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On the Tropical Rainfall Measuring Mission (TRMM)

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With 9 Figures

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Summary

The importance of quantitative knowledge of tropical rainfall, its associated latent heating and variability is summarized in the context of climate change. Since the tropics are mainly covered with oceans, with some deserts and jungles, the monthly precipitation is not known within a factor of two. Hence the only way to measure it adequately for climate and general circulation models is from space. The paper describes the Tropical Rainfall Measuring Mission (TRMM). This joint Japan-U.S. cooperative Earth Probe satellite will be launched from Japan in 1997 for a three-year mission. The scientific basis of the instrument and orbit selection is explained. The precipitation instrument complement comprises the first rain radar to be flown in space (PR), and a multi-channel passive microwave sensor (TMI) improved relative to the SSM/I[1] by an additional channel at 10 GHz. The third rain instrument is a five-channel VIS/IR (VIRS) sensor. Progress in construction of instruments, observatory, data system, and the ground validation program is summarized. A report is also given concerning development of the algorithms by which rainfall and its associated latent heat release will be calculated from the several instruments, separately and in combination, and how the scientists will interact with the data system to obtain the 32 rain data products necessary to fulfill the science requirements.

1. TRMM Background, Motivation, and Goals

The atmosphere gets three-fourths of its heat energy from the release of latent heat by precipitation. Two thirds of global precipitation falls in the tropics and rain variability in low latitudes affects the weather around the world. Tropical rainfall and its variability also impact upon the structure of the upper ocean layer by the fresh water from rain and by the wind squalls produced by the large rain cloud systems.

Precipitation is the most difficult atmospheric variable to measure, mainly because of its concentration into a few cloud systems. Rainfall, therefore, shows huge fluctuations in space and time. Presently tropical rain is not known within a factor of two.

In addition to climate fluctuations, an important impact of rain and its variability is on the biosphere, including humans. The "average" rainfall is rarely observed. Instead, several seasons of drought and starvation are often followed by a year or two of torrential downpours and disastrous floods. Cloud and rain processes are now simulated fairly well on the scale of cloud ensembles (50–100 km). However, global models for prediction of weather and climate have much coarser resolution, therefore they must "parameterize" cloud processes. Most of these parameterizations are extremely crude.

In the tropics particularly, it is vitally important to have rain and its latent heating in the initialization of global weather and climate models as well as in their prediction stage. Presently there are large discrepancies among the results of the different models. All of these models do badly in predicting precipitation and soil moisture. The poor simulation of cloud properties

[1] SSM/I stands for Special Sensor Microwave Imager.

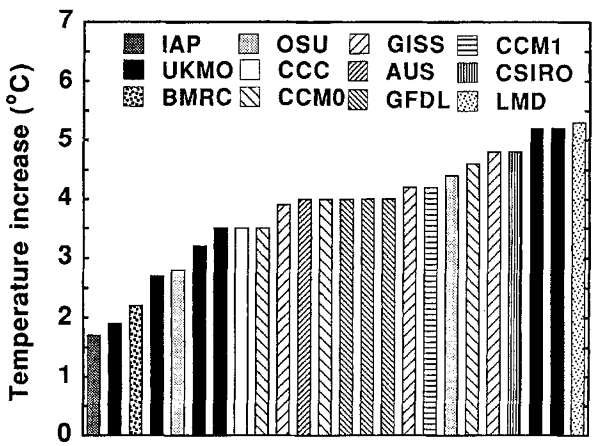


Fig. 1. Summary of the increase in global mean equilibrium surface temperature caused by a doubling of atmospheric CO_2 concentrations. These results are from simulations with atmospheric GCM's with a seasonal cycle, a mixed layer ocean and interactive clouds. Multiple simulations were performed for several models in the context of sensitivity studies related to specific processes. Changes in cloud parameterizations for the United Kingdom Meteorological Office (UKMO) produced the greatest difference (after Cess et al., 1990)

is one of the factors (which also include cloud optical properties) causing the models to differ so widely regarding the amount of global warming which would result from doubled carbon dioxide (greenhouse effect).

Figure 1 (after Cess et al., 1993) compares the predictions of global warming by twelve of the major models when the atmospheric carbon dioxide is doubled. The predicted global warming differs among the models by about three degrees Celsius. With fairly minor changes in parameterization of cloud properties in the UKMO model, the global warming is reduced from above 5 °C to about 2 °C. Clearly decision makers cannot determine what action, if any, to undertake in response to possible global warming, since at present the atmospheric models not only differ among themselves, but also are sensitive to variables for which few reliable measurements exist. The contrast between two different rain parameterizations in a regional model[2] under identical initial and boundary conditions is illustrated in Fig. 2 (Wang et al., 1994). In fact, scarcity of quantitative precipitation information has been a frustrating longtime bottleneck for atmospheric science. This gap in the centerpiece of the hydrologic cycle has had negative impacts on nearly all Earth sciences and their applications. Since the tropics are 75 per cent covered with ocean, precipitation over the global tropics can be measured satisfactorily only from space.

As early as 1981 (Atlas and Thiele, 1981), a group of scientists met at Goddard Space Flight Center, NASA, to discuss this challenge. The feasibility of satellite measurement of tropical rain was examined. Since the diurnal and semi-diurnal variability of tropical rain is large, the orbit of any proposed satellite should not be sun-synchronous. To cover the global tropics, an inclination of about 30 degrees was considered. To utilize the microwave part of the spectrum with both adequate resolution and modest antenna sizes, the spacecraft would need a low altitude orbit. A major question at that time was whether a low altitude (about 300 km), inclined orbit could adequately sample the rainfall.

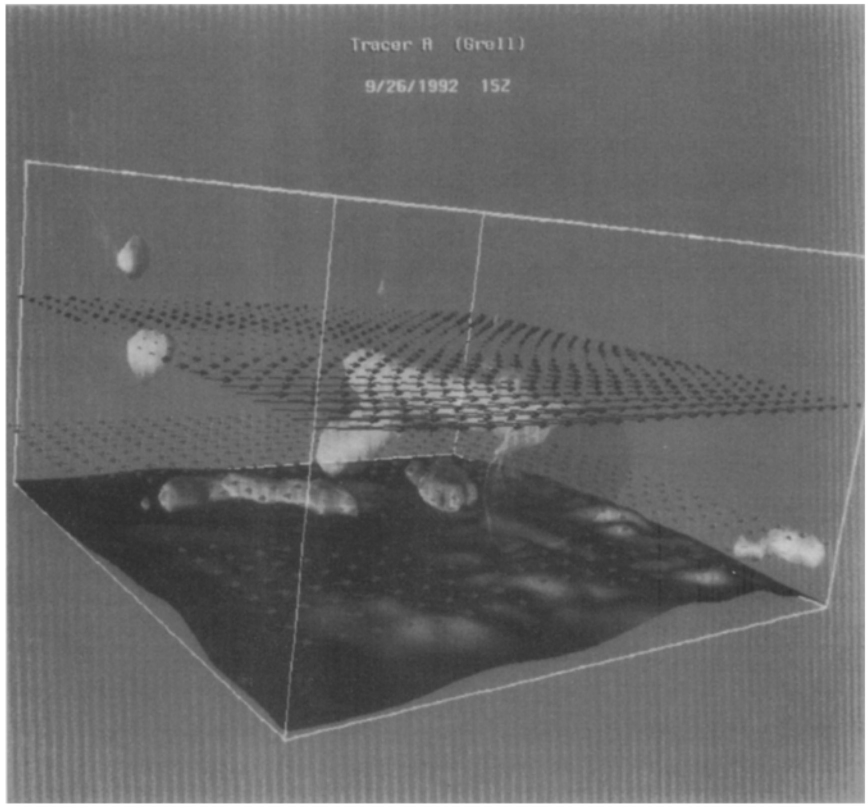
To address this sampling question, fortunately, the GATE[3] shipboard radars provided an excellent rain data set over a substantial area in the Inter Tropical Convergence Zone (ITCZ) off the west coast of Africa. A test orbit was selected to precess through the 24 hours in a month. Extrapolating the area of the GATE data up to boxes about 5° by 5°, studies showed that the sampling error for monthly rain over 5° by 5 boxes should be less than 10 per cent. The crucial feature of the GATE rain that allows the low sampling error is that it self-correlates adequately over 12 to 14 hours. North and colleagues (Shin and North, 1988; Bell et al., 1990) have shown similar autocorrelations in other parts of the ITCZ and in the SPCZ[4]. For whole seasons, their analyses show sampling errors of 10 per cent or less over all the tropical oceans. However, away from the tropical convergence zones and over one land mass (Florida), some evidence has been presented (Seed and Austin, 1990) that the autocorrelations are much lower, leading to sampling errors from the TRMM orbit as large as 20–25 per cent, which is not acceptable. As might have been expected,

[2] The Penn State/NCAR Mesoscale Model (MM5) is now in use at the NASA/Goddard Mesoscale Dynamics and Precipitation Branch.

[3] GATE stands for GARP Atlantic Tropical Experiment. GARP stands for Global Atmospheric Research Program.

[4] SPCZ stands for South Pacific Convergence Zone.

MESOSCALE
(30 KM GRID RESOLUTION)
SIMULATION OF AIR MOTIONS & CLOUDS
OVER PART OF SOUTH AMERICA
COMPARISON
OF TWO
"PARAMETERIZATIONS"
OF RAIN CLOUDS



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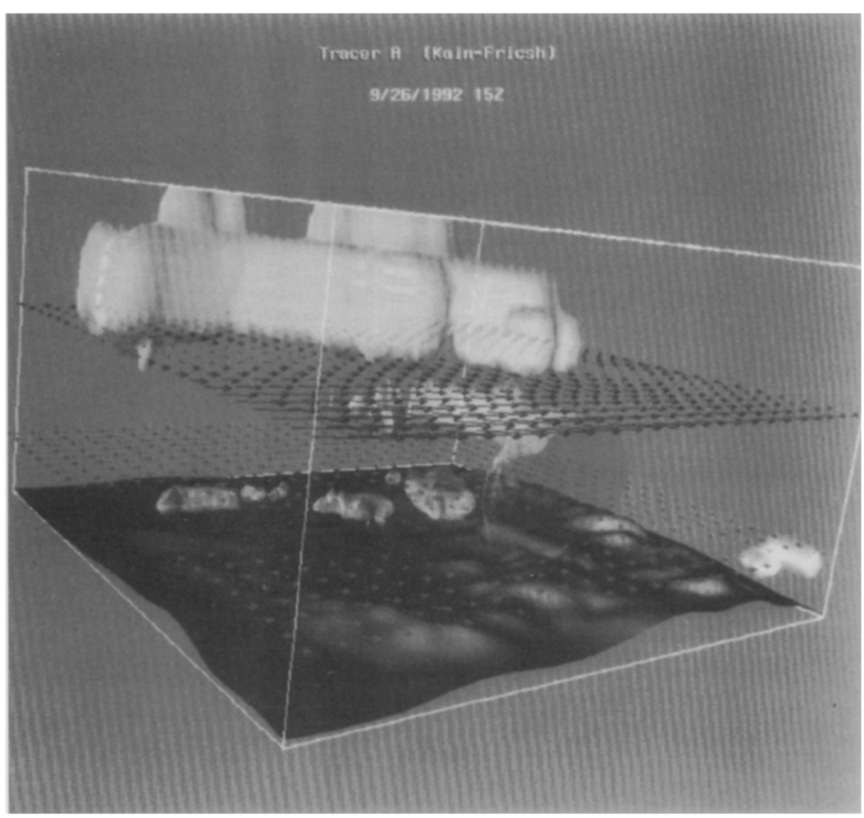

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Fig. 2. (a) Depiction of the 0.01 $g\,kg^{-1}$ mixing ratio of hydrometeor iso-surface for a South American mesoscale convective system simulated from the Penn State/NCAR MM5 model using Grell cumulus parameterization scheme. (b) Is the same as (a) except using Kain-Fritsch cumulus parameterization scheme. Also the wind vectors at 8 km and at 0.5 km were shown. (Note that $2190 \times 2190 \times 17\,km^3$, which is only part of model domain, is shown in this Figure)

the sampling errors for a region are inversely related to the amounts of rain. Thus there must be more sampling studies prior to TRMM launch and a careful sampling verification plan put in place for after launch. For accurate short-term rain products, TRMM data probably will have to be combined from products of other satellites in those parts of the tropics where "TRMM alone" data show that the error due to sampling significantly exceeds 10 per cent.

At about the same time that the sampling calculations for satellite rainfall looked encouraging, some scientists from the U.S. and Japan were advancing the hypothesis that rain measurement from space could be optimized by combining passive microwave with radar. Early in 1984, the NASA headquarters' atmospheric Program Manager held an informal competition for an inexpensive space mission that could answer focused science questions about the atmosphere and Earth environment. The winner, TRMM, was proposed by Goddard Scientists North, Wilheit and Thiele. In 1985, joint aircraft experiments with Japan showed a common interest in rain measurement from space.

The agreement reached with the Japanese was that Japan would build the precipitation radar and provide the launch services, while the U.S. would provide the spacecraft, passive microwave and VIS/IR sensors. The 20 person TRMM Science Steering Group (SSG), chaired by E. Rasmusson had several joint workshops in both countries, from which two books and numerous research papers were published (see TRMM bibliography by Greenstone, 1992). During the SSG deliberations, it was recognized that the vertical profiles of precipitation and related profiles of latent heat release were needed to understand the Madden-Julian waves in the tropics that modulate rain and also those waves which propagate from the tropics, affecting global weather features far away (teleconnections). It was further recognized that the profiles of precipitation-sized hydrometeors and of latent heating are not the same, and use of a cloud process simulation would be required to obtain the latent heating profile from the profile of the TRMM-measured rain-sized particles.

In 1988 the SSG report was issued: "TRMM: A Satellite Mission to Measure Rainfall" (Simpson, 1988a) and a shorter summarizing article was published by Simpson et al. (1988). The SSG report contains the science background, requirements and desirements[5], goals, and specific questions the mission is to address. It spelled out specifications of the rain instruments and suggested how they are envisaged to complement each other. Accuracy requirements and error analyses were included. This report contains the physics upon which the rain retrieval algorithms are based. Algorithms for the passive microwave sensor were farthest advanced in application. Numerous radar retrieval methods were outlined for different ranges of rain rate, including a class of algorithms that use the Area-Integral and probability matching concepts. A means for getting precipitation profiles over the oceans, using the passive microwave to constrain the radar equation was described. The use of TRMM with other satellite products to obtain rainfall was mentioned, but not outlined in detail.

The "Ground Truth" validation plan is a vital part of TRMM. The SSG report described how 10–12 surface radar sites would be selected and their use was outlined. The surface radar sites are maintained and operated by various National Weather Services and other Projects, which TRMM does not own, but has arranged to obtain the needed rain data. Since validation of rain measurements is difficult, it is clear that to obtain the best algorithms, the space data need to be validated in a series of steps, beginning about six months after launch, when the space and ground data will be compared and the algorithms improved or replaced thereby. For this improvement process to continue as the validation data set grows, the rain data require yearly reprocessing during the mission as the algorithms improve after comparison with the validation data. Finally the report offered a tentative design for the TRMM Information and Data System (TSDIS).

In late 1990, the pressure exerted by the science community led to a congressional initiative to budget for the TRMM new start in 1991. TRMM was designated as one of the first in NASA's Earth Probe Series, which is part of

[5] A requirement is regarded as essential to a successful mission; a desirement is something that the scientists would like to have to improve the products, if the available resources permit.

Table 1. *TRMM Sensor Summary–Rain Package*

Microwave radiometer (TMI)	Radar (PR)	Visible/Infrared radiometer (VIRS)
10, 19*, 21, 37, 85.5 GHz (dual polarized) *21 km resolution 760 km swath	14 GHz 4 km footprint 250 m range res 220 km swath	0.63 μm & 10 μm also 1.6, 3.75 & 12 μm @ 2.2 km resolution 720 km swath

Additional (eos) instruments: one ceres (cloud & earth radiant system) & one lis (lightning imaging sensor)

Orbit
35° inclination
350 km altitude
(High resolution, rapid precession)

Extensive validation by 10–12 surface radar sites required

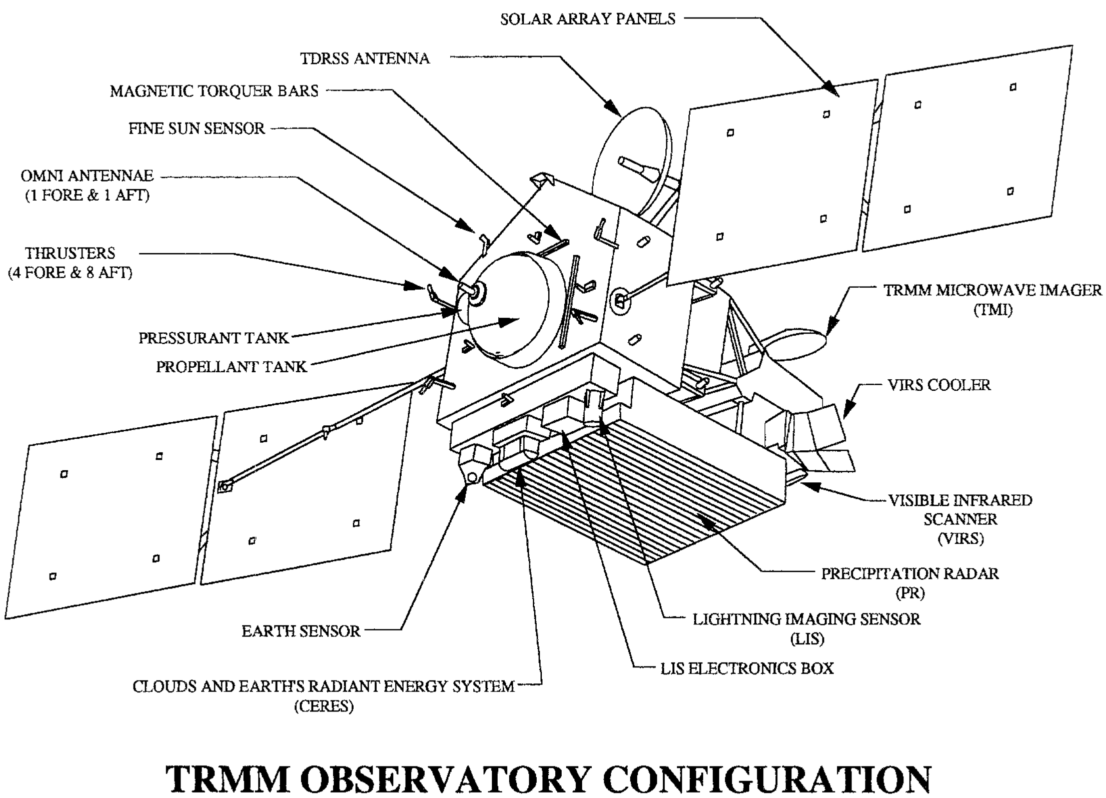

Fig. 3. Diagram of the TRMM spacecraft with all its sensors. In flight it will be blanketed so that there will be openings only for the sensors and antennas

Mission to Planet Earth. In 1991, the TRMM Project got staffed and organized, Goddard in-house design for the spacecraft got underway and the first Science Team of 31 scientists was selected from over 100 proposals submitted in response to a NASA Research Announcement.

2. Selection of the Final Instrument Complement

Between 1991 and 1994, the instrument complement evolved in several important ways. Table 1 shows the final instrument complement. Figure 3 is a sketch of the instruments mounted on the spacecraft. In flight, the observatory will be blanketed except for the openings for the sensors.

Important changes in the TRMM Microwave Instrument (TMI are: 1) the addition of the 10 GHz channel, which has much more nearly linear relationship between brightness temperature T_B and rain rate and 2) the frequency of the water vapor channel has been changed slightly compared to SSM/I to 21.3 GHz, to reduce saturation in the moist tropics. The final instrument complement leads to considerable complexity in the co-registration of the TMI data with data from the other instruments. The TMI channels conically scan ahead of the spacecraft while the two other instruments scan downward across nadir. Since the desired altitudes of overlap between instrument products are likely to differ among the scientists, the co-registration code is being written allowing that altitude to vary. Note, however, that the TMI has much coarser resolution than the other two instruments except at 85.5 GHz where resolutions are comparable.

Due to budget limitations, the radar's originally planned dual frequency was reduced to a single frequency at 13.8 GHz. There was an unavoidable reduction in the radar sensitivity to detection of a minimum rain rate of 0.7 mm hr^{-1}. The VIRS has 5 channels, adding 1.65, 3.75 and 12 μm to the basic VIS and IR. The additional channels are to help identify warm rain and to use split window techniques. Note that the footprint of the VIRS is roughly twice that of the AVHRR. This change was made to reduce the immense load on the data system that finer resolution would have imposed.

Two additional instruments were added to the TRMM spacecraft by the Earth Observing System, EOS. These are a CERES (Cloud and Earth Radiant Energy System) to measure upwelling radiation from the earth and the cloud tops and a LIS (Lightning Imaging Sensor) to measure lightning. While the data from these two instruments will go to other NASA Centers for processing, they both will contribute to the value of the science from TRMM. The CERES will permit obtaining the atmosphere's radiative heating/cooling component which, in addition to latent heating/cooling is the total diabatic heating/cooling. The LIS will help identify strong updrafts in cumulonimbus thunder clouds and add to understanding of cloud electrification.

The TRMM launch is scheduled for August 17, 1997 aboard an H-II Rocket from Tanegashima, Japan, for a nominal three-year mission. The actual life will depend on the solar cycle and drag at the TRMM altitude during the mission.

3. The Subteams of the U.S. Science Team

During 1991–1993 the entire U.S. Science Team met twice. It was divided up into 6 subteams, namely

1. Passive microwave
2. Radar
3. Combined algorithms from TRMM instruments only
4. TRMM Retrievals using other Satellite Products
5. Modeling and Analysis
6. Ground Truth Validation

There were several meetings each of the various subteams, particularly those teams involved with developing algorithms for rain retrievals. TRMM algorithm development was greatly helped by three factors: The flying of the passive microwave SSM/I instruments on military satellites, the collection in Darwin, Australia, of good surface radar and rain gauge data for four rainy seasons and the international TOGA COARE[6] field campaign.

Testing of passive microwave algorithms using the Darwin data to examine SSM/I brightness temperatures as proxies for TRMM passive microwave products was immensely valuable. Particularly noteworthy were: 1) the excellent agreement between rain volumes obtained from SSM/I overpasses compared to that of the surface Darwin radar[7] 2) the rapid development of retrievals using geosynchronous products (GPI) adjusted by SSM/I to obtain monthly rain maps over the global tropics by Adler et al. (1994) and Huffman et al. (1994). This combination avoids the TRMM sampling limitations and the physical

[6] TOGA stands for Tropical Ocean Global Atmosphere. COARE stands for Coupled Ocean Atmosphere Response Experiment.

[7] In Darwin comparisons of rain rates for the area covered by the surface radar agreed within ±20 per cent using the passive microwave algorithm of Kummerow (1994a; 1994b). This good agreement did not prevail over the Japanese islands in the summer of 1989, probably because of a significant amount of rainfall from cloud without ice, e.g. "warm rain".

limitations of the GPI at the same time. Later it is expected to use the best TRMM rain products to calibrate the GPI. 3) the development by Tao and colleagues of an algorithm to obtain latent heat profiles from hydrometeor profiles using simplified versions of the Goddard Cumulus Ensemble (GCE) model (Tao et al., 1991; 1993). The resulting profiles are highly dependent on the ratio of convective to stratiform rain and 4) the demonstration by Krishnamurti that a global tropical model initialized with rain and associated latent heat (using SSM/I and gauge data as proxies for TRMM data) gives far better initial and 24 hr forecast rain patterns than the large-scale models with conventional initialization.

The COARE field project in 1993 gave excellent tests for the PR and the TMI. Preliminary comparison of the reflectivities from the 14 GHz Airborne Rain Mapping Radar (ARMAR) with reflectivities obtained by other (NOAA) aircraft radars are so far consistent although many more comparisons remain to be done before the TRMM launch algorithms are specified.

4. Second Phase of Pre-Launch Research—the Joint TRMM Science Team

4.1 The Science Teams Selected in 1994; the Joint TRMM Science Team

In February 1994, new TRMM Science Teams were selected in both the U.S. and Japan, from proposals in response to a joint NASA/NASDA Research Announcement. These comprise the TRMM Science team for 4 years, until the TRMM launch in August 1997. The U.S. selected 38 PI's to be divided into the same subteams as was the first Science Team. NASDA has selected a comparable number of TRMM PI's, divided into three subteams, algorithms, modeling and analysis, and validation. Clearly more than 70 persons is too large a group to make decisions effectively, hence a Joint TRMM Science Team (JTST) has been chosen which consists of eight members from each country. The U.S. Team consists of the Headquarters Program Scientist, the Project Scientist, Deputy Project Scientist (focused on the data system) and the Team Leaders. The Joint Team held its first meeting in the U.S. in September 1994. The meeting addressed cooperation in all aspects of TRMM, particularly the algorithms and data systems interactions, as well as completion of the Memorandum of Understanding (MOU) between the two countries will spell out how this cooperation will be implemented.

4.2 Mission Objectives and the TRMM Science Data and Information System

Rainfall products, their error budgets and the vertical structure of latent heating from the cornerstone of TRMM science. In designing the TRMM Science Data and Information System (TSDIS) to generate these products under very tight budget and schedule constraints, it was necessary to spell out each product and the algorithm(s) by which it is to be obtained. In August 1992, the first Science Requirements document for TSDIS was released. There were 53 products desired by the Science Team which had increased to 63 products by the revised November 1992 version of the document. Then it became clear that the available resources in both dollars and manpower for TSDIS to process this many algorithms would not be available. Consequently, a critical review of the TSDIS Science Requirements was made. The latest and probably final version of the Requirements Document[8] was distributed in March of 1994. By reducing the number of algorithms calculating similar products, the total number of rainfall products was reduced to 33 without adversely affecting the computed geophysical parameters. The 24 algorithms needed to calculate the above products in TSDIS are illustrated in flow diagram form in Fig. 4.

Following is a description of products which will be generated by the TRMM Project through the TRMM Data and Information System (TSDIS). The products are separated by level (see Table 2). Level 1B, for VIRS, TMI, PR and ground based radar represents calibrated/Earth located data for each of the instruments. In the TRMM mission, a level 1C is further defined for both the ground and space based radar data. The level 1C data allows for the removal of spurious signals as well as the removal of scans for which no significant echoes are present. The large data

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[8] Copies may be obtained from Dr. Christian Kummerow, Deputy Project Scientist, at Code 912, Goddard Space Flight Center, Greenbelt, MD 20771.

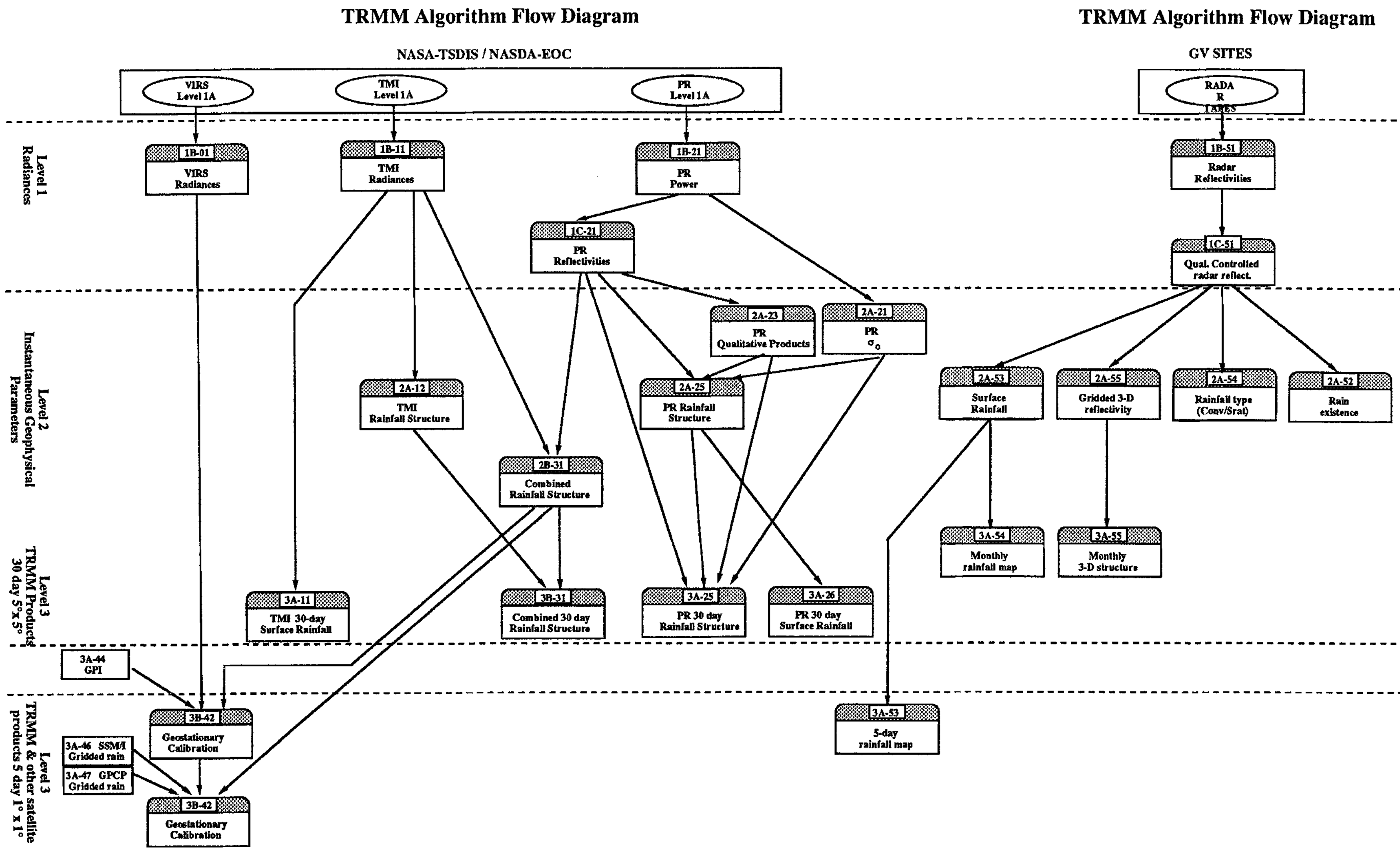


Fig. 4. Schematic diagram showing the data flow for TSDIS products. Ovals represent algorithms while rectangles are used for data products

Table 2. *Definition of Data Levels*

Level 1A	Instrument data in full resolution, reconstructed, and redundancy removed. Radiometric and geometric calibration, i.e., platform ephemeris, computed and appended, but not applied to Level 0 data. It is possible to recon struct Level 0 data from Level 1A data.
Level 1B	Instrument data in full resolution with calibration and Earth location computed. It may not be possible to reconstruct Level 1A from Level 1B.
Level 2A	Derived physical parameters in full resolution.
Level 2B	Derived physical parameters with some averaging process applied. Will preserve orbital structure.
Level 3	Space- and/or time-averaged data product. Mapped on the Earth grids.
Level 4	Model and analysis results.

volumes associated with radars (>2 GBytes/day for both space and ground based radars) makes these products vital if productive use is to be made of these data in the research community. Level 2 products (instantaneous geophysical parameters at the sensor resolution) are calculated for the TMI, PR and Ground based radars. For the TMI, a profiling algorithm (see Smith et al., 1994 for a review) will be used to retrieve vertical structure of hydrometeors as well as surface rainfall. The PR level 2 products consist of the retrieved surface cross-section as a function of scan angle, a qualitative product (freezing level height, bright band presence and storm type) as well as a 3-D rain profile product. The validation products consist of a rain existence product (used internally to find good rainfall events), the surface rainfall, the rainfall type (i.e. convective or stratiform) and a 3-D gridded reflectivity field for direct validation with the PR observed reflectivities. The most challenging of the level 2 products is the combined product which will initially make use of the TMI derived total attenuation to constrain the radar solution, thus producing a better vertical distribution of hydrometeors. Although this product does not make optimal use of all the available information, it does reflect the philosophy of using physically sound, conservative approaches whenever necessary to insure that TRMM products are credible. More advanced schemes are currently being developed for this product and should be available shortly after launch.

Level 3 products will be generated by all five algorithm groups. The TMI algorithm consists of an emission technique over oceans only (Wilheit et al., 1991). Individual rainfall rates are then binned into histograms and fitted to lognormal distributions to improve the sampling – particularly at the high rainfall tail of the distribution. The PR algorithms consists of a) a simple sum of the instantaneous rains as well as a b) a histogram approach similar to the TMI product. The combined level 3 algorithm will make use of the instantaneous combined retrievals to firstly calibrate the wider swath retrieval of the TMI profiling algorithm. The calibrated TMI product will then be summed, thus making use of the high quality narrow swath retrievals as well as the wider swath TMI retrievals. All the above products will be produced for 30-day, $5^\circ \times 5^\circ$ areas. The TRMM and other satellites product consist of a calibration of geostationary IR data obtained by matching local TRMM rainfall to measured IR temperatures. This calibrated geostationary product can be used to fill the gaps between TRMM visits. The second product shown in Fig. 4 is then a weighted mean of the TRMM data, the calibrated geostationary product, any SSM/I retrieved rainfall and raingauge products. The weights will be consistent with the expected confidence of each product. These two rainfall maps will be products for 5 day, $1^\circ \times 1^\circ$ resolution to reflect the fact that higher temporal and spatial resolution are possible with the improved sampling of this product. The validation products (5- and 30 day rainfall totals as well as the 30 day vertical structure) represent sums of the instantaneous products needed to validate the level 3 products derived from the satellite.

It should be emphasized that the products listed in Fig. 4 are the official products of TRMM which will be calculated on an operational basis and turned over to EOSDIS for archiving and distribution, beginning at about six months after launch. After initial algorithm adjustments during the first 6 months, the algorithms will be improved at scheduled yearly intervals after comparisons with the validation data. The Joint Science Team or a group designated by it will decide what algorithms are to be used in TSDIS to produce the

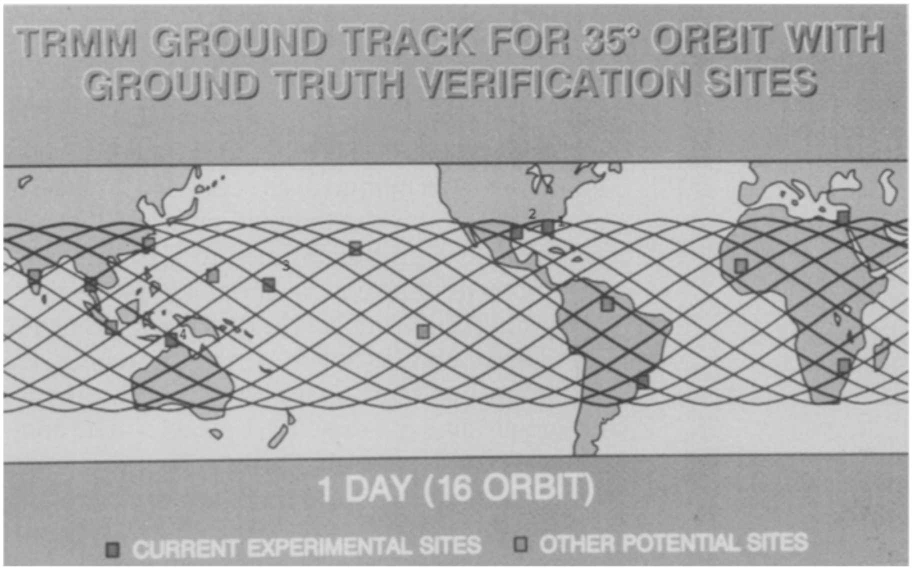


Fig. 5. TRMM Ground Truth Validation sites. The red squares denote primary sites where the raw data come in to be processed by TSDIS. The red circles denote primary sites where skilled meteorologists will quality control the reflectivities and send rain products to TSDIS. The yellow squares are possible sites, some of which are hoped will be implemented. Darwin, Australia and Melbourne, Florida are already in operation and providing data. It is hoped that Kwajalein atoll in the west-central Pacific (the only ocean Ground Truth station) will have sufficiently improved equipment to begin sending good data in early 1996

"official" rain and latent heat products. A detailed validation plan is in progress.

Naturally, as the data begin to accumulate, many individual scientists will wish to try out quite different algorithms on their work stations and compare these to the validation data. For example, some scientists may wish to use lightning data in their rain retrievals. Any scientist can submit an algorithm to the Joint Science Team as a candidate for selection by TSDIS. If not selected, the scientist can run as many cases and comparisons as s/he has resources, interpret the results and submit them for publication. As occurred in GATE, these rainfall re-evaluations and new ideas from them will probably still be going on two decades after the TRMM space flight is finished.

4.3 *The "Ground Truth" Sites for Validation*

Figure 5 shows the location and type of validation sites which will be providing data for TSDIS. These "official" validation sites have had to be limited to 10 to 12 ground stations because of the limitations on TSDIS imposed by resource reduction. Individuals and groups of scientists may be able to access many other sources of validation information both on the ground and above it. On Fig. 5, the black squares represent "P. I. sites" from which rain products will come to TSDIS quality-checked. The "direct" sites are those where raw reflectivities are taken in to TSDIS where they must be quality checked and converted from reflectivity to rain.

The Cape Canaveral site in Florida will be the most heavily instrumented with gauge networks of various spacings, automatic surface weather stations, wind profilers, and an offshore radar periodically, if resources permit. The several NEXRAD and other radars in both Florida and Texas will make these the only locations where monthly water budget calculations may be made accurately enough over a substantial area to compare the budget-derived areal rain to that measured by TRMM. A TRMM Validation Plan[9] is in preparation.

The Joint Science Team has decided that a major part of the validation process will depend on departures of space products from ground truth products, and the biases of the space products

[9] Houze (U.S. Ground Truth Team Leader) and others held a Ground Truth Workshop in December, 1994, which led to a draft of this plan.

relative to the Ground Truth products. The Team also decided that individual algorithm producers need to develop the methods to validate their algorithms. Part of algorithm validation could be how well the rain and latent heating produced by an algorithm improves model initialization and prediction. These decisions pose a major challenge to Science Team members, individually and collectively. Clearly a strictly objective validation method to select the next-stage improved algorithms cannot be applied from Day One. Equally clearly, it is more important to have an algorithm validate best in the areas of heavy, frequent rain, such as the ITCZ, than in drier areas, since it has been known for nearly a half century (Riehl, 1954) that the most rain and most latent heating in the tropics are concentrated in the large, multi-merger cloud clusters in the Equatorial Trough Zone.

5. Development and Validation of TRMM Rain Retrieval Algorithms

5.1 Single Instrument Algorithms

5.1.1 The TMI

The multi-channel passive microwave instrument TMI is the "workhorse" of TRMM. The TRMM sampling calculations are based on its 760 km wide swath. The 220 km wide swath of the PR (restricted by available resources) is inadequate to sample monthly rainfall accurately enough for most uses. Over oceans, where the background emission is fairly constant, SSM/I tests have shown that passive microwave does an excellent job of retrieving all types of rainfall. TRMM will be able to do much better. The lower-altitude orbit results in better spatial resolution than the SSM/I, hence a decreased beam-filling problem. TRMM also has, as mentioned, the additional channel at 10 GHz which is not on the SSM/I. Moreover, the other passive microwave instruments are in sun-synchronous orbit which do not permit determining the diurnal and semi-diurnal variability characteristic of tropical rain.

There are two basic types of passive microwave algorithms that TSDIS will produce. These are:

1. Histograms using the emission properties of the 10, 19 and 37 GHz channel to obtain monthly rainfalls (Wilheit et al., 1991) over ocean areas. In this technique, the observed emission signal is related to rainfall in each channel via relationships obtained from radiative transfer calculations through modeled raining atmospheres. After correcting for footprint filling biases, the computed rainfall rates are binned into $5^\circ \times 5^\circ$ boxes for 30 day intervals and log-normal distributions are fitted to the observed distributions of rainfall. Since each microwave frequency has a distinct dynamic range, the algorithms being developed will blend the rainfall distributions obtained from each of the channels to derive a single fitted distribution. The rainfall accumulations are then inferred from the fitted distribution. By taking advantage of the known statistical distributions of rainfall rates, this technique can thus compensate for the poor sampling of an orbiting radiometer, especially at the high rainfall rates. Validation for this algorithm which will work only over oceans and must come from rain gauge and surface radar measurements on tiny atolls or buoys. The radar on the Kwajalein atoll has been identified as critical for this product.
2. Profiling algorithms such as those of Kummerow et al. (1989, 1994a) or Smith et al. (1992) make use of the fact that weighting functions for various frequencies peak at different levels within a rainy atmosphere in order to determine the vertical structure of hydrometeors. Because the total information which needs to be retrieved far exceeds the number of independent observations, however, these algorithms generally make use of cloud dynamical models to provide first guess profiles. Over many years, Tao and colleagues have developed the cumulus ensemble (GCE) model which solves the hydrodynamical, thermodynamical and microphysical equations on a grid with about 1 km resolution. This model, when given boundary and initial conditions (related to cumulus forcing) produces groups of cumuli with varying fractions of stratiform and convective rain which agree well with properties of the cumulus clusters observed over many different regions of the tropics (Tao and Simpson, 1993; Simpson and Tao, 1993). Various methods, including 3-D backwards Monte Carlo (Roberti et al., 1994) methods are now available to compute upwelling brightness temperatures from these cloud model profiles.

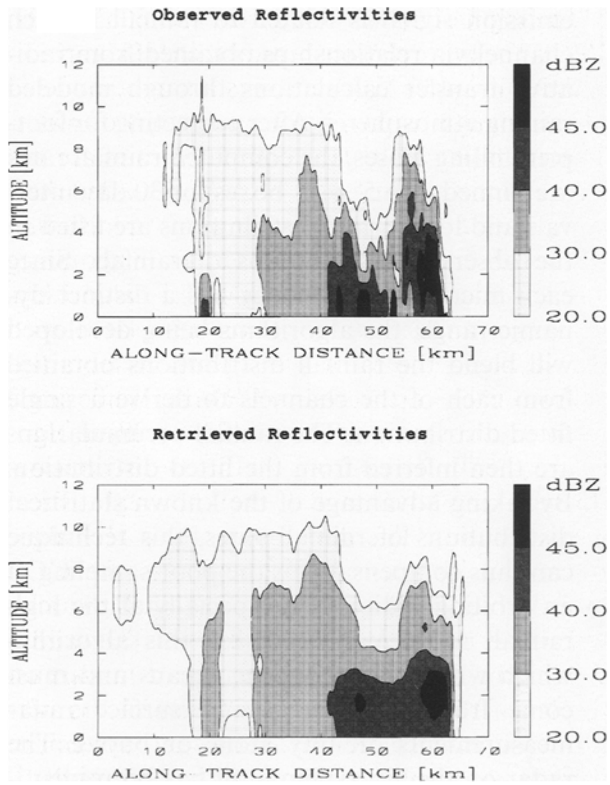


Fig. 6. Preliminary results of Kummerow and Olson profile retrieval scheme (bottom panel) using passive microwave data from the AMPR instrument. Radiative transfer calculations are used to convert the retrieved hydrometeor profiles into the effective reflectivity that would be measured from radar. Validation data, shown in the top panel, is available from the ER2 Doppler radar (EDOP) instrument. Both sensors are mounted on the NASA ER2 aircraft

While the details of the various algorithms differ, all algorithms seek a closest fit between brightness temperatures calculated from the model rain profile and the observed ones. One example comparing the measured reflectivities from EDOP with the equivalent reflectivities derived from the retrieved hydrometeor structure using AMPR radiometric measurements is illustrated in Fig. 6. While this method can be applied to any modeled and measured cloud ensemble profile, such as that of radar reflectivity[10], only the T_b that will be seen by TMI are used here. These algorithm profiles have compared well with Ground Truth radar-derived profiles when it is raining at the time the SSM/I passes over the surface radar over oceanic regions. Over land, the algorithms can function in the much the same manner as over ocean, but the reduced information content make the retrieval more dependent upon the cloud models than over ocean. For validating the 3-dimensional structure retrieved by this class of algorithms, it is imperative that at least one site such as Darwin, Australia, which measures cross-polarized returns (for determining the phase of hydrometeors) be available. A good ocean surface radar and gauges is also needed to validate the oceanic component of this algorithm. Aircraft underflights and other short-term methods will also be needed.

[10] This precipitation profile retrieval method is being applied by Olson and Kummerow (work in progress) to develop profiling algorithms that combine both the TRMM radar and passive microwave products.

5.1.2 Radar Algorithms

There are two basic types of radar algorithms under consideration for TRMM, namely statistical and deterministic. The statistical probability matching method has been developed by Atlas, Rosenfeld and their colleagues (Atlas et al., 1990; Rosenfeld et al., 1990). Early in the TRMM flight mission, it is unlikely that this type of algorithm would be run operationally on TSDIS but instead will be tested by groups in widely differing precipitation regimes. Research on this method showed quite clearly that in tropical convective rain systems, the relationship between reflectivity Z and rainfall R differs substantially between convective and stratiform rain, which will be helpful in the deterministic algorithms.

Deterministic algorithms must deal with two distinct problems – finding the correct Z-R relationship and dealing with attenuation of the radar signal. The 13.8 GHz radar attenuates sufficiently that unless corrections are made, the surface rainfall will be severely underestimated in heavy rainfall ($R \geqslant 20$ mm/hr). At launch, the TRMM PR algorithms will probably be limited to a two class (convective, stratiform) description of drop size distributions for converting the return power to rainfall. With experience and comparison to ground based radars, however, it is hoped that the drop size distribution can be better represented as the mission progresses. In order to deal with attenuation, the TRMM PR algorithms are likely to use a hybrid approach where a Hitchfield-

Borden solution is used for light rain while a surface reference technique will be applied for strongly attenuated observations. The most important validation for these products will come from simultaneous, collocated comparisons between space- and ground based retrievals. After validation, it is expected that the physical insight into vertical structure provided by this product will be extremely useful to improve or train the GCE model. This class of algorithm can also document the conditions favorable for warm rain over land and ocean, and how much of it occurs in various locations.

5.1.3 Combined TRMM Algorithms

The most powerful TRMM algorithms by the end of the mission are expected to use input from all three rain instruments. In particular, algorithms derived from combining the PR and TMI are important. Early algorithms will make use of the total path attenuation measured by the TMI to aid the radar path attenuation estimates. However, combined TRMM algorithms which will more fully use both data sets are already being developed by a number of TRMM investigators. For example, Schols and Weinman (1994) are developing a profiling algorithm which uses the passive microwave to constrain the radar equation. This algorithm may not work over land (due to loss of the TMI emission channels). Also, the radar must be looking at the same precipitation hydrometeors as seen by the passive microwave, which requires data co-registration. A separate effort by Kummerow and Olson[11] extends the concept of the passive microwave profiling scheme to include PR and IR data in the retrieval. This technique has been designed so that perfect co-registration is not required if the weight given to the PR or the IR measurements is reduced by an amount commensurate with coregistration uncertainty.

6. Latent Heating Retrieval Algorithms

Two latent heating retrieval algorithms, hydrometeor heating (HH) and convective-stratiform heating (CSH) algorithms, have been developed by the Goddard Cumulus Ensemble (GCE) Modeling Group at Goddard (Tao et al., 1991; 1993). The basic physics behind the HH algorithm is that the latent heat release is a consequence of phase change (vapor, liquid and solid) of water. Therefore, it would be possible to estimate the latent heating by clouds if TRMM provided their complete vertical hydrometeor profiles, including the small drops just condensed or evaporating and the small ice particles. The HH algorithm, therefore, requires information associated with the vertical profiles of small hydrometeors (ice and water) not measured by TRMM. While small hydrometeors may be inferred by profiling algorithms, it must be understood that the inference is through a cloud model, not through direct measurements. The derivation of the HH algorithm will later use modifications of the GCE model to deduce the distribution of small particles when only the larger ones are known. The validation of the HH algorithm was based in part on results of the unmodified GCE model. Its performance has also been tested on cloud systems in various geographic locations with good results.

A second algorithm, the CSH algorithm, has been developed. The inputs for this new approach are surface precipitation rates, amount of stratiform rain, and information on the type and location of observed cloud systems. The CSH algorithm is based on a look-up table which consists of latent heating profiles associated with various types of cloud systems occurring in different geographic locations. The heating profiles in Fig. 7 are derived for a TOGA COARE Westerly Wind Burst Event from the CSH algorithm. The algorithm gives results in reasonable agreement with the heating budget determined by diagnostic study from observations. Much more work needs to be done on these algorithms, including testing them over those TRMM Ground Truth sites where diagnostic studies of the latent heating can be done from observations.

6.1 Rain Retrieval Algorithms Using TRMM Products with those from other Satellites

Adler, Huffman and colleagues (Huffman et al., 1994; Adler et al., 1994) have been developing proxy TRMM rainfalls to adjust the rain products determined by an empirical relationship between the cold cloud tops and rainfall, called the Geosynchronous Precipitation Index (GPI). The

[11] Work in progress at the Goddard Space Flight Center. To be published.

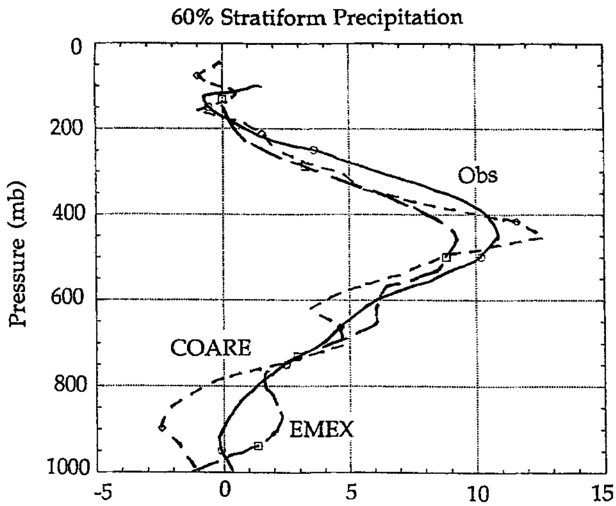


Fig. 7. The TOGA COARE latent heating profiles derived by applying diagnostic budget (solid line), by using 60% of stratiform rain for a EMEX squall (long dashed lines) and for a COARE squall system. The unit is °C/2 day. (The 5 day mean TOGA COARE diagnostic heating profile is provided by Dr. Sui at Goddard)

GPI was formulated empirically by Arkin and Meisner (1987), and has been used operationally for a number of years with the large-scale weather prediction models as the best and only estimate of rainfall.

Currently, Adler, Huffman et al. (loc. cit.) use rain rates obtained from a simple scattering algorithm applied to the 86 GHz channel on the SSM/I[12]. Throughout the SSM/I orbits for a month, they average the rain obtained from the microwave over the 2.5° by 2.5° resolution of the GPI. They adjust the GPI to agree with the microwave rain along the SSM/I swaths and then apply the adjustment to the GPI values outside the SSM/I swaths, thereby obtaining an estimate of the monthly rainfall over boxes 2.5° by 2.5° between 40 °N and 40 °S latitudes (the zone of useful IR data).

Figure 8a shows how these calculations are made and Fig. 8b shows a result for August 1987. The upper panel gives rain calculated from the scattering algorithm (GSCAT). The middle panel shows the corresponding rain map using the GPI. Note that the cold cloud areas where the GPI indicates rain are much larger than those of the passive microwave. Cold high cirrus which does not rain virtually always causes the GPI to overestimate rain areas. The bottom panel shows the microwave-adjusted GPI (AGPI). At this time, these authors validate their results mainly by comparison with monthly rainfalls from rain gauges. These comparisons show that the combined rain product, adjusted GPI (AGPI), is very much better than either product alone.

By the time of the TRMM launch, the GPI will be available for 5 day averages over 0.5° by 0.5° areas. The best "TRMM alone" product will be used to adjust the GPI. Clearly this is the only way to use TRMM data to get high resolution rain results, because it overcomes the sampling deficiency of the TRMM orbit. It does this by using the continuous viewing of the world-wide geosynchronous satellites. The only shortcoming of this method is that so far it gives only the surface rainfall. Vertical rain and heating profiles could be estimated using the CSH of Tao et al. (1993) described in Section 5. Whether this would be successful would depend on how well the AGPI can estimate the fraction of convective versus stratiform rain over the unit area of the GPI.

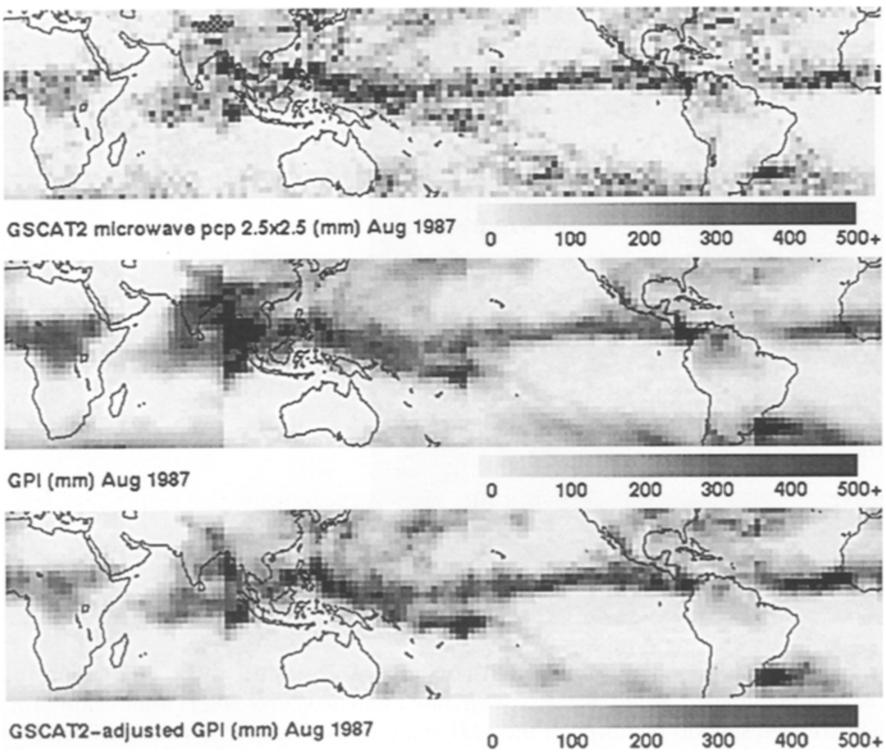
7. Concluding Remarks and Future Outlook

7.1 Outlook for TRMM

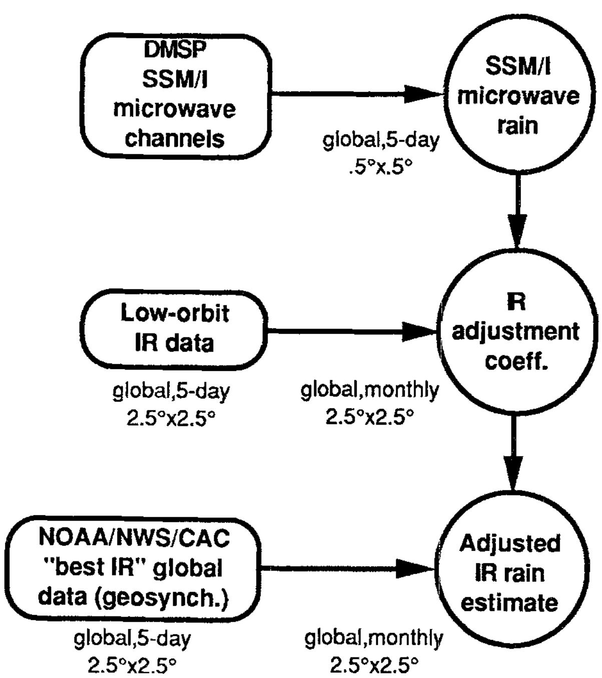
The TRMM observatory entered its Integration and Test Phase in early 1995. The Project is so far within budget and on schedule. A photograph of the Observatory at Goddard Space Flight Center undergoing its many tests is shown in Fig. 9. Instrument simulators are designed to assure that they have their centers of mass exactly coincident with those of the real instruments.

The Science Team is preparing a "Science Operations Plan" or Users Handbook in 1995, which will require time and hard work. The algorithm developers are coding their own algorithms, as required, and the passive microwave team has its algorithms and TSDIS interface software well along. The coding and delivery of algorithms to TSDIS is accomplished in stages. Version 1 of the algorithms which represent written description of the algorithms and their computational needs

[12] The Goddard scattering algorithm (GSCAT) is derived from the GCE-produced relationship between T_B and rainfall for 86 GHz. This scattering algorithm is based on empirical knowledge that the 86 GHz T_B's are approximately inversely related to the rain amount from the cloud in raining areas. As a first step, various combinations of channels are applied to screen out non-raining areas.



a



b

Fig. 8. a) Precipitation estimates (in mm) on a 2.5° by 2.5° latitude/longitude grid for August 1987 from microwave data as computed by the GSCAT (top), geo-IR data as computed by the GPI (middle) and the AGPI (bottom) and b) Flow diagram showing how these estimates are obtained

have already been delivered to TSDIS. Version 2 of the algorithms which represents generally correct software has been delivered. Version 3, which consists of the final coded algorithms will be due in 1996 although it is expected that modest internal code changes which do not affect the data system will be possible until approximately 6 months before launch. To facilitate the delivery and testing of the algorithm software, TSDIS is providing synthetic TRMM data which was generated using the GCE model in conjunction with radiative transfer routines. Most of these data are available to TRMM scientists through anonymous FTP.

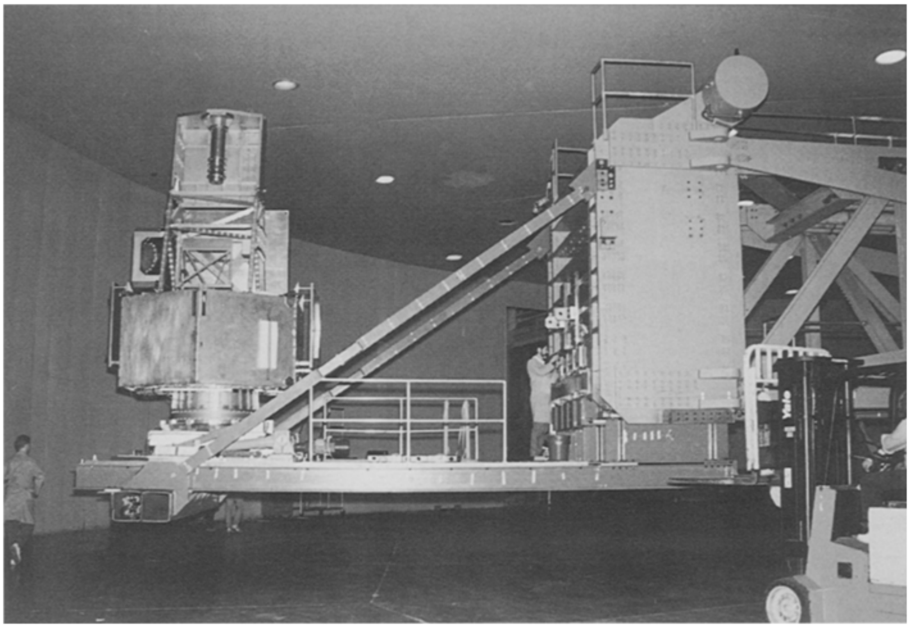


Fig. 9. Photograph of spacecraft under construction in Goddard Test Laboratory in mid-September, 1994. It is about 5 m (17 ft) tall. In flight, the camera would be looking upward, seeing the very large radar antenna(silver color) from below. The gold color square above the radar is the instrument support platform for the TMI and the VIRS (instruments not visible). The satellite will normally fly in the direction toward the top of the page, but reverses flight direction occasionally to protect the VIRS from the sun. Below the radar antenna is the support platform for the CERES, LIS and Earth sensor, which cannot be seen in this picture

Validation data should be available before launch. Through a cooperative agreement between the TRMM office and TSDIS it is expected that ground based radar data from Darwin, Australia and Melbourne, Florida is being processed on a semi-routine basis. Two more sites in Texas and Kwajalein are scheduled for addition to the system starting in late 1996.

TRMM prelaunch research, including the airborne flight of all the instruments in TOGA COARE has been immensely beneficial. Considerably better insight into rain systems in a wide variety of locations has resulted. Even more importantly, a number of advance warnings have been obtained with regard to problem areas while there is still time to address them. The first problem area relates to sampling, since the GATE trial area had much better than average tropical rain persistence. This problem has been solved by bringing in data from other satellites, as described.

The second, perhaps major, problem relates to warm rain over land. Studies need to be made in different areas to estimate what fraction of the total rain falls from clouds without ice. If warm rain is a significant fraction of the total, ways of relating the information gained from the narrow swath of the radar need to be found in order to extrapolate those results to the wider swaths of the TMI and VIRS. Fortunately, this is a problem over land areas only, where rain gauge data are available over much of the land mass. Rosenfeld and Gutman (1994) have published a method to detect warm rain (qualitatively) using several VIRS channels and their differences, but this would not work if a cloud layer existed between the raining lower clouds and the satellite.

7.2 *A Possible TRMM Follow on Mission*

It is clear that climate fluctuations related to rain variability cannot be fully clarified in only a three-year mission. For example, since the El Niño occurs about twice in a decade, there is a substantial chance that one will not occur during the three years that TRMM flies. Also there are almost certainly longer period linked fluctuations between rain and other processes in the coupled atmosphere-ocean-land system than can be detected in three years. Rain outside the tropics may play a crucial role in some of these linkages, as for

Table 3. *List of Acronym Definitions*

Acronym	Definition
AGPI	Adjusted Geosynchronous Precipitation Index
AMPR	Advanced Microwave Precipitation Radiometer
ARMAR	Airborne Rain Mapping Radar
AVHRR	Advanced Very High Resolution Radiometer
CERES	Cloud and Earth Radiant Energy System
CSH	Convective-Stratiform Heating
EDOP	ER-2 Doppler Radar
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information System
GATE	GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment
GCE	Goddard Cumulus Ensemble
GPI	Geosynchronous Precipitation Index
HH	Hydrometer Heating
ITCZ	Inter Tropical Convergence Zone
JTST	Joint TRMM Science Team
LIS	Lightning Imaging Sensor
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NEXRAD	Next Generation of Meteorological Radars
NOAA	National Oceanic and Atmospheric Administration
SPCZ	South Pacific Convergence Zone
SSG	Science Steering Group
SSM/I	Special Sensor Microwave Imager
TMI	RMM Microwave Instrument
TOGA COARE	Tropical Ocean Global Atmosphere. Coupled Ocean Atmosphere Response Experiment.
TRMM	Tropical Rainfall Measuring Mission
TSDIS	TRMM Information and Data System
UKMO	United Kingdom Meteorological Office
VIS	Visible
VIS/IR	Visible/Infrared

example, the formation of deep ocean water in the North Atlantic. Furthermore, for large scale forecasts in midlatitudes, baroclinic cyclones and their precipitation, which is often snow, are vital. Hence a follow-on satellite to TRMM is needed by the Earth science community, which has a higher inclination and a longer mission life. A dual frequency radar would be particularly important.

A TRMM Follow-On is in the feasibility study stage in both the U.S. and Japan. The progress of this study when finished will be reported elsewhere.[13]

Acknowledgments

A large team of hard working scientists and engineers in two nations has brought TRMM from an idea to a real satellite that we can watch as it is tested and prepared for launch in a relatively short time. The community is grateful to all of them. For the preparation of this paper, the authors particularly want to thank George Huffman for material on TRMM with other satellites, Gerry North and Tom Bell for elucidation on the sampling problem, Otto Thiele and Bob Houze for validation information, William Olson for rain retrievals, and Patricia Gregory for all her help with the figures. Everyone involved in TRMM is grateful for the unwavering support over a decade of the TRMM Headquarters Program Scientist, Dr. John Theon, to whom this paper is dedicated. The work in this paper was performed under RTOP Number 4602354 from NASA Headquarters.

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