Tropical Rainfall Measuring Mission
(TRMM)
Precipitation Radar Algorithm

Instruction Manual
(Version 1.0)

TRMM Precipitation Radar Team

National Space Development Agency
of Japan (NASDA)

National Aeronautics
and Space Administration (NASA)

January 29, 1999

Tropical Rainfall Measuring Mission
Precipitation Radar Algorithm
Instruction Manual

Table of Contents

0. Introduction

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 1 *[Oikawa et al., 1997, Kummerow et al., 1998]*. Observation geometry of PR is shown in Fig 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, “over sample ” 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 over sampled 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 in 5° x 5° grid boxes required by the TRMM mission. The characteristics of TRMM PR algorithms are summarized in Table 2 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. 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 σ^0 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 σ^0 by rain using no rain surface scattering coefficient σ^0 as a reference *[Meneghini, 1998]*. 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 isolated warm 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, 1997].* 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 5° x 5° grid boxes. It also outputs the monthly averaged bright band height over 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. On this instruction manual of TRMM PR

This instruction manual of TRMM PR is for the PR algorithms and products that were released to the public on 1 September 1998. There will be a slight improvement in the next version of algorithms and products that are scheduled in September 1999.

The file content description for level 2 and 3 algorithms can be found in the Interface Control Specification (ICS) between the Tropical Rainfall Measuring Mission Science Data and Information System (TSDIS) and the TSDIS Science User (TSU) Volume 4: File Specification for TSDIS Products-Level 2 and 3 File Specifications. It is available at:

http://tsdis02.nascom.nasa.gov/tsdis/Documents/ICSVol4.pdf

0-4. Reference

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.

T. Iguchi, T. Kozu, R. Meneghini and K. Okamoto [1997], “Rain profiling algorithm for the TRMM precipitation radar," *Proceedings of the IEEE 1997 International Geoscience and Remote Sensing Symposium*, August 3-8, Singapore, pp. 1633-1635.

C. Kummerow, W. Barnes, T. Kozu, J. Shiue and J. Simpson [1998], "The tropical rainfall measuring mission (TRMM) sensor package," *Journal of Atmospheric and Oceanic Technology*, **15**, 3, pp. 809-817.

R. Meneghini, T. Kozu, J. A. Jones, T. Iguchi and K. Okamoto [1998], "Estimate of path attenuation for the TRMM radar," *Proceedings of the IEEE 1998 International Geoscience and Remote Sensing Symposium*, July 6-10, Seattle, pp.1882-1884.

K. Oikawa, K., T. Kawanishi, H. Kuroiwa, M. Kojima and T. Kozu [1997], "Development results of TRMM precipitation radar," *Proceedings of the IEEE 1997 International Geoscience and Remote Sensing Symposium*, August 3-8, Singapore, pp. 1630-1632.

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.

Table 0-1. 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	4.3 km (nadir)
Vertical resolution	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

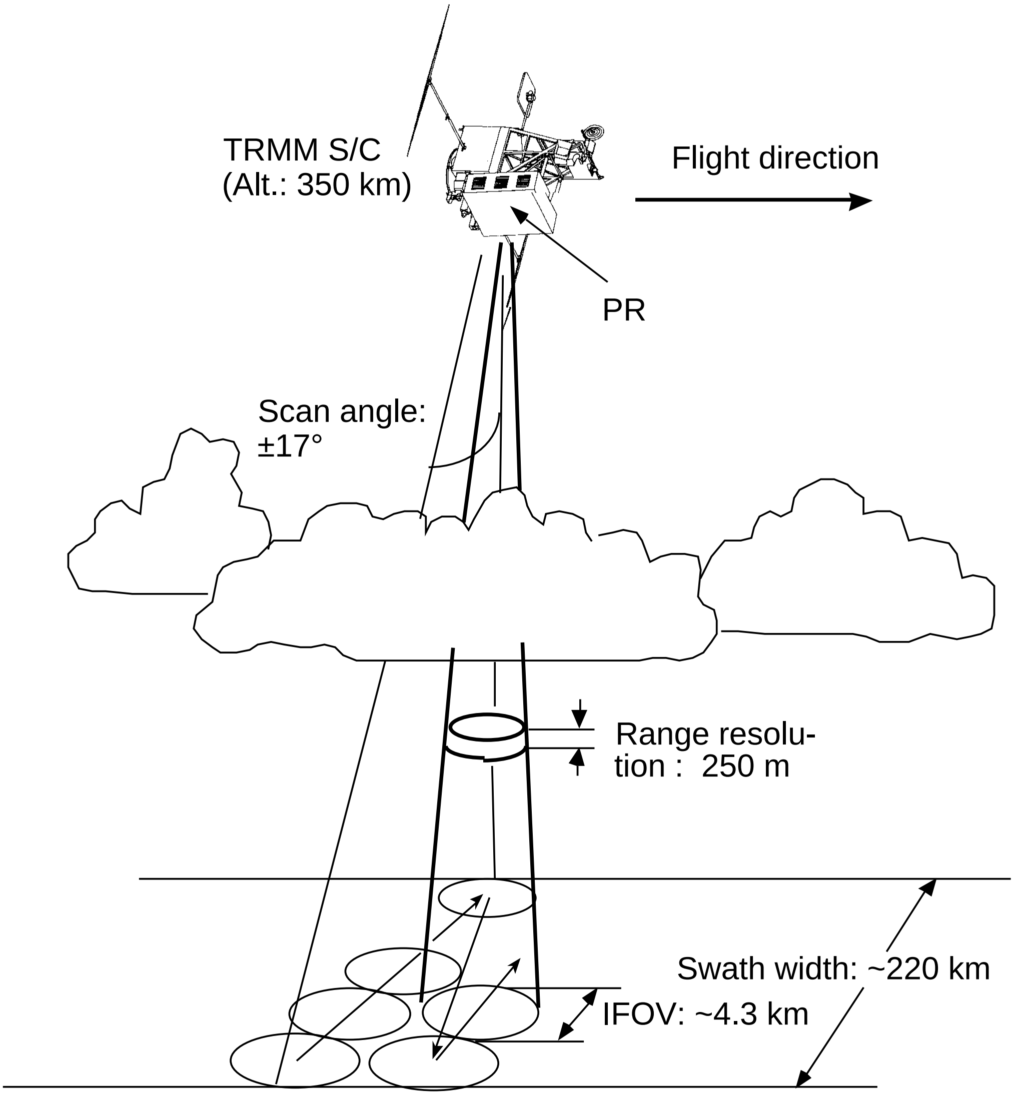


Figure 0-1. Observation concept of the PR.

Table 0-2. TRMM Standard (Day 1) PR Algorithms

Number / Name	Contact Person	Products	Algorithm Description
1B21: PR calibration Rain / No rain	NASDA / EOC, H. Kumagai	Total received power, Noise Level Rain / No rain flag, Storm height, 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.
1C21: PR reflectivities	NASDA / EOC	Profiled reflectivity factors Zm in case of rain	Conversion of the power and noise value to reflectivity factors (Z factors) in case of rain without rain attenuation correction
2A21: σ^0	R. Meneghini	Rain attenuation value 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 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	Bright band (presence or no), Bright band height, Rain type classification Warm rain	Whether a bright band exists in rain echoes and determination of bright band height when it exists. The rain type is classified into stratiform, convective and others. Isolated rain, the height of which is below the 0 deg. height is classified as warm rain.
2A25: PR profile	T. Iguchi	Range profiles of rain rate Average rain rate between predefined heights (2,4 km)	The rain rate estimate is given at each resolution cell. This algorithm employs hybrid method of the surface reference method and Hitschfeld-Borban method.
3A25: Space-time average of radar products	R. Meneghini	Space-time averages of accumulations of 1C21, 2A21, 2A23, 2A25. Monthly averaged rain rate over 5 degs. x 5 degs. boxes.	To calculate various statistics over a month from the 1C21, and level 2 PR output products. Four types of statistics are calculated: (a) probabilities of occurrence(count value), (b)means and standard deviations, (c) histogram, (d) correlation coefficients
3A26: Space-time average using a statistical method	R. Meneghini	Monthly averaged rain rate over 5 degs. x 5 degs. boxes using a statistical method	Rainfall accumulations and rain rate averages over 5 deg.by 5 deg. by 1 month boxes using a statistical method (multiple threshold method).

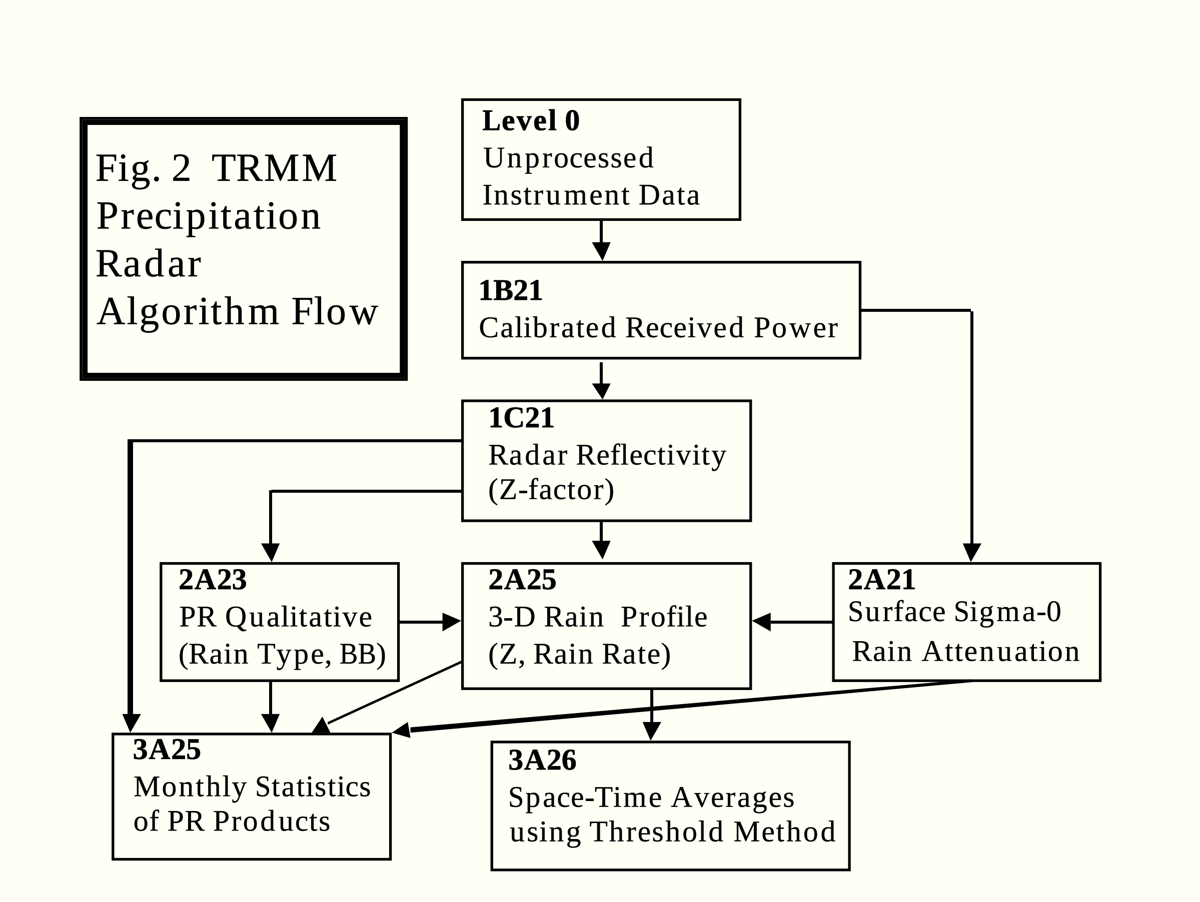


Figure 0-2. TRMM Precipitation Radar Algorithm Flow

1. Level 1

1-1. 1B21 - PR received power, 1C21 - PR radar reflectivity

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.
To convert the count value to the input power, extensive internal calibrations are applied, which are mainly based upon the system model, temperature dependence of model parameters and many temperature sensors attached at various locations of the PR. Periodically the input-output characteristics are measured using an internal calibration loop for the IF unit and later receiver stages. To make an absolute calibration, an Active Radar Calibrator (ARC) is placed at Kansai Branch of CRL and the overall system gain of the PR is being measured every 2 months. Using the transfer function based on the above internal and external calibrations, the PR received power is obtained. Note that the value assumes that the signal follows the Rayleigh fading, so if the fading characteristics of a scatter is different, a small bias error may occur (within 1 or 2 dB).

The 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: One value 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).
- Over-sample data: In order to improve the accuracy of surface echo measurement, and to obtain a better vertical rain profile, every 125-m data are available at a near-nadir rain region (up to 7.5 km) and around surface (±10 deg. scan angles).
- 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

The 1C21 calculates the effective radar reflectivity factor at 13.8 GHz without any propagation loss (due to rain or any other atmospheric gas) correction (Zm). 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.

1-1. 2. File Format

1-1.2.1. 1B21 PRODUCT FILE

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

The file name convention at NASDA EOC is as follows:
PR1B21.YYYYMMDD.nnnnn
YYYYMMDD: Observation Date, nnnnn : granule ID

The PR1B21 product is written in Hierarchical Data Format (HDF).
HDF was developed by the U.S. National Center for Supercomputing Applications (NCSA).
HDF manuals and software tools are available via anonymous ftp at ftp.ncsa.uiuc.edu.

The file structure of 1B21 products is shown in Table 1-1.

Table 1-1 1B21 product file structure

Name	Byte	Note
Data Granule		Data object per granule
Metadata		
Calibration Coefficients	72 byte	
Ray Header	60 byte*49	
Swath Data		Data object per scan (0.6 sec.)
Scan Time	table 8 byte*nscan	
Geolocation	float 4 byte*2*49*nscan	latitude, longitude
Scan Status	Table 15 byte*nscan	
Navigation	table 88 byte*nscan	
Power	table 6 byte*nscan	
System Noise	int 2 byte*49*nscan	dBm / 100
System Noise Warning Flag	int 1 byte*49*nscan	
Minimum Echo Flag	int 1 byte*49*nscan	
First Echo Height	int 2 byte*2*49*nscan	range bin number
Range Bin Number of Ellipsoid	int 2 byte*49*nscan	range bin number
Range Bin Number of Clutter-free Bottom	int 2 byte*49*nscan	range bin number
Range Bin Number of Mean DID	int 2 byte*49*nscan	range bin number
Range Bin Number of Top of DID	int 2 byte*2*49*nscan	range bin number
Range Bin Number of Bottom of DID	int 2 byte*2*49*nscan	range bin number
Satellite Local Zenith Angle	float 4 byte*49*nscan	deg
Spacecraft Range	float 4 byte*49*nscan	m
Bin Start of Over Sample	Int 2 byte*2*29*nscan	
Land / Ocean Flag	Int 2 byte*49*nscan	
Topographic Height	Int 2 byte*49*nscan	m

Bin Number of Surface Peak	int 2 byte*49*nscan	range bin number
Normal Sample	int 2 byte*140*49*nscan	dBm / 100
Surface Oversample	Int 2 byte*5*29*nscan	dBm / 100
Rain Oversample	Int 2 byte*28*11*nscan	dBm / 100

Note.

nscan: number of total packets (scans) in one granule (one orbit from sauthernmost point to the next southernmost point).
In PR, one granule (about 91 minutes) has about 9100 scans because the PR performs one scan every 0.6 seconds.

dBm / 100: For example, -9436 represents –94.36 dBm

1. Metadata

Metadata are defined as the inventory information of the TRMM data.
EOSDIS[1] has divided the metadata elements into two types: core metadata (EOSDIS Core System (ECS) metadata) and product-specific metadata. Core metadata are common to most Earth Observing System (EOS[2]) data products. Product-specific metadata include the specific information of each product.

The detailed information is provided in the Annex.

2. Calibration Coefficients

Calibration coefficients consist of several parameters describing the PR electronic performance. They are controlled by NASDA based on the results of PR calibration data analysis.

These coefficients are applied in 1B21 (PR received power) calculations.

Table 1-2. Calibration coefficients

Name	Format	Note
Transmitter gain correction factor	float 4 byte	
Receiver gain correction factor	float 4 byte	
LOGAMP Input/Output characteristics	float 16*4 byte	

3. Ray Header

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.

---

[1] EOSDIS: EOS Data and Information System (NASA)

[2] EOS: Earth Observing System (NASA)

Table 1-3. Ray Header

Name	Format	Note
Ray Start	int 2 byte	range bin number of starting normal sample, see Note (a)
Ray Size	int 2 byte	number of normal samples in 1 angle see Note (a)
Scan Angle	float 4 byte	unit deg, see Note (b)
Starting Bin Distance	float 4 byte	distance (m) between the satellite and the starting bin sample. unit m, see Note (c)
Rain Threshold #1	float 4 byte	see Note (d)
Rain Threshold #2	float 4 byte	see Note (d)
Transmitter Antenna Gain	float 4 byte	unit dB
Receiver Antenna Gain	float 4 byte	unit dB
One-way 3dB Along-track Beam Width	float 4 byte	unit rad, see Note (e)
One-way 3dB Cross-track Beam Width	float 4 byte	unit..rad, see Note (e)
Equivalent Wavelength	float 4 byte	unit m, see Note (f)
Radar Constant	float 4 byte	unit dB, see Note (g)
PR Internal Delayed Time	float 4 byte	set to 0
Range Bin Size	float 4 byte	unit m, see Note (a), (h)
Logarithmic Averaging Offset	float 4 byte	unit dB, see Note (i)
Main Lobe Clutter Edge	int 1 byte	see Note (j)
Side Lobe Clutter Range	int 3*1 byte	see Note (k)

Notes:

a) The Precipitation Radar (PR) has 400 internal (logical) range bins (A/D sample points) and records “normal sample data” every other range bin from “Ray Start” 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.”
The Nth normal sample data can be converted to the internal logical range bin number as follows;
Logical range bin number at Nth normal sample
$= \text{Ray Start} + 2 \times (N - 1)$

b) Scan Angle 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.*[3] The angle is positive when the antenna beam is rotated counter

---

[3] If there is no attitude error, +X (or sometimes –X, see Spacecraft Orientation in Scan Status) is along the spacecraft flight direction, +Z is along the local nadir, and +Y is defined so that the coordinates become a right-hand Cartesian system.

clockwise (CCW) from the nadir about the +X axis of the radar electric coordinates.

c) Starting Bin Distance is determined by the sampling timing of the PR. The distance between the satellite and the center of the Nth normal sample bin is calculated as follows:

$$\text{Distance} = \text{“Starting Bin Distance”} + \text{“Range Bin Size”} \times (N-1)$$

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

d) Rain Thresholds are used in the minimum echo test.

e) Beam widths, both along track beam width and cross track beam width, are recorded based on the fact that the PR main beam is assumed to have a two-dimensional Gausian beam pattern.

f) “Equivalent Wavelength” $= 2c/(f_1 + f_2)$

where c is the speed of light, and f_1 and f_2 are PR’s two frequencies.

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

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

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

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).*[4] With this constant, users can convert from PR receiving powers to rain reflectivity. (See the 1C products.)

h) Range Bin Size is the PR range resolution and is the width at which pulse electric power decreases 6dB (-6 dB width).

i) Logarithmic Averaging Offset 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.

j) Main Lobe Clutter Edge 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.

k) 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: Items j) and k) are not useful for detailed examination of radar echo range profile, especially over land. Please refer to 1.11, 1.14 - 1.17 and 1.27.

---

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

4. Scan Time

Scan Time is the center time of 1 scan (the time at center of the nadir beam transmitted pulse)
It is expressed as the UTC seconds of the day.

5. Geolocation

The earth location of the beam center point per angle bins at the altitude of the earth ellipsoid.
This is recorded as latitude and longitude, in that order.

If the earth location cannot be calculated, the geolocation output becomes -9999.9. (dummy output)
Latitude is positive north, negative south.
Longitude is positive east, negative west.

6. Scan Status

The status of each scan, that is, quality flags of spacecraft and instrument, are stored.

Table 1-4. Scan Status

Name	Format	Note
Missing	int 1 byte	The values are: 0: normal 1: missing (missing packet and calibration mode) 2: No-rain
Validity	int 1 byte	The summary of operation mode. If all items are normal, zero is recorded. Bit meaning if bit=1 <bit1>: Non-routine spacecraft orientation (2 or 3 or 4) <2>: Non-routine ACS mode (other than 4) <3>: Non-routine yaw update status (0 or 1) <4>: PR operation mode (other than 1) <5>: Non-routine QAC (QAC bit 2, 6 or 7 is not zero)
QAC	int 1 byte	Quality information regarding demodulation status at Level-0 processing (quality accounting capsule) <bit1>： RS header error <2>： Data unit length code wrong <3>： RS frame error <4>： CRC frame error <5>： Data unit sequence count error <6>： Detected frame error during generation of this data unit <7>： Data unit contains fill data
Geolocation Quality	int 1 byte	Bit meaning if bit =1 <0>: latitude limit error <1>: geolocation discontinuity

		<2>: attitude change rate limit error <3>: attitude limit error <4>: maneuver <5>: using the predictive orbit data <6>: geolocation calculation error If geolocation quality is not zero, the geolocation accuracy is not assured.
Data Quality	int 1 byte	Total summary of scan data. If this is not zero, the data is not processed in 1C. Bit meaning if bit =1 <0>=1： Missing (No data) <5>=1： Bad Geolocation Quality <6>=1： Bad Validity
Spacecraft Orientation	int 1 byte	The information in spacecraft Attitude Control System. Value 0 and 1 is normal. Value Meaning 0：+x forward 1：-x forward 2：-y forward 3：CERES calibration 4：Unknown orientation
ACS mode	int 1 byte	The mode of spacecraft Attitude Control System. Value: Meaning 0: stand-by 1: Sun acquire 2: Earth acquire 3: Yaw acquire 4: Normal 5: Yaw maneuver 6: Delta-H (Thruster) 7: Delta-V (Thruster) 8: CERES Calibration
Yaw Update Status	int 1 byte	The information in spacecraft Attitude control system. Value: Meaning 0: inaccurate 1: indeterminate 2: accurate
PR Mode	int 1 byte	Value: Meaning 0: other mode 1: Observation mode
PR status #1	int 1 byte	Bit meaning if bit =1 <0>： LOGAMP noise limit error <1>： Noise level limit error <2>： Out of PR dynamic range <3>： Not reach surface position <7>： FCIF mode change (see 1.27)
PR status #2	int 1 byte	Bit meaning if bit =1 <0> Warning for clutter because of strong nadir surface echo. (see 1.28)
Fractional Orbit Number	float 4 byte	The fractional part of the orbit at scan time. (Scan time - Orbit Start Time)/ (Orbit End time- Orbit Start Time)

Notes:

	MSB							LSB
• bit number	7	6	5	4	3	2	1	0

a) PR Status #1 in Scan Status

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.

<1> Noise level limit error: The meaning of this warning is the same as § 1.10

<2> Surface echo is so strong that it exceeds the PR receiver dynamic range. Calibration with the saturated echo may be questionable.

<3> If Surface echo is out of range window, Bin Surface Peak and related data become uncertain.

b) PR Status #2 in Scan Status

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).

7. Navigation

This is the output of NASA’s geolocation toolkit.
This is recorded each angle.

Table 1-5. Navigation

Name	Format	Note
X component of spacecraft position	float 4 byte	unit: m
Y component of spacecraft position	float 4 byte	unit: m
Z component of spacecraft position	float 4 byte	unit: m
X component of spacecraft velocity	float 4 byte	unit: m/s
Y component of spacecraft velocity	float 4 byte	unit: m/s
Z component of spacecraft velocity	float 4 byte	unit: m/s
Spacecraft geodetic latitude	float 4 byte	
Spacecraft geodetic longitude	float 4 byte	
Spacecraft geodetic altitude	float 4 byte	unit: m
Roll of spacecraft attitude	float 4 byte	unit: deg
Pitch of spacecraft attitude	float 4 byte	unit: deg
Yaw of spacecraft attitude	float 4 byte	unit: deg
Sensor Orientation Matrix #1	float 4 byte	
Sensor Orientation Matrix #2	float 4 byte	

Sensor Orientation Matrix #3	float 4 byte	
Sensor Orientation Matrix #4	float 4 byte	
Sensor Orientation Matrix #5	float 4 byte	
Sensor Orientation Matrix #6	float 4 byte	
Sensor Orientation Matrix #7	float 4 byte	
Sensor Orientation Matrix #8	float 4 byte	
Sensor Orientation Matrix #9	float 4 byte	
Greenwich Hour Angle	float 4 byte	unit: deg

Notes :

a) spacecraft position: The position (unit m) in Geocentric Inertial Coordinates at the Scan time.
   These coordinates will be True of Date, as interpolated from the data in NASA flight dynamics facility ephemeris files.

b) sensor orientation matrix: The rotation matrix from the instrument coordinate frame to geocentric inertial coordinate.

8. Power

Power is recorded for each scan and consists of the calibrated PR transmitter power and the transmitter pulse width.

Table 1-6. Power

Name	Format	Note
PR transmitter power	int 2 byte	unit: dBm / 100
PR transmitter pulse width	float 4 byte	unit: sec

Note: dBm / 100: For example, -9436 represents –94.36 dBm

9. System Noise

System Noise is recorded in each angle bin. This is the value estimated by averaging four noise samples. Unit is 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.
If data is missing, the dummy value (-32734) is recorded.

10. System Noise Warning Flag

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.

PR may receive radio interference in the following areas.

N3.1 E 101.7 (in Malaysia)

N33.8 W118.2 (around Los Angeles)
S34.8 W68.4 (around Santiago)
N10.5 W66.9 (in Chili)
N4.7 E36.9 (around Ethiopia – Kenya border)
S32.8 W63.4 (around Amazon)

11. Minimum Echo Flag

Five values are used 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.)

Please be careful using the Minimum Echo Flag except when it is 0 or 20.

12. First Echo Height

The First Echo Height (storm height) is represented by the logical range bin number (1 to 400, 125-m interval). Two types of First Echo Height are estimated, depending on wheter the minimum echo flag = 10 or 20. (If the first echo is detected below the clutter-free bottom, the two types depend on whether the flag = 11 or 12.)

13. Range Bin Number of Ellipsoid

Ellipsoid Height is represented by the logical range bin number (1 to 400).
This is calculated by the following equation.

binEllipsoid[j] = Normal sample start range bin +
(Spacecraft Range - Distance between satellite and the normal sample start range) / binsize×2

14. Range Bin Number of Clutter-free Bottom

This is the bottom range-bin number (logical range bin number) in clutter-free range bins estimated by the algorithm provided by Dr. Awaka (Hokkaido Tokai Univ. in Japan).
binClutterFreeBottom [49][0]: clutter free certain,
binClutterFreeBottom [49][1]: clutter free probable.

15. Range Bin Number of Mean DID

binDIDHmean represents the range bin number corresponding to the mean height of all DID data samples available in a 5×5km area that overlaps most with the footprint.

16. Range Bin Number of Top of DID

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

17. Range Bin Number of Bottom of DID

The definition is the same as that of binDIDHtop[49][2] except that the value represents the lowest value (bottom) of all DID samples in a 5×5km or 11×11km box.

18. Satellite Local Zenith Angle

The angle between the local zenith (on the Earth ellipsoid) and the beam center line.

19. Spacecraft Range

The distance between the spacecraft and the center of the footprint of the beam on the Earth ellipsoid.

20. Bin start of oversample

The first byte indicates that logical range bin number of starting the oversample.
The second byte indicates the status of the onboard surface tracker (0, normal; 1, Lock off).
Oversample only applies to 29 angles (angle 11 to 39).

21. Land/Ocean Flag

The land or ocean information from the Digital Terrain Elevation Dataset (DTED) Intermittent Dataset (DID) provided by NASA/JPL.

0 =water (ocean or inland water)
1 = land
2 = coast (not water nor land)

22. Topographic Height

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

23. Bin Number of Surface Peak

The bin surface peak indicates the logical range bin number of the peak surface echo.
The algorithm to detect the surface peak is provided Dr. Kozu, CRL.
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 over-sample data.

24. Normal Sample (PR received power)

The normal sampled PR received powers are recorded (unit: dBm / 100).

The data is stored in the array of 49 angles 140 elements.
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.

25. Surface Oversample

The PR records the over-sampled 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) 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” in every other logical range bin, then merge with the interleaving normal sample data.

26. Rain Oversample

The PR records the over-sampled data at 28 range bins in a total of 11 angle bins (nadir± 5 angles) 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.

1-1.2.2 1C21 PRODUCT FILE

The main output of the PR Level-1C, 1C21, is the radar “reflectivity factor.”
The file format is exactly the same as that of 1B21 except for the replacement of the received power by the radar reflectivity factor and noise (no echo range bin) is by a dummy value.

Table 1-7. 1C21 products file structure

Name	Format	note
Data Granule		
Metadata		
Calibration Coefficients	72 byte	
Ray Header	60 byte*49	
Swath Data		
Scan Time	table 8 byte*nscan	
Geolocation	float 4 byte*2*49*nscan	
Scan Status	table 15 byte*nscan	
Navigation	table 88 byte*nscan	
Power	table 6 byte*nscan	dBm / 100

System Noise	int 2 byte*49*nscan	dBm / 100
System Noise Warning Flag	int 1 byte*49*nscan	
Minimum Echo Flag	int 1 byte*49*nscan	
First Echo Height	int 2 byte*2*49*nscan	
Range Bin Number of Ellipsoid	int 2 byte*49*nscan	
Range Bin Number of Clutter-free Bottom	int 2 byte*2*49*nscan	
Range Bin Number of Mean DID	int 2 byte*49*nscan	
Range Bin Number of Top of DID	int 2 byte*2*49*nscan	
Range Bin Number of Bottom of DID	int 2 byte*2*49*nscan	
Satellite Local Zenith Angle	float 4 byte*49*nscan	unit: deg
Spacecraft Range	float 4 byte*49*nscan	unit: m
Bin Start of Oversample	int 2 byte*2*29*nscan	
Land / Ocean Flag	int 2 byte*49*nscan	
Topographic Height	int 2 byte*49*nscan	unit: m
Bin of Surface Peak	int 2 byte*49*nscan	
Normal Sample	int 2 byte*140*49*nscan	dBZ / 100
Surface Oversample	int 2 byte*28*11*nscan	dBZ / 100
Rain Oversample	int 2 byte*5*29*nscan	dBZ / 100

NotesFor example, -9436 represents –94.36 dBm
For example, -9436 represents –94.36 dBZ

The 1C21 product has the same format as 1B-21.

In 1C-21, the normal sample, surface orversample and rain oversample contain radar reflectivity factors (dBZ, mm^6 / m^3) which are converted from the PR received powers in the corresponding places in 1B21 output. The radar equation used is

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

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

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

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

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 atomospheric attenuation.

1-1. 3. 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. 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 sugna-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 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 maybe 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 maybe noise or surface clutter
(Some weak echoes exist in possibly cluttered ranges), and
rain possible but maybe clutter
12 = (Some strong echoes exist in possibly cluttered ranges).

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

6. Information concerning the surface location in 1B21 and 1C21.

The following variables are newly added in 1B21 and 1C21 products.

a. Range bin number of Ellipsoid (binEllipsoid)
b. Range bin number of clutter free bottom (binClutterFreeBottom)
c. Range bin number of mean DID (binDIDHmean)
d. Range bin number of top of DID (binDIDHtop)
e. Range bin number of bottom of DID (binDIDHbottom)

As you can imagine from the name of each variable, those represent range bin numbers corresponding to the surface height from the Earth ellipsoid, which may be useful to analyze a range profile of PR received power or radar reflectivity factor.

7. Bin_surface_peak 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). 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 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 over-sample 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" 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.

8. 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. 4. Planned Improvements

Routine monitoring of PR performance and periodical ARC calibrations are being conducted. Depending on the drift of PR system parameters, the calibration factors may be updated in future.

1-1. 5. 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.

1-2. DID access routine

1-2. 1. Objectives

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

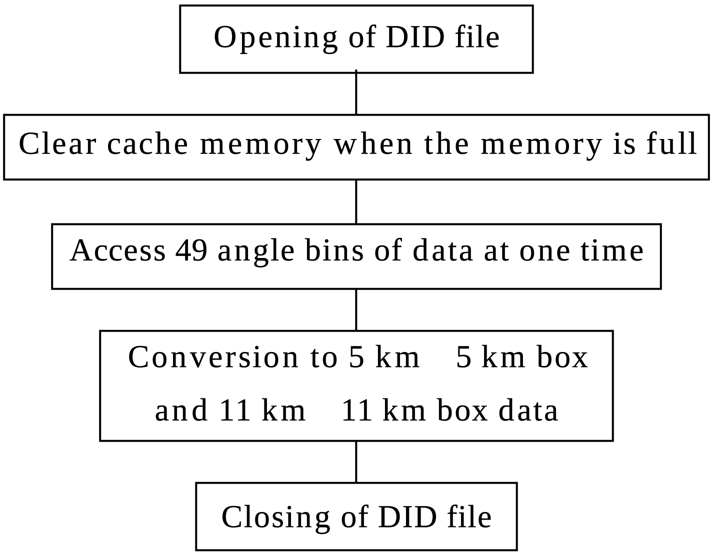
(a) To output the elevation information over a 5 km 5 km box and a 11 km 11 km box using DID elevation data,
(b) To output the land/water information over a 5 km 5 km box using DID land/water data.

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

1-2. 2. Method used

(a) Conversion of DID data having 1 km horizontal resolution to 5 km 5 km box and 11 km 11 km box. The center of each box includes the point where the beam center of the TRMM PR intersects the surface.

1-2. 3. Flowchart



1-2. 4. Some details of the algorithm

(a) Height_mean

A mean of DID elevation over 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 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 5 km 5 km box, is straightforward.

1-2. 5. Input data

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

1-2. 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: mixed */

1-2. 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: mixed.

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

1-2. 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(j),
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.

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

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

1-2. 9. Special notes (caveats)

None.

1-2.10. References

None.

1-3. Clutter rejection routine

1-3. 1. Objectives of clutter rejection routine

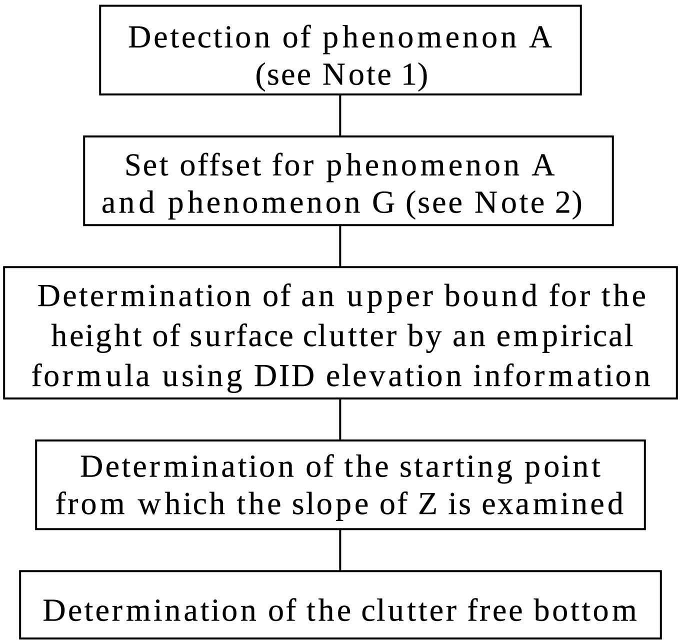
A clutter rejection routine is developed to be included in the Level 1 PR algorithm 1B21. The main objective is:

(a) Determination of the boundary of clutter free region, where the clutter means the mainlobe surface clutter.

1-3. 2. Method used

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

1-3. 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 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 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.

1-3. 4. Outline of the algorithm

(a) Detection of phenomenon A:

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

(1) Phenomenon A occurs because of an inaccuracy of DID 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 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 elevation over an 11 km 11 km box.

(d) Starting position of the examination of slope:

A point where the received power 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 stating point.

(e) Determination of the clutter free bottom:
First, whether the stating 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.

1-3. 5. Input data

```
float normalSample[49][140],  /* unit [dBm]; L1b21swathdata->normalSample   */
float systemNoise[49],        /* unit [dBm]; L1b21swathdata->systemNoise    */
float zenith[49],             /* unit [deg]; L1b21swathdata->scLocalZenith */
float lat[49],                /* unit [deg] */
float lon[49],                /* unit [deg] */
int rayStart[49],             /* L1b21header->rayHdr[].rayStart             */
int binEllips[49],            /* L1b21swathdata->binEllipsoid               */
int binSurfP[49],             /* L1b21swathdata->binSurfPeak                */
int Height_mean[49],          /* unit [m]; mean. of DID elev. (5 km box)              */
int Height_max[49][2],        /* unit [m]; Max. of DID elev. [0]: 5 km, [1]: 11 km */
int Height_min[49][2],        /* unit [m]; Min. of DID elev. [0]: 5 km, [1]: 11 km */
int Hmedian[49],              /* unit [m]; Median of DID elev. 5 km * 5 km            */
int Hstd[49],                 /* unit [m]; RMS dev. 5km * 5km                          */
int LWflag[49],               /* DID land/water/coast flag; 0:W, 1:L, 2:C   */
```

1-3. 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 elevation doubtful.   */
```

1-3. 7. Output file specifications

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)

1-3. 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 clutter information.

1-3. 9. Special notes (caveats)

The current clutter rejection routine is estimated to work for more than 99 % of cases.

1-3.10. References

None.

2. Level 2

2-1. 2A-21 - Surface Cross Section

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

The primary objective 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 within and outside the rain provides a measure of the PIA.

Two types of non-rain normalized radar surface cross section (sigma-zero or NRCS) reference estimates are used: spatial and temporal. In the spatial surface reference data set, the mean and standard deviation of the surface cross sections are calculated over a running window of Ns fields of view before rain is encountered. These operations are performed separately for each of the 49+2 incidence angles of TRMM, corresponding to the cross-track scan from -17 degrees to + 17 degrees with respect to nadir. The 2 additional angle bins (making the total 51 rather than 49) are used to take care of non-zero pitch / roll angles that can shift the incidence angle outside the normal range.

For the temporal surface reference data set, the running mean and standard deviation are computed over a 1 degree x 1 degree (latitude, longitude) grid. Within each 1 degree x 1 degree cell, the data are further categorized into incidence angle categories (26). The number of observations in each category, Nt, are also recorded. 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 are only 25 + 1, where the additional bin is used to store data from angles outside the normal range.

When rain is encountered, the mean and standard deviations of the reference sigma-zero values are retrieved from the spatial and temporal surface reference data sets. To determine which reference measurement is to be used, the algorithm checks whether Nt >= Ntmin and Ns >= Nsmin, where Ntmin and Nsmin are the minimum number of samples that are needed to be considered a valid reference estimate for the temporal and spatial reference data sets, respectively. (Presently, Ntmin = 50 and Nsmin = 8). If neither condition is satisfied, no estimate of the PIA is made and the flags are set accordingly (see below). If only one condition is met, then the surface reference data which corresponds to this is used. If both conditions are satisfied, the surface reference data is taken from that set which has a smaller sample standard deviation.

If a valid surface reference data set exists (i.e., either Nt >= Ntmin or Ns >= Nsmin or both) then the 2-way path attenuation (PIA) is estimated from the equation:

PIA = <sigma-zero (reference value) > - sigma-zero(in rain)

where sigma-zero (in rain) is the value of the normalized radar surface cross section over the rain volume of interest and <sigma-zero(reference value)> is the mean value obtained from either the temporal or spatial reference data sets, the choice of which depends on the considerations discussed above.

To obtain information as to the reliability of this PIA estimate we consider the difference between the PIA, as derived in the above equation, and the standard deviation as calculated from the no-rain sigma-zero values and stored in the reference data set. Labeling this as std dev (reference value), then the reliability factor of the PIA estimate is obtained from:

reliabFactor = PIA - std dev(reference value)

When this quantity is large, the reliability is considered high and conversely. This is the basic idea. Specific definitions of the reliability flag and reliability factors are given in the definitions of the output variables. Description of the HDF output variables for 2a-21 can be found in Volume 4 - levels 2 and 3 file specifications available at:

http://tsdis02.nascom.nasa.gov/tsdis/Documents/ICSVol4

Two comments should be made.

i. The PIA is often defined as the one-way path attenuation rather than the 2-way attenuation used here. Note also that the PIA (2-way) is related to the specific attenuation or attenuation coefficient k (dB/km) by the equation:

   PIA(2-way) = 2 integral [0, rs] k(s) ds

   where the path integral is taken along the direction of the main beam and where the integration limits range from the radar to the surface. Since the attenuation from the radar to the storm top is negligible, the integral can also be thought of as going from the storm top to the surface.

ii. A case can be made for defining the reliability factor other than that given above. For example, we can define reliability factors by:

   Rel = [PIA - std dev(reference value)]/PIA

   Rel' = PIA/ std dev(reference value)

   so that Rel= 1 (or Rel' going to infinity) would correspond to a perfect estimate whereas increasingly smaller values of Rel (including negative values) would correspond to lower reliabilities. Since the numerator and denominator of the expressions for Rel and Rel' are available from the output data, the user can compute these.

2-1.2a. Source Code:

(on anonymous ftp site: priam.gsfc.nasa.gov, directory pub/trmm_code/v4_2a21/)

f2a21_v4.73_HDF.f	(79973 Bytes)	{latest revision: 26 August 1998}
read2a21_v4.73_HDF.f	(21761 Bytes)	{latest revision: 26 August 1998}

2-1.2b. Running the program (on priam.gsfc.nasa.gov)

i. type: 'make -f Makefile_v4.73' [uses Makefile in same subdirectory]
ii. type: 'f2a21_v4.73_HDF "input file" "output file" "int_tr" "int_tw" "int_s" "vfile"'

where

"input file"	is the 1B-21 HDF file
"output file"	is the 2A-21 HDF output file
"int_tr"	is the read-only temporal intermediate file
"int_tw"	is the write-only temporal intermediate file
"int_s"	is the spatial intermediate file
"vfile"	is the verification (diagnostic) file

note that the vi file is created in the program and should not exist prior to execution

- A script file that executes the command line argument can be found in the present directory where the file name is: run_2a21_v4.73

2-1.2c. Output files

example for orbit 1332 on Feb. 20, 1998:

i. 2A21_980220.1332.2.HDF - HDF output file
    [11 MBytes]
ii. 2A21_980220.1332.2.DIAG - diagnostic file
    [5.6 MBytes] text - large size because of misalignment error messages
iii. 2A21_980220.1332.2.INT_TR.dat - read-only temporal reference file
    [8.1 Mbytes] binary file
  2A21_980220.1332.2.INT_TW.dat - write-only temporal reference file
    [8.1 Mbytes] binary file
  2A21_980220.1332.2.INT_S.dat - spatial reference file
    [9.8 kBytes] binary file

2-1. 3. Input Data

example of input file from orbit 1332 on Feb. 20, 1998:

1B21.980220.1332.2.HDF - HDF file, 149.4 MBytes

variables used from 1B-21:

geolocation(2, 49)	(real 4)
systemNoise(49)	(real 4)
minEchoFlag(49)	(byte)
binSurfPeak(49)	(integer 2)
scLocalZenith(49)	(real 4)
binEllipsoid(49)	(integer 2)
normalSample(140,49)	(real 4)

osBinStart(29)	(integer 2)
osSurf(5, 29)	(real 4)
peakPower, scAlt	(real 4)
scanTime	(real 8)

Total Input/ Scan: 30 kBytes

3 Internal Storage Requirements:

Intermediate file 1: temporal surface reference (read-only and write-only) Includes the mean, mean square and number of points comprising these statistics at each (lat, long, angle-bin)

variables:

avs0nr(lat, long, mangle): running mean at (lat, long) and incidence angle bin 'mangle'
sqs0nr(lat, long, mangle): running mean square " " "
nccnr(lat, long, mangle) : number of observations " " "

(lat = 72, long = 360, mangle = 26)

storage required: 72 x 360 x 3 variables x 4 bytes = 8.1 Mbytes since there are now 2 temporal intermediate files, the storage requirement is doubled to: 16.2 Mbytes

Intermediate file 2: spatial surface reference. These files contain the last Ns no-rain estimates of the surface cross section (as well as the square of these cross sections) at each of 51 incidence angles. Separate matrices are defined for land, ocean and coastline surface types. (Ns = 8 with a maximum possible value of 20)

variables:

avocean(kkoc, mang), sqocean(kkoc, mang)
avland(kkl, mang), sqland(kkl, mang)
avcoast(kkcoast, mang), sqcoast(kkcoast, mang)

(kkoc=kkl=kkcoast = 20 (maximum); presently, set equal to 8)
(mang = 51; to account for incidence angles lying outside the standard 49 angle bins, 2 additional angle bins are introduced to account for non-zero values of pitch and roll.)

Note that avocean contains the last kkoc measurements of the surface cross section at each of mang incidence angle bins for an ocean background and for those cases in which rain is not detected along the radar beam; sqocean is identical to avocean except that the square of the surface cross sections are stored.

(avland, sqland) are defined in an identical way to (avocean, sqocean) but for land
(avcoast, sqcoast) " " " " but for coastline

The matrices sqocean, sqland, sqcoast are not essential since they can be obtained taking the square of the elements in avocean, avland, avcoast, respectively.

maximum storage required:
6 variables x 4 bytes x 51 angles x 20 IFOVS = 25 kBytes

2-1.4a. Output Data Volume

The output products are sigma-zero, the path-attenuation, the incidence angle, the latitude, longitude of the peak surface return, two reliability parameters and a rain-flag.

sigmaZero(49)	(real 4)
pathAtten(49)	(real 4)
incAngle(49)	(real 4)
geolocation(2, 49)	(real 4)
reliabFactor(49)	(real 4)
reliabFlag(49)	(integer 2)
rainFlag(49)	(integer 2)

Output per Scan:	1.372	kBytes
Output per Orbit:	10.93	Mbytes

2-1.4b. 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
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 wrt nadir (in degrees); pitch / roll correction is included
pathAtten(49) [real*4]:	Estimated 2-way path-attenuation in (dB) where pathAtten = 2 int[0,rs] k(s) ds where k(s) is the atten. coeff. 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
reliabFlag(49) [integer*2]:	reliability Flag for the PIA estimate, pathAtten, where

$$\text{reliabFlag} = 10000\ iv + 1000\ iw + 100\ ix + 10\ iy + iz$$

where

iv is a rain / no-rain indicator
iw is an indicator of the reliability of the PIA estimate
ix indicates the type of surface reference used
iy provides information about surface detection
iz gives the background type

iv = 1 (no rain along path)
   = 2 (rain along path)

iw = 1 (PIA 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)

ix = 1 (spatial surface reference is used to estimate PIA)
   = 2 (temporal   "   "   "   PIA)
   = 3 (neither exists - i.e. insufficient # of data points)
   = 4 (unknown background type)
   = 5 (no-rain case & low snr - do not update temporal or spatial SRs)
   = 9 (no-rain case)

iy = 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)

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

Note: for missing data set reliabFlag = -9999

reliabFactor(49) [real*4]: reliability Factor for the PIA estimate, pathAtten, is given by

reliabFactor = pathAtten - std dev(reference value)

where PIA is the 2-way path-integrated attenuation (dB), and std dev(reference value) is the standard deviation as calculated from the no-rain sigma-zero values. Both quantities are in dB. The parameter iw (in reliabFlag) is determined from reliabFactor and the SNR of the surface return (in dB).

As presently defined:

iw = 1 (reliable) if ((reliabFactor.ge.3).and.(SNR(dB).gt.3))
   = 2 (marginally reliable) if:
      ((reliabFactor.ge.1) and (reliabFactor.lt.3) and (SNR(dB).gt.3))

= 3 (unreliable) if either (reliabFactor.lt.1) or
((SNR(dB).le.3).and.(reliabFactor.lt.3))
= 4 (lower bound) if ((reliabFactor.ge.3) and (SNR(dB).le.3))

[The iw = 4 case is defined because, while the attenuation estimate will be negatively biased because of a low signal-to-noise ratio, it may lead to the best rain estimate possible under the circumstances.]

[SNR is the signal-to-noise ratio; expressed in dB this is given by the difference between the noise-corrected radar return power (dBm) and the radar noise power (dBm)]

Note: for missing data, set reliabFactor = -9999.9

Note: pathAtten is output as long as the estimate is greater than 0, regardless of the value of iw.

2-1. 5. Description of the Processing Procedure

At each angle bin, calculate the normalized radar surface cross section, sigma-zero, and check whether rain is present. Also, find the (1 degree x 1 degree x angle bin) element into which the measurement falls.

If rain is present, retrieve the mean and standard deviations from the temporal and spatial reference data sets (formed from previously measured data under no-rain conditions). If both temporal and spatial reference data sets satisfy certain conditions, check which sample mean has the lower variance. Using the sample mean associated with the smaller variance, compute an estimate of the path-integrated attenuation and an associated reliability factor.

If rain is absent, update the temporal statistics (mean and mean square) of sigma-zeroat the relevant (1 degree x 1 degree x angle bin) element. Also, update the spatial statistics of sigma-zero. Note that the surface reference measurement which will be used is that for which the sample variance is smaller.

2-1. 6. Interfaces to other algorithms

The input data from this algorithm comes from 1B-21; the output is used by 2A-25, 3A-25 and 3A-26.

2-1. 7. Comments and Issues

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

b. The radar return power used in computing sigma-zero 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. Sigma-zero 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 = 2 (rain certain); minEchoFlag = 1 (rain possible) and and minEchoFlag = 0 (rain absent) are treated as no-rain cases. Note that the minEchoFlag variable is read from 1B-21.

e. Images of path attenuation from 2a-21 sometimes show a striated or streaky pattern where the attenuation estimates at one or more angles are larger than the estimates at adjacent angles. This seems to occur more often at near-nadir angles where high values of the surface cross section are observed under no-rain conditions. To avoid this kind of error, spatial surface reference values that are much larger than the mean value (as determined from large space-time regions) may need to be replaced either by a global mean value and the associated standard deviation. Tests of this procedure will be carried out to determine whether it provides any improvement in the PIA estimates and whether the operational 2a-21 algorithm should be changed.

2-1. 8. Description of Temporal Intermediate File

Two temporal intermediate files are used to store (write-only file) and read (read-only file) the no-rain statistics of the normalized surface cross sections as a function of incidence angle (26 categories) and location (1 x 1 degree latitude-longitude grid).

For the first month of data (December), the read-only and write-only temporal intermediate files are initialized to zero. During the processing of data from this month, the no-rain statistics are continuously updated and stored in the write-only file. At the end of the month, the write-only file for December is used as the read-only file for January and the write-only file is re-initialized to zero. This means that for the data processed in January, the statistics compiled in December will be used for the temporal reference data set. At the end of the processing of the January data, the write-only file, used to store the statistics for January, is used as the read-only file for the month of February.

In general, the write-only file from the previous month is used as the read-only file (i.e. the reference data set) for the present month and where the write-only file is re-initialized at the beginning of each month.

2-1. 9. References

Caylor I.J., G.M. Heymsfield, R. Meneghini, and L.S. Miller, 1997: Correction of sampling errors in ocean surface cross-sectional estimates from nadir-looking weather radar. J. Atmos. Oceanic Technol., 14, 203-210.

Iguchi, T. and R. Meneghini, 1994: Intercomparisons of single-frequency methods for retrieving a vertical rain profile from airborne or spaceborne radar data. J. Atmos. Oceanic Technol., 11, 1507-1516.

Kozu, T., 1995: A generalized surface echo radar equation for down-looking pencil beam radar. IEICE Trans. Commun., E78-B, 1245-1248.

Marzoug, M. and P. Amayenc, 1994: A class of single- and dual-frequency algorithms for rain rate profiling from a spaceborne radar. Part I: Principle and tests from numerical simulations. J. Atmos. Oceanic Technol., 11, 1480-1506.

Meneghini, R. and K. Nakamura, 1990: Range profiling of the rain rate by an airborne weather radar. Remote Sens. Environ., 31, 193-209.

2-2. 2A23

2-2. 1. Objectives of 2A23

Main objectives of 2A23 are as follows:

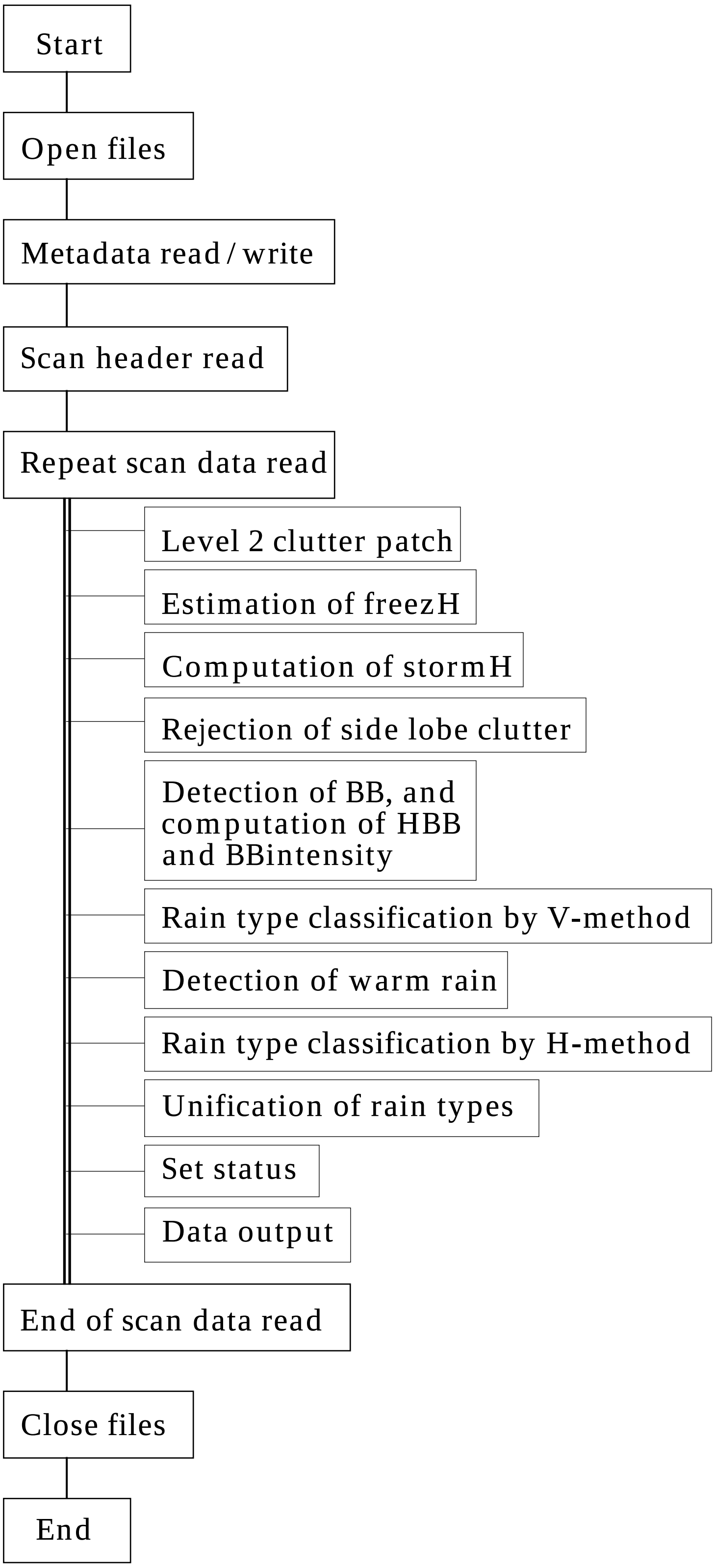
(a) Detection of bright band (BB) and determination of the height of BB and its strength when BB exists.
(b) Classification of rain type into the following three categories:
  - stratiform,
  - convective,
  - other.
(c) Detection of warm rain.
(d) Output of Rain / No-rain flag.
(e) Computation of the estimated height of freezing level.
(f) Output of the height of storm top.

2-2. 2. Method used in 2A23

(a) Detection of bright band (BB):
  - Peak search using a spatial filter with several conditions imposed on the height profile of BB [1].
(b) Rain type classification:
  - Vertical profile method (V-method)[1],
  - Horizontal pattern method (H-method)[2].
(c) Detection of warm rain:
  - A simple examination of the height of storm top being much lower than the estimated height of freezing level and with a test that warm rain must satisfy an isolation condition.
(d) Rain / No-rain flag:
  - Almost identical to minEchoFlag recorded in 1C21 HDF file. (Dead copy of minEchoFlag recorded in 1C21 HDF file in the normal condition; see 2-2.6(a) and also (2) of Appendix.).
(e) Estimated height of freezing level:
  - Temporal and spatial interpolation of a climatological sea surface temperature, and a use of a constant lapse rate of temperature.
(f) Height of storm top:
  - A simple conversion from range bin number to the height above the sea level.

2-2. 3. Flowchart

Flow chart of 2A23 is shown below. Some details are given in Appendix.



2-2. 4. Input data

(a) From 1C21 HDF file:
Name used in 2A23 code
(1) TK_ALGORITHM_ID (metadata) ---> algorithmID
(2) TK_ORBIT_SIZE (metadata) ---> i_end
(3) TK_BEGIN_DATE (metadata) ---> begin_date
(4) TK_BEGIN_TIME (metadata) ---> begin_time
(5) TK_END_DATE (metadata) ---> end_date
(6) TK_END_TIME (metadata) ---> end_time

(7) rayHdr[49].rayStart (scan header) ---> binStart[49]
(8) rayHdr[49].mainlobeEdge (scan header) ---> mainlobeEdge[49]
(9) rayHdr[49].sidelobeRange[3] (scan header) ---> clutter_warning[49][3]

(10) scanStatus.missing (L1C_21_SWATHDATA) ---> flag_scan_rain
(11) geolocation[49][2] (L1C_21_SWATHDATA) ---> pixlat[49], pixlon[49]
(12) minEchoFlag[49] (L1C_21_SWATHDATA)
(13) binStormHeight[49][2] (L1C_21_SWATHDATA) ---> binStormH0[49],
binStormH1[49]
(14) scRange (L1C_21_SWATHDATA)
(15) scLocalZenith[49] (L1C_21_SWATHDATA) ---> zenith[49]
(16) binEllipsoid[49] (L1C_21_SWATHDATA)
(17) binSurfPeak[49] (L1C_21_SWATHDATA) ---> binSurfP[49]
(18) landOceanFlag[49] (L1C_21_SWATHDATA) ---> sea_or_land[49]
(19) normalSample[49][140] (L1C_21_SWATHDATA)
(20) normalSample_scale[49][140] (L1C_21_SWATHDATA)
(21) binClutterFreeBottom[49][2] (L1C_21_SWATHDATA)
(22) osSurf[29][5] (L1C_21_SWATHDATA)
(23) binDIDHmean[49] (L1C_21_SWATHDATA)

(b) From sst-hou.grd file:

(1) sstdata[144][91][2]

2-2. 5. Output data

(1) metadata	
(2) scanTime	---- same as that of 1C21
(3) geolocation[49][2]	---- same as that of 1C21 (geolocation(2,49) in FORTRAN)
(4) scanStatus (structure)	---- same as that of 1C21
(5) navigate (structure)	---- same as that of 1C21
(6) rainFlag[49]	Rain / No-rain flag (1 byte integer)
(7) rainType[49]	Rain type (1-byte integer)
(8) warmRain[49]	Warm rain flag (1-byte integer)
(9) status[49]	Status (1-byte integer)
(10) rangeBinNum[49]	Range bin number for BB (2-byte integer)
(11) HBB[49]	Height of BB [m] (2-byte integer)
(12) BBintensity[49]	Strength of BB [dBZ] (4-byte float)
(13) freezH[49]	Estimated height of freezing level [m] (2-byte integer)

(14) stormH[49]	Height of storm top [m] (2-byte integer)
(15) spare[49]	Spare (4-byte float)

2-2. 6. Output file specifications

This section describes details of items (6)-(14) in the previous section.

(a) int8 rainFlag[49]: Identical to minEchoFlag of 1C21.

= 0 : no rain
10 : rain possible
11 : rain possible
12 : rain possible
20 : rain certain

-99 : data missing

Note: Rigorously speaking, rainFlag may not be identical to minEchoFlag of 1C21 in a 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 the normal conditions, rainFlag is identical to minEchoFlag of 1C21.

(b) int8 rainType[49]:

In 2A23 ver. 5.3, the rainType[i] (i=0 to 48) indicates the unified rain type as follows:

```
rainType[i]
        = 10: Stratiform certain.
                When R_type_V[i] = T_stra;      (BB exists)
                and   R_type_H[i] = T_stra;

          11: Stratiform certain.
                When R_type_V[i] = T_stra;      (BB exists)
                and   R_type_H[i] = T_others;

          12: Probably stratiform.
                When R_type_V[i] = T_others;
                and   R_type_H[i] = T_stra;

          13: Maybe stratiform.
                When R_type_V[i] = T_stra;     (BB detection certain)
                and   R_type_H[i] = T_conv;

          20: Convective certain.
                When R_type_V[i] = T_conv;     (no BB)
                and   R_type_H[i] = T_conv;

          21: Convective certain.
                When R_type_V[i] = T_others;
                and   R_type_H[i] = T_conv;
```

22: Convective certain.
When R_type_V[i] = T_conv;
and R_type_H[i] = T_others;

23: Probably convective.
When R_type_V[i] = T_conv; (BB exists)
and R_type_H[i] = T_conv;

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

25: Maybe convective.
When R_type_V[i] = T_stra; (BB detection not so
and R_type_H[i] = T_conv; confident)

30: Others.
When R_type_V[i] = T_others;
and R_type_H[i] = T_others;

where

R_type_V: rain type classified by the V-method,
R_type_H: rain type classified by the H-method, which is based on SHY95 developed by Prof. Houze and his group [2].

The above assignment of numbers has the following meaning:

When rainType[i] > 0,

rainType[i] / 10 = 1: stratiform,
2: convective,
3: others.

rainType[i] % 10 = This indicates the level of confidence, which decreases as the number increases.

where rainType[i] % 10 means MOD(rainType(i),10) in FORTRAN.

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

<<Sample program to obtain rain type and level of confidence>>

By the sample code below, rain type would be stored in type[i] and its level of confidence (0:certain, 1:probably, 2:maybe) in conf_level[i]. (Error handling, however, is omitted in the sample code below, so that the users must add an appropriate error check by themselves.)

```
    if (rainType[i]>0) {
```

```
        type[i] = rainType[i] / 10;
        i_conf = rainType[i] % 10;
        if (type[i]==1) {
                if (i_conf<2) {
                        conf_level[i] = 0;          /* stratiform certain    */
                }
                else if (i_conf==2) {
                        conf_level[i] = 1;          /* probably stratiform */
                }
                else {
                        conf_level[i] = 2;          /* maybe stratiform       */
                }
        }
        else if (type[i]==2) {
                if (i_conf<3) {
                        conf_level[i] = 0;          /* convective certain    */
                }
                else if (i_conf==3) {
                        conf_level[i] = 1;          /* probably convective */
                }
                else {
                        conf_level[i] = 2;          /* maybe convective       */
                }
        }
        else {
                conf_level[i] = 0;                  /* other certain           */
        }
}
```

or in the case of a FORTRAN program, it may be something like

```
IF (rainType(j) .GT. 0) THEN
    type(j) = rainType(j) / 10
    i_conf = MOD(rainType(j), 10)
    IF (type(j) .EQ. 1) THEN
        IF (i_conf .LT. 2) THEN
            conf_level(j) = 0
        ELSEIF (i_conf .EQ. 2) THEN
            conf_level(j) = 1
        ELSE
            conf_level(j) = 2
        ENDIF
    ELSEIF (type(j) .EQ. 2) THEN
        IF (i_conf .LT. 3) THEN
            conf_level(j) = 0
        ELSEIF (i_conf .EQ. 3) THEN
            conf_level(j) = 1
        ELSE
            conf_level(j) = 2
        ENDIF
```

```
        ELSE
            conf_level(j) = 0
        ENDIF
    ENDIF
```

(c) int8 warmRain[49]: Warm rain flag

= 0 : no warm rain
1 : Maybe warm rain
2 : Warm rain (with confidence)

-88 : no rain
-99 : data missing

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

= 0: good (over water)
10: BB detection may be good (over water)
20: R-type classification may be good (over water)
(BB detection is good or BB does not exist)
30: Both BB detection and R-type classification may be good (over water)
50: not good (because of warnings) (over water)
100: bad (possible data corruption) (over water)

1: good (over land)
11: BB detection may be good (over land)
21: R-type classification may be good (over land)
(BB detection is good or BB does not exist)
31: Both BB detection and R-type classification may be good (over land)
51: not good (because of warnings) (over land)
101: bad (possible data corruption) (over land)

2: good (over land / water mixed area)
12: BB detection may be good (over land / water mixed area)
22: R-type classification may be good (over land / water mixed area)
(BB detection is good or BB does not exist)
32: Both BB detection and R-type classification may be good (over land / water mixed area)
52: not good (because of warnings) (over land / water mixed area)
102: bad (possible data corruption) (over land / water mixed area)

9: may be good (land / sea error)
19: BB detection may be good (land / sea error)
29: R-type classification may be good (land / sea error)
(BB detection is good or BB does not exist)
39: Both BB detection and R-type classification may be good (land / sea error)
59: not good (because of warnings) (land / sea error)
109: bad (possible data corruption) (land / sea error)

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

Assignment of the above numbers are based on the following rules:

When status >= 0,

status / 100 = 0: good, maybe good, or not good.
1: doubtful.

(status / 10)%10 = 0: good or may be good when status < 100, and bad when status >= 100.
1: BB detection not so confident.
2: R-type classification not so confident (but BB detection is good, or when BB does not exist).
3: BB detection is not so confident and R-type classification not so confident.
5: Over-all quality of the processed data for the j-th scan angle is not good (but may not be too bad to be classified as bad data).

Note: In FORTRAN, (status / 10)%10 should be read as MOD(status / 10, 10).

status % 10 = 0: over ocean.
1: over land.
2: over land / water mixed area.
9: when land / water data is corrupted. (Even in this case, if the other data is normal, the result may be good, in particular over water.)

Note: In FORTRAN, status % 10 should be read as MOD(status, 10).

In other words, we can check the confidence level of 2A23 by the following way:

status >= 100 : bad (untrustworthy because of possible data corruption).
100> status >= 10 : result not so confident (warning).
status = 9 : may be good.
9> status >= 0 : good.

(e) int16 rangeBinNum[49]: Range bin number for the height of bright band. The numbering is conforming to that of 1C-21 normal sample.

> 0 : Range bin number. This also indicates that the bright band exits.
= -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 exits.
= -1111 : No bright band
= -8888 : No rain
= -9999 : Data missing

NOTE: Although 2A23 does not output the BB_flag explicitly, it can be reconstructed from rangeBinNum or from HBB, e.g. in the following way:

In the case of C program, it may be something like

```
for (i=0; i<49; i++) {
      if (HBB[i]>0) {
             BB_flag[i] = 1;           /* bright band exists */
      }
      else {
             BB_flag[i] = 0;           /* No bright band        */
      }
}
```

or in the case of a FORTRAN program, it may be something like

```
      DO 10 j=1, 49
            IF (HBB(j).GT.0) THEN
                  BB_flag(j) = 1
            ELSE
                  BB_flag(j) = 0
            ENDIF
   10 CONTINUE
```

(g) float32 BBintensity[49]: Bright band intensity in dBZ.
= -1111.0 : No bright band
= -8888.0 : No rain
= -9999.0 : Data missing

(h) int16 freezH[49]: Height of freezing level estimated from the climatological surface temperature data (sst-hou data).

> 0 : Estimated height of freezing level [m]
= -5555 : When error occurred in the estimation of freezH
= -8888 : No rain
= -9999 : Data missing

(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. Hence, it is computed by

stormH[i] = (binEllipsoid[i]
- binStormHeight[i][1])*125*cos(zenith)

where zenith is the zenith angle expressed in radian. When rain is possible, i.e. minEchoFlag[i]=10, 11, 12, it is set to the following value:

stormH[i] = -1111

NOTE: The most annoying part is in the computation of stormH. 1C21 outputs two kinds of binStormHeight: one with higher level of confidence and the other with lower level of confidence. A straightforward answer to handle this situation would be to make 2A23 also output two kinds of stormH. However, I feel that the present file format for 2A23 may be fully acceptable to most users because of the following reason.
If the users want to examine a possible storm height with lower level of confidence, they should use 1C21 because the height with lower level of confidence is noise-prone and unreliable, the users have to examine the original Z profile stored in 1C21 anyway.

2-2. 7. 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. 8. Special notes (caveats)

(a) Bright band (BB) detection has angle bin dependence because of smearing of BB near the antenna scan edges.
Sample test indicates the rate of BB detection is about 80% near nadir directions (at antenna scan angle ranging from about -7 to about +7 degrees), but the rate decreases as low as about 20% at the antenna scan edge.

(b) When a large numbers of orbit data are processed, statistics of rain type shows angle bin dependence because the rain / no-rain judgment in 1B21 also seems to have angle bin dependence.

(c) Bright band detection and rain type classification are carried out for rain-certain case only. For rain possible, rain type is automatically classified as other type.

(d) When rain is 'certain' and rain type is 'other', it is most probable that there exists cloud only.

(e) Side lobe clutter may still affect the detection of BB, hence affects rain type classification as well, though a side lobe clutter rejection is tried in the algorithm.

(f) When warm rain is detected, the rain type by the V-method is set to be convective, and the unified rain type is also set to be convective.

2-2. 9. 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, pp.143-146, 1998.

[2] 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, pp.1978-2007, 1995.

Appendix. - Some details of 2A23

(1) Level 2 clutter patch

Though the clutter rejection routine is included in Level 1 algorithm (1B21), the value binClutterFreeBottom is found to become somewhat large or small in rare occasions. Since information about DID elevation is recorded in 1C21 HDF file, 2A23 can make a level 2 patch to the clutter rejection routine. When binClutterFreeBottom shows somewhat large or small value, a fine-tuning of binClutterFreeBottom is made by examining a slope of Z profile.

(2) rainFlag[i] and stormH[i] (i=0, ..., 48)

rainFlag[i] is a copy of minEchoFlag[i] recorded in 1C21 HDF file

```
write_data.rainFlag[i] = read_data.minEchoFlag[i];
```

unless 2A23 detects bad input data and override it with a missing value (-99).

stormH[i] (unit in [m]) is computed only when the storm top is certain:

```
stormH[i] = floor(Hstorm1[i]   1000.+0.5);
```

where

```
Hstorm1[i] = (read_data.binEllipsoid[i]
                    - read_data.binStormHeight[i][1])/2   0.25    cos(zenith);
```

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

The height of freezing level, freezH[i], is computed as follows:

freezH[i] = (sst_interp -273.15) / T_lapse 1000. [m]

where sst_interp is the interpolated surface temperature (interpolation with respect to space and time), and T_lapse is the lapse rate of the temperature (= 6.0 [deg/km]).

(4) Rejection of sidelobe clutter

Rejection of sidelobe clutter is made before the BB detection and rain type classification.

When a clear peak exists at a possible position of side lobe clutter, the peak is flattened by an interpolation using the data above and below the peak. However, the condition for a clear peak in 2A23 ver. 5.3 does not seem to be sufficient; there are some chances that the sidelobe clutter peak is mistaken as BB, and the number of stratiform rain, characterized by the existence of clear BB, increases by the false BB at angle bins where the sidelobe clutter appears appreciably. It is planned to solve this problem in the next revision of the algorithm.

(5) BB detection

BB detection is made with several steps. Outline is as follows:

First, BB detection is made by using a spatial filter method for a search of a possible BB peak. Here, the spatial filter is based on the second derivative of Z with respect to the range [1]. Since the spatial filter uses 3 adjacent angle bins of data, the first BB detection can miss BB, e.g., when the peaks are out of phase. Hence, the BB detection is made once again on the same vertical plane of one scan data. 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) HBB must be close to freezH (within +/-1.5km),
(b) Z must decay appreciably at height above HBB,
(c) HBB must be close to each other (within +/-0.65 km at most in one vertical plane with 49 angles bins of data),
(d) When Z at HBB exceeds 42 dBZ, the standard deviation of Z below HBB in the range from HBB-0.5km down to the clutter free height is smaller than 2 dB.

The condition (d) is newly introduced to the algorithm in order to avoid a false BB peak due to a strong attenuation in the case of strong convective rain.

Details are as follows:

1st step: Candidates for BB peak are selected, on one vertical plane with 49 angle bin data, using a spatial filter technique. Let the height of BB candidate as HBB. (The first step examines three adjacent angle bins of data at one time because of the usage of spatial filter. After the first step, each angle bin data is examined individually.)

2nd step: Among the BB candidates, those which pass the following tests are regarded as stringent BB:

(a) HBB must be close to freezH (within +/-1.5km),
(b) BB has a clear peak,
(c) Z at height above HBB by 0.5km or higher must be smaller than the Z at HBB at least by 2 dB (in other words, Z must decay appreciably at height above HBB).
(d) When Z at HBB exceeds 42 dBZ and the peak is not sharp enough, the standard deviation of Z below HBB in the range from HBB-0.5km down to the clutter free height is smaller than 2 dB.
(e) Below HBB, Z in the range from HBB-0.5km to HBB-1.75km must be smaller than Z at HBB by 1 dB or more (by at least 1 dB)
(f) HBB must be close to the median of HBB, which is computed among survived BB candidates (the difference between HBB and the median must be within +/-0.4km).

Note: In (f), if the average of HBB was used, instead of using the median of HBB, the average value would have a bias when a few data are far way from the average. This problem can be solved by the use of median (a median filter concept was suggested by Prof. T. Sato, Kyoto University).

3rd step: If there exists at least one stringent BB on one vertical plane with 49 angle bins of data, detection of BB is made once again on the same plane for all the other rain certain angle bins, because the spatial filter method used in the selection of BB candidate and in the detection of stringent BB may fail to detect BB in several cases. The conditions for BB in the 3rd step are as follows:

(a) HBB must be close to freezH (within +/-1.5km),
(b) BB has a peak,
(c) Z must decay appreciably at height above HBB.
(d) When Z at HBB exceeds 42 dBZ and the peak is not sharp enough, the standard deviation of Z below HBB in the range from HBB-0.5km down to the clutter free height is smaller than 2 dB.
(e) Below HBB, Z in the rage from HBB-0.5km to HBB-1.0km must be smaller than Z at HBB by at least 1 dB.
(f) HBB must be close to the average of HBB (within +/-0.65km). Implicit assumption here is that most of the BB detection is done in the 2nd step, hence the use of average, instead of the use of median as in the stringent case, may be sufficient.

Last step: Detection of smeared BB is tried, but it has not been so successful, yet.

In the 1st step, real value of Z is used, while in the 2nd and 3rd steps, dB value of Z is used. It should also be noted that the selection of BB candidates is made first (in the 1st step), and the possible BB window is used later (in (a) of the 2nd step). The reason for using real value of Z in the first step and the later use of the possible BB window is to try to avoid a false BB peak which appears when there exists a large attenuation due to a strong convective rain. The idea behind this approach is as follows:

> When the real value of Z is used in the spatial filter method, the height of detected peak scatters in wide range except for the height of BB peak which appears almost at the same height because the spatial filter method with real value of Z is almost identical to the search of maximum value of Z which differs very significantly from profile to profile when BB does not exists. Hence, if BB exists, since BB appears almost at the same height, the median of the detected peaks within the possible BB window may indicate the most probable (a kind of averaged) BB height with a high level of confidence.

Since the examination of the standard deviation of Z below HBB is newly introduced to avoid a false BB peak due to strong attenuation, the use of real value of Z in the first step and the later use of the possible BB window may not be necessary. In the next revision of the algorithm, a possible change of the algorithm by using a much simpler peak search within the possible BB window from the beginning will be examined.

Note that the BB detection is eventually carried out in the possible BB window, which is computed from the estimated height of freezing level (freezH). A test using 6 orbits of data indicates that the current choice of BB window (i.e., freezH +/-1.5 km) is a reasonable one.

(6) Detection of warm rain

The following two conditions are imposed for warm rain detection:

(a) Storm top of warm rain is much lower than the height of freezing level. (This condition implies that when BB is detected, it is not warm rain because the existence of BB means that the storm top is higher than the height of freezing level).
(b) Warm rain must be isolated from the other rain certain areas.

Detail of the first condition is as follows:
When

Hstorm < freezH - 1500 m (1.5 km) -----> warm rain possible,
Hstorm < freezH - 2000 m (2.0 km) -----> warm rain,

where the height of freezing level, freezH, is computed by the equation shown in the explanation of item (3).

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.

If warm is detected over land, the judgment is always 'warm rain possible' no matter how low the height of storm top is because freezH may not be so trustworthy over land.

(7) Rain type classification by V-method

The vertical profile method (V-method) classifies rain into 3 categories: stratiform, convective, and other. Outline of V-method is as follows:

(a) When BB exists, rain is basically classified as stratiform,
(b) When BB is not detected, and maximum value of Z at a given angle bin exceeds 39 dBZ, rain type for this angle bin is classified as convective,
(c) Other type is defined as not-stratiform and not-convective.

The above (a) means that even when BB exists, rain type is not always stratiform; the exception is as follows:

When

$$Zmax > ZBB$$

and

$$Zmax > 42 \text{ dBZ}$$

where ZBB is the Z factor at the BB peak, and Zmax is the maximum value of Z in the rain region (see the illustration below), rain type is classified as convective, but not stratiform, even though BB clearly exists.

```
                 *
                       *
                              *
                                *    -------    BB peak
                            *
                        *
                       *
                          *
                              *
                                 *
                                   *    ------ Zmax
                                  *
                                  *
```

In fact, the profile as illustrated above can happen, though the occurrence of such a case may be very rare; in this case, there may co-exist both stratiform character and convective character. For a rainfall rate retrieval purposes, the case illustrated above should be classified as convective because rainfall rate may be predominated by that of convective type of rain.

In (b), the threshold for convective rain is 39 dBZ, which is 1 dB smaller than the threshold for convective center by the H-method (see below).
The value 39 dBZ is used here because there may not exist a clear cut threshold

for convective rain. The 1 dB difference would be regarded as a margin.

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.

The other type of rain consists of 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 exists,
(D) Simply noise.

(8) Rain type classification by H-method

The horizontal pattern method (H-method) also classifies rain into 3 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 [2], 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 conditions is satisfied at a pixel, which corresponds 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 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 (minus 1 km 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.

(9) 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 '6. Output file specifications'). The unified rain type is expressed by 2 digits: the first digit indicates the rain type (1: stratiform, 2: convective, 3: other), and the last digit indicates a level of confidence, which decreases as the number increases. 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).

2-3. 2A25

2-3. 1. Objectives

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

2-3. 2. Algorithm Overview

2A25 basically uses a hybrid of the Hitschfeld-Bordan method and the surface reference method to estimate the vertical true radar reflectivity Z profile. (The hybrid method is described in Iguchi and Meneghini (1994).) The vertical rain profile is then calculated from the estimated true Z profile by using an appropriate Z-R relationship. One major difference from the method described in the above reference is that in order to deal with the beam-filling problem, a non-uniformity parameter is introduced and is used to correct the bias in the surface reference arising from the horizontal non-uniformity of rain field within the beam. Since radar echoes from near the surface are contaminated by the mainlobe clutter, 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. 3. More Detailed Description of the Algorithm (Taken from Iguchi et al. (1998))

The major input data to 2A25 are the measured radar reflectivity factor Z_m, the apparent decrease of the surface cross section ($\Delta\sigma^0$) by the attenuation due to rain, 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 climatological freezing height 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 and Z-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 relationship $k=\alpha Z^{\beta}$ 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 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 inappropriate choice of α 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]. The PIA is first estimated from the precipitation echo alone. The weight given by the hybrid method to the PIA estimate from the surface reference increases as the attenuation estimate increases. 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 or unreliable, it is replaced by an equivalent $\Delta\sigma^0_c$ that would make the attenuation-corrected Z-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 occurs more frequently over land than ocean since the fluctuations of surface cross section is, in general, larger over the land.

The attenuation correction procedure requires two processing cycles. In the first cycle, the correction is made without taking the non-uniform beam filling effect into account. From these attenuation-corrected profiles, the PIA at each angle bin is calculated. The low resolution variability of the PIA for a given angle bin is calculated from the PIAs at the angle bin in question and the eight surrounding angle bins. The high resolution variability of PIA, which is the variability within the horizontal resolution of the radar, is then estimated from the variability of the low resolution PIAs [Kozu and Iguchi, 1996]. The normalized standard deviation of the estimated high resolution PIAs is treated as the index of non-uniformity. The PIA estimate from the surface reference ($\Delta\sigma^{0}$) is modified according to the index of non-uniformity in such a way that the modified PIA would be observed if the same amount of rain were distributed uniformly at each height within the radar beam.

In the second processing cycle, the modified $\Delta\sigma^{0}$ is used. If $\Delta\sigma^{0}$ is unreliable or unavailable, however, the equivalent $\Delta\sigma^{0}_{c}$ for a constant vertical Z near surface is substituted as described above. The resultant Z-profile is the profile written to the output file.

The rainfall estimates are calculated from the Z -profiles by using a power law: $R=aZ^{b}$ 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 atmospheric pressure are taken into account. The coefficient a is further modified by the index of non-uniformity.

2-3. 4. 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 used in 2A-25:
1C21: rayHdr[].rayStart
rayHdr[].mainlobeEdge
rayHdr[].sidelobeRange[]

2-3. 5. Output data

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

Data format

The file content description for 2A25 can be found in the Interface Control Specification (ICS) between the Tropical Rainfall Measuring Mission Science Data and Information System (TSDIS) and the TSDIS Science User (TSU) Volume 4: File Specification for TSDIS Products - Level 2 and 3 File Specifications. It is available at: http://tsdis02.nascom.nasa.gov/tsdis/Documents/ICSVol4.pdf

Output data (in alphabetical order):

attenParmAlpha[][]	k-Z parameter alpha at 5 nodes
attenParmBeta[]	k-Z parameter beta
attenParmNode[][]	bin numbers of 5 nodes for alpha
correctZFactor[][]	attenuation-corrected Z factor in dBZ
epsilon[]	final correction factor for SRT
geolocation[][]	geolocation
method[]	method used
nubfCorrectFactor[][]	non-uniform beam filling correction factors
qualityFlag[]	quality flag
rain[][]	rainfall rate in mm/h.
rainFlag[]	status flag for rainfall estimate
rainAve[][]	average rainfall rate between 2 and 4 km
rangeBinNum[][]	bin numbers of BB, storm top, etc.
reliab[][]	reliability of the output
spare[][]	spare (bin number of surface rain and Z and _—in v5.3)
scanTime	scanTime
thickThPIZ[]	range bin number where PIZ > threshPIZ
weightW[]	weight for the calculation of epsilonf
xi[][]	normalized standard deviation of PIA
zeta[][]	integral of alpha*Zm^beta
zeta_mn[][]	mean of zeta over 3x3 IFOVs

zeta_sd[][]	standard deviation of zeta
zmmax[]	maximum of Zm
ZRParmA[][]	Z-R parameter a in R=a*Z^b at 5 nodes
ZRParmB[][]	Z-R parameter b in R=a*Z^b at 5 nodes
ZRParmNode[][]	bin numbers of 5 nodes for a & b
nearSurfRain[]	estimated rain rate near surface
nearSurfZ[]	estimated Z near surface
pia2a25[]	path-integrated attenuation from final Z
errorRain[]	error estimate of Z near surface in dB
errorZ[]	error estimate of rain rate near surface in dB

For details, see the attached description at the end of this document.

2-3. 6. 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. 7. Caveats

1. 2A25 produces many output variables. Please read sector 2-3.11 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 Zm is below the noise level, the rain estimate there is set to 0. This procedure does not cause any serious problem except when the measured Zm 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 forth bit of 'reliab' and the forth 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. Because only the first order terms in the Taylor expansion is used in the calculation, the error estimates are not reliable at all when they are large.

3. 2A25 processes data in both 'rain certain' and 'rain possible' angle bins. It processes all data below the height at which the first 'possibly' rain echo is detected. In fact, almost all data in 'rain possible' angle bins and data between 'storm height possible' and 'storm height certain' in 'rain certain' angle bins are noise data. The users of the PR data should be aware of this fact, even though some of the weak echoes are produced by rain.

4. Over some area with a very high surface reflectivity, sidelobe clutters may appear in the radar signal and they are sometimes misidentified as rain echoes. 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 echo in 2A25, particularly in mountain regions.

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

7. The value of alpha in the k-Z relationship (k = alpha Z^beta) and the value of a in the R-Z relationship (R = a Z^b) used in the final calculations of correctZFactor[][] and rain[][] are not the same as the numbers given in attenParmAlpha[][], ZRParmA[][]. (attenParmBeta[] and ZRParmB[][] are the same as the final values.) To get the final value of alpha at a given height, first calculate the alpha by linearly interpolating the values given in attenParmAlpha[][], and then multiply the result by 'epsilon' for that angle bin. To get the final value of 'a' at a given height is not possible only from the data given in the output of 2A25. Similar to the case of 'alpha', first calculate the 'a' at a given height by interpolating the numbers in ZRParamA[][], and then multiply it by nubfCorrectFactor[][1] and then further multiply it by the ratio of the terminal velocity at the given height to that at the sea level. This ratio is not given in the output of 2A25. It is calculated in 2A25 by using equation (9) in "Terminal Velocity of Raindrops Aloft" by G.B. Foote and P.S. du Toit in J. Applied Meteorology, pp.249-253, vol.8, 1969, and standard atmospheric pressures at 21 altitudes. The numbers at 21 heights are as follows:

```
1.00000    vratio[0]        /* Terminal velocity ratio at 0 km */
1.04900    vratio[1]        /* Terminal velocity ratio at 1 km */
1.10200    vratio[2]        /* Terminal velocity ratio at 2 km */
1.15900    vratio[3]        /* Terminal velocity ratio at 3 km */
1.22000    vratio[4]        /* Terminal velocity ratio at 4 km */
1.28600    vratio[5]        /* Terminal velocity ratio at 5 km */
1.35800    vratio[6]        /* Terminal velocity ratio at 6 km */
1.43500    vratio[7]        /* Terminal velocity ratio at 7 km */
1.52000    vratio[8]        /* Terminal velocity ratio at 8 km */
1.61100    vratio[9]        /* Terminal velocity ratio at 9 km */
1.71200    vratio[10]       /* Terminal velocity ratio at 10 km */
1.82100    vratio[11]       /* Terminal velocity ratio at 11 km */
1.94000    vratio[12]       /* Terminal velocity ratio at 12 km */
2.06600    vratio[13]       /* Terminal velocity ratio at 13 km */
2.20100    vratio[14]       /* Terminal velocity ratio at 14 km */
2.34400    vratio[15]       /* Terminal velocity ratio at 15 km */
2.49600    vratio[16]       /* Terminal velocity ratio at 16 km */
2.65900    vratio[17]       /* Terminal velocity ratio at 17 km */
2.83300    vratio[18]       /* Terminal velocity ratio at 18 km */
3.01700    vratio[19]       /* Terminal velocity ratio at 19 km */
3.21400    vratio[20]       /* Terminal velocity ratio at 20 km */
```

(I plan to modify the code and give the final values in attenParmAlpha[][] and ZRParmA[][] in the next version. Please watch out for the note of changes.)

8. The rain rate estimate from a given reflectivity factor depends on the storm type and the phase of precipitating particles.

2A25 essentially uses only two types of storm; stratiform or convective. Since the classification of storm types may not be perfect, since there are intermediate states between stratiform and convective rain, and since the estimate of the zero-degree C height and the phase classification are rather crude, the estimates of rain rate may include large errors.

2-3. 8. Known Deficiencies

Note that since the algorithm has been tested only for a few rain cases, more deficiencies may be found in the future.

1. The non-uniform beam filling correction tends to over-correct the attenuation in some heavy rain range bins. This happens probably because the range dependence of apparent attenuation coefficient in non-uniform rain cases is neglected. To avoid the unrealistically large *Z*-factors and rain rates, a limit for the non-uniform beam filling correction for attenuation is introduced.

2. Sidelobe contamination occurs when the nadir surface cross section is very large. A simple routine to remove such sidelobe clutter is included in the algorithm, but it does not completely remove the sidelobe signals. Care must be taken when small signals are used.

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,
``A preliminary study of non-uniform beam filling correction for spaceborne radar rainfall measurement," IEICE Trans. Commun., E79-B, pp. 763-769, June 1996.

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.

2-3.10. Detailed description of output variables

Variable type

nray = 49,
nbin = 80,
ncell2 = 5,
ncell3 = 6,

ncell4 = 2.

```
    float32         rain[nray][nbin];
    int8            reliab[nray][nbin];
    float32         correctZFactor[nray][nbin];
    int16           attenParmNode[nray][ncell2];
    float32         attenParmAlpha[nray][ncell2];
    float32         attenParmBeta[nray];
    int16           ZRParmNode[nray][ncell2];
    float32         ZRParmA[nray][ncell2];
    float32         ZRParmB[nray][ncell2];
    float32         zmmax[nray];
    int16           rainFlag[nray];
    int16           rangeBinNum[nray][ncell3];
    float32         rainAve[nray][ncell4];
    float32         weightW[nray];
    int16           method[nray];
    float32         epsilon[nray];
    float32         zeta[nray][ncell4];
    float32         zeta_mn[nray][ncell4];
    float32         zeta_sd[nray][ncell4];
    float32         xi[nray][ncell4];
    int16           thickThPIZ[nray];
    float32         nubfCorrectFactor[nray][ncell4];
    int16           qualityFlag[nray];
    float32         nearSurfRain[nray];
    float32         nearSurfZ[nray];
    float32         pia2a25[nray];
    float32         errorRain[nray];
    float32         errorZ[nray];
    float32         spare[nray][ncell4];
```

2-3.11. Definitions of the output variables

```
float32   rain[nray][nbin];
REAL*4    rain(nbin,nray)
```

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 rainrate is always set to 0.

If the input radar reflectivity factor Zm is below the noise level, the rain estimate there is set to 0. This procedure does not cause any serious problem except when the measured Zm 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 -99.9 (approximate) is stored.
This situation may happen at range bins above 15 km high because NASDA only guarantees the data collection below 15 km.

The bin number of the lowest range bin that contains valid rain data is (rangeBinNum[][1] - 1 in C) or (rangeBinNum(2,*) - 1 in FORTRAN). Below this level, CLUTTER value of -88.9 (approximate) is stored. The lowest valid range bin is calculated from the surface range bin and the main-lobe clutter flag.

……

```
float32   correctZFactor[nray][nbin];
REAL*4     correctZFactor(nbin,nray)
```

Estimated true Z-factor in dBZ.

If the input radar reflectivity factor Zm is below the noise level, or if the estimate is below 0 dB, -77.8 (approximate) is substituted.

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

……

```
int8   reliab[nray][nbin];
BYTE   reliab(nbin,nray)
```

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 (Zm < 20 dBZ)
sixth bit : estimated Z < 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 the version 3, the threshold is chosen that approximately corresponds to the attenuation of 10 dB.

……

int16 attenParmNode[nray][ncell2];
INTEGER*2 attenParmNode(ncell2,nray);

Range bin numbers of the nodal points at which the attenuation parameter alpha is given in attenParmAlpha[nray][ncell2] (attenParmAlpha(5,nray)).

For each angle bin, 5 nodal points are defined.
These 5 points correspond to the array specified by nray.
The range bin number is not the same as 1B-21 or 1C-21, but the bin number in the array of 80 elements so that it takes a number between 0 and 79.

attenParmNode[][] gives the range bin numbers of the nodes at which the values of attenuation parameter "alpha" are given in attenParmAlpha[][]. The values of alpha between the nodes are linearly interpolated. The range of attenParmNode is between 0 and 79. (See the note for rangeBinNum above.)

For no-rain angle bins, attenParmNode[][] is set to the surface range bin number.

……

float32 attenParmAlpha[nray][ncell2];
REAL*4 attenParmAlpha(ncell2,nray)

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

"alpha" is given at five nodal points.
alpha values between the nodes are calculated by linear interpolation.
The range bin numbers of the nodes are stored in attenParmNode[nray][ncell2].

……

float32 attenParmBeta[nray];
REAL*4 attenParmBeta(nray)

Attenuation parameter beta
k = alpha Z^beta.

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

……

int16 ZRParmNode[nray][ncell2];
INTEGER*2 ZRParmNode(ncell2,nray);

Range bin numbers of the nodal points at which the Z-Rparameters "a" and "b" are given in ZRParmA[nray][ncell2] (ZRParmA(ncell2,nray)) and ZRParmB[nray][ncell2] (ZRParmB(ncell2,nray)).

ZRParmNode[][] give the range bin numbers of the nodes at which the Z-R parameters "a" and "b" are given in ZRParmA[][] and ZRParmB[][], respectively. The values of a and b between the nodes are linearly interpolated.
The range of ZRParmNode is between 0 and 79. (See the note for rangeBinNum above.)

For no-rain angle bins, attenParmNode[][] is set to the ellipsoid range bin number (=79).

……

float32 ZRParmA[nray][ncell2];
REAL*4 ZRParmA(ncell2,nray)

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 the ZRParmNode[nray][ncell2] (ZRParmNode(ncell2,nray)).

……

float32 ZRParmB[nray][ncell2];
REAL*4 ZRParmB(ncell2,nray)

Z-R parameter 'a' 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 the ZRParmNode[nray][ncell2] (ZRParmNode(ncell2,nray)).

……

float32 zmmax[nray];

REAL*42 zmmax[nray]

zmmax is the maximum value of measured Z-factor expressed in dBZ at each IFOV.
The unit is in dBZ or 10 log of mm^6/m^3.
The range of the variable is between 0 and 100. (Typically between 10 and 60.)

……

int16 rainFlag[nray];
INTEGER*2 rainFlag(nray)

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
+2: (bit 2) rain certain
+4: (bit 3) zeta^beta > 0.5 (PIA larger than 3 dB)
+8: (bit 4) large attenuation (PIA larger than 10 dB)
+16: (bit 5) stratiform
+32: (bit 6) convective
+64: (bit 7) BB exist
+132: (bit 8) warm rain
+256: (bit 9) rain bottom above 2 km
+512: (bit 10) rain bottom above 4 km
+16384: (bit 15) data missing between rain top and bottom

11th to 14th bits are currently not used. 16th bit (sign bit) is not used either.

Bits 3 and 4 are set if the integral of 0.2 ln(10) beta alpha Zm^beta to the rain bottom exceeds the given threshold.

……

int16 rangeBinNum[nray][ncell3];
REAL*4 rangeBinNum(ncell3,nray)

rangeBinNum[][0]: the top range bin number of the interval that is processed as meaningful data in 2A-25.
rangeBinNum[][1]: 1 plus the bottom range bin number of the interval that is processed as meaningful data in 2A-25.
See note below.
rangeBinNum[][2]: the actual surface range bin number.
rangeBinNum[][3]: the range bin number of the bright band if it exits.
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.

All these range bin numbers are indexed vertically from top to bottom with 0 as the highest elevation and 79 as 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.

Range bin numbers are unitless.

Note: 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.

……

```
float32     rainAve[nray][ncell4];
REAL*4      rainAve(ncell4,nray)
```

rainAve[][0] :
rainAve(1,*) : Average of rainfall rate between 2 and 4 km.

If the lowest bin processed is higher than 2 km, the average is taken between the lowest altitude and 4 km. In this case, 6th bit in the 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 the rainFalg is set.

rainAve[][1] :
rainAve(2,*) : Integrated rainfall rate from the rain top to the bottom. Unit is mm / h*km.

……

```
float32     weightW[nray];
REAL*4      weightW(nray)
```

Weighting factor in the calculation of epsilon (SRT correction factor) in the hybrid method. The number is always between 0 and 1.

……

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

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
+3: (bit 2) others (inland lake, etc.)
+4: (bit 3) constant-Z-near-surface method
+8: (bit 4) rain less than 5 bins
+16: (bit 5) not enough (<5) successive rain data
+32: (bit 6) positive slope near surface
+64: (bit 7) zeta >= 1.0
+128: (bit 8) quadratic weighting
+256: (bit 9) NUBF correction very large (> 2.0)
+512: (bit 10) No NUBF because NSD unreliable
+1024: (bit 11) NUBF for Z-R below lower bound
+2048: (bit 12) NUBF for PIA above upper bound
+4096: (bit 13) NUBF for PIA below lower bound
+8192: (bit 14) surface attenuation after NUBF correction > 60 dB
+16384: (bit 15) data missing between rain top and bottom

16th bit is currently not used.

If the surface reference is reliable, a quadratic weighting is used for the calculation of the weighting factor. If it is only marginally reliable, a linear weighting is used so that the surface reference has less weight than the reliable case. In both cases, the larger the attenuation, the larger the weight for the surface reference.

The constant Z method is used only when the surface reference is unreliable. This routine fit a straight line to the lowest 5 successive data in the measured Zm profile that are above the noise level. If there are not enough data points for regression, the fourth or fifth bit is set.
In this case, no attenuation correction is applied.

```
float32     epsilon[nray];
REAL*4       epsilon(nray)
```

Surface reference correction factor

```
float32     zeta[nray][ncell4];
REAL*4       zeta(ncell4,nray)
```

Integral of 0.2 ln(10) beta alpha Z^beta

zeta[][0]: zeta = Integral of 0.2*ln(10) beta alpha Z^beta from the rain top to the bottom
(lowest altitude processed).

zeta[][1]: PIA_est = -10 (log10(1-zeta_cr))/beta

zeta is always between 0 and 100, typically between 0 and 2. (There is no bound check routine for zeta[][0] in the present version of 2A-25, but zeta[][1] is bounded from above by 50/beta which is approximately equal to 70.)

zeta is unitless.

……

```
float32     zeta_mn[nray][ncell4];
REAL*4       zeta_mn(ncell4,nray)
```

Mean of zeta and PIA in 9 adjacent (3x3) beams.
At scan edges, mean is calculated in 6 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.

……

```
float32     zeta_sd[nray][ncell4];
REAL*4       zeta_sd(ncell4,nray)
```

Standard deviation of zeta and PIA_est in 9 adjacent (3x3) beams.
At scan edges, it is calculated in 6 beams.

zeta_sd[][0]: zeta_sd = standard deviation of zeta
zeta_sd[][1]: PIA_sd = standard deviation of pia_est

Since zeta only takes a positive value, its standard deviation must be less than the maximum of zeta. In other words, zeta_sd must be between 0 and 100 always.

zeta_sd is unitless.

……

```
float32       xi[nray][ncell4];
REAL*4         xi(ncell4,nray)
```

Normalized standard deviation of zeta and PIA_est

xi[][0]: xi = zeta_sd / zeta_mn
xi[][1]: nsd_l = normalized standard deviation of pia_est

When zeta_mn (or pia_mn) is very small (or 0) and xi (or nsd_l) takes a large number, it is redefined to 99.0 so that xi (or nsd_l) always takes a number between 0 and 99.

xi is unitless.

……

int16 thickThPIZ[nray];
INTEGER*2 thickThPIZ[nray];

'thickThPIZ' is the number of range bins (250 m resolution) between the highest range at which rain is certain and the range at which the path-integrated Z-factor first exceeds the given threshold. This is an indicator of the rainfall rate or attenuation. This is a unitless quantity and its range is between 0 and 79.

……

float32 nubfCorrectFactor[nray][ncell4];
REAL*4 nubfCorrectFactor(ncell4,nray)

'nubfCorrectFactor' is the non-uniform beam filling correction factor.

nubfCorrectFactor[][0] is the correction factor for the k-Z relation and its range is between 1.0 and 3.0 in version 3.5 of 2A-25.

nubfCorrectFactor[][1] is the correction factor for the Z-R relation and its range is between 0.8 and 1.0 in version 3.5 of 2A-25.

……

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

Quality flag for each angle bin data

The default value is 0.

The following meanings are assigned to each bit

0: (bit 1) normal
+1: (bit 1) unusual situation in rain average
+2: (bit 2) mean of zeta too small for NSD (xi) calculation (flag_xi & 1 = 1)
+4: (bit 3) NSD of zeta (xi) calculated from less than 6 points (flag_xi & 2 =2)

+8: (bit 4) mean of PIA too small for NSD (PIA) calculation
+16: (bit 5) NSD of PIA calculated from less than 6 points
+32: (bit 6) epsilon not reliable
+64: (bit 7) 2A21 input data not reliable
+128: (bit 8) 2A23 input data not reliable (flag_2a23.status > 99)
+256: (bit 9) range bin error
+512: (bit 10) sidelobe clutter removal
+16384: (bit 15) data missing between rain top and bottom

11th to 14th bits are currently not used.
16th bit (sign bit) is not used either.
The contents are exact copy of flag_qlty.

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

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 the estimated attenuation down to this point is larger than the threshPIZ defined in the parameter file (it is currently set to 3 dB), 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 spare[][0] in v5.3.

Therefore,
nearSurfRain[n_anglebin] = rain[n_anglebin][(int)spare[n_anglebin][0]];
nearSurfRain(n_anglebin) = rain(INT(spare(1,n_anglebin)+1),n_anglebin)

float32 nearSurfZ[nray];
REAL*4 nearSurfZ(nray)

Near-surface Z-factor

See nearSurfRain[] for the definition of "Near-surface".
nearSurfZ[n_anglebin] = correctZFactor[n_anglebin][(int)spare[n_anglebin][0]];
nearSurfZ(n_anglebin) = correctZFactor(INT(spare(1,n_anglebin)+1),n_anglebin)

float32 pia2a25[nray];
REAL*4 pia2a25(nray)

Path-integrated attenuation from the estimated Z profile

This attenuation is calculated from the attenuation-corrected Z-profile in correctZFactor [][] and adjusted alpha.
The number represents the two-way attenuation to the surface.
A proportional factor d1/d2 where
d1 = distance of the rain top certain to the surface
d2 = distance of the rain top certain to the bottom of the valid data,
is multiplied by the attenuation calculated from the Z profile (which goes only down to the bottom of the valid data) to obtain the estimate of the attenuation to the surface. See "spare" below.

……

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

error estimate of rain near the surface expressed in dB

The error is calculated assuming infinitesimal error formulas.
Therefore, when the estimate is large, it may not be reliable at all.

……

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

error estimate of correctZFactor near the surface expressed in dB.

The error is calculated assuming infinitesimal error formulas.
Therefore, when the estimate is large, it may not be reliable at all.

……

```
float32     spare[nray][ncell4];
REAL*4       spare(ncell4,nray)
```

spare

spare[nray][0] : The range bin number (0-79) of surface rain rate and Z is stored in v5.3, i.e.,

```
nearSurfRain = rr[(int)spare[][0]]
nearSurfZ      = correctZFactor[(int)spare[][0]]
```

See the description of "nearSurfRain" for the definition of this number.

spare[nray][1] : Delta simga~0 from 2A21 is tentatively stored in v5.21.

……

Appendix 1.   Output data structure defined in the toolkit

```
/**************************************/
/* Define L2A-25 data structure.       */
/**************************************/

typedef struct
{
int8                  mainlobeEdge;
int8                  sidelobeRange[3];
} CFLAGS;

typedef struct
{
CFLAGS                clutFlag[CLUTFLAG_TBL_SIZE];
} CLUTTER_FLAGS;

typedef struct
{
float64               scanTime;
float32               geolocation[49][2];
PR_SCAN_STATUS    scanStatus;
NAVIGATION            navigate;
int16                 rain_scale[49][80];
float32               rain[49][80];
int8                  reliab[49][80];
int16                 correctZFactor_scale[49][80];
float32               correctZFactor[49][80];
int16                 attenParmNode[49][5];
int16                 attenParmAlpha_scale[49][5];
float32               attenParmAlpha[49][5];
int16                 attenParmBeta_scale[49];
float32               attenParmBeta[49];
int16                 ZRParmNode[49][5];
int16                 ZRParmA_scale[49][5];
float32               ZRParmA[49][5];
int16                 ZRParmB_scale[49][5];
float32               ZRParmB[49][5];
float32               zmmax[49];
int16                 rainFlag[49];
int16                 rangeBinNum[49][6];
int16                 rainAve_scale[49][2];
float32               rainAve[49][2];
int16                 weightW_scale[49];
float32               weightW[49];
int16                 method[49];
float32               epsilon[49];
float32               zeta[49][2];
float32               zeta_mn[49][2];
float32               zeta_sd[49][2];
float32               xi[49][2];
int16                 thickThPIZ[49];
```

```
        float32           nubfCorrectFactor[49][2];
        int16              qualityFlag[49];
        float32           spare[49][2];
        } L2A_25_SWATHDATA;

/*-------------------------------------------------------------------
```

Appendix 2.   Flags used in the main program

```
-------------------------------------------------------------------*/

/* ------- Variables related to status flags --------------
     For most flags, 0 indicates the normal status.
------------------------------------------------------- */

int    flag_rnr;                     /* rain/no-rain flag */
     0: no rain
     1: rain possible
     2: rain certain

int    flag_norm;                      /* const.-Z-near-surface condition used */
     0: normal
     1: not enough range bins in rain interval
     2: not enough range bins that continuously exceed the threshold
     3: slope of Zm profile is positive

int    flag_ave;                     /* average rain status flag */
     0: normal
     1: rbinBottom is above 2 km
     2: no valid data between 2 and 4 km

int    flag_xi[NANGLE];              /* xi status flag */
     0: normal
    +1: (first bit is set) zeta_mean too small (less than SMALLZETA = 0.01)
    +2: (second bit is set) valid number of data points less than 6
     3: 1 and 2 (first and second bits are set)

int    flag_nsd[NANGLE];             /* nsd_l status flag */
     0: normal
     1: (first bit is set) nsd_mean too small (less than SMALLPIA = 0.1)
     2: (second bit is set) valid number of data points less than 6
     3: 1 and 2 (first and second bits are set)

int    flag_surf;                    /* surface condition flag */
     0: ocean
     1: land
     2: coastline
     4: inland lake
     8: no surface information

int    flag_epsi;                    /* epsilon status flag */
```

```
    0: normal
    1: pintz larger than 1
    2: quadratic weighting function is used (SRT reliable)
    3: linear weighting function is used (SRT marginally reliable)

int   flag_attn[NANGLE];            /* surface attenuation flag */
    0: normal
    1: attenuation from 2A21 less than 0
    2: surface attenuation after NUBF correction becomes larger than 60 dB

int   flag_th[NPOL][NANGLE];        /* PIZ exceeds threshold */
    0: zeta does not exceed the threshold.
    1: zeta exceeds the threshold. (attenuation larger than 3 dB)
       The threshold value is actually defined in the parameter file.

int   rbinFlag1[NPOL][NANGLE];      /* flag from rangeBinNum1()   */
    0: (bit 1) normal
   +1: (bit 1) range bin number of surface in 1C-21 out of interval [0,140].
   +2: (bit 2) range bin number of rain bottom in 1C-21 out of interval [0,140].
   +4: (bit 3) rain top in 1C-21 lower than rain bottom.
   +8: (bit 4) range bin number of rain top in 1C-21 less than 0.

int   rbinFlag2[NPOL][NANGLE];      /* flag from rangeBinNum2()   */
    0: (bit 1) normal
   +1: (bit 1) range bin number of ellipsoid in 1C-21 out of interval [0,140].
   +2: (bit 2) local zenith angle too large. (theta > 0.5 radian)
   +4: (bit 3) range bin number of 2 km out of interval [0,140].
   +8: (bit 4) range bin number of 4 km out of interval [0,140].
  +16: (bit 5) range bin number of freezing (0C) height out of interval [0,140].
  +32: (bit 6) bright band exists and below rain bottom or out of interval [0,140].

int   flag_rbin[NPOL];              /* flag from range bin calculations */
    0: normal
    1: at least one error in rangeBinNum1() or rangeBinNum2().

int   flag_2a21;                    /* 2a21 status flag */
    flag_2a21 =  L2A21_dummy[jpol].reliabFlag[i]/1000
                  -(L2A21_dummy[jpol].reliabFlag[i]/10000)*10;

int   flag_2a23;                    /* 2a23 status flag */
    flag_2a23 = (int)L2A23_dummy[jpol].status[i];

int   flag_warm[NPOL][NANGLE];      /* 2a23 warm rain flag */
      flag_warm[jpol][i] = L2A23_dummy[jpol].warmRain[i];
    (g) int8 warmRain[49]:    Warm rain flag
    0: no warm rain
    1: Maybe warm rain
    2: Warm rain (with confidence)
  -88: no rain
  -99: data missing
```

```
int    status_ifov[NMTX][NANGLE]; /* input status of IFOV */
      0: invalid data between the rain top and bottom.
      1: valid data = no data is missing between the rain top and bottom.

int    status_scan[NMTX];            /* input data status of scan: 0=valid   */
       0: normal
       1: some of the data in the scan are missing or corrupted.
          (L1C21_dummy[jpol].scanStatus.missing != SS_MISSING ||
           L1C21_dummy[jpol].scanStatus.dataQuality != SS_DataQuality)

int    status_nubf[NANGLE];           /* status of NUBF correction   */
       0: NUBF correction
       1: no NUBF correction because NSD is not reliable
      +2: NUBF for Z-R relation is below the lower bound ( < 0.8)
      +4: NUBF for PIA is above the upper bound ( > 3.0)
      +8: NUBF for PIA is below the lower bound ( < 1.0)

int    flag_rain;                    /* output rain flag */
        0: (bit  1) no rain
       +1: (bit   1) rain possible
       +2: (bit   2) rain certain
       +4: (bit   3) zeta^beta > 0.5 (PIA larger than 3 dB)
       +8: (bit   4) large attenuation (PIA larger than 10 dB)
      +16: (bit   5) stratiform
      +32: (bit   6) convective
      +64: (bit   7) BB exist
     +128: (bit   8) warm rain
     +256: (bit   9) rain bottom above 2 km
     +512: (bit  10) rain bottom above 4 km
   +16384: (bit  15) data missing between rain top and bottom

   11th to 14th bits are currently not used.
   16th bit (sign bit) is not used either.

int    flag_mthd;                    /* output method flag */
        0: (bit  1) no rain
   if rain
        0: (bit   1) over ocean
        1: (bit   1) over land
        2: (bit   2) over coast
        3: (bit   2) others (inland lake, etc.)
       +4: (bit   3) constant-Z-near-surface method
       +8: (bit   4) rain less than 5 bins
      +16: (bit   5) not enough (<5) successive rain data
      +32: (bit   6) positive slope near surface
      +64: (bit   7) zeta >= 1.0
     +128: (bit   8) quadratic weighting
     +256: (bit   9) NUBF correction very large ( > 2.0)
     +512: (bit  10) No NUBF because NSD unreliable
```

```
   +1024: (bit   11) NUBF for Z-R below lower bound
   +2048: (bit   12) NUBF for PIA above upper bound
   +4096: (bit   13) NUBF for PIA below lower bound
   +8192: (bit   14) surface attenuation after NUBF correction > 60 dB
  +16384: (bit   15) data missing between rain top and bottom

   16th bit is currently not used.

int     flag_qlty;                      /* output quality flag */
         0: (bit   1) normal
        +1: (bit   1) unusual situation in rain average
        +2: (bit   2) mean of zeta too small for NSD (xi) calculation (flag_xi & 1 = 1)
        +4: (bit   3) NSD of zeta (xi) calculated from less than 6 points (flag_xi & 2 = 2)
        +8: (bit   4) mean of PIA too small for NSD (PIA) calculation
       +16: (bit   5) NSD of PIA calculated from less than 6 points
       +32: (bit   6) epsilon not reliable
       +64: (bit   7) 2A21 input data not reliable
      +128: (bit   8) 2A23 input data not reliable (flag_2a23.status > 99)
      +256: (bit   9) range bin error
      +512: (bit 10) sidelobe clutter removal
  +16384: (bit 15) data missing between rain top and bottom

   11th to 14th bits are currently not used.
   16th bit (sign bit) is not used either.

int    flag_sidelobe[NPOL][NANGLE];
/* sidelobe correction is made if this is set to 1 */
```

……

END

3. Level 3

3-1. 3A-25 - Space Time Statistics of Level 2 PR Products

3-1. 1. Objective of the algorithm

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

The standard space scale is a 5 degree by 5 degree latitude x longitude cell.
A subset of the products, however, is also produced over 0.5 degree x 0.5 degree cells.

3-1.2a. Source Code

(anonymous ftp site of priam.gsfc.nasa.gov: directory pub/trmm_code/v4_3a25/)

f3a25_v4.84_HDF.f	(207.4 kBytes)	{latest revision: 18 Sept 1998}
readinto_3a25_v4.84.f	(19.5 kBytes)	{latest revision: 18 Sept 1998}

3-1.2b. Running the program:

i type: 'make' [uses Makefile in same subdirectory]
ii type: 'f3a25_v4.84_HDF "1C-21 file" "2A-21 file" "2A-23 file" "2A-25 file" "3A-25 output file" ¥ "int file1" 'int file 2" "int file 3" "int file 4" "int file 5" "verification file" ¥ "begin/middle/end graule for month" "year" "month" '

Examples:

```
f3a25_v4.84_HDF 1C21.970317.100.1.HDF 2A21_970317.HDF
2A23.970317.100.1.HDF ¥ 2A25.970317.100.1.HDF 3A25_970317_v4.5_B.hdf
3A25_970317_INT1 3A25_970317_INT2 ¥ 3A25_970317_INT3
3A25_970317_INT4 3A25_970317_INT5 3A25_970317_DIAG_B 'BEGIN' 1998
3
```

```
f3a25_v4.84_HDF 1C21.970317.100.1.HDF 2A21_970317.HDF
2A23.970317.100.1.HDF ¥ 2A25.970317.100.1.HDF 3A25_970317_v4.5_E.hdf
3A25_970317_INT1 3A25_970317_INT2 ¥ 3A25_970317_INT3
3A25_970317_INT4 3A25_970317_INT5 3A25_970317_DIAG_E 'END' 1998 3
```

3-1. 3. Input Data

Data are read from 1C-21, 2A-21, 2A-23, and 2A-25.

The data volumes per scan are approximately:

0.9 kbytes	from 2a-21
0.4 kbytes	from 2a-23
42.0 kbytes	from 2a-25
17.0 kbytes	from 1C-21

Total: 60.3 kbytes per scan

3-1. 4. Output Data Volume (per month)

Approximately 40 Mbytes

3-1.5a. Internal Storage Requirements

Five intermediate files are needed to store the running statistics. The storage needed for all 5 files is approximately 51 Mbytes.
An example of the storage requirements for the 5 intermediate files is:

147464 bytes	3A25_980217.1288.4.HDF_INT1
728072 bytes	3A25_980217.1288.4.HDF_INT2
5391368 bytes	3A25_980217.1288.4.HDF_INT3
320264 bytes	3A25_980217.1288.4.HDF_INT4
44755208 bytes	3A25_980217.1288.4.HDF_INT5

3-1.5b. Output Variables

a. arrays for the calculation of probabilities [4-byte integers]

example of notation used:

rainPix1(16,72,6) = # of rain observations at each 5 x 5 degree x 1 mo. box at 5 heights and over full path

rainPix1(i,j,1) @ h = 2 km; lat box i, longitude box j
rainPix1(i,j,2) @ h = 4 km
rainPix1(i,j,3) @ h = 6 km
rainPix1(i,j,4) @ h = 10 km
rainPix1(i,j,5) @ h = 15 km
rainPix1(i,j,6) over full path

Notes: - the same height convention is used for variables with height information
- all heights are measured from the ellipsoid
- the convention for the 16 latitude boxes are:
box 1 runs from 40 S to 35 S
box 16 runs from 35 N to 40 N

- the convention for the 72 longitude boxes are:
box 1 runs from 180 W to 175 W
box 72 runs from 175 E to 179.99 E

rainPix1(16,72,6) = # of observations at each 5 x 5 degree x 1 mo. box at 5 heights and over full path with rain present
stratRainPix1(16,72,6) = same as above but for stratiform rain
convRainPix1(16,72,6) = same as above but for convective rain
wrainPix(16,72) = # of observations of warm rain (see 2a-23 documentation)
ttlPix1(16,72) = # of observations (rain and no-rain)
bbPixNum1(16,72) = # of observations for which BB is present
epsilonPix1(16,72) = counts for epsilon when SRT value of PIA used (see 2a-25 documentation)
ttlAnglePix1(16,72,4) = # of observations at each 5 x 5 degree x 1 mo. box at angles (approx) of 0, 5, 10, and 15
rainAnglePix1(16,72,4) = # of rain observations at each 5 x 5 degree x 1 mo. box at angles (approx) of 0, 5, 10, and 15

surfRainPix1(16,72) = # of rain observations at range gate closest to surface ('rain-certain' only)
surfRainAllPix1(16,72) = # of rain observations at range gate closest to surface ('rain-certain' and 'rain possible')

note: at (lat, long) = (i, j), and height k, the following probabilities, among others, can be calculated:

Pr(rain) = rainPix1(i,j,k) / ttlPix1(i,j)
Pr(stratiform rain) = stratRainPix1(i,j,k) / ttlPix1(i,j)
Pr(convective rain) = convRainPix1(i,j,k) / ttlPix1(i,j)
Pr(bright-band) = bbPixNum(i,j) / ttlPix1(i,j)
Pr(stratiform rain | rain) = stratRainPix1(i,j,k) / rainPix1(i,j,k)
Pr(convective rain | rain) = convRainPix1(i,j,k) / rainPix1(i,j,k)
Pr(bright-band | rain) = bbPixNum(i,j) / rainPix1(i,j,6)

note the difference among quantities of the following kind:

Pr(stratiform rain | rain) = stratRainPix1(i,j,k) / rainPix1(i,j,k)

Pr'(stratiform rain | rain) = stratRainPix1(i,j,k) / rainPix1(i,j,6)

Pr''(stratiform rain | rain) = stratRainPix1(i,j,6) / rainPix1(i,j,6)

Pr'' 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. Pr is the probability that, given rain is present at a particular height level (denoted by the index 'k'), that the rain is stratiform. Pr' is the probability, given that rain is present somewhere along the beam, that rain is present at height level 'k' and that the rain is stratiform.

b. means and mean squares [4-byte real]

units of rain rates: millimeters / hour

rainMean1(16,72,6) mean of rain rate (5 levels + path-av), conditioned on rain

rainDev1(16,72,6): standard deviation of rain rate (5 levels + path-av), conditioned on rain

stratRainMean1(16,72,6): mean of rain rate (5 levels + path-av), conditioned on stratiform rain

stratRainDev1(16,72,6): standard deviation of rain rate (5 levels + path-av), conditioned on stratiform rain

convRainMean1(16,72,6): mean of rain rate (5 levels + path-av), conditioned on convective rain

convRainDev1(16,72,6): standard deviation of rain rate (5 levels + path-av), conditioned on convective rain

surfRainMean1(16,72): mean of 'near-surface' rain rate ('rain-certain' only)

surfRainDev1(16,72): standard deviation of 'near-surface' rain rate ('rain-certain' only)

surfRainAllMean1(16,72): mean of 'near-surface' rain rate ('rain-certain' and 'rain-possible')

surfRainAllDev1(16,72): standard deviation of 'near-surface' rain rate ('rain-certain' and 'rain-possible')

units of reflectivity factors: 10 log(Z), Z in (millimeters^6 / meter^3)

zmMean1(16,72,6): mean of dBZm (apparent refl. factor) (5 levels + path-av), conditioned on rain

zmDev1(16,72,6): standard deviation of Zm (5 levels + path-av), conditioned on rain

stratZmMean1(16,72,6): mean of Zm (5 levels + path-av), conditioned on stratiform rain

stratZmDev1(16,72,6): standard deviation of Zm (5 levels + path-av), conditioned on stratiform rain

convZmMean1(16,72,6): mean of Zm (5 levels + path-av), conditioned on convective rain

convZmDev1(16,72,6): standard deviation of Zm (5 levels + path-av), conditioned on convective rain

ztMean1(16,72,6): mean of Zt (refl. factor) (5 levels + path-av), conditioned on rain

ztDev1(16,72,6): standard deviation of Zt (5 levels + path-av), conditioned on rain

stratZtMean1(16,72,6): mean of Zt (5 levels + path-av), conditioned on stratiform rain

stratZtDev1(16,72,6): standard deviation of Zt (5 levels + path-av), conditioned on stratiform rain

convZtMean1(16,72,6):	mean of Zt (5 levels + path-av), conditioned on convective rain
convZtDev1(16,72,6):	standard deviation of Zt (5 levels + path-av), conditioned on convective rain

bbZmaxMean1(16,72):	mean of maximum reflectivity in bright band
bbZmaxDev1(16,72):	standard deviation of same

units of path-integrated attenuation (PIA) dB/km - PIA is the 1-way path attenuation

piaSrtMean(16,72,4):	mean of SRT PIA at 4 inc. angles (0, 5, 10, 15)
piaSrtDev(16,72,4):	standard deviation of SRT PIA at same 4 inc. angles
piaHbMean(16,72,4):	mean of HB PIA at same 4 angles
piaHbDev(16,72,4):	standard deviation of HB PI at same 4 angles
pia0Mean(16,72,4):	mean of 0th-order PIA at same 4 angles
pia0Dev(16,72,4):	standard deviation of 0th-order PIA at same 4 angles

units of bright-band height, storm height, snow depth, etc, are all in meters

bbHtMean(16,72):	mean of height of BB
bbHtDev(16,72):	standard deviation of height of BB
stormHtMean(16,72,3):	mean of storm height (cond on rain type)
stormHtDev(16,72,3):	standard deviation of storm height (cond on rain type)
sdepthMean1(16,72):	mean of snow depth (only when BB is present)
sdepthDev1(16,72):	std dev of snow depth (only when BB is present)
zpzmm(16,72):	mean of (dBZ(at BB - epsilon) - dBZ(at BB + epsilon)) : NOT CALCULATED
zpzmm2(16,72):	std dev of (dBZ(at BB - epsilon) - dBZ(at BB + epsilon)): NOT CALCULATED
bbwidthMean1(16,72):	mean of width of bright band : NOT CALCULATED
bbwidthDev1(16,72):	std dev. of same : NOT CALCULATED

following 6 quantities are unitless

xiMean(16,72):	mean of xi (see 2a-25 documentation)
xiDev(16,72):	standard deviation of xi
nubfCorMean(16,72):	mean of non-uniform beam filling correction factor (see 2a-25)
nubfCorDev(16,72):	standard deviation of non-uniform beam filling correction factor
epsilonMean1(16,72):	mean of epsilon conditioned on use of SRT in 2a-21 (see 2a-25)
epsilonDev1(16,72):	std dev of same

c. histograms [2-byte integers]: see bin definitions in 5c
: all histograms use 30 bins
: histograms are simple counts - unitless

rainH(16,72,30,6):	histograms of rain rate; 6 height levels; unconditioned on rain type
stratRainH(16,72,30,6):	histograms of rain rate; 6 levels; for stratiform rain
convRainH(16,72,30,6):	histograms of rain rate; 6 levels; for convective rain
surfrainH(16,72,30):	histograms of near-surface rain rates; unconditioned on rain type ('rain-certain' only)
surfrainAllH(16,72,30):	histograms of near-surface rain rates; unconditioned on rain type ('rain-certain' and 'rain-possible')

ztH(16,72,30,6):	histograms of Zt (dB); 6 levels; unconditioned on rain type
stratZtH(16,72,30,6):	histograms of Zt (dB); 6 levels; for stratiform rain
convZtH(16,72,30,6):	histograms of Zt (dB); 6 levels; for convective rain

zmH(16,72,30,6):	histograms of Zm (dB); 6 levels; unconditioned on rain type
stratZmH(16,72,30,6):	histograms of Zm (dB); 6 levels; for stratiform rain
convZmH(16,72,30,6):	histograms of Zm (dB); 6 levels; for convective rain

piaSrtH(16,72,30,4):	histograms of SRT PIA at 4 angles
piaHbH(16,72,30,4):	histograms of HB-derived PIA at 4 angles
pia0H(16,72,30,4):	histograms of zeroth-order PIA at 4 angles

BBHH(16,72,30):	histogram of BB height
stormHH(16,72,30):	histogram of storm height (unconditioned on rain type)
stratStormHH(16,72,30):	histogram of storm height (conditioned on stratiform rain)
convtStormHH(16,72,30):	histogram of storm height (conditioned on convective rain)
bbZmaxH(16,72,30):	histogram of max Zt in bright-band (conditioned on presence of bright-band)

snowIceLH(16,72):	histogram of 'snow depth' (hstorm - hbb) (stratiform rain)
nubfH(16,72,30):	histogram of beam-filling factor (first argument of 2a-25 output)
xiH(16,72,30):	histogran of xi (first argument of 2a-25 output)
epsilonH(16,72,30):	histogram of epsilon conditioned on use of SRT in 2a-25
zpzmH(16,72,30):	histogram of dBZm(BB - eps) - dBZm(BB + eps): NOT CALCULATED
zmGradH(16,72,30,3):	histogram of vertical gradient of Zm at 3 levels: NOT CALCULATED

d. correlation coefficients (5 x 5 x 1 mo boxes)

[all 4-byte real except ncoer and ncoepia which are 4-byte integers]

- statistics compiled only when rain rates at 2 km, 4 km, and 6 km are all non-zero

rainCCoef(16,72,3):	correlation coefficient of rain rates at heights: (2 km, 4 km), (2 km, 6 km), (4 km, 6km) for all rain types
stratRainCCoef(16,72,3):	correlation coefficient of rain rates at heights: (2 km, 4 km), (2 km, 6 km), (4 km, 6km) for stratiform rain
convRainCCoef(16,72,3):	correlation coefficient of rain rates at heights: (2 km, 4 km), (2 km, 6 km), (4 km, 6km) for convective rain

- following done only when all 3 PIAs exist and are reliable or marginally so

piaCCoef(16,72,4,3):	correlation coefficients of PIA values for (HB, SRT), (0th, SRT), (0th, HB) at 4 incidence angles

- several correlation coefficient were defined but presently are not being computed:

xiZmCCoef:	corr. coeff. between xi and maximum value of Zm along path
stormHtZmCCoef:	corr. coeff. between storm height and maximum value of Zm along path

e. high resolution statistics (0.5 x 0.5 x 1 mo boxes)

i. counts (unitless; 4-byte integers)

ttlPix2(148,720)	total count number
rainPix2(148,720,4)	rain count number (all rain types) at 4 levels (2 km, 4 km, 6 km & path-av)
stratRainPix2(148,720,4)	stratiform rain counts at 4 levels (2 km, 4 km, 6 km & path-av)
convRainPix2(148,720,4)	convective rain counts at 3 levels (2 km, 4 km, 6 km & path-av)
surfRainPix2(148,720)	near-surface rain counts (all rain types)
bbPixNum2(148,720)	bright-band rain counts
wrainPix2(148,720)	warm rain counts

surfRainPix2(148,720)	near-surface rain rate counts ('rain-certain' only)
surfRainAllPix2(148,720)	near-surface rain rate counts ('rain-certain' and 'rain-possible')

ii. rain rates (millimeters / hour; 4-byte real)

rainMean2(148,720,4)	mean rain rates at 4 levels (for all rain types)
rainDev2(148,720,4)	std dev of rain rates at 4 levels (for all rain types)
stratRainMean2(148,720,4)	mean rain rates at 4 levels (for stratiform rain)
stratRainDev2(148,720,4)	std dev of rain rates at 4 levels (for stratiform rain)
convRainMean2(148,720,4)	mean rain rates at 4 levels (for convective rain)
convRainDev2(148,720,4)	std dev of rain rates at 4 levels (for convective rain)
surfRainMean2(148,720)	mean near-surface rain rates ('rain-certain' only)
surfRainDev2(148,720)	std dev of same ('rain-certain' only)
surfRainAllMean2(148,720)	mean near-surface rain rates ('rain-certain' and 'rain-possible)
surfRainAllDev2(148,720)	std dev of same ('rain-certain' and 'rain-possible')

iii. dBZ values (10 log Z; Z in mm^6/m^3; 4-byte real)

zmMean2(148,720,4)	mean dBZm at 4 levels (for all rain types)
stratZmMean2(148,720,4)	mean dBZm at 4 levels (for stratiform rain)
convZmMean2(148,720,4)	mean dBZm at 4 levels (for convective rain)
ztMean2(148,720,4)	mean Zt at 4 levels (for all rain types)
stratZtMean2(148,720,4)	mean Zt at 4 levels (for stratiform rain)
convZtMean2(148,720,4)	mean Zt at 4 levels (for convective rain)
bbZmaxMean2(148,720)	mean of maximum reflectivity in bright band : NOT COMPUTED
bbZmaxDev2(148,720)	std dev of same

iv. heights of effective storm top, bright-band height, snow depth, etc.
(meters; 4-byte real)

stormHeightMean2(148,720,3)	mean of storm height [meters] for: 1. stratiform rain 2. convective rain 3. all rain types
stormHeightDev2(148,720,3)	std dev of same
bbHeightMean2(148,720)	mean of bright-band height
bbHeightDev2(148,720)	std dev of same
sdepthMean2(148,720)	mean of snow depth
sdepthDev2(148,720)	std dev of same

3-1.5c. Definition of Bins for Histograms

for radar reflectivity factor histograms: ztH, convZtH, stratZtH
zmH, convZmH, stratZmH

the 31 bin boundaries are:

```
      data bhz/0.01,12.,14.,16.,18.,20.,
                22.,24.,26.,28.,30.,32.,34.,
     1          36.,38.,40.,42.,44.,46.,48.,
     1          50.,52.,54.,56.,58.,60.,62.,
     1          64.,66.,68.,70./
```

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:

```
      data bhbb/0.01,0.25,0.5,0.75,1.,1.25,1.5,1.75,2.,2.25,
     1          2.5,2.75,3.,3.25,3.5,3.75,4.,4.25,4.5,4.75,5.,
     1          5.25,5.5,5.75,6.,6.25,6.5,6.75,7.,7.5,20./
```

for storm height histograms, stormHH, stratStormHH, convStormHH, (in km), the 31 bin boundaries [km] are:

```
      data bhstorm/0.01,0.5,1.,1.5,2.,2.5,3.,3.5,4.,4.5,5.,
     1             5.5,6.,6.5,7.,7.5,8.,8.5,9.,9.5,10.,10.5,
     1             11.,11.5,12.,12.5,13.,14.,15.,16.,20./
```

for distance from storm top to bright-band height histogram, snowIceLH, the 31 bin boundaries [km] are:

```
      data bhdepth/0.01,0.5,0.75,1.,1.25,1.5,1.75,2.,2.25,
     1          2.5,2.75,3.,3.25,3.5,3.75,4.,4.25,4.5,4.75,5.,
     1          5.25,5.5,5.75,6.,6.25,6.5,6.75,7.,7.25,7.5,20./ !31
```

for the path-averaged attenuation estimate histograms, piaSrtH, piaHbH, pia0H, the 31 bin boundaries [dB] are:

```
      data bhpia/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,
     1           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,
     1           8.5,9.0,9.5,10.,100./            ! 31
```

for non-uniform beamfilling factor histogram, nubfH, the 31 bin boundaries [dimensionless] are:

```
        data bhnubf/0.,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.,1.1,
     1           1.2,1.3,1.4,1.5,1.6,1.7,1.8,1.9,2.,2.1,2.2,2.3,
     1           2.4,2.5,2.6,2.7,2.8,2.9,3.0/ ! 31
```

for xi (=standard deviation of zeta/ mean of zeta) histogram, xiH, the 31 bin boundaries [dimensionless] are:

```
        data bhxi/0.,0.2,0.4,0.6,0.8,1.,1.2,1.4,1.6,1.8,2.,2.2,2.4,
     1           2.6,2.8,3.,3.2,3.4,3.6,3.8,4.,4.2,4.4,4.6,4.8,5.,
     1           10.,20.,30.,50.,10000./     ! 31
```

for the parameter epsilon (see 2a-25) the 31 bin boundaries are:

```
        data bhepsilon/0.,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.,1.1,
     1           1.2,1.3,1.4,1.5,1.6,1.7,1.8,1.9,2.,2.1,2.2,2.3,
     1           2.4,2.5,2.6,2.7,2.8,2.9,3.0/
```

3-1.5d. Other Input Parameters

```
c CAPPI   heights relative to the ellipsoid


      data hh/2.,4.,6.,10.,15./


c angle bins at which the statistics of the various PIA estimates are to be evaluated
c these angle bins approx. correspond to the port-side angles of
c 0, 5, 10, and 15 degrees incidence:

      data jars/25, 32, 38, 45/
```

3-1. 6. 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 achor 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 belong. Note that a single scan is composed of 49 observations each at a different incidence angle.

(coarse resolution boxes are 5 degree x 5 degree cells)
(fine resolution boxes are 0.5 degree x 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. 7. Comments and Issues

i. With the exception of one quantity, all statistics in 3a-25 are computed only when rain is judged in 1c-21 to be 'certain'. What this means is that when rain is judged in 1c-21 to be 'possible' the observation is treated as a 'no-rain' observation. The one exception to this rule is the near-surface rain rate. For this quantity, the statistics (mean, standard deviation and histogram) are computed for 'rain-certain' and 'rain-possible' as well as for the usual 'rain-certain' category.

The near-surface rain rate statistics computed under 'rain-possible' and 'rain-certain' conditions are:

-Low resolution products (5 x 5 degrees x 1 month)

surfRainAllPix1(i,j): total counts of 'rain-possible' and 'rain-certain' at (latitude, longitude) box = (i,j)
surfRainAllMean1(i,j): mean rain rate (mm/h), given rain is present
surfRainAllDev1(i,j): standard deviation of the rain rate (mm/h), given rain is present
surfRainAllH(i,j,30): histogram classified into 30 bins

-High Resolution products (0.5 x 0.5 x 1 month)

surfRainAllPix2(i,j): total counts of 'rain-possible' and 'rain-certain' at (latitude, longitude) box = (i,j)
surfRainAllMean2(i,j): mean rain rate (mm/h), given rain is present
surfRainAllDev2(i,j): standard deviation of the rain rate (mm/h), given rain is present

The statistics of near-surface rain rate computed only under 'rain-certain' conditions are denoted by:

-Low resolution products (5 x 5 degrees x 1 month)

surfRainPix1(i,j): total counts of 'rain-certain' at (latitude, longitude) box = (i,j)
surfRainMean1(i,j): mean rain rate (mm/h), given 'rain-certain'
surfRainDev1(i,j): standard deviation of the rain rate (mm/h), given 'rain-certain'

surfRainH(i,j,30):	histogram classified into 30 bins, given 'rain-certain'

-High Resolution products (0.5 x 0.5 x 1 month)

surfRainPix2(i,j):	total counts of 'rain-certain' at (latitude, longitude) box = (i,j)
surfRainMean2(i,j):	mean rain rate (mm/h), given 'rain-certain'
surfRainDev2(i,j):	standard deviation of the rain rate (mm/h), given 'rain-certain'

The 'rain-possible' cases are dominated by noise so that the probability of false-alarm is high; the 'rain-certain' statistics should be considered more representative of the TRMM radar data. This does not mean, however, that the light rain cases that are undetected by the radar are necessarily negligible.

ii. Several output variables that were defined but are not being computed

zmGradH(16,72,30,3):	histogram of vertical gradient of Zm at 3 heights
zpzmH(16,72,30):	histogram of difference of Zm at BB peak and in snow
stormHtZmCCoef(16,72):	correlation coeff. between storm height & maximum Zm
xiZmCCoef(16,72):	correlation coeff. between xi and maximum Zm
zpzmm(16,72):	mean of (dBZ(at BB - epsilon) - dBZ(at BB + epsilon))
zpzmm2(16,72):	std dev of (dBZ(at BB - epsilon) - dBZ(at BB + epsilon))
bbwidthMean1(16,72):	mean of width of bright band
bbwidthDev1(16,72):	std dev. of same

iii. It is assumed in the program that the verification file does not exist; if it is already exists an error will occur.

iv. 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.

v. 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.

vi. 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.

vii. 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) are being output under rain-possible conditions. With the exception noted above (in comment i.) 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.

viii. 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 = 200 R^1.6 or in dB:

$$\mathrm{dBR} = 0.625\ \mathrm{dBZ} - 14.38\ .$$

For example, the dBZ histogram bin from 12 dB to 14 dB corresponds to the rain rate histogram bin (10 log mm/hr) from -6.88 dB to -5.63 dB. The lowest dBR value (the lower boundary of the first bin) is 0.625 * 0.01 - 14.38 = -14.32 dB. It is possible, however, for dBR 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 dBR 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.

ix. There are 3 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 which is not corrupted by the surface clutter. Two sets of products are being computed from these data: the first set of statistics uses only those rain rate for which rain is classified as 'certain'; the second set uses those rain rates for which rain is classified either as 'possible' or 'certain'.

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 which, in turn, effects 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.

x. 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 more a more reliable indicator of the near-surface rain rate.

3-2 3A-26 - Estimation of Space-Time Rain Rate Statistics Using a Multiple Thresholding Technique

3-2.1a. Objectives of the algorithm

The primary objective of 3a-26 is to compute the rain rate statistics over 5 degree (latitude) x 5 degree (longitude) x 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.

3-2.1b. 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].

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 on 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. Denoting the Q threshold by Q*, then using Q as a threshold means that 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. Conversely, if Q exceeds Q* the corresponding rain rate estimate is rejected and therefore the measurement 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 and conversely. 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 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 independent estimates of the rain rate is on the order of 1000, the best accuracy is usually obtained by using a threshold value of 0.3. To estimate the actual number of rain rate measurements at a 5 x 5 degree x 1 month space-time region, note that the average number of measurements in a typical space-time box of this size is approximately 184,000. (This number is obtained by noting that the radar cross-track scan, consisting of 49 measurements at 49 incidence angles, is performed in 0.6 sec and that the total number of 5 x 5 degree boxes over the TRMM coverage is 16 x 72). If the probability of rain is taken to be 3%, the average number of measurements of rain at each box is about 5,500. These measurements are clustered in time so that in a single overpass several hundred measurements of the rain rate may be made; because the rain is spatially correlated not all the measurements are independent so that the effective number of independent samples will be smaller; i.e., on the order of 1000. A threshold Q value of 0.3 corresponds to the 3rd array element so that the monthly mean rain rate (using the Z-R method) over the 5 x 5 degree box with indices (lat, long) at the height level index, 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 on the order of 10,000), the use of smaller threshold values (Q = 0.1 or 0.2) leads 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 = 0.9999 (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 log-normal 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.

3-2.1c. 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:

ih	height above ellipsoid
1	2 km
2	4 km
3	6 km
4	path-average

For 3a-25 products, the height levels relative to the ellipsoid are:

ih	height above ellipsoid
1	2 km
2	4 km
3	6 km
4	10 km
5	15 km
6	path-average

In an 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 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 x 5 degree latitude-longitude box specified by (lat, long) for the rain rates measured at a height level given by the index ih.

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), where both rainPix1 and ttlPix1 are output variables from 3a-25. To convert this to a monthly accumulation, the unconditioned rain rate is multiplied by the number of hours in a month, Nmo, so that the MRA (mm/month) as derived from the 3a-25 products, is:

MRA(3a-25) = rainMean1(lat,long,ih)*PrRain(lat,long,ih)*Nmo

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) is:

MRA(3a-26) = zeroOrderFit(lat,long,ih,1,iqthres) Nmo

For the 3rd threshold, Q = 0.3, the MRA is

MRA(3a-26) = zeroOrderFit(lat,long,ih,1,3) Nmo

or, equivalently,

MRA(3a-26) = rainMeanTH(lat,long,ih) Nmo

3-2.1d. 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 are stored in the arrays:

zeroOrderpDf(16, 72, 25, 4, 6)
hbpDf(16, 72, 25, 4, 6)
pDf2A25(16, 72, 25, 4, 6)

where the 5 dimensional array refers to:

(latitude, longitude, rain rate threshold, height, Q threshold)

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', 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,ir,ih,iqthres) is the number of rain counts above the rain rate threshold corresponding to the 'ir' indice. Denote this rain rate by RR_th. The fractional area below the rain rate threshold RR_th at height level ih at the Q threshold, iq, using the Z-R estimates of rain rates is:

Fr_Area {R<RRth_0thR} (lat,long,ih) =
zeroOrderpDf'(lat,long,ir,ih,iq) / ntot(lat,long)

The fractional area above this threshold is:

Fr_Area_RR>RRth_0th(lat,long,ih) = 1 - Fr_Area_R<RRth_0th(lat,long,ih)

For example, to compute the fractional area above the threshold of 2.05 mm/h (ir = 9 - see definition of RRcategories 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:

Fr_Area {R>2.05} (lat,long,ih=1) = 1 - Fr_Area {R<2.05} (lat,long,ih=1)

Fr_Area {R<2.05} (lat,long,ih=1) =
zeroOrderpDf'(lat,long,ir=9,ih=1,iq=6) / ntot(lat,long)

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)

So that the fractional area above 2.05 mm/h over the 5 x 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)

3-2.1e. Reliability estimates

The reliability estimate is taken to be the rms difference between the 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)

if the number of data points is too few or an error occurs in the fitting procedure, the following default values for reliab* and *Fit will be used.

if # of rain occurrences, nrain, in the (lat, long) box are too few, then:
Fit and reliab are set to -999.

if warning error occurs in the fitting or if the fit is determined to be unstable, then:
Fit and realib are set to -888.

if number of rain rate thresholds over which the distribution increases is fewer than twice the # of unknowns then
Fit and reliab are set to -777.

3-2.1f. Definition of the latitude-longitude boxes

The products are defined on a 5 degree x 5 degree x 1 month grid that covers the TRMM orbit. The latitude boxes are labeled from 1 to 36 where box 1 covers the region from 40 S to 35 S and box 36 covers the region 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.

3-2.2a. Source Code

(anonymous ftp site: priam.gsfc.nasa.gov, directory: pub/trmm_code/v4_3a26/

f3a26_v4.80_HDF.f	(133.6 kBytes)	{latest version: 18 Sept 1998}
readinto_3a26_v4.77.f	(18.0 kBytes)	{latest version: 18 Sept 1998}
r1mach.f	(13.1 kBytes)	
cmlib.f	(172.5 kBytes)	
xsetun.f	(1.1 kBytes)	

3-2.2b. Running the program (on priam.gsfc.nasa.gov workstation:)

I type: 'make' [uses Makefile in same subdirectory]

Ii type: 'f3a26_v4.3_HDF "1C-21 input file" "2A-21 input file" "2A-23 input file" "2A-25 input file" "3a-26 output file" "3a-26 int file" '3a-26 verification file" "begin/middle/end granule of month: ch string" "year: ch string" "month: ch string"'

where, for example,

"1C-21 input file" = 1C21.970317.100.1.HDF

"2A-21 input file" = 2A21.970317.HDF

"2A-23 input file" = 2A23.970317.100.1.HDF

"2A-25 input file" = 2A25.970317.100.1.HDF

"3A-26 output file" = 3A26_970317_B.HDF (for first granule of month)
= 3A26_970317_E.HDF (for last granule of month)

"3a-26 int file" = 3A26_970317_INT (intermediate file)

"3a-26 VI file" = 3A26_970317_DIAG_B (verification or diagnostic file for 1st granule)

"begin/middle/end granule"
= character string equal to 'BEGIN' 'MIDDLE' or 'END'

"year" = character string - input as integer

"month" = character string - input as integer

3-2.3a. Input Data (Same as 3a-25)

Data are read from 1C-21, 2A-21, 2A-23, and 2A-25.

The data volumes per scan are approximately:

0.9	kbytes from 2a-21
0.4	kbytes from 2a-23
42.0	kbytes from 2a-25
17.0	kbytes from 1C-21
Total: 60	kbytes per scan

3-2.3b. Input Parameters (initialized in 3a-26)

```
data QUthres0th /0.1,0.2,0.3,0.5,0.75,0.9999/     ! Q-thresholds for Z-R and 2a-25 rain
```

```
rates
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/0.205, 0.27, 0.3646, 0.4863, 0.648, 0.865,         ! in mm/hr
                   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 log-normal 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; the upper rain rate threshold is calculated as that threshold beyond which the count value does not increase by at least 'nfu' counts, where:

nfu = 30

3-2.4a. Output Variables

a. arrays for the calculation of probabilities [int 4]

ttlCount(16,72) = # of observations at each 5 x 5 degree box over the month

rainCount(16,72,4) = # of rain observations at each 5 x 5 degree box over the month (rain present)

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

b. arrays for output of 'truncated' histograms at each 5 x 5 x 1 mo 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 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 arg: 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

c. {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

d. reliability factors:

reliabOrderFit(16,72,4,6)
reliabHBfit(16,72,4,6)
reliab2A25fit(16,72,4,6)

if the number of data points is too few or an error occurs in the fitting procedure, reliab* and *Fit are set to the following:

if # of rain occurrences, nrain, in the (lat, long) box are too few, then:
Fit and reliab are set to -999.

if warning error occurs in the fitting or if the fit is determined to be unstable, then:
Fit and realib are set to -888.

if number of rain rate thresholds over which the distribution increases is fewer than twice the # of unknowns then:
Fit and reliab are set to -777.

3-2.4b. Output Data Volume (per month)

Approximately 9.7 Mbytes

3-2. 5. Internal Storage Requirements

One intermediate files is needed to store the running statistics. The storage needed is somewhat larger than the output data volume: 11.1 Mbytes

3-2. 6. 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 resolution boxes to which the 49 IFOVs belong (coarse resolution boxes are 5 degree x 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 x 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, std deviation and probability of rain for each distribution.

vii. Re- initialize the intermediate file

3-2. 7. Comments and Issues

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. All the output products are over a 5 degree x 5 degree x 1 month space-time region. After each granule (orbit) 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 is used to output the desired 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 ln10 beta int(0,r) [alpha* Zm**beta] where

   Zm is the 'measured' or 'apparent' reflectivity factor
   k = alpha * Z ** beta, where
   - k = attenuation coefficient or specific attenuation (dB/km)
   - Z = actual reflectivity factor (mm 6/m 3) the coefficients alpha, and beta are read from the 2a-25 output

   Note that as Q = zeta increases toward unity the path-integrated-attenuation (pia)
   increases w/o bound if k-Z relationship is exact

6. For the thresholding method implemented in 3a-26, the quantity used as a threshold should be a monotonic function of the quantity that we wish to estimate (rain rate). For example, in the presence of attenuation, the apparent reflectivity factor at the surface Zm(surface), or the rain rate estimate based on Zm, is a double-valued function of the true rain rate; as such it is not an appropriate choice for this method. On the other hand, Q (or zeta) is a monotonic function of the path-integrated rain rate and is an valid threshold.

7. 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 for evaluation.

8. 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 by assuming that the rain rate distribution is log-normal, than to attempt to measure directly the distribution at these extremes. Reasons for the poor performance of the radar at high and low rain rates are:

   i. low SNR at low rain rates
   ii. low SNR at high rain rates and deeper storm penetrations due to signal attenuation
   iii. higher variability in Z-R laws at low rain rates
   iv. errors in the attenuation correction

9. 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)

10. Presently, 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)

11. if the number of samples of the histogram is small, then the estimated pDf is unreliable. To circumvent this problem, the total number of rain measurements over the space-time region (5 x5 degree x 1 month) must be larger than some fixed number, iqqmin, which presently is set at 200.

12. It is assumed in the program that the verification file does not exist; if it already exists an error will occur.

13. 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.

14. Presently, the height levels are being defined relative to the ellipsoid and not the local surface.

15. 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, intersects the height of interest.

16. 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:

    $R = a \quad Z(est) \quad b$

    where a and b are obtained from 2a-25.

    The HB or Hitschfeld-Bordan solution to the reflectivity factor, Z, is obtained by using an 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.

3-2. 8. References

[1] Meneghini, R., 1998, J. Appl. Meteor., 37, 924-938.
[2] Meneghini, R., and J. Jones, 1993, J. Appl. Meteor., 32, 386-398.

[3] Short, D.A., K. Shimizu, B. Kedem, 1993, J. Appl. Meteor., 32, 182-192.
[4] Kedem, B., L.S. Chiu, G.R. North, 1990, J. Geophys. Res., 96, 1965-1972.
[5] Atlas, D., D. Rosenfeld, D.A. Short, 1990, J. Geophys. Res., 95, 2153-2160.

PR Team Members

PR Team Leader:

Ken'ichi Okamoto

Communications Research Laboratory
4-2-1, Nukui-kitamachi, Koganei-shi, Tokyo, 184, Japan
Phone: +81-423-27-7554 Fax: +81-423-27-6687
e-mail: okamoto@crl.go.jp

1B21, 1C21 Algorithm Developers:

Hiroshi Kuroiwa

Earth Observation System Engineering Department
National Space Development Agency of Japan
World Trade Center Bldg., 2-4-1,
Hamamatsu-cho, Minato-ku, Tokyo 105-8060, Japan
Phone: +81-3-3438-6352 Fax: +81-3-5401-8702
e-mail: Kuroiwa.Hiroshi@nasda.go.jp

Hiroshi Kumagai

Communications Research Laboratory
4-2-1 Nukui-kita Koganei, Tokyo 184-8795 Japan
Phone: +81-42-327-7457 Fax: +81-42-327-7586
e-mail: kumagai@crl.go.jp

Toshiaki Kozu

Communications Research Laboratory
4-2-1 Nukui-kita Koganei, Tokyo 184-8795 Japan
Phone: +81-42-327-7543 Fax: +81-42-327-6666
e-mail: kozu@crl.go.jp

Jun Awaka

Hokkaido Tokai University
Minami-ku, Minami-sawa, 5-1-1, Sapporo 005-8601, Japan
Phone: +81-11-571-5111 Fax: +81-11-571-7879
e-mail: awaka@de.htokai.ac.jp

2A21, 3A25, 3A26 Algorithm Developer:

Robert Meneghini

NASA Goddard Space Flight Center
Code 975, Greenbelt, Maryland 20771, USA
Phone: +1-301-286-9128 Fax: +1-301-286-0294
e-mail: bob@meneg.gsfc.nasa.gov

2A23 Algorithm Developer:

Jun Awaka
Hokkaido Tokai University
Minami-ku, Minami-sawa, 5-1-1, Sapporo 005-8601, Japan
Phone: +81-11-571-5111   Fax: +81-11-571-7879
e-mail: awaka@de.htokai.ac.jp

2A25 Algorithm Developer:

Toshio Iguchi
Kashima Space Research Center
Communications Research Laboratory
Hirai 893-1, Kashima, Ibaraki 314-0012, Japan
Phone: +81-299-84-7117   Fax: +81-299-84-7157
e-mail: iguchi@crl.go.jp