of radar products	R. Meneghini (USA)	Space-time averages of accumulations of 1C21, 2A21, 2A23, 2A25.	Calculation of various statistics over a month from the level 2 PR output products. Four types of statistics are calculated. 1. probabilities of occurrence, 2. means and standard deviations, 3. histograms, 4. correlation coefficients.
3A26	Estimation of space-time rain rate statistics	R. Meneghini (USA)	Rain rate statistics over 5 degree x 5 degree 1 month space-time regions using a multiple thresholding technique.	Estimated values of the probability distribution function of the space-time rain rate at 4 levels, and the mean, standard deviation, and so on.

Figure 0-2. TRMM Precipitation Radar Algorithm Flow.



1. Level 1

1-1. 1B21: PR received power

1-1. 1. Algorithm Overview

The 1B21 calculates the received power at the PR receiver input point from the Level-0 count value which is linearly proportional to the logarithm of the PR receiver output power in most received power levels.
To convert the count value to the input power of the receiver, internal calibration data is used. The relationship between the count value and the input power is determined by the system model and the temperature in the PR. This relationship is periodically measured using an internal calibration loop for the IF unit and the later receiver stages. To make an absolute calibration, an Active Radar Calibrator (ARC) is placed at Kansai Branch of NICT and the overall system gain of the PR is being measured nearly every 3-6 months. Based on the data from the internal and external calibrations, the PR received power is obtained. Note that the calculation assumes that the signal follows the Rayleigh fading, so if the fading characteristics of a scatter are different, a small bias error may occur (within 1 or 2 dB).

Other ancillary data in 1B21 include:

- Locations of Earth surface and surface clutter (range bin number).
  Those are useful to identify whether the echo is rain or surface.
- System noise level: Four range bins data per angle bin.
  This is the reference noise floor which is used to extract echo power from the "total" received power in 1B21 (echo + noise).
- Oversample data: In order to improve the accuracy of surface echo measurement, and to obtain a better vertical rain profile, 125-m intervals data are available at near-nadir angle bins for rain-oversample (up to 7.5 km) and ±10 deg. scan angles for surface-oversample.
- Minimum echo flag: A measure of the existence of rain within a beam.
  There are multiple confidence levels and users may select up to what confidence level they treat as rain.
- Bin storm height: The maximum height at which an echo exists for a specific angle bin.
- Land/ocean flag and Topographic height

1-1. 2. File Format

The main output of the Tropical Rainfall Measurement Mission (TRMM) /Precipitation Radar (PR) Level-1B product, 1B21 is “PR received power.”

The PR1B21 product is written in Hierarchical Data Format 4 (HDF4).
HDF was developed by the U.S. National Center for Supercomputing Applications (NCSA). HDF manuals and software tools are available via homepage at http://www.hdfgroup.org/products/hdf4/

1-1. 3. Structure of output variables

The PR Level-1B product, 1B21, "PR Power," is written as a Swath Structure. The following sections describe the structure and contents of the format.

Dimension definitions:
nscan: Number of scans in the granule.
nray (= 49): Number of angle bins in each scan.

Figure 1-1-1 through Figure 1-1-8 show the structure of this algorithm. The text below describes the contents of objects in the structure, the C Structure Header File and the Fortran Structure Header File.

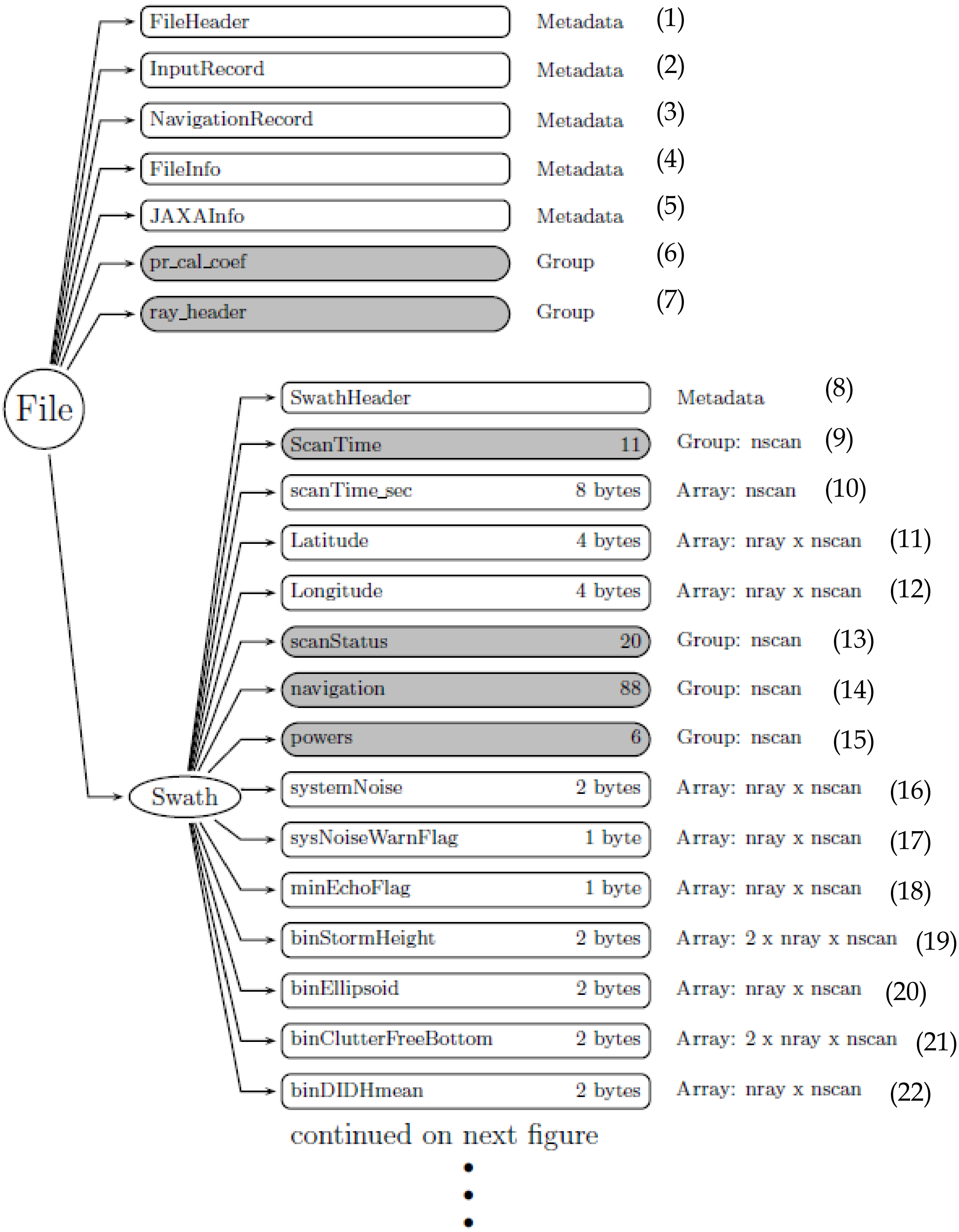


Figure 1-1-1. Data format structure for 1B21 (1/2)

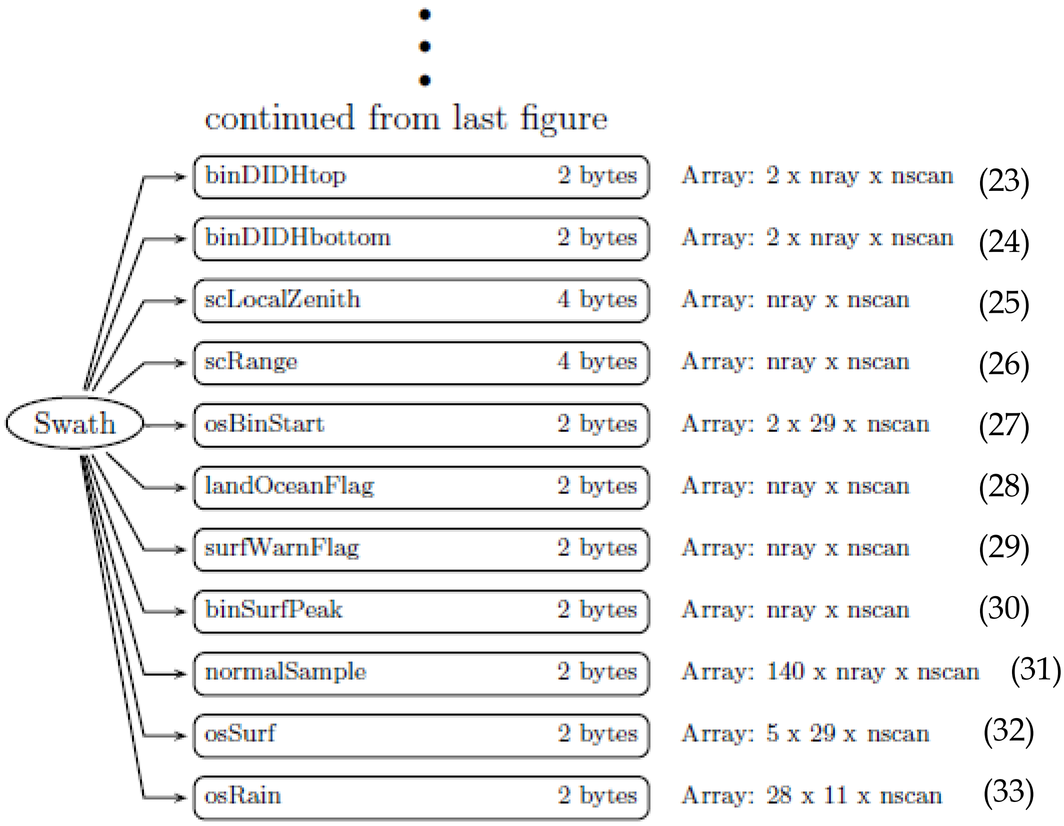


Figure 1-1-2. Data format structure for 1B21 (2/2)

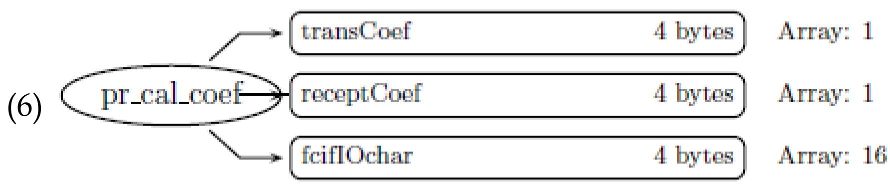


Figure 1-1-3. Data format structure for pr_cal_coef

(7)

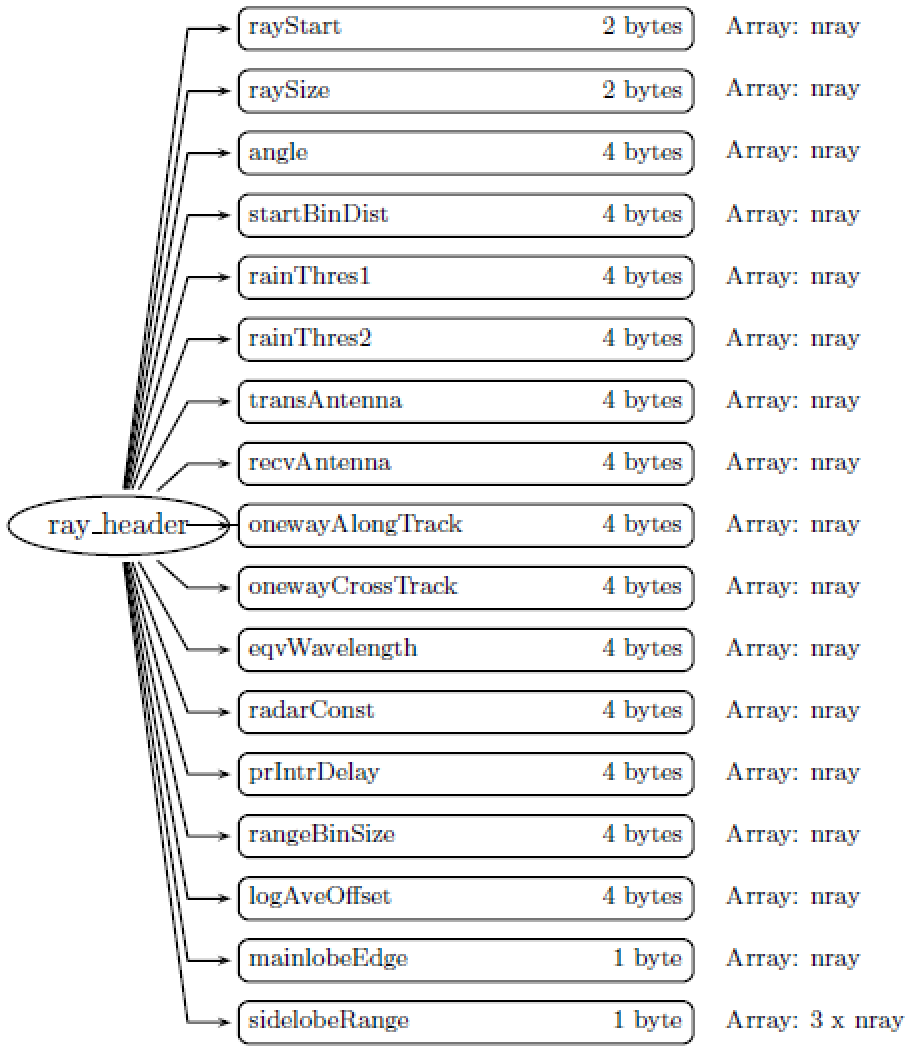


Figure 1-1-4. Data format structure for ray_header

(9)

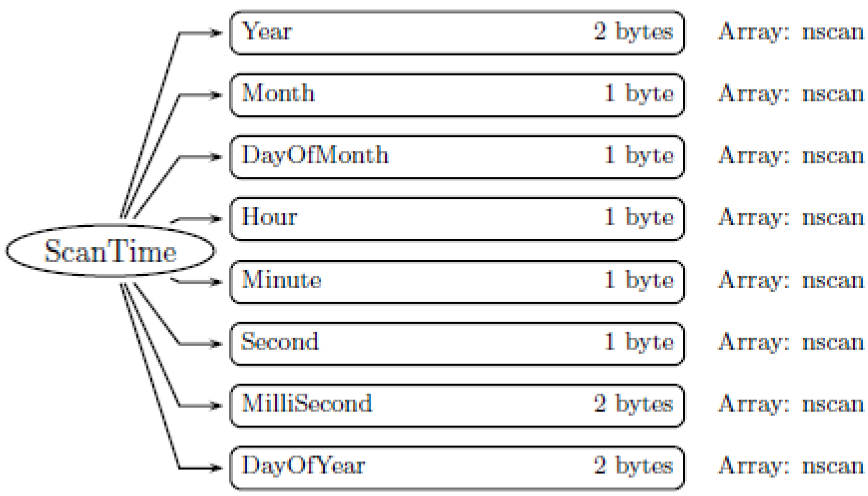


Figure 1-1-5. Data format structure for ScanTime

(13)

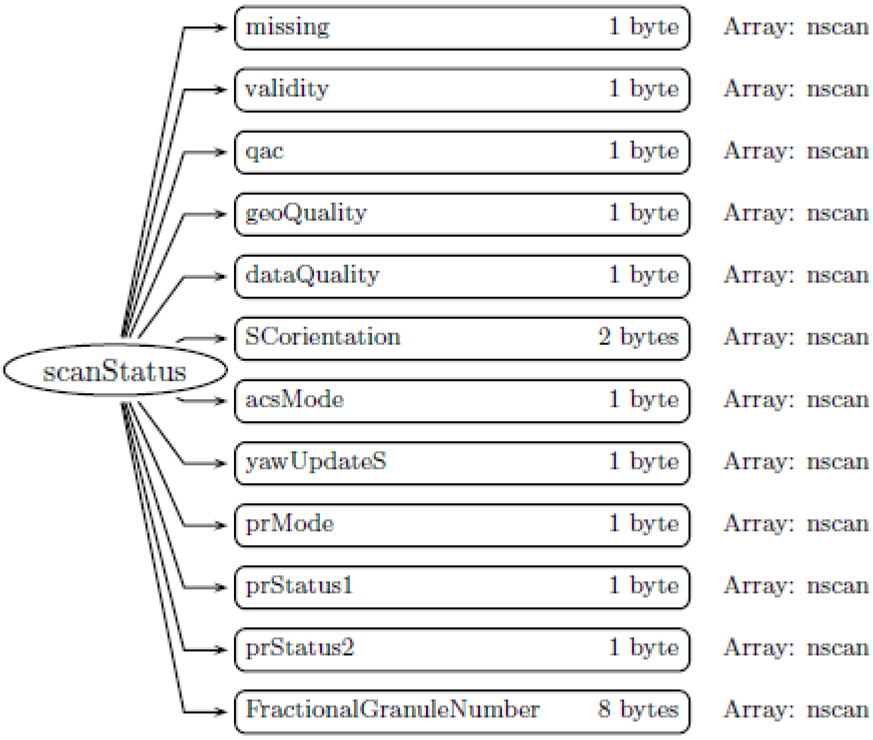


Figure 1-1-6. Data format structure for scanStatus

(14)

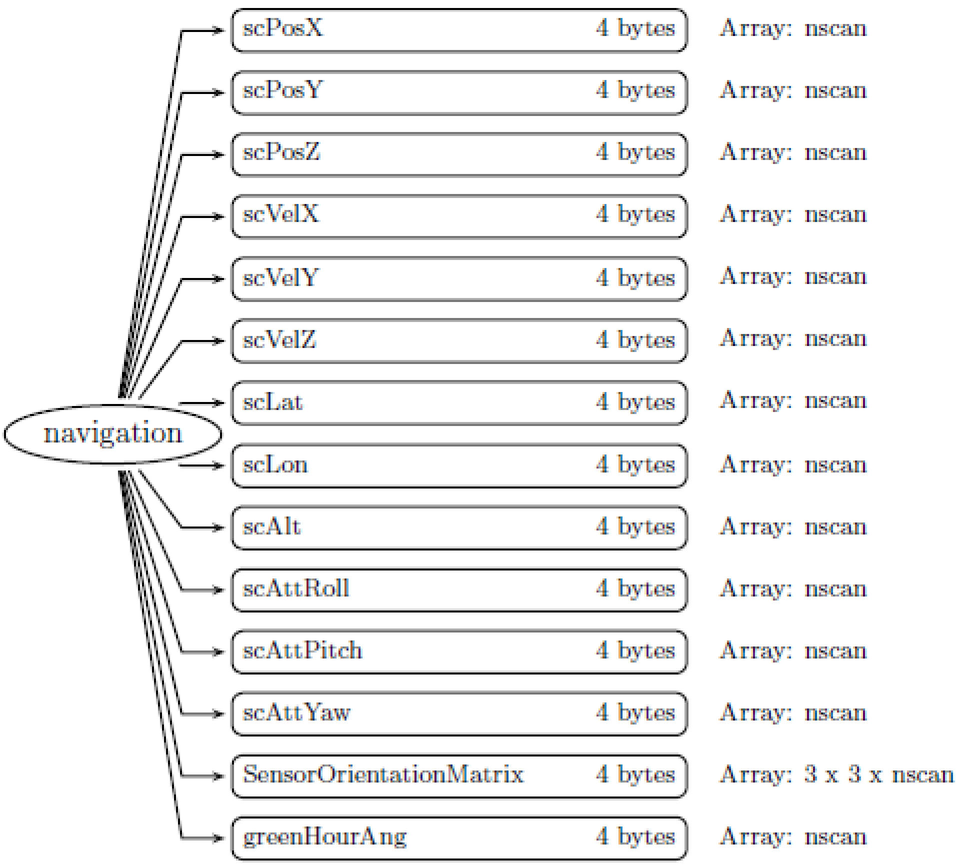


Figure 1-1-7. Data format structure for navigation

(15)

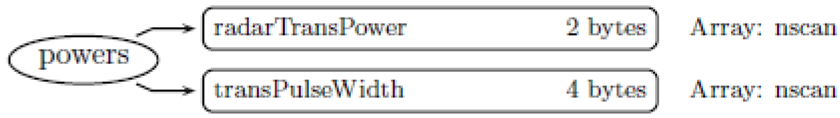


Figure 1-1-8. Data format structure for powers

1-1. 4. Detailed description of output variables

(1) FileHeader (Metadata)

FileHeader contains metadata common to all GPM products.

AlgorithmID:
The name of the algorithm that generated this product. For example, 1B21.

AlgorithmVersion:
The version of the algorithm that generated this product.

FileName:
The file name of this granule.

GenerationDateTime:
The date and time this granule was generated. The format is YYYY-MM-DDTHH:MM:SS.sssZ, where YYYY is 4-digit year, MM is month number, DD is day of month, T is "T", HH is hour, MM is minute, SS is second, sss is millisecond, and Z is "Z". All fields are zero-filled.

StartGranuleDateTime:
The start time of the data in this granule. There may be overlap scans in the file before the start time as described in NumberScans-BeforeGranule. The format is the same as Generation-DateTime.

StopGranuleDateTime:
The stop time of the data in this granule. There may be overlap scans in the file before the start time as described in NumberScans-BeforeGranule. The format is the same as GenerationDateTime.

GranuleNumber:
The number of this granule, which starts as defined in GranuleStart. If the GranuleStart is identical to the orbit start, then the GranuleNumber will be the same as the orbit number.

NumberOfSwaths:
The number of swaths in this granule.

NumberOfGrids:
The number of grid structures in this granule.

GranuleStart:
The starting place in the orbit of this granule. Currently defined values are "SOUTHERNMOST LATITUDE" and "NORTHBOUND EQUATOR CROSSING".

TimeInterval:
The time interval covered by this granule. Values are "ORBIT", "HALFORBIT", "HOUR", "3 HOUR", "DAY", "MONTH".

ProcessingSystem:
The name of the processing system, e.g., "PPS".

ProductVersion:
The data version assigned by the processing system.

MissingData:
The number of missing scans.

InputFileNames:
InputFileNames contains a list of input file names for this granule.

InputAlgorithmVersions:
InputFileNames contains a list of algorithm versions of the input files for this granule.

InputGenerationDateTimes:
InputFileNames contains a list of algorithm versions of the input files for this granule.

(2) InputRecord (Metadata)

InputRecord contains a record of input files for this granule. This group appears in Level 1 and Level 2 data products. Level 3 products have the same information separated into 3 groups since they have many inputs.

InputFileNames:
InputFileNames contains a list of input file names for this granule. Since some algorithms may have 2000 input files, this group is a "Long Metadata Group", which has no elements. This group appears in Level 3 products.

InputAlgorithmVersions:
InputAlgorithmVersions contains a list of input algorithm versions for this granule. Since some algorithms may have 2000 input files, this group is a "Long Metadata Group", which has no elements. This group appears in Level 3 products.

InputGenerationDateTimes:
InputGenerationDateTimes contains a list of input generation datetimes for this granule. Since some algorithms may have 2000 input files, this group is a "Long Metadata Group", which has no elements. This group appears in Level 3 products.

(3) NavigationRecord (Metadata)

NavigationRecord contains navigation metadata for this granule. This group appears in Level 1 and Level 2 data products.

LongitudeOfMaximumLatitude:
The longitude of the maximum latitude of the orbit track of this granule.

SolarBetaAngleAtBeginningOfGranule:
The solar beta angle at the start of this granule.

SolarBetaAngleAtEndOfGranule:
The solar beta angle at the end of this granule.

(4) FileInfo (Metadata)

FileInfo contains metadata used by the PPS I/O Toolkit. This group appears in all data products.

DataFormatVersion:
The version of the data format used to write this file. This version is separate for each AlgorithmID. The order is: "a" "b" ... "z" "aa" "ab" ... "az" "ba" "bb" ...

TKCodeBuildVersion:
Usually TKCodeBuild-Version is "1". If the I/O routines built by TKIO change even though the DataFormatVersion is unchanged, then TKCodeBuild-Version increments to "2", "3", ... If subsequently DataFormatVersion changes, TKCodeBuildVersion becomes "1" again.

MetadataVersion:
The version of metadata used to write this file. This version is separate for each AlgorithmID. The order is: "a" "b" ... "z" "aa" "ab" ... "az" "ba" "bb" ...

FormatPackage:
The underlying format of this granule. Values are "HDF4", "HDF5", "NETCDF", "TKBINARY"

BlueprintFilename:
The filename of the primary blueprint file that defined the format used to write this file.

BlueprintVersion:
The BlueprintVersion of the format definition.

TKIOVersion:
The version of TKIO used to create I/O routines to write this file. TKIOVersion does not define the format used to write this file.

MetadataStyle:
The style in which the metadata was written, e.g., "PVL". "PVL" means < parameter >=< value >;

EndianType:

The endian type of the system that wrote this file. Values are "BIG ENDIAN" and "LITTLE ENDIAN".

(5) JAXAInfo (Metadata)

JAXAInfo contains metadata requested by JAXA. Used by PR algorithms only.

CalibrationCoefficientVersion:
Version of the calibration coefficients.

GranuleFirstScanUTCDate:
Orbit First Scan UTC Date. Date is a 10 character string with the following characters: YYYY/MM/DD, where YYYY = year, MM = month number, DD = day of month and “/” is a literal. If the granule is empty, the value is ‘0/0/0’. In 2A-52, UTC date is stored as “/” is replaced by “-”. In 1B-11 and 2A-12, UTC date is stored in separate words for year, month and day of month.

GranuleFirstScanUTCTime:

Orbit First Scan UTC Time. Time is an 8 character string with the following characters: HH:MM:SS, where HH = hour, MM = minute, SS = second, and “:” is a literal. If the granule is empty, the value is ‘0:0:0’. In 1B-11 and 2A-12, UTC time is stored in separate words for hour, minute, and second.

GranuleFirstScanUTCMilliseconds:

Orbit First Scan UTC Milliseconds. Milliseconds is a 3 character string with the following characters: MMM, where MMM = the number of milliseconds later than the last whole second.

GranuleLastScanUTCDate:
Orbit Last Scan UTC Date. See Orbit First Scan UTC Date.

GranuleLastScanUTCTime:
Orbit Last Scan UTC Time. Decided by L1A file header. See Orbit First Scan UTC Time.

GranuleLastScanUTCMilliseconds:
Orbit Last Scan UTC Milliseconds. See Orbit Last Scan UTC Milliseconds.

SoftwareVersion:

Version of the Software.

DatabaseVersion:
Version of PR Database in the PR L1 software

TotalQualityCode:
Total quality of the PR L1 product. Values are ‘G’, ‘F’, or ‘P’.

LongitudeOnEquator:
Longitude on the equator from the ascending node. Range is -180.000 to 179.999.

UTCDateOnEquator:
UTC date on the equator. See Orbit First Scan UTC Date.

UTCTimeOnEquator:
UTC time on the equator. See Orbit First Scan UTC Time.

UTCMillisecondsOnEquator:
UTC millisecond on the equator. See Orbit First Scan UTC Milliseconds.

CenterScanUTCDate:
UTC date at orbit center scan. See Orbit First Scan UTC Date.

CenterScanUTCTime:
UTC time at orbit center scan. See Orbit First Scan UTC Time.

CenterScanUTCMilliseconds:
UTC milliseconds at orbit center scan. See Orbit First Scan UTC Milliseconds.

FirstScanLat:
Latitude of orbit first scan. Range is -40.000 to 40.000

FirstScanLon:
Latitude of orbit first scan. Range is -180.000 to 179.999.

LastScanLat:
Latitude of orbit last scan. Range is -40.000 to 40.000.

LastScanLon:
Longitude of orbit last scan. Range is -180.000 to 179.999.

NumberOfRainScans:
Number of rain scan whose minEchoFlag is rain certain (20) or rain possible (10, 11, 12, 13).

(6) pr_cal_coef (Group)

Calibration coefficients consist of several parameters describing the PR electronic performance. They are controlled by JAXA based on the results of PR calibration data analysis. These coefficients are applied in 1B21 (PR received power) calculations.

transCoef (4-byte float):
Transmitter gain correction factor.

receptCoef (4-byte float):
Receiver gain correction factor.

fcifIOchar [16] (4-byte float):
LOGAMP Input/Output characteristics. The power level at the IF unit corresponding to the count value is calculated by a look-up table which represents input to output characteristics of the IF unit measured by internal calibrations. PR received power is then calculated from this power level and the receiver gain at RF stage.

(7) ray_header (Group)

The Ray Header contains information that is constant in the granule, such as the parameters used in the radar equation, the parameters in the minimum echo test, and the sample start range bin number. These parameters are provided for each angle bin.

rayStart [49] (2-byte integer):
Range bin number of starting normal sample. See note (a).

raySize [49] (2-byte integer):
Number of normal samples in 1 angle. See note (a).

angle [49] (4-byte float):
Scan angle (degree) is defined as the cross-track angle at the radar electric coordinates which are rotated by 4 degrees about the Y-axis (Pitch) of spacecraft coordinates, which is almost same direction with nadir. The angle is positive when the antenna beam is rotated counter clockwise (CCW) from the nadir about the +X axis of the radar electric coordinates.

startBinDist [49] (4-byte float):
Distance (m) between the satellite and the starting bin number of the normal sample for the ray. See note (b).

rainThres1 [49] (4-byte float):
The threshold is used in minimum echo test.

rainThres2 [49] (4-byte float):
The threshold is used in minimum echo test.

transAntenna [49] (4-byte float):
Transmitted radar antenna effectiveness (dB).

recvAntenna [49] (4-byte float):
Received radar antenna effectiveness (dB).

onewayAlongTrack [49] (4-byte float):
Along track beam widths (radians) is recorded based on the fact that the PR main beam is assumed to have a two-dimensional Gaussian beam pattern.

onewayCrossTrack [49] (4-byte float):
Cross track beam widths (radians) is recorded based on the fact that the PR main beam is assumed to have a two-dimensional Gaussian beam pattern.

eqvWavelength [49] (4-byte float):
Equivalent wavelength (m). See note (c).

radarConst [49] (4-byte float):
Radar constant dC (units are dB), which relates Received Power to Radar Reflectivity. See note (d).

prIntrDelay [49] (4-byte float):
The time (seconds) between when echo returns at antenna and when echo is recorded in onboard processor. Set to 0.

rangeBinSize [49] (4-byte float):
Range Bin Size (rangeBinSize) is the PR range resolution and is the width at which pulse electric power decreases 6dB (-6 dB width).

logAveOfset [49] (4-byte float):
Logarithmic Averaging Offset (logAveOffset) is the offset value between the logarithmic average and the power-linear average. The PR outputs the data of 1 range bin which is the average of 64 LOGAMP outputs. "Received power" in the PR1B21 output is corrected for the bias error caused by the logarithmic average and is thus equal to normal average power.

mainlobeEdge [49] (1-byte integer):
Main Lobe Clutter Edge (mainlobeEdge) is a parameter previously used as the lowest range bin for the minimum echo test. This is the absolute value of the difference in range bin number between the surface peak and the edge of the clutter from the main lobe.

sidelobeRange [3][49] (1-byte integer):
Absolute value of the difference in Range bin numbers between the bin number of the surface peak and the possible clutter position. A maximum of three range bins can be allocated as "possible" clutter locations. "Zero" indicates no clutter.

Note (a)
The Precipitation Radar (PR) has 400 internal (logical) range bins (A/D sample points) and records "normal sample data (*normalSample*)" every other range bin from "Ray Start (*RayStart*)" in order to sample radar echoes from 0-km (the reference ellipsoid surface) to 15-km height.
The number of recorded samples at an angle bin depends on the scan angle and is defined by "Ray Size (RaySize)." The *N-th* normal sample data can be converted to the internal logical range bin number as follows;

$$\text{Logical range bin number at } N\text{-}th \text{ normal sample} = RayStart + 2 \times (N-1)$$

Note (b)
Starting Bin Distance is determined by the sampling timing of the PR. The distance between the satellite and the center of the N-th normal sample bin is calculated as follows:

$$\text{Distance} = \text{"Starting Bin Distance } (startBinDist)\text{"} + \text{"Range Bin Size } (rangeBinSize)\text{"} \times (N-1)$$

This distance is defined as the center of a radar resolution volume which extends ± 125 m .

Note (c)

"Equivalent Wavelength (eqvWavelength)" $= 2c/(f_1 + f_2)$

where c is the speed of light, and f1 and f2 are PR's two frequencies.

Note (d)

Radar Constant (radarConst) is defined as follows, and is used in the radar equation:

$$C_0 = 10log\left[\pi^3 \frac{|K|^2}{2^{10} ln2} 10^{-18}\right]$$

$$K = (\varepsilon - 1)/(\varepsilon + 2)$$

ε : *the relative dielectric constant of water*

$|K|^2 = 0.9255$

$|K|^2$ is the calculated value at 13.8 GHz and 0 degree C based on Ray (1972).*[1] With this constant, users can convert from PR receiving powers to rain reflectivity. (See the 1C products.)

(8) SwathHeader (Metadata)

SwathHeader contains metadata for swaths. This group appears in Level 1 and Level 2 data products.

NumberScansInSet :

The scans read by TKreadScan are a "set". For single swath data, one scan is read so NumberScansInSet=1. In case of PR, NumberScansInSet=1.

MaximumNumberScansTotal :

The maximum allowed number of total scans in this swath. Total scans = overlap scans before granule + scans in granule + overlap scans after granule.

1 Ray, P.S., 1972: Broadband complex refractive indices of ice and water. Appl.Opt., Vol.11, No.8, 1836-1844.

NumberScansBeforeGranule :
The number of overlap scans before the first scan of the granule in this swath.
In case of PR, NumberScansBeforeGranule=0.

NumberScansGranule :
The number of scans in the granule in this swath.

NumberScansAfterGranule :
The number of overlap scans after the last scan of the granule in this swath.
In case of PR, NumberScansAfterGranule=0.

NumberPixels :
The number of IFOV in each scan in this swath. In case of PR, NumberPixels=49.

ScanType :
The type of scan in this swath. Values are: "CROSSTRACK" and "CONICAL". In case of PR, ScanType="CROSSTRACK".

(9) ScanTime (Group)

Scan time is the center time of 1 scan (the time at center of the nadir beam transmitted pulse).

Year [nscan] (2-byte integer):
4-digit year, e.g., 1998. Values range from 1950 to 2100 years.
Special values are defined as:
-9999 MissingValue.

Month [nscan] (1-byte integer):
Month of the year. Values range from 1 to 12 months.
Special values are defined as:
-99 MissingValue

DayOfMonth [nscan] (1-byte integer):
Day of the month. Values range from 1 to 31 days.
Special values are defined as:
-99 MissingValue

Hour [nscan] (1-byte integer):
UTC hour of the day. Values range from 0 to 23 hours.
Special values are defined as:
-99 MissingValue

Minute [nscan] (1-byte integer):
Minute of the hour. Values range from 0 to 59 minutes.
Special values are defined as:
-99 MissingValue

Second [nscan] (1-byte integer):
Second of the minute. Values range from 0 to 60 s.
Special values are defined as:
-99 MissingValue

MilliSecond [nscan] (2-byte integer):
Thousandths of the second. Values range from 0 to 999 ms.
Special values are defined as:
-9999 MissingValue

DayOfYear [nscan] (2-byte integer):
Day of the year. Values range from 1 to 366 days.
Special values are defined as:
-9999 MissingValue

(10) scanTime_sec [nscan] (8-byte float):

Scan time is the center time of 1 scan (the time at center of the nadir beam transmitted pulse). Scan time is expressed as the UTC seconds of the day. Values range from 0 to 86400 s.
Special values are defined as:
-9999.9 MissingValue

(11) Latitude [49][nscan] (4-byte float):

The latitude of the center of the IFOV at the altitude of the earth ellipsoid. Values range from -90 to 90 degrees. Special values are defined as:

-9999.9 MissingValue

(12) Longitude [49][nscan] (4-byte float):

The earth longitude of the center of the IFOV at the altitude of the earth ellipsoid. Values range from -180 to 180 degrees. Special values are defined as:
-9999.9 MissingValue

(13) scanStatus (Group)

missing [nscan] (1-byte integer):
Missing indicates whether information is contained in the scan data.
The values are:
0 normal
1 missing (missing packet and calibration mode)
2 No-rain

validity [nscan] (1-byte integer):
Validity is a summary of status modes. If all status modes are routine, all bits in Validity=0. Routine means that scan data has been measured in the normal operational situation as far as the status modes are concerned. Validity does not assess data or geolocation quality. Validity is broken into 8 bit flags. Each bit = 0 if the status is routine but the bit = 1 if the status is not routine. Bit 0 is the least significant bit (i.e., if bit i = 1 and other bits = 0, the unsigned integer value is 2**i).
The non-routine situations follow:
Bit Meaning if bit = 1
0 Spare (always 0)
1 Non-routine spacecraft orientation (2 or 3)
2 Non-routine ACS mode (other than 4)
3 Non-routine yaw update status (0 or 1)
4 Non-routine instrument status (other than 1)
5 Non-routine QAC (non-zero)
6 Spare (always 0)
7 Spare (always 0)

qac [nscan] (1-byte integer):
The Quality and Accounting Capsule of the Science packet as it appears in Level-0

data. If no QAC is given in Level-0, which means no decoding errors occurred, QAC in this format has a value of zero.

geoQuality [nscan] (1-byte integer):
Geolocation quality is a summary of geolocation quality in the scan. A zero integer value indicates 'good' geolocation. A non-zero value broken down into the following bit flags indicates the following, where bit 0 is the least significant bit (i.e., if bit i = 1 and other bits = 0 the unsigned integer value is 2**i):
Bit Meaning if bit = 1
0 latitude limit error
1 geolocation
2 attitude change rate limit error
3 attitude limit error
4 satellite undergoing maneuvers
5 using predictive orbit data
6 geolocation calculation error
7 not used

dataQuality [nscan] (1-byte integer):
Data quality is a summary of data quality in the scan. Unless this is 0 (normal), the scan data is meaningless to higher processing. Bit 0 is the least significant bit (i.e., if bit i =1 and other bits = 0, the unsigned integer value is 2**i).
Bit Meaning if bit = 1
0 missing
5 Geolocation Quality is not normal
6 Validity is not normal

SCorientation [nscan] (2-byte integer):
The positive angle of the spacecraft vector (v) from the satellite forward direction of motion, measured clockwise facing down. We define v in the same direction as the spacecraft axis +X, which is also the center of the TMI scan. Values range from 0 to 360 degrees.
0:+x forward
180:-x forward
90:-y forward
Special values are defined as:
-9999 MissingValue
-8003 Inertial
-8004 Unknown

acsMode [nscan] (1-byte integer):
Value Meaning
0 Standby
1 Sun Acquire
2 Earth Acquire
3 Yaw Acquire
4 Nominal
5 Yaw Maneuver
6 Delta-H (Thruster)
7 Delta-V (Thruster)
8 CERES Calibration

yawUpdateS [nscan] (1-byte integer):
Value Meaning
0 Inaccurate
1 Indeterminate
2 Accurate

prMode [nscan] (1-byte integer):
Value Meaning
1 Observation Mode
2 Other Mode

prStatus1 [nscan] (1-byte integer):
The flags listed here indicate warnings of PR conditions (noise level, echo power and echo position, and mode change). In data processing, users should be cautions with the following as a scan with non-zero status includes questionable range bins or angle bins.
Bit Meaning if bit = 1
0 LOGAMP noise limit error
1 Noise level limit error: The meaning of this warning is the same as "System Noise Warning Flag".
2 Out of PR dynamic range: Surface echo is so strong that it exceeds the PR receiver dynamic range. If this bit is ON, surface echo level may be questionable.
3 Not reach surface position: If Surface echo is out of range window, Bin Surface Peak and related data become uncertain.
7 FCIF mode change

prStatus2 [nscan] (1-byte integer):

In some cases, antenna sidelobes are directed to nadir receive surface echo positions. When the main beam is off nadir, the timing of such nadir-surface clutter can contaminate the rain echo. In "PR STATUS2," a warning flag is set ON (1) when the nadir surface echo (at the nadir angle bin #25) exceeds a predetermined threshold. When the flag is ON, please be careful about the echoes at all angle bins around the same logical range bin number as the Bin-surface-peak at nadir (angle bin number 25).

Bit meaning if bit =1

0 Warning for clutter because of strong nadir surface echo.

FractionalGranuleNumber [nscan] (8-byte float):

The floating point granule number. The granule begins at the Southern-most point of the spacecraft's trajectory. For example, FractionalGranuleNumber = 10.5 means the spacecraft is halfway through granule 10 and starting the descending half of the granule.

(14) navigation (Group)

scPosX [nscan] (4-byte float):

The x component of the position (m) of the spacecraft in Geocentric Inertial Coordinates at the Scan mid-Time (i.e., time at the middle pixel/IFOV of the active scan period). Geocentric Inertial Coordinates are also commonly known as Earth Centered Inertial coordinates. These coordinates will be True of Date (rather than Epoch 2000 which are also commonly used), as interpolated from the data in the Flight Dynamics Facility ephemeris files generated for TRMM.

scPosY [nscan] (4-byte float):

The y component of the position (m) of the spacecraft in Geocentric Inertial Coordinates at the Scan mid-Time (i.e., time at the middle pixel/IFOV of the active scan period). Geocentric Inertial Coordinates are also commonly known as Earth Centered Inertial coordinates. These coordinates will be True of Date (rather than Epoch 2000 which are also commonly used), as interpolated from the data in the Flight Dynamics Facility ephemeris files generated for TRMM.

scPosZ [nscan] (4-byte float):

The z component of the position (m) of the spacecraft in Geocentric Inertial Coordinates at the Scan mid-Time (i.e., time at the middle pixel/IFOV of the active scan period). Geocentric Inertial Coordinates are also commonly known as Earth Centered Inertial coordinates. These coordinates will be True of Date (rather than Epoch 2000 which are also commonly used), as interpolated from the data in the Flight Dynamics Facility ephemeris files generated for TRMM.

scVelX [nscan] (4-byte float):
The x component of the velocity (ms^-1) of the spacecraft in Geocentric Inertial Coordinates at the Scan mid-Time.

scVelY [nscan] (4-byte float):
The y component of the velocity (ms^-1) of the spacecraft in Geocentric Inertial Coordinates at the Scan mid-Time.

scVelZ [nscan] (4-byte float):
The z component of the velocity (ms^-1) of the spacecraft in Geocentric Inertial Coordinates at the Scan mid-Time.

scLat [nscan] (4-byte float):
The geodedic latitude (decimal degrees) of the spacecraft at the Scan mid-Time.

scLon [nscan] (4-byte float):
The geodedic longitude (decimal degrees) of the spacecraft at the Scan mid-Time.

scAlt [nscan] (4-byte float):
The altitude (m) of the spacecraft above the Earth Ellipsiod at the Scan mid-Time.

scAttRoll [nscan] (4-byte float):
The satellite attitude Euler roll angle (degrees) at the Scan mid-Time. The order of the components in the file is roll, pitch, and yaw. However, the angles are computed using a 3-2-1 Euler rotation sequence representing the rotation order yaw, pitch, and roll for the rotation from Orbital Coordinates to the spacecraft body coordinates. Orbital Coordinates represent an orthogonal triad in Geocentric Inertial Coordinates where the Z-axis is toward the geocentric nadir, the Y-axis is perpendicular to the spacecraft velocity opposite the orbit normal direction, and the X-axis is approximately in the velocity direction for a near circular orbit. Note this is geocentric, not geodetic, referenced, so that pitch and roll will have twice orbital frequency components due to the onboard control system following the oblate geodetic Earth horizon. Note also that the yaw value will show an orbital frequency component relative to the Earth fixed ground track due to the Earth rotation relative

to inertial coordinates.

scAttPitch [nscan] (4-byte float):
The satellite attitude Euler pitch angle (degrees) at the Scan mid-Time. The order of the components in the file is roll, pitch, and yaw. However, the angles are computed using a 3-2-1 Euler rotation sequence representing the rotation order yaw, pitch, and roll for the rotation from Orbital Coordinates to the spacecraft body coordinates. Orbital Coordinates represent an orthogonal triad in Geocentric Inertial Coordinates where the Z-axis is toward the geocentric nadir, the Y-axis is perpendicular to the spacecraft velocity opposite the orbit normal direction, and the X-axis is approximately in the velocity direction for a near circular orbit. Note this is geocentric, not geodetic, referenced, so that pitch and roll will have twice orbital frequency components due to the onboard control system following the oblate geodetic Earth horizon. Note also that the yaw value will show an orbital frequency component relative to the Earth fixed ground track due to the Earth rotation relative to inertial coordinates.

scAttYaw [nscan] (4-byte float):
The satellite attitude Euler yaw angle (degrees) at the Scan mid-Time. The order of the components in the file is roll, pitch, and yaw. However, the angles are computed using a 3-2-1 Euler rotation sequence representing the rotation order yaw, pitch, and roll for the rotation from Orbital Coordinates to the spacecraft body coordinates. Orbital Coordinates represent an orthogonal triad in Geocentric Inertial Coordinates where the Z-axis is toward the geocentric nadir, the Y-axis is perpendicular to the spacecraft velocity opposite the orbit normal direction, and the X-axis is approximately in the velocity direction for a near circular orbit. Note this is geocentric, not geodetic, referenced, so that pitch and roll will have twice orbital frequency components due to the onboard control system following the oblate geodetic Earth horizon. Note also that the yaw value will show an orbital frequency component relative to the Earth fixed ground track due to the Earth rotation relative to inertial coordinates.

SensorOrientationMatrix [3][3][nscan] (4-byte float):
SensorOrientationMatrix is the rotation matrix from the instrument coordinate frame to Geocentric Inertial Coordinates at the Scan mid-Time. It is unitless.

greenHourAng [nscan] (4-byte float):
The rotation angle (degrees) from Geocentric Inertial Coordinates to Earth Fixed Coordinates.

(15) powers (Group)

radarTransPower [nscan] (2-byte integer):
The total (sum) power of 128 SSPA elements corrected with SSPA temperature in orbit, based on temperature test data of SSPA transmission power. The units are dBm * 100. For example, -9436 represents -94.36 dBm.

transPulseWidth [nscan] (4-byte float):
Transmitted pulse width (s) corrected with FCIF temperature in orbit, based on temperature test data of FCIF.

(16) systemNoise [49][nscan] (2-byte integer):

System Noise (dBm) is an average of the 4 measured system noise values, multiplied by 100 and stored as a 2-byte integer. The units are dBm * 100. The system noise consists of external noise and PR internal noise, and is recorded as the total equivalent noise power at the PR antenna output. Missing data are given the value of -32,734.

(17) sysNoiseWarnFlag [49][nscan] (1-byte integer):

System Noise Warning Flag indicates possible contamination of lower window noise by high towers of rain. 0 means no possible contamination. If the system noise level exceeds the noise level limit, the flag is set to 1. This will occur when (1) a radio interference is received, (2) system noise increases anomalously, or (3) noise level exceeds the limit due to the statistical variation of the noise. In cases (1) and (2), data should be used carefully. In case (3), this flag may be neglected. Received power levels in all range bins will increase in cases (1) and (2) as much as the increase of the system noise.

(18) minEchoFlag [49][nscan] (1-byte integer):

This value shows the existence of the rain echo at each angle bin.
Six values are used in the Minimum Echo Flag: 0, 10, 20, 11, 12, and 13.

0: No rain. (Echoes are very weak.)

10: Rain possible but may be noise.
(Some weak echoes above noise exist in clutter free ranges.)
20: Rain certain. (Some strong echoes above noise exist in clutter free ranges.)
11: Rain possible but may be noise or surface clutter.
(Some weak echoes exist in possibly cluttered ranges.)
12: Rain possible but may be clutter.
(Some strong echoes exist in possibly cluttered ranges.)
13: Rain possible but probably sidelobe clutter.
(Some strong echoes above noise exist but they are most likely caused by sidelobe clutter.)

(19) binStormHeight [2][49][nscan] (2-byte integer):

Range Bin Number of the storm top, which is represented by the logical range bin number (1 to 400). The Bin Storm Heights are generated in the procedure to determine the Minimum Echo Flag. The first dimension is threshold, with values of possible[10] rain threshold and certain rain[20] threshold in that order. Missing data are given the value of -9999.

(20) binEllipsoid [49][nscan] (2-byte integer):

The range bin number of the earth ellipsoid, which is represented by the logical range bin number (1 to 400). This is calculated by the following equation.
binEllipsoid = RayStart + (scRange - startBinDist)/rangebinSize x 2

(21) binClutterFreeBottom [2][49][nscan] (2-byte integer):

The range bin number of the lowest clutter free bin. Clutter free bin numbers are given for clutter free certain and possible, respectively. The clutter free certain bin is always less than or equal to the clutter free possible bin number.
binClutterFreeBottom [0][]: clutter free certain,
binClutterFreeBottom [1][]: clutter free probable.
Missing data are given the value of -99.

(22) binDIDHmean [49][nscan] (2-byte integer):

binDIDHmean represents the range bin number corresponding to the mean height of all DID/SRTM30 data samples available in a 5 5km area that overlaps most with the footprint. Here, DID stands for Digital Terrain Elevation Dataset (DTED) Intermittent Dataset (DID), and SRTM30 stands for Shuttle Radar Topography Mission 30 arc-seconds. In V7, SRTM30 data were used instead of DID data in some wide area such as Tibet, India, and Andes.

(23) binDIDHtop [2][49][nscan] (2-byte integer):

binDIDHtop[0][][] represents the range bin number corresponding to the highest value (top) of all DID/SRTM30 data samples in a 5 x 5km box, and binDIDHtop[1][][], the range bin number corresponding to the highest value in a 11 x 11km box.

(24) binDIDHbottom [2][49][nscan] (2-byte integer):

The definition is the same as that of binDIDHtop except that the value represents the lowest value (bottom) of all DID/SRTM30 samples in a 5 5km or 11 11km box.

(25) scLocalZenith [49][nscan] (4-byte float):

The angle, in degrees, between the local zenith and the beam's center line. The local (geodetic) zenith at the intersection of the ray and the earth ellipsoid is used.

(26) scRange [49][nscan] (4-byte float):

Distance (m) between the spacecraft and the center of the footprint of the beam on the earth ellipsoid.

(27) osBinStart [2][29][nscan] (2-byte integer):

The first dimension is the Bin Start of Oversample and Surface Tracker Status. The second dimension is the ray. The number of rays is 29 because this information only applies to the rays that have oversample data (rays 11 to 39). The third dimension is the scan. The Bin Start of Oversample is the starting range bin number of the oversample (either surface or rain) data, counting from the top down, which is represented by the logical range bin number (1 to 400). The Surface Tracker Status has the value of 0 (Lock) or 1 (Unlock), where Lock means that (1) the on board surface detection detected the surface and (2) the surface detected later by processing on the ground fell within the oversample bins. Unlock means that Lock was not achieved.

(28) landOceanFlag [49][nscan] (2-byte integer):

Land or ocean information.
The values of the flag are:
0 = ocean
1 = land
2 = coast (not water nor land)
3 = inland water
4 = ocean (surface peak is not correctly detected because of high attenuation)
5 = land (surface peak is not correctly detected because of high attenuation)
6 = coast (surface peak is not correctly detected because of high attenuation)
7 = inland water (surface peak is not correctly detected because of high attenuation)
In the product version 7, two categories are added in the landOceanFlag. The new flags appear when the land (or ocean) surface position is not correctly detected because of high attenuation relating to heavy rainfall. This is determined by the Clutter routine in 1B21. The landOceanFlag is 4 when the surface peak is not detected correctly over ocean. In this case, binSurfPeak is set at binEllipsoid.
If the phenomena happened over land or coast, landOceanFlag is 5 or 6 and the binSurfPeak is recalculated using data between the binClutterFreeBottom and binClutterFreeBottom+8 (bins) toward the Earth.

(29) surfWarnFlag [49][nscan] (2-byte integer):

The topographic mean height (m) of all DID samples in a 5 x 5km.

(30) binSurfPeak [49][nscan] (2-byte integer):

The range bin number of the peak surface echo, which is represented by the logical range bin number (1 to 400). This peak is determined by the post observation ground processing, not by the on board surface detection. If the surface is not detected, Bin Surface Peak is set to a value of -9999. Note that the echo peak may appear either in the normal sample data or in the oversample data.

(31) normalSample [140][49][nscan] (2-byte integer):

Received power (dBm) of the normal sample, multiplied by 100 and stored as a 2-byte integer. The units are dBm * 100. Since each angle has a different number of samples, the elements after the end of sample are filled with a value of -32767. If a scan is missing, the elements are filled with the value -32734.

(32) osSurf [5][29][nscan] (2-byte integer):

Received power (dBm) of the surface echo oversample for the central 29 rays (rays number 11-39), multiplied by 100 and stored as a 2-byte integer. The units are dBm * 100. The PR records the oversampled data in five range bins around the surface peak detected on board (not Bin Surface Peak) in a total of 29 angle bins (nadir 14 angles, angle bins 11 to 39) to examine the surface peak precisely. If the surface tracker status is lock-off, the data position is unknown. To use the oversample data, fill the five data starting at "Bin Start of Over_Surface (osBinStart)" in every other logical range bin, then merge with the interleaving normal sample data. If a scan is missing, the elements are filled with the value -32734.

(33) osRain [28][11][nscan] (2-byte integer):

Received power (dBm) of the rain echo oversample for the central 11 rays (rays number 20-30), multiplied by 100 and stored as a 2-byte integer. The units are dBm * 100. The PR records the oversampled data at 28 range bins in a total of 11 angle bins (nadir 5 angles: angle bins 20 to 30) to record the detailed vertical profile of the rain.
The 125m interval dataset in heights from 0 km to 7.5 km can be generated by interleaving the Normal Samples with the Surface Oversamples and rain

oversamples. The data are merged in the same way as the Surface Oversample. The osBinStart expresses the start angle bin of rain oversample for the rain oversample angle bins and the surface oversample follows the rain oversample continuously. Therefore, the logical range bin number of the Surface Oversample and Rain Oversample is as follows:

Angle bin 11 - 19, 31-39 :

Logical range bin number at Nth surface oversample = osBinStart +2(N-1)

Angle bin 20-30:

Logical range bin number at Nth rain oversample = osBinStart+2(N-1):

Logical range bin number at Nth surface oversample= osBinStart+56+2(N-1)

1-1. 5. Major changes in 1B21 algorithm for product version 7

1. Improvement of surface peak range bin number detection algorithm.

This routine is for the cases that the surface echo is fully attenuated by strong rainfall. In this case, surface peak is searched again using the output from clutter routine by Dr. Awaka. For the case of ocean, binSurfPeak is replaced by binEllipsoid.

2. Refurbishment of calibration table

Discontinuity between linear fitting part and parabolic fitting part should be corrected. Modification of calibration table in order to be applicable to the data around December 15, 1997, when the NASDA performed initial check out of PR by changing internal attenuation for various values.

3. Correction for a known error in the receiver calibration factor

It should be about -1.0 dB instead of -0.65dB. (input for 1B21)

4. Data format

Science data and meta data are defined by PPS I/O Toolkit. Some variable names are renamed and added.

1-1. 6. Changes in 1B21 after the satellite boost in August 2001

1. Outline of the boost

The TRMM satellite changed its altitude from 350 km to 402.5 km in August 2001 in order to save the fuel for altitude maintenance. Major impacts of the attitude change (hereafter boost) on the PR are 1) degradation of sensitivity by about 1.2 dB and 2) occurrence of mismatch between transmission and reception angles for one pulse among 32 onboard averaging pulses. The latter causes unknown error of the PR's data because the mismatch pulse is averaged with other 31- nominal pulses by onboard processor. In order to mitigate the mismatch error in PR data, level one algorithm (1B21) added mismatch correction routine.

2. The mismatch correction algorithm in 1B21

The basic idea of the mismatch correction algorithm is to retrieve the power of mismatch pulse received by PR based on the antenna pattern of mismatch pulse as mentioned previous section. In the current correction algorithm of mismatch in 1B21 algorithm assumes followings: 1) mismatch pulse power can be expressed as the average of power from current angle bin and one previous angle bin with 6 dB gain reduction, 2) the one previous angle bin data can be used without correction to avoid the accumulation of error to the following angle bins, though it contains mismatch error, and 3) the data of angle bin 1 (the first angle bin each scan) contains 31 normal pulse data and one noise data as mentioned in previous section.

The correction algorithm is preferred to be expressed by simple equation and be applied for various occasions such as rain echo and surface echo.

The equation of mismatch correction in 1B21 algorithm is expressed as

$$Pc(N) = \left(32 \cdot P(N) - 10 \cdot \log 10 \left(\frac{10^{P(N)/10} + 10^{P(N-1)/10}}{2} \right) + 6 \right) \Big/ 31$$

where N is angle bin number (angle bin to be corrected), P(N) is observed power at a certain range bin of angle bin N in dBm (containing mismatch echo), P(N-1) is the one previous angle bin data of same distance from the PR used as the “reference”, and Pc(N) is corrected power in dBm. In this equation, since the obtained data is the result from averaging of 32 pulses, 32 times of P(N) stands for the total received power.

The estimated correction error is less than 0.2 dB for rain echo and less than 0.3 dB for surface echo.

1-1. 7. Comments on PR Level 1 products

1. Calibration accuracy

The TRMM Precipitation Radar (PR) has been working without any problem since the first turn-on of the PR power in the beginning of December 1997 except PR hardware switch from A-side to B-side on May 2009. The initial checkout of the PR was completed by NASDA and CRL at the end of January 1998. The overall calibration of the PR including the transmit and receiving antenna pattern measurements were made by using an ARC. It was concluded that the ARC calibration results are reasonable and consistent with the corresponding values calculated by using the PR system parameters. Also the ocean surface sigma-0 obtained by the PR has been found to be quite consistent with those observed from previous airborne and satelliteborne scatterometers.

2. Sensitivity

The minimum detectable Zm (corresponding to the noise-equivalent received power) improved from 23.3 dBZ (based upon the specifications requirement) to 20.8 dBZ as determined from the pre-launch ground test and from the orbit test. This is mainly due to the increased transmit power and the decrease of the receiver noise figure. Actually the rain echo power is measured from the subtraction of the system noise power from the total receiver power (rain echo power + system noise power). The accuracy of rain echo power can be characterized by the effective signal-to-noise ratio (S/N), that is the ratio of mean to standard deviation of rain echo power. By considering these facts, the actual minimum detectable Zm can be considered to be about 16-18 dBZ after the detailed statistical calculation. The effective signal-to-noise ratio (S/N) of 3 dB is obtained when Zm is 17 dBZ.

3. Discrimination of rain from surface clutter

It is generally very difficult to discriminate rain echo from surface clutter especially in mountainous regions. An algorithm has been implemented which analyzes the radar echo range profile very carefully to determine the boundary between rain and surface echoes. The result has been reflected into the surface location related variables described in Item 6. Even though, there is a very small possibility that a surface echo is treated as a rain echo (and in mountainous regions, clutter position when it rains can happen to become too high in a very rare occasion). Please be careful when you use the PR Level-2 data to study rain structure in mountainous regions. Strong echoes near the surface are likely surface clutter and should be excluded from rain analysis.

4. Surface clutter from the coupling between nadir-direction antenna sidelobe and strong surface radar cross-section (NRCS)

It has been found that the echo strength from nadir direction is sometimes extremely strong, which exceeds the anticipated value in the PR design. This seems to occur wet and flat land areas rather than ocean. Even dry dessert regions, the NRCS seems very strong in some cases. In such cases antenna sidelobes directed to nadir receive surface echoes. When main beam is off-nadir, the timing of such nadir-surface clutter can contaminate the rain echo. In "PR STATUS2", a warning flag is set ON when the nadir surface echo (at the nadir angle bin, #25) exceeds a pre-determined threshold. When it is ON, please be careful about the echoes in all angle bins at the same range bin number as the Bin_surface_peak (binSurfPeak) at nadir (angel bin number 25).

5. Discrimination of rain echo from noise

In order to help users utilization of the data, the 1B21 product contains the "Minimum Echo Flag" which indicates the existence of rain in the clutter free range or in the clutter range. Since thermal noise, rain echo and resulting thermal noise plus rain echo follow Rayleigh fading, the PR received echo is a result of the averaging 64 number of independent samples. The averaged value still has small fluctuations of about 0.7 dB to 1 dB, depending on signal-to-noise ratio. In order not to miss weak echo which is sometimes useful to study rain structure, etc, the threshold to set the flag = rain possible is currently about 90% value of the cumulative distribution of thermal noise. This means quite a large fraction of data having "rain possible" flag is only thermal noise. Since this rain/no-rain discrimination is sometimes affected by the surface clutter at especially mountainous area.
In the clutter region, rain/no-rain discrimination often misidentifies clutter as rain.

Minimum Echo Flag includes clutter flag.
There are five levels in the Minimum Echo Flag; 0, 10, 20, 11, and 12:
0: No rain. (Echoes are very weak.)
10: Rain possible but may be noise.

(Some weak echoes above noise exist in clutter free ranges.)
20: Rain certain. (Some strong echoes above noise exist in clutter free ranges.)
11: Rain possible but may be noise or surface clutter.
(Some weak echoes exist in possibly cluttered ranges.)
12: Rain possible but may be clutter.
(Some strong echoes exist in possibly cluttered ranges.)
13: Rain possible but probably sidelobe clutter.
(Some strong echoes above noise exist but they are most likely caused by sidelobe clutter.)

Therefore please be careful in using the Minimum Echo Flag except 0 and 20.

6. Bin_surface_peak (binSurfPeak) and oversample data

In PR 1B21, the data called Bin_surface_peak indicates the range bin number at which PR received power has the maximum within a range window centered at the range bin number determined from a Digital Elevation Model (DID or SRTM30). In most cases, the Bin_Surface_Peak gives the correct location corresponding to the location of actual surface. There may be small number of cases where Bin_surface_peak is wrong. One possibility a case in which DID/SRTM30 is in error, and the other is a case in which rain echo is so strong so that surface echo is masked by the rain echo. We expect those cases are rare, but please keep in mind those may occur with a small probability.

The oversample data are recorded onboard based on the location of surface echo peak detected by an onboard surface tracking function. Since this tracker may be locked-off in mountainous regions, there are cases in which oversample data are recorded outside the location of surface echo. In such cases the oversample data may not be useful because it may not be used for improving the accuracy of surface echo power or for detailed study of vertical storm structure. The difference between the location of surface echo estimated by the onboard tracker (Note 1) and Bin_surface_peak is a measure of the goodness of oversample data in terms of its covering region in the radar range profile.

Note 1:

The surface echo location estimated onboard (Y) can be obtained from "Bin_start_oversample (*osbinStart*)" data.

Let X be Bin_start_oversample,
Y = X + 60 or + 61 (angle bins between 20 and 30) and Y = X + 4 or +5

(between 11 and 19 and between 31 to 39).
We cannot judge either 60 or 61 (or 4 or 5) from 1B21 itself, however.

7. Interference from other radio services around 13-14 GHz

There have been several cases where PR suffered from interferences from other radio services, mainly from satellite tracking and control stations using 13-14 GHz bands. The probability is very small, and the impact to TRMM mission appears to be negligible. In a typical interference case, the noise level increases a few to several decibels over entire range bins for a very short period (one or two scans). In such a case, PR sensitivity to detect weak echo is degraded accordingly.

1-1. 8. References

T. Kozu, T. Kawanishi, K. Oshimura, M. Satake, H. Kumagai; TRMM precipitation radar: calibration and data collection strategies, Proc. IGARSS'94, 2215-2217, Pasadena, 1994.

M. Satake, K. Oshimura, Y. Ishido, S. Kawase, T. Kozu: TRMM PR data processing and calibration to be performed by NASDA, Proc. IGARSS'95, 426-428, Florence, 1995.

N. Takahashi and T. Iguchi; Estimation and correction of beam mismatch of the precipitation radar after an orbit boot of the Tropical Rainfall Measuring Mission satellite, IEEE Trans. Geo. and Remote Sens., 42, 2362-2369, 2004.

1-1. 9. DID access routine

1. Objectives

A DID access routine is used in a Level-1 PR algorithm, 1B21. Main objectives of the DID access routine are:

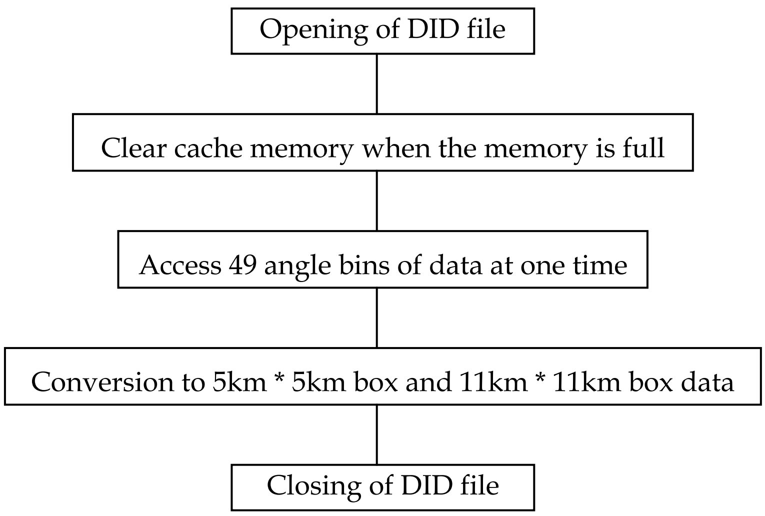
(a) To output the elevation information over a 5 km * 5 km box and an 11 km * 11 km box using DID elevation data, with the center for the 5 km * 5 km box being the same as the center for the 11 km * 11 km box.
(b) To output the land/water information over a 5 km * 5 km box, which is the same as the 5 km * 5 km box for (a), using DID land/water data.

Note: DID stands for DTED (Digital Terrain Elevation Dataset) Intermediate Dataset.

2. Method used

(a) Conversion of DID data having 1 km horizontal resolution to a 5 km * 5 km box and an 11 km * 11 km box.

3. Flowchart



4. Some details of the algorithm

(a) Height_mean

A mean of DID elevation over a 5 km * 5km box, Height_mean, is computed with the following weights:

0.014,	0.028,	0.034,	0.028,	0.014,
0.028,	0.055,	0.069,	0.055,	0.028,
0.034,	0.069,	0.088,	0.069,	0.034,
0.028,	0.055,	0.069,	0.055,	0.028,
0.014,	0.028,	0.034,	0.028,	0.014.

(b) Land/water flag

The original land/water information having 7 categories is summarized into the following information over the 5 km * 5 km box with 3 categories:

(1) water if the 5 km * 5 km box has the following categories of data only,
- deep ocean,
- shallow ocean,
- deep inland water,
- shallow inland water.

(2) land if the 5 km * 5 km box has the following category only,
- land.

(3) mixed if the 5 km * 5 km box includes
- both land and water categories, or
- at least one pixel is coast, or
- at least one pixel is ephemeral inland water.

Computation of other quantities, such as maximum of DID elevation over the 5 km * 5 km box, is straightforward.

5. Input data

(a) DID data set.
(b) latitude/longitude

6. Output data

(a) int Height_mean[49], /* Unit in m (5km * 5km) */

(b) int Height_max[49][2], /* Unit in m (5km * 5km and 11km * 11km) */
(c) int Height_min[49][2], /* Unit in m (5km * 5km and 11km * 11km) */
(d) int Hmedian[49], /* Unit in m (5km * 5km) */
(e) int Hstd[49], /* Unit in m (5km * 5km) */
(f) int LWflag[49], /* 0: water, 1: land, 2: coast, */
/ * 3: inland water */

7. Output file specifications

(a) int Height_mean[i]: Weighted sum of DID elevation over 5 km * 5 km box. Unit is in [m].

(b) int Height_max[i][0]: Maximum of DID elevation over 5 km * 5 km box. Unit is in [m].

int Height_max[i][1]: Maximum of DID elevation over 11 km * 11 km box. Unit is in [m].

(c) int Height_min[i][0]: Minimum of DID elevation over 5 km * 5 km box. Unit is in [m].

int Height_min[i][1]: Minimum of DID elevation over 11 km * 11 km box. Unit is in [m].

(d) int Hmedian[i]: Median of DID elevation over 5 km * 5 km box. Unit is in [m].

(e) int Hstd[i]: Standard deviation of DID elevation over 5 km * 5 km box. Unit is in [m].

(f) int LWflag[i]: Land/water flag for 5 km * 5 km box.
LWflag[i] = 0: water,
1: land,
2: coast,
3: inland water.

where i runs from 0 to 48 (in C language).

8. Interfaces with other algorithms

1B21 outputs some results of the DID access routine with the height being converted to the range bin number. 1B21 outputs the followings:

===== In C language =====

int16	binDIDHmean[i]:	Range bin number for Height_mean[i],
int16	binDIDHtop[i][0]:	Range bin number for the maximum of DID elevation over 5 km * 5 km box,
int16	binDIDHtop[i][1]:	Range bin number for the maximum of DID elevation over 11 km * 11 km box,
int16	binDIDHbottom[i][0]:	Range bin number for the minimum of DID elevation over 5 km * 5 km box,
int16	binDIDHbottom[i][1]:	Range bin number for the minimum of DID elevation over 11 km * 11 km box,
int16	landOceanFlag[i]:	Land/water flag for 5 km * 5 km box, plus additional information

where i runs from 0 to 48 and the range bin numbers are those for 125m intervals.

===== In FORTRAN language =====

INTEGER*2	binDIDHmean(j):	Range bin number for Height_mean(j),
INTEGER*2	binDIDHtop(1,j):	Range bin number for the maximum of DID elevation over 5 km * 5 km box,
INTEGER*2	binDIDHtop(2,j):	Range bin number for the maximum of DID elevation over 11 km * 11 km box,
INTEGER*2	binDIDHbottom(1,j):	Range bin number for the minimum of DID elevation over 5 km * 5 km box,
INTEGER*2	binDIDHbottom(2,j):	Range bin number for the minimum of DID elevation over 11 km * 11 km box,
INTEGER*2	landOceanFlag(j):	Land/water flag for 5 km * 5 km box, plus additional information.

where j runs from 1 to 49 and the range bin numbers are those for 125m intervals.

9. SRTM30 patch to DID access routine

A patch to DID access routine is added in V7. In the patch, SRTM30 elevation data are used instead of DID elevation data. The patched area includes over India, over Tibet, and over South America.

10. Special notes (caveats)

None.

11. References

None.

1-1 10. Main-lobe clutter rejection routine

1. Objectives of main-lobe clutter rejection routine

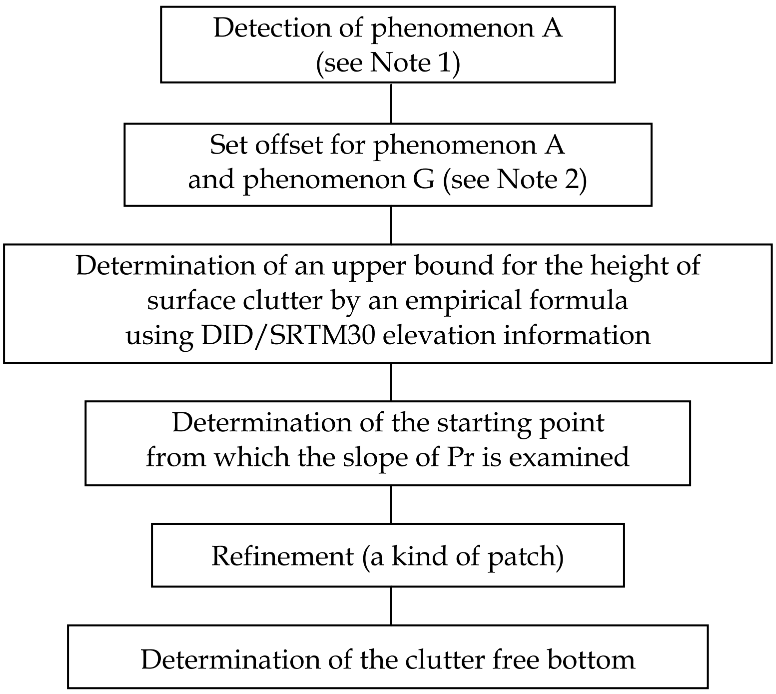
A main-lobe clutter rejection routine is developed to be included in the Level 1 PR algorithm 1B21. The main objective is:

(a) Determination of the boundary of clutter free region, where the clutter means the main-lobe surface clutter.

2. Method used

(a) Examination of the slope of Z profile at the top of surface clutter.

3. Flowchart



Note 1: Description of phenomenon A and phenomenon G.

Phenomenon A:
Detected position of surface peak is too low from the actual position because of inaccurate DID/SRTM30 elevation data, which indicates a too low height. This phenomenon was first observed in the data over the Andes area.
Phenomenon G:
Detected position of surface peak is too high from the actual position because of inaccurate DID/SRTM30 elevation data, which indicates a too high height. This phenomenon was first observed in the data over the Guiana Highlands.

Note 2: Detection of phenomenon G is already made before the clutter rejection routine is used in 1B21.

4. Outline of the algorithm

(a) Detection of phenomenon A:
When the radar echo at and around binSurfPeak, which is detected by surface peak detection routine of 1B21, shows that the echo is eventually noise, there may exist the following three possibilities:

(1) Phenomenon A can occur due to an inaccuracy of DID/SRTM30 elevation data,
(2) Strong attenuation makes the radar echo at and around binSurfPeak very small, indistinguishable from noise,
(3) The radar echo at and around binSurfPeak is actually very small because of a specular reflection over a very flat surface when the antenna beam points away from the nadir direction.

When the radar echo at and around binSurfPeak is very small to be indistinguishable from noise, a search is made upper-wards until an appreciable echo is detected. If the appreciable echo has a peak and has a large slope at the bottom part of the peak, which is typical to the surface clutter, it is judged that the phenomenon A occurs.

(b) Offset:
Since the clutter rejection code is written in such a way to consult the DID/SRTM30

elevation, offset is needed when phenomenon A or G occurs.

(c) Upper bound for the height of surface clutter:
Empirical upper bound for the height of surface clutter is obtained by using
 (i) nominal clutter offset for a flat surface,
 (ii) maximum height of DID/SRTM30 elevation over an 11 km * 11 km box.

(d) Starting position of the examination of slope:
A point where the received power, Pr, is 10 dB larger than the noise level is used as the starting point from which the slope is examined. If the 10 dB up point is not found, the empirical upper bound obtained by (c) is used as the starting point.

(e) Determination of the clutter free bottom:
First, whether the starting point obtained by (d) belongs to a rain region or not is examined; if the echo above the starting point has appreciable value and slope is small, it is judged that the starting point belongs to a rain region. If the starting point belongs to a rain region, climb 'up' the surface peak until the slope becomes very large, which is typical to the surface clutter. On the contrary, if the starting point does not belong to a rain region, climb 'down' the surface peak as long as the slope is large.

5. Input data

```
float normalSample_in[49][140],   /* unit [dBm]; L1b21swathdata->normalSample */
float osSurf_in[29][5],           /* unit [dBm]; L1b21swathdata->osSurf       */
float osRain_in[11][28],          /* unit [dBm]; L1b21swathdata->osRain       */
int   osBinStart[29][2],          /* L1b21swathdata->osBinStart               */
float systemNoise_in[49],         /* unit [dBm]; L1b21swathdata->systemNoise  */
float zenith[49],                 /* unit [deg]; L1b21swathdata->scLocalZenith */
float lat[49],                    /* unit [deg]                               */
float lon[49],                    /* unit [deg]                               */
float scRange[49],                /* unit [m]; L1b21swathdata->scRange        */
int rayStart[49],                 /* L1b21header->rayHdr[].rayStart           */
```

```
int binEllips[49],              /* L1b21header->binEllipsoid                    */
int binSurfP_in[49],            /* L1b21swathdata->binSurfPeak                  */
int Height_mean_in[49],         /* unit [m];                                    */
                                /* Mean of DID/SRTM30 elev. (5 km box)          */
int Height_max_in[49][2],       /* unit [m];                                    */
                                /* Max. of DID/SRTM30 elev. [0]: 5 km, [1]: 11 km */
int Height_min_in[49][2],       /* unit [m];                                    */
                                /* Min. of DID/SRTM30 elev. [0]: 5 km, [1]: 11 km */
int Hmedian_in[49],             /* unit [m];                                    */
                                /* Median of DID/SRTM30 elev. 5 km * 5 km       */
int Hstd[49],                   /* unit [m]; RMS dev.   5km * 5km               */
int LWflag[49],                 /* DID land/water/coast flag;                   */
                                /*     = 0: water (ocean),                      */
                                /*       1: land,                               */
                                /*       2: coast,                              */
                                /*       3: inland water.                       */
```

6. Output data

```
int binClutterFreeBottom[49][2],   /* bin number with 125 m resol.       */
                                   /* (valid range: 1 - 400, and -99)    */
int ist[49].                       /* status for each bin.               */
                                   /*   ist[i] = 0: normal,              */
                                   /*            1: missing data input and/or */
                                   /*              data corruption,      */
                                   /*            2: bug (please notify author), */
                                   /*            3: DID/SRTM30 elev. doubtful, */
                                   /*            4: binSurfPeak doubtful     */
```

```
/*              maybe due to large ATT,      */
/*            5: binSurfPeak doubtful        */
/*              but not so serious as ist=4.  */
```

7. Output file specifications

The algorithm 1B21 outputs binClutterFreeBottom[49][2]:

==== In C language ====

```
int16 binClutterFreeBottom[49][2]:

    binClutterFreeBottom[i][0]: range bin number (with 125 m interval)
                                for clutter-free-bottom certain
    binClutterFreeBottom[i][1]: range bin number (with 125 m interval)
                                for clutter-free-bottom possible
```

where i stands for angle bin number running from 0 to 48, and

```
    binClutterFreeBottom[i][0] <= binClutterFreeBottom[i][1]
```

==== In FORTRAN language ====

```
INTEGER*2 binClutterFreeBottom (2,49)

    binClutterFreeBottom(1,j): range bin number (with 125 m interval)
                               for clutter-free-bottom certain
    binClutterFreeBottom(2,j): range bin number (with 125 m interval)
                               for clutter-free-bottom possible
```

where j stands for angle bin number running from 1 to 49, and

```
    binClutterFreeBottom(1,j) <= binClutterFreeBottom(2,j)
```

8. Interfaces with other algorithms

The clutter information, binClutterFreeBottom[49][2], is included in the output of

1B21 and 1C21 HDF files: binClutterFreeBottom[49][2] is used by Level 2 algorithms which need the main-lobe clutter information.

9. Special notes (caveats)

Though SRTM30 patch is introduced in the product-ver. 7(V7), there still remains the chance of occurring bad clutter free bottom (the occurrence of bad clutter free bottom is estimated to be less than 1 %, but not zero). Tibet and Andes are the most suspicious regions where bad clutter free bottom would still occur.

Main changes made in the V7 are as follows:

(a) Only normal sample data are used,
(b) In V7, binClutterFreeBottom is raised by the amount of one normal range bin when compared to that in V7 on average.

10. References

None.

1-1. 11. Redefinition of the Minimum Echo Flag

1. Introduction

After the TRMM satellite was launched, it was found that sidelobe echoes from the surface at nadir appeared in the radar received signal and that they sometimes were misidentified as rain echoes. In order to decrease the number of such misidentifications, the algorithm for defining the minEchoFlag was modified. A new algorithm was added to redefined the minEchoFlag by using the radar echo signals after removing some of the possible sidelobe echoes. The following section describes the algorithm to remove sidelobe echoes from the original radar echoes for this purpose.
Note, however, that the modified radar echoes are used only for this purpose internally, i.e., to redefine the minEchoFlag in 1B21, and that the output data from 1B21 are original radar echoes.
Note also that since the parameters for the removal of sidelobe surface echoes are chosen in a conservative way in order not to miss a real rain echo, some of the sidelobe echoes remain to be identified as rain echoes.

2. Sidelobe removal algorithm

The Precipitation Radar (PR) occasionally observes exceptionally large surface echoes at nadir. Since the PR sensitivity turned out to be better than the minimum requirement, a weak surface echo that is picked up by a sidelobe in the nadir direction appears occasionally in the echo region above the surface when the mainlobe is pointed offnadir. Such sidelobe surface echoes are sometimes identified as rain echoes if they are strong and appear in successive range bins.
Since the sidelobe echoes are caused by the reflection of sidelobe signal at nadir, they appear only at the range equal to the nadir range to the surface regardless of the mainbeam direction. Although the magnitudes of the sidelobe echoes naturally correlate with the magnitude of the mainlobe echo at the nadir, the ratio fluctuates substantially from one scan to another. In fact, the sidelobe echoes at different angle bins in a single scan do not correlate very well, either. Therefore, it is not possible to estimate the magnitudes of the sidelobe echoes from the mainlobe nadir return power and to subtract them from the radar echoes at slant incidence angles to remove the sidelobe echoes.

The basic strategy of the sidelobe removing algorithm adopted is as follows:

(1) Find a peak echo around the range corresponding to the nadir surface range,

(2) If this peak value is higher than the signal threshold and if the signals at 500 m above and 500 m below the peak are lower than the threshold, this peak echo and adjacent range bin echoes are identified as sidelobe clutter echoes.

(3) The data identified as sidelobe clutter are replaced by the interpolated data.

However, there are exceptions:

(4) Near the center of swath, the sidelobe range bin is too close to the surface and the bin 500 m below it is totally contaminated by the mainlobe clutter. In such an angle bin, only the comparison with the data above the expected sidelobe bin is made (in a rather conservative way to avoid missing a true rain echo).

(5) Except around the center of swath, the signal at the same height in the adjacent (inward) angle bin is also compared with the threshold, and unless this signal is smaller than the threshold, the original peak is not identified as sidelobe echo. This procedure is included to avoid misidentifying the bright band echo as a sidelobe echo.

3. Redefinition of minEchoFlag

With the data modified in the way explained above, the new algorithm runs the minimum echo detection routine with the rain certain threshold in the same way as the standard routine. If the result is low (not rain certain) and if the original minEchoFlag=20 (rain certain), then the added routine replaces the minEchoFlag of 20 by 13. If the result is high (rain certain) and if the original minEchoFlag=20, then it keeps minEchoFlag as 20 but replaces the binStormHeight for rain certain by the range bin number at which the rain certain flag is first set with the modified data.

1-2. 1C21: PR radar reflectivity

1-2. 1. Algorithm Overview

The 1C21 calculates the effective radar reflectivity factor at 13.8 GHz (Zm) without any correction of propagation loss (due to rain or any other atmospheric gas). Therefore, the Zm value can be calculated just by applying a radar equation for volume scatter with PR system parameters. The noise-equivalent Zm is about 21 dBZ. Through the subtraction of the system noise, the Zm value as small as 16 or 18 dBZ are still usable although the data quality is marginal. In 1C21, all echoes stored in 1B21 are converted to "dBZ" unit.
This is not relevant for "non-rain" echo; however, this policy is adopted so that the 1B21 and 1C21 product format should be as close as possible except for the following points:

- Radar quantity is Zm in dBZ unit instead of received power (dBm).
- Data at echo-free range bins judged in 1B21 are replaced with a dummy value.

1-2. 2. File Format

The 1C21 product is written in Hierarchical Data Format 4 (HDF4) as same with 1B21.

1-2. 3. Structure of output variables

The structure of output variables is exactly the same as that of 1B21.

1-2. 4. Detailed description of output variables

The main output of the PR Level-1C, 1C21, is the radar “reflectivity factor.”
All variables are copy of 1B21 products except for the replacement of the received power by the radar reflectivity factor and noise (no echo range bin) by a dummy value.

(31) normalSample [140][49][nscan] (2-byte integer):
Radar reflectivity factor (dBZ, mm6/m3) of the normal sample, multiplied by 100 and stored as a 2-byte integer. The units are dBZ * 100. For example, -9436

represents –94.36 dBZ.
The radar equation used is

$$Pr(range) = \frac{\pi^3 |K|^2}{2^{10} ln2} \frac{Pt * Gt * Gr * along * cross * c * pulse}{wavelength^2} \frac{1}{range^2} Zm$$

$$dBZm = 10log\left(10^{(Ps/10)} - 10^{(Pn/10)}\right) - C + 20log(range)$$

Ps: 1B21 received power
Pn：1B21 noise level
range：Distance

$$C = Pt + Gt + Gr + 10log(along \times cross) + 10log(c \times pulse) - 20log(wavelength) + C_0$$

Pt: transmitter power (in power）
pulse：transmitter pulse width (in power）
Gt: transmit antenna gain (in ray header）
Gr: receive antenna gain (in ray header）
along：Along-track beam width (in ray header）
cross：Cross-track beam width (in ray header）
c：speed of light
wavelength：wave length (in ray header）
C_0:Radar Constant (in ray header)

If received power is below the noise level, the reflectivity is filled with a dummy value of -32700.

*Note that the radar reflectivity factors given in 1C-21 are apparent values and include rain or atmospheric attenuation.

(32) osSurf [5][29][nscan] (2-byte integer):
Radar reflectivity factor (dBZ, mm6/m3) of the surface echo oversample for the central 29 rays (rays number 11-39), multiplied by 100 and stored as a 2-byte integer. The units are dBZ * 100.

(33) osRain [28][11][nscan] (2-byte integer):
Radar reflectivity factor (dBZ, mm6/m3) of the rain echo oversample for the central 11 rays (rays number 20-30), multiplied by 100 and stored as a 2-byte integer. The units are dBZ * 100.

1-2. 5. Major changes in 1C21 algorithm for product version 7

1. Data format

Science data and meta data are defined by PPS I/O Toolkit. Some variable names are renamed and added.

2. Level 2

2-1. 2A-21: Surface Reference Technique (Version 7)

2-1. 1. Objectives and functions of the algorithm

The primary purpose of 2A-21 is to compute the path-integrated attenuation (PIA) using the surface reference technique (SRT). The surface reference technique rests on the assumption that the difference between the measurements of the normalized surface cross section outside and within the rain provides an estimate of the PIA. The secondary purpose of 2A-21 is to compute the normalized radar cross sections (σ^0 or NRCS) of the surface under rain-free conditions.

A spatially or temporally averaged estimate of the rain-free normalized radar surface cross section (σ^0 or NRCS) is used as a reference value for computing the PIA. The algorithm computes up to five alternative estimates of PIA (corresponding to five different σ^0 reference estimates, one temporal and up to four spatial). An effective PIA is obtained by weighting the individual estimates by a factor proportional to the inverse of the variance of the estimate and summing the results. Some of the reference estimates depend on the direction of processing, so the orbit is processed twice—in the forward direction, and again backward with respect to the orbital direction. This provides two reference values for the direction-sensitive methods. The estimates used are listed below:

Along-track Spatial Average: This is formed from an average of the N_s most recent rain-free σ^0 measurements in same angle bin and with the same surface type (currently N_s=8). In version 7, two values of this reference are obtained by running the orbit forward and backward.

Hybrid or Cross-Track: The hybrid reference data results from a quadratic fit of the along-track spatial average data over the 49 angles bins within the cross-track swath. In version 7, separate fits are done for the inner (less than 11.25°) and outer swath (greater than 11.25°). As with the along-track spatial reference, the cross-track hybrid is computed twice by processing the orbit forward and backward.

Temporal Average: In versions prior to version 7, the temporal average was computed as the monthly average of the rain-free σ^0 data at 1°×1° latitude-longitude cells, categorized into 26 incidence angles ±0.75° × j, j=0,..,24 where a 26th category is defined to account for incidence angles beyond 18°. In version 7, the temporal reference data set are provided at a 0.1°×0.1° latitude-longitude resolution where the data sets have been computed off-line for each month using 12 years (1998-2009, inclusive) of rain-free σ^0 measurements. As in previous versions, the data are categorized into 26 incidence angles. Unlike earlier versions, however, three 0.1°×0.1° files are computed for each month (for a total of thirty-six temporal reference files) for land, ocean and coastal backgrounds.

Different estimates for along-track and hybrid methods are obtained from forward and backward processing. This provides up to five estimates of path attenuation—*Forward Along-track*, *Forward Hybrid*, *Backward Along-track*, *Backward Hybrid*, *and Temporal*—for each rain observation. Note that the hybrid estimates are only available over ocean since the cross-track fitting procedure does not work well over land. The different reference estimates are filtered according to various criteria. For example, an along-track estimate is dropped if the location of the reference data is too far from the observed rain point. A temporal estimate is dropped if the number of prior rain-free observations in the reference cell is too few. The surviving estimates are weighted by the inverse of their associated variance. The weighted estimates are summed to yield an effective PIA, `pathAtten`. The individual estimates, `PIAalt`, and their weights, `PIAweight,` are included in the 2A-21 product. A discussion of the weights and the effective PIA, variance, and reliability factor is given in section 9.

In addition to the sample mean of the NRCS as a function of angle bin, the reference data sets also include the standard deviation and number of data points used to compute the sample mean.

The temporal surface reference data sets were computed from version-6 2A-21 `sigmaZero` data for each month for the 12 years 1998 to 2009 inclusive. Separate data sets were computed for Ocean, Land, and Coast surface types so that a total of 36 temporal reference files are obtained. The statistics were computed over a 0.1°×0.1° (latitude, longitude) grid. Within each 0.1°×0.1° cell, the data are further categorized into incidence angle categories (26). The mean, standard deviation, and number of observations in each category is recorded. In summary, 36 temporal reference files have been generated each with dimension (740, 3600, 26, 3) which correspond to the number of latitude, longitude, incidence angles, and statistical bins (mean, standard deviation and counts), respectively. Note that in the temporal reference data set no distinction is made between the port and starboard incidence angles so that instead of 49 incidence angles, there is only 25+1, where the additional bin is used to store data from angles outside the normal range.

In version 6, the temporal data set was computed over the previous month during regular 2A-21 processing. The latitude-longitude resolution was 1°×1°, and there was no ocean-land-coast surface type distinction so that only one (rather than three) reference data set was generated.

In the spatial (along-track) surface reference data set, the mean and standard deviation of the NRCS are calculated over a running window of N_s fields of view before rain is encountered (currently, N_s=8). These operations are performed separately for each of the 49+2 incidence angles of TRMM, corresponding to the cross-track scan from -18° to +18° with respect to nadir. The 2 additional angle bins (making the total 51 rather than 49) are used to account for non-zero pitch/roll angles that can shift the incidence angle outside the normal range. Note that the zenith angle increment is taken to be 0.75° so that the angle bins can be defined by ±0.75° × j, j=0,..,24.

When rain is encountered, the mean and standard deviations of the reference σ^0 values are retrieved from the along-track spatial (forward and backward), the hybrid (forward and backward) and temporal surface reference data sets.
If a valid surface reference data set exists for one of the above estimates, then, denoting this by the jth estimate, the 2-way path attenuation (PIA) for the jth estimate is computed from the equation:

$$\mathrm{PIA}_j = \left\langle \sigma^0_{NR} \right\rangle_j - \sigma^0$$

where $<\sigma^0_{NR}>_j$ is the jth reference estimate and σ^0 is the value of the apparent normalized radar surface cross section at the rain field of view of interest. The PIA(2-way) is related to the specific attenuation or attenuation coefficient k (dB/km) by the equation:

$$\text{PIA}(2\text{-way}) = 2\int_0^{r_s} k(s)ds$$

To obtain information as to the reliability of the jth PIA estimate we consider the ratio of the PIA, as derived in the above equation, to the standard deviation as calculated from the rain-free σ^0 values and stored in the reference data set. Labeling this as $\texttt{std\_dev}_j$(reference value), then the reliability factor of the jth PIA estimate is defined as:

$$\text{reliabFactor}_j = \frac{\text{PIA}_j}{\text{std\_dev}_j(\text{reference value})}$$

When this quantity is large, the reliability is considered high and conversely.

The effective PIA, PIA_{eff}, and the corresponding reliability factor can be expressed in similar ways. From section 9, we have:

$$PIA_{eff} = (\Sigma u_j)^{-1}\Sigma u_j PIA_j$$

$$\text{Rel}_{eff} = (\Sigma u_j)^{-1/2}\Sigma u_j PIA_j$$

Where u_j is the inverse of the variance, σ_j^2, associated with the jth reference data set:

$$u_j = 1/\sigma_j^2$$

The summations are assumed to range over all valid reference data sets, even if the PIA's are negative. Over land, there can be a maximum of 3 valid reference data sets (forward and backward along-track and temporal) while over ocean there can be as many as five since the forward/backward hybrid reference data sets may be valid as well. It is worth mentioning that the definitions for the effective PIA and reliability factor reduce to those for the individual estimate when only a single PIA estimate is available. Note, finally, that in the notation used above:

$$\sigma_j = std\_dev_j(reference\_value)$$

2-1. 2. Definitions of Output Variables

`sigmaZero(49)` [real*4]

Normalized backscattering radar cross section of the surface (dB) (NRCS) for the 49 angles bins in the radar scan (unitless).

pathAtten(49) [real*4]

Estimated 2-way path-attenuation in (dB) where

$$\texttt{pathAtten} = 2\int_0^{r_s} k(s)ds$$

where *k(s)* is the attenuation coefficient in dB/km and integral runs from storm top to the surface. The path attenuation is often designated as the PIA, the path-integrated attenuation.

In the notation used above and in section 9:

$$\texttt{pathAtten} = PIA_{eff} = (\Sigma u_j)^{-1}\Sigma u_j PIA_j$$

Where u_j is equal to the inverse of the variance associated with the jth estimate of the PIA:

$$u_j = 1/\sigma_j^2$$

PIAalt(5,49) [real*4]

The path-integrated attenuation from the jth estimate, where

`PIAalt`(j=1, k)= PIA from forward along-track spatial at kth angle bin
`PIAalt`(j=2, k)= PIA from forward hybrid at kth angle bin
`PIAalt`(j=3, k)= PIA from backward along-track spatial at kth angle bin
`PIAalt`(j=4, k)= PIA from backward hybrid at kth angle bin
`PIAalt`(j=5, k)= PIA from temporal at kth angle bin

PIAweight(5,49) [real*4]

These are the weights of the individual PIA estimates used in deriving the effective PIA. The sum of the weights should equal one.

$$w_j = \frac{1}{\sigma_j^2}\frac{1}{\Sigma\frac{1}{\sigma_j^2}} \equiv u_j/\Sigma u_j$$

where

$$u_j = 1/\sigma_j^2$$

$$\sum w_j = 1$$

reliabFlag(49) [integer*2]

Reliability Flag for the PIA_{eff} estimate,

= 1 (PIA_{eff} estimate is reliable) - see definitions below

= 2 (is marginally reliable)

= 3 (is unreliable)

= 4 (provides a lower bound to the path-attenuation)

= 9 (no-rain case)

reliabFactor(49) [real*4]

Reliability Factor for the effective PIA estimate, `pathAtten`. This is defined as:

$$\texttt{reliabFactor} = \mathrm{Rel}_{eff} = (\Sigma u_j)^{-1/2} \Sigma u_j PIA_j$$

RFactorAlt(5,49) [real*4]

The reliability factors associated with the individual PIA estimates.

$$\texttt{RFactorAlt}_j = \mathrm{Rel}_j = PIA_j / \sigma_j ; j = 1,...,5$$

rainFlag(49) [integer*2]

Rain/no-rain flag (rain=1; no-rain=0). The rain-possible category from 1B-21 is included in the no-rain category; only the rain-certain category is considered rain.

incAngle(49) [real*4]

Incidence angle with respect to nadir (in degrees); pitch/roll correction is included.

refScanID(2,2,49) [integer*2]

`refScanID` gives the number of scan lines between the current scan and the beginning (or end) of the along-track reference data at each angle bin. The values are computed by the equation: `Current Scan Number - Reference Scan Number`. The values are positive for the Forward estimates and negative for the Backward estimates. The Fortran indices are:

1,1 - Forward - Near reference

2,1 - Forward - Far reference

1,2 - Backward - Near reference

2,2 - Backward - Far reference

refMethodFlag(49) [integer*2]

[This flag is currently not used. The output variable `PIAweight` can be used to obtain the influence of an individual PIA on the effective PIA.].

surfaceTracker(49) [integer*2]

= 1 (surface tracker locked - central angle bin)

= 2 (unlocked - central angle bin)

= 3 (peak surface return at normally-sampled gate - outside central swath)

= 4 (not at normally-sampled gate - outside central swath)

surfTypeFlag(49) [integer*2]

= 0 (ocean)
= 1 (land)
= 2 (coast)
= 3 (unknown or of a category other than those above or 'mixed' type)

2-1. 3. Description of the Processing Procedure

In v7, the granule is processed twice, in the forward orbit sequence, and again backwards. This is done because the along-track and hybrid methods use rain-free reference observations near the rain observation. By processing the orbit backwards, an independent estimate of rain attenuation is obtained. This gives up to 5 estimates that can be combined or filtered to select a "best" estimate. The five estimates are *Forward Along-track*, *Forward Hybrid* (Ocean only), *Backward Along-track*, *Backward Hybrid* (Ocean only), and *Temporal*.

2-1. 4. Interfaces to other algorithms

All input data for this algorithm is from 1B-21; the outputs are used by 2A-25, 3A-25 and 3A-26.

2-1. 5. Comments and Issues

a. A Gaussian beam approximation is used to represent the TRMM antenna pattern.

b. The radar return power used in computing σ^0 is that for which a 2.5 dB correction has been made. The factor accounts for the logarithmic averaging loss. Like the rain, the surface is treated as a Rayleigh target.

c. σ^0 is being computed from that (single) gate where the return power is a (local) maximum.

d. The algorithm assumes that rain is present only if `minEchoFlag/10` = 2 (rain certain); `minEchoFlag/10` = 1 (rain possible) and `minEchoFlag` = 0 (rain absent) are treated as no-rain cases. Note that the `minEchoFlag` variable is read from 1B-21.

e. Before version 6, images of path attenuation from 2A-21 sometimes showed a striated or streaky pattern where the attenuation estimates at one or more angles are larger than the estimates at adjacent angles. This occurred more often at near-nadir angles where high values of the surface cross section are observed under rain-free conditions. Where it is used, the cross-track-spatial hybrid method appears to eliminate most of these streaky patterns. As pointed out by Seto and Iguchi (2007), however, the quadratic function does not provide a good fit to the data over the full swath. In version 7, separate quadratic fits for the inner swath (angles less than 11.25^0) and outer swath (angles greater than 11.25^0) are used to improve the fitting function.

f. In previous versions of the algorithm (versions 1-4) the `reliabFactor` was defined as the difference: `pathAtten` - `std_dev`(reference value). In version 5 and 6, `reliabFactor` is defined as the ratio: `pathAtten/std_dev`(reference value).

g. Prior to version 6, when the PIA < 0, `pathAtten` was set to 0.0. `reliabFactor`, which in version 5 is proportional to PIA, was computed before `pathAtten` was set to 0, so it could be negative; `pathAtten` was never less than zero. In versions 6 and 7, `pathAtten` is no longer set to zero. Negative values are possible, although they will always be marked unreliable in the `reliabFlag`.

2-1. 6. Description of Temporal Intermediate File

In version 7, three temporal files (for Ocean, Land, and Coast) were computed for each month by averaging rain-free surface cross sections from 12 years of version 6 data. The statistics are computed as a function of incidence angle (26 categories) and location (0.1°×0.1° latitude-longitude grid). The statistics include mean, standard deviation, and number of counts.

2-1. 7. The Cross-track or Hybrid Surface Reference Method

In version 7, cross-track fitting of the data is done in the forward and backward directions for ocean surfaces. Cross-track fitting is not used for land or coast. Unlike version 6, separate cross-track fits are done for the inner (less than 11.25°) and outer swath (greater than 11.25°).

The input data for the cross-track fits are obtained from the spatial average for each angle bin. As in the along-track method, the average is computed from the last 8 rain-free observations over the same background type (i.e., ocean, land, or coast). The standard deviation from the spatial average is used as a weight in the fitting procedure. The fitted function is a quadratic where the fitting routine is based on the `LFIT` routine from Numerical Recipes (Press, et. al., 1989).

The spatial average at the *i*th angle bin is the average of the last 8 rain-free surface reflectivity values, σ^0_{NR},

$$y_i = \left\langle \sigma^0_{\mathrm{NR}}(\theta_i) \right\rangle$$

and, using "AS" to denote the along-track spatial reference, the standard deviation is

$$S_{\mathrm{AS}}(\theta_i) = \sqrt{\mathrm{var}(\sigma^0_{\mathrm{NR}}(\theta_i))}$$

The fit function for both the inner and outer swaths is the quadratic

$$\mathrm{yfit}(\theta_i) = a + b\theta_i + c\theta_i^2$$

Letting θ_{j1} and θ_{j2} denote the angles -11.25^0 and 11.25^0 with respect to nadir, then for the inner swath, the parameters *a*, *b*, and *c* are determined by minimizing

$$\chi^2 = \sum_{i=j1}^{j2} \left(\frac{y_i - \text{yfit}(\theta_i)}{S_{\text{AS}}(\theta_i)} \right)^2$$

A similar minimization is carried out over the angles from -18^0 to -11.25^0 and 11.25^0 to 18^0

$$\chi^2 = \sum_{i=1}^{j1-1} \left(\frac{y_i - \text{yfit}(\theta_i)}{S_{\text{AS}}(\theta_i)} \right)^2 + \sum_{i=j2+1}^{49} \left(\frac{y_i - \text{yfit}(\theta_i)}{S_{\text{AS}}(\theta_i)} \right)^2$$

(In practice there is a 2-bin overlap between the fits of the inner and outer swaths to ensure continuity.) The (2-way) cross-track or hybrid PIA is the difference between the Surface Reference value, `yfit(`θ_i`)`, and the apparent (attenuated) surface cross section, $\sigma^0{}_i$:

$$A_i = \text{yfit}(\theta_i) - \sigma_i^0$$

The standard deviation associated with this estimate is taken to be

$$std\_dev(S_{\text{AS}}) = \sqrt{\frac{1}{49} \sum_{j=1}^{49} S_{\text{AS}}^2(\theta_j)}$$

so that the reliability factor associated with the cross-track method is given by

$$\text{reliabFactor} = \frac{A_i}{std\_dev(S_{\text{AS}})}$$

2-1. 8. Revised Angle Bin Definitions

2A-21 defines two angle bins. The first, angle1, is computed from the absolute value of the incidence angle, and is used to categorize observations for the temporal Surface Reference Technique (SRT). It ranges from 1 to 26 (Fortran array convention). The other angle bin, angle2, depends on the signed incidence angle, and is used for the spatial SRT. It ranges from 1 to 51.

The angle bins angle1 and angle2 are defined such that

$$(\text{angle1} - 1 - 0.5)\Delta\theta \le |\theta| < (\text{angle1} - 1 + 0.5)\Delta\theta$$

$$(\text{angle2} - 26 - 0.5)\Delta\theta \le \theta < (\text{angle2} - 1 + 0.5)\Delta\theta$$

where θ is the incidence angle and $\Delta\theta$ is the angle bin size.

These relations can be expressed more simply by

$$\text{angle1} = \text{int}\left(\frac{|\theta|}{\Delta\theta} + 1 + 0.5\right)$$

$$\text{angle2} = \text{int}\left(\frac{\theta}{\Delta\theta} + 26 + 0.5\right)$$

respectively.

There was a problem with the implementation of this algorithm before version 6: $\Delta\theta$ was defined as the cross-track beam width, which is read from the 1B-21 Ray Header. The beam *positions* (as opposed to the beam width) are uniformly spaced with equal steps of 0.75°.

One effect of the old angle bin definition is that the angle bins were not uniformly populated. In general, each scan should have one beam position in each "angle2 bin" except for the extra edge bins (1 and 51). In fact, some bins were under-populated and some were over-populated because the angle bins did not correspond with the actual beam spacing.

In versions 6 and 7 of the 2A-21 algorithm, $\Delta\theta$ has been set to a constant value of 0.75°.

2-1. 9. Definitions of the Effective PIA, Variance and Reliability Factor

In version 7 of 2A-21, multiple estimates of PIA are generated. These correspond to different surface reference estimates – i.e., the estimate of the rain-free NRCS or σ°_{NR}. Specifically, we have the following situation

$$PIA_j = \left\langle \sigma^0_{NR} \right\rangle_j - \sigma^0 \quad (1)$$

where the first term on the right-hand side is the jth surface reference value and the second term is the apparent NRCS in rain. Note that there are as many as five reference values, corresponding to forward along-track, forward hybrid (cross-track), backward along-track, backward hybrid (cross-track) and temporal. Over land and coast, however, only three are used since the hybrid approach is not reliable. Associated with the jth reference data set is a variance, σ_j^2:

$$\text{var}(PIA_j) = \text{var}[\left\langle \sigma^0_{NR} \right\rangle_j] = \sigma_j^2 \quad (2)$$

From these PIA estimates we want to obtain an effective PIA. We assume it can be written in the form:

$$PIA_{eff} = \Sigma w_j PIA_j \quad (3)$$

Where the weights, w_j, are such that

$$\Sigma w_j = 1 \tag{4}$$

We assume that the individual PIA estimates are statistically independent so that the variance of PIA_{eff} is:

$$\text{var}(PIA_{eff}) = \Sigma w_j^2 \sigma_j^2 \tag{5}$$

To minimize this, subject to the side condition given by (4), we use the method of Lagrange multipliers where the expression

$$\Sigma w_j^2 \sigma_j^2 + \lambda(\Sigma w_j - 1) \tag{6}$$

is minimized with respect to the weights, w_j. Taking the partial derivatives of (6) with respect to w_i, then

$$2w_i \sigma_i^2 + \lambda = 0 \Rightarrow w_i = -\lambda / 2\sigma_i^2 \tag{7}$$

Also, using (4) gives

$$\Sigma w_j = -(\lambda/2)\Sigma(1/\sigma_j^2) = 1 \Rightarrow \lambda = -2/\Sigma(1/\sigma_j^2) \tag{8}$$

Substituting (8) into (7) gives an expression for the weights:

$$w_j = \frac{1}{\sigma_j^2} \frac{1}{\Sigma \frac{1}{\sigma_j^2}} \equiv u_j / \Sigma u_j \tag{9}$$

Where

$$u_j = 1/\sigma_j^2 \tag{10}$$

The effective PIA is then

$$PIA_{eff} = (\Sigma u_j)^{-1} \Sigma u_j PIA_j \tag{11}$$

In previous versions of 2A-21, the reliability factor, Rel, was defined as the ratio of the PIA to the standard deviation of the reference estimate, so that for the jth reference estimate, we can write:

$$\text{Rel}_j = PIA_j / \sigma_j \tag{12}$$

To apply this definition to the present situation, we define Rel_{eff} by the equation:

$$PIA_{eff} = (\Sigma u_j)^{-1}\Sigma u_j PIA_j \equiv \sigma_{eff}\,\mathrm{Rel}_{eff} \qquad (13)$$

Computing Rel_{eff} requires a value for the standard deviation of the effective PIA. This can be found by substituting (9) into (5) and by noting that $\sigma_{eff}^2 = \mathrm{var}(PIA_{eff})$. This gives

$$1/\sigma_{eff}^2 = \Sigma(1/\sigma_j^2) \Rightarrow \sigma_{eff}^2 = (\Sigma(1/\sigma_j^2))^{-1} = (\Sigma u_j)^{-1} \qquad (14)$$

Using (14) in (13) gives

$$\mathrm{Rel}_{eff} = (\Sigma u_j)^{-1/2}\Sigma u_j PIA_j \qquad (15)$$

Equations (9), (11) and (15) define, respectively, the weights, effective PIA, and effective reliability factor as computed in version 7 of 2A-21.

There are several issues related to these equations. For example, what should be done if none of the reference data sets exist? This situation can occur for measurements over small islands or small bodies of water or at coastal fields of view. For example, over a small island, there may be an insufficient number of non-raining fields of view adjacent to the rain area to form a valid spatial reference. In most cases, the temporal reference data set would be used (j=1 in the above equations) and the other reference estimates would be discarded. However, in some cases, there may be an insufficient number of data points in the temporal file to provide a valid estimate. In this case, a flag is set indicating that no valid reference data are available and all the output variables are set to -999. (Definitions of valid spatial and temporal reference data sets are discussed in sections 10 and 11 below.)

A somewhat different situation occurs if some of the reference data sets exist but all yield a negative PIA. For these cases, the individual variances will exist so that Rel_{eff}, PIA_{eff} and the effective variance should all exist. Note that for these cases Rel_{eff}, PIA_{eff} will be negative but the effective variance will be positive, as it should be.

A third type of situation occurs if one or more of the PIA estimates are positive and one or more of the PIA estimates are negative. In this case, the negative PIAs will be included in the definition of PIA_{eff}. In general, as long as the reference data is considered to be valid, the PIA will be used even if the value is negative.

According to these scenarios, there will be only one type of raining situation where the output variables will need to be set to some default value and this occurs when none of the reference data sets exist or are valid. This is expected to be a very small fraction relative to the total number of rain cases.

2-1. 10. Excluding Spatial Reference Data based on the refScanID Variable

This section addresses the conditions under which the spatial reference estimate is taken to be valid. For the forward-going spatial reference, reference data will almost always exist. An exception is if rain is encountered at the beginning of the orbit before N_s (=8) rain-free fields of view have been measured at a particular incidence angle. A similar exception occurs for the backward spatial methods: this occurs, however, at the end of the orbit rather than the beginning. In all other cases, forward and backward spatial reference data should exist. The question is how to exclude a spatial reference estimate if the data, used to form this estimate, are taken at locations far from the raining area. To implement this, the variable refScanID (section 2) is used. This is defined by

`refScanID(2,2,49)` [integer*2]

`refScanID` gives the number of scan lines between the current scan and the beginning (or end) of the along-track reference data at each angle bin. The values are computed by the equation: `Current Scan Number - Reference Scan Number`. The values are positive for the Forward estimates and negative for the Backward estimates. The Fortran indices are:

1,1 - Forward - Near reference

2,1 - Forward - Far reference

1,2 - Backward - Near reference

2,2 - Backward - Far reference

The forward along-track spatial reference data will be assumed to be invalid (at angle bin j) if:

|refScanID(2,1,j)| > 100 for ocean and

|refScanID(2,1,j)| > 50 for land and coast.

Similarly, the backward along-track spatial reference data will be assumed to be invalid (at angle bin j) if:

|refScanID(2,2,j)| > 100 for ocean and

|refScanID(2,2,j)| > 50 for land and coast.

The above conditions are equivalent to stating that, for a particular incidence angle, all the spatial reference data must be taken within 50 scans of the scan at which rain is encountered.

The criteria for the hybrid cross-track are more complicated because two quadratic fits are used for the inner and outer portion of the swath. Nominally, we will assume that if there are 15 or more angle bins in the inner portion of the swath for which:

|refScanID(2,1,j)| ≤ 100

then the forward hybrid cross-track method will be applied. Note that the hybrid cross-track is only applied to ocean backgrounds.

Similarly in the outer portion of the swath, if there are 15 or more angle bins in this portion of the swath for which:

$|refScanID(2,1,j)| \leq 100$

then the forward hybrid cross-track method will be applied.

Application of the backward cross-track follows the same rules using refScanID(2,2,j) instead of refScanID(2,1,j) .

2-1. 11. Excluding Temporal Reference Data

Under raining conditions, the temporal data file that is accessed depends on the month and surface type under which the raining measurement is made. The reference data at the 0.1°×0.1° cell and angle-bin of interest consists of the mean, mean square and number of rain-free data points, N_t, accumulated in the 12-year period from 1998 to 2009, inclusive. The reference data are considered valid if $N_t > 10$; otherwise, the reference data are considered invalid and will not be used in the calculation of the effective PIA.

2-1. 12. Command line arguments

`jobname`	PPS jobname
`1B21.inputfile.HDF`	the 1B-21 HDF file
`2A21.outputfile.HDF`	the 2A-21 HDF output file
`2A21.tr_ocean.dat`	the temporal file for ocean
`2A21.tr_land.dat`	the temporal file for land
`2A21.tr_coast.dat`	the temporal file for coast
`2A21.diag`	the verification (diagnostic) file

Note that the verification file is created in the program and should not exist prior to execution.

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2-2. 2A23

2-2. 1. Objectives of 2A23

Main objectives of 2A23 are as follows:

(a) Detection of bright band (BB) and determination of the height of BB, the strength of BB, and the width (i.e. thickness) of BB when BB exists.

(b) Classification of rain type into the following three categories:
- stratiform,
- convective,
- other,

where "other" means (ice) cloud only and/or maybe noise.

(c) Detection of shallow isolated and shallow non-isolated.

(d) Output of Rain/No-rain flag.

(e) Computation of the estimated height of freezing level.

(f) Output of the height of storm top.

2-2. 2. Main changes from the previous version

The current product version of 2A23 is V7 (version 7).

Main changes are as follows:

(a) Introduced a concept of small rain cell, which is classified as convective. (Effect appreciable.)
(b) About 40% of shallow non-isolated is classified as convective. (Effect appreciable.)
(c) GANAL data (Global analysis data by Japanese Meteorological Agency, JMA) is used for estimating 0C height, which was estimated using a climatological data in V6.
(d) When BB is detected, rain type is basically stratiform. Exception is introduced that even when BB is detected, rain type is convective if Z in the rain region exceeds a threshold. (The occurrence of this turns out to be very infrequent.)
(e) When storm top > 15 km and BB is not detected, rain type is convective.

(Occurrence is small, but affects some 3A25 statistics).
(f) Increased rain-type sub-categories.

2-2. 3. Method used in 2A23

(a) Detection of bright band (BB):
- Peak search by (1) using a spatial filter method [1], and (2) examining the slope in the upper part of BB profile. In the peak search, several conditions are imposed on the height profile of BB.

(b) Determination of the width of BB:
- By detecting upper and lower boundaries of BB along the slant path, then computing the thickness (i.e. width) of BB [2].

(c) Rain type classification:
- Vertical profile method (V-method) [1][2],
- Horizontal pattern method (H-method) [2][3].

(d) Detection of shallow isolated and shallow non-isolated:
- A simple examination of the height of storm top being much lower than the estimated 0C height. When an isolation condition is satisfied, the type is shallow isolated, otherwise shallow non-isolated. Here, the isolated condition means that the shallow area is isolated from the non-shallow area.

(e) Rain/No-rain flag:
- Almost identical to minEchoFlag recorded in 1C21 HDF file. Difference occurs when rain probable is detected or, on rare occasion, when corrupted input data are detected.

(f) Estimation of 0C height:
- 0C height is computed using GANAL data in the standard product of 2A23. A Temporal and spatial interpolation is made to obtain 0C height at a given location and a given observation time.
- For a real time product, 0C height is estimated from a climatological surface temperature data by assuming a constant lapse rate of 6.0 deg./km.

(g) Height of storm top:
- A simple conversion from range bin number to the height above the sea level.

2-2. 4. Processing Flow

(1) Open files.

(2) Read in 1C21 metadata, and copy the metadata to 2A23 HDF file.

(3) Read in necessary GANAL data for the estimation of 0C height (freezH).

(4) Read in scan header from 1C21 HDF file.

(5) Repeat reading in 1C21 scan data until the end of 1C21 HDF file, and do the following data processing for each scan:
   (a) Estimate freezH.
   (b) Compute the height of storm top (stormH).
   (c) Detect sidelobe clutter.
   (d) Detect BB. When BB is detected, compute the height of BB, the strength of BB, upper and lower boundaries of BB, and the width of BB, and set the status flag on BB detection.
   (e) Classify rain type by V-method. Reject sidelobe clutter during this processing.
   (f) Detect shallow isolated and shallow non-isolated.
   (g) Classify rain type by H-method. Reject sidelobe clutter during this processing.
   (h) Unify rain types.
   (i) Set status flag.
   (j) Write output to 2A23 HDF file.

(6) Close files and end the processing.

2-2. 5. Input data

(a) From 1C21 HDF file:

(1) metadata	
(2) rayStart[49]	(L1C21_RAY_HEADER)
(3) startBinDist[49]	(L1C21_RAY_HEADER)
(4) ScanTime (structure)	(L1C21_SWATH)
(5) scanTime_sec	(L1C21_SWATH)
(6) scanStatus.missing	(L1C21_SWATH)
(7) scanStatus.dataQuality	(L1C21_SWATH)
(8) Latitude[49]	(L1C21_SWATH)
(9) Longitude[49]	(L1C21_SWATH)
(10) minEchoFlag[49]	(L1C21_SWATH)
(11) binStormHeight[49][2]	(L1C21_SWATH)
(12) binEllipsoid[49]	(L1C21_SWATH)
(13) binClutterFreeBottom[49][2]	(L1C21_SWATH)

(14) binDIDHmean[49]	(L1C21_SWATH)
(15) scLocalZenith[49]	(L1C21_SWATH)
(16) scRange[49]	(L1C21_SWATH)
(17) osBinStart[29][2]	(L1C21_SWATH)
(18) landOceanFlag[49]	(L1C21_SWATH)
(19) binSurfPeak[49]	(L1C21_SWATH)
(20) normalSample[49][140]	(L1C21_SWATH)
(21) normalSample_scale[49][140]	(L1C21_SWATH)
(22) osSurf[29][5]	(L1C21_SWATH)
(23) osRain[11][28]	(L1C21_SWATH)

(b) Estimated height of 0C From GANAL for standard 2A23, and a climatological SST data (sst-hou.grd) for real time 2A23.

2-2. 6. Output data

(1) metadata	
(2) ScanTime (structure)	---- same as that of 1C21
(3) scanTime_sec	---- same as that of 1C21
(4) Latitude[49]	---- same as that of 1C21
(5) Longitude[49]	---- same as that of 1C21
(6) scanStatus (structure)	---- same as that of 1C21
(7) navigation (structure)	---- same as that of 1C21
(8) rainFlag[49]	Rain/No-rain flag (1-byte integer)
(9) rainType[49]	Rain type (2-byte integer)
(10) shallowRain[49]	Shallow rain flag (1-byte integer)
(11) status[49]	Status (1-byte integer)
(12) binBBpeak[49]	Range bin number for BB (2-byte integer)
(13) HBB[49]	Height of BB [m] (2-byte integer)
(14) BBintensity[49]	Strength of BB [dBZ] (4-byte float)
(15) freezH[49]	Estimated height of freezing level [m] (2-byte integer)
(16) stormH[49]	Height of storm top [m] (2-byte integer)
(17) BBboundary[49][2] (BBboundary(2,49) in FORTRAN)	Upper and lower boundaries of BB (2-byte integer)
(18) BBwidth[49]	Width of BB [m] (2-byte integer)
(19) BBstatus[49]	Status flag for BB (1-byte integer)
(20) spare[49]	Spare (2-byte integer)

2-2. 7. Output file specifications

This section describes details of items (8)-(19) in the previous section.

(a) int8 rainFlag[49]:

= 0 : no rain
10 : rain possible
11 : rain possible
12 : rain possible
13 : rain possible
15 : rain probable
20 : rain certain

-99 : data missing

Note: rainFlag is almost identical to minEchoFlag of 1C21 except for rain probable case and the following very exceptional case.
The exception occurs if 2A23 detects data missing but 1C21 says the data is normal - this can happen when the input data is corrupted. In normal conditions, the rain certain case in rainFlag is identical to the rain certain case in minEchoFlag of 1C21.

(b) int16 rainType[49]:

In V7 of 2A23, the flag rainType[i] (i=0 to 48) indicates the unified rain type by 3-digits numbers.

rainType[i]

= 100: Stratiform.
When R_type_V[i] = T_stra, (BB detected.)
and R_type_H[i] = T_stra.

105: Stratiform. --- added in V7.
When R_type_V[i] = T_stra, (BB detected.)
and R_type_H[i] = T_stra,
But storm top (determined by 2A23) is too high.

110: Stratiform.
When R_type_V[i] = T_stra, (BB detected.)
and R_type_H[i] = T_other.

115: Stratiform. --- added in V7.
When R_type_V[i] = T_stra, (BB detected.)

and   R_type_H[i] = T_other.
But storm top (determined by 2A23) is too high.

120: Probably stratiform.   (BB may exist but not detected.)
When R_type_V[i] = T_other,
and   R_type_H[i] = T_stra.

130: Maybe stratiform.
When R_type_V[i] = T_stra,   (BB detected.)
and   R_type_H[i] = T_conv.

135: Maybe stratiform.   --- added in V7.
When R_type_V[i] = T_stra,   (BB detection certain.)
and   R_type_H[i] = T_conv.
But storm top (determined by 2A23) is too high.

140: Maybe stratiform. (BB hardly expected.)
When R_type_V[i] = T_other,
and   R_type_H[i] = T_stra.

152: Maybe stratiform:
When R_type_V[i] = T_other,
R_type_H[i] = T_stra,
and shallowRain[i] = 20 or 21.
(Shallow non-isolated is detected.)

160: Maybe stratiform, but rain hardly expected near surface.
BB may exist but is not detected.
When R_type_V[i] = T_other,
and   R_type_H[i] = T_stra.

170: Maybe stratiform, but rain hardly expected near surface.
BB hardly expected.   Maybe cloud only.
Distinction between 170 and 300 is very small.
When R_type_V[i] = T_other,
and   R_type_H[i] = T_stra.

200: Convective.
When R_type_V[i] = T_conv,
and   R_type_H[i] = T_conv.

210: Convective.
When R_type_V[i] = T_other,
and   R_type_H[i] = T_conv;

220: Convective
When R_type_V[i] = T_conv,
and R_type_H[i] = T_other;

230: Probably convective. ---> Re-introduced in V7.
When R_type_V[i] = T_stra; (BB exists)
R_type_H[i] = T_conv;
and Z below BB is strong.

235: Probably convective. ---> Added in V7.
When R_type_V[i] = T_other;
R_type_H[i] = T_stra;
But storm top (determined by 2A23) is too high.

237: Probably convective. ---> Added in V7.
When R_type_V[i] = T_other;
R_type_H[i] = T_stra;
But the cell size is small.

240: Maybe convective.
When R_type_V[i] = T_conv,
and R_type_H[i] = T_stra;

251: Convective.
When R_type_V[i] = T_conv,
R_type_H[i] = T_conv,
and shallowRain[i] = 10 or 11;
(Shallow isolated is detected)

252: Convective.
When R_type_V[i] = T_conv,
R_type_H[i] = T_conv,
and shallowRain[i] = 20 or 21;
(Shallow non-isolated is detected)

261: Convective.
When R_type_V[i] = T_conv,
R_type_H[i] = T_conv;
and shallowRain[i] = 10 or 11;
(Shallow isolated is detected)

262: Convective.
When R_type_V[i] = T_conv,

R_type_H[i] = T_other;
and shallowRain[i] = 20 or 21;
(Shallow non-isolated is detected)

271: Convective.
When R_type_V[i] = T_other,
R_type_H[i] = T_conv;
and shallowRain[i] = 10 or 11;
(Shallow isolated is detected)

272: Convective.
When R_type_V[i] = T_other,
R_type_H[i] = T_conv;
and shallowRain[i] = 20 or 21;
(Shallow non-isolated is detected)

281: Convective.
When R_type_V[i] = T_conv,
R_type_H[i] = T_stra;
and shallowRain[i] = 10 or 11;
(Shallow isolated is detected)

282: Convective.
When R_type_V[i] = T_conv,
R_type_H[i] = T_stra;
and shallowRain[i] = 20 or 21;
(Shallow non-isolated is detected)

291: Convective:
When R_type_V[i] = T_other;
R_type_H[i] = T_stra;
and shallowRain[i] = 10 or 11;
(Shallow isolated is detected)

292: Convective: --- added in V7.
When R_type_V[i] = T_other;
R_type_H[i] = T_stra;
and shallowRain[i] = 20 or 21;
Though this is shallow non-isolated, the appearance is 'sporadic', hence convective.

297: Convective: --- added in V7.
When R_type_V[i] = T_other;
R_type_H[i] = T_stra;

shallowRain[i] = 20 or 21;
(Shallow non-isolated is detected)
But the cell size is small.

300: Other.
When R_type_V[i] = T_other;
and R_type_H[i] = T_other;
This category includes very weak echo (possibly noise) and/or cloud.

311: Others. --- added in V7.
When R_type_V[i] = T_other,
R_type_H[i] = T_other;
and shallowRain[i] = 10 or 11;
(Shallow isolated is detected)

312: Other.
When R_type_V[i] = T_other,
R_type_H[i] = T_other;
and shallowRain[i] = 20 or 21;
(Shallow non-isolated is detected)

313: Other.
When R_type_V[i] = T_other,
R_type_H[i] = T_other;
If sidelobe clutter were not rejected, shallow isolated would be detected.

where T_stra, T_conv, and T_other are three distinctive values specifying rain types. Three major rain categories, stratiform, convective, and other, can be obtained as follows:
When rainType[i] > 0,
rainType[i] / 100 =1: stratiform,
2: convective,
3: other.

When it is "no rain" or "data missing", rainType[i] contains the following values:
-88 : no rain
-99 : data missing

Caution: When rainFlag[i]=10-15 (rain possible/rain probable), rainType[i]/100=3 because if it is rain, the type may not be startiform nor convective, suggesting that the type maybe other. However, 2A25 does not compute rainfall rate for rain possible/rain probable. Please don’t examine rainType[i] for rainFlag[i]<20, otherwise users may find a paradoxical situation that the rain type is other but no rainfall rate is calculated for rain possible/rain probable. Users should regard rain possible/rain probable as no rain case, and should not be bothered by the content of rainType[i], which should be examined only when rainFlag[i]=20 (i.e., rain certain).

(c) int8 shallowRain[49]:

= 0 : no shallow isolated
10 : maybe shallow isolated
11 : shallow isolated (with confidence)
20 : maybe shallow non-isolated
21 : shallow non-isolated (with confidence)

-88 : no rain
-99 : data missing

(d) int8 status[49]: Status flag for the processing of 2A23.

This flag is meaningful when status >= 0, and indicates a confidence level of 2A23 as follows:

0 <= status < 10 : good,
10 <= status < 50 : maybe good,
50 <= status < 100 : result not so confident (warning),
100<= status : bad (untrustworthy because of possible data corruption).

This flag also takes the following values:

-88 : no rain
-99 : data missing

(e) int16 binBBpeak[49]: Range bin number for the height of bright band peak.

> 0 : Range bin number corresponding to 125m intervals.
This also indicates that the bright band is detected.
= -1111 : No bright band
= -8888 : No rain
= -9999 : Data missing

(f) int16 HBB[49]: Height of bright band.

> 0 : Height of bright band expressed in [m]
This also indicates that the bright band is detected.
= -1111 : No bright band
= -8888 : No rain
= -9999 : Data missing

HBB[i] (i=0 to 48) is computed by the following formula:

HBB[i] = (L1c21_swath_data->scRange[i] - rangeBB)* cos(zenith[i]);

where
rangeBB = (binBBpeak[i]
- L1c21header->rayHdr[i].rayStart)*125
+ L1c21header->rayHdr[i].startBinDist;

(g) float32 BBintensity[49]: Bright band intensity in dBZ.
> 0 : Peak value of Z in BB [dBZ]
= -1111.0 : No bright band
= -8888.0 : No rain
= -9999.0 : Data missing

(h) int16 freezH[49]:
Estimated 0C height obtained from GANAL data.
> 0 : Estimated 0C height [m]
= -5555 : When error occurred in the estimation of freezH
= -9999 : Data missing

(In a real time version of 2A23, however, a climatological SST data (sst-hou.grd) is used for computing freezH.)

(i) int16 stormH[49]: Height of storm top.
> 0 : Height of storm top [m] (with high level of confidence)
= -1111 : No stormH with high level of confidence
= -8888 : No rain
= -9999 : Data missing

This height is computed only in the case of rain certain, i.e., minEchoFlag[i]=20.

It is computed by

stormH[i] = (L1c21_swath_data->scRange[i] - range)* cos(zenith[i]);

where
range = (binStormHeight[i][1]
- L1c21header->rayHdr[i].rayStart)*125
+ L1c21header->rayHdr[i].startBinDist;

NOTE: Though 1C21 outputs the following two kinds of binStormHeight for each angle bin,

binStormHeight[i][0]: possible value,

binStormHeight[i][1]: certain value,

2A23 converts only the certain value of binStormHeight to stormH.

(j) int16 BBboundary[49][2]: Upper and lower boundaries of BB.
This flag is meaningful when >0, and indicates
BBboundary[i][0]: range bin number for upper boundary of BB (BBboundary(1,i) in FORTRAN),
BBboundary[i][1]: range bin number for lower boundary of BB (BBboundary(2,i) in FORTRAN),

where range bin number specifies range with 125 m intervals.

(k) int16 BBwidth[49]: Width of BB (meaningful when >0).
At nadir (i=24 in C language), the width of BB [m] is computed simply byBBwidth[24] = (BBboundary[24][1]- BBboundary[24][0])*125;
At other angles, the effect of oblique incidence is subtracted using an Empirical formula (see item (4) in Appendix). In V7, BBwidth is trustworthy only at nadir direction.

(l) int8 BBstatus[49]:
This flag indicates the quality of BB detection, BB boundaries, and BB width in the following way:

```
BBstatus[i] = BB_detection_status * 16
    + BB_boundary_status * 4
    + BB_width_status;
```

where, each status on the right hand side takes the following values
1: poor,
2: fair,
3: good.
BBstatus is meaningful when >0.

2-2. 8. Interfaces with other algorithms

(a) 2A23 uses 1C21 HDF file as an input file.
(b) 2A23 output is used by 2A25, 2B31, 3A25, and 3A26.

2-2. 9. Special notes

(a) Bright band (BB) detection has angle bin dependence because of the smearing of the shape of BB peak near the antenna scan edges.

(b) When 2A23 misses strong BB, rain type may sometimes be mis-classified as convective. This possibility would be high for low-altitude BB which exists near antenna scan edges.

(c) The height of BB shows a large variations mainly because of a relatively coarse range resolution of 250m.

(d) Bright band detection is carried out for rain-certain case only, and rain type classification is meaningful only for rain-certain case.

(e) Rain type is expressed by 3-digits number inV7.

(f) Rain type of all the shallow isolated is convective in V7, though the echo intensity of most of the shallow isolated is weak (see [4] for details). About 40 % of shallow non-isolated is convective in V7. Since most of shallow rain is masked by the surface clutter near antenna scan edges, the count of shallow rain shows dependence on antenna scan angle. In V7, the count of convective rain also shows dependence on antenna scan angle because of the angle bin dependence of shallow rain.

(g) Though rainType[i] for "rain possible/rain probable" is given by 2A23 V7 (and V6 as well), users should not use this information. The flag rainType[i] is meaningful for the case of rain certain (i.e., rainFlag[i]=20) only. (See the note at the end of the item (b) of 2-2.7.)

(h) Effect of satellite boost from 350 km altitude to 400 km altitude on 2A23 is small. When statistical analysis is made on 2A23 quantities (such as rain type count and BB count), only a small difference shows up between the statistics of 2A23 quantities before the boost of the TRMM satellite and those after the boost.

(i) V7 outputs freezH even when there is 'no rain'.

2-2. 10. References

[1] Awaka, J., T. Iguchi, and K. Okamoto, "Early results on rain type classification by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar," Proc. 8th URSI Commission F Open Symp., Aveiro, Portugal, 143-146, 1998.

[2] Awaka, J., T. Iguchi, and K. Okamoto, "TRMM PR standard algorithm 2A23 and its performance on bright band detection, " J. Meteor. Soc. Japan, 87A, 31-57, 2009.

[3] Steiner, M., R.A. Houze, Jr., and S.E. Yuter, "Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data," J. Appl. Meteor., 34, 1978-2007, 1995.

[4] Schumacher, C. and R.A. Houze, Jr., "The TRMM Precipitation Radar's View of Shallow, Isolated Rain," J. Appl. Meteor., 42, 1519-1524, 2003.

[5] Fabry, F. and I. Zawadzki, "Long-term radar observations of the melting layer of precipitation and their interpretation," J. Atmos. Sci., 52, 838-851, 1995.

[6] Klaassen, W., "Radar observations and simulation of the melting layer of precipitation," J. Atmospheric Sciences, 45, 3741-3753, 1988.

Appendix. Some details of 2A23

(1) freezH[i] (i=0, ..., 48)

In the standard product of 2A23, the 0C height, freezH[i], is computed using GANAL, which has a 1.25 x 1.25 degrees horizontal resolution and is available 4 times a day at 0 LT (Local Time), 6 LT, 12 LT, and 18 LT.

The 0C height at an observing location is spatially and bi-linearly interpolated at T1, which is 0LT or 6LT or 12 LT or 18 LT, and T1 satisfies T1 <= t < T1+6 [hours] where t is the observation time. The 0C height at the observing location at T1+6 [hours] is also spatially and bi-linearly interpolated. From thus obtained 0C heights at T1 and T2, the 0C height for the observing location at t is linearly interpolated with respect to time.

(In the real time product of 2A23, the 0C height, freezH[i], is computed from a climatological surface temperature by assuming the lapse rate of the temperature of 6.0 [deg/km].)

(2) BB detection

In the BB detection, several conditions are imposed on BB, whose height is designated by HBB. Major conditions for the existence of BB are as follows:

(a) BB has a peak,
(b) HBB must be close to freezH-0.5km (within +/-2.5km) ,
(c) Z must have a large slope at height above HBB,
(d) HBB must be close to each other,
(e) When Z at HBB, Z_hbb, exceeds 40 dBZ, Z below HBB should not decrease rapidly.

Note: The condition (e) is to avoid a false peak due to a strong attenuation in the case of strong convective rain.

A two dimensional BB filter is introduced in 2A23 V7 to filter out the false BB.

(3) Upper and lower boundaries of BB

The lower boundary of BB is detected first. The lower boundary of BB is defined as the point where there is the largest change in the slope of Z in the region just below the BB peak (and of course the point is not far away from the BB peak).

The upper boundary of BB is determined by finding the following two points A and B:

Point A: where there is the largest change in the slope of Z in the upper region of BB peak.

Point B: where Z becomes smaller than Z at the lower boundary of BB for the first time when Z is examined upward in the upper part of BB starting from the BB peak.

When points A and B are the same, the upper boundary of BB is defined as the point A (which is the same as the point B in this case). When points A and B are different, the upper boundary of BB is defined as either A or B which is closest to the BB peak. Here, the definition of the lower boundary of BB is very close to that by Fabry and Zawadzki [5], and the definition of the upper boundary is the one which is somewhere in between the definition by Fabry and Zawadzki [5] and that by Klaassen [6].

(4) Width of BB

The width of BB in the nadir direction is computed as follows:

```
BBwidth[24] = (BBboundary[24][1]- BBboundary[24][0])*125;
```

where BBwidth[24] is the width of BB in the nadir direction, and BBboundary[24][0] and BBboundary[24][1] are respectively range bin number for upper boundary of BB and that for lower boundary of BB (see section 2-2.7).

At other antenna scan angles, the effect of oblique incidence is subtracted using the following empirical formula:

```
BBwidth[i] = (BBboundary[i][1] - BBboundary[i][0]
                              – L sinTH[i] ) * cosTH[i] * 125;
```

where the index i denotes the angle bin number, TH[i] is the local zenith angle, and L is given by

```
L = (Lo F) / (cosTH[i])^2
```

and where Lo is the footprint diameter of antenna beam (which is about 4.3 km when the altitude of the TRMM satellite is 350 km), and F is an empirical correction factor (F = 0.5).

The above formula for BBwidth[i] sometimes gives unrealistically small value, or in some cases even negative value. To avoid such a difficulty, a lower bound for BBwidth[i] is set as follows:

If the above formula gives BBwidth[i] being smaller than 500*cosTH[i] meters (when normal sample data is used), the width of BB is computed by

BBwidth[i] = 500 * cosTH[i] [m] (for normal sample)

When oversample data is available, the lower bound for BBwidth[i] is given by

BBwidth[i] = 250 * cosTH[i] [m] (when oversample data is available)

(5) Shallow isolated and shallow non-isolated.

The following two conditions are imposed for the detection of shallow isolated:

(a) Shallow condition: Storm top is much lower than the 0C height.
(b) Isolated condition: Shallow isolated must be isolated from the other non-shallow rain areas.

When the first condition (a) is satisfied, it then goes on to test whether the isolation condition is satisfied or not by examining the horizontal pattern of rain types. Shallow non-isolated is the rain which satisfies the condition (a) only.

When shallow isolated is detected, shallowRain flag is set to 10 or 11 depending on the level of confidence. Similarly, when shallow non-isolated is detected, shallowRain flag is set to 20 or 21 depending on the level of confidence.

Hstorm < freezH - 1000 m (1.0 km)
→ shallowRain[i] = 10: maybe shallow isolated,
20: maybe shallow non-isolated,

Hstorm < freezH - 1500 m (1.5 km)
→ shallowRain[i] = 11: shallow isolated
(with higher level of confidence),
21: shallow non-isolated
(with higher level of confidence),

where freezH is the estimated 0C height.

If shallow isolated or shallow non-isolated is detected over land, the judgment is always 'maybe shallow isolated' or 'maybe shallow non-isolated' no matter how low the height of storm top is because freezH may not be trustworthy over land.

(6) Rain type classification by V-method

The vertical profile method (V-method) classifies rain into three categories: stratiform, convective, and other. Outline of the V-method is as follows:

(a) When BB exists, rain is classified as stratiform,
(b) When BB is not detected, and the maximum value of Z at a given angle bin exceeds 40 dBZ, rain type for this angle bin is classified as convective,
(c) Other type is defined as not-stratiform and not-convective.

It should be noted in (c) that other type of rain by the V-method is defined as not convective and not stratiform: this means that

(i) there exists appreciable radar echo but it is not strong enough to be convective,
(ii) BB is not detected.

Therefore the other type by the V-method consists of the following cases:

(A) Cloud,
(B) Actually stratiform, but BB detection fails,
(C) Ambiguous because radar echo is not strong enough to be convective and BB does not exist,
(D) Simply noise.

(7) Rain type classification by H-method

The horizontal pattern method (H-method) also classifies rain into three categories: stratiform, convective, and other, but with the definitions of these being different from those of the V-method. The H-method is based on the University of Washington convective/stratiform separation method [3], which examines the horizontal pattern of Z at a given height; where Z has a 2 km horizontal resolution. In 2A23, the following modifications are made:

(a) Instead of examining a horizontal pattern of Z at a given height, a horizontal pattern of Zmax is examined; here, Zmax is the maximum of Z along the range for each antenna scan angle below freezH (minus 1 km margin).
(b) Parameters are changed so that they may be suitable for the TRMM data with 4.3 km horizontal resolution. Choice of parameters was made before the launch of TRMM using a test GV data in such a way that a 4.3 km resolution data produces almost the same result as that with a 2 km resolution data.

(c) Other type of rain is introduced to handle noise.

In the H-method, detection of convective rain is made first. If one of the following condition is satisfied at a pixel, which correspond to the angle bin data being considered, it is judged that the pixel is a convective center:

(A) Zmax exceeds 40 dBZ, or
(B) Zmax stands out against the background area.

Rain type for a convective center is convective, and rain type for the (four) pixels nearest to the convective center is also convective.

If rain type is not convective and if the rain echo is certain to exist, rain type is stratiform.

Rain type by the H-method is 'other' if the radar echo below freezH (with a margin) at a given angle bin is possibly noise.This means that the other type by the H-method includes the case of (i) noise, and (ii) cloud.

(8) Unification of rain type

Since the algorithm 2A23 includes two independent methods for classifying rain type, it would not be friendly to the users if 2A23 outputs the rain types by the two methods separately. To make the result user-friendly, 2A23 outputs the unified rain type (for details, see (b) of '2-2.7. Output file specifications'). The unified rain type is expressed by 3 digits: the first digit indicates the rain type (1: stratiform, 2: convective, 3: other), and the last two digits indicate sub categories.
Note that the rain types by V-method and H-method can be reconstructed from the unified rain type by using a suitable table (in other words, the unification of rain type is made without loss of information).

(9) Small rain cell

When there is a single rain pixel or there are two adjacent rain pixels, those are regarded as small cells, and the rain type for small cell pixels are classified as convective in 2A23 V7.

(10) Rain type of shallow non-isolated

When shallow non-isolated appears “randomly” in one antenna scan, those “randomly” appeared shallow non-isolated are classified as convective in 2A23 V7. Here, “random” appearance of the shallow non-isolated is defined as follows:

(Definition) Examine one antenna scan data (which means that to examine the data in the direction perpendicular to the satellite movement). When the count of shallow non-isolated is smaller than 3 or equal to 3 but not being contiguous, it is judged that shallow non-isolated appears “randomly”.

2-3. 2A25

2-3. 1. Objectives

The objectives of 2A25 are to correct for the rain attenuation in measured radar reflectivity (Z_m) and to estimate the instantaneous three-dimensional distribution of rain from the TRMM Precipitation Radar (PR) data. The estimated vertical profiles of attenuation-corrected radar reflectivity factor (Z_e) and rainfall rate (R) are given at each resolution cell of the PR. The estimated rainfall rate at the actual surface height and the average rainfall rate between the two predefined altitudes (2 and 4 km) are also calculated for each beam position.

2-3. 2. Changes from V6 to V7

The major points of improvement in V7 are as follows:

The adjustment parameter ε for α in the k-Z_e relationship (α in k=α $Z_e{}^{\beta}$) is estimated by the maximum likelihood method instead of calculating the expected value of ε.

- The vertical profile of α (phase state model) is substantially changed above 0 degree C height. The ratios of ice and water in a precipitation particle as a function of height are redefined. The new profile assumes that particles are 100% ice above -20℃ level. The value of α is linearly interpolated between the top of bright band (for stratiform rain with a bright band) or 0℃ level and -20℃ level. (Note that the profile in V7 is different from what is written in Iguchi et al. 2009.)

- A new drop size distribution (DSD) model which is defined in terms of the Z-R relation is introduced as the default DSD model. In the new stratiform rain model, Z decreases by 0.5 dB. With this Z-R relation, R increases by about 8%, if no adjustment is carried out. new Z_e-R and k-Z_e relations are introduced based on a non-spherical rain drop model. (R decreases for heavy rain)

- Errors in the PIA estimates from the surface reference technique (SRT) and in ζ are redefined. In V7, the fading noise in Z_m is taken into account when we calculate the error of ζ which depends on α and Z_m. The error in the non-uniform beam filling (NUBF) correction is also taken into account. As a result the adjustment of the *R*-*Z* relation by change in ε decreases (*R* increases in regions where ε is less than 1).

- NUBF correction which was abandaned in V6 is re-introduced in V7. The error in the NUBF correction formula in V5 was corrected. The introduction of NUBF correction will in general increase rain estimates for heavy rain.

- Blurring of the bright band at off-nadir angle bins is compensated to some extent when Z_e profiles are converted into *R* profiles.

Details of these changes except the compensation of blurring effect are described in Iguchi et al. (2009).

2-3. 3. Algorithm Overview

2A25 basically uses a hybrid of the Hitschfeld-Bordan method and the surface reference method to estimate the vertical profile of attenuation-corrected effective radar reflectivity factor (Z_e). (The hybrid method is described in Iguchi and Meneghini (1994).) The vertical rain profile is then calculated from the estimated Z_e profile by using an appropriate Z_e-R relationship. One major difference from the method described in the above reference is that in order to deal with the uncertainties in measurements of the scattering cross section of surface as well as the rain echoes, a probabilistic method is used. Since radar rain echoes from near the surface are hidden by the strong surface echo, the rain estimate at the lowest point in the clutter-free region is given as the near-surface rainfall rate for each angle bin.

2-3. 4. More Detailed Description of the Algorithm

The major input data to 2A25 are the measured radar reflectivity factor Z_m, the apparent decrease of the surface cross section ($\Delta\sigma^0$), its reliability, the rain type and miscellaneous height information. The algorithm first defines the region for processing: It processes only the data between the rain top and the lowest height above the surface that is free from the surface clutter. (The current algorithm does not use any data below the surface, i.e., the mirror image.)

The bright-band height and freezing height given by 2A23 are used to define the regions of liquid (water), solid (ice), and mixed phase of precipitating particles. The initial values of the coefficients in the k-Z_e and Z_e-R relationships at different altitudes are accordingly defined.

The attenuation correction is, in principle, based on the surface reference method. This method assumes that the decrease in the apparent surface cross section is caused by the propagation loss in rain. The coefficient α in the k-Z_e relationship $k=\alpha Z_e^{\beta}$ is adjusted in such a way that the path-integrated attenuation (PIA) estimated from the measured Z_m-profile will match the reduction of the apparent surface cross section. The attenuation correction of Z_e is carried out by the Hitschfeld-Bordan method with the modified α. Since α is adjusted, we call this type of surface reference method the α-adjustment method.
The α-adjustment method assumes that the discrepancy between the PIA estimate from $\Delta\sigma^0$ and that from the measured Z_m-profile can be attributed to the deviation of the initial α values from the true values which may vary depending on the raindrop size distribution and other conditions. It assumes that the radar is properly calibrated and that the measured Z_m has no error.

The surface reference method generally works rather well as long as the apparent decrease in surface cross section $\Delta\sigma^0$ is much larger than the fluctuations of the true surface cross section. When the decrease is not significant, however, the relative error associated with this method in the estimates of rainfall rate becomes large since the fluctuation of surface cross section, which remains finite even when there is no rain, translates to the absolute error of the rain estimates.

In order to avoid inaccuracies in the attenuation correction when rain is weak, a hybrid of the surface reference method and the Hitschfeld-Bordan method is used [Iguchi and Meneghini, 1994]. In versions 5, 6 and 7 of 2A25, the errors in these methods are treated in a probabilistic manner. Because the relationship between the error in α and that in the Hitschfeld-Bordan method changes substantially with the attenuation, the relative weight on the surface reference method to the Hitschfeld-Bordan method varies with the attenuation. When rain is very weak and the attenuation estimate is small, the PIA estimate from the surface reference is effectively neglected. With the introduction of the hybrid method, the divergence associated with the Hitschfeld-Bordan method is also prevented.

When the PIA estimate from the surface reference ($\Delta\sigma^0$) is unavailable, it is replaced by an equivalent $\Delta\sigma^0_c$ that would make the attenuation-corrected Z_e -profile near the surface nearly constant vertically if the correction by the surface reference method is applied with this equivalent $\Delta\sigma^0_c$. This does not imply that the final vertical profile near the surface after the attenuation correction becomes constant because of the use of the hybrid method. Note also that negative values of $\Delta\sigma^0_c$ are reset to zero. The use of $\Delta\sigma^0_c$ instead of $\Delta\sigma^0$ from the surface reference seldom occurs.

The attenuation correction procedure requires two processing cycles. In the first cycle, the correction is made without taking the attenuation by cloud liquid water (CLW), water vapor (WV) and molecular oxygen (O2) into account. From the attenuation-corrected profile, the rainfall rate at the surface is estimated. Based on this rainfall rate and the statistical relationship between the surface rain rate and the vertical profile of cloud liquid water, the attenuation of radar rain echo caused by CLW is estimated at each range bin. Similarly, the attenuation due to WV is estimated from the estimated surface temperature and by assuming the 90% relative humidity within the raining footprint and 70% outside the raining area. The attenuation due to O2 is a simple function of the altitude. Then in the second cycle, the vertical profile of Z_m is corrected for the attenuation by CLW, WV and O_2, and this attenuation-corrected Z_m is corrected for the attenuation by rain.

The corrections for the non-uniform beam filling (NUBF) effect in the attenuation correction and in the conversion from Z_e to rainfall rate R are reintroduced in V7. The non-uniformity of rain distribution within a field of view is estimated from the low resolution variability of the PIA that is calculated from the PIAs at the angle bin in question and the eight surrounding angle bins.

The rainfall estimates are calculated from the attenuation-corrected Z_e-profiles by using a power law: $R=aZ_e^b$ in which the parameters a and b are both functions of the rain type, existence of bright-band, freezing height, storm height and absolute height. Effects of the difference in the raindrop size distribution by rain type, the phase state, the temperature, and the difference in terminal velocity due to changes in the air density with height are taken into account. The parameters a and b are expressed as a function of the adjustment parameter (ε_α) of α in the k-Z_e relation and adjusted in accordance with the α-adjustment in the attenuation correction.

2-3. 5. Input data

Input files:
1C-21 HDF data file
2A-21 HDF data file
2A-23 HDF data file

Input swath data from 1C-21 which are used in 2A-25:

```
binClutterFreeBottom[][]
binEllipsoid[]
binStormHeight[][]
binSurfPeak[]
geolocation[][]
minEchoFlag[]
normalSample[][]
scanStatus.dataQuality
scanStatus.missing
scanStatus.prStatus2
scanTime
scLocalZenith[]
scRange[]
```

Input swath data from 2A-21 which are used in 2A-25:

```
pathAtten[]
reliabFlag[]
reliabFactor[]
sigmaZero[]
```

Input swath data from 2A-23 which are used in 2A-25:

```
rainType[]
warmRain[]
status[]
freezH[]
HBB[]
```

Input header data from 1C21 used in 2A-25:

```
rayHdr[].rayStart
rayHdr[].mainlobeEdge
rayHdr[].sidelobeRange[]
```

2-3. 6. Output data

Output files:
2A-25 HDF data file
VI file

The main part of 2A25 output data is stored in the variables listed below:

Output data (in alphabetical order):

float attenParmAlpha[49][5]; k- Z_e parameter alpha at 5 nodes
float attenParmBeta[49]; k- Z_e parameter beta
float correctZFactor[49][80]; attenuation-corrected Z factor in dBZ
float epsilon[49]; correction factor with the hybrid method
float epsilon_0[49]; correction factor with the SRT
float epsilon_alpha[49]; correction factor for alpha (new)
float epsilon_nubf[49]; correction factor for alpha due to NUBF (new)
float errorRain[49]; error estimate of rain rate near surface in dB
float errorZ[49]; error estimate of Z_e near surface in dB
float e_SurfRain[49]; estimated rain rate at the actual surface
float freezH[49]; freezing height from 2A23
short method[49]; method used
float nearSurfRain[49]; estimated rain rate near surface
float nearSurfZ[49]; estimated Z_e near surface
float nubfCorrectFactor[49][3]; non-uniform beam filling correction factors (new definitions)
short parmNode[49][5]; bin numbers of 5 nodes for alpha, a and b
float pia[49][3]; path-integrated attenuations from final Z_e, in surface clutter, and from 2A21
float pia_srt[49][6]; 6 PIA estimates by SRT (new)
float precipWaterParmA[49][5]; PWC- Z_e parameter a in PWC=a* Z_e^b at 5 nodes
float precipWaterParmB[49][5]; PWC- Z_e parameter b in PWC=a* Z_e^b at 5 nodes
float precipWaterSum[49][2]; sum of PWC (2dimensional and new definitions)
short qualityFlag[49]; quality flag
float rain[49][80]; rainfall rate in mm/h.
float rainAve[49][2]; average rainfall rate between 2 and 4 km

short rainFlag[49]; status flag for rainfall estimate
short rainType[49]; rain type from 2A23
short rangeBinNum[49][7]; bin numbers of BB, storm top, etc.
signed char reliab[49][80]; reliability of the output
float scLocalZenith[49]; spacecraft local zenith angle
float sigmaZero[49]; surface scattering cross section sigmaZero from 2A21
float spare[49][2]; spare (New definitions)
float stddev_zeta[49]; standard deviation of zeta (new)
float stddev_PIAsrt[49]; standard deviation of PIA by SRT (new)
float stddev_alpha[49]; standard deviation of epsilon (new)
float stddev_srt[49][6]; reliability factors corresponding to pia_srt[49][6] (new)
float stddev_Zm[49]; standard deviation of epsilon_f (new)
float zeta[49][2]; integral of alpha*Z_m^beta
float zeta_mn[49][2]; mean of zeta over 3x3 IFOVs
float zeta_sd[49][2]; standard deviation of zeta
float zmmax[49]; maximum of Z_m
float ZRParmA[49][5]; Z_e-R parameter a in R=a* Z_e^b at 5 nodes
float ZRParmB[49][5]; Z_e-R parameter b in R=a* Z_e^b at 5 nodes

L2A25_SCANTIME ScanTime; scanTime
double scanTime_sec;
float Latitude[49];
float Longitude[49];
geolocation[][] geolocation
L2A25_SCANSTATUS scanStatus; scanStatus
L2A25_NAVIGATION navigation; navigation data

Obsolete

thickThPIZ[] range bin number where PIZ > threshPIZ
weightW[] weight for the calculation of epsilonf
xi[][] normalized standard deviation of PIA

For details, see section 2-3. 10.

2-3. 7. Interfaces with other algorithms

As described in "Input data" section, 2A25 reads data from 1C21, 2A21 and 2A23. The output data of 2A25 is used in 3A25 and 3A26.

2-3. 8. Caveats

1. 2A25 produces many output variables. Please read section 2-3.10 carefully before using them. For example, negative numbers are stored in rain[][] and correctedZFactor[][] when the data are missing or in the possibly cluttered ranges.

(IMPORTANT)
If the input radar reflectivity factor Z_m is below the noise level, the corresponding rain estimate is set to 0. This procedure does not cause any serious problem except when the measured Z_m becomes smaller than the noise level by rain attenuation. In such a case, even if some heavy rain exists near the surface, and the actual rain rate there is rather large, the number in rain[][] is 0.
To know whether such low radar reflectivity factors are caused by large attenuation or not, look at the fourth bit of 'reliab' and the fourth bit of 'rainFlag'.

2. The error estimates in 'rain' and 'correctZFactor' are given in 'errorRain[]' and 'errorZ[]'. However, these estimates indicate only very crude estimates.

3. 2A25 processes data in 'rain certain' angle bins only. It processes all data downward from 1 km above the height at which the first 'certain' rain echo is detected. This new definition of the processing region in 2A25 is introduced in version V5 and retained in V6 and V7.

4. Over some area with a very high surface reflectivity, surface echoes picked up in antenna sidelobes may appear in the radar signal and they are sometimes misidentified as rain echoes. The sidelobe clutter rejection routine in 1B21 and 2A25 removes some of the sidelobe clutters internally, but not all sidelobe signals are completely removed.

5. 2A25 relies on the output of 1C21 to separate the surface cluttered ranges from the clutter free ranges. Because the clutter identification routine used in 1B21 is

not perfect (it never can be), some surface clutter (mainlobe clutter) may be occasionally misidentified as rain echoes in 2A25, particularly in mountain regions. It is strongly suggested that you look at the vertical profile if the surface clutter seems present in the data.

6. The range bin numbers in the output of 2A25 are all relative to the Earth's ellipsoid (which is nearly equal to the mean sea level) with the ellipsoid range bin corresponding to 79. For example, if the range bin number is 75, its height from the ellipsoid is (79-75)*0.25 = 1.0 km. This number is NOT the height above the actual surface.

7. In V6 and V7, the value of α in the k-Z_e *R*elationship ($k = \alpha Z_e^{\beta}$) at 5 nodal points are given in attenParmAlpha[ ][ ].
The values in attenParmAlpha[ ][ ] are the initial values of α. To obtain the values of alpha used in the final attenuation estimation, the initial values must be multiplied by epsilon[ ].

8. The values of a and b given in ZRParmA[ ][ ]and ZRParmB[ ][ ] are
the final values of a and b in the R-Z_e *R*elationship ($R = a Z_e^{b}$) at the nodal points, respectively. In the case of stratiform rain with a bright band, smearing effect due to the canting scattering volume is compensated to some extent. In this case, mean values of a and b over the height profile of the scattering volume are used.
(In fact, the reciprocal of the mean of $1/a$ (and $1/b$) with a weighting function defined by the antenna pattern is used for smeared a (and smeared b).

2-3. 9. References

Iguchi, T., and R. Meneghini, "Intercomparison of Single Frequency Methods for Retrieving a Vertical Rain Profile from Airborne or Spaceborne Data," *Journal of Atmospheric and Oceanic Technology*, 11, 1507-1516 (1994).

Kozu, T., and T. Iguchi, "Nonuniform Beamfilling Correction for Spaceborne Radar Rainfall Measurement: Implications from TOGA COARE Radar Data Analysis," *J. Atmos. Oceanic Technol.*, 16, 1722-1735 (1999).

Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, "Preliminary results of rain profiling with TRMM Precipitation Radar," *Proc. of URSI-F International Triennial Open Symposium on Wave Propagation and Remote Sensing*, Aveiro, Portugal, pp.147-150, 1998.

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Meneghini, R., T. Iguchi, T. Kozu, L. Liao, K. Okamoto, J. A. Jones, and J. Kwiatkowski, "Use of the surface reference technique for path attenuation estimation from the TRMM Precipitation radar," *Journal of Applied Meteorology,* Vol.39, No.12, pp.2053-2070, 2000.

Iguchi, T., T. Kozu, J. Kwiatkowski, R. Meneghini, J. Awaka, and K. Okamoto, "Uncertainties in the Rain Profiling Algorithm for the TRMM Precipitation Radar," Journal of the Meteorological Society of Japan, Vol. 87A, pp. 1-30, 2009.

2-3. 10. Detailed description of output variables

New Output Variables

```
float epsilon_alpha[49];   correction factor for alpha (new)
float epsilon_nubf[49];    correction factor for alpha due to NUBF (new)
float pia_srt[49][6];    6 PIA estimates by SRT (new)
float stddev_zeta[49];   standard deviation of zeta (new)
float stddev_PIAsrt[49];  standard deviation of PIA by SRT (new)
float stddev_alpha[49];   standard deviation of epsilon (new)
float stddev_srt[49][6];   standard deviation of pia_srt (new)
float stddev_Zm[49];    standard deviation of epsilon_f (new)
```

New Definitions

```
int16    method[49]; (bit 4, 5, 6, 7, 8, 9, 10, 11, 12, 13)
int16    qualityFlag[49]; (bit 2, 3, 4, 5, 11, 12, 13)
int16    rainFlag[49]; (bit 3, 4, 11)
float nubfCorrectFactor[49][3]; non-uniform beam filling correction factors
(new definitions)
float precipWaterSum[49][2]; sum of PWC (2dimensional and new definitions)
float32  pia[49][3];
float spare[49][2];      spare (New definitions)
```

Obsolete (No data in V7)

```
int16    attenParmNode[49][5]; moved to parmNode[49][5];
float32  pia2a25[49]; moved to pia[49][0]
float32  thickThPIZ[49];
float32  weightW[49]; replaced by epsilon_0[49]
float32  xi[49][2]; normalized standard deviation of PIA
int16    ZRParmNode[49][5]; moved to parmNode[49][5];
```

List of 2A25 scan data

```
float32       attenParmAlpha[49][5];
int16         attenParmAlpha_scale[49][5];
float32       attenParmBeta[49];
int16         attenParmBeta_scale[49];
int16         attenParmNode[49][5];          Obsolete
float32       correctZFactor[49][80];
int16         correctZFactor_scale[49][80];
float32       epsilon[49];
float32       epsilon_0[49];
float epsilon_alpha[49];                    New
float epsilon_nubf[49];                     New
float32       errorRain[49];
float32       errorZ[49];
float32       e_SurfRain[49];
float32       freezH[49];
float32       geolocation[49][2];
int16         method[49];
float32       nearSurfRain[49];
float32       nearSurfZ[49];
float32       nubfCorrectFactor[49][2];
int16         parmNode[49][5];
float32       pia[49][3];
float pia_srt[49][6];                        New
float32       pia2a25[49];                  Obsolete
float32       precipWaterParmA[49][5];
float32       precipWaterParmB[49][5];
float precipWaterSum[49][2];            New dimension
int16         precipWaterSum_scale[49];
int16         qualityFlag[49];
```

```
float32        rain[49][80];
int16          rain_scale[49][80];
float32        rainAve[49][2];
int16          rainAve_scale[49][2];
int16          rainFlag[49];
int16          rainType[49];
int16          rangeBinNum[49][7];
int8           reliab[49][80];
float64        scanTime;
float32        scLocalZenith[49];
float32        sigmaZero[49];
float32        spare[49][2];
float stddev_zeta[49];                        New
float stddev_PIAsrt[49];                      New
float stddev_alpha[49];                       New
float stddev_srt[49][6];                       New
float stddev_Zm[49];                        New
int16          thickThPIZ[49];                 Obsolete
float32        weightW[49];                    Obsolete
int16          weightW_scale[49];              Obsolete
float32        xi[49][2];                      Obsolete
float32        zeta[49][2];
float32        zeta_mn[49][2];
float32        zeta_sd[49][2];
float32        zmmax[49];
int16          ZRParmA_scale[49][5];
float32        ZRParmA[49][5];
int16          ZRParmB_scale[49][5];
float32        ZRParmB[49][5];
int16          ZRParmNode[49][5];              Obsolete

L2A25_SCANTIME ScanTime;              New
double scanTime_sec;
float Latitude[49];
float Longitude[49];
geolocation[][]
L2A25_SCANSTATUS scanStatus;                   New
L2A25_NAVIGATION navigation;                 New
```

Description of each output variable

attenParmAlpha

```
float32    attenParmAlpha[49][5];
REAL*4     attenParmAlpha(5,49)
```

Attenuation parameter alpha at nodes.
k = alpha*Z^beta.

"alpha" is given at five nodal points. These numbers are initial values of alpha. The mean values of alpha used in the attenuation correction are obtained by multiplying attenParmAlpha[49][5] by epsilon[49].

The alpha values between the nodes are calculated by linear interpolation. The range bin numbers of the nodes are stored in ParmNode[49][5] (in version 5, they were stored in attenParmNode[49][5]).

attenParmBeta

```
float32    attenParmBeta[49];
REAL*4     attenParmBeta(49)
```

Attenuation parameter beta
k = alpha*Ze^beta.

beta is given for each angle bin.
A constant beta is used for all ranges in one angle bin.

correctZFactor

```
float32    correctZFactor[49][80];
REAL*4     correctZFactor(80,49)
```

Internally this quantity is stored as
int16 correctZFactor_scale[49][80] after multiplied (scaled) by 100.

Estimated effective Z-factor in dBZ at 13.8 GHz after attenuation correction.

If the input radar reflectivity factor Zm is below the noise level, or if the estimate is below 0 dB, correctZFactor is set to 0.0.

Everythingelse is the same as rain[49][80] (rain(80,49)).

epsilon

float32 epsilon[49];

REAL*4 epsilon(49)

The multiplicative correction factor to zeta. alpha in the k-Z_e relation is a part of zeta. Look at the description for epsilon_alpha below. In V7, a non-uniform beam filling (NUBF) correction is also applied in the attenuation correction. In the final form of the modified Hitschfeld-Bordan attenuation correction, zeta is multiplied by epsilon[] and nubfCorrectFactor[][0](the latter is expressed by ε_{NUBF} in Iguchi et al. 2009).

The value of epsilon is the maximum likelihood estimate with the likelihood function of epsilon defined by the rain echo, surface echo and their uncertainties.

epsilon_0

float32 epsilon_0[49];

REAL*4 epsilon_0(49)

The multiplicative correction factor to alpha in the k-Z_e relation if the weight to the path-integrated attenuation (PIA) given by the surface reference technique is 100%. This output is given only when the PIA estimate from 2A21 is either reliable or marginally reliable.

When it is not reliable, epsilon_0 is set to 0.

The exact formula used is as follows.

When pia[][0]>0, we define pia_ratio = (pia[][0]-pia[][1])/pia[][0].

If pia[][0]=0, pia_ratio=1.

```
att_f_bttm = pow(10.0,-(pia[][2] * pia_ratio)/10.0);
epsilon_0 = (1-pow(att_f_bttm,beta))/zeta;
```

I.e., the PIA estimate from 2A21 that represents the attenuation to the surface is converted to the attenuation to the bottom of clutter-free range and the latter is used for the calculation of epsilon_0.

epsilon_alpha (new)

float epsilon_alpha[49]

epsilon_alpha is the multiplicative correction factor to alpha in the k-Z_e relation. This value is used to modify the R-Z_e and LWC-Z_e relations. Note that zeta is modified by epsilon which is larger than epsilon_alpha. In other words, the total adjustment of zeta is done by epsilon, but only a part of it is attributed to the DSD bias. The latter adjustment corresponds to the adjustment of alpha by epsilon_alpha.

epsilon_nubf (new)

float epsilon_nubf[49]

epsilon_nubf is the NUBF correction factor for the k-Z_e relation, and its value is between 0.8 and 1.0.

errorRain

```
float32    errorRain[49];
REAL*4     errorRain(49)
```

Error estimate of rain rate near the surface expressed in dB.

errorZ

```
float32    errorZ[49];
REAL*4     errorZ(49)
```

Error estimate of correctZFactor near the surface expressed in dB.

e_SurfRain (New variable)

```
float32    e_SurfRain[49];
REAL*4     e_SurfRain(49)
```

Estimated rainfall rate at the actual surface. e_SurfRain is calculated by assuming a constant slope of dBZe from the bottom of the valid (clutter-free) rain echo. The assumed slope is 0 dB/km for all rain types except for the stratiform rain over land where -0.5 dB/km toward the surface is assumed. Note that 0 dB/km in Z_e corresponds to -0.17 dB/km in rainfall rate (decreases toward the surface).

freezH (New variable)

```
float32    freezH[49];
REAL*4     freezH(49)
```

Freezing height expressed in meter estimated from the climatological surface temperature. This is a copy of freezH given in 2A23.(freezH in 2A23 is given as an integer, but it is stored as a float number in 2A25.)

geolocation

```
float32     geolocation[49][2];
REAL*4      geolocation(2,49)
```

The earth location of the center of the IFOV at the altitude of the earth ellipsoid. The first dimension is latitude and longitude, in that order. Values are represented as floating point decimal degrees. Off-earth is represented as -9999.9.
Latitude is positive north, negative south. Longitude is positive east, negative west. A point on the 180° meridian is assigned to the western hemisphere.

method

```
int16         method[49];
INTEGER*2     method(49)
```

Method (rain model) used in the retrieval of vertical profiles of Z and R

The default value is 0 (including no rain case).
The following meanings are assigned to each bit in the 16-bit integer.
(See flag_mthd)

```
    0: (bit  1) no rain
 if rain
    0: (bit  1) over ocean
    1: (bit  1) over land
    2: (bit  2) over coast, river, etc.
    3: (bit  2) others (impossible)
   +4: (bit  3) PIA from constant-Z-near-surface assumption
   +8: (bit  4) spatial reference
  +16: (bit  5) temporal reference
  +32: (bit  6) global reference
  +64: (bit  7) hybrid reference
 +128: (bit  8) good to take statistics of epsilon.
 +256: (bit  9) HB method used, SRT totally ignored
 +512: (bit 10) very large pia_srt for given zeta
```

+1024: (bit 11) very small pia_srt for given zeta
+2048: (bit 12) no ZR adjustment by epsilon
+4096: (bit 13) no NUBF correction because NSD unreliable
+8192: (bit 14) surface attenuation > 60 dB
+16384: (bit 15) data partly missing between rain top and bottom

16th bit is currently not used.

The constant Z method is used only when the surface reference is unreliable. This routine calculates the average slope of the Zm profile (expressed in dBZ) near the bottom of radar echo and attributes the slope to the attenuation. If there are not enough valid data points in the profile, it returns with 0 attenuation. The constant Z method is seldom used.

navigate

NAVIGATION   navigate;

Look at the TSDIS INTERFACE CONTROL SPECIFICATION (ICS) Vol. 3, Appendix B “Navigation”

nearSurfRain

float32   nearSurfRain[49];
REAL*4   nearSurfRain(49)

Near-surface rainfall rate estimate

"Near-surface" is defined as the lowest point in the clutter free ranges in almost all cases. However, if Zm at this point is below the noise level and if zeta which corresponds to the estimated attenuation down to this point is larger than the zeta_th_L defined in the parameter file (it is currently set to 0.7 which approximately corresponds to 4 dB of attenuation),
in other words,
if the first bit of reliab[][] = 0 and
if the forth bit of reliab[][] = 0,

then the lowest range bin at which Zm is above the noise threshold is chosen as the near-surface range bin. The actual value of this near-surface range bin is stored in rangeBinNum[][6] in V6.

Specifically,

```
nearSurfRain[n_anglebin] = rain[n_anglebin][rangeBinNum[n_anglebin][6]];
nearSurfRain(n_anglebin) = rain((rangeBinNum(7,n_anglebin)+1),n_anglebin)
```

nearSurfZ

```
float32    nearSurfZ[49];
REAL*4     nearSurfZ(49)
```

Near-surface Z-factor

See nearSurfRain[] for the definition of "Near-surface".

```
nearSurfZ[n_anglebin]=
  correctZFactor[n_anglebin][rangeBinNum[n_anglebin][6]];
nearSurfZ(n_anglebin)=
  correctZFactor((rangeBinNum(7,n_anglebin)+1),n_anglebin)
```

nubfCorrectFactor (new definitions)

```
float32    nubfCorrectFactor[49][3];
REAL*4     nubfCorrectFactor(3,49)
```

'nubfCorrectFactor` is the non-uniform beam filling (NUBF) correction factor.

nubfCorrectFactor[][0] is the NUBF correction factor for the surface reference and its range is between 1.0 and 10.0.

nubfCorrectFactor[][1] is the NUBF correction factor for the R-Z_e relation.

nubfCorrectFactor[][2] is the NUBF correction factor for the LWC-Z_e relation.

Note that the NUBF correction factor for the k-Z_e relation is stored in epsilon_nubf.

parmNode

```
int16      parmNode[49][5];
INTEGER*2  parmNode(5,49)
```

Range bin numbers of the nodal points at which the attenuation parameter alpha and the Z-R parameters "a" and "b" are given in attenParmAlpha[49][5] (attenParmAlpha(5,49)), ZRParmA[49][5] (ZRParmA(5,49)), and

ZRParmB[49][5] (ZRParmB(5,49)), respectively.

For each angle bin, 5 nodal points are defined.

ParmNode[][] gives the range bin numbers of the 5 nodes at which the values of attenuation parameter "alpha" and the *Z-R* parameters "*a*" and "*b*" are given in ParmAlpha[][], ZRParmA[][] and ZRParmB[][], respectively. The values of alpha, *a* and *b* between the nodes are linearly interpolated. The range of ParmNode is between 0 and 79. (See the note for rangeBinNum.)

In no-rain angle bins, ParmNode[][] is set to 0.

Note that the definition of range bin number in 2A25 is not the same as 1B-21 or 1C-21. The bin number shows the position in the 80-element array so that it takes a number between 0 and 79 (inclusive).
Bin number 79 corresponds to the surface of the ellipsoid which is approximately equal to the sea surface.

pia

```
float32    pia[49][3];
REAL*4     pia(3,49)
```

pia[][0]
Path-integrated attenuation from rain top to surface.
This attenuation is calculated from the attenuation-corrected Z-profile in correctZFactor[][] and adjusted alpha.
The number represents the two-way attenuation to the actual surface.

pia[][1]
Path-integrated attenuation between the clutter-free bottom and the surface.
This is the attenuation estimate in the range that is cluttered by the surface echo.

pia[][2]
Path-integrated attenuation to surface estimated by the surface reference technique in 2A21. This is an exact copy of pathAtten(49) in 2A21.

pia_srt (new)

```
float32    pia_srt[49][6];
REAL*4     pia_srt(6,49)
```

The values of 6 kinds of path-integrated attenuation (PIA) given by 2A21.

pia_srt[][0]
This value is used in 2A25. This is identical to pia[][2].

pia_srt[][1]
This is an exact copy of PIAalt[][0] in 2A21.

pia_srt[][2]
This is an exact copy of PIAalt[][1] in 2A21.

pia_srt[][3]
This is an exact copy of PIAalt[][2] in 2A21.

pia_srt[][4]
This is an exact copy of PIAalt[][3] in 2A21.

pia_srt[][5]
This is an exact copy of PIAalt[][4] in 2A21.

precipWaterParmA

float32 precipWaterParmA[49][5];

READ*4 precipWaterParmA(5,49)

Coefficient *a* in the relation between the precipitation water content (PWC) and Ze at 5 nodal points. The unit of PWC is g/m^3 and that of Z_e is mm^6/m^3.

PWC = $a*Z_e$^b.

'*a*' is given at five nodal points.
These values are stored in the first 5 elements of the array.
'*a*' values between the nodes can be calculated by linear interpolation.
The range bin numbers of the nodes are stored in the ParmNode[49][5] (ParmNode(5,49)).

Note that the sum of PWC's calculated from Z=correctZFactor with formula PWC = $a*Z_e$^b where *a* and *b* from the interpoloted values of precipWaterParmA and precipWaterParmB does not necessarily agree with precipWaterSum. precipWaterSum also includes the precipitation water content in the surface clutter range.

precipWaterParmB

float32 precipWaterParmB[49][5];

READ*4   precipWaterParmB(5,49)

Coefficient *a* in the relation between the precipitation water content (PWC) and Z_e at 5 nodal points. The unit of PWC is g/m^3 and that of Z_e is mm^6/m^3.

PWC = $a*Z_e$^*b*.

'*b*' is given at five nodal points.
'*b*' values between the nodes can be calculated by linear interpolation.
The range bin numbers of the nodes are stored in the ParmNode[49][5] (ParmNode(5,49)).

precipWaterSum (New dimension)

float32   precipWaterSum[49][2];
REAL*4   precipWaterSum(2,49)

Vertically integrated value of precipitation water content.
The unit is g km/m^3 or equivalently kg/m^2.

"precipWaterSum[0]" give the sum of the precipitation liquid water content from the freezing height to the actual surface. The water content in the surface clutter range is estimated with the same assumption that is used in the attenuation correction.
"precipWaterSum[1]" give the sum of the precipitation ice content from the top of storm to the freezing height.

qualityFlag (New definition)

int16   qualityFlag[49];
INTEGER*2   qualityFlag(49)

Quality flag for each angle bin data

The default value is 0.
In V6, the definitions of bits 2, 3, 4, 5 are changed, and bits 13 and 14 are added. The flags indicated by bits 4, 5 and 13 in V6 are moved from method flag in V5.

0: normal
+1: unusual situation in rain average
+2: NSD of zeta (xi) calculated from less than 6 points (flag_xi >= 2)

+4: NSD of PIA calculated from less than 6 points (flag_nsd >= 2)
+8: upper bound of nubfCFs ((status_nubf/4)%2==1)
+16: lower bound of nubfCFs ((status_nubf/8)%2==1)
+32: epsilon not reliable, epsi_sig <= 0.0 (flag_epsi==1)
+64: 2A21 input data not reliable (flag_2a21>=3)
+128: 2A23 input data not reliable (flag_2a23>99)
+256: range bin error (flag_rbin)
+512: sidelobe clutter removal (flag_sidelobe)
+1024: lower bound of nubfCFkz ((status_nubf/2)%2==1)

+4096: const Z is invalid
+8192: reliabFactor in 2A21 is NaN (flag_2a21_rf!=0)
+16384: data missing

16th bit (sign bit) is not used.

The contents are exact copy of internal variable flag_qlty.

rain

```
float32   rain[49][80];
REAL*4    rain(80,49)
```

Internally this quantity is stored as
int16 rain_scale[49][80] after multiplied (scaled) by 100.

rainfall rate in mm/h

49 elements in the 2-D array correspond to the angle bins and 80 elements (first argument in FORTRAN convention) in the 2-D array correspond to the range bins.

If the estimated Z-factor is below 0 dBZ, the rain rate is always set to 0. If the input radar reflectivity factor Z_m is below the noise level, the corresponding rain estimate is set to 0. This procedure does not cause any serious problem except when the measured Z_m becomes smaller than the noise level by rain attenuation. In such a case, even if some heavy rain exists near the surface,the number in this variable is 0.
To know whether such low radar reflectivity factors are caused by large attenuation or not, look at the forth bit of 'reliab' and the forth bit of rainFlag.

80 range bins are filled with data from top to bottom in height.
The last element corresponds to the ellipsoid height, i.e., 0 m high above the model ellipsoid (not the actual surface). The first element corresponds to the radar resolution cell about 20 km above in slant range along the beam from the footprint on the ellipsoid. The range resolution is 250 m.

If the radar data is missing, MISSING value of -99.99 is stored.
This situation may happen at range bins above 15 km high because JAXA only guarantees the data collection below 15km.
(The highest edge of the radar's receiving window comes down to nearly 15km above the sea level near the equator.)

The bin number of the lowest range bin that contains valid rain data is (rangeBinNum[][6] - 1 in C) or (rangeBinNum(7,.) - 1 in FORTRAN).
Below this level, CLUTTER value of -88.88 is stored.

If the estimated rainfall rate exceeds 300 mm/h, it is reset to 300 mm/h.

rainAve (New definition)

```
float32    rainAve[49][2];
REAL*4     rainAve(2,49)
```

rainAve[][0] :
rainAve(1,*) : Average of rainfall rate between 2 and 4 km. The unit is mm/h.

If the lowest bin processed is higher than 2 km, the average is taken between the lowest altitude and 4 km.In this case, the 6th bit in rainFlag is set.
If the lowest bin processed is higher than 4 km, the average is not calculated.
In this case, 0 is stored, and the seventh bit of rainFalg is set.

rainAve[][1] :
rainAve(2,*) : Integrated rainfall rate from the rain top to the bottom.
The unit in V6 and V7 is (cm/h)*km, and NOT (mm/h)*km. This odd unit is adopted to avoid the overflow when the sum is stored as int16 after scaled by 100.
(It is not possible to use different scale factors for rainAve[][0] and rainAve[][1]. Cases with overflow were found in V5.)

rainFlag

int16 rainFlag[49];

INTEGER*2 rainFlag(49)

Rain flag for each angle bin (See flag_rain in Appendix 2.)

The default value is 0.

The following meanings are assigned to each bit in the 16-bit integer.

```
      0: (bit  1) no rain
     +1: (bit  1) rain possible (this bit is set even when rain is certain)
     +2: (bit  2) rain certain
     +4: (bit  3) zeta > zeta_th(=0.7) (PIA larger than approximately 4 dB)
     +8: (bit  4) zeta is too large (zeta > zeta_max=5.0)
    +16: (bit  5) stratiform
    +32: (bit  6) convective
    +64: (bit  7) bright band is detected
   +128: (bit  8) warm rain
   +256: (bit  9) rain bottom above 2 km
   +512: (bit 10) rain bottom above 4 km
  +1024: (bit 11) rain rate is above upper limit
 +16384: (bit 15) data partly missing between rain top and bottom
```

12th to 14th bits are currently not used.

16th bit (sign bit) is not used either.

rainType

int16 rainType[49];

INTEGER*2 rainType(49)

This is an exact copy of rainType in 2A23.

rangeBinNum (New definition)

int16 rangeBinNum[49][7];

INTEGER*2 rangeBinNum(7,49)

rangeBinNum[][0]: range bin number at the top of the interval that is processed as meaningful data in 2A-25. This is 4 range bins (1 km) above the first (highest) rain-certain range bin.

rangeBinNum[][1]: range bin number at the top of the surface clutter defined in 1B21.

rangeBinNum[][2]: range bin number at the actual surface.

rangeBinNum[][3]: range bin number of the bright band if it exits. If not, the range bin number of the phase transition height (estimated 0C height) is stored. (Read the note for freezH.)

rangeBinNum[][4]: the range bin number at which the path-integrated Z-factor first exceeds the given threshold. If the path-integrated Z-factor does not exceed the threshold, it is set to 79.

rangeBinNum[][5]: the range bin number at which the measured Z-factor is maximum. If no rain, it is set to 79.

rangeBinNum[][6]: the range bin number at the bottom of the interval that is processed as meaningful data in 2A-25. The attenuation-corrected Ze and rainfall rate R at this range bin are defined as nearSurfZ and nearSurfRain. See note below.

All these range bin numbers are indexed vertically from top to bottom with 0 at the highest elevation and 79 at the earth ellipsoid.
(All negative bin numbers are set to 0, and numbers larger than 79 are set to 79.)

Exception: If the actual surface is lower than the ellipsoid, the number in rangeBinNum[][2] may be larger than 79. This situation happens occasionally, especially over Indian Ocean where the geoid surface is lower than the model ellipsoid. The same situation may happen at a very low place over land, for example, at Dead Sea where the surface is nearly 400 m below the sea level.

Range bin numbers are unitless.

Note 1: rangeBinNum[][1] contains the range bin number that is the top of the possibly surface cluttered ranges. This number is larger than the bin number for the bottom of the clutter-free ranges by one.

Note 2: rangeBinNum[][6] contains the range bin number that corresponds to the bottom of the interval that is processed as meaningful data in 2A-25. This range bin is one bin above the top of the region that is cluttered either by the surface echo in the antenna mainlobe or by noise. In the former case, this number is identical to (rangeBinNum[][1]-1), but in the latter case, rangeBinNum[][6] is different from (rangeBinNum[][1]-1). The latter case may happen when the rain echo near surface becomes lower than the noise level by very large attenuation due to heavy rain. When rain is light and the echo near surface is below the noise level, the data smaller than the noise level are treated as valid data and the rainfall rate at that bin is set to zero.

reliab

int8 reliab[49][80];
BYTE reliab(80,49)

Reliability parameter at each range bin
The default value is 0.
Each bit in the byte indicates the status shown below:

lowest (first) bit : 0 : measured signal below noise
lowest (first) bit : rain
second bit : rain certain
third bit : bright band
forth bit : large attenuation
fifth bit : weak return (Z_m < 20 dBZ)
sixth bit : estimated Z_e < 0 dBZ
seventh bit : main-lobe clutter or below surface
eighth bit : missing data

For example, if the first bit is 0, i.e., if the number is an even number, then the measured signal in that range bin is below the noise level (noise threshold).

The large attenuation flag is set below the height at which the integral of 0.2*ln(10)*beta*alpha*Zm^beta first exceeds the given threshold.
In V 7, the threshold is 0.7 which approximately corresponds to the attenuation of 4 dB.

scanStatus

```
PR_SCAN_STATUS    scanStatus;
```

See the description of the 1B21 Scan Status in the TSDIS INTERFACE CONTROL SPECIFICATION (ICS) Volume 3.

scanTime

```
float64     scanTime;
REAL*8      scanTime
```

See the description of the 1B21 Scan Status in the TSDIS INTERFACE CONTROL SPECIFICATION (ICS) Volume 3.

scLocalZenith (New variable)

```
float32     scLocalZenith[49];
REAL*4      scLocalZenith(49)
```

Local zenith angle of the satellite at the center of the footprint.
The number corresponds to the incidence angle of the radar beam to the surface (ellipsoid surface).

sigmaZero (New variable)

```
float32     sigmaZero[49];
REAL*4      sigmaZero(49)
```

Exact copy of sigmaZero from 2A21.

spare (New definition)

```
float32     spare[49][2];
REAL*4      spare(2,49)
```

spare[49][0] : dist
spare[49][1] : pia_error

stddev_alpha (new)

```
float32 stddev_alpha [49]
REAL*4  stddev_alpha (49)
```

standard deviation of epsilon total which corresponds to the estimated uncertainty of alpha.

```
epsi_alpha =
exp(log(epsilonf)*stddev_epsi*stddev_epsi/(stddev_epsi_f*stddev_epsi_f));
```

stddev_PIAsrt (new)

```
float32 stddev_PIAsrt[49]
REAL*4  stddev_PIAsrt(49)
```

standard deviation of PIA given by surface reference technique (SRT) used in 2A25. This value is different from the value from 2A21. Some minimum fluctuation is assumed in the surface cross section measurement.

```
stddev_sigma;   /* new */
```

stddev_srt (new)

```
float32 stddev_srt[49][6]
REAL*4  stddev_srt(6,49)
```

standard deviations of 6 kinds of PIA given by 2A21. stddev_srt[][0] is the actual value used in 2A25.

stddev_zeta (new)

```
float32 stddev_zeta[49]
REAL*4  stddev_zeta(49)
```

standard deviation of zeta

stddev_Zm (new)

```
float32 stddev_Zm [49]
REAL*4  stddev_Zm (49)
```

standard deviation of of epsilon_f

```
stddev_epsi_f = sqrt(stddev_epsi_total*stddev_epsi_total +
stddev_epsi_nubf*stddev_epsi_nubf);
```

weightW (Obsolete. No data in V6 and V7. Can be calculated from epsilon and epsilon_0.)

```
float32    weightW[49];
```

REAL*4 weightW(49)

Internally this quantity was stored as
int16 weightW_scale[49] after multiplied (scaled) by 1000.

Weighting factor in the calculation of epsilon (SRT correction factor) in the hybrid method. The number is always between 0 and 1 (inclusive).

Note that in V6 and V7, epsilon_0 is output instead of weightW.
The relationship among epsilon, epsilon_0 and weightW is as follows.

epsilon = 1 + weightW*(epsilon_0 - 1)

zeta

float32 zeta[49][2];
REAL*4 zeta(2,49)

Integral of 0.2*ln(10)*beta*alpha*Z_m^beta from rain top to the clutter-free bottom.

zeta[][0]: zeta = Integral of 0.2*ln(10)*beta*alpha*Z_m^beta from the rain top to the bottom (lowest altitude processed).
zeta[][1]: PIA_est = -10*(log10(1-zeta_cr))/beta where zeta_cr is a corrected zeta (This zeta_cr is calculated by using the value of epsilon in the first cycle of processing which is different from the final estimate of epsilon.).

zeta is always between 0 and 100, typically between 0 and 2. When it is larger than 5, the 4th bit of rainFlag is set.
zeta is unitless.

zeta_mn

float32 zeta_mn[49][2];
REAL*4 zeta_mn(2,49)

Mean of zeta and PIA of 9 adjacent (3x3) beams.

At scan edges, the mean is calculated of 6 beams. At the scan edges of the first and last scans of the granule, the mean is calculated from only 4 beams.

zeta_mn[][0]: zeta_mn = mean of zeta
zeta_mn[][1]: PIA_mn = mean of PIA_est
The range of output value is the same as zeta itself.
zeta_mn is unitless.

zeta_sd

float32   zeta_sd[49][2];
REAL*4   zeta_sd(2,49)

Standard deviation of zeta and PIA_est in 9 adjacent (3 x 3) beams.
At scan edges, it is calculated in 6 beams. At the scan edges of the first and last scans of the granule, the mean is calculated from only 4 beams.

zeta_sd[][0]: zeta_sd = standard deviation of zeta
zeta_sd[][1]: PIA_sd = standard deviation of pia_est

zeta_sd is unitless.

zmmax

float32   zmmax[49];
REAL*4   zmmax(49)

zmmax is the maximum value of measured Z-factor expressed in dBZ at each IFOV.
The unit is dBZ or 10 log of mm^6/m^3. The range of the variable is between 0 and 100. (Typically between 10 and 60.)

ZRParmA

float32   ZRParmA[49][5];
REAL*4   ZRParmA(5,49)

Z-R parameter '*a*' at nodal points.

*R = a*Z^b*.

'*a*' is given at five nodal points.
These values are stored in the first 5 elements of the array.

'a' values between the nodes are calculated by linear interpolation.

The range bin numbers of the nodes are stored in ParmNode[49][5] (ParmNode(5,49)).

ZRParmB

```
float32    ZRParmB[49][5];
REAL*4     ZRParmB(5,49)
```

Z-R parameter '*b*' at nodal points.

*R = a*Z^b.*

'*b*' is given at five nodal points.
The nodal points are the same as those for alpha.
'*b*' values between the nodes are calculated by linear interpolation.
The range bin numbers of the nodes are stored in ParmNode[49][5] (ParmNode(5,49)).

ZRParmNode (Obsolete. No data in V6)

```
int16         ZRParmNode[49][5];
INTEGER*2     ZRParmNode(5,49);
```

This parameter is absorbed in parmNode[49][5].

Appendix 1. Output data structure defined in the toolkit

```
#ifndef _TK_2A25_H_
#define _TK_2A25_H_

#ifndef _L2A25_NAVIGATION_
#define _L2A25_NAVIGATION_

typedef struct {
   float scPosX;
   float scPosY;
   float scPosZ;
   float scVelX;
   float scVelY;
   float scVelZ;
   float scLat;
```

```
   float scLon;
   float scAlt;
   float scAttRoll;
   float scAttPitch;
   float scAttYaw;
   float SensorOrientationMatrix[3][3];
   float greenHourAng;
} L2A25_NAVIGATION;

#endif

#ifndef _L2A25_SCANSTATUS_
#define _L2A25_SCANSTATUS_

typedef struct {
   signed char missing;
   signed char validity;
   signed char qac;
   signed char geoQuality;
   signed char dataQuality;
   short SCorientation;
   signed char acsMode;
   signed char yawUpdateS;
   signed char prMode;
   signed char prStatus1;
   signed char prStatus2;
   double FractionalGranuleNumber;
} L2A25_SCANSTATUS;

#endif

#ifndef _L2A25_SCANTIME_
#define _L2A25_SCANTIME_

typedef struct {
   short Year;
   signed char Month;
   signed char DayOfMonth;
   signed char Hour;
   signed char Minute;
   signed char Second;
   short MilliSecond;
   short DayOfYear;
} L2A25_SCANTIME;

#endif
```

```
#ifndef _L2A25_SWATH_
#define _L2A25_SWATH_

typedef struct {
   L2A25_SCANTIME ScanTime;
   double scanTime_sec;
   float Latitude[49];
   float Longitude[49];
   L2A25_SCANSTATUS scanStatus;
   L2A25_NAVIGATION navigation;
   float scLocalZenith[49];
   float rain[49][80];
   signed char reliab[49][80];
   float correctZFactor[49][80];
   float attenParmAlpha[49][5];
   float attenParmBeta[49];
   short parmNode[49][5];
   float precipWaterParmA[49][5];
   float precipWaterParmB[49][5];
   float ZRParmA[49][5];
   float ZRParmB[49][5];
   float zmmax[49];
   short rainFlag[49];
   short rangeBinNum[49][7];
   float rainAve[49][2];
   float precipWaterSum[49][2];
   float epsilon_0[49];
   short method[49];
   float epsilon[49];
   float epsilon_alpha[49];
   float epsilon_nubf[49];
   float zeta[49][2];
   float zeta_mn[49][2];
   float zeta_sd[49][2];
   float sigmaZero[49];
   float freezH[49];
   float nubfCorrectFactor[49][3];
   float stddev_zeta[49];
   float stddev_PIAsrt[49];
   float stddev_alpha[49];
   float stddev_Zm[49];
   short qualityFlag[49];
   float nearSurfRain[49];
   float nearSurfZ[49];
   float e_SurfRain[49];
   float pia[49][3];
   float pia_srt[49][6];
```

```
   float stddev_srt[49][6];
   float errorRain[49];
   float errorZ[49];
   float spare[49][2];
   short rainType[49];
} L2A25_SWATH;

#endif

#ifndef _L2A25_CLUTTER_
#define _L2A25_CLUTTER_

typedef struct {
   signed char mainlobeEdge[49];
   signed char sidelobeRange[49][3];
} L2A25_CLUTTER;

#endif

#endif
```

```
Scale factors:
#define L2A25_RAIN          100
#define L2A25_CORRECTZFACTOR     100
#define L2A25_ATTENPARMALPHA     10000000
#define L2A25_ZRPARMA         100000
#define L2A25_ZRPARMB         10000
#define L2A25_RAINAVE         100
#define L2A25_LIQWATERSUM     1000
#define L2A25_ATTENPARMBETA     10000
#define L2A25_WEIGHTW         1000
#define L2A25_NEARSURFRAIN       100
#define L2A25_NEARSURFZ          100
```

Appendix 2. Parameters defined in “param_general_7.6.dat”

This parameter file for V7 is identical to that for V6. Note that nubf_cf's are read but not used in V7 of 2A25.

```
 1 /* parameter file for v7.2 of 2A25. Aug. 21, 2010 */
 2 /* Do not delete empty lines. */
 3 /* Do not add or delete lines. Absolute line numbers are important. */
 4 1.0000   vratio[0]     /* Terminal velocity ratio at 0 km */
 5 1.0396   vratio[1]     /* Terminal velocity ratio at 1 km */
 6 1.0817   vratio[2]     /* Terminal velocity ratio at 2 km */
 7 1.1266   vratio[3]     /* Terminal velocity ratio at 3 km */
 8 1.1745   vratio[4]     /* Terminal velocity ratio at 4 km */
 9 1.2257   vratio[5]     /* Terminal velocity ratio at 5 km */
10 1.2806   vratio[6]     /* Terminal velocity ratio at 6 km */
11 1.3394   vratio[7]     /* Terminal velocity ratio at 7 km */
12 1.4026   vratio[8]     /* Terminal velocity ratio at 8 km */
13 1.4706   vratio[9]     /* Terminal velocity ratio at 9 km */
14 1.5440   vratio[10]    /* Terminal velocity ratio at 10 km */
15 1.6234   vratio[11]    /* Terminal velocity ratio at 11 km */
16 1.7283   vratio[12]    /* Terminal velocity ratio at 12 km */
17 1.8404   vratio[13]    /* Terminal velocity ratio at 13 km */
18 1.9597   vratio[14]    /* Terminal velocity ratio at 14 km */
19 2.0867   vratio[15]    /* Terminal velocity ratio at 15 km */
20 2.2219   vratio[16]    /* Terminal velocity ratio at 16 km */
21 2.3658   vratio[17]    /* Terminal velocity ratio at 17 km */
22 2.5189   vratio[18]    /* Terminal velocity ratio at 18 km */
23 2.6819   vratio[19]    /* Terminal velocity ratio at 19 km */
24 2.8554   vratio[20]    /* Terminal velocity ratio at 20 km */
25 0.075    lprate        /* 1/20 of the lapse rate per 250 m */
26 1.0      fhcf_strat    /* FH correction factor for stratiform rain */
27 1.2      fhcf_conv     /* FH correction factor for convective rain */
28 0.3      nsd_cnv_ocean[0]  /* Conv. factor of NSD for stratiform */
29 0.3      nsd_cnv_ocean[1]  /* Conv. factor of NSD for convective */
30 0.3      nsd_cnv_ocean[2]  /* Conv. factor of NSD for default */
31 0.3      nsd_cnv_land[0]   /* Conv. factor of NSD for stratiform */
32 0.5      nsd_cnv_land[1]   /* Conv. factor of NSD for convective */
33 0.3      nsd_cnv_land[2]   /* Conv. factor of NSD for default */
34 0.10     zeta_min      /* Threshold value of zeta for SRT */
35 5.00     zeta_max      /* Threshold for zeta to judge something wrong. */
36 0.70     zeta_th_L     /* Threshold for zeta to judge large attenuation. */
37 0.00     z_offset      /* Offset to be added to 1C21 Z factor in dB   */
38 0.00     z_slope[0][0] /* Slope for ocean strat in clutter. + for larger Z toward surf.
*/
39 0.00     z_slope[0][1] /* Slope of dBZ/km for ocean conv. in cluttered range */
40 0.00     z_slope[0][2] /* Slope of dBZ/km for ocean others in cluttered range */
41 -0.50    z_slope[1][0] /* Slope of dBZ/km for land strat in clutter. */
42 0.00     z_slope[1][1] /* Slope of dBZ/km for land conv. in cluttered range */
43 0.00     z_slope[1][2] /* Slope of dBZ/km for land others in cluttered range */
44 1.00     epsi_init[0][0] /* initial offset factor of epsilon for ocean stratiform rain
*/
45 1.00     epsi_init[0][1] /* initial offset factor of epsilon for ocean convective rain
```

```
*/
 46  1.00     epsi_init[0][2] /* initial offset factor of epsilon for ocean other rain */
 47  1.00     epsi_init[1][0] /* initial offset factor of epsilon for land stratiform rain
*/
 48  1.00     epsi_init[1][1] /* initial offset factor of epsilon for land convective rain
*/
 49  1.00     epsi_init[1][2] /* initial offset factor of epsilon for land other rain */
 50  0.08     atten_O2_surf   /* PIA due to O2 at 0 m from geoid */
 51  7.70     scale_h_O2      /* scale height of O2 in km */
 52  90.0     r_humid_in_rain /* relative humidity inside the raining area */
 53  70.0     r_humid_out_rain  /* relative humidity outside the raining area */
 54  2.00     scale_h_H2O     /* scale height of H2O in km */
 55 -20.0     temp_p_ice      /* temperature of the height above which particles are 100%
ice */
```

Appendix 3. Parameters defined in "param_error_7.3.dat"

Note that many of the parameters defined in this file are not used in V7.
The parameters marked with "n" are not used.

```
 01 0.7      d_Zm_typ       /* Typical error (offset) in Zm in dB */
 02 0.5      d_alpha_typ    /* Typical error in alpha in dB */
 03 0.05     d_beta_typ     /* Typical error in beta in dB */
 04 0.6      d_zra_typ      /* Typical error in a in dB */
 05 0.05     d_zrb_typ      /* Typical error in b in dB */
 06 1.5      d_surf_typ     /* Typical error in sigma^0 in dB */
 07 1.0      d_nubfCf_s     /* Typical error in NUBF correct. factor for surf.*/
 08 0.2      d_nubfCf_zr    /* Typical error in NUBF correct. factor for ZR */
 09 -0.2     dv_dh          /* Typical change of velocity per km in dB*/
 10 1.0      height_err_0C  /* 0C height error in km */
 11 0.3      height_err_BB  /* BB height error in km when it exists */
 12 -0.07    dalpha_dT      /* Change of alpha per 1 degree in dB */
 13 0.01     dbeta_dT       /* Change of beta per degree in dB */
 14 0.02     da_dT          /* Change of a in ZR per degree in dB */
 15 -0.005   db_dT          /* Change of b in ZR per degree in dB */
 16 1.3      d_alpha_id     /* Error in alpha in dB caused by wrong ident. */
 17 -0.05    d_beta_id      /* Error in beta in dB caused by wrong ident. */
 18 2.00     d_zra_id       /* Error in a in dB caused by wrong identification */
 19 0.02     d_zrb_id       /* Error in b in dB caused by wrong identification */
 20 0.25     stddev_epsi_strat   /* nominal error of epsilon for strat in linear unit
*/
 21 0.25     stddev_epsi_conv    /* nominal error of epsilon for conv in linear unit */
 22  0.7     stddev_SRT_O   /* nominal error of SRT over ocean in dB */
 23  0.7     stddev_SRT_L   /* nominal error of SRT over land in dB */
 24  5.0     stddev_SRT_N   /* nominal error of SRT in const-Z method in dB */
```

Appendix 4. Parameters defined in "param_strat_4.dat"

```
1  /* parameter file for v6.9 of 2A25. January 18, 2008. SPO, Oblate */
2  /* Do not delete empty lines. */
3  /* Do not add or delete lines. Absolute line numbers are important. */
4  /* stratiform parameters */
5  /* coefficients for R-Z relationship: R = a * Z^b
6  log10(a) = zr_a_c0 + zr_a_c1*x + zr_a_c2*x*x
7  log10(b) = zr_b_c0 + zr_b_c1*x + zr_b_c2*x*x
8  where x = log10(alpha_final/alpha_initial)  */
9  /* initial coefficients of k-Z relationship: k = alpha * Z^beta */
10  0.000031244  alpha_init[0][0]   /* alpha for snow, no water */
11  0.00012651  alpha_init[0][1]   /* alpha for low density snow, 0.017 */
12  0.00050167  alpha_init[0][2]   /* alpha for high density snow, 0.170 */
13  0.00031110  alpha_init[0][3]   /* alpha for rain (stratiform) 0C  */
14  0.00030719  alpha_init[0][4]   /* alpha for rain (stratiform) 20C  */
15  0.78069   beta_init[0]      /* beta for stratiform column, strat */
16 /* R-Ze coefficients */
17 -1.7219 zr_a_c0[0][0]   /* stratiform, bb.000   */
18 -1.8539 zr_a_c0[0][1]   /* stratiform, bb.017   */
19 -2.3052 zr_a_c0[0][2]   /* stratiform, bb.170   */
20 -1.6599 zr_a_c0[0][3]   /* stratiform, 0C   */
21 -1.6085 zr_a_c0[0][4]   /* stratiform, 20C   */
22
23  1.4946 zr_a_c1[0][0]   /* stratiform, bb.000 */
24  1.4974 zr_a_c1[0][1]   /* stratiform, bb.017 */
25  1.3411 zr_a_c1[0][2]   /* stratiform, bb.170 */
26  0.8867 zr_a_c1[0][3]   /* stratiform, rain 0C */
27  0.8766 zr_a_c1[0][4]   /* stratiform, rain 20C */
28
29  -0.2649 zr_a_c2[0][0]   /* stratiform, bb.000 */
30  -0.3013 zr_a_c2[0][1]   /* stratiform, bb.017 */
31  -0.4044 zr_a_c2[0][2]   /* stratiform, bb.170 */
32  -0.5135 zr_a_c2[0][3]   /* stratiform, rain 0C */
33  -1.2587 zr_a_c2[0][4]   /* stratiform, rain 20C */
34
35 -0.1144 zr_b_c0[0][0]   /* stratiform, bb.000 */
36 -0.1191 zr_b_c0[0][1]   /* stratiform, bb.017 */
37 -0.1380 zr_b_c0[0][2]   /* stratiform, bb.170 */
38 -0.1647 zr_b_c0[0][3]   /* stratiform, rain  0C */
39 -0.1752 zr_b_c0[0][4]   /* stratiform, rain 20C */
40
41 -0.0916 zr_b_c1[0][0]   /* stratiform, bb.000 */
42 -0.0801 zr_b_c1[0][1]   /* stratiform, bb.017 */
43 -0.0206 zr_b_c1[0][2]   /* stratiform, bb.170 */
44  0.1022 zr_b_c1[0][3]   /* stratiform, rain  0C */
45  0.1179 zr_b_c1[0][4]   /* stratiform, rain 20C */
46
47  0.1120 zr_b_c2[0][0]   /* stratiform, bb.000 */
48  0.1077 zr_b_c2[0][1]   /* stratiform, bb.017 */
49  0.0889 zr_b_c2[0][2]   /* stratiform, bb.170 */
50  0.0849 zr_b_c2[0][3]   /* stratiform, rain  0C */
51  0.2340 zr_b_c2[0][4]   /* stratiform, rain 20C */
52 /* LWC-Ze coefficients (log10 of a and b in LWC = a Ze^b) */
```

```
-2.4161 zl_a_c0[0][0]   /* stratiform, bb.011, a=0.00383613 */
-2.4881 zl_a_c0[0][1]   /* stratiform, bb.02,  a=0.00325046 */
-3.1290 zl_a_c0[0][2]   /* stratiform, bb.17,  a=0.00074301 */
-2.6994 zl_a_c0[0][3]   /* stratiform, 0C ,    a=0.00199806 */
-2.6502 zl_a_c0[0][4]   /* stratiform, 20C ,   a=0.00223787 */
 1.5422 zl_a_c1[0][0]   /* stratiform, bb.011 */
 1.8509 zl_a_c1[0][1]   /* stratiform, 0C */
 1.8344 zl_a_c1[0][2]   /* stratiform, 0C */
 1.5283 zl_a_c1[0][3]   /* stratiform, 0C */
 1.5422 zl_a_c1[0][4]   /* stratiform, 20C */
-0.2365 zl_a_c2[0][0]   /* stratiform, bb.011 */
-0.2254 zl_a_c2[0][1]   /* stratiform, 0C */
-0.3571 zl_a_c2[0][2]   /* stratiform, 0C */
-0.5889 zl_a_c2[0][3]   /* stratiform, 0C */
-1.6158 zl_a_c2[0][4]   /* stratiform, 20C */
-0.1471 zl_b_c0[0][0]   /* stratiform, bb.011, b=0.71266 */
-0.1520 zl_b_c0[0][1]   /* stratiform, bb.02,  b=0.70472 */
-0.1768 zl_b_c0[0][2]   /* stratiform, bb.17,  b=0.66564 */
-0.2122 zl_b_c0[0][3]   /* stratiform, 0C,     b=0.61342 */
-0.2243 zl_b_c0[0][4]   /* stratiform, 20C,    b=0.59658 */
-0.1056 zl_b_c1[0][0]   /* stratiform, bb.011 */
-0.0915 zl_b_c1[0][1]   /* stratiform, 0C */
-0.0442 zl_b_c1[0][2]   /* stratiform, 0C */
 0.0630 zl_b_c1[0][3]   /* stratiform, 0C */
 0.0751 zl_b_c1[0][4]   /* stratiform, 20C */
 0.1453 zl_b_c2[0][0]   /* stratiform, bb.011 */
 0.1357 zl_b_c2[0][1]   /* stratiform, 0C */
 0.1265 zl_b_c2[0][2]   /* stratiform, 0C */
 0.1913 zl_b_c2[0][3]   /* stratiform, 0C */
 0.4320 zl_b_c2[0][4]   /* stratiform, 20C */
```

Appendix 5. Parameters defined in “param_conv_4.dat”

```
/* parameter file for v6.9 of 2A25. January 18 2008, SPO, Oblate*/
/* Do not delete empty lines. */
/* Do not add or delete lines. Absolute line numbers are important. */
/* convective rain parameters */
/* coefficients for R-Z relationship: R = a * Z^b
log10(a) = zr_a_c0 + zr_a_c1*x + zr_a_c2*x*x
log10(b) = zr_b_c0 + zr_b_c1*x + zr_b_c2*x*x
where x = log10(alpha_final/alpha_initial)  */
/* initial coefficients of k-Z relationship: k = alpha * Z^beta */
0.000048144 alpha_init[1][0]   /* alpha for snow, no water */
0.000141036  alpha_init[1][1]   /* alpha for low density snow, 0.011 */
0.000428637  alpha_init[1][2]   /* alpha for rain (convective) 0C  */
```

```
 0.000428637  alpha_init[1][3]   /* alpha for rain (convective) 0C  */
 0.000432574  alpha_init[1][4]   /* alpha for rain (convective) 20C */
 0.758892044     beta_init[1]       /* beta for convective column, conv */
/* R-Ze coefficients */
-1.6071 zr_a_c0[1][0]   /* convective, bb.000 */
-1.6929 zr_a_c0[1][1]   /* convective, bb.011, a=0.02027, a'= 174.09 */
-1.4336 zr_a_c0[1][2]   /* convective, 0C ,    a=0.03484, a'= 159.44 */
-1.4336 zr_a_c0[1][3]   /* convective, 0C ,    a=0.03484, a'= 159.44 */
-1.3754 zr_a_c0[1][4]   /* convective, 20C ,    */

 1.6925 zr_a_c1[1][0]   /* convective, bb.000 */
 1.7174 zr_a_c1[1][1]   /* convective, bb.011 */
 0.8576 zr_a_c1[1][2]   /* convective, 0C */
 0.8576 zr_a_c1[1][3]   /* convective, 0C */
 0.9149 zr_a_c1[1][4]   /* convective, 20C */

-0.4980 zr_a_c2[1][0]   /* convective, bb.000 */
-0.5336 zr_a_c2[1][1]   /* convective, bb.011 */
-1.1231 zr_a_c2[1][2]   /* convective, 0C */
-1.1231 zr_a_c2[1][3]   /* convective, 0C */
-2.0411 zr_a_c2[1][4]   /* convective, 20C */

-0.1215 zr_b_c0[1][0]   /* convective, bb.000 */
-0.1217 zr_b_c0[1][1]   /* convective, bb.011, b=0.7556, 1/b=1.3234 */
-0.1885 zr_b_c0[1][2]   /* convective, 0C,     */
-0.1885 zr_b_c0[1][3]   /* convective, 0C,     */
-0.1999 zr_b_c0[1][4]   /* convective, 20C,    */

-0.1163 zr_b_c1[1][0]   /* convective, bb.000 */
-0.1163 zr_b_c1[1][1]   /* convective, bb.011 */
+0.0980 zr_b_c1[1][2]   /* convective, 0C */
+0.0980 zr_b_c1[1][3]   /* convective, 0C */
+0.0989 zr_b_c1[1][4]   /* convective, 20C */

 0.1293 zr_b_c2[1][0]   /* convective, bb.000 */
 0.1302 zr_b_c2[1][1]   /* convective, bb.011 */
 0.1915 zr_b_c2[1][2]   /* convective, 0C */
 0.1915 zr_b_c2[1][3]   /* convective, 0C */
 0.3602 zr_b_c2[1][4]   /* convective, 20C */
/* LWC-Ze coefficients (log10 of a and b in LWC = a Ze^b) */
-2.2070 zl_a_c0[1][0]   /* convective, bb.011, a=0.00620868 */
-2.4070 zl_a_c0[1][1]   /* convective, 0C ,    a=0.00391752 */
-2.4070 zl_a_c0[1][2]   /* convective, 0C ,    a=0.00391752 */
-2.4070 zl_a_c0[1][3]   /* convective, 0C ,    a=0.00391752 */
-2.3522 zl_a_c0[1][4]   /* convective, 20C ,   a=0.004444 */

 2.0441 zl_a_c1[1][0]   /* convective, bb.011 */
 1.5269 zl_a_c1[1][1]   /* convective, 0C */
 1.5269 zl_a_c1[1][2]   /* convective, 0C */
 1.5269 zl_a_c1[1][3]   /* convective, 0C */
 1.5766 zl_a_c1[1][4]   /* convective, 20C */
```

```
-0.5818 zl_a_c2[1][0]   /* convective, bb.011 */
-1.0761 zl_a_c2[1][1]   /* convective, 0C */
-1.0761 zl_a_c2[1][2]   /* convective, 0C */
-1.0761 zl_a_c2[1][3]   /* convective, 0C */
-2.2027 zl_a_c2[1][4]   /* convective, 20C */

-0.1618 zl_b_c0[1][0]   /* convective, bb.011, b=0.68902 */
-0.2377 zl_b_c0[1][1]   /* convective, 0C,     b=0.57855 */
-0.2377 zl_b_c0[1][2]   /* convective, 0C,     b=0.57855 */
-0.2377 zl_b_c0[1][3]   /* convective, 0C,     b=0.57855 */
-0.2500 zl_b_c0[1][4]   /* convective, 20C,    b=0.56232 */

-0.1259 zl_b_c1[1][0]   /* convective, bb.011 */
 0.0533 zl_b_c1[1][1]   /* convective, 0C */
 0.0533 zl_b_c1[1][2]   /* convective, 0C */
 0.0533 zl_b_c1[1][3]   /* convective, 0C */
 0.0545 zl_b_c1[1][4]   /* convective, 20C */

 0.1724 zl_b_c2[1][0]   /* convective, bb.011 */
 0.2681 zl_b_c2[1][1]   /* convective, 0C */
 0.2681 zl_b_c2[1][2]   /* convective, 0C */
 0.2681 zl_b_c2[1][3]   /* convective, 0C */
 0.5077 zl_b_c2[1][4]   /* convective, 20C */
```

Appendix 6. Parameters defined in "param_other_4.dat"

```
 /* parameter file for v6.9 of 2A25. January 18 2008, SPO, Oblate*/
 /* Do not delete empty lines. */
 /* Do not add or delete lines. Absolute line numbers are important. */
 /* convective rain parameters */
 /* coefficients for R-Z relationship: R = a * Z^b
 log10(a) = zr_a_c0 + zr_a_c1*x + zr_a_c2*x*x
 log10(b) = zr_b_c0 + zr_b_c1*x + zr_b_c2*x*x
 where x = log10(alpha_final/alpha_initial)  */
 /* initial coefficients of k-Z relationship: k = alpha * Z^beta */
 0.000048144 alpha_init[2][0]   /* alpha for snow, no water */
 0.000141036  alpha_init[2][1]   /* alpha for low density snow, 0.011 */
 0.000428637  alpha_init[2][2]   /* alpha for rain (convective) 0C  */
 0.000428637  alpha_init[2][3]   /* alpha for rain (convective) 0C  */
 0.000432574  alpha_init[2][4]   /* alpha for rain (convective) 20C */
 0.758892044     beta_init[2]       /* beta for convective column, conv */
/* R-Ze coefficients */
-1.6071 zr_a_c0[2][0]   /* convective, bb.000 */
-1.6929 zr_a_c0[2][1]   /* convective, bb.011, a=0.02027, a'= 174.09 */
-1.4336 zr_a_c0[2][2]   /* convective, 0C ,    a=0.03484, a'= 159.44 */
-1.4336 zr_a_c0[2][3]   /* convective, 0C ,    a=0.03484, a'= 159.44 */
-1.3754 zr_a_c0[2][4]   /* convective, 20C ,    */

 1.6925 zr_a_c1[2][0]   /* convective, bb.000 */
 1.7174 zr_a_c1[2][1]   /* convective, bb.011 */
```

```
 0.8576 zr_a_c1[2][2]   /* convective, 0C */
 0.8576 zr_a_c1[2][3]   /* convective, 0C */
 0.9149 zr_a_c1[2][4]   /* convective, 20C */

-0.4980 zr_a_c2[2][0]   /* convective, bb.000 */
-0.5336 zr_a_c2[2][1]   /* convective, bb.011 */
-1.1231 zr_a_c2[2][2]   /* convective, 0C */
-1.1231 zr_a_c2[2][3]   /* convective, 0C */
-2.0411 zr_a_c2[2][4]   /* convective, 20C */

-0.1215 zr_b_c0[2][0]   /* convective, bb.000 */
-0.1217 zr_b_c0[2][1]   /* convective, bb.011, b=0.7556, 1/b=1.3234 */
-0.1885 zr_b_c0[2][2]   /* convective, 0C,      */
-0.1885 zr_b_c0[2][3]   /* convective, 0C,      */
-0.1999 zr_b_c0[2][4]   /* convective, 20C,     */

-0.1163 zr_b_c1[2][0]   /* convective, bb.000 */
-0.1163 zr_b_c1[2][1]   /* convective, bb.011 */
+0.0980 zr_b_c1[2][2]   /* convective, 0C */
+0.0980 zr_b_c1[2][3]   /* convective, 0C */
+0.0989 zr_b_c1[2][4]   /* convective, 20C */

 0.1293 zr_b_c2[2][0]   /* convective, bb.000 */
 0.1302 zr_b_c2[2][1]   /* convective, bb.011 */
 0.1915 zr_b_c2[2][2]   /* convective, 0C */
 0.1915 zr_b_c2[2][3]   /* convective, 0C */
 0.3602 zr_b_c2[2][4]   /* convective, 20C */
/* LWC-Ze coefficients (log10 of a and b in LWC = a Ze^b) */
-2.2070 zl_a_c0[2][0]   /* convective, bb.011, a=0.00620868 */
-2.4070 zl_a_c0[2][1]   /* convective, 0C ,    a=0.00391752 */
-2.4070 zl_a_c0[2][2]   /* convective, 0C ,    a=0.00391752 */
-2.4070 zl_a_c0[2][3]   /* convective, 0C ,    a=0.00391752 */
-2.3522 zl_a_c0[2][4]   /* convective, 20C ,   a=0.004444 */

 2.0441 zl_a_c1[2][0]   /* convective, bb.011 */
 1.5269 zl_a_c1[2][1]   /* convective, 0C */
 1.5269 zl_a_c1[2][2]   /* convective, 0C */
 1.5269 zl_a_c1[2][3]   /* convective, 0C */
 1.5766 zl_a_c1[2][4]   /* convective, 20C */

-0.5818 zl_a_c2[2][0]   /* convective, bb.011 */
-1.0761 zl_a_c2[2][1]   /* convective, 0C */
-1.0761 zl_a_c2[2][2]   /* convective, 0C */
-1.0761 zl_a_c2[2][3]   /* convective, 0C */
-2.2027 zl_a_c2[2][4]   /* convective, 20C */

-0.1618 zl_b_c0[2][0]   /* convective, bb.011, b=0.68902 */
-0.2377 zl_b_c0[2][1]   /* convective, 0C,     b=0.57855 */
-0.2377 zl_b_c0[2][2]   /* convective, 0C,     b=0.57855 */
-0.2377 zl_b_c0[2][3]   /* convective, 0C,     b=0.57855 */
-0.2500 zl_b_c0[2][4]   /* convective, 20C,    b=0.56232 */
```

```
-0.1259 zl_b_c1[2][0]   /* convective, bb.011 */
 0.0533 zl_b_c1[2][1]   /* convective, 0C */
 0.0533 zl_b_c1[2][2]   /* convective, 0C */
 0.0533 zl_b_c1[2][3]   /* convective, 0C */
 0.0545 zl_b_c1[2][4]   /* convective, 20C */

 0.1724 zl_b_c2[2][0]   /* convective, bb.011 */
 0.2681 zl_b_c2[2][1]   /* convective, 0C */
 0.2681 zl_b_c2[2][2]   /* convective, 0C */
 0.2681 zl_b_c2[2][3]   /* convective, 0C */
 0.5077 zl_b_c2[2][4]   /* convective, 20C */
```

3. LEVEL3

3-1. 3A-25: Space Time Statistics of Level 2 PR Products

3-1. 1. Objective of the algorithm

The objective of the algorithm is to calculate various statistics over a month from the level 2 PR output products. Four types of statistics are calculated:

1. Probabilities of occurrence (count values)
2. Means and standard deviations
3. Histograms
4. Correlation coefficients

In all cases, the statistics are conditioned on the presence of rain or some other quantity such as the presence of stratiform rain or the presence of a bright-band. For example, to compute the unconditioned mean rain rate, the conditional mean must be multiplied by the probability of rain which, in turn is calculated from the ratio of rain counts to the total number of observations in the box of interest. Details of the procedure are given in section 8.

The standard space scale is a 5×5-degree latitude×longitude cell. A subset of the products, however, is also produced over 0.5×0.5-degree cells.

The types of statistics computed include:

At 5×5-degree×1-month cells:

- Means, standard deviations, and count values ("pixel counts")
- Histograms
- Correlation coefficients
- RZ coefficients, a and b, $R = aZ^b$

At 0.5×0.5-degree×1-month cells:

- Means, standard deviations, and count values
- RZ coefficients, a and b, $R = aZ^b$

The 5×5-degree statistics are stored in arrays dimensioned (16,72,*), with a product name ending with "1" (generally). There are 16 latitude cells, 72 longitude cells, and possibly other dimensions, as noted, for height, rain type, etc. Histograms are dimensioned (16,72,30,*) with 30 categories.

The 0.5×0.5-degree statistics are dimensioned (148,720,*), and have a product name ending with "2". There are 148 latitude cells and 720 longitude cells.

3-1.2. Output Variables

3-1. 2.1. Variable naming convention

Variable names consist of a word or several words strung together describing the geophysical quantity, and ending with an abbreviation designating the statistic type. For example, the 5×5-degree mean of stratiform rain rate is stratRainMean1. The statistic type designations are

`Mean1`	5×5-degree means
`Dev1`	5×5-degree standard deviations
`Pix1`	5×5-degree pixel counts
`H`	histograms
`CCoef`	correlation coefficients
`rz..A1`	RZ-relation a-coefficient, 5×5 degrees; “rz” is a prefix
`rz..B1`	RZ-relation b-coefficient, 5×5 degrees
`Mean2`	0.5×0.5-degree means
`Dev2`	0.5×0.5-degree standard deviations
`Pix2`	0.5×0.5-degree pixel counts
`rz..A2`	RZ-relation a-coefficient, 0.5×0.5 degrees
`rz..B2`	RZ-relation b-coefficient, 0.5×0.5 degrees

For example, a typical set of statistics, for rain rate is:

`rainMean1(16,72,6)`	1-month mean, 5×5-degree cells
`rainDev1(16,72,6)`	Standard deviation, 5×5-degree cells
`rainPix1(16,72,6)`	Count, 5×5-degree cells
`rainH(16,72,30,6)`	Histogram, 5×5-degree cells
`rainMean2(148,720,4)`	1-month mean, 0.5×0.5-degree cells
`rainDev2(148,720,4)`	Standard deviation, 0.5×0.5-degree cells
`rainPix2(148,720,4)`	Count, 0.5×0.5-degree cells

3-1. 2.2. Variable Definitions

Number of observations (rain and no-rain)

`ttlPix1(16,72)`	integer
`ttlPix2(148,720)`	integer

Rain Rate Statistics

Rain rates in mm/h

CAPPIs

Conditioned on the detection of rain (‘rain-certain’ flag), computed at 5 heights + path-averaged. The heights are 2, 4, 6, 10, 15-km and full-path. High-resolution statistics are computed at 3 heights + path-averaged, 2, 4, 6-km and full path.

All rain types

`rainMean1(16,72,6)`	real
`rainDev1(16,72,6)`	real
`rainPix1(16,72,6)`	integer
`rainH(16,72,30,6)`	integer*2
`rainMean2(148,720,4)`	real
`rainDev2(148,720,4)`	real
`rainPix2(148,720,4)`	integer

Convective rain

`convRainMean1(16,72,6)`	real
`convRainDev1(16,72,6)`	real
`convRainPix1(16,72,6)`	integer
`convRainH(16,72,30,6)`	integer*2
`convRainMean2(148,720,4)`	real
`convRainDev2(148,720,4)`	real
`convRainPix2(148,720,4)`	integer

Stratiform rain

`stratRainMean1(16,72,6)`	real
`stratRainDev1(16,72,6)`	real
`stratRainPix1(16,72,6)`	integer
`stratRainH(16,72,30,6)`	integer*2
`stratRainMean2(148,720,4`	real
`stratRainDev2(148,720,4)`	real
`stratRainPix2(148,720,4)`	integer

Near-surface rain

Conditioned on the detection of rain (‘rain certain’), computed at the nearest range bin judged free of ground clutter. The height in the input data varies with angle bin.

All rain types

`surfRainMean1(16,72)`	real
`surfRainDev1(16,72)`	real
`surfRainPix1(16,72)`	integer
`surfRainH(16,72,30)`	integer*2
`surfRainMean2(148,720)`	real
`surfRainDev2(148,720)`	real
`surfRainPix2(148,720)`	integer

Convective rain

`surfRainConvMean1(16,72)`	real
`surfRainConvDev1(16,72)`	real
`surfRainConvPix1(16,72)`	integer
`surfRainConvH(16,72,30)`	integer*2
`surfRainConvMean2(148,720)`	real

```
surfRainConvDev2(148,720)      real
surfRainConvPix2(148,720)      integer
```

Stratiform rain

```
surfRainStratMean1(16,72)      real
surfRainStratDev1(16,72)       real
surfRainStratPix1(16,72)       integer
surfRainStratH(16,72,30)       integer*2
surfRainStratMean2(148,720)    real
surfRainStratDev2(148,720)     real
surfRainStratPix2(148,720)     integer
```

Estimated surface rain

Conditioned on the detection of rain ("rain certain"), surface rain rate, estimated in 2A-25.

All rain types

```
e_surfRainMean1(16,72)         real
e_surfRainDev1(16,72)          real
e_surfRainPix1(16,72)          integer
e_surfRainH(16,72,30)          integer*2
e_surfRainMean2(148,720)       real
e_surfRainDev2(148,720)        real
e_surfRainPix2(148,720)        integer
```

Convective rain

```
e_surfRainConvMean1(16,72)     real
e_surfRainConvDev1(16,72)      real
e_surfRainConvPix1(16,72)      integer
e_surfRainConvH(16,72,30)      integer*2
e_surfRainConvMean2(148,720)   real
e_surfRainConvDev2(148,720)    real
e_surfRainConvPix2(148,720)    integer
```

Stratiform rain

```
e_surfRainStratMean1(16,72)    real
e_surfRainStratDev1(16,72)     real
e_surfRainStratPix1(16,72)     integer
e_surfRainStratH(16,72,30)     integer*2
e_surfRainStratMean2(148,720)real
e_surfRainStratDev2(148,720)   real
e_surfRainStratPix2(148,720)   integer
```

Shallow/Shallow-isolated rain

Near-surface rain, computed when rain is flagged "Shallow" or "Shallow-isolated". The categories Shallow and Shallow-isolated are mutually exclusive.

`shallowRainMean1(16,72)`	real
`shallowRainDev1(16,72)`	real
`shallowRainPix1(16,72)`	integer
`shallowRainH(16,72,30)`	integer*2
`shallowRainMean2(148,720)`	real
`shallowRainDev2(148,720)`	real
`shallowRainPix2(148,720)`	integer

`shallowIsoRainMean1(16,72)`	real
`shallowIsoRainDev1(16,72)`	real
`shallowIsoRainPix1(16,72)`	integer
`shallowIsoRainH(16,72,30)`	integer*2
`shallowIsoRainMean2(148,720)`	real
`shallowIsoRainDev2(148,720)`	real
`shallowIsoRainPix2(148,720)`	integer

Measured reflectivity factors, Zm

dBZ, Z in mm^6/m^3

CAPPIs

Computed at the same heights and conditions as rain CAPPIs. The count values are the corresponding rain-rate pixel counts. 0.5×0.5-degree standard deviations are not computed.

All rain types

`zmMean1(16,72,6)`	real
`zmDev1(16,72,6)`	real
`zmH(16,72,30,6)`	integer*2
`zmMean2(148,720,4)`	real

Convective rain

`convZmMean1(16,72,6)`	real
`convZmDev1(16,72,6)`	real
`convZmH(16,72,30,6)`	integer*2
`convZmMean2(148,720,4)`	real

Stratiform rain

`stratZmMean1(16,72,6)`	real
`stratZmDev1(16,72,6)`	real
`stratZmH(16,72,30,6)`	integer*2
`stratZmMean2(148,720,4)`	real

Attenuation-corrected estimate of reflectivity factor, Zt ("Z-true")
dBZ, Z in mm^6/m^3

CAPPIs
Computed at the same heights and conditions as rain CAPPIs. The count values are the corresponding rain-rate pixel counts. 0.5×0.5-degree standard deviations are not computed.

All rain types

`ztMean1(16,72,6)`	real
`ztDev1(16,72,6)`	real
`ztH(16,72,30,6)`	integer*2
`ztMean2(148,720,4)`	real

Convective rain

`convZtMean1(16,72,6)`	real
`convZtDev1(16,72,6)`	real
`convZtH(16,72,30,6)`	integer*2
`convZtMean2(148,720,4)`	real

Stratiform rain

`stratZtMean1(16,72,6)`	real
`stratZtDev1(16,72,6)`	real
`stratZtH(16,72,30,6)`	integer*2
`stratZtMean2(148,720,4)`	real

Epsilon-0 and epsilon
Epsilon_0 is defined as the multiplicative factor of α (in the $k=\alpha Z^{\beta}$ relation) such that the path attenuation from Hitschfeld-Bordan estimate is equal to that from the surface reference technique (SRT). For small values of attenuation it is approximately equal to the ratio of the path attenuation from the SRT to that of the Hitschfeld-Bordan path attenuation. It is computed only when the path attenuation from 2A-21 is judged to be reliable or marginally reliable (see 2A-21) and when bit 8 of the `method` flag from 2A-25 is set to one.

Epsilon is the multiplicative factor of α for the hybrid method of 2A-25. For small values of attenuation it is approximately equal to the ratio of the path attenuation from 2A-25 to that of the Hitschfeld-Bordan path attenuation. The epsilon values are stored only under the conditions for which the epsilon_0 data are stored. The number of counts for epsilon and epsilon_0 should be the same. Specifically,

```
epsilon0StratPix1 = epsilonStratPix1
epsilon0ConvPix1 = epsilonConvPix1
epsilon0StratPix2 = epsilonStratPix2
epsilon0ConvPix2 = epsilonConvPix2
```

Epsilon is the ratio of the path attenuation from 2A-25 to that of the Hitschfeld-Bordan path attenuation (see 2a25).

`epsilon0ConvMean1(16,72)`	real
`epsilon0ConvDev1(16,72)`	real
`epsilon0ConvPix1(16,72)`	integer
`epsilon0ConvH(16,72,30)`	integer*2
`epsilon0ConvMean2(148,720)`	real
`epsilon0ConvDev2(148,720)`	real
`epsilon0ConvPix2(148,720)`	integer

`epsilon0StratMean1(16,72)`	real
`epsilon0StratDev1(16,72)`	real
`epsilon0StratPix1(16,72)`	integer
`epsilon0StratH(16,72,30)`	integer*2
`epsilon0StratMean2(148,720)`	real
`epsilon0StratDev2(148,720)`	real
`epsilon0StratPix2(148,720)`	integer

`epsilonConvMean1(16,72)`	real
`epsilonConvDev1(16,72)`	real
`epsilonConvPix1(16,72)`	integer
`epsilonConvH(16,72,30)`	integer*2
`epsilonConvMean2(148,720)`	real
`epsilonConvDev2(148,720)`	real
`epsilonConvPix2(148,720)`	integer

`epsilonStratMean1(16,72)`	real
`epsilonStratDev1(16,72)`	real
`epsilonStratPix1(16,72)`	integer
`epsilonStratH(16,72,30)`	integer*2
`epsilonStratMean2(148,720)`	real
`epsilonStratDev2(148,720)`	real
`epsilonStratPix2(148,720)`	integer

Storm height (meters)
Dimension 3 signifies that the statistics are conditioned on rain type where: 1=stratiform, 2=convective, 3=all rain.

`stormHtMean(16,72,3)`	real
`stormHtDev(16,72,3)`	real
`stormHH(16,72,30)`	integer*2
`convStormHH(16,72,30)`	integer*2
`stratStormHH(16,72,30)`	integer*2
`stormHeightMean(148,720,3)`	real
`stormHeightDev2(148,720,3)`	real

Bright-band height (meters) and Maximum reflectivity in bright band (dBZ)
Bright-band statistics where height (Ht) is in meters and the maximum reflectivity statistics refer to 10 log10 of the maximum radar reflectivity in the bright band.

`bbHtMean(16,72)`	real
`bbHtDev(16,72)`	real
`bbPixNum1(16,72)`	integer
`BBHH(16,72,30)`	integer*2
`bbHeightMean(148,720)`	real
`bbHeightDev2(148,720)`	real
`bbPixNum2(148,720)`	integer

`bbZmaxMean1(16,72)`	real
`bbZmaxDev1(16,72)`	real
`bbZmaxH(16,72,30)`	integer*2
`bbZmaxMean2(148,720)`	real
`bbZmaxDev2(148,720)`	real

Nadir bright-band statistics
Height and width (meters) and maximum reflectivity (dBZ). The statistics are computed at the nadir angle bin only.
High-resolution (0.5 degrees) statistics are not computed (see 2a23).

`bbNadirHtMean1(16,72)`	real
`bbNadirHtDev1(16,72)`	real
`bbNadirPix1(16,72)`	integer
`bbNadirHH(16,72,30)`	integer*2

`bbNadirWidthMean1(16,72)`	real
`bbNadirWidthDev1(16,72)`	real
`bbNadirWidthH(16,72,30)`	integer*2

`bbNadirZmaxMean1(16,72)`	real
`bbNadirZmaxDev1(16,72)`	real
`bbNadirZmaxH(16,72,30)`	integer*2

Snow depth (meters)

Depth of layer from storm top to upper boundary of the bright-band.

Computed only when bright band is present. Pixel counts (number of occurrences) are bbPixNum1 and bbPixNum2 for the low and high-resolution boxes, respectively.

`sdepthMean1(16,72)`	real
`sdepthDev1(16,72)`	real
`sdepthMean2(148,720)`	real
`sdepthDev2(148,720)`	real
`snowIceLH(16,72,30)`	integer*2

Path-integrated attenuation (1-way) (dB/km)

Dimension 3 represents 4 angle bins (0, 5, 10, 15 degrees) and all 49 angle bins combined. For example, `piaSrtMean(i,j,2)`, `piaSrtMean(i,j,5)` represent the mean PIA from the surface reference technique at the `(i,j)` box using data, respectively, from an incidence angle of 5 degrees and from all incidence angles. No adjustment is made for the differing path lengths for the off-nadir angle bins. The 5-, 10-, and 15-degree bins combine data from both sides of the scan. (This is a change from version 5, which included data from one side only). Also note that the convention differs from that in 2A-21 where the 2-way path attenuation is used.

Notation:

'Srt' denotes the path attenuation determined from the surface reference technique in 2A-21. Data are added to the computation only when the path attenuation is judged to be reliable or marginally reliable.

'Hb' denotes the Hitschfeld-Bordan path attenuation from 2A-25. In some cases, the estimate diverges so the estimates are not included in the statistics

'2a25' denotes the final path attenuation estimate from 2a25

'0' denotes the zeroth-order estimate of path attenuation as determined from the integral of αZ_m^{β} integrated from the storm top to the lowest range gate. α and β are estimated in 2A-25

`piaSrtMean(16,72,5)`	real
`piaSrtDev(16,72,5)`	real
`piaSrtPix(16,72,5)`	real
`piaSrtH(16,72,30,5)`	integer*2
`piaHbMean(16,72,5)`	real
`piaHbDev(16,72,5)`	real
`piaHbPix(16,72,5)`	real
`piaHbH(16,72,30,5)`	integer*2
`pia0Mean(16,72,5)`	real
`pia0Dev(16,72,5)`	real
`pia0Pix(16,72,5)`	real
`pia0H(16,72,30,5)`	integer*2
`pia2a25Mean(16,72,5)`	real
`pia2a25Dev(16,72,5)`	real
`pia2a25Pix(16,72,5)`	real
`pia2a25H(16,72,30,5)`	integer*2

Subset PIA statistics are the same as the above statistics, except that the input data are filtered the same way as the epsilon statistics.

```
piaSrtssMean(16,72,5)          real
piaSrsstDev(16,72,5)           real
piaSrtssPix(16,72,5)           real
piaSrtssH(16,72,30,5)          integer*2

piaHbssMean(16,72,5)           real
piaHbssDev(16,72,5)            real
piaHbssPix(16,72,5)            real
piaHbssH(16,72,30,5)           integer*2

pia0ssMean(16,72,5)            real
pia0ssDev(16,72,5)             real
pia0ssPix(16,72,5)             real
pia0ssH(16,72,30,5)            integer*2

pia2a25ssMean(16,72,5)         real
pia2a25ssDev(16,72,5)          real
pia2a25ssPix(16,72,5)          real
pia2a25ssH(16,72,30,5)         integer*2
```

Xi (unitless)

`Xi` is the normalized standard deviation of `zeta` (see 2A-25), `zeta_sd/zeta_mn`. `Xi` is no longer a product in 2A-25, but `zeta_sd` and `zeta_mn` are available. In version 6, `xi` is now computed in 3A-25. `Xi` is set to zero when `zeta_mn` is less than 0.01.

```
xiMean(16,72)                  real
xiDev(16,72)                   real
xiH(16,72,30)                  integer*2
```

Non-uniform beam filling correction factor (unitless, see 2a25)

```
nubfCorFacMean(16,72)          real
nubfCorFacDev(16,72)           real
nubfH(16,72,30)                integer*2
```

RZ-relation coefficients, *a* and *b*, $R = aZ^b$

Computed near-surface (last array dimension = 1) and at 2-km (last dimension = 2).
At each lat-lon cell, a log*R*-log*Z* fit is computed for all pairs of points (log*R*, log*Z*) that are estimated within the box (at either near-surface or 2 km) for the month. Note that *R* is rain rate (mm/h) and *Z* is the attenuation-corrected reflectivity. If the *a* coefficient exceeds 10, the fit is assumed to have failed, and both *a* and *b* are set to -999.0.

All rain types

```
rzA1(16,72,2)                  real
rzB1(16,72,2)                  real
```

`rzPix1(16,72,2)`	integer
`rzA2(148,720,2)`	real
`rzB2(148,720,2)`	real
`rzPix2(148,720,2)`	integer

Convective rain

`rzConvA1(16,72,2)`	real
`rzConvB1(16,72,2)`	real
`rzConvPix1(16,72,2)`	integer
`rzConvA2(148,720,2)`	real
`rzConvB2(148,720,2)`	real
`rzConvPix2(148,720,2)`	integer

Stratiform rain

`rzStratA1(16,72,2)`	real
`rzStratB1(16,72,2)`	real
`rzStratPix1(16,72,2)`	integer
`rzStratA2(148,720,2)`	real
`rzStratB2(148,720,2)`	real
`rzStratPix2(148,720,2)`	integer

Correlation coefficients
Correlation of rain rate between pairs of heights.
The last dimension represents the height pairs, as follows:

1 (2 km, 4 km)
2 (2 km, 6 km)
3 (4 km, 6 km)

All rain types

`rainCCoef(16,72,3)`	real
`rainCCoefPix(16,72,3)`	real

Convective rain

`convRainCCoef(16,72,3)`	real
`convCCoefPix(16,72,3)`	real

Stratiform rain

`stratRainCCoef(16,72,3)`	real
`stratCCoefPix(16,72,3)`	real

Correlation coefficients between storm height and maximum value of Zm along path

`stormHtZmCCoef(16,72)`	real

Correlation coefficients between xi and maximum Zm

`xiZmCCoef(16,72)`	real

PIA correlation coefficients

These are the correlations between various PIA estimates. Dimension 3 represents 4 angle bins (0, 5, 10, 15 degrees) and all 49 angle bins combined. The last dimension represents the various pairs amongst four PIA estimates, as follows:

1 [SRT,HB]
2 [SRT,0th-order]
3 [HB,0th-order]
4 [2a25,SRT]
5 [2a25,HB]
6 [2a25,0th-order]

`piaCCoef(16,72,5,6)`	real
`piaCCoefPix(16,72,5)`	real
`ttlAnglePix1(16,72,4)`	integer*2
`rainAnglePix1(16,72,4)`	integer*2

Epsilon Fit

Computed for each 5×5-degree cell. This is the slope of a regression between x and y,

$$y = \zeta(r_b) = \texttt{l2a25.zeta(1, i)}$$
$$x = 1 - 10^{-0.1\beta\,\mathrm{PIA_{SRT}}}$$

where `i` is the angle bin, and

$$\beta = \texttt{l2a25.attenParmBeta(i)}$$
$$\mathrm{PIA_{SRT}} = \texttt{l2a25.pia(3,i)}$$

Points are included only when 2A-21 `reliabFlag` ≤ 2 (reliable or marginally reliable) and `zeta` > 0.1.

The inverse slope, 1/slope, is an estimate of epsilon. The intercept is forced to be zero.

$$\text{slope} = \frac{1}{\hat{\varepsilon}} = \frac{\sum xy}{\sum x^2}$$
$$\texttt{epsilonFit} = 1/\text{slope}$$
$$\text{sum square error} = \sum y^2 - \frac{2}{\hat{\varepsilon}}\sum xy + \frac{1}{\hat{\varepsilon}^2}\sum x^2$$
$$\texttt{epsilonFitRMS} = \sqrt{\frac{\text{sse}}{N-2}}$$

`epsilonFit(16,72)`	real
`epsilonFitRMS(16,72)`	real

`epsilonFitPix(16,72)` integer

3-1. 2.3. Definition of Bins for Histograms

For radar reflectivity factor histograms:

`ztH`, `convZtH`, `stratZtH`
`zmH`, `convZmH`, `stratZmH`
`bbZmaxH`, `bbNadirZmaxH`,

the 31 bin boundaries are:

```
 0.01
12.0  14.0  16.0  18.0  20.0  22.0  24.0  26.0  28.0  30.0
32.0  34.0  36.0  38.0  40.0  42.0  44.0  46.0  48.0  50.0
52.0  54.0  56.0  58.0  60.0  62.0  64.0  66.0  68.0  70.0
```

For all rain rate histograms: `rainH`, `stratRainH`, `convRainH`, `surfRainH`, the 31 bin boundaries are (mm/h):

```
  0.01
  0.2050482  0.2734362  0.3646330   0.4862459   0.6484194
  0.8646811   1.153071   1.537645    2.050482    2.734362
  3.646330    4.862459   6.484194    8.646811   11.53071
 15.37645    20.50482   27.34362   36.46331    48.62460
 64.84194    86.46812  115.3071   153.7645    205.0482
273.4362    364.6331   486.2460   648.4194    864.6812
```

For bright band height histogram, `HHBB`, the 31 bin boundaries [km] are:

```
0.01
0.25  0.50  0.75  1.00  1.25  1.50  1.75  2.00  2.25  2.50
2.75  3.00  3.25  3.50  3.75  4.00  4.25  4.50  4.75  5.00
5.25  5.50  5.75  6.00  6.25  6.50  6.75  7.00  7.50 20.00
```

For storm height histograms, `stormHH`, `stratStormHH`, `convStormHH`, (in km), the 31 bin boundaries [km] are:

```
 0.01
 0.5   1.0   1.5   2.0   2.5   3.0   3.5   4.0   4.5   5.0
 5.5   6.0   6.5   7.0   7.5   8.0   8.5   9.0   9.5  10.0
10.5  11.0  11.5  12.0  12.5  13.0  14.0  15.0  16.0  20.0
```

For distance from storm top to bright-band height histogram, `snowIceLH`, `bbNadirWidthH`, the 31 bin boundaries [m] are:

```
   0.0
 125.0   250.0   375.0   500.0   625.0
 750.0   875.0  1000.0  1125.0  1250.0
1375.0  1500.0  1625.0  1750.0  1875.0
2000.0  2125.0  2250.0  2375.0  2500.0
2625.0  2750.0  2875.0  3000.0  3125.0
3250.0  3375.0  3500.0  3625.0  3750.0
```

For the path-averaged attenuation estimate histograms, `piaSrtH`, `piaHbH`, `pia0H`, and `pia2a25H`, the 31 bin boundaries [dB] are:

```
0.01
0.1   0.2   0.3   0.4   0.5   0.6   0.8   1.0   1.2   1.4
1.6   1.8   2.0   2.5   3.0   3.5   4.0   4.5   5.0   5.5
6.0   7.0   8.0   9.0  10.0  15.0  20.0  25.0  30.0  100.
```

For non-uniform beamfilling factor histogram, `nubfH`, the 31 bin boundaries [dimensionless] are:

```
1.00
1.05  1.10  1.15  1.20  1.25  1.30 1.35  1.40  1.45  1.50
1.55  1.60  1.65  1.70  1.75  1.80 1.85  1.90  1.95  2.00
2.10  2.20  2.30  2.40  2.50  2.60 2.70  2.80  2.90  3.00
```

For xi (=standard deviation of zeta/mean of zeta) histogram, `xiH`, the 31 bin boundaries [dimensionless] are:

```
0.0
0.2   0.4   0.6   0.8   1.0   1.2   1.4   1.6   1.8   2.0
2.2   2.4   2.6   2.8   3.0   3.2   3.4   3.6   3.8   4.0
4.2  4.4   4.6   4.8   5.0  10.0  20.0  30.0  50.0  10000.
```

For the parameters `epsilon` and `epsilon0` (see 2a25) the 31 bin boundaries are:

```
0.0
0.1   0.2   0.3   0.4   0.5   0.6   0.7   0.8   0.9   1.0
1.1   1.2   1.3   1.4   1.5   1.6   1.7   1.8   1.9   2.0
2.1   2.2   2.3   2.4   2.5   2.6   2.7   2.8   2.9   3.0
```

3-1. 2.4. Other Input Parameters:

CAPPI heights relative to the ellipsoid: 2, 4, 6, 10, 15 km.

Angle bins at which the statistics of the various PIA estimates are to be evaluated: 5, 12, 18, 25, 32, 38, 45, which correspond approximately to angles of 0, 5, 10, and 15 degrees incidence (port and starboard).

3-1. 2.5. Definitions of low and high resolution grids

The low resolution grid consists of 16×72 latitude-longitude elements corresponding to a 5×5-degree grid that covers the TRMM region from 40 S to 40 N where:

latitude index		
1	-40 to -35	(40 S to 30 S)
2	-35 to -30	(35 S to 30 S)
	…	

16   35 to 40   (35 N to 40 N)

longitude
index
1   -180 to -175   (180 W to 175 W)
2   -175 to -170   (175 W to 170 W)
…
72   175 to 180   (175 E to 180 E)

The high resolution grid consists of 160×720 latitude-longitude elements corresponding to a 0.5×0.5-degree grid that covers the TRMM region from 37 S to 37 N where:

latitude
index
1   -37.0 to -36.5   (37.0 S to 36.5 S)
2   -36.5 to -36.0   (36.5 S to 36.0 S)
…
160   36.5 to 37.0   (36.5 N to 37.0 N)

longitude
index
1   -180.0 to -179.5   (180.0 W to 179.5 W)
2   -179.5 to -179.0   (179.5 W to 179.0 W)
…
720   179.5 to 180.0   (179.5 E to 180.0 E)

3-1. 3. Processing Procedure:

The basic steps in the procedure are:

i. Read in data (scan by scan) from 2A-21, 2A-23, 2A-25 and 1C-21.

ii. Adjust the numbering conventions so that Zm, Zt and R are aligned properly; this is done by using the anchor point of `binEllipsoid` in 1C-21 and the corresponding bin ellipsoid of 2A-25 which, by convention, is the 80th element of Zt.

iii. Find the coarse and fine resolution boxes to which each of the 49 observations belongs. Note that a single scan is composed of 49 observations each at a different incidence angle.
(coarse resolution boxes are 5×5-degree cells)
(fine resolution boxes are 0.5×0.5-degree cells)

iv. Resample Zm, Zt and R from the range direction onto the vertical.

v. Update the various statistics.

vi. If a month transition occurs within the granule, write the HDF output file and reinitialize the intermediate files.

3-1. 4. Comments and Issues:

i. In version 6, the rain statistics are computed only when the 'rain-certain' flag is set in 1C-21. The 'rain-possible' flag is treated the same as a 'no-rain' flag. Products defined in version 4 (which contained the term 'All' in the product name) and which included 'rain-certain' and 'rain-possible' data, have been deleted from the list of version 6 products.

ii. It is assumed in the program that the verification file does not exist; if it is already exists an error will occur.

iii. There are 2 definitions of `zeta` and `nubf` (from 2A-25). In both cases the original definitions of these quantities are used; i.e., the first element of the array.

iv. The height levels are being defined relative to the ellipsoid and not the local surface. This may cause difficulties in the interpretation of the statistics over some land areas at the lower height levels because the level can be below the local surface. In these cases, the rain rate is always set to some flag value and is not counted in the statistics. On the other hand, `ttlPix1` (or `ttlPix2`), the total number of valid observations at the low (high) resolution averaging box, will be incremented so that the observations 'below the surface' will be counted as 'no-rain' events. This will introduce a negative bias into the mean rain rate at the (lat,long) box in question.

v. Missing data scans are being checked by monitoring the `scanStatus` flags in 1C-21. If this indicates a missing scan, no processing is done for that scan. Checks for individual missing variables are not being done explicitly, however.

vi. There are several subtle, interrelated issues regarding the definitions of rain and no-rain and how these definitions affect the statistics. For most of the output products from level 2, numbers that represent a physical quantity (non-flagged values) are being output only if the `minEchoFlag` variable in 1C-21 is set to 'rain-certain'. However, an important category of products (`Zt` and rain rate from 2A-25 and `Zm` from 1C-21) is being output under rain-possible conditions. With the exception noted above only those products for which rain detection is classified as 'certain' are included in the statistics (that is, the statistics conditioned on rain being present). Although some rain events will be missed, the advantage of this selection is that the set of products should be self-consistent. The above was valid for version 4. In versions 5 and 6 the rain-possible flag is always treated as a no-rain occurrence (see comment i.).

vii. The quantity '`minEchoFlag`' (from 1B-21 and 1C-21) provides information on the presence/absence of rain along each of the 49 angle bins that comprise the cross-track scan. To test whether rain is present at a particular range bin or height above the ellipsoid, a threshold value must be used. Presently, this threshold is dBZt > 0.01 dB so that if `minEchoFlag` indicates the certainty of rain along the beam and if dBZt > 0.01 dB at a particular range bin or height level, then the data (e.g., rain rate, dBZm, dBZt, etc) are used in the calculation of the statistics (mean and standard deviation).

A difficulty arises in defining the histograms for the rain rates. The lowest histogram bin for dBZt and dBZm is taken from 0.01 dB to 12 dB; the subsequent bins are taken equal to 2 dB so that the bin boundaries are 14 dB, 16 dB,…, 70 dB. Since the Z-R relationship that is used in 2A-25 can change depending on the storm type and vertical structure, and because the histogram bins must be fixed, the bins for the quantity 10 log *R* (where *R* is the rain rate in mm/h) are determined from the nominal relationship $Z = 200R^{1.6}$ or in dB:

$$\mathrm{dB}R = 0.625\ \mathrm{dBZ} - 14.38\ .$$

For example, the dB*Z* histogram bin from 12 dB to 14 dB corresponds to the rain rate histogram bin from -6.88 dB to -5.63 dB. The lowest dB*R* value (the lower boundary of the first bin) is $0.625 \times 0.01 - 14.38 = -14.32$ dB. It is possible, however, for dB*R* to be less than this because the actual Z-R relationship used in 2A-25 differs from the nominal relationship. In order to count all non-zero rain rates (under 'rain-certain' conditions), the lower boundary of the first dB*R* histogram bin is set to -20 dB rather than -14.32 dB. The reason for doing this is to ensure that the number of data points that are categorized in the rain rate histogram are equal to the number of data points used in the calculation of the mean and standard deviation of this quantity.

viii. There are 4 types of rain rates that are defined in 3a-25.

The first is a 'near-surface' rain rate that is obtained from the range bin closest to the surface that is not corrupted by the surface clutter. In version 4, two sets of products were being computed from these data: the first set of statistics used only those rain rate for which rain is classified as 'certain'; the second set used those rain rates for which rain is classified either as 'possible' or 'certain'. For version 5, the determination was made to eliminate products using the 'rain-possible' flag (see comment i).

The second type of rain rate is the path-averaged rain rate calculated by summing the values from the storm top (first gate where rain is detected) to the last gate (gate nearest to the surface uncontaminated by the surface clutter) and dividing by the number of gates in the interval.

The third type of rain rate is that at a fixed height above the ellipsoid (2, 4, 6, 10 and 15 km). For an arbitrary incidence angle there will be several range gates that intersect the height: to estimate dBZm, dBZt and rain rate at that height, a gaussian weighting is done in dB space for the reflectivity factors and in linear space for the rain rates. This resampling lowers the minimum detectable threshold that, in turn, affects the histogram counts in the 2 lowest bins. In other words, the histogram counts at the lowest 2 bins will generally be larger for the height-profiled quantities than for the 'near-surface' or 'path-averaged' quantities.

The fourth type, added in version 6, is an estimated surface rain rate. See 2a25 for a discussion.

ix. As noted in comment v., the rain rate statistics over mountainous regions at the height levels of 2 and 4 km will tend to underestimate the actual values; for these cases, the near-surface rain rate statistics (under 'rain-certain' conditions) should be a more reliable indicator of the near-surface rain rate.

x. All of the statistics in 3a25 are conditioned on the existence of one or more variables. To compute the unconditioned statistic, it is necessary to compute the probabilities of the events upon which the statistic is conditioned. For example, `rainMean1(i,j,k)` is the conditional mean rain rate in the box (*i,j*) at the *k*th height level. To convert this into an unconditional mean rain rate, *R*m say, it is necessary first to compute the probability of rain at the appropriate latitude-longitude box and height:

$$P_r(i,j,k) = \frac{\text{rainPix1}(i,j,k)}{\text{ttlPix1}(i,j)}$$
$$R_m(i,j,k) = P_r(i,j,k) \times \text{rainMean1}(i,j,k)$$

To convert this to an accumulation (in mm) over a time period consisting of *N* hours, a multiplication of R_m by *N* would be used. For example, the accumulation in mm in a 30 day month $N = 720$.

Similarly, to compute the unconditional mean rain rate for stratiform rain, R_m^{Strat}, at (*i,j,k*):

$$P_r^{\text{Strat}}(i,j,k) = \frac{\text{stratRainPix1}(i,j,k)}{\text{ttlPix1}(i,j)}$$
$$R_m^{\text{Strat}}(i,j,k) = P_r^{\text{Strat}}(i,j,k) \times \text{stratRainMean1}(i,j,k)$$

Note also the following probabilities:

$$P_r(\text{bright - band}) = \frac{\text{bbPixNum}(i,j)}{\text{ttlPix1}(i,j)}$$
$$P_r(\text{stratiform rain}|\text{rain}) = \frac{\text{stratRainPix1}(i,j,k)}{\text{rainPix1}(i,j,k)}$$
$$P_r(\text{convective rain}|\text{rain}) = \frac{\text{convRainPix1}(i,j,k)}{\text{rainPix1}(i,j,k)}$$
$$P_r(\text{bright - band}|\text{rain}) = \frac{\text{bbPixNum}(i,j,k)}{\text{rainPix1}(i,j,k)}$$

Note the difference among quantities of the following kind:

$$P_r(\text{stratiform rain}|\text{rain}) = \frac{\text{stratRainPix1}(i,j,k)}{\text{rainPix1}(i,j,k)}$$
$$P_r'(\text{stratiform rain}|\text{rain}) = \frac{\text{stratRainPix1}(i,j,k)}{\text{rainPix1}(i,j,6)}$$
$$P_r''(\text{stratiform rain}|\text{rain}) = \frac{\text{stratRainPix1}(i,j,6)}{\text{rainPix1}(i,j,6)}$$

P_r'' corresponds to what is the most common definition of the probability of stratiform rain: given that rain is present, what is the probability that it is stratiform. P_r is the probability that, given rain is present at a particular height level (denoted by the index k), that the rain is stratiform. P_r' is the probability that, given rain is present somewhere along the beam, that rain is present at height level k and that the rain is stratiform.

3-1. 5. Changed Variables in Version 6

3-1. 5.1. New variables

bbNadirPix1
bbNadirHtMean1
bbNadirHtDev1
bbNadirHH
bbNadirWidthMean1
bbNadirWidthDev1
bbNadirWidthH
bbNadirZmaxMean1
bbNadirZmaxDev1
bbNadirZmaxH

e_surfRainPix1
e_surfRainMean1
e_surfRainDev1
e_surfRainH
e_surfRainPix2
e_surfRainMean2
e_surfRainDev2
e_surfRainConvPix1
e_surfRainConvMean1
e_surfRainConvDev1
e_surfRainConvH
e_surfRainConvPix2
e_surfRainConvMean2
e_surfRainConvDev2

e_surfRainStratPix1
e_surfRainStratMean1
e_surfRainStratDev1
e_surfRainStratPix2
e_surfRainStratMean2
e_surfRainStratDev2
e_surfRainStratH

epsilon0ConvPix1
epsilon0ConvMean1
epsilon0ConvDev1
epsilon0ConvH
epsilon0ConvPix2
epsilon0ConvMean2
epsilon0ConvDev2
epsilon0StratPix1
epsilon0StratMean1
epsilon0StratDev1
epsilon0StratH
epsilon0StratPix2
epsilon0StratMean2
epsilon0StratDev2

epsilonConvPix1
epsilonConvMean1

epsilonConvDev1
epsilonConvH
epsilonConvPix2
epsilonConvMean2
epsilonConvDev2
epsilonStratPix1
epsilonStratMean1
epsilonStratDev1
epsilonStratH
epsilonStratPix2
epsilonStratMean2
epsilonStratDev2

pia0Pix
pia2a25Pix
piaHbPix
piaSrtPix
piaCCoefPix

piaSrtssPix
piaSrtssMean
piaSrsstDev
piaSrtssH
piaHbssPix
piaHbssMean

piaHbssDev
piaHbssH
pia0ssPix
pia0ssMean
pia0ssDev
pia0ssH
pia2a25ssPix
pia2a25ssMean
pia2a25ssDev

pia2a25ssH

convCCoefPix
stratCCoefPix
rainCCoefPix

rzPix1
rzA1
rzB1
rzPix2
rzA2
rzB2
rzConvPix1
rzConvA1
rzConvB1
rzConvPix2
rzConvA2
rzConvB2
rzStratPix1
rzStratA1
rzStratB1
rzStratPix2
rzStratA2
rzStratB2

shallowIsoRainPix1
shallowIsoRainMean1
shallowIsoRainDev1
shallowIsoRainH
shallowIsoRainPix2
shallowIsoRainMean2
shallowIsoRainDev2

shallowRainPix1
shallowRainMean1
shallowRainDev1
shallowRainH
shallowRainPix2
shallowRainMean2
shallowRainDev2

surfRainStratPix1
surfRainStratMean1
surfRainStratDev1
surfRainStratH
surfRainStratPix2
surfRainStratMean2
surfRainStratDev2
surfRainConvPix1
surfRainConvMean1
surfRainConvDev1
surfRainConvH
surfRainConvPix2
surfRainConvMean2
surfRainConvDev2

3.1.5.2. Deleted Variables

bbwidthMean1
bbwidthDev1

epsilonPix1
epsilonMean1
epsilonDev1
epsilonH

stormHtZmCCoef
wrainPix1
wrainPix2
xiZmCCoef
zmGradH
zpzmH

surfRainAllPix1
surfRainAllMean1
surfRainAllDev1
surfRainAllH
surfRainAllPix2
surfRainAllMean2
surfRainAllDev2

3.1.5.3. Spelling Corrected

stratZtH ; was "startZtH"

3.1.6. New Variables in Version 7

epsilonFit
epsilonFitRMS
epsilonFitPix

3-2. 3A-26: Estimation of Space-Time Rain Rate Statistics Using a Multiple Thresholding Technique

3-2. 1. Objective of the algorithm

The primary objective of 3A-26 is to compute the rain rate statistics over 5-degree (latitude)×5-degree (longitude)×1-month space-time regions. The output products include the estimated values of the probability distribution function of the space-time rain rates at 4 "levels" (2 km, 4 km, 6 km and path-averaged) and the mean, standard deviation, and probability of rain derived from these distributions. Three different rain rate estimates are used for the high-resolution rain rate inputs to the algorithm: the standard Z-R (or 0th-order estimate having no attenuation correction), the Hitschfeld-Bordan (H-B), and the rain rates taken from 2a-25. (Fits based on the high-resolution inputs from the surface reference technique are output to the diagnostic file for evaluation).

This algorithm is based on a statistical procedure. Although the radar team believes that a statistical method of this type should be implemented for TRMM, the method is relatively new and the testing has been carried out only on simulated data and on preliminary TRMM data. Caution on the use of the results is well warranted.

3-2. 2. Description of the Method

A general understanding of the method can be gained by noting that the amount of attenuation in the TRMM radar signal depends on the 2-way path attenuation down to the range gate of interest. This attenuation increases as the range gate is taken deeper into the storm (closer to the surface) and as the rain rate increases. Although some general features of the rain are used in 2a-25, the rain rate estimates are obtained at each instantaneous field of view (IFOV) of the instrument. The space-time statistics of these high-resolution estimates are done in 3a-25. Most users of the TRMM radar data will be interested in the output data from 3a-25 and not the data from 3a-26.

Algorithm 3a-26 serves as an alternative way of estimating the space-time rain statistics. The idea behind the method is that because of attenuation at high rain rates and low signal to noise ratios at light rain rates, there will usually exist an intermediate region over which the rain rate estimates are most accurate. Using only these estimates and an assumption as to the form of the probability distribution function (log-normal), the parameters of the distribution can be found by minimizing the rms difference between the hypothetical distribution and the values of the distribution obtained directly from the measurements. Once the distribution is estimated, the mean and standard deviation of the distribution can be calculated [Refs. 1-2, Ref. 6].

Useful by-products from the calculation of the probability distribution of rain rates are the fractional areas above (or below) particular rain rate thresholds. These data can be used as inputs to some of the area-time integral (ATI) methods that have been proposed [Refs. 3-5]. Although the data can be used to implement the ATI method, the method used in 3a-26 is itself not an ATI method.

The behavior of the estimates depends strongly on the magnitude and type of threshold as well as the method that is used to determine the high-resolution rain rates. There are 3 methods that are used to determine the high-resolution rain rates: the Z-R (0th order without attenuation correction), the Hitschfeld-Bordan (H-B), and the hybrid method of 2a-25. A fourth method, based solely upon the surface reference method, is implemented in the code but the results are output only to a diagnostic file for evaluation. For the 3 estimates of rain rate (Z-R, HB and 2a-25), Q (or zeta as defined in 2a-25) is used as the threshold parameter. What this means is that if the threshold is set to a particular value, Q^*, then if the measured value of Q is less than Q^*, the corresponding rain rate is accepted - that is, it is used to update the distribution function of rain rates. On the other hand, if Q exceeds Q^* the corresponding rain rate estimate is rejected - that is, it is not used to update the distribution function. As the threshold value, Q, is increased a larger percentage of the rain rates will be accepted. The converse holds so that as Q is decreased a smaller percentage of the rain rates will be used in estimating the distribution function. It should be noted that Q is a proxy for the attenuation and usually assumes a value between 0 and 1.

If the Z-R method (without attenuation correction) of estimating the high resolution rain rates is considered, the corresponding output files include the rain rate distribution function, `zeroOrderpDf`, and the mean, standard deviation, and probability of rain derived from the distribution, `zeroOrderFit`, for 6 different values of the Q threshold. The six values of Q are: 0.1, 0.2, 0.3, 0.5, 0.75 and 0.9999. Which set of values corresponding to which threshold should be used? Simulations suggest that if the total number of rain points is on the order of 500 to 1000, the best accuracy is usually obtained by using a threshold value of 0.3. This corresponds to the 3rd array element so that the monthly mean rain rate (using the Z-R method) over the 5×5-degree box (lat, long) at height level, `ih`, is given by:

```
mean = zeroOrderFit(lat, long, 1, ih, iq = 3)
```

The standard deviation and probability of rain are given by:

```
std dev  = zeroOrderFit(lat, long, 2, ih, iq = 3)
Pr (Rain) = zeroOrderFit(lat, long, 3, ih, iq = 3)
```

Simulations indicate that for a large number of rain points (N > 5000), the use of smaller threshold values (Q = 0.2) may lead to better estimates of the mean space-time rain rate. In the case of Q = 0.2 we have:

```
mean     = zeroOrderFit(lat, long, 1, ih, iq = 2)
std dev   = zeroOrderFit(lat, long, 2, ih, iq = 2)
Pr (Rain) = zeroOrderFit(lat, long, 3, ih, iq = 2)
```

A useful set for comparison is the choice: Q = 0.999 (array element 6). In this case nearly all of the Z-R rain rate estimates are accepted so that the method reduces to fitting almost all the Z-R derived rain rates to a lognormal distribution:

```
mean     = zeroOrderFit(lat, long, 1, ih, iq = 6)
std dev   = zeroOrderFit(lat, long, 2, ih, iq = 6)
Pr (Rain) = zeroOrderFit(lat, long, 3, ih, iq = 6)
```

The estimate of the mean as determined from the `zeroOrderFit` HDF output variable should be considered the primary output of the algorithm. Since Q = 0.3 is considered, nominally, as the optimum choice of threshold, the variable, `rainMeanTH`, has been defined to store these values. In particular:

```
rainMeanTH(lat,long,ih) = zeroOrderFit(lat,long,ih,1,3)
```

The accuracy of the results at other *Q* thresholds and the statistics derived from the Hitschfeld-Bordan (`hbFit`) and rain rates from 2a-25 (`fit2A25`) will be evaluated as additional data from the TRMM radar become available.

3.2- 3. Relationship of 3a-26 outputs to those of 3a-25

In comparing the statistics from 3a-25 and 3a-26 there are 2 differences between these data sets that should be kept in mind. The first is that the statistics produced from 3a-25 are conditioned either on the presence of rain or on the presence of a particular type of rain (stratiform or convective). For the 3a-26 products the means and standard deviations derived from the `zeroOrderFit`, `hbFit` and `fit2A25` arrays are unconditioned - that is, the statistics include both rain and no-rain events. The second difference is that the set of heights for the 3a-26 products is a subset of the heights used for the (low resolution) products of 3a-25.

For the 3a-26 products, the height levels relative to the ellipsoid are:

`hlevel`	Height above ellipsoid
1	2 km
2	4 km
3	6 km
4	Path-average

For the low-resolution 3a-25 products, the height levels relative to the ellipsoid are:

`hlevel`	Height above ellipsoid
1	2 km
2	4 km
3	6 km
4	10 km
5	15 km
6	Path-average

In earlier versions of the program, the height levels were defined relative to the local surface. In the latest versions of 3a-25 and 3a-26 (version 3 and later) all heights are measured relative to the earth's ellipsoid.

As an example, assume that the monthly rain accumulations, MRA (millimeters/month), are to be computed over the 5-degree×5-degree latitude-longitude box specified by (lat, long) for the rain rates measured at a height level given by `hlevel`.

From 3a-25, the mean rain rate (mm/hr), conditioned on rain being present at height level, `ih`, is given by:

```
rainMean1(lat, long, ih).
```

To convert this to an unconditioned mean rain rate the quantity is first multiplied by the probability of rain. This can be approximated by the ratio of the number of rain counts (`rainPix1(lat,long,ih)`) to the total number of observations over the month (`ttlPix1(lat,long)`). To convert this to a monthly accumulation, the unconditioned rain rate is multiplied by the number of hours in a (30 day) month, 720, so that the monthly rain accumulation, MRA (mm/month), as derived from the 3a-25 products, is:

```
MRA(3a-25) = rainMean1(lat,long,ih)*PrRain(lat,long,ih)*720
```

where

```
PrRain(lat,long,ih) = rainPix1(lat,long,ih)/ttlPix1(lat,long)
```

From the 3a-26 products, the MRA (mm/month), using the zeroth-order estimate (Z-R), and the same conversion from mm/h to mm/month (720), is:

```
MRA(3a-26) = zeroOrderFit(lat,long,ih,1,iqthres)*720
```

For the 3rd threshold, $Q = 0.3$, the MRA is

```
MRA(3a-26) = zeroOrderFit(lat,long,ih,1,3)*720
```

or, equivalently,

```
MRA(3a-26) = rainMeanTH(lat,long,ih)*720
```

3-2. 4. Relationship between 3a-26 and the fractional areas above particular thresholds

The single threshold technique (ATI) uses the fractional area above a particular rain rate threshold as a linear estimator for the area-average rain rate. Estimates of the fractional areas above a threshold can be obtained from the estimated distribution functions described above.

As noted above, the counts, which are proportional to the probability distribution functions of rain rate, are stored in the arrays:

```
zeroOrderFit(16, 72, 4, 3, 6)
hbFit(16, 72, 4, 3, 6)
fit2A25(16, 72, 4, 3, 6)
```

where the 5 dimensional array refers to: latitude, longitude, height, fitting parameter, *Q* threshold)

and where

```
fitting parameter = 1 (mean value of log-normal distribution)
                  = 2(standarddeviation of log-normal distribution)
```

```
                = 3  (probability of rain)
```

It is important to note that these counts only include rain counts. To add in the no-rain counts, note that the total number of counts, `ntot(lat,long)`, and the total number of rain counts (at level `ih`), `nrain(lat,long,ih)`, are output variables so that

```
N_no-rain(lat,long,ih) = ntot(lat,long) - nrain(lat,long,ih)
```

The probability distribution function, `zeroOrderpDf'` (unnormalized), that includes the no-rain cases, is given by:

```
   zeroOrderpDf'(lat,long,ir,ih,iq) =
     zeroOrderpDf(lat,long,ir,ih,iq) + N_no-rain(lat,long,ih)

     for   ir = 1,..,25
           iq = 1,..,6
```

the formulas for `hbpDf` and `pDf2a25` are identical

The variable `zeroOrderpDf'(lat,long,irainth,ih,iqthres)` is the number of rain counts above the rain rate threshold corresponding to the '`ir`' indice. Denote this rain rate by `RR(ir)`. The fractional area below the rain rate threshold `RR(ir)` at height level `ih` at the *Q* threshold, `iq`, using the Z-R estimates of rain rates is:

```
     Fr_Area{R < RR(ir)}(lat,long,ih) =
           zeroOrderpDf'(lat,long,ir,ih,iq)/ntot(lat,long)
```

The fractional area above this threshold is:

```
Fr_Area_RR > RR(ir)(lat,long,ih) = 1 - Fr_Area{R < RR(ir)}(lat,long,ih)
```

For example, to compute the fractional area above the threshold of 2.05 mm/h (`ir` = 9 - see definition of the rain rate threshold categories in 3b below) at the *Q* threshold of 0.9999 (`iq` = 6) at a height of 2 km above the ellipsoid (`ih` =1) the following equations are used:

```
zeroOrderpDf'(lat,long,ir=9,ih=1,iq=6) =
  zeroOrderpDf(lat,long,ir=9,ih=1,iq=6) + N_no-rain(lat,long,ih=1)

N_no-rain(lat,long,ih=1) = ntot(lat,long) - nrain(lat,long,ih=1)

Fr_Area{RR<2.05}(lat,long,ih=1) =
    zeroOrderpDf'(lat,long,ir=9,ih=1,iq=6)/ntot(lat,long)

Fr_Area{RR>2.05}(lat,long,ih=1) = 1 - Fr_Area{RR<2.05}(lat,long,ih=1)
```

So that the fractional area above 2.05 mm/h over the 5×5-degree box (lat, long) over the month (which uses the Z-R derived rain rates and nearly all the data, `iq` = 6) can be expressed in terms of the HDF outputs:

```
zeroOrderpDf(lat,long,ir=9,ih=1,iq=6)
nrain(lat,long,ih=1)
ntot(lat,long)
```

3-2. 5. Reliability estimates

The reliability is defined as the rms difference between experimentally determined values of the pDf and the fitted values of the pDf at those values for which the experimentally-determined pDf increases monontonically.

```
reliabZeroOrder(16,72,4,6)
reliabHB(16,72,4,6)
reliabSRT(16,72,4,6)
```

In version 7, several changes have been made to subroutine fncfit3 to eliminate occurences of Inf and NaN. One consequence is that several of the error flags have been changed, new error flags added and some old flags deleted. The error flag definitions for version 7 are given below.

one or more of the fitting parameters have been set to NaN
set fitting parameters & reliab factor to -222.

errors in one or more of the fitting coefficients
set fitting parameters & reliab factor to -333.

large (or possibly negative) rms error in fit
set fitting parameters & reliab factor to -444.

concave parameter less than 0
set fitting parameters & reliab factor to -666.

insufficient # of thresholds or n1 or n2 = 0
set fitting parameters & reliab factor to -777.

insufficient # of points for accurate fit
set fitting parameters & reliab factor to -999.

Note that the old flag values -555 and -888 have been eliminated since these error conditions are covered by those above.

3-2. 6. Definition of the latitude-longitude boxes

The products are defined on a 5-degree×5-degree×1 month grid that covers the TRMM orbit. The latitude boxes are labeled from 1 to 36 where box 1 covers from 40 S to 35 S and box 36 covers from 35 N to 40 N. The longitude boxes are labeled from 1 to 72 where box 1 runs from 180 W to 175 W and box 72 runs from 175 E to 179.999 E.

3-2. 7. Notes on the processing procedure

1. Assume that 1 granule of data corresponds to 1 orbit.

2. The program is set up to read a scan line of data at a time from 1C-21, 2A-21, 2A-23 and 2A-25 until the full granule of data has been processed.

3. As all the output products are over a 5-degree×5-degree×1 month space-time region, after each granule is processed, the program will write the partially accumulated products to temporary storage. When the next processing cycle begins, these products will be read from temporary storage, and then overwritten once the updated statistics are completed.

4. At the end of the processing cycle (1 month), a subroutine within the program will be used to output the statistics to the HDF file.

5. For the 0th and HB estimates of rain rate, the EDR (effective dynamic range) is based on the quantity zeta (as defined in 2a-25) or Q (as defined in 3a-26), where:

   $$Q = \zeta = 0.2 \ln \beta \int_0^r \alpha Z_m^\beta$$

   where Z_m is the *measured* or *apparent* reflectivity factor, $k = \alpha Z^\beta$, and k is the attenuation coefficient or specific attenuation (dB/km), and Z is the actual reflectivity factor (mm^6/m^3). The coefficients α, and β are read from the 2a-25 output. Note that as $Q = \zeta$ goes to one, the path-integrated-attenuation (pia) increases without bound if k-Z relationship is exact.

   As noted above, the 3a-26 products are defined for height levels of 2 km, 4 km, and 6 km referenced to the ellipsoid. For a height of 2 km, for example, r is that range gate the center of which is closest to the surface drawn 2 km above the ellipsoid.

6.
7. For the multiple threshold method, a necessary condition is that the random variable (that characterizes the radar-measured quantity) be a monotonic function of the quantity that we wish to measure. For example, in the presence of attenuation, the apparent reflectivity factor at the surface Z_m(surface) [or the rain rate estimate based on Z_m] is a non-monotonic function of the true rain rate; as such it is not an appropriate choice for this method. On the other hand, Q (or ζ) is a monotonic function of the path-integrated rain rate and is appropriate for the 0th order and HB estimates of RR.

8. For the path-integrated attenuation (PIA) as derived from the surface reference technique (and the corresponding rain rate), an appropriate proxy variable is the SRT estimate of PIA itself. Results based on the SRT are output only to a diagnostic file.

9. The motivating principle of the multiple threshold method is that for area-wide estimates of the rain rate it is more accurate to extrapolate to the low and high regions of rain rate than to attempt to measure the distribution of these values directly. Reasons for the possible poor performance of the radar at high and low rain rates are:
   i. low SNR at low rain rates
   ii. signal attenuation at high rain rates
   iii. higher variability in Z-R laws at low rain rates

10. In the multiple threshold method, an effective dynamic range (EDR) is selected. The EDR is defined as the region over which the rain rates or *Zm* estimates are expected to

have the highest accuracy (where the signal-to-noise ratio is high and attenuation is low).

11. Currently, the maximum number of thresholds within the EDR is taken to be 25 (the optimum number is still an issue and will depend upon the number of samples and the range of the variable).

12. If the number of samples of the histogram is small, then the estimated pDf is generally unreliable. To circumvent this, we assume that the total number of IFOVs over the averaging domain, with rain present be larger than some number, `iqqmin`. Presently, `iqqmin` = 200.

3-2. 8. Input Parameters (initialized in 3a-26)

Thresholds:

```
data QUthres0th /0.1,0.2,0.3,0.5,0.75,0.9999/      ! Q-thresholds for Z-R and 2a-25
data QUthresHB  /0.1,0.2,0.3,0.5,0.75,0.9999/      ! Q-thresholds for HB
data QLsrt      /1.5,1.,0.8,0.6,0.4,0.1/           ! PIA-thresholds for SRT
```

The rain rate distribution functions consist of the count values in the following 25 rain rate categories

```
data RRcategories ! In mm/hr
   /0.205, 0.27, 0.3646, 0.4863, 0.648, 0.865,
    1.153, 1.537, 2.050, 2.734, 3.646, 4.862,
    6.484, 8.6468, 11.531, 15.376, 20.505, 27.344,
    36.463, 48.625, 64.84, 86.47, 115.31, 153.76, 205.048/
```

At present, a lognormal fitting through the points of the rain rates distribution is made only when the following condition is satisfied:

`iqqmin = 200` ! Minimum number of valid rain occurrences needed for fitting to be done.

In identifying the number of valid thresholds, we require that the count value increase by a certain amount from between successive rain rates thresholds; in fact, the upper rain rate threshold can be identified as that threshold beyond which the count value does not increase by at least `nfu` counts, where:

```
nfu = 30
```

3-2. 9. Output Variables

Arrays for the calculation of probabilities [`int*4`].

`ttlCount(16,72)`

Number of observations at each 5×5-degree box over the month.

`rainCount(16,72,4)`

Number of rain observations at each 5×5-degree box over the month. Note that all height levels are measured relative to the ellipsoid.

`nrain(i,j,1)` h = 2 km
`nrain(i,j,2)` h = 4 km
`nrain(i,j,3)` h = 6 km
`nrain(i,j,4)` path-averaged

Arrays for output of "truncated" histograms at each 5×5×1 month box for 3 RR estimates/4 "levels".

`zeroOrderpDf(16,72,25,4,6)`

Number of counts in the probability distribution function (25 categories) using 0th order (Z-R) rain rate estimate at heights with respect to the ellipsoid of 2, 4, 6 km and path-av for 6 *Q* thresholds.

`hbpDf(16,72,25,4,6)`

Same as above except using the HB estimate of rain rate.

`pDf2A25(16,72,25,4,6)`

Same as above except using the rain rate estimates from 2a-25.

Convention for `zeroOrderpDf(16,72,25,4,6)`, `hbpDf(16,72,25,4,6)`, and `pDf2A25(16,72,25,4,6)`

first argument: latitude
second: longitude
third: rain rate category for pDf
fourth: height "level": 1 = RR @ 2 km
2 = RR @ 4 km
3 = RR @ 6 km
4 = path-averaged RR
fifth: *Q* threshold

Mean, std dev, Pr(Rain) derived from log-normal assumption to rain rate distribution

`zeroOrderFit(16,72,4,3,6)`

3 statistics [mean, std dev, Pr(R)] of distribution fit of the rain rates as derived from the 0th (Z-R) method for 6 thresholds at 4 "levels".

`hbFit(16,72,4,3,6)`

Same as above except Hitschfeld-Bordan method used for rain rate estimates.

`fit2A25(16,72,4,3,6)`

Same as above except data from 2a-25 are used for rain rates estimates.

Reliability factors:

```
reliabOrderFit(16,72,4,6)
reliabHBfit(16,72,4,6)
reliab2A25fit(16,72,4,6)
```

See section **3.2.1.4** for details on computation of the reliability factors.

3-2. 10. Processing Procedure

The basic steps in the procedure are (first 4 are similar to 3a-25 algorithm):

i. Read in data (scan by scan) from 2a-21, 2a-23, 2a-25 and 1c-21

ii. Adjust the range gate numbering conventions so that *Zm*, *Zt* and *R* are aligned properly

iii. Find the coarse boxes to which the 49 IFOVs belong (coarse resolution boxes are 5-degree×5-degree latitude-longitude boxes)

iv. Resample *Zm*, *Zt* and *R* from the range direction onto the vertical

v. Update the estimated probability distribution function for the various rain rate methods at each 5×5-degree box at the various heights, and for threshold values.

vi. If the granule crosses the month boundary, do a nonlinear least squares fit to the distributions determined in step 5, assuming a log-normal distribution; from the fitting parameters, calculate the mean, standard deviation and probability of rain for each distribution.

vii. Re- initialize the intermediate file

3-2. 11. Comments and Issues

i. It is assumed in the program that the verification file does not exist; if it already exists an error will occur.

ii. Differences exists between the height levels at which the 3a-25 and 3a-26 statistics are calculated; for 3a-25 the levels are [2, 4, 6, 10, 15] km and the path-average while for 3a-26 the levels are [2, 4, 6] km and the path-average.

iii. Presently, the height levels are being defined relative to the ellipsoid and not the local surface.

iv. Resampling of the radar data from the range direction to the vertical is done differently in 3a-25 and 3a-26. In 3a-25, the estimate of the reflectivity factor at a particular height is done by a gaussian weighting of the range gates that intersect that height. 3a-26 uses only a single value of *Z* and *R* - that gate, the center of which is closest to the height of interest.

v. The Z-R or 0th method refers to the zeroth order solution of the reflectivity factor from the basic weather radar equation. In this approximation, no compensation is made for attenuation so the reflectivity factor is directly proportional to the measured radar return power. This approximate reflectivity factor is sometimes called the apparent or measured reflectivity factor. In converting any estimate of the reflectivity factor, *Z*(est), to rain rate, *R*, the power-law approximation is used: $R = aZ(\text{est})^b$ where *a* and *b* are obtained from 2a-25.

The HB or Hitschfeld-Bordan solution to the reflectivity factor, *Z*, is obtained by using a specific attenuation-reflectivity factor (k-Z) relationship and then solving the weather radar equation for *Z*.

Description of the rain rates from 2a-25 is given in the documentation for this algorithm.

vi. In version 5 and higher versions of the algorithm, additional error flags have been added that are used to specify the behavior of the second derivative of the estimated distribution function, *F*, at a rain rate of 0.01 mm/h. Since *F* is assumed to be log-normal, then for *R*>0 it can be written:

$$F(R) = 0.5p[1 + \text{erf}(u)]$$
$$\text{erf}(u) = \frac{1}{\sqrt{\pi}} \int_0^u \exp(-t^2)dt$$
$$u = \frac{\ln R - \mu}{s\sqrt{2}}$$

The sign of the second derivative can be determined by:

if (ì - ln*R*) > s^2, then $\frac{d}{dR}\frac{dF}{dR} > 0$

if (ì - ln*R*) < s^2, then $\frac{d}{dR}\frac{dF}{dR} < 0$

where in the code, *R* is evaluated at *R* = 0.01 mm/h.

If $\frac{d}{dR}\frac{dF}{dR} < 0$, then an error flag is set (see above).

The following rule can be shown to give a more stable estimate of rain rate:

Begin with *Q* = 0.3 and evaluate $\frac{d}{dR}\frac{dF}{dR}$. If this is greater than 0 then accept the parameters of this distribution. However, if $\frac{d}{dR}\frac{dF}{dR} < 0$, increase *Q* and evaluate

$\frac{d}{dR}\frac{dF}{dR}$ again; continue this until a Q is found for which $\frac{d}{dR}\frac{dF}{dR} > 0$ at which point accept the corresponding distribution.

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