Algorithm Theoretical Basis Document (ATBD)
Version 01-02

NASA Global Precipitation Measurement (GPM) Precipitation Retrieval and Profiling Scheme (PRPS)

Prepared for:

Global Precipitation Measurement (GPM)
National Aeronautics and Space Administration (NASA)

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1. INTRODUCTION

1.1 Objective

This document describes the algorithm and processing sequence for the Precipitation Retrieval and Profiling Scheme (PRPS) for the Global Precipitation Measurement (GPM) mission's constellation, specifically for the version, the SAPHIR instrument. This technique is intended to exploit the capabilities of the passive microwave sounding instruments of the GPM constellation, in particular, to provide better temporal and spatial sampling than would be possible with just the passive microwave imaging sensors alone. The technique described here is the initial version of the scheme and will therefore have a number of known and unknown issues present in the resulting product. Where possible these are addressed and notes taken on improvements for future releases.

1.2 Revision History

Version	*Date*	*Author*	*Description*
1.0	29 January 2018	Chris Kidd	Initial version of ATBD

2. OBSERVING SYSTEM

2.1 Role of Passive Microwave Sounding Instruments

The retrieval of precipitation from satellite-based sensors relies primarily upon visible, infrared, passive and active microwave instrumentation. While the active microwave instruments undoubtedly provide the most direct measure of satellite-based precipitation, current observations are confined to the GPM DPR and CloudSat CPR, and thus are very much limited in time and space. Visible and infrared techniques are capable of providing relatively fine scale temporal and spatial estimates of precipitation from geostationary and low Earth orbiting (LEO) platforms, but such estimates are indirect since they rely upon cloud-top to surface precipitation relationships. Passive microwave (PMW) estimates fall between these two extremes: hydrometeors providing the main source of atmospheric attenuation. However, since the PMW sensors occupy only LEOs, multiple sensors are required to provide good temporal and spatial coverage.

While much work has been done on the extraction of precipitation information from passive microwave imagers (aka conical scanning), less work has been concentrated upon retrievals from sounding (aka. cross-track) instruments. However, work on the latter is critical for a) providing additional observations to meet the necessary sampling requirements for precipitation, and b) for longer-term studies, particularly since the future of passive microwave radiometry rests largely upon sounding instruments.

This document refers specifically to the retrieval scheme for the SAPHIR instrument onboard the French-Indian Megha-Tropiques satellite; pertinent information to this satellite and sensor is described below.

Table 1: Recent and present microwave sensors contributing to the GPM constellation.

Satellite	Sensor	Channels	Retrieval resolution
Active microwave instruments			
GPM	DPR	13.6/35.5 GHz	5.4 x 5.4 km
TRMM	PR	13.6 GHz	4.3 x 4.3 km
Cloudsat	CPR	94 GHz	1.4x1.4 km
Passive microwave imagers			
GPM	GMI	10.7-183.31 GHz	10.9 x 18.1 km*
DMSP-F16 DMSP-F17 DMSP-F18 DMSP-F19	SSMIS	19.35-183.31 GHz	45 x 74 km*
GCOM-W1	AMSR2	6.7-89.0 GHz	14 x 22 km*
TRMM	TMI	10.7-89.0 GHz	20.9 x 34.6 km*
Passive microwave sounders			
NOAA-18 NOAA-19 METOPA METOPB	MHS	89.0- 183.31 GHz	17.12 x 21.64 km*
NPP	ATMS	23.0-183.31 GHz	16.51 x 16.22 km*
MeghaTropiques	SAPHIR	183.31 GHz (x6)	7.34 x 7.27 km*
MeghaTropiques	*SAPHIR*		*5.4 x 5.4 km#*

* relate to current GPROF retrieval resolutions (at nadir for sounders)
# resolution of the PRPS retrieval scheme

2.2 The Megha-Tropiques mission

The Megha-Tropiques mission occupies a low-inclination Earth orbit, designed to maximize the temporal sampling of the Tropics. The mission operates at an altitude of between 850 and 868 km with a ground track between about 20°N and 20°S, as shown in Figure 1 below. The instrument provides data over a 1700 km swath (Figure 2 illustrates the viewing geometry) and thus observes a region on the Earth's surface between 28°N and 28°S. The mission provides a total of just over 14 orbits each day, resulting in up to 5 independent overpasses per day.

The satellite carries a suite of instruments to provide observations relevant to the Earth's water and energy cycle. These instruments are the Microwave Analysis and Detection of Rain and Atmospheric Structures (MADRAS), the Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie (SAPHIR) and the Scanner for Radiation Budget (ScaRaB). The Megha-Tropiques mission contributes to the international constellation element of the NASA/JAXA Global Precipitation Measurement (GPM) mission, enhancing the sampling of precipitation over the lower latitudes.

Although the MADRAS instrument was to be implemented at the main instrument for precipitation studies only a limited amount of usable data has been obtained from the sensor.

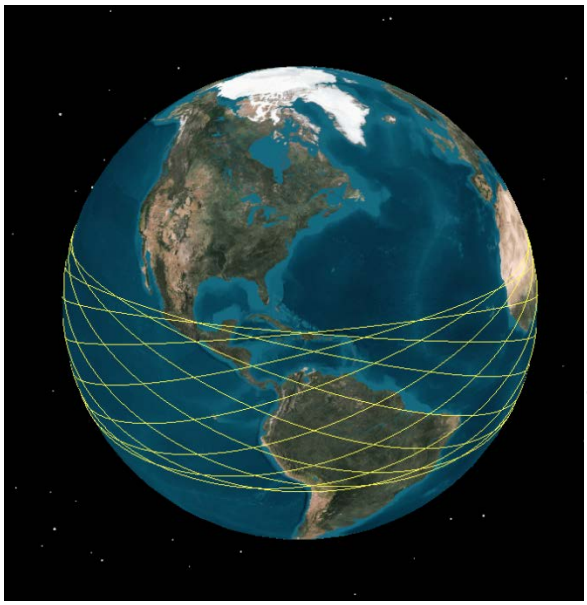


Figure 1: Ground track (nadir) for the Megha-Tropiques satellite for 1 day (12:00:00 UTC 2 November 2017 to 12:00:00 UTC 3 November 2017).

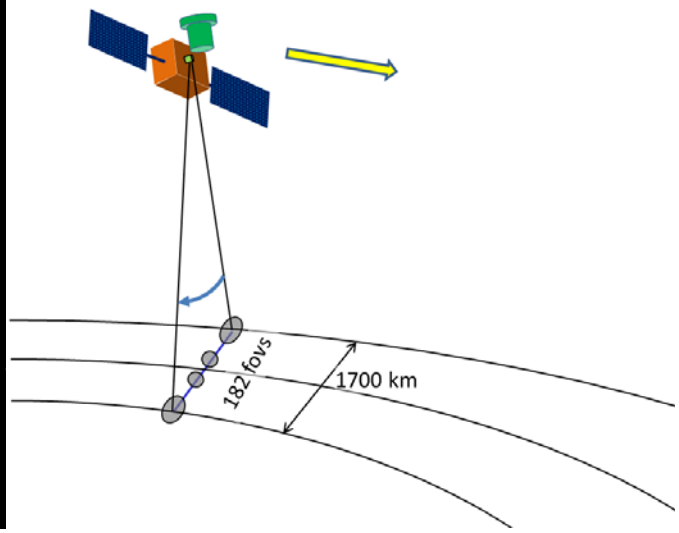


Figure 2: Schematic of the scanning characteristics of the SAPHIR instrument on the Megha-Tropiques satellite.

2.3 The SAPHIR instrument

Comprehensive information about the SAPHIR instrument can be found in the Megha-Tropiques L1 Products Handbook available at:

http://www.icare.univ-lille1.fr/projects_data/mt/docs/megha-tropiques_handbook_final_09_2015.pdf

This document provides comprehensive details of the instrument; below is a summary of the sensor relevant to the retrieval scheme.

As noted above, the SAPHIR instrument provides observations across a 1700 km swath. It should be noted that although the instrument is designed to provide a symmetrical scan pattern, i.e. equal number of fovs each side of nadir, the sensor is slightly offset and therefore produces an asymmetrical swath. Each scan line provides 182 scan positions; being a cross-track sensor these produce the finest resolution at nadir, becoming coarser towards the edge of scan. (However, it should be noted that the resolution even at the edge of scan is better than many conically-scanning radiometers).

The SAPHIR observes the Earth and atmosphere around the 183.31 GHz water vapour channel. Table 2 below shows the channel characteristics; all channels are the same spatial resolution for each scan position. The finer (smaller) deviations (±0.2 GHz) from the central frequency are more attuned to the water vapour channel and therefore are essentially atmosphere-only channels, whereas the larger deviations (±11.0 GHz) are more responsive to the lower levels of the atmosphere, and potentially the surface where little water vapour intervenes.

Table 2: Channel frequencies for the SAPHIR sensor.

Channels	Central nominal frequencies (GHz)	Channels bandwidth
C1	183.31 ± 0.2	200 MHz
C2	183.31 ± 1.1	350 MHz
C3	183.31 ± 2.8	500 MHz
C4	183.31 ± 4.2	700 MHz
C5	183.31 ± 6.8	1200 MHz
C6	183.31 ± 11	2000 MHz

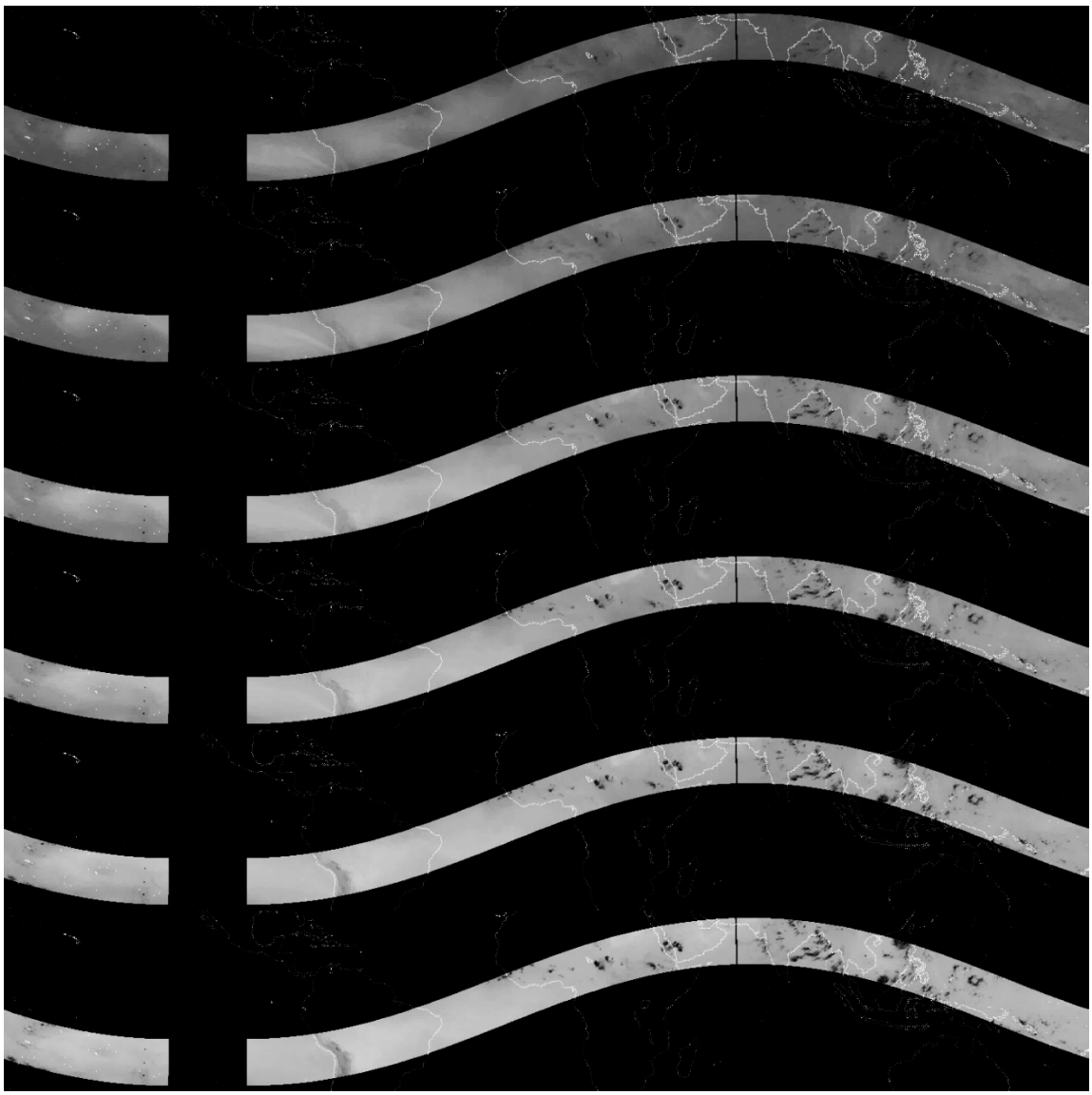


Figure 3: Mapped brightness temperatures for SAPHIR channels 1-6 (top-bottom). Channel 1 represents the most restricted bandwidth and therefore is most sensitive to the upper level moisture, while channel 6 is the least restrictive and under dry conditions over regions of high altitude can see the Earth's surface (e.g. over the Andes in South America).

2.4 Algorithm considerations

The most important consideration for the retrieval of precipitation from the SAPHIR sounding channels is that the relationship between the observed Tcs and surface precipitation is not necessarily direct. This is due to the fact that the 183.31 GHz channels relate to water vapour, not precipitation, and that with high levels of water vapour the channel information relates to the upper levels of the atmosphere, rather than near the surface. Since the 183.31 GHz channels relate to emissions from water vapour in the atmospheric column, decreases in the Tcs usually is indicative of greater concentrations of water vapour, causing the sensitivity to 'peak' higher in the atmosphere, hence lower temperatures. However, the 183.31 GHz is also sensitive to the scattering of upwelling radiation by ice particles in clouds and by precipitation, the latter of which is exploited here to identify precipitation. Nevertheless, it should be noted that the amount of scattering by ice is not necessarily directly related to surface precipitation, and high amounts of water vapour in the atmospheric column above clouds or precipitation layer may negate any depression in the Tcs.

3. ALGORITHM DESCRIPTION

The Precipitation Retrieval and Profiling Scheme (PRPS) described here is designed to provide a best-estimate of precipitation based upon matched SAPHIR-DPR observations. This fulfils in part the essence of GPM (and its predecessor, TRMM) in which the core observatory acts as a calibrator of precipitation retrievals for the international constellation of passive microwave instruments. In doing so the retrievals from the partner constellation sensors are able to provide greater temporal sampling and great spatial coverage than is possible from the DPR instrument alone. However, the limitations of the DPR instrument are transferred through the retrieval scheme to the resulting precipitation products.

3.1. Algorithm Overview

Fundamental to the design of the PRPS is the independence from any dynamic ancillary data sets: the retrieval is based solely upon the satellite radiances, a static *a priori* radiance-rainrate database (and index), and (static) topographical data. Critically, the technique is independent of any model information, unlike the retrievals generated through the Goddard PROFiling (GPROF) scheme: this independence is advantageous when generating products across time scales from near real-time (inaccessibility to model data) to climatological scales (circumventing trends in model data).

The algorithm is designed to generate instantaneous estimates of precipitation at a constant resolution (regardless of scan position), for all scan positions and scan lines. In addition to the actual precipitation estimate, an assessment of the error is made, and a measure of the 'fit' of the observations to the database provided. A quality flag is also provided, with any bad data generating a 'missing flag' in the retrieval.

3.2 Input Data

Five input data sets are required:
i) *a priori* database of DPR(rainrate)-SAPHIR(Tc radiances);

ii) *a priori* database index;
iii) *a priori* topography data;
iv) *a priori* scan-position correction database, and;
v) Level 1C SAPHIR data.

3.2.1 DPR-SAPHIR database

The DPR-SAPHIR database is the key element of the PRPS, linking the observed radiances of the SAPHIR instrument with the precipitation measured by the DPR. The currently available database is derived from 3.5 years of DPR-SAPHIR data (March 2014-September 2017) and is deemed (assumed) to be representative of all the precipitation systems that SAPHIR will encounter; future versions will incorporate updated databases as more data becomes available.

Processing to find the entries for the database is as follows:

- Initial orbital analysis of the (GPM-CO) DPR and (Megha-Tropiques) SAPHIR on to establish latitude/longitudes of cross-over locations to within ±5 minutes (note that actual scan geolocations are used, rather than sub-satellite positions) ;

- the above cross-over information is then used to map both DPR near surface rain rates and SAPHIR Tcs to a 5 km equal-area grid. GMI Tcs and ancillary data from L2A products (where available) are also included for further analysis;

- coincident SAPHIR and DPR fovs, together with interpolated GMI fields (for information only) are extracted and saved to intermediate files for each cross-over match, together with additional information from L2A files including T2m, TPW, surface type;

- final database entries are extracted from above files, to include SAPHIR Tcs, GPROF rainrate (for reference only), DPR near surface rain rate, surface type (for reference only) and SAPHIR scan position: the database is stored as a simple ascii text file with one line per matched entry.

The distribution of the locations of the DPR-SAPHIR cross-overs are shown in Figure 4. Since only the cross-over locations are plotted for the nadir scan positions of both the DPR and SAPHIR, the latitudinal extent is limited to ±20°N/S, however, the actual latitude range of the database points extend to the full swath coverage of the SAPHIR instrument. Table 3 summaries the properties of the information for the database: over the 3.5 year period a total of 2439 cross-overs were observed (with the ±5 minute window), resulting in 1,209,168 matches where DPR, SAPHIR and GMI fovs were matched (without interpolation), and 10,365,732 where only the DPR and SAPHIR were matched (the GMI fovs were interpolated). The latter matches form the basis of the entries of the database used in the PRPS.

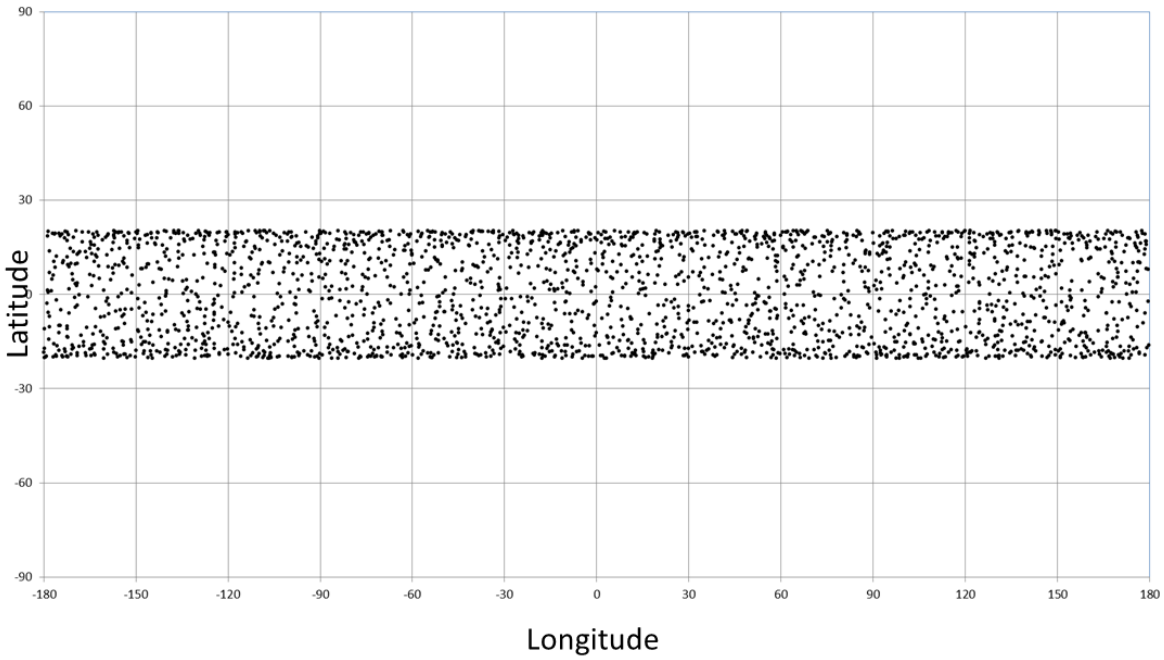


Figure 4: SAPHIR-GPM coincident nadir orbital crossings (<5 minutes, < 2.5 km) From March 2014 through September 2017.

Table 3: Entries in DPR-SAPHIR database based upon 2439 independent cases (locations shown in Figure 4), with a total of 1,209,168 fovs where DPR, GMI and SAPHIR match, and 10,365,732 where DPR, GMI (interpolated) and SAPHIR match; the latter is used for the DPR-SAPHIR database.

	#cases	**non-int**	**GMI-int**
DPR-SAPHIR	2439	1209168	10365732

3.2.2 Database Index

To expedite the retrieval process, the DPR-SAPHIR database is indexed. Although the GPROF technique uses a TPW/T2m defined scheme, the PRPS described here does away with the requirement for external model information, replying instead upon the sensed Tcs. Land and sea areas are treated separately (although using the same database); early studies showed that the Tc:rainrate relationships were quiet different over land and ocean regions.

The channels on SAPHIR are all centred on 183±31 GHz and are therefore highly correlated, resulting in much redundant information. As an alternative to the GPROF TPW/T2m separation, the PRPS database index is based upon the two SAPHIR channels showing the greatest variance with each other; namely channels 1 and 6. The index describes the start and end point of the entries in the database array, together with the number of entries per bin. Accessing the correct entries in the database is therefore merely looking up the starting entry (istart(Tc1, Tc6)) and ending entry (iend(Tc1,Tc6)).

3.2.3 Topographic Data

The sounding channels utilised by the SAPHIR instrument attenuate primarily within the atmosphere and are therefore essentially surface-blind. However, in regions where there are only minimal amounts of water vapour in the observed atmospheric column, the surface is visible. For the orbital bounds of the SAPHIR observations, this is primarily constrained to the Andes in South America, and to a lesser (widespread) extent over the Himalayas. Over these regions, for this version (V01) of the PRPS, retrieval of precipitation is ill-advised. Consequently topographic data is used, with a threshold of 2000 m to flag observations where topography stops viable estimates. The topographic data currently is based upon the NOAA 30 arcsec GLOBE elevation data (https://www.ngdc.noaa.gov/mgg/topo/globeget.html), which is resampled to 0.05 degrees for the purpose of this retrieval scheme.

3.2.4 Scan-position correction database

One of the main challenges of utilising cross-track sounding instruments is the changing scan geometry resulting in a varying Earth Incidence Angle, atmospheric path and resolution. While it is possible to model the effects of the scan geometry, the correction of these issues is often difficult to fully resolve. The strategy adopted here is to correct all the retrievals to those at the centre of scan through probability distribution function (PDF) matching of the rain intensities. The main benefit of this approach is that the correction is done through a lookup table which is computationally efficient, while ensuring consistency across all scan positions.

The scan-correction look-up-table is based upon an initial set of retrievals for the first 3.5 years of the GPM-era SAPHIR observations, from March 2014-September 2017. Histograms were generated based upon the scan position (1-182) and for rain intensities from 0.00-200.00 mmh^{-1} in 0.01 mmh^{-1} steps. To ensure consistency, only SAPHIR retrievals between 20°N and 20°S were used in order that precipitation systems were observed at both nadir and edge-of-scan. The PDF of each scan position is then matched against that of scan position 92 and 93, to provide a link between the input rainrate and the scan-corrected rainrate.

Figure 5 illustrates the scheme with examples for scan positions 21 and 31. Essentially the procedure lowers the rainrates at the extremes of scan by about 15-20%. Note that although the centre of scan for SAPHIR is at scan position 91, the plotted values shown a certain degree of asymmetry; for example, 10.0 mmh^{-1} at scan position 61 and 122 maps into 9.82 mmh^{-1} and 9.91 mmh^{-1} respectively, while at scan positions 31 and 152 10.0 mmh^{-1} maps onto 9.20 mmh^{-1} and 9.41 mmh^{-1} respectively.

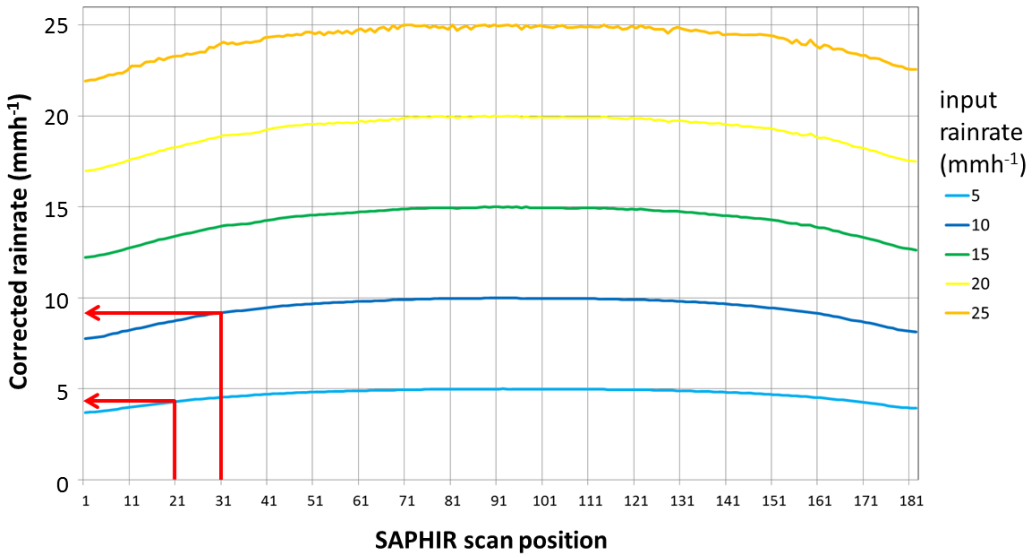


Figure 5: Schematic of the scan-correction scheme showing the mapping for selected input rainrates. For example, at scan position 21 an input rainrate of 5 mmh^{-1} will be mapped onto a retrieval rainrate of about 4.3 mmh^{-1}. Similarly, at scan position 31 an input rainrate of 10 mmh^{-1} is mapped into about 9.1 mmh^{-1}.

3.2.5 Level 1C SAPHIR data

The key input data from the L1C SAPHIR data files are the data and time for each scan line and the latitude, longitude and Tcs for each fov. Although the nominal SAPHIR orbit produces around 3780 scan lines, data ingested in near real time by the PPS may contain up to 9000 scan lines; each scan line has 182 scan positions. The data, time and geolocation (lat/lon) data from the L1C files is passed directly to the L2A output without modification, while the geolocation and Tc data are used in the generation of the retrieval.

3.3 Processing Outline

The processing stages are relatively straightforward and follow a sequential order of quality check, precipitation retrieval, error estimation and the generation of the 'fit' of the retrieval.

3.3.1 Quality check

The quality check array is initially set to 'missing' to account for the variable number of scan lines per file. If a scan/position exists, by default it is assumed that the retrieval is potentially good, and the quality flag is set to 0 (zero).

A test is then undertaken to ascertain the validity of the input L1C Tcs. This checks that the Tcs for each channel lie between 50 and 350 K; if one or more lies outside this range the retrieval is set to missing, and the quality flag is incremented by 1. The altitude is then checked. Regions over 2000 m are flagged as

'no-retrieval' and the retrieval is assigned a missing value, and the quality flag is incremented by 2. Consequently, a value of 0 indicates that a valid retrieval has taken place, 1 signifies bad input Tcs, 2 high surface topography (altitude) and 3 bad Tcs and altitude.

3.3.2 Precipitation retrieval: database match

The database index file is initially interrogated to establish the search radius required for the database matching: this ensures that the minimum number of MHS:DPR entries can be used for the retrieval. The Tcs of channels 1 and 6 are used to extract the starting and ending location of the relevant database entries from the database index, the database index being a simple 2D array. If the number of entries for a particular entry in the database index is greater than 12, only those in that index are used, otherwise the above predefined radius is used to search the area around that index to ensure sufficient comparisons. Each database entry within the specified range is compared against the L1C observed Tcs, and the Euclidian distance calculated in database space. Each entry is ranked (1-6, based upon this distance) alongside the associated DPR rain rate (from the database). When the database search has finished, the 6 DPR rain rates are then processed to correct for the scan-position (see below). The retrieval rain rate is then calculated from the mean (scan-position corrected) DPR rain rate; if 5 out of the 6 entries have zero precipitation the resulting retrieval is set to zero.

3.3.3 Error estimate

In addition to the rain rate being generated from the mean of the 6 selected entries, the RMSE of these 6 rain rates is used to generate an 'error' estimate. Thus, if all 6 of the entries are similar a low error estimate is generated, while if the entries are disparate, a large error estimate is generated.

3.3.4 Fit of retrieval

A measure of the fit of the retrieval is also provided which is the RMSE of the (observed Tcs – database Tcs): this provides a measure of confidence in the representativeness of the retrieval.

3.4 Output data

The PPS provides a complete description of PRPS file layout and explanation of files parameters. This can found on the PPS home page, pps.gsfc.nasa.gov, together with the GPM file specifications at ftp://gpmweb2.pps.eosdis.nasa.gov/pub/GPMfilespec/filespec.GPM.pdf.

An example of a PRPS product file is shown below. The naming convention of the files is:

level.satellite.instrument.algorithm-version.date.start-time.end-time.orbit.processing-version.filetype

Note each entry is delimited by a full-stop/period. Below is a dump of the file parameters using the h5dump –n command:

```
h5dump -n 2A.MT1.SAPHIR.PRPS2017v1-02.20111125-S184222-E202417.000631.V05A.HDF5
```

```
HDF5 "2A.MT1.SAPHIR.PRPS2017v1-02.20111125-S184222-E202417.000631.V05A.HDF5"
{
FILE_CONTENTS {
 group      /
 group      /S1
 dataset    /S1/Latitude
 dataset    /S1/Longitude
 group      /S1/ScanTime
 dataset    /S1/ScanTime/DayOfMonth
 dataset    /S1/ScanTime/DayOfYear
 dataset    /S1/ScanTime/Hour
 dataset    /S1/ScanTime/MilliSecond
 dataset    /S1/ScanTime/Minute
 dataset    /S1/ScanTime/Month
 dataset    /S1/ScanTime/Second
 dataset    /S1/ScanTime/SecondOfDay
 dataset    /S1/ScanTime/Year
 dataset    /S1/error
 dataset    /S1/fit
 dataset    /S1/qualityFlag
 dataset    /S1/surfacePrecipitation
 }
}
```

The data is arranged by scan line, each scan line containing the date and time, followed by each parameter for the whole scan line (182 values).

3.5 Transition to Level 3 product

The L2A products are accumulated into monthly 1x1 degree L3 products. The L3 data parameters are:
data quality: percent of good quality (L2A qualityFlag=0) pixels. A value of 100 means all data is good.

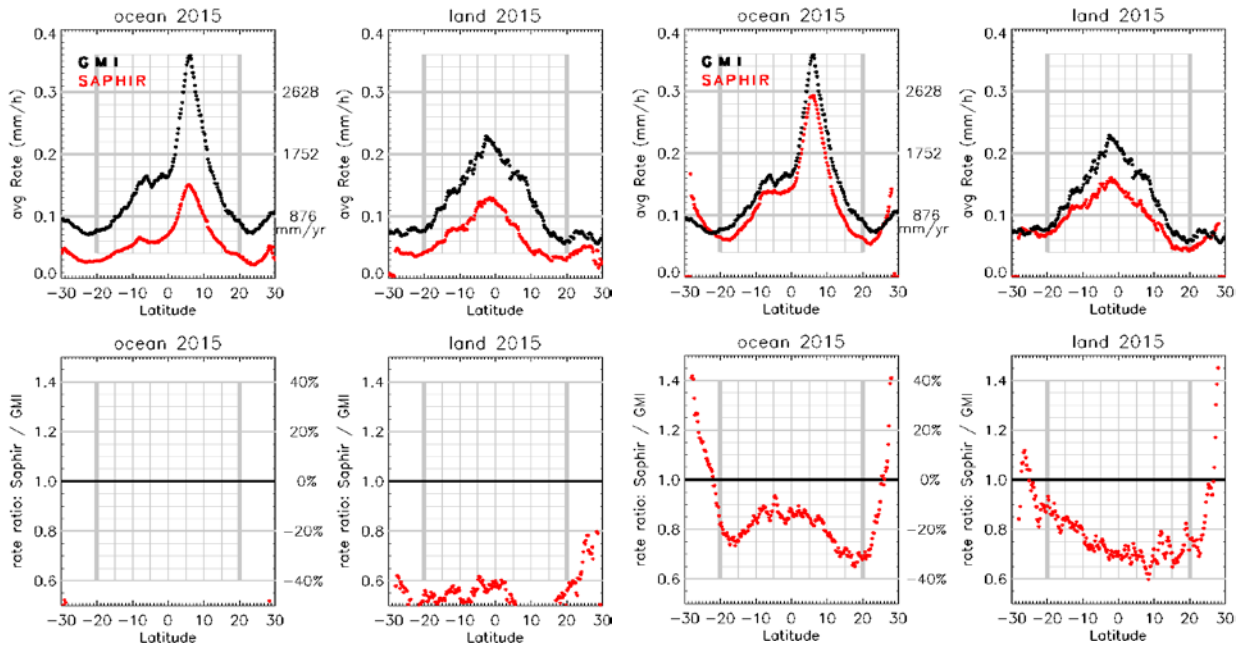
- error: RMS of the L2A error values
- fit: RMS of the L2A fit values
- npixPrecipitation: number of pixels with surfacePrecipitation > 0
- npixTotal: total number of pixels with valid surfacePrecipitation (surfacePrecipitation >=0)
- surfacePrecipitation: mean of surfacePrecipitation

4. TESTING

A number of rudimentary tests have been carried out to check that the PRPS precipitation products are reasonable and in line with expectations.

Figure 6 below shows the mean annual latitudinal precipitation rates for both the current GPROF V3 SAPHIR retrieval, and that of the PRPS precipitation product, together with the GMI product for comparison. It can be seen that the PRPS product is much better than the GPROF product across all latitudes, although the PRPS does underestimate the precipitation by about 20%: this is a consequence of the averaging of the six closest precipitation profiles in the retrieval scheme. It can also be seen that outside the 20°N-20°S region, the extent of the nadir coverage, the PRPS starts to overestimate the precipitation, particularly at the extremes around 28°N and 28°S. This may be in part due to the extremes

of swath (and therefore resolution/atmospheric path issues), and number of samples, which reduces substantially towards the SAPHIR's northernmost/southernmost latitudes.



GPROF V03

PRPS v01-02

Figure 6a: GPROF V3 SAPHIR retrievals for ocean and land, annual total for 2015. (Source: Owen Kelley)

Figure 6b: PRPS v01-02 SAPHIR retrievals for ocean and land, annual total for 2015. (Source: Owen Kelley)

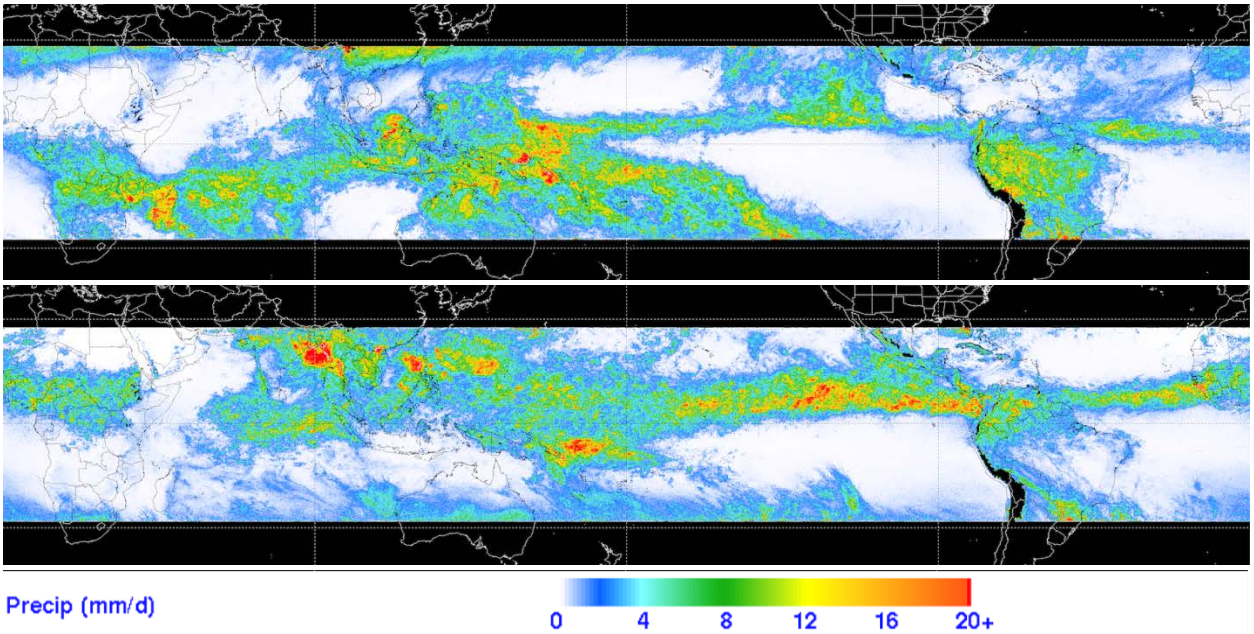


Figure 7: Monthly mean daily precipitation totals generated from the PRPS SAPHIR data product. The top image is for January 2015, while the bottom is for July 2015. (Source: Eric Nelkin)

The effect mentioned above is apparent in the images in Figure 7: there is an increase in precipitation near the 28°N and 28°S latitudes. Although this is somewhat subtle over most longitudes there is a region of high precipitation around 100-120°E (southern China). This artefact will be subject to an ongoing investigation.

5. PRACTICAL CONSIDERATION

The current version of the PRPS scheme is at the first initial version, consequently there will be issues that arise with the accuracy of the final product. Users are encouraged to contact the providers to help refine and improve the products in later versions.

6. ASSUMPTIONS AND LIMITATIONS

The PRPS technique, like any other technique, is based upon a number of assumptions leading to limitations in the final product; these include:

- the rain rates are based upon the DPR retrievals, and therefore the PRPS product is intrinsically linked to the accuracy of the DPR;

- all scan positions are assigned the same resolution: a correction is applied to the rain rates for each scan position which mitigates this to a certain extent;

- the technique is surface-blind, which is usually the case, but under dry atmospheric conditions the surface may be observable particularly over high ground.

7. REFERENCES

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8 ACRONYMS

CPR	Cloud Profiling Radar
DMSP	Defense Meteorological Satellite Program
DPR	Dual frequency Precipitation Radar
FOV	Field of View

GCOM-W1	Global Change Observation Mission – Water 1
GMI	GPM Microwave Imager
GPM	Global Precipitation Measurement (mission)
GPROF	Goddard PROFiling scheme
JAXA	Japan Aerospace Exploration Agency
L1C	Level 1C (data)
LEO	low Earth orbit
MADRAS	Microwave Analysis and Detection of Rain and Atmospheric Structures
MetOp	Meteorological Operational satellite programme
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
PRPS	Precipitation Retrieval and Profiling Scheme
SAPHIR	Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie
ScaRaB	Scanner for Radiation Budget
Tc	calibrated brightness temperature
TRMM	Tropical Rainfall Measurement Mission