On Requirements for a Satellite Mission to Measure Tropical Rainfall

NASA

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PREFACE

This workshop was convened to discuss a conceptual proposal to measure tropical precipitation from a low-inclination orbit using a combination of active and passive microwave sensors together with a visible/infrared sensor to overcome many of the previous limitations of remote sensing of precipitation from space. Tropical rainfall data are crucial in determining the role of tropical latent heating in driving the circulation of the global atmosphere. Also, the data are particularly important for testing the realism of climate models, and their ability to simulate and predict climate accurately on the seasonal time scale. Other scientific issues such as the effects of El Niño on climate could be addressed with a reliable, extended time series of tropical rainfall observations.

The passive microwave sensor is planned to provide information on the integrated column precipitation content, its areal distribution, and its intensity. The horizontal resolution will allow the definition and investigation of most rainfall types, including convective cells. The technique is best suited for estimates over oceans where data are needed most for climate model verification.

The planned active microwave sensor (radar) will define the layer depth of the precipitation and provide information about the intensity of rain reaching the surface, the key to determining the latent heat input to the atmosphere. The very high horizontal resolving power of this sensor will also better define the coverage and intensity of rain. Moreover, it will permit the measurement of rain over land, where the passive microwave channels have more difficulty.

The visible/infrared sensor will provide very high resolution information on cloud coverage, type, and top temperatures and also serve as the link between these data and the long and virtually continuous coverage by the geosynchronous meteorological satellites.

The unique combination of sensor wavelengths, coverages, and resolving capabilities together with the low altitude, non-Sun-synchronous orbit provide a sampling capability that should yield monthly precipitation amounts to a reasonable accuracy over a 500- by 500-km grid. Such a climatology would go a long way toward meeting the scientific requirements for studying latent heating of the atmosphere for modeling and diagnostic studies. Utilization of these data is also being considered for experiments involving soil moisture and vegetation.

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EXECUTIVE SUMMARY

A science workshop was convened November 18, 19, and 20, 1985 to address a proposal to observe tropical rainfall from space (see Appendix B for agenda). The purpose was to develop recommendations to better define mission objectives and technical approach. The proposed mission would observe precipitation from a low-inclination orbit using a combination of active and passive microwave sensors together with a visible/infrared sensor to overcome many of the previous limitations of remote sensing of precipitation from space. Tropical rainfall data are crucial in determining the role of tropical latent heating in driving the circulation of the global atmosphere. Also, such data are particularly important for testing the realism of climate models and their ability to simulate and predict climate accurately on the seasonal time scale. Causes of climate variability on the 2- to 5-year scale, notably El Niño/Southern Oscillation (ENSO), could be fruitfully addressed.

The workshop consensus was that for the first time the Tropical Rainfall Measuring Mission (TRMM) would give us credible direct estimates of precipitation throughout the tropics. Up to now, we have had to use surrogate variables, such as Infrared (IR) cloud top temperatures, especially over the oceans. Accordingly, it should be a top priority for atmospheric sciences to develop accurate simulations and to provide direct observations of precipitation to studies of the global climate system. We must be able to quantify the accuracy of our precipitation estimates, whether of absolute values, changes, or anomalies. With the data from TRMM, we will have observations of the coverage and quality suitable for the validation of the improved general circulation models (GCMs) and climate models of the next decade.

After an overview and discussion of the overall mission objectives, the workshop participants were divided into panels to consider the following three broad topics:
- Science goal and mission objectives
- Measurements
- Ground truth

The findings of the three panels follow:

Science Goal and Mission Objectives

The science goal is to increase our understanding of the energetic and hydrologic processes in the tropics, especially as they influence the global circulation of the atmosphere and oceans and climate variability. A major advance in our understanding of the general circulation can be achieved by collecting accurate data for rainfall throughout the tropical latitudes. This is because rainfall rate is a signature of latent heat release and its conversion to sensible heat and the pressure forces which maintain the large-scale wind circulations of the tropics, such as the trade winds and the large-scale meridional Hadley circulation. Recent research on the variations in the more-zonal Walker circulation in the Pacific and the associated southern oscillation suggests that variations in convective clouds and their latent heat release are a key link in the chain of events leading to the irregular outbreaks of El Niño and associated far-reaching and sometimes devastating global effects. To the tropical oceans, rainfall is a source of fresh, usually cooler water that can play a role in the formation of important thermohaline contrasts (ocean fronts). Over land, rainfall nourishes vegetation and replenishes soil moisture, which in turn have pronounced impacts on the structure and circulation of the overlying air. While the main purposes for developing a tropical rainfall data set are to support climate and long-range weather diagnostics, model validation, and model impact studies, there are secondary purposes: these include the study of the characteristics of tropical rain systems and the collection of a climatology for objective assessment of drought and other climate anomalies.

Six specific mission objectives have been identified:
1. Obtain a minimum 3-year data set of monthly averaged estimated rainfall-rate probabilities, averaged over grid boxes of the order of 500 km on a side with sampling errors of a few percent.
2. Develop new techniques for measuring rainfall by combining the measurements from several instruments to reduce statistical biases and to learn how to combine measurements from other satellite and ground instruments to ensure that major storms are not missed between visits by the satellite track.
3. Develop data sets for studies of diabatic initialization of weather forecast models. These impact studies require different data reduction algorithms for selected time segments during the mission.
4. Validate GCMs and climate models.
5. Develop a comprehensive ground truth program to be conducted both before and after launch through international collaboration, in particular, overlapping with the goals of the Tropical Oceans and Global Atmosphere (TOGA) program.

6. Develop techniques for studying and removing the diurnal cycle from temporally and spatially smoothed rainfall data obtained by using a non-Sun-synchronous orbit.

Based upon discussions of the foregoing proposed science and mission objectives, the following position was adopted by the panel on science goals:

1. An oceanic rainfall data set averaged over 10-day periods and areas of order 500- by 500-km as proposed here is critical to GCM and climate diagnostics progress in the 1990's. Without such a data set our ability to forecast climate may be limited by a lack of data crucial for model verification.

2. Rainfall estimates over oceans with accuracies of order 10 percent are a reasonable and very useful target. This is an order of magnitude better than conventional oceanic climatologies and a factor of 2 or 3 better than present satellite estimates. Sampling errors can be significantly reduced if the data are combined with polar and geosynchronous data,

3. While the proposed satellite measurements will be most accurate over oceans, when combined with other data they can contribute to rainfall estimates over land sufficiently well to objectively assess many climate anomalies such as drought in the Sahel. Many other effects such as the diurnal cycle and soil moisture can be studied over land as well.

4. While many secondary benefits will accrue, *the mission should not compromise its main objective of obtaining a climatological (space-time smoothed) tropical precipitation time series.*

Recommendations

1. More progress must be made in the development of simulation models for assessing the adequacy of the proposed mission configuration. These models span the hierarchy from simple stochastic rain field models based upon surface data, such as from the GATE experiment, to 3-dimensional models of tropical convective systems, coupled with cloud radiative transfer models.

2. Simulation studies are needed to refine estimates of:
   a. Rainfall from radiances and radar signals measured from space
   b. Sampling errors
   c. Diurnal cycle removal
   d. Seasonal cycle bias
   e. Beam filling bias
   f. Effects of variable heights of rain
   g. Effects of averaging in the vertical
   h. Benefits of introducing more data sources of varying quality
   i. Utility of combining simultaneous measurements by different sensors on the same spacecraft

3. Periodic reviews should be held to assess progress in the areas of algorithm development and of sampling statistics and the probability of meeting mission goals.

4. GCM and climate diagnostic studies are needed to estimate the magnitude of the signals we are looking for so adequate designs can be constructed (e.g., squares versus rectangles).

5. Available data sets such as SMMR, SSM/I and ESMR-5 as well as VIS/IR data from all sources should be studied in anticipation of data from this mission, both for algorithm development and basic science related to mission requirements.

Measurement Approach and Instrumentation

The tropical rainfall mission proposes to use a free-flying satellite in a 30° inclination orbit at an altitude of 300 km (which has some flexibility during the period of deciding the instrument complement). With a 30° inclined orbit, the sampling rate in the tropics is twice that of polar orbiters. The orbit precesses over a full cycle in just over 3 weeks, allowing for approximately uniform sampling of the diurnal cycle over a month.

To achieve sufficient sampling and the necessary parameters to derive rain rate over the area of interest, a complement of scanning instruments is suggested that includes a precipitation radar, a multichannel microwave radiometer, and a visible/infrared radiometer.

The radar should have the capability of estimating the rain column height (± 200 m) over land and sea at a horizontal resolution of 3 km. The resulting column height climatology is needed in the interpretation of the microwave radiometer results and may be a good estimator of rain rate itself. In addition, the radar should be capable of

estimating rain rate by backscattered power at two frequencies (~ 15 and ~ 35 GHz). Another analysis mode to be explored is the extinction of power as the beam goes through the rain and is reflected back from the surface. The radar is planned to have a swath width of 150 km; hence, the sampling density is less than that of the passive microwave radiometer by a factor of about four, but the number of physically independent measurements of rain rate is significantly augmented.

It is planned that the passive microwave radiometer have several channels, including both emission and ice scattering frequencies. The Electrically Scanning Microwave Radiometer (ESMR) (19.35 GHz) is available now and may be part of the system. It can measure light-to-moderate rainfall over the ocean. With a 300 km orbit altitude, ESMR has a swath width along the satellite track of 600 km with about 80 pixels of size roughly 7 km each. The crosstrack sweep time is such that contiguous rows of pixels can be achieved along the track. Using these values and the orbit characteristics, studies show that 180,000 readings can be taken in 30 days with ESMR for any given ~ 500-km grid box. The orbit inclination is such that any box is at least partially visited twice or more every day. If the individual pixel readings are all *statistically independent*, rainfall-rate probabilities in the grid-box-month can be estimated to within a few percent even for categories as rare as one-percent probable. Relaxation of the assumptions, as suggested with studies using GATE independent measurements, is very important since the methodology of data interpretation is likely to involve the estimation of several parameters in a multiparameter rain-rate probability distribution function. It is important to increase the dynamic range of rainfall measurements over that of the ESMR with a multifrequency microwave radiometer. However, the multiparameter approach using other instruments in conjunction with a microwave radiometer also enhances the dynamic range.

The visible/infrared radiometer is necessary as a cross-check and as yet another independent measure of rain. Several IR rain rate estimation schemes from geosynchronous orbit have shown qualitatively encouraging results (Arkin, 1979; Griffith and Woodley, 1978). Their estimates have been shown to explain about 50 percent of the variance of monthly tropical rainfall as compared with gage networks. The experience with the Advanced Very High Resolution Radiometer (AVHRR) shows that it is capable of measuring cloud top temperature and other cloud parameters relevant to rain rates. This sensor with its < 1 km horizontal resolution will provide a base rainfall predictor to be improved upon by the passive and active microwave techniques. Also, it provides a transfer standard from previous technology, and a bridge back to improved geosynchronous estimations.

The diurnal variation problem is to be analyzed by assuming uniform statistics through the month over the grid box and by estimating and removing the harmonics by a regression technique. Considering the number of visits per month, this should be a very reliable procedure.

The classic microwave radiometer beam-filling problem (pixel size comparable to or larger than the horizontal scales of rain) will be approached by several methods. First, the microwave pixels contemplated for this mission for the 19.35 GHz channel are smaller (by at least a factor of 11/3) than those of any previously flown satellite passive microwave sensor. Indeed, the horizontal distance of 7 km may be less than the autocorrelation length of tropical rain. If brute force decrease of pixel size is not enough to solve beam filling, several other strategies are possible using the complementarity of the instrument readings in a parameter estimation algorithm. For example, the use of a dual-polarized channel at 37 GHz produces a linear relationship that makes the beam-filling problem less serious when the fractional cloudiness is known from AVHRR (Kummerow, 1986).

Recommendations and conclusions reached by the Panel on Instruments and Algorithms are summarized as follows:

- The three instrument approach (VIS/IR, passive microwave, and radar) is an effective way to make the needed measurements. However, the single channel ESMR is not adequate to measure high rain rates, so the addition of a multifrequency microwave radiometer such as an SSM/I or SMMR is proposed. If it can be managed within cost constraints, the most feasible technical approach recommended is the design and development of a multifrequency microwave instrument specifically tailored to the tropical rainfall mission concept.

- A dual frequency (~ 15 and ~ 35 GHz) radar as originally proposed is considered appropriate for the mission. However, continued studies are needed to refine the choice of frequencies and to consider a variety of technical design options.

- The visible/infrared radiometer (e.g., AVHRR) should have a minimum of two channels, one in the thermal infrared and one for visible reflected light. Additional channels such as 1.6 micrometers for liquid/ice discrimination and a nocturnal visible reflected light sensor similar to that used on the DMSP OLS to allow nocturnal rain investigations would be useful as well.

- Relevant analytical and algorithm development studies to estimate rainfall using available VIS/IR, passive microwave, and radar data should be vigorously continued.

- An airborne sensor development program and experimental activities to investigate instrumentation concepts and to verify the interpretation algorithms are extremely important and must be conducted.
- The series of ground-based and airborne (VIS/IR/microwave) experiments in conjunction with planned large-scale experiments such as the Cooperative Huntsville Meteorological Experiment (COHMEX), the Equatorial Mesoscale Experiment (EMEX), the Florida Deep Convection Experiment, and planned shuttle experiments, ISCCP, ISLSCP, and the National STORM Program must continue to be supported and their analyses used in algorithm testing and improvement.

Ground Truth Strategy for a Tropical Rainfall Mission

Rainfall arriving at the surface is extremely difficult to quantify even in areas where extensive rain gage networks and weather radars are in place. Attempting to make rainfall estimates through indirect remote sensing from space poses a much greater problem. This is primarily because there are no methods available to calibrate the satellite instruments in terms of actual precipitation observed prior to flight. Therefore, a validation scheme using "ground truth" data is essential for the mission.

Since the objective of the proposed mission is to measure rainfall around the circumference of the Earth in tropical latitudes, ground truth sites should be located at several representative points in low latitudes. At these sites, instrumentation should be established for the accurate determination of instantaneous surface precipitation rates over areas corresponding to the size of the proposed mission footprint, as well as average amounts over larger areas (e.g., 500 by 500 km) and longer time periods (e.g., one month). In addition to the rainfall amount, the horizontal variability, time variability, and vertical distribution of the precipitation should be determined in detail throughout a representative volume of the atmosphere surrounding the ground truth site.

Since no single technique appears to be adequate for determining the amount and structure of precipitation in a volume of the atmosphere, an observational module consisting of a combination of instruments will have to be formulated for each site. Only by employing several techniques at a given site can the desired accuracy be achieved. For example, each module might be developed around a radar located on a coastline. Disdrometers should be employed to determine the raindrop-size-spectrum characteristics required to calibrate the radar reflectivity measurements. A high-density network of rain gages located over the land could be used to check the calibration of the radar measurements and allow them to be applied over the sea with confidence. By employing a network of surface, boundary-layer and upper-air observations (possibly using profiler techniques supplemented by other means at low levels) throughout the region covered by the radar, an independent measure of the net precipitation in the region could be obtained through analysis of the water vapor budget of the region.

The establishment of acceptable "ground truth" regions will require a substantial long-term development program. This will involve research, field experiments, and development of measurement standards to properly calibrate the ground truth sites and to interpret the rainfall observations during the mission.

Four major phases of activity were identified at the workshop:

- *Development of a primary standard.* The proposed key elements of the primary standard are: a two-frequency microwave attenuation link (path length approximately 500 m); a visible and IR attenuation link if feasible; high-precision "rate" rain gages; disdrometers; high-precision vertical and horizontal anemometers; upward-looking microwave radiometers; and upward-viewing Doppler radar if possible.

- *Development of transfer standards.* The second proposed phase will be to transfer the primary standard technology to a large-area array. Because of extensive meteorological instrumentation already in place, the vicinity of the Kennedy Space Center, Florida has been suggested. Long microwave attenuation links (10 to 30 km) perhaps in a circular pattern were proposed along with the temporary use of one of the National Science Foundation (NSF)-supported multiparameter radars (e.g., NCAR CP-2 radar). The multiparameter radar, calibrated with the microwave attenuation links, would then become the large-area transfer standard. The array would also contain rain gages and Doppler radar and possibly upward-viewing radiometers. Rainfall amount over the area could also be derived indirectly through flux divergence analysis (i.e., analysis of downward mass transport of air in precipitating convective systems). This will require several Portable Automated Mesonet Systems (PAMs) in the array. For ocean pre-mission ground truth studies, it is proposed to upgrade and digitize at least one island station radar (e.g., Kwajalein). Establishment of attenuation links on oil rigs in the Gulf of Mexico and the possible use of submerged hydrophones for acoustic determination of rainfall should also be investigated.

- *Development of the mission ground truth system.* The next phase would be the calibration and/or deployment of ground truth systems in representative regions for the flight mission. It is anticipated that for hundreds of kilometer size area statistics, available weather radars and associated conventional equipment can be, for the most part, calibrated well enough with the transfer standards. However, it may be necessary to augment standard meteorological measurements, perhaps using PAMS, in some regions to estimate total rainfall through mass transport/heat budget analysis over the area, if that technique proves feasible.

- *Field experiments.* Field experiments, which are an integral part of research associated with a flight project such as that proposed here, cannot be adequately assessed at this time because of their multipurpose nature and dependence on many other sequential factors. In most, if not all cases, pre-mission field experiments will serve a multiplicity of research and mission development objectives, that is, aircraft flights for radar and radiometer instrument/system development, algorithm development and testing, physical process studies of rainfall initiation and distribution characteristics, and not least, the development of primary and transfer standards leading to establishment of large-area ground truth for the mission. *During the mission,* carefully designed field experiments will be necessary to assess, understand, and possibly enhance the 3-year data set that is to be developed. Both for time advantage and to conserve resources, an important task will be to identify related experiments being planned for other projects and research efforts that can be augmented or influenced in such a way as to help meet mission requirements and NASA's precipitation research efforts, e.g., the Equatorial Mesoscale Experiment, Florida Deep Convection Experiment, the National STORM program, etc.

1. INTRODUCTION

1.1 Importance of Tropical Precipitation to Global Climate

The planetary scale movements of the atmosphere and ocean are driven mainly by thermal contrasts over the horizontal expanse of the Earth. On the largest spatial scales these contrasts are ultimately caused by the nonuniform heating of the atmosphere brought about by the differences between absorbed solar radiation and emitted terrestrial radiation back to space — the Earth radiation budget.

Most of the heat actually gets into the atmosphere first in the form of latent heat of water vapor, evaporated into the air from the warm low latitude oceans and continents. In the tropics, the air currents carry the water vapor equatorward; it is only released as sensible heat much later when precipitating clouds are formed. The main firebox of the tropical atmosphere is concentrated in a relatively few convergent portions of the equatorial trough zone where clusters of towering cumulonimbus clouds (about 2000 "hot towers" at any one time around the globe, Riehl and Simpson, 1979) create the pressure gradients which drive the meridional circulation of the Hadley cell, which has localized rising motions in the cloud clusters near the Equator and is mainly dominated by compensating subsidence elsewhere, particularly in the equatorward-flowing trade wind zones of both hemispheres.

Tropical cloud clusters are formed by a complex combination of dynamical processes throughout the depth of the troposphere. They may live from several hours to several weeks, generally migrating or propagating in the direction of the prevailing airflow. Strong modulations in their intensity are often produced by continents, coast lines, or strong sea surface temperature anomalies. In a gross statistical sense, precipitation is a rough indication of the location and intensity of latent heat release, although the actual condensation of the water vapor into small cloud drops may take place as much as tens of kilometers away from where the much larger precipitating hydrometeors form and fall to the surface as rain.

In addition to the near-equatorial band of clusters playing the key role in maintaining the poleward overturning meridional circulation of the Hadley cell, longitudinal variations in cluster frequency and intensity associated with continent-ocean boundaries, particularly in the Pacific basin area, act as a key mechanism in a long-time-scale zonal circulation pattern, called the Walker circulation. The shifts between two predominant patterns in the Walker circulation are called the Southern Oscillation. Of particular interest is the ENSO linkage (El Niño Southern Oscillation) in the Pacific and Indian Ocean areas shown in Figure 1 (Rasmusson and Carpenter, 1981) although similar phenomena have been hypothesized to occur in other ocean basins (e.g., Philander, 1986). In a "normal" or non El Nino situation, cloud clusters and their associated ascent are strong over the maritime continent (of Australia) with trans-Pacific clusters lying along a single or double band displaced 5° or more away from the equatorial waters, which are usually cool due to upwelling.
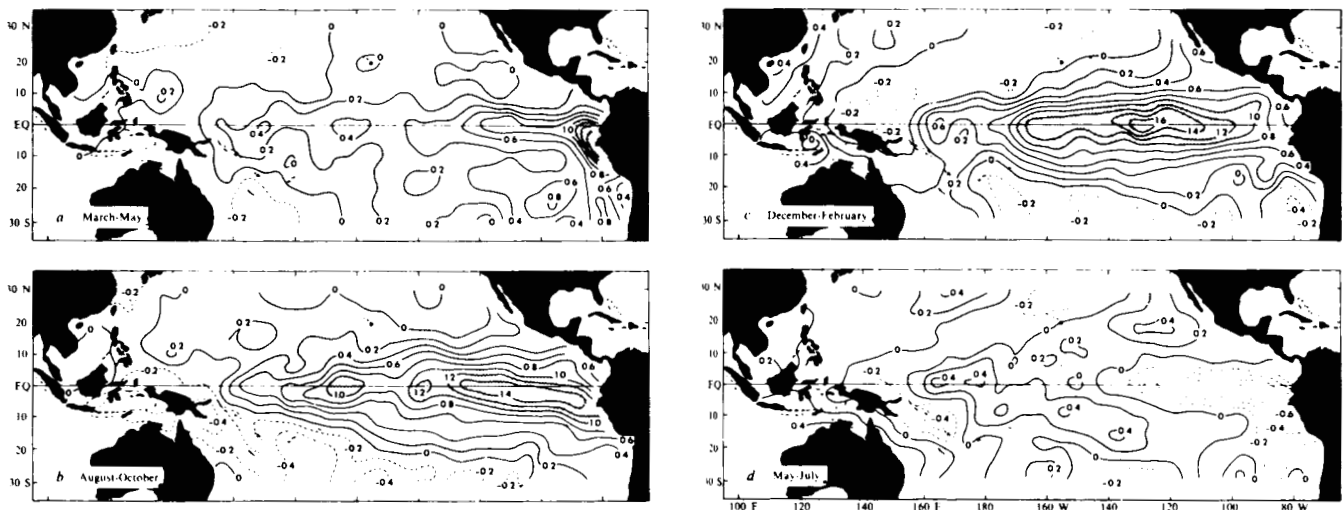
Figure 1. Sea-surface temperature anomalies for a composite El Niño event (from Rasmusson and Carpenter, 1981). (A) March, April, and May average during El Niño; (B) Average for the following August through October; (C) Average for the following December through January.

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An ENSO event is the result of a dynamical instability of the coupled ocean-atmosphere system (Lau, 1981; Philander et al., 1984). It is believed to begin as a weakening of the trade winds in the western Pacific, leading to reduced equatorial upwelling and to a pool of very warm water in the eastern Pacific Ocean surface waters. The warm pool begins to evolve westward toward the dateline (Cane, 1983; Philander, 1983). A composite of such a sequence is shown in Figure 1, indicating a typical life cycle which lasts about a year and usually is strongly phase locked with the seasonal cycle. The events recur with irregular intervals of roughly 2 to 6 years. During an ENSO event there are profound effects upon the weather worldwide but especially throughout the tropics, where climate anomalies are manifested in terms of large variations in precipitation. For example, during the great El Nino event of 1982 to 1983, there was very severe drought across the entire Indian Ocean Basin—from Africa eastward to Australia and northward to India and the Phillippines. A great fire in Borneo in 1983 burned a wooded area the size of Massachusetts and Connecticut combined. The East Indies island group, stretching from Indo-China to Australia, exhibits enormous seasonal and interannual variability in precipitation, much of which is correlated with ENSO events.

Tropical rain pattern variations can also affect midlatitude climate. A teleconnection mechanism has been identified in the large-scale atmospheric wave source action of the increased convective activity in the mid-Pacific when the sea surface temperature warm anomalies occur (Shukla and Wallace, 1983). In GCM experiments, nearly stationary wave patterns emanate from the intensified convection over the central Pacific, which is postulated to result from the warm anomalies. The positioning of the peaks and troughs of these persistent wave patterns are believed to have long-lasting weather and climate implications, not only for nearby regions but also for areas thousands of kilometers away. Rasmusson and Wallace (1983) found that weather and climate systems even in North America are shifted persistently for months during an ENSO event. The role of the 40-to 50-day variation in tropical rainfall is also of particular interest, since it is strongest at the location of the maritime continent and may act as a trigger for ENSO (Lau and Chan, 1985, 1986; Lau and Lau, 1986; Knutson and Weickmann, 1987). Figure 2 shows such a teleconnection pattern in the geopotential height field derived from 30 years of radiosonde data (Horel and Wallace, 1981). Smaller intensity analogs to ENSO occur almost every year as part of the normal seasonal cycle; hence, clues about tropical forcing and its consequences can be found in data sets that do not contain a full ENSO event.
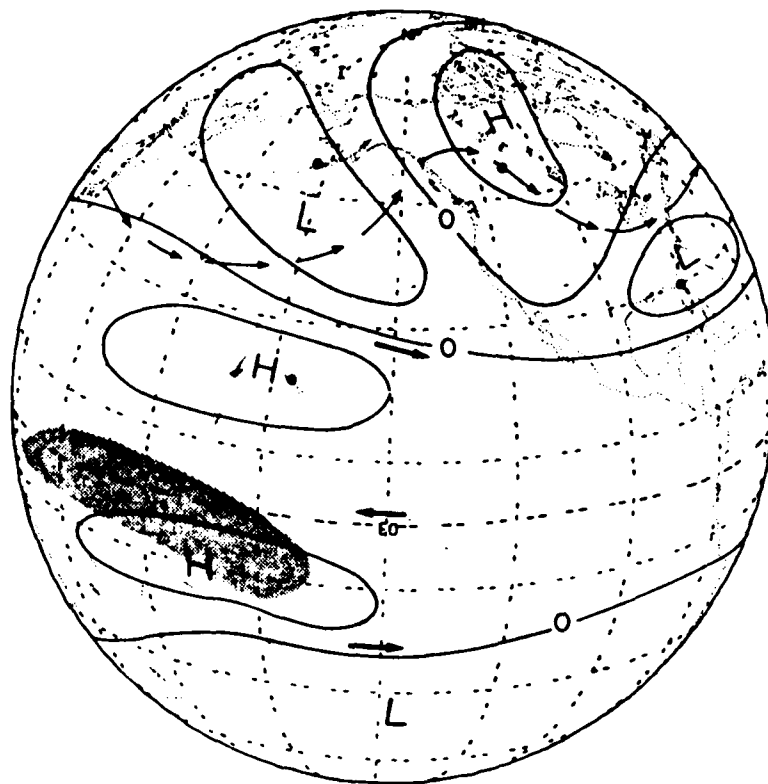
Figure 2. Schematic illustration of hypothesized global pattern of middle and upper tropospheric geopotential height anomalies (solid lines) during a Northern Hemisphere winter that occurs during an episode of warm sea surface temperatures in the equatorial Pacific (from Horel and Wallace, 1981).

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The large-scale aspects of how a tropical sea surface temperature anomaly is translated into anomalous global weather have been the subject of many recent modeling studies (e.g., Suarez, 1985, other papers in the same volume). These studies with sophisticated global atmospheric simulation models are encouraging from a practical forecasting point of view, in that they do exhibit the long-range influences connected to tropical heat sources that have been found in statistical data studies.

1.2 Establishment of Organized Programs to Study Climate in the Tropics

The ability to forecast global-scale effects of tropical climate anomalies is a major goal of climate research and one that may have significant societal benefits. The World Climate Research Programme (WCRP), in cooperation with the Government science agencies of many countries and especially with the strong support of the United States National Academy of Sciences (NAS), has emphasized the importance of the tropical/global climate connection and has initiated a 10-year project beginning in 1985 to gain a better understanding of these phenomena (Interannual Variability of the Tropical Oceans and Global Atmosphere (TOGA). TOGA goals include gathering improved data over the tropical regions in order to determine the level of predictability of the tropical ocean/global atmosphere. Parallel modeling studies will be oriented toward understanding observed changes and forecasting the effects of evolving conditions on future climate.

1.3 Observational Data Needs

With these concerns regarding the crucial need for tropical precipitation observations, a free-flying satellite dedicated to the measurement of rainfall in the tropics is proposed. The primary aim is to collect data that will be useful in the understanding of weather, climate, and hydrological processes. The spacecraft orbit and sensors are especially selected to overcome the unique challenges inherent in measuring rainfall. The main data-set goal is to obtain a 3-year-minimum time series of 30-day averages of rainfall rates. The data set will be for rectangles in the tropics, at all longitudes, whose area is equivalent to 500-km-sided squares. Sampling errors are to be of the order of a few percent.

The plan is to launch the spacecraft in a 30° inclination orbit at about 300-km altitude. Sensors planned to be on board the spacecraft include a multichannel scanning passive microwave radiometer with about 7-km resolution in key channels, a dual-frequency microwave precipitation radar with 3- to 4-km resolution, and a multichannel visible/infrared radiometer with better than 0.5-km resolution. All three instruments will scan across nadir, making a very dense sample of measurements along the spacecraft track. Strategies are being developed to make best use of data from all three instruments as well as other satellite data that may be available to reduce the biases in the measurements of the individual instruments.

The mission as now conceived will overlap with the international TOGA project, which is to run through 1995. Not only will valuable precipitation data be provided on a worldwide basis to TOGA, but also TOGA experiments will be able to provide large-scale ground truth information to support mission data interpretation and analysis.

Although the specific sensors to be flown have not been defined, it is convenient to focus on an existing passive microwave radiometer and an existing visible/infrared radiometer to help clarify the planning process. The electrically scanning microwave radiometer (ESMR) is taken as the prototype passive radiometer in what follows and the Advanced Very High Resolution Radiometer (AVHRR) is taken as the prototype visible/infrared radiometer with a provision for a nighttime visible channel. ESMR flew successfully on the Nimbus-5 satellite, and AVHRR is still flying on the NOAA weather satellites. A precipitation radar on the other hand has not flown on any previous free-flyer missions, but its proposed characteristics are discussed in Section 3 of this report.

ESMR can measure light-to-moderate rainfall over the oceans. It will have a swath width along the satellite track of 600 km with about 80 pixels of size roughly 7 km each. The crosstrack sweep time is such that contiguous rows of pixels can be achieved along the track. Consequently, 180,000 readings can be taken in 30 days with ESMR for any given 500-km-sided grid box. The orbit inclination is such that any box is at least partially visited twice or more every day.

AVHRR is capable of measuring cloup-top temperatures and other cloud parameters relevant to rain rates. This sensor with its < 0.5-km horizontal resolution will provide a base rainfall predictor that can then be improved upon by the passive and active microwave techniques. It will also serve as a transfer standard from previous technology.

The proposed precipitation radar has the capability of estimating the rain column height (± 200 m) over land and sea at a horizontal resolution of 3 km. The resulting column-height climatology is needed in the interpretation of

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ESMR results and may be a good estimator of rain rate itself. In addition, the radar should be capable of estimating rain rate by backscattered power at two frequencies. Another analysis mode to be explored is the extinction of power as the beam goes through the rain and is reflected back from the surface.

The radar is planned to have a swath width of 150 km; hence, the sampling density is less than ESMRs by a factor of four, but the number of physically independent measurements of rain rate is significantly augmented. The number of physically independent measurements is very important since the methodology of data interpretation is likely to involve the estimation of several parameters in a multiparameter rain-rate probability distribution function.

Figure 3 shows an example of how a satellite might be configured for this experiment, making use of the shuttle-compatible bus that was used on the Earth Radiation Budget Satellite.
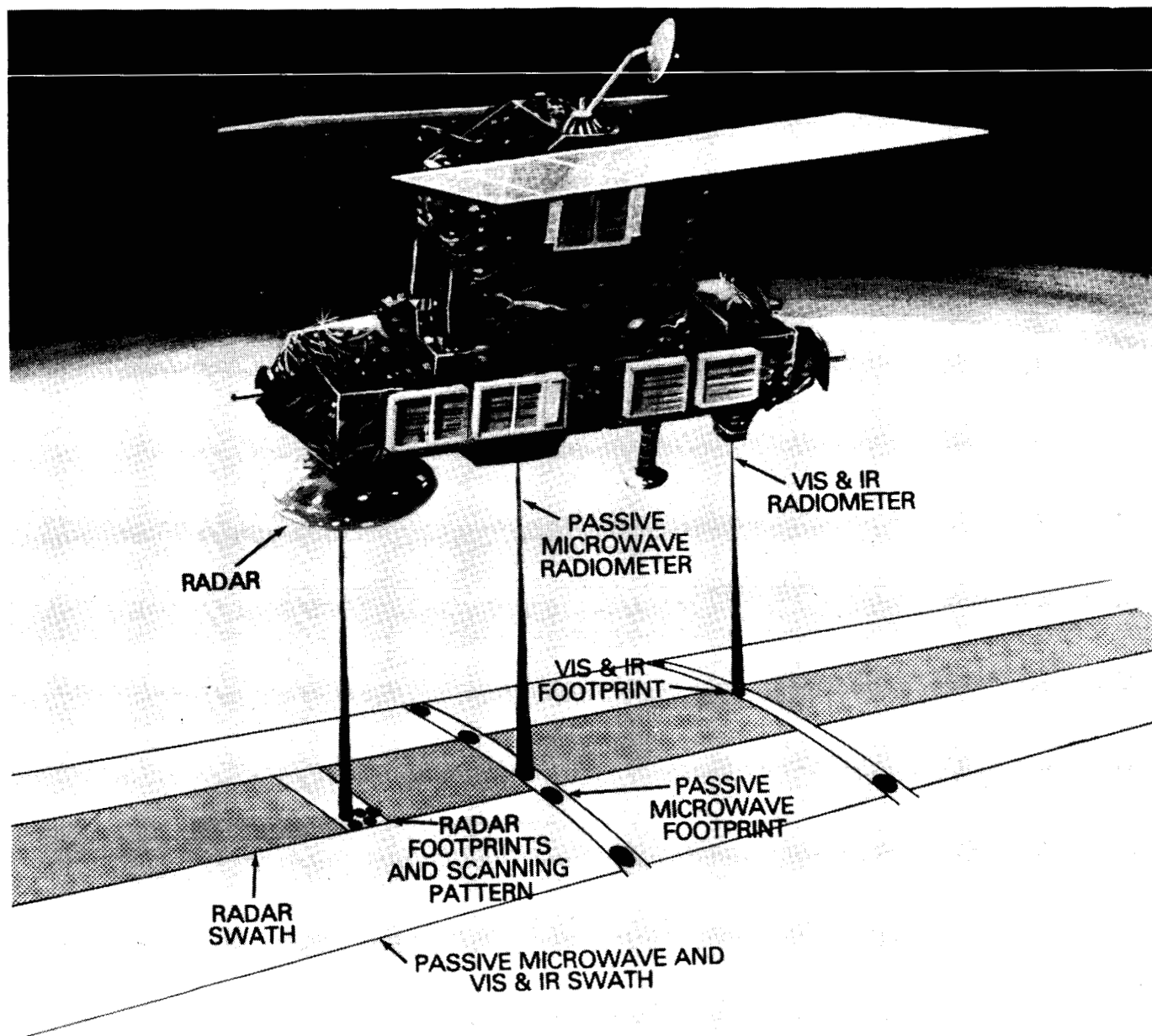
Figure 3.   Sketch of possible tropical rainfall measuring satellite.

1.4 Relationship of a Proposed Tropical Rainfall Measuring Mission to Goals of the World Climate Research Programme

The weakest link in our understanding of the sequence of processes connecting sea-state anomaly and distant climate is lack of a good rainfall time series over the tropical Earth for validating our climate models. The ability of numerical simulation models of the atmosphere to mimic the migratory behavior of rain patterns is a measure of their ability to translate boundary condition changes into predictions of interest. However, since the conversion of latent heat to precipitation through the cloud-clustering mechanism occurs on scales much smaller than any global numerical model can resolve, there are many "subgrid scale" effects that must be incorporated in the models semi-empirically. Such formulations require data for testing and verification. As models and theoretical understanding improve with increased computing resources and smarter algorithms, there will be an impasse in the 1990's when the data used to validate the models will simply be inadequate for the task. *Unless the planning and means for gathering a high quality precipitation data set for model verification in the next decade are set in place now, climate forecast skill will be stunted far short of its potential.*

Precipitation fields in space and time are extremely difficult to measure, even more difficult to predict, and extremely difficult to verify mainly because of their sparse and noisy space/time textures. This is especially true over remote regions of the tropical oceans. The present status of large-scale precipitation monitoring, being limited by the expense and sheer logistic difficulties of continuous space/time coverage, is notoriously inadequate for modern climate forecasting research. *Therefore, to assure an adequate precipitation data set, space-based observations are required.*

1.5 Principal Focus of Tropical Rainfall Measuring Mission Studies — the Tropical Convergence Zones

The organization of tropical convection has been the subject of many theoretical and field studies over the last thirty years (for an overview see the articles by J. Simpson, 1983a, 1983b, 1983c). Figure 4 (Houze, 1981) illustrates the contrast between the low-latitude convective band in the central and eastern Pacific and cloud fields in the midlatitudes. It is clear that the cloud systems across the Pacific are very grainy but are clearly grouped together in clusters. This fine ribbon of clouds is usually found a few degrees north of the Equator over the Atlantic and Pacific Oceans. The behavior of this feature, as well as the regional and global effects of the massive area of convective activity associated with the west Pacific Australasian monsoon complex are of crucial concern to this mission. Other high priority areas of study include the precipitation maximum that migrates seasonally between the Amazon Basin and the Central American region, and a similar, seasonally migrating maximum over sub-Sahara Africa, whose importance has been vividly illustrated by the recent, devastating African droughts. It is the clouds in this fine ribbon around the globe that concern us in this mission. Note that over land such as the Amazon valley, the convective activity is much more extensive and certainly more intense.
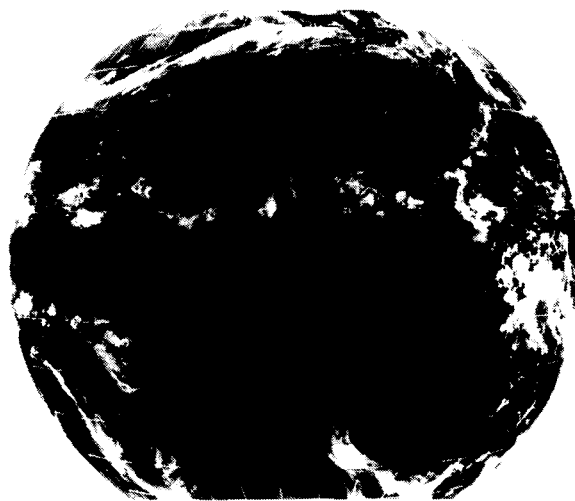
Figure 4.   Infrared satellite picture illustrating location of the ITCZ over the Pacific (from Houze, 1981).

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Much has been learned about tropical convection from case studies in the field such as GATE (GARP Atlantic Tropical Experiment; Global Atmospheric Research Program (GARP). More than 1000 research papers came from this detailed study (perhaps most pertinent here is the paper by Houze and Betts, 1981). A key part of the experiment was conducted using 12 ships with radars and sounding equipment and numerous aircraft in the tropical Atlantic during the summer of 1974 during three intensive periods lasting about three weeks each (GATE I, II, and III). During each period an array of ships was placed in an area of horizontal radius 280 km. Rain rate and other variables were monitored by gages and radars from all the ships and the data were pooled at 15-minute intervals and binned in 4-km square boxes. From these data we get some idea about the space/time scales of tropical rain and how it is distributed between thin convective towers and larger mesoscale features. Because of its continuous coverage and the availability of the data, GATE has provided one of the most important data sets that can be used in preparatory research for TRMM.

More research with tropical clusters is needed to further understand the TRMM measurement process because the scales of convective activity are comparable to the footprint size of both the proposed passive and active microwave instruments. In addition, TRMM passive microwave sensors can only read vertical integrals of raindrops. This vertical integral smooths to some extent the horizontal irregularities of the patterns. Such smoothing helps in controlling certain measurement biases, which will be discussed later. Our present knowledge of the vertical structure of these systems is meager and more field experiments (such as the Equatorial Mesoscale Experiment (EMEX), to be conducted off the northern coast of Australia in January 1987) are needed to clarify some of these questions. Data acquisition and analysis must also be accompanied by a significant modeling component. For example, Tao and Simpson (1984) have demonstrated the usefulness of a numerical convection model with horizontal resolution of one kilometer. A more advanced version of this model and other cloud microphysical-dynamic models are being coupled with microwave radiative transfer models to test and improve the rainfall retrieval algorithms for the planned instrument complement. This kind of modeling research, with more complete descriptions of the phase of hydrometeors, will be useful in tailoring TRMM measurement algorithms.

1.6   Additional Benefits of Tropical Rainfall Measuring Mission

In addition to developing a climatological rainfall data set for purposes of model validation, TRMM can contribute to a number of other areas of scientific inquiry. The monsoon of India still has many poorly understood aspects and such a mission will help to clarify these by building a reliable data set of the precipitation over the Indian Ocean. For example, the Monsoon Experiment (MONEX) provided a detailed case study of one such monsoon cycle during the 1979 summer, but there is need for a reliable smoothed time series of rainfall patterns over the region. Such a data set will help in model verification for monsoon prediction and further our understanding of the process of combining rain gage data with satellite data.

TRMM studies should also improve our understanding of diurnal variations in rainfall. For example, during winter MONEX (December 9 to 29, 1978), aircraft and coastal radar studies off the coast of Borneo demonstrated important cooperative effects between land and sea surface that in fact dominate the entire maritime continent. Such effects can lead to exaggerated diurnal variations in precipitation even over ocean surfaces (e.g., Churchill and Houze, 1984).

TRMM measurements can improve the quality of precipitation time series from land areas and at long last may allow us to compare the time series over land and ocean. Many tropical land surface regions of the world have poorly recorded precipitation time series, yet such data are of immense value in climate dynamics research because of their implications for the global energy budget. Aside from weather and climate forecasting, precipitation and surface (including biosphere) monitoring (Tucker et al., 1985) can be used to objectively assess the recent history of the environmental state in these (mainly) economically less developed regions. This information can be of use for policy planning purposes. For instance, the recent episodes of drought in the Sahel region of Africa have occurred in regions where station density and observation reliability are especially poor. In fact, the most severely affected areas have such poor station sampling that it would not be possible to tell objectively from them whether or not there was a drought in Ethiopia in 1984 (Ropelewski, 1984). From the present TRMM viewpoint it appears that precipitation systems in North Africa are long-enough lived (several days but propagating) that twice daily revisits with a space-based radar would give sufficient sampling to provide an improved objective monitoring of moisture in that region.

Results from TRMM may contribute toward understanding longer-term (decadal-scale) changes in tropical precipitation. Nicholson (1983) has collected data from a wide variety of sources to conclude that there are long-term trends in the precipitation regimes in sub-Saharan Africa over the last 75 years. Unlike some other areas in Africa, drought in North Africa does not appear to be dominated by ENSO time scales, but rather tends to occur on decadal

time scales. There are some indications that these trends may be related to decadal-scale trends in ocean surface temperatures (Parker, 1986).

Passive microwave measurements have been demonstrated to be potentially useful in the estimation of soil moisture, especially if two different polarizations are available (Rodgers et al., 1979; Savage and Weinman, 1975). However, even an unpolarized signal can be used in some cases where there is extensive flooding (Allison et al., 1979). Most of the needs of hydrology are in the short-time-scale regime, where the total amount of water falling in a short interval over a catchment basin can be used in a forecast model for ground and surface water runoff. Hydrologists have been successful in developing simulation models for rain fields for use in such applications (Committee on Precipitation, AGU, 1984). While the TRMM orbit sampling characteristics are very different from a network of point gages, the same simulation modeling concepts can be used in the satellite sampling studies. It is possible that TRMM data can be used at least experimentally with other available sources such as point gages or other satellites to fill in sampling gaps and improve hydrology modeling for practical applications in agriculture, power generation, and public safety.

Tropical storms of hurricane or typhoon strength also originate in the neighborhood of the ITCZ before propagating into the subtropics. While tracking of these storms on an operational basis should not be a priority for TRMM, since it can be done better with available geosynchronous sensors, TRMM can contribute to the understanding of these storms by measuring and mapping the precipitation intensity, thus shedding light on the evolution of the storms' energetics. Tropical storms are large-scale compared to TRMM footprints and differ significantly from the smaller, more common clusters that populate the ITCZ. For this reason the biases associated with lack of uniformly filled footprints will be smaller and the month-long averaging process discussed below will not be necessary. Hence, it should be possible to estimate rain from a large tropical storm in essentially real time. Up until now, there has been no way to accurately estimate the rainfall from oceanic tropical cyclones, nor to assess what their contribution is to the tropical water budget and tropical ecology. One of the most important climate questions is the relationship between ENSO and tropical cyclones.

By looking down from space with a pulsed radar, one can also learn about the instantaneous vertical distribution of precipitation-sized hydrometeors. As mentioned earlier, this distribution is related in a gross statistical sense to the distribution of latent heat release, which could be determined accurately from the net difference between condensation and evaporation in an air column. It may be possible, using cloud models combined with observations, to estimate an area average of the vertical distribution of latent heating from the radar observations from TRMM. Some theoretical studies (Hartman, Hendon, and Houze, 1984) indicate that changing the height of the maximum net heating (including radiation) in a model atmosphere from its conventional altitude of about 3500 m to about 7000 m, has a significant effect on the type of planetary waves generated. This suggests that having a climatology of hydrometeor height distribution could be of great benefit to understanding the energy propagation characteristics from the tropics.

Research is underway to investigate how to use the data to obtain the vertical latent heat profile, which would be desirable for this kind of application.

1.7 Existing Rain Climatologies

1.7.1 Surface-Based Observations

For model verification studies, a spatially smoothed time series of monthly precipitation averages is required so that concurrent time-evolving sea surface temperatures can be fed into the atmospheric model as a lower boundary condition. In other words, the interannual variability as it responds to slowly evolving anomalies in surface properties is the desired data set to be used in model verification. There have been numerous attempts over the years to assemble a global precipitation data set (for a brief review, see Mintz, 1981a). As is to be expected, the reliability of the resulting maps is very region dependent. In areas over land that are well populated and economically well developed, the statistics are sufficiently good to use even for hydrological modeling purposes. On the other hand, over much of the world, particularly in the tropics and over the oceans, the situation is far from adequate for climate diagnostics research or for numerical general circulation model verification studies. For example, Figure 5 shows a station network used by climatologists at the National Center for Atmospheric Research (NCAR) (Shea, 1985) for studying the normal monthly precipitation climatology (each indicated station has at least 10 Januaries contributing to the 29-year sample). Stippled areas represent areas where the sampling is especially inadequate.
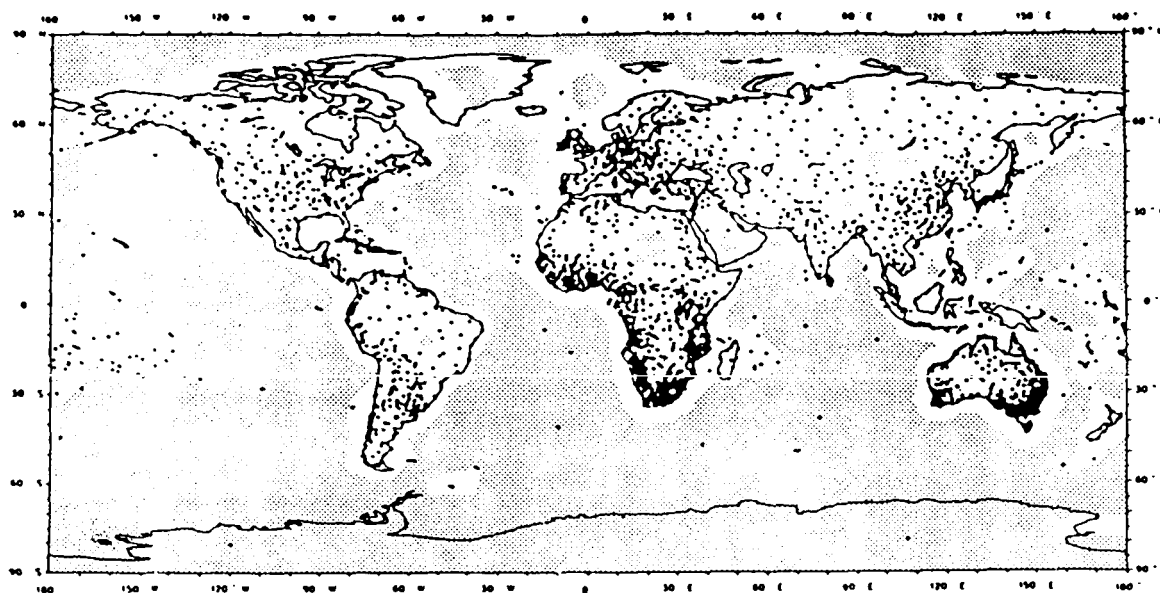
Figure 5. Rainfall station network used by climatologists at NCAR (courtesy D. Shea). Data are for January (1950 to 1979).

Several climatologists have gathered and integrated millions of ship observations of rain *frequency* or other routine weather observations aboard ships-of-opportunity to estimate average total rainfall by various empirical procedures (Jaeger, 1976; Reed and Elliott, 1979; Dorman and Bourke, 1979, 1981). While these reports represent serious attempts with the only existing information, the maps differ from one another in seasonal normals by as much as a factor of two in some regions. Also, these studies only reported maps of the seasonal normals of precipitation as opposed to smoothed time series of data.

1.7.2 Space-Based Observations

The first attempt to map a space-based rainfall time series over the oceans was by Rao et al., (1976). This study used data from the passive electrically steered microwave radiometer (ESMR) on board Nimbus-5. Although their retrieval algorithms were still evolving and sampling rates were low for their smoothing boxes (the instrument was intended for other uses), these investigators were able to unambiguously identify eastward movement of precipitation anomalies associated with an El Niño event.

Motivated by the needs of the TOGA program, plans have been initiated for assembling a smoothed precipitation time series, at least for parts of the tropical Earth, from existing satellite data (World Climate Research Programme, 1986). Pioneered by P. Arkin, a strategy for using infrared data from geosynchronous satellites has been developed. The method (Arkin, 1979; Richards and Arkin, 1981) makes use of an empirical relationship between rainfall and the area of cloud top colder than a certain threshold temperature. When averaged over a month and areas of at least 200 by 200 km², the variations in such an index can explain as much as 70 percent of the variance of rainfall at selected sites (however, 50 percent is a more common figure). Unfortunately, the calibration coefficients change with season and geographical location. Hence, the method is limited simply because it is impossible to calibrate it precisely where the data set is needed most. As an interim standard, however, this data set will have to serve.

As new microwave radiometers are launched on the Defense Meteorological Satellite Program (DMSP) series of polar-orbiting satellites, there will be a new stream of data that can be related to precipitation. WCRP plans to integrate this microwave data with infrared data to improve the precipitation time series. The microwave data from the DMSP satellites will still have the diurnal cycle bias because orbits are Sun synchronous. Furthermore, the satellite sensor, special sensor microwave imager (SSM/I), and platform height will produce footprints several times larger than those proposed for TRMM. *Because of these limitations, existing or planned rainfall data sets are inadequate for resolving crucial scientific questions necessary to progress in climate diagnostic studies and GCM improvement. The significant advances offered by the proposed TRMM observations will substantially reduce the shortcomings previously mentioned.*

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2. SCIENCE REQUIREMENTS AND RELATED PROBLEMS

2.1 Requirements

In mission planning it is imperative to have well-established science requirements so that error tolerances can be set rationally. For the planning exercise we can use the existing data sets even though we understand their limitations. Figure 6 shows the distribution of estimated mean precipitation totals based on the previously mentioned NCAR data set for the month of January. While these are not very reliable, we can obtain some idea of the range of values to be measured and roughly what the climatological requirements shall be. Figure 7 shows the corresponding interannual variability for January precipitation. Note, for example, that over the eastern tropical Pacific the values are near 300 mm in a thin band along the Equator and this varies quickly to a value of 50 mm only about 10° latitude poleward. Similarly the interannual variability is about one-half to a whole of the mean throughout the tropics. *These data suggest that a space/time smoothed series of roughly the resolution of about 5 by 5° in space and 30 days in time will be adequate if the desired accuracy is about 10 to 20 percent* (see Mintz, 1981b; Shukla, 1986). Note that along the equator one may choose averaging boxes that are oblong boxes of the same area rather than squares.
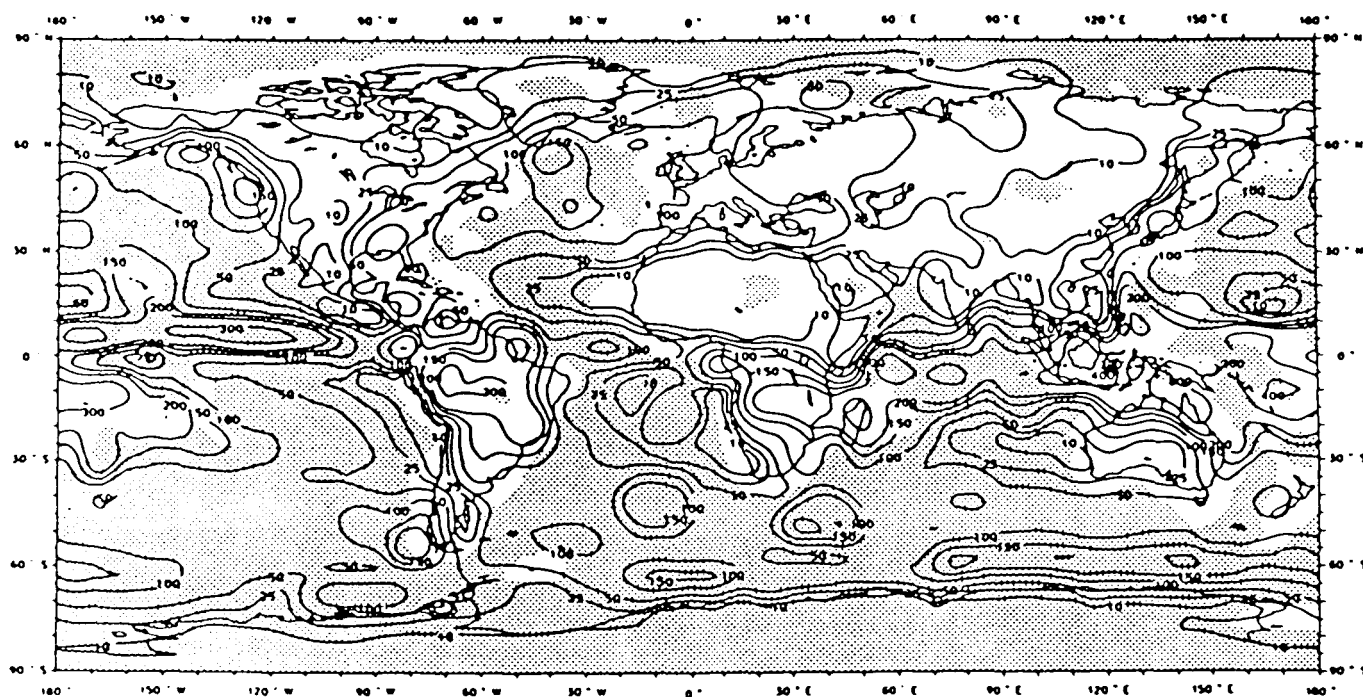
Figure 6.   Mean January precipitation (1950 to 1979) in NCAR climatology (courtesy D. Shea).

The required level of accuracy corresponds to about 0.5 to 1.0 mm/day. The energy equivalent is 15 to 30 Watts/m², which is 5 to 10 percent of the diurnally averaged solar constant. If a 5-km column of air is involved, we can express such a heating rate as 0.2 to 0.4°C per day. Figure 8 (adapted from Schlesinger and Mintz, 1979) shows a 20-day-mean, zonally averaged heating rate from a GCM run to give an idea of these magnitudes. Note in the figure the strong gradient in the troposphere, which is associated with convective motion of this magnitude.

The foregoing discussion of data set error analyses requires clarifying a distinction between statistical descriptions of error such as "variance explained" and the expression of error used here, *percent of true monthly mean.* There will always be measurement error due to sampling gaps or even instrumental noise that is random and unbiased when added to the true monthly value. We can decompose the variance of an ensemble of monthly means as having additive contributions from the natural variability and the random measurement error. For a given measurement error size, large natural variability will lead to a large portion of the total variance of the measurements being accounted for by
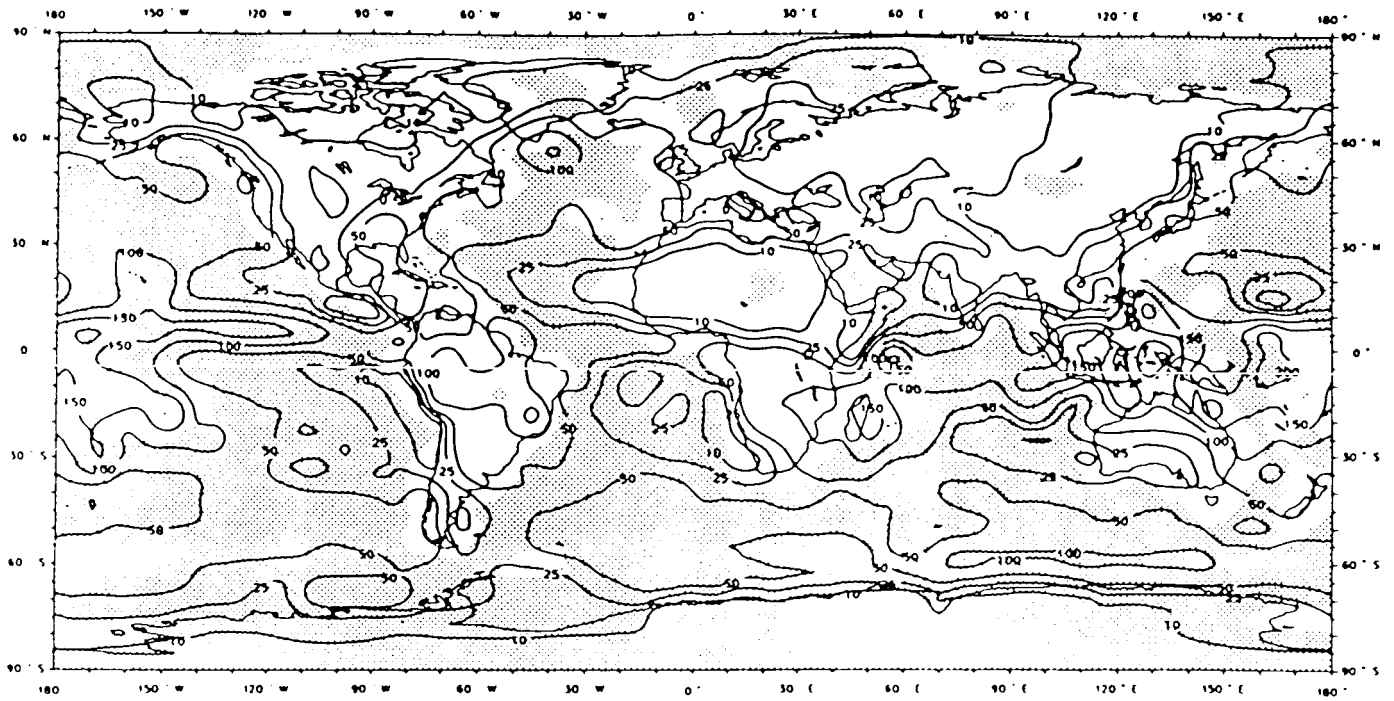
Figure 7. Standard deviation (mm/month) of January rainfall means for the period (1950 to 1979) in NCAR climatology (courtesy D. Shea).
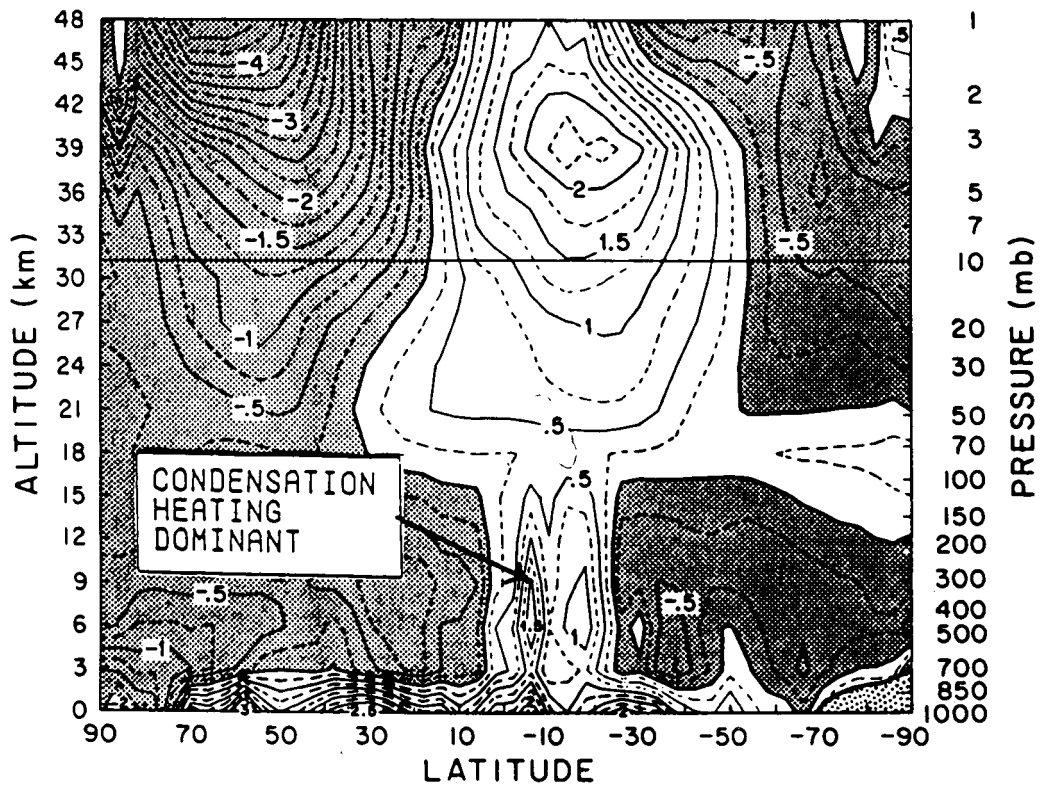
Figure 8. Zonal mean heating rates averaged through 20 days in January for UCLA GCM (from Schlesinger and Mintz, 1979). Note the dominance by latent heat release in the ITCZ.

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the true natural variability. Figure 9 shows how the simple error model just described leads to a relationship between errors in the mean and variance explained. The upper curve is for a highly variable climate (see Figures 6 and 7) and a climate regime that has natural variability about 50 percent of the mean. Most of the tropical precipitation climates of the Earth lie between these values seen as in Figures 6 and 7. Note that a random error in the estimate of the mean monthly rainfall of 10 or even 20 percent still accounts for more than 90 percent of the variance over areas of interest. This figure is to be compared with the variance explained by the empirical methods, which usually are in the range of 35 to 70 percent.

FRACTION OF VARIANCE EXPLAINED
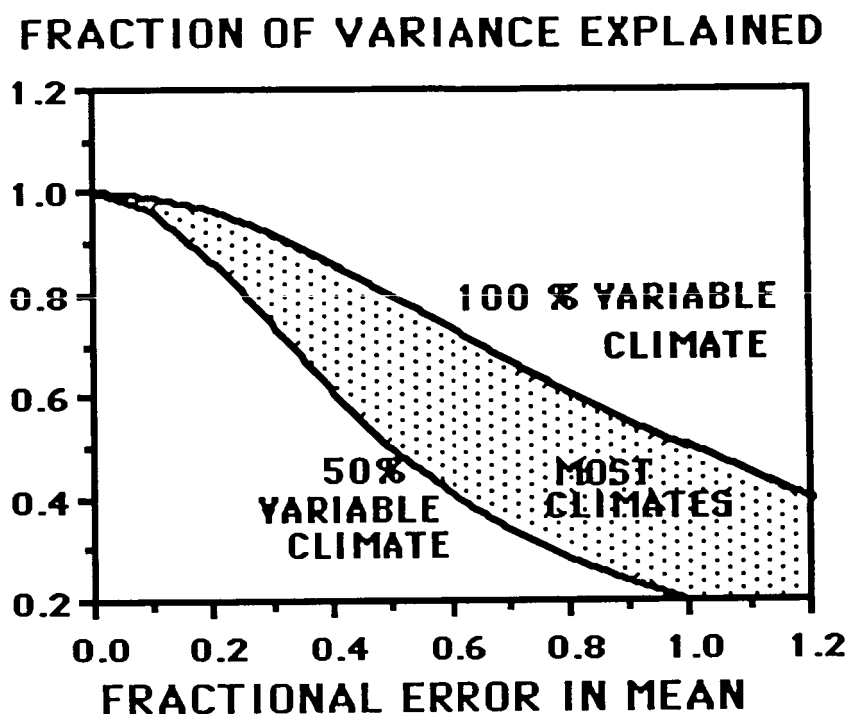
Figure 9. The effect of climate variability on estimates of mean and variance. This figure illustrates that a highly variable climate will lead to a large portion of the total variance in measurements accounted for by the true natural variability. Most tropical climates lie between the two values on this curve.

In the next few sections several challenges will be enumerated and discussed in connection with gathering a tropical precipitation data set. The first of these is sampling errors. Since any physical measurement system involves gaps in space/time there will be errors incurred in estimating the space/time integral of precipitation. Sampling error analysis is an especially difficult task for rain since the probability and statistics of rain are so unusual and so poorly understood. A sampling strategy will be outlined which seems adequate from several lines of reasoning but which still requires further research. Second, the diurnal cycle will be discussed with respect to orbital and sampling studies. Finally, there will be a discussion of the effects of nonuniformly filled footprints. At 19.35 GHz this effect leads to a bias and a random error because of the nonlinear relation between microwave brightness temperature and rainfall rate. Therefore, it is planned to circumvent this problem with the addition of other microwave channels, some of which will be dual polarized. Much of the present sampling error analysis, however, has been based, for a starter, on the 19.35 GHz ESMR channel only.

2.2 Sampling Errors

2.2.1 Need for Hierarchy of Statistical Models

Since it is impossible at present to configure a rain measuring system without some space/time gaps, it is necessary

to employ some kind of sampling design. The present proposed orbit is one with inclination 30° to the Equator. The plan is to estimate the sampling errors in a hierarchy of statistical models, each having its own advantage of simplicity versus veracity.

2.2.2 Sampling Constraints from TRMM Orbit

The first and simplest sampling model counts all the pixel readings that TRMM can collect in the course of a month in a grid box and treats them as independent bits of information. The proposed TRMM orbit, Figure 10, covers the Earth from 30°N to 30°S, one-half the Earth's area, 2.26 by 10^{14} m². (In what follows, ESMR is used as an example of a possible passive microwave radiometer onboard TRMM.) Since ESMR makes about 72 measurements per second, there will be 1.87 by 10^8 readings per month along the track. There are about six hundred 5° by 5° TRMM averaging boxes in the tropics; hence, on the average there will be about 300,000 readings per month in an average TRMM grid box. The density of readings is not uniform over the tropics but is peaked at 30° latitude; at an equatorial box the total is about 180,000 readings. The functional dependence of the sampling density is shown in Figure 11 as a function of latitude for a 30° and a 45° inclination orbit. For the radar, which has 1/4 the swath width and 1/2 the pixel size of ESMR, we find about half this many measurements. Ordinarily in the tropics we can expect it to be raining only about 4 percent of the time so that we can expect to find about 12,000 raining ESMR pixels in a given month in a particular grid box.
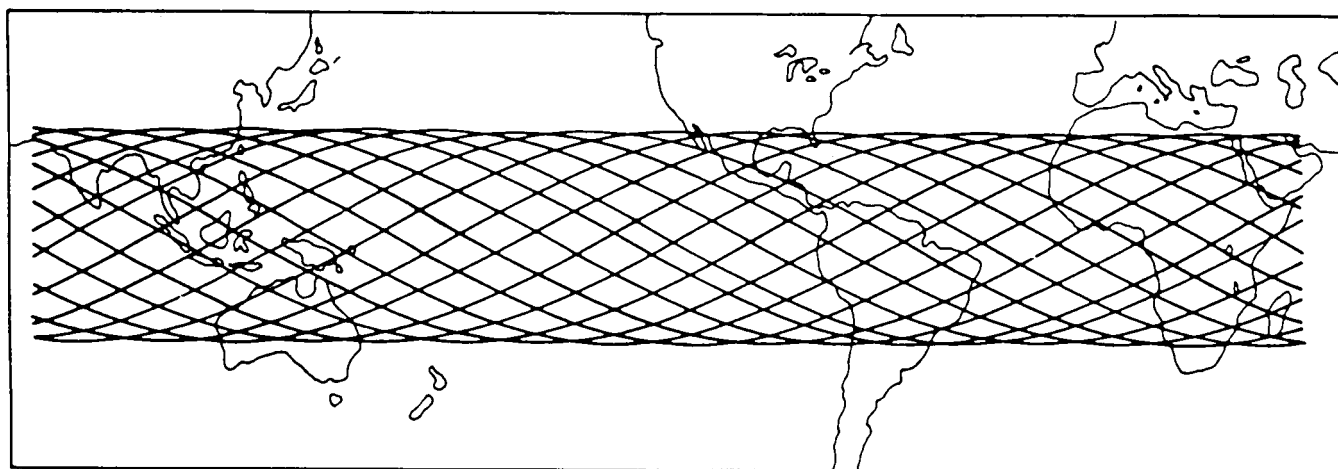
1 DAY (16 ORBIT)

Figure 10. Proposed TRMM orbit.
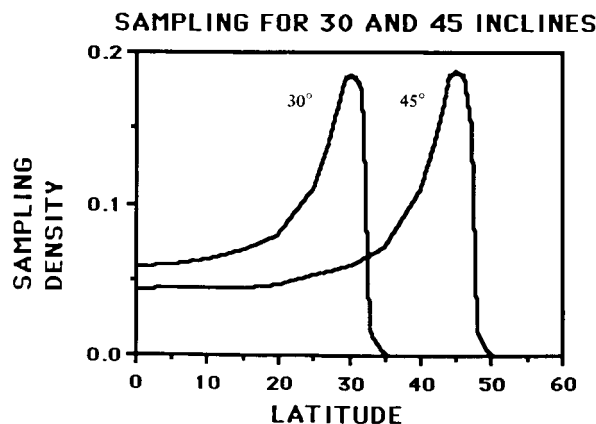
Figure 11. The effect of different orbital inclinations on sample density versus latitude.

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2.2.3 A First-Order Estimate of Rain Rate

According to the foregoing we have about 12,000 measurements each month on which to base our estimate of total rainfall in the averaging box. As a first-order estimate of total rain we need to perform an integral over the probability of different rain rates. Figure 12 is a schematic of such a discrete probability distribution function. If we divide the probability into different discrete categories, we can proceed to estimate the probability of a certain rate category for the month and in turn we can estimate the sampling errors associated with this procedure by Poisson statistics (Bulmer, 1979). Roughly speaking, if the categories correspond to probabilities of about $p_i = 1\%$, then the standard error as a fraction of p_i (Poisson statistics) is $1/(p_iN)^{1/2}$, where N is the total number of independent samples (300,000 here if all readings were independent; therefore, p_iN is 3,000). The problem with this method is that we do not know how many independent samples we have since the information in one pixel is correlated with that in neighboring pixels in space/time. Since the size of tropical cells is about 10 km, we might estimate that their autocorrelation distance is about that size. If this holds, then about 1/10 of the raining pixels are independent and $p_iN = 300$ and therefore, the standard error in estimating the p_i for a certain category is approximately 5.8 percent. When the integral is performed there is a further cancellation since there are 4 categories and we obtain a standard error of 2.9 percent for the total rainfall for the month in an averaging box. If the calculation is repeated for the radar, the result is 5.8 percent.
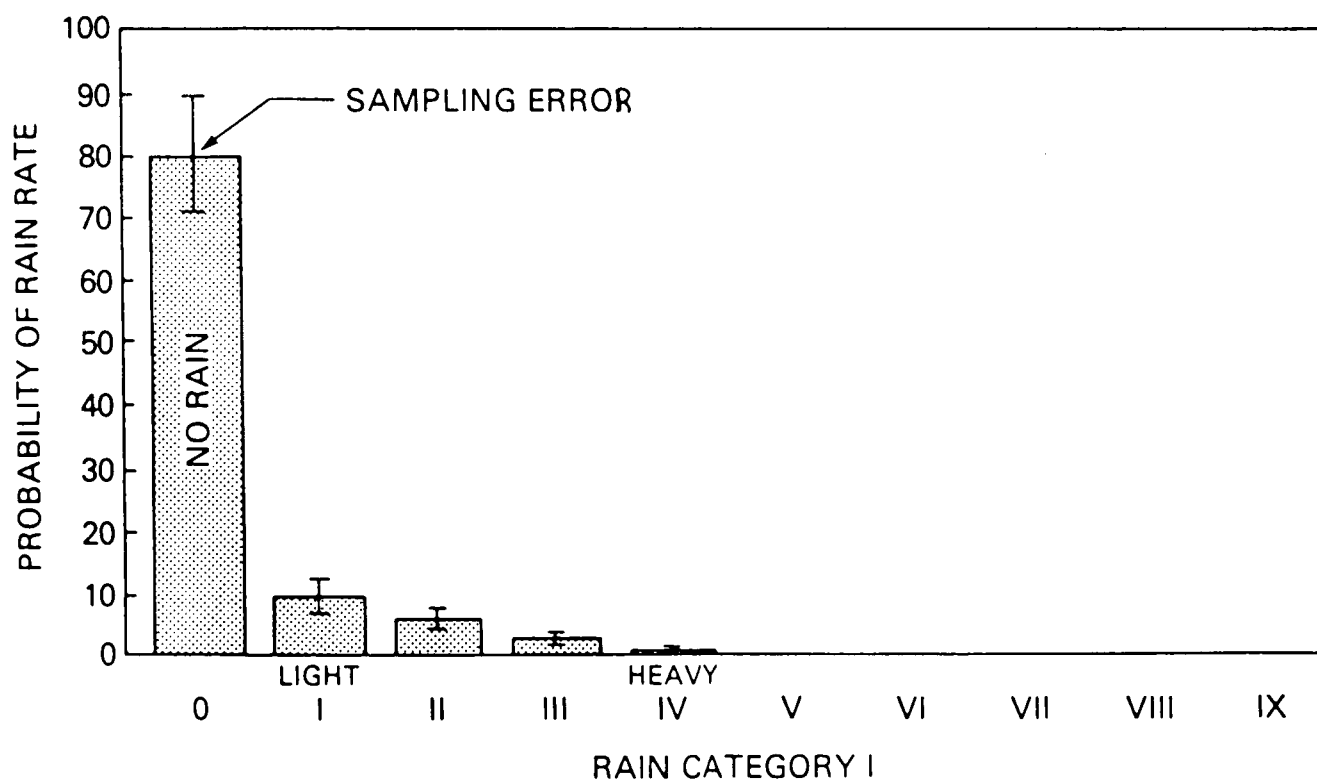
Figure 12. Schematic diagram illustrating probability density function of rainfall rate by categories.

2.2.4 Utilization of GATE Data to Constrain Statistical Models

While the foregoing model is appealing because of its simplicity, we cannot rely on it in practice because of the arbitrariness of the assumptions about the space/time correlation structure. We must try models constrained, if possible, with real data. The most comprehensive data set of tropical rain on a scale comparable to that of interest here is that of GATE (GARP Atlantic Tropical Experiment); (Hudlow and Patterson, 1979), an experiment performed with an array of ships in the tropical Atlantic in the summer of 1974. The ships had radars calibrated with gages on board and the data were taken at 15-minute intervals and binned in 4-km boxes. The GATE area is a hexagonal shape (Figure 13) with width of 280 km. Hence, the GATE area is about 1/4 the size of a TRMM box.

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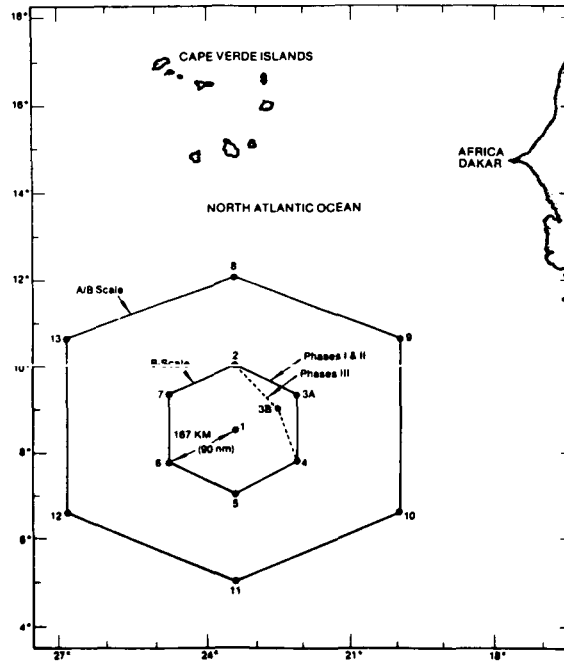
Figure 13.   Observational network for GATE.

   Laughlin (1981) used the GATE I and II data in a study to determine the sampling characteristics as a function of the averaging area. First, it was necessary to study the autocorrelation function of rainfall for different-sized areas. He found that the autocorrelation function could be fitted with an exponential decay function with reasonable accuracy. The characteristic time varied roughly linearly (2/3 power would be more accurate) with length of the edge of an averaging square from about 0.5 hours for a 4 by 4 km² area to about 6.5 hours for a 280 by 280 km² averaging area. GATE I and II analyses showed about the same values for these functions. For many purposes one can consider an independent sampling interval for such a case (exponential autocorrelation function) to be about twice the autocorrelation time (see, for example, Leith, 1973). Figure 14 shows Laughlin's GATE II calculation for the standard error of estimating total rain for the entire GATE area as a function of sampling interval for different averaging periods. The main result for our purposes is that a 12-hour sampling rate leads to errors slightly less than 10 percent. The GATE I calculations are almost identical.
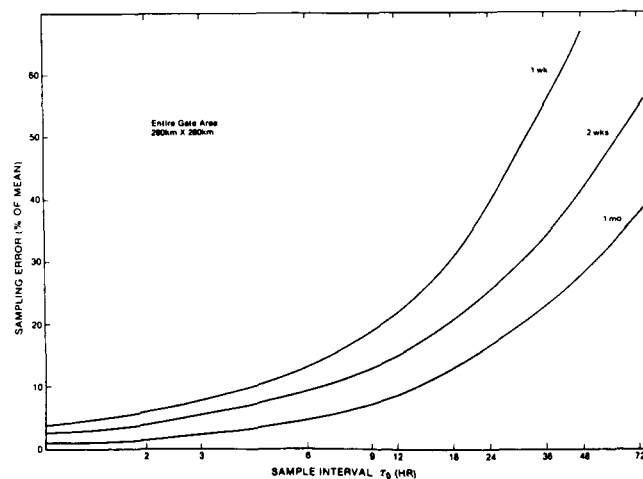
Figure 14.   The relation between sampling error and sampling interval for GATE rainfall data (from Laughlin, 1981).

14

Laughlin's result is less optimistic than the Poisson model because the space/time correlation functions for tropical rain have longer range than we assumed earlier. Some evidence (McConnell, personal communication, 1985) even suggests that these functions are a weak power law [distance$^{-2/3}$]. Laughlin's results also implicitly show that the variance associated with area averages falls off as $A^{-1/3}$ as opposed to A^{-1}; the latter would hold if adding more area simply increased the number of independent samples linearly. Such long-range correlation structure is characteristic of random fields that are statistically self similar (cf., Lovejoy, 1985; Waymire and Gupta, 1985). The main point here is that the fields have unusual properties and caution must be exercised.

While Laughlin's error result is several times larger than the naive model, 10 percent is still well within our tolerances, especially if we consider the addition of other types of data to the pool and that the TRMM averaging areas are 4 times larger (if the averaging area is visited every 12 hours, this would reduce sampling errors by a factor of $(4)^{-1/3} = 0.63$; in fact TRMM would make a partial visit to the grid box at least every 12 hours).

The results of Laughlin's study are of considerable importance to the sampling strategy of TRMM, because they support the conjecture that discontinuous sampling of a highly fluctuating variable can produce reliable estimates of the mean state, provided that the sampling interval for a space/time average is less than the autocorrelation time over the same field. Stated in a different way, if the autocorrelation time is sufficiently long, then multiple sampling provides redundant information and does not add greatly to the statistical significance of the final product. It is clearly necessary to test this conclusion with a number of different approaches. It is the purpose of the next section to outline progress made on some different approaches. Results from these studies support Laughlin's conclusions and therefore the basic goals of the TRMM mission.

2.2.5 Additional Tests of Laughlin's Conclusions

McConnell and North (1986) utilized the GATE rainfall data to test whether discontinuous sampling can yield reliable estimates of different rain rate categories. This approach was motivated by the well-known observation that the heaviest rainfall category involves events of very short duration — the type least likely to be detected with a discontinuous sampling procedure. McConnell and North developed an ensemble estimate of rainfall rate by category by sampling the GATE data at 650-minute intervals, with 9 different starting times for the sampling. They then compared individual ensemble members and their aggregates of snapshots to form an estimate of the contribution to the total by each category. Results (Figure 15) indicate that estimates from discontinuous sampling are within 10 percent of the true averages for each category (based on compilation of data at 15-minute intervals). Results were very similar for both phases I and II of GATE.

GATE Phase I

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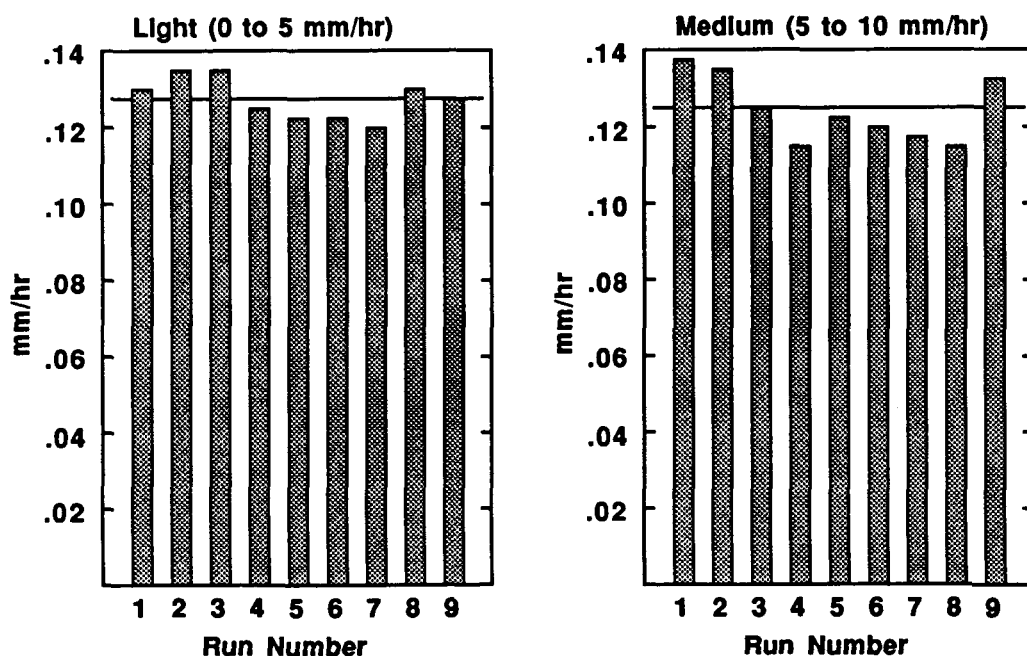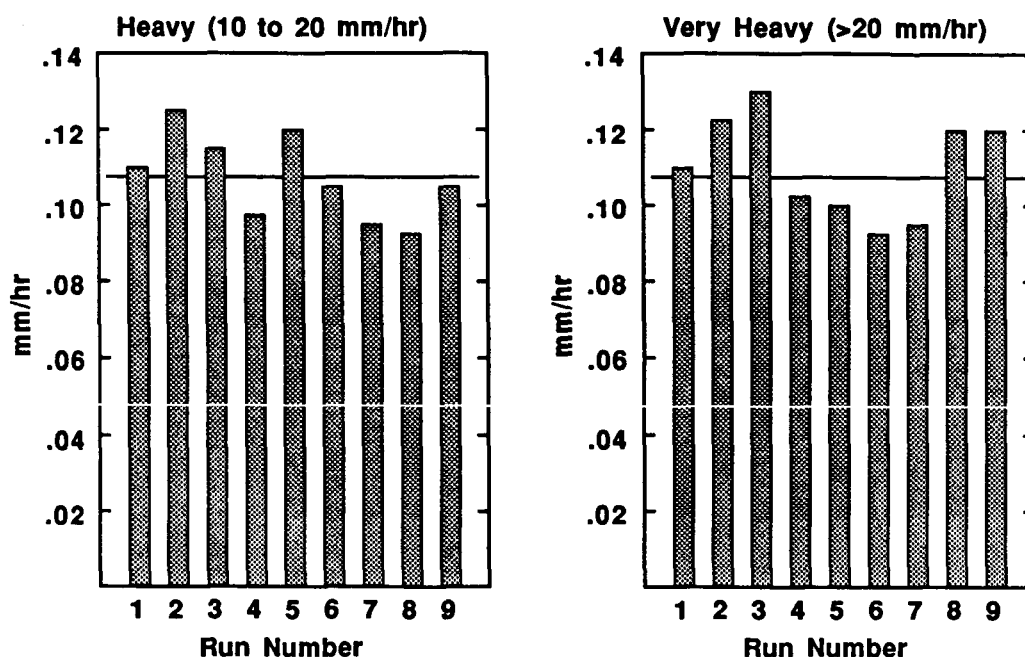
Figure 15. Results from nine realizations of estimates of contributions to area average rainfall from four precipitation categories (from McConnell and North, 1986). The first run was for an imaginary satellite started at 8 a.m. of the first day of GATE phase I with a snapshot of the entire area and returning every 650 minutes throughout the entire 18 days. Run 2 was the same except initialized at 9 a.m. of the first day. The horizontal line shows the "true" contribution from the particular category, as estimated from radar (Hudlow and Patterson, 1979).

Results of McConnell and North (1986) support the hypothesis that, although individual heavy rainfall events are short-lived, their frequency of occurrence is dependent on larger-scale phenomena that have a time scale comparable to the TRMM sampling interval. Enough events are triggered by the large-scale phenomena to yield reliable estimates of the mean by discontinuous sampling of a subset of the data.

There are many other studies from the GATE experiment that are relevant. The review paper by Houze and Betts (1981) points out a number of interesting statistical properties of the GATE rainfall data. Many variates in this data are distributed lognormally; for example, the rain rates, the rain column heights, and the size scale. These facts can be used in parameterizing more sophisticated sampling models as we will now demonstrate.

Chiu et al., (1986) reported at this workshop on a sampling study of the GATE data using a mixed distribution approach. The method involves parameterizing the probability density function (pdf) of rainfall as a sum of a delta function at nonrain weighted by p, the probability of no rain at a visit to a point, and a conditional pdf when raining is lognormal, the latter containing 2 parameters. The strategy is to use the entire pool of data (say for the month or for one of the GATE periods in these exercises) to first estimate the 3 parameters by minimizing a chi square error of fit variable, then to calculate the rain from the expectation value of the pdf. The method has several advantages. For example, one does not have to invoke any assumptions about the correlations in the data. It is easy to study the estimated rain rate for several sparse sampling designs in space/time over the GATE I period. One finds that when the design is too dense, chi square is large because of correlations, but as the sampling density is reduced one finds a convergence (standard error about 2 percent) to the correct rain rate at some optimal sampling density. By employing this procedure one can find for both GATE I and GATE II very good fits to the lognormal pdf (the gamma distribution was noticeably less satisfactory).

As an application of the parameter estimation method to the TRMM orbit design, consider the graph shown in Figure 16. In this case every pixel is read during the GATE I period but the entire GATE B-scale area (see Figure 13) is only visited every 10 hours. The continuous line is the lognormal fit to the data collected in the histogram represented by the blocks. The estimated average rain rate from this procedure for the 18-day period was 0.45 mm/hr with a standard error of 0.03 mm/hr (6.7 percent). The reason for using 10 hours in this example was to cover the diurnal cycle in the 18-day period, as would be the case with TRMM. When a 12-hour revisit time was used, the standard error was

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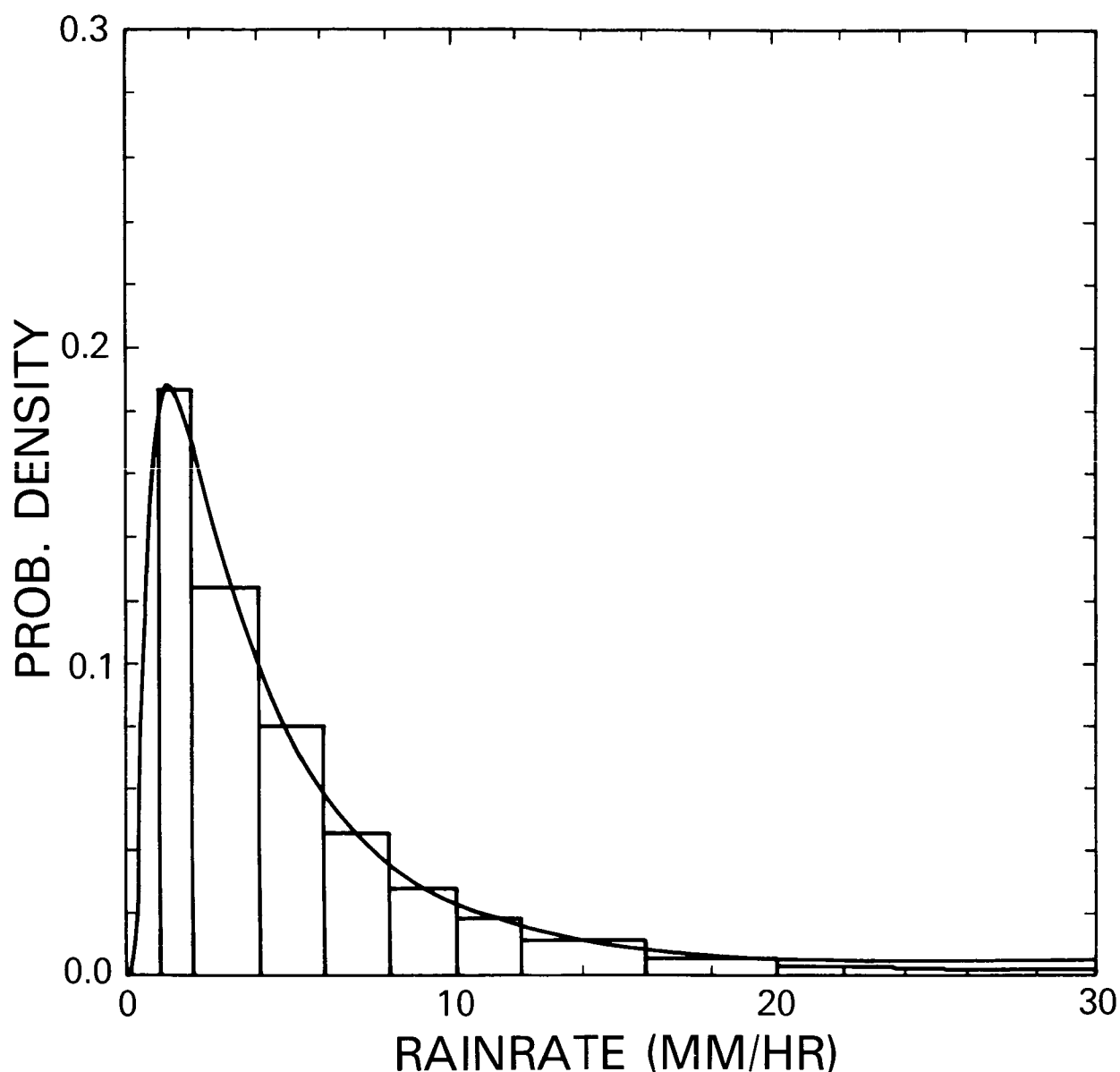
Figure 16.   The probability density function for GATE phase I rainfall. The continuous line is the lognormal fit to the data (from Chiu et al., 1986). This fit shows how low rain rates tend to determine the lognormal parameters.

11 percent. By generating another orbit every 15 minutes, one can develop an ensemble of estimates. They are not statistically independent, of course, but provide some idea of the range of errors. A histogram of estimates of the average rain rate is shown in Figure 17.

Another advantage of the pdf parameter estimation approach is that if the TRMM instruments are unable to measure accurately some of the high rain rate categories, the pdf can still be reliably estimated with the lower categories. This is easily seen by imagining lumping together some of the bins in Figure 16 for the higher rain rates. Indeed, these studies with GATE data indicate that combining all events having rates greater than 15 mm/hr into a single category has hardly any effect (additional random error less than 5 percent) on the final estimate of rain for an interval of the GATE duration (18 days). The results of this study are quantitatively consistent with Laughlin's for the GATE area; that is, on the order of 10 percent errors for the spatially dense, twice-a-day discrete sampling rates in time.

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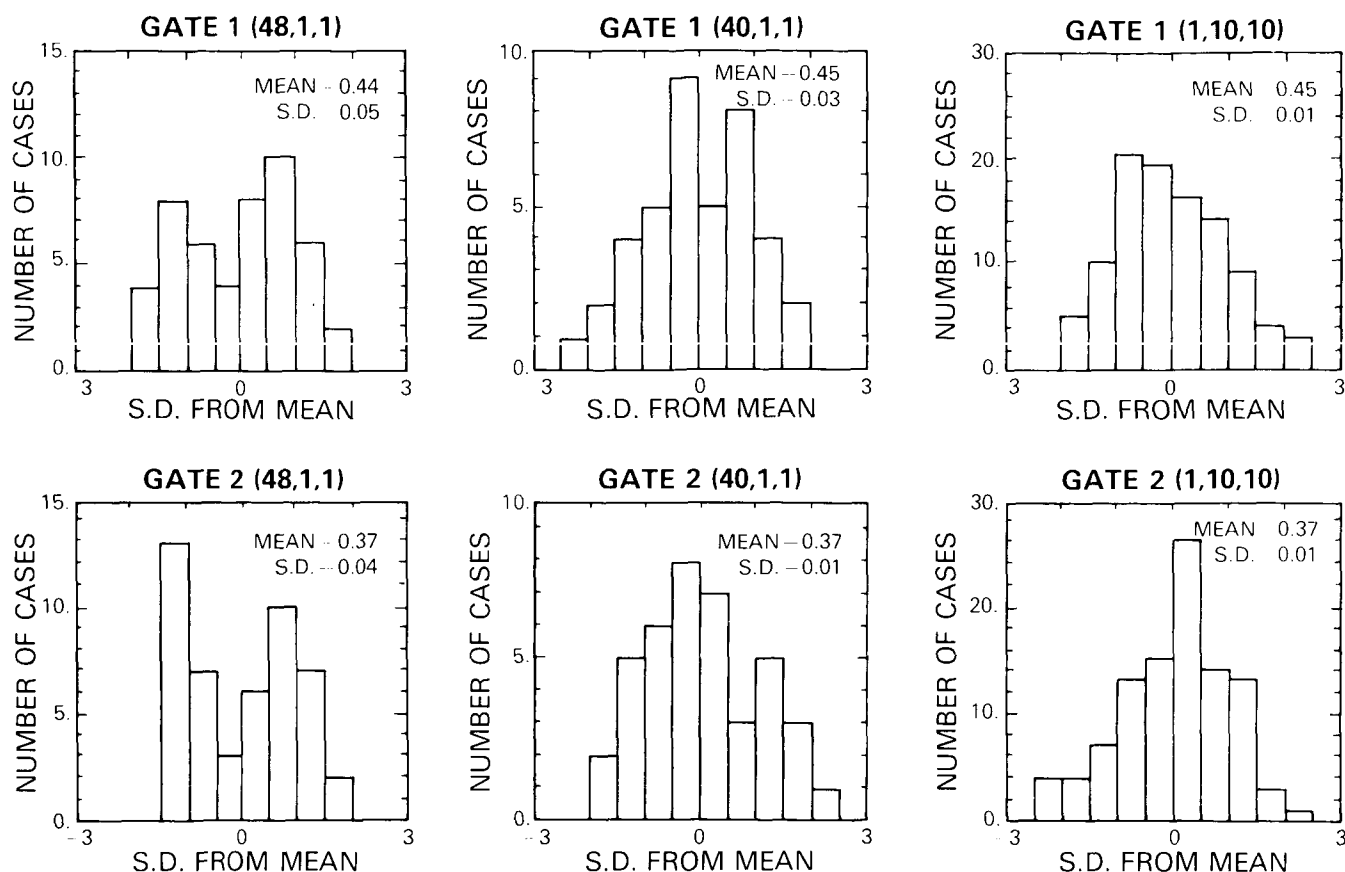
Figure 17.   Histogram of estimates of mean rainfall rates for GATE phases I and II, determined by the probability density function technique of Chiu et al. (1986). Different panels illustrate different sampling strategies. Note that the means for different strategies are very similar, and that the standard deviations are generally 10 percent of the mean, in accordance with results from Laughlin (1981).

Bell (1986) reported on methods of simulating rain from a stochastic rainfield model. The main idea is to develop an algorithm that will produce artificial rain fields that have as much in common with real tropical rain as possible; at least the model fields should be at least as badly behaved as real rain fields are thought to be. These constraints include the lognormal distributions for the size of raining areas and rain rates. Similarly, the space/time autocorrelation structure has to be close to that found in GATE. The group has produced rain fields that look like the GATE data and are efficient enough to use Monte Carlo sampling studies. With this kind of model one hopes to mimic seasonal and diurnal cycles as well as latitude dependences of rain by parameter perturbations to see if these artificial signals can be extracted from sampling and other noise. Another application of the simulation models is to study the advantages of adding in other sources of data such as point rain gages or other geosynchronous and Sun-synchronous satellite data.

While the Bell approach starts with a spectral representation of a Gaussian space/time process and takes the extreme events and converts them to a lognormal process, it is likely that other approaches will be desirable as well, since there will never be enough data to pin down some of the possibly important properties. For example, the hydrology research community has in recent years developed models for floods and other applications. Some of these models employ a constructive probabilistic model in which a sequence of nested Poisson processes generates moving bands of rain (Waymire and Gupta, 1981a, 1981b).

2.2.6 Diurnal Cycle

The diurnal cycle of rainfall over the oceans can be sizable as can be seen in the GATE measurements in Figure 18 (taken from Albright et al., 1981). The typical afternoon maximum in the GATE area seems to be no fluke as it was
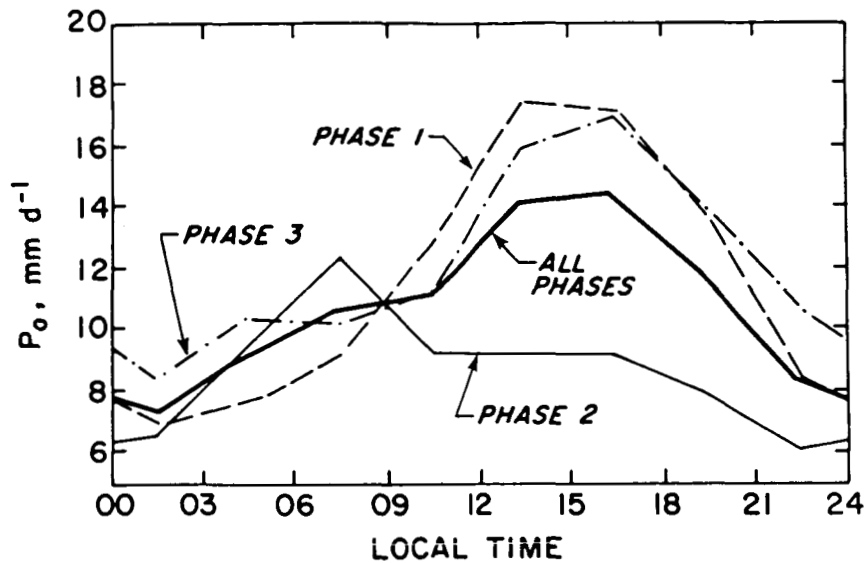
Figure 18. The diurnal cycle of rainfall over the GATE B-scale area (from Albright et al., 1981).

seen again in a study of the summer of 1978 in a study of infrared data by McGarry and Reed (1978). The phase of oscillation is very dependent on geography. Not so far away over the neighboring coastal zone of Africa the maximum is in the evening. It does appear that the GATE diurnal cycle was dominated by its first harmonic, hence Sun-synchronous sampling would not lead to a large bias in this case. However, as we will see in the following, the diurnal cycle need not be dominated by the first harmonic and it may depend upon the season as well as the geography. In what follows we shall examine some evidence about the diurnal cycle. None of the evidence is direct, since it is impossible to eliminate errors in the conventional data having to do with island effects or the inherent problems with IR inference of rain from space.

Figure 19 shows the diurnal cycle as measured by surface gages on the atoll of Eniwetok (11.3N, 162.1E). In this data we can see the seasonal cycle modulation of the diurnal cycle and the strong influence of higher harmonics in the signal. It follows that although GATE gives us an idea of the magnitude of the seasonal cycle during summer, there can be quite different effects at other locations and at different times of year. Note that in the Eniwetok data an early morning maximum is usually dominant.
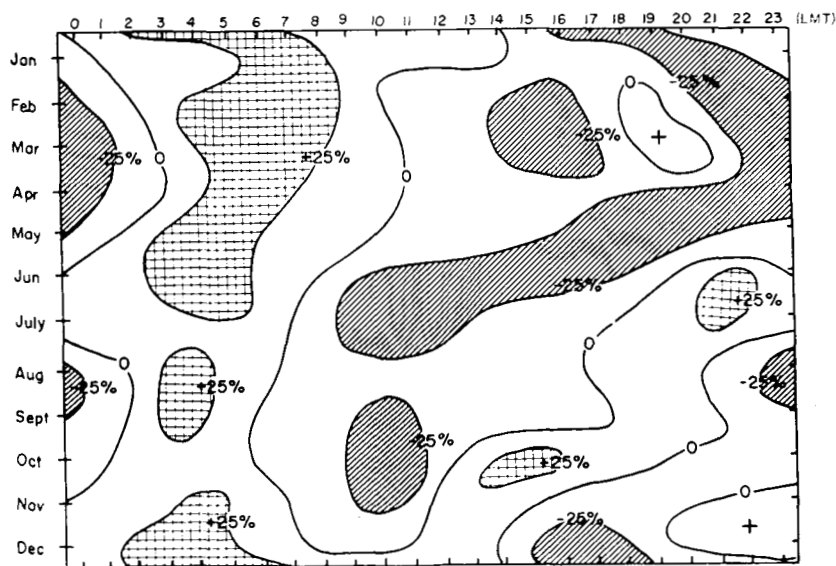
Figure 19. The diurnal cycle of precipitation over Eniwetok for different seasons shown as percent of the total average for the day (from Lavoie, 1963).

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Figure 20 shows several diurnal cycle regimes used in a study by Albright et al. (1985). In this study an IR technique similar to that of Richards and Arkin (1981) is used; the area of cloud colder than a certain threshold is correlated with rain. Some caution must be exercised as mentioned earlier because coefficients may change from place to place and season to season. Nevertheless, we can use the method to explore at least qualitatively the different regimes of the diurnal cycle over the oceans. Figures 21 and 22 show the daily variation over the five different regions in the Pacific. All of these data are for northern summer conditions. Without elaborating, it is clear that second harmonic contributions are common. Another point worth noting is that these regions, which the authors indicate are reasonably homogeneous meteorologically, comprise many TRMM averaging boxes each. This means that in trying to detect the diurnal cycle with TRMM orbital visits, we can average many boxes together, bringing sampling errors to negligible levels.
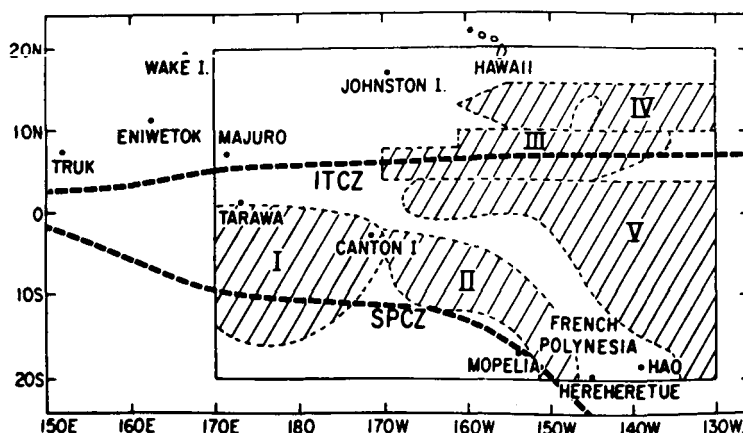
Figure 20.   Examples of different diurnal cycle regimes over the Pacific Ocean (from Albright et al., 1985).
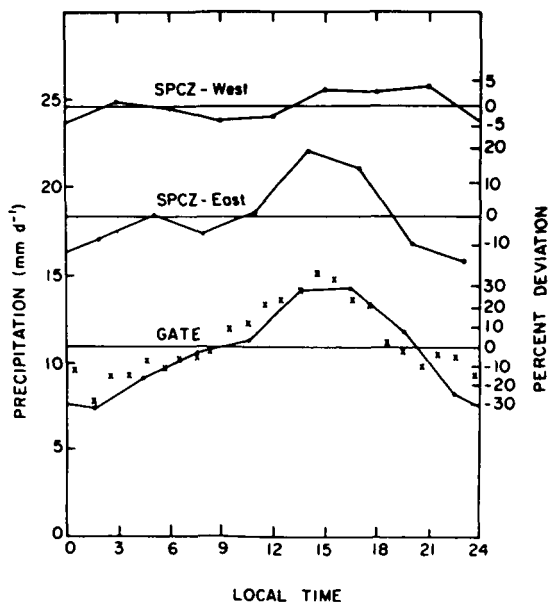
Figure 21. Estimated rainfall rates and percent deviations from the daily means in the South Pacific Convergence Zone (SPCZ)—West and SPCZ—East regions (cf., Figure 19), versus observed rainfall rate and percent deviation from daily mean in the GATE B-scale network. Crosses indicate estimated GATE rainfall rate (from Albright et al., 1985).
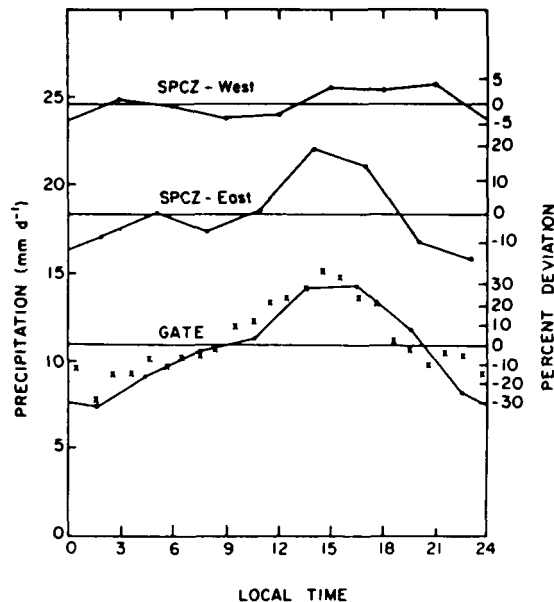
Figure 22. Estimated rainfall rates and percent deviations of clouds with tops colder than 36°C from the daily means in the ITCZ, an area of tropical intrusion, and regions of suppressed convection. Note that in the suppressed region, there is a semi-diurnal cycle with the primary maximum in the early afternoon (from Albright et al., 1985).

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It should be possible to not only remove the diurnal cycle effectively throughout the tropics with TRMM, but to study it with some precision. This hypothesis is very important, since the diurnal cycle has a rather complicated geographic and seasonal dependence. The dynamical reasons for this are not all clear, except in cases where a nearby land mass controls a sea/land breeze effect. Figure 23 shows an example from winter MONEX (Houze et al., 1981), where the diurnal cycle is enormous over the ocean but not so large over the nearby landmass (Borneo).
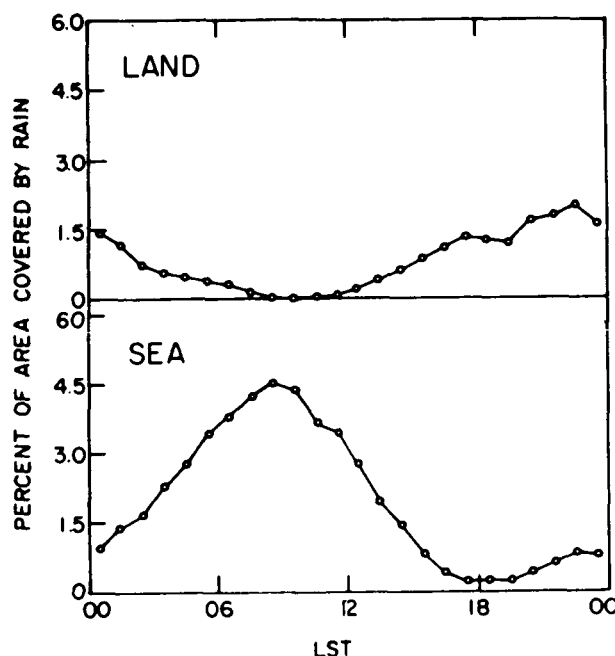
Figure 23.   Diurnal cycles of fractional area covered by precipitation, as observed over land and sea by the MIT radar in Borneo during winter MONEX (December 8 to 31, 1978) (from Houze et al., 1981).

The method for studying the diurnal cycle with TRMM data is that of simple Fourier analysis of the data taken over multibox areas. It can be shown that sampling errors for a month in estimating even high harmonic coefficients should be negligible.

2.2.7 Beam Filling Bias

At low microwave frequencies (6 to 40 GHz) the passive method for estimating rainfall rate over the oceans relies upon the fundamental relationship between microwave brightness temperature and rain rate (Wilheit et al., 1977). (See also Section 3 of this report.) In a very crude approximation, the relationship (we use 19.3 GHz as an example) may be represented by a saturating exponential $T(R) = T_0 + T_1(1 - e^{-aR})$ where T_0 is the apparent microwave temperature of the ocean surface (here about 150 K) and T_1 is the maximum elevation of temperature one might expect over heavy rain (about 100 K here). R is rain rate and a^{-1} is about 10 mm/hr; a is also proportional to the column height of the rain. The constants depend on the frequency of microwave chosen, but the principle is the same.

The measured quantity is the integral of the microwave temperature over the pixel area (about 7 by 7 km² for a nadir ESMR pixel from 300-km altitude). The desired quantity is the area integral of R. Since R and T are nonlinearly related by the saturating exponential formula, we find that [T(R)] is not equal to T([R]), where the square brackets imply area average. In fact, it is clear that using the point formula for finite areas always leads to an underestimate of the rain rate. If [R]' is the estimate of [R] taken from inverting the [T(R)] formula, we find that for any given rain field map, [R]' < [R], except in the case that the pixel is uniformly filled. The difference [R]' − [R] for each realization of the field R can be called the offset, B.

As we examine an ensemble of rain fields, R, there will be a statistical distribution of R at each point and conse-

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quently a statistical distribution of [R] and in turn distributions of T and [T]. R and T are random fields; [R] and [T] are random variables. Even for climatologically identical conditions there will be variability in the fields R and T. In the applications of most interest for TRMM we will want to obtain monthly averages of [R] which might be approximated by the ensemble average $<$[R]$>$, angular brackets denoting ensemble average. The probability distributions of [R] and [R]' will differ, and hence their ensemble averages will differ. This difference, $<$B$>$, is called the bias. It is always such that we underestimate the true rain rate.

By making some straightforward approximations, it is possible to derive the following formula for the bias:

$$<B> = <[(R - [R])^2]>T''/2T'$$

where the derivatives of T are from the T versus R curve and evaluated at R $= <$R$>$. For the saturating exponential curve, we can write T''/T' = a, which is roughly inversely related to the frequency of microwave, and equal to (10 mm/hr)$^{-1}$ for ESMR. This crude formula for $<$B$>$ reveals the fundamental basis for the so-called "beam filling" problem. The factor multiplying the saturation scale a is the average variance of R over the pixel. It follows that the horizontal wavenumber spectrum of R is extremely important in determining the bias, since the variance for a horizontally homogeneous random field can be apportioned into a sum of contributions from each of the Fourier components. If the random field R is spatial white noise, the (approximate!) formula above diverges, since each wavenumber out to infinity will contribute equal finite amounts to the total area variance. The variance may also be large or divergent in the case of weakly red (spatial) noise as is the case in some self-similar fields, whose spectrum is characterized by a power law with exponent greater than -1. It follows that the horizontal statistical properties of rain fields are critically important for understanding field-of-view as well as sampling errors.

In principle we could adopt a rain field model by specifying its spectrum and proceed to study the bias as a function of pixel size. This only makes sense if there is a length scale in the field (ruling out self-similar fields) so that the pixel size can be expressed in units of this inherent length. For real rain we do not actually know whether there is a horizontal length scale in the range of 1 to 50 km, since the data are insufficient. For the purpose of illustration, suppose there is such a length scale (say of the order of 10 km although the magnitude merely sets the scale of units with which to measure the pixel size). We can formulate a classical Gaussian noise model of the horizontal statistics and evaluate the variance factor in the bias formula above. Figure 24 shows how the bias decreases as the pixel size is made comparable to or less than the length scale in this very hypothetical example.
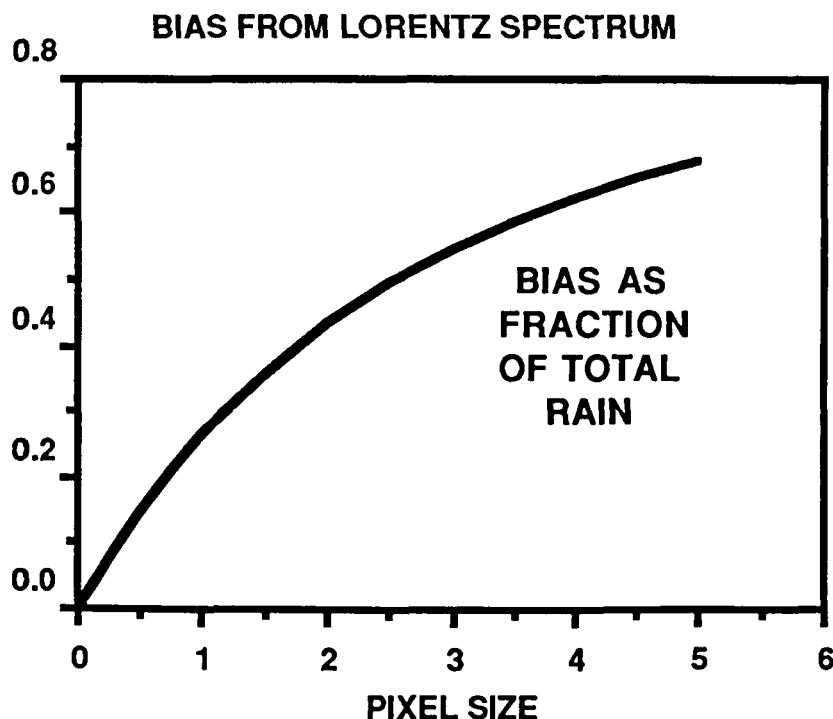
Figure 24.   The effect of pixel width on beam filling bias (see text).

Even if surface-evaluated real rain fields do not have a true horizontal length scale, the satellite actually does not see such horizontal slices of the field. Instead, it sees vertical integrals of rain, and, since there are natural vertical length scales, there will be a horizontal length scale induced by the slab integral. For this reason the divergence discussed above cannot actually enter in the satellite problem, and the natural length scale in this worst-case scenario is the vertical scale of the rain columns.

As with sampling, the easiest data set to use for beam-filling studies is from GATE. Figure 25 shows the expected bias from GATE I and II data as a function of pixel size. It must be kept in mind that the 4 by 4 km averaging bins used in the GATE data reduction process induce a finite length scale in the data. It may be that because of this length scale, we see the same kind here as in Figure 24. This figure also suggests that ESMR at an altitude of 300 km (corresponding to 7-by 7-km nadir pixels) leads to a bias reduction of about 50 percent over the Nimbus-5 case (1100-km altitude and 28-by 28-km nadir pixels).
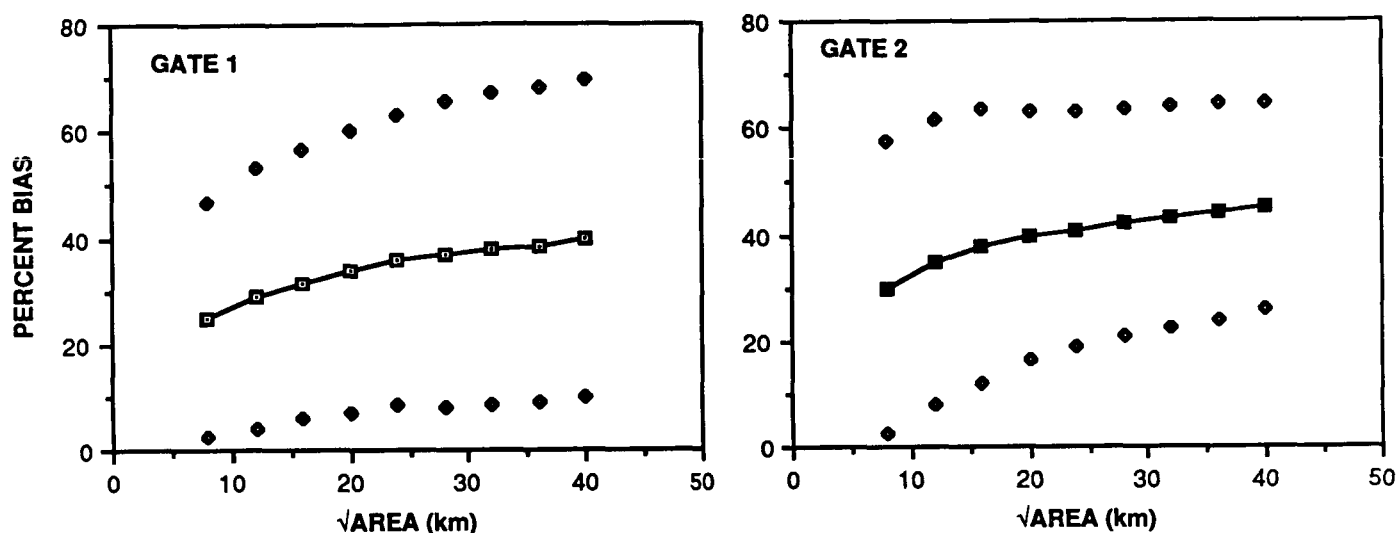
Figure 25.   Expected bias from GATE I and II data with error limits as function of pixel size (from Chiu et al., 1986).

2.3   Science Requirements: Conclusions and Recommendations

Panel 1 of the workshop, considering scientific goals, objectives, and requirements, developed a consensus on the following key issues:

1.   A monthly averaged oceanic rainfall data set over boxes of the order 10^5 km^2 as proposed here is critical to GCM and climate diagnostics progress in the 1990's. Without such a data set our ability to forecast climate may be limited by a lack of data crucial for model verification.

2.   Rainfall accuracies over oceans of order 10 percent are a reasonable and very useful target. This is an order of magnitude better than conventional oceanic climatologies and a factor of 2 or 3 better than present satellite estimates. Sampling errors can be significantly reduced if the data are combined with polar and geosynchronous data.

3.   While the proposed satellite measurements will be most accurate over oceans, when combined with other data they can contribute to rainfall estimates over land sufficiently well to objectively assess many climate anomalies such as drought in the Sahel. Many other effects such as the diurnal cycle and soil moisture can be studied over land as well. Quantitative comparison of time series over land and water should be available for the first time.

4.   While many secondary benefits will accrue, the mission should not compromise its main objective of obtaining a climatological (space-time smoothed) tropical precipitation time series.

Recognizing the many outstanding problems related to designing and accomplishing a mission of such complexity, the Panel outlined a number of recommendations that are considered necessary to establish reasonable confidence in meeting the stated scientific goals and objectives:

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1. More progress must be made in the development of simulation models for assessing the adequacy of the proposed mission configuration. These models span the hierarchy from simple stochastic rain field models based on surface data, such as from the GATE experiment, to 3-dimensional models of tropical convective systems, coupled with cloud radiative transfer models.
2. Simulation studies are needed to refine estimates of:
   a. Rainfall from radiances and radar signals measured from space
   b. Sampling errors
   c. Diurnal cycle removal
   d. Seasonal cycle bias
   e. Beam filling bias
   f. Effects of variable heights of rain
   g. Effects of averaging in the vertical
   h. Benefits of introducing more data sources of varying quality
   i. Utility of combining simultaneous measurements by different sensors on the same spacecraft.
3. Periodic reviews should be held to assess progress in the area of algorithm development, sampling statistics, and the possibility of meeting mission goals.
4. GCM and climate diagnostic studies are needed to estimate the magnitude of the signals we are looking for so that adequate designs can be constructed (e.g., squares versus rectangles).
5. Available data sets such as SMMR, SSM/I, and ESMR-5 as well as VIS/IR data from all sources should be studied in anticipation of data from this mission, both for algorithm development and basic science related to mission requirements.

3. INSTRUMENTATION

3.1 Introduction

Conventional measurements of rainfall are woefully inadequate. Even in technologically advanced areas, sampling by rain gages is marginal at best, and in the less-advanced areas the gages are sparsely distributed and often unreliable. Over vast ocean areas no direct measurements of precipitation exist. In some areas surface-based radar could extend the gage measurements, but additional calibration work would be required. Even so, vast land areas would remain inaccessible to radar measurements due to economic, political, and terrain factors. Spaceborne remote sensing must, therefore, be a major element in any global-scale precipitation measurement system.

A variety of schemes using visible and infrared observations from both geostationary and low Earth orbiting satellites have been applied to the precipitation estimation problem (Atlas and Thiele, 1981; Barrett and Martin, 1981). Many of these schemes have met with a measure of success and certainly have the advantage of spatial and temporal resolution. However, they represent observations of only the tops of the clouds and they must be tuned for specific locations and thus are difficult to apply globally.

Passive microwave techniques have been explored through the Nimbus series of satellites. Over oceans, the measurements agree with radiative transfer models and can yield quantitative measures of rain rate based on first principles. Over land areas, the passive microwave results are substantially less quantitative but, nevertheless, are a significant improvement over the presently available visible and infrared techniques.

Radar (active microwave) techniques have not yet been tested from space primarily because it is extremely difficult to achieve a sufficiently wide swath width to meet sampling requirements for an economically viable cost. However, the passive microwave techniques have weaknesses and uncertainties that can be directly addressed by radar measurements. A system exploiting the complementary strengths of visible, infrared, radar, and passive microwave techniques would greatly improve our ability to measure rainfall globally.

3.2 Passive Microwave

Passive microwave rainfall measurements fall into two regimes, absorption and scattering. In the absorption case one estimates rainfall through the emission associated with absorption (Kirchhoff's law). A cold background is required to make such observations, so the absorption regime is applicable only for a surface-based, upward-viewing geometry or for downward viewing over the oceans, which are highly reflective at microwave frequencies. Land surfaces have larger and variable emissivities that render absorption-mode measurements ambiguous. Liquid raindrops themselves are the dominant contributors to this absorption and emission, providing a direct physical relationship between the rainfall and the observed microwave radiances.

In the scattering regime, the rainfall is observed by the scattering within the rain column, which then reflects the cold cosmic background towards the downward-viewing observer. This process allows the observation of rainfall over any background, but because the scattering is primarily due to the frozen hydrometeors aloft, the relationship to the rain rate is less direct than in the absorption regime. Generally, at frequencies below the 22 GHz water vapor line, absorption is the dominant process and, at frequencies above the 60 GHz oxygen complex of lines, scattering dominates. Between 22 and 60 GHz either can be dominant according to the specific situation.

The effect of most nonraining clouds on microwave observations is minor, especially at the low frequency end of the spectrum. Microwave radiances are primarily related to the hydrometeors themselves and thereby represent a great potential for improved satellite observations of precipitation.

3.2.1 Models relating radiances to rainfall

3.2.1.1 Pioneering model work

Figure 26 depicts the first model used in relating observed brightness temperature (radiances) to rain rates (Wilheit et al., 1977). A layer of rain drops described by a Marshall-Palmer (M-P) (1948) drop size distribution from the surface to the freezing level (0°C isotherm) is assumed. A nonprecipitating cloud containing 25 mg/cm^2 of liquid water is arbitrarily assigned to the 1/2 km just below the freezing level. The surface may be either land or ocean. The atmospheric lapse rate is assumed to be 6.5°C/km, and 80-percent relative humidity at the surface is assumed. The relative humidity increases linearly with height to 100 percent at the freezing level and above. The atmospheric water

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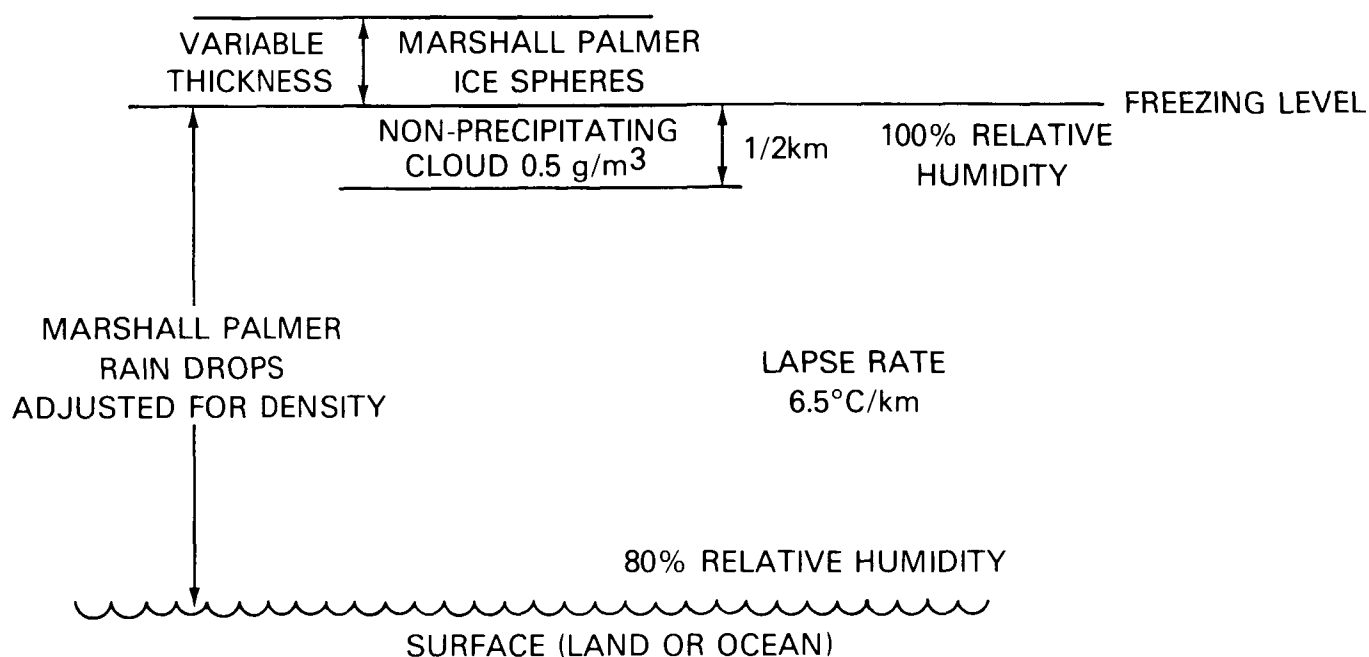
Figure 26.   Model used to relate passive microwave brightness temperatures to rain rates.

vapor and the surface temperature are therefore slaved to the freezing level parameter in the calculation. Above the freezing level a variable thickness of frozen hydrometeors is assumed. Lacking anything better for the moment, the same M-P distribution of ice spheres as in the rain layer below is used. At frequencies below the 22 GHz water vapor line, the details of the assumed ice layer are not important. This model is left with three free parameters, freezing level (rain layer thickness), ice layer thickness, and the rain rate through the M-P distribution. Better descriptions of the ice layer, the nonprecipitating cloud, and the water vapor profile are subjects of ongoing research.

The absorption and emission by the ice layer are extremely small and for low frequencies (absorption regime), the scattering due to the ice is a minor effect relative to various absorption processes. Thus, for the moment, the ice layer is ignored, permitting this model to be used to generate a set of curves such as those shown in Figure 27. Here the brightness temperature over the ocean for a frequency of 19.35 GHz (the frequency of Nimbus-5 ESMR and the lowest frequency on the SSM/I) is shown as a function of rain rate for 5 different freezing level assumptions. For all freezing levels, the brightness temperature rises rapidly as a function of rain rate to a maximum in the neighborhood of 20 mm/hr. The brightness temperatures then merge and drop off slowly with further increases in rain rate due to the rather weak scattering by the liquid hydrometeors in the now opaque rain layer. The divergence of the curves at the low rain rate limit is due to the dependence of water vapor on the freezing level assumption. The ignored ice layer is not important at this and lower frequencies, but becomes quite important at higher frequencies, as will be shown later. In this absorption regime, the details of the assumed drop size distribution are also not important.
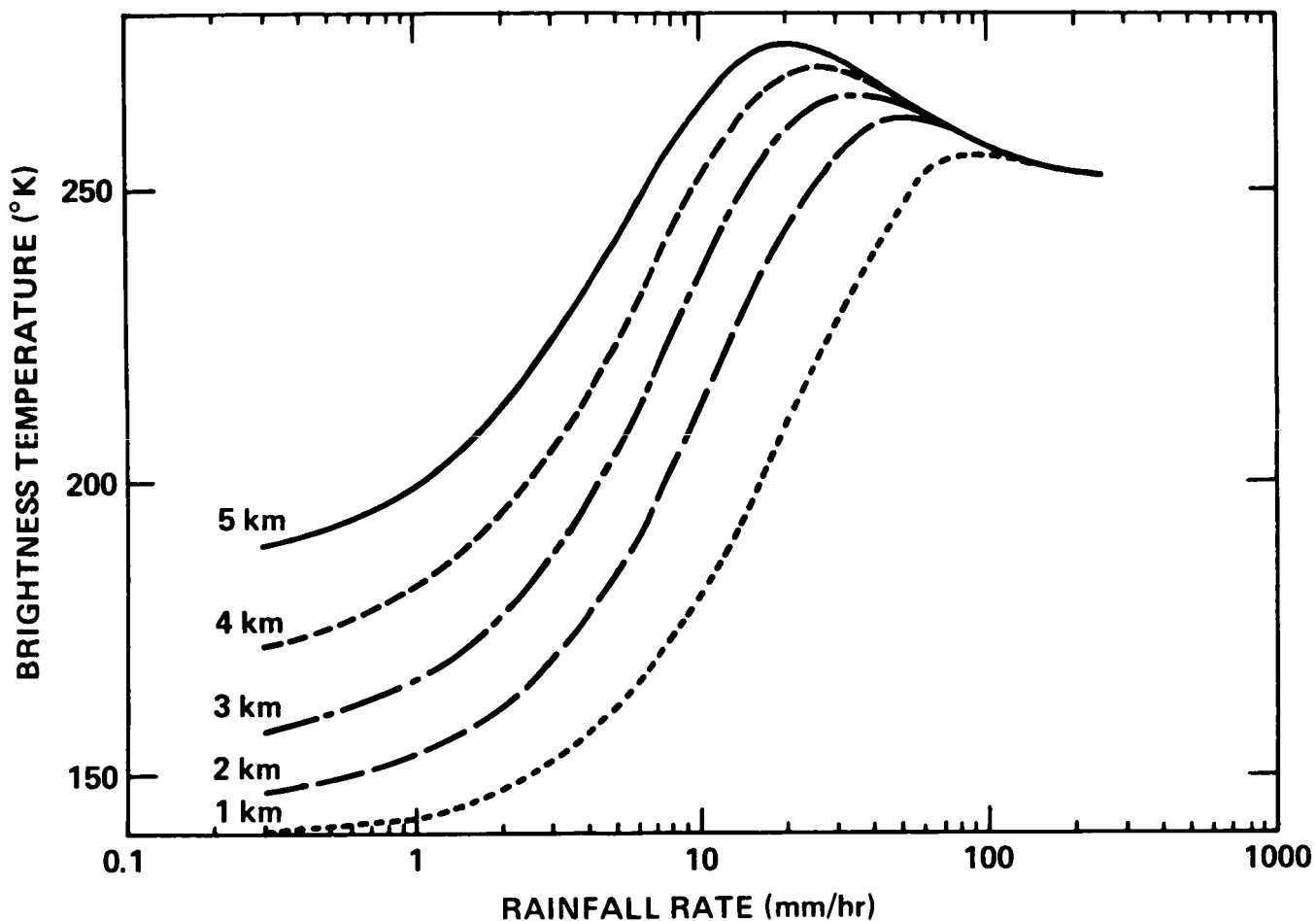
Figure 27. Brightness temperature (at 19.35 GHz) versus rain rate over the oceans for five assumed freezing levels.

This model has been given some support both by comparing a few spaceborne radiometric observations with ground-based radar and by comparing ground-based, upward viewing observations with direct rain measurements (Wilheit et al., 1977). Figures 28 and 29 show the results of this ground-based validation at 19.35 and 37 GHz, respectively. The agreement at both frequencies between the observations and the theory, which has no free parameters, suggests that the atmospheric assumptions in the model are essentially correct at least for the conditions observed. The freezing level for all these validation data was near 4 km. Rao et al. (1976) found some difficulty with this model for freezing levels greater than 4 km or less than 3 km and were forced to use ad hoc corrections in the generation of their rainfall atlas.
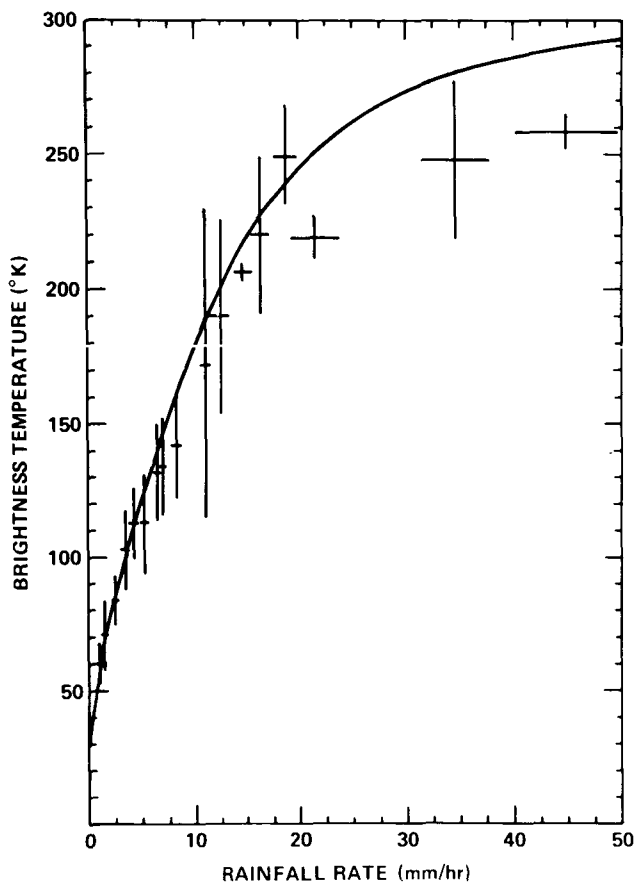
Figure 28.   Ground-based validation of brightness
temperature/rain rate model, at 19.35 GHz.
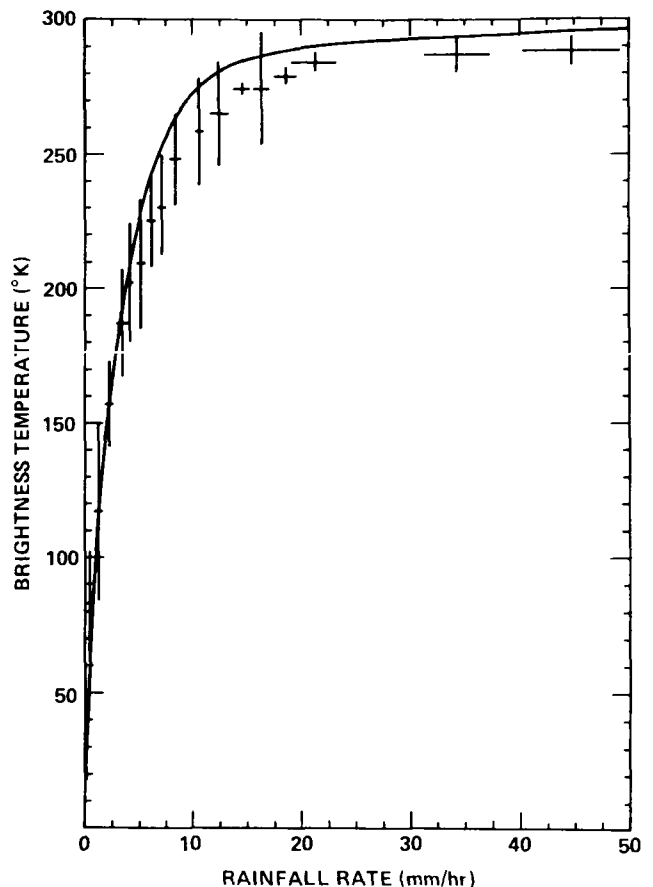
Figure 29.   Ground-based validation of brightness
temperature/rain rate model, at 37 GHz.

The model with the ice layer thickness set at zero cannot possibly account for observations such as those in Figure 30. These observations were taken with the 92 GHz channel of the Advanced Microwave Moisture Sounder, (AMMS) on the NASA RB-57 aircraft over severe thunderstorms near Tampa, Florida in 1979. The area imaged is shown as a dashed-line box drawn over the rainfall data from the WSR-57 10 cm wavelength Tampa radar. The calibration in rain rate of the radar that is shown is doubtful and should only be used in a relative sense. The radiometric data themselves are shown in two different dynamic ranges. In the darker image the range is approximately 200 to 300°K and the lighter image shows the same data in a 100 to −200° range. In both cases the lighter the tone, the higher the brightness temperature. Brightness temperatures as low as 150 K are observed here and are commonly observed in cumuliform precipitation in many circumstances.

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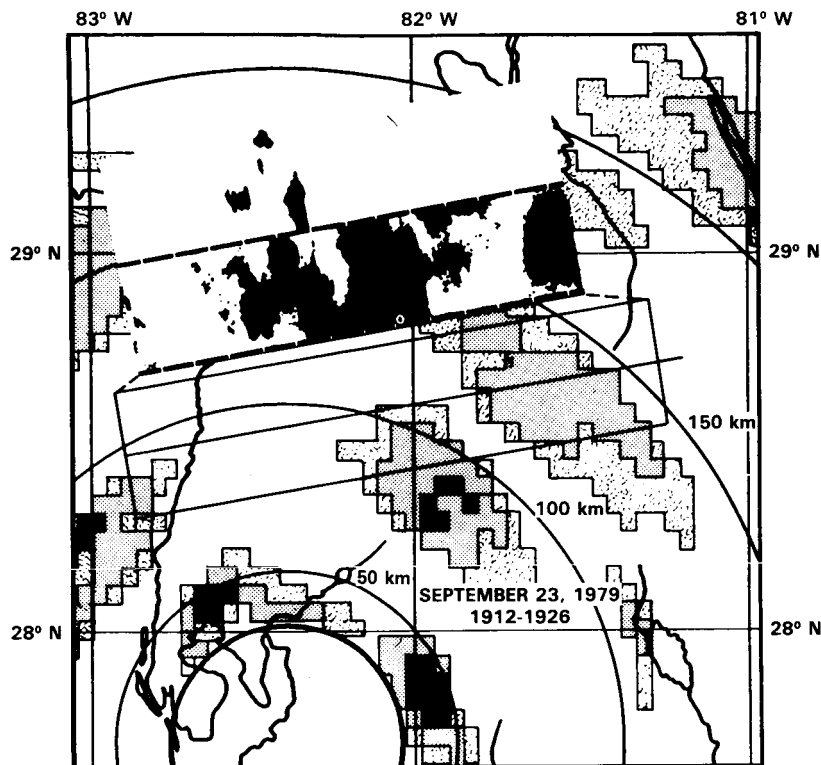
Figure 30.   Brightness temperatures at 92 GHz compared with radar rain rates during severe thunderstorms near Tampa, Florida in 1979.

To predict brightness temperatures lower than about 250 K for this situation, a layer of ice particles must be included in the model. Figure 31 shows the results of the model calculation (Wilheit et al., 1982) for 92 GHz. For ice layers of
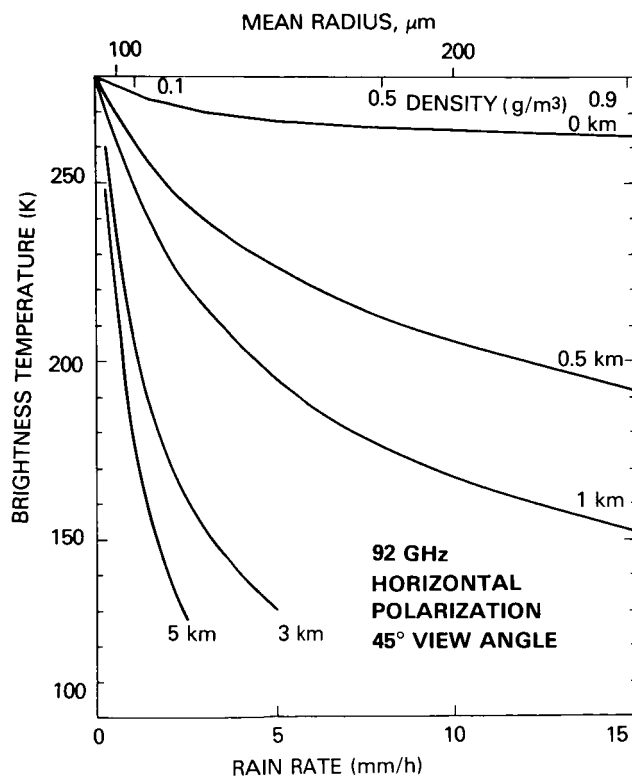
Figure 31.   Model brightness temperatures at 92 GHz versus rain rate for various ice layer thicknesses.

even 0.5 km thickness, it is possible to get extremely low brightness temperatures. Although the brightness temperatures are expressed as a function of rain rate, it is more appropriate to consider the alternate abscissae shown at the top of the graph. The M-P distribution is a convenient way to express the ice sphere diameter and density through a physically reasonable range.

Scattering results in low brightness temperatures for particles with diameters of a few hundred microns and densities of a few tenths of a gram per cubic center. Ice particles of this size are generally associated with the rain drop formation process. These are the particles that will precipitate through the freezing level, melt, and hit the surface as rain. The ice particles associated with cirrus clouds are much too small to cause any great effect. Thus, the extremely low brightness temperatures observed in convective rainfall are caused by frozen hydrometeors.

Although the observations of this scattering as a strong effect have been confined to 92 to 183 GHz, the phenomenon is present in some measure at lower frequencies. Spencer et al. (1983) have exploited this fact to develop an empirical rain-rate algorithm for use over land using Scanning Multichannel Microwave Radiometer (SMMR) data from the Nimbus-7 satellite. The performance of the algorithm is quite reasonable. The primary rain information from SMMR data is contained in the 37 GHz vertically polarized channel but many of the remaining channels are used for corrections.

3.2.1.2 Passive microwave algorithm development using coupled cloud radiative and microphysical models together with aircraft observations

In more recent work, Szejwach et al. (1986) have developed a much improved version of the pioneering slab-cloud radiative model by Wilheit et al., (1977). They have updated the refractive indices of ice, introduced an (optional thickness) mixed phase layer above the freezing level, and have divided the vertical axis into 20 layers, permitting much more vertical variability in hydrometeor sizes, types, and concentrations than in the earlier model. They have used the improved model with a one-dimensional time-dependent cloud microphysical-dynamical model (Cheng, 1981) and observations from high-level aircraft flying multichannel radiometers over storms. The preliminary "retrieval" method has been to adjust the hydrometeor characteristics of the model cloud so that they are simultaneously compatible with dynamical/microphysical requirements and produced the observed T_B's at each microwave frequency. To obtain a measure of the total rainfall rate from an ensemble of storms at different stages of evolution within a given measurement box, knowledge of the stage of evolution of each storm would be required to determine the total emission at all microwave frequencies. In the 1986, Cooperative Huntsville Meteorological Experiment (COHMEX) flights over the Southeastern United States, the channels were 18, 37, 92, and 183 GHz. Surprisingly low temperatures were found at 18 GHz over tall, heavily precipitating storms and so far no reasonable distribution of hydrometeors reproduces these while constrained at the same time to give T_B's observed by the other microwave channels.

More sophisticated dynamical-microphysical models must also be used with the radiative model, in view of the FOV (of the order of 10 by 10 km to 20 by 20 km) and beam-filling problems from satellite orbit altitude for the passive microwave instruments and also in view of the radar precipitation studies by Houze and colleagues (Leary and Houze, 1979; Houze, 1982) that suggest that 30 to 40 percent of the tropical rain falling from convective cloud clusters is found in the anvil or stratiform portions of the clouds, although we believe there is still uncertainty that all this precipitation reaches the surface without evaporation. The three-dimensional cloud population model of W.-K. Tao is presently being coupled to the radiative model. First, it will be determined at selected individual locations what T_B's would be given by the vertical hydrometeor distribution, and the radiation model relationship between T_B and rain rate will be compared with the actual rain rate reaching the surface below the model cloud. The next step will be to use the whole model domain, under varying degrees of cloudiness and rainfall, and deduce the distribution of T_B and its area average for each microwave frequency, comparing the radiative-model-deduced mean area rain rate with the area-averaged rain rate actually prevailing in the cloud population model. It may prove desirable to use this coupled model approach to investigate dual-polarized microwave T_B's and the gains that can be made in coping with the "beam-filling" problem if both polarizations are used. The multichannel retrieval method of Olson (1986) can also be tested in this context, particularly expedited by its need for only a small computer or a miniparallel processor.

3.3 Measurement Issues

3.3.1. Cloud Liquid Water

The success of microwave techniques for precipitation measurement is based on the transparency of nonraining clouds relative to rain. However, this transparency is not total, and clouds must be accounted for in the radiative transfer modeling of rain, and uncertainties in the cloud amount will determine a minimum detectable rain rate. Cloud water in its various phases manifests itself as an attenuation in both volume scattering and volume absorption. The attenuation is frequency dependent, and the magnitude of the attenuation is associated with the time-dependent nature of rain-bearing systems. Although observations such as those shown in Figures 28 and 29 indicate that the cloud assumptions used are at least reasonable, any algorithm for the retrieval of rain rates from passive microwave measurements must recognize that cloud water is not invisible. It is reasonable to expect that its effect of contaminating the rainfall signal can be seized upon advantageously. In fact, the work of Prabhakara et al. (1983) demonstrated the feasibility of remotely sensing the total liquid water content (cloud and rain) as one parameter from SMMR 10.7 GHz data. Rainfall estimation over the global oceans by Prabhakara et al. (1986) based on this parameter emphasizes the importance of liquid water sensing.

Therefore, it is preferable that the TRMM payload incorporate a range of microwave frequencies such that: (1) a low-frequency channel (e.g., 10 GHz) be used to quantify a total liquid water content (LWC), (2) a high-frequency channel (e.g., 90 GHz) be used to quantify ice water content (IWC), and (3) various intermediate frequencies (e.g., 19 and 37 GHz) be used to separate out the rainfall water content (RWC) by an emission/scattering algorithm, which itself eliminates cloud water effects.

3.3.2 Dynamic Range of Measurements

The required dynamic range for the TRMM rainfall measurements is a difficult question, particularly for the oceanic areas. There are not enough measurements to establish the requirement with certainty. Examination of the GATE data suggests that half of the total rainfall occurs at rain rates greater than 15 mm/hr. For such a regime rain rates less than about 5 mm/hr would not be particularly important. However, in the neighborhood of the 30° latitude extremes of the TRMM orbit, a larger fraction of the precipitation may be stratiform, particularly in the winter, and therefore measurements of much lower rain rates would be required. Pending improved data, a provisional dynamic range requirement of 1 to 50 mm/hr will be used.

Theoretical calculations of Szejwach et al. (1986) indicate that rain rate can be measured up to 15 mm/hr, using 19 GHz. However, heavy rain events (i.e., greater than 15 mm/hr) are common in the tropics. Heavy rain events usually are associated with clouds that have ice in the middle and upper levels, permitting approximate measurements via the scattering mechanism if appropriate frequencies are included in the passive measurement strategy.

At low rain rates the problem becomes one of discriminating between nonprecipitating and weakly precipitating clouds or, at the microphysical level, between cloud droplets of the order of 50 micrometers in diameter and smaller, versus hydrometeors larger than about 100 micrometers. Measurements of typical and extreme liquid water contents in nonprecipitating clouds are rare, but it appears from the Nimbus-5 data that useful measurements can be made down to 1 or 2 mm/hr using 19 GHz. If higher frequencies are used, the sensitivity to low rain rates is enhanced somewhat. The inclusion of 37 GHz measurements in the strategy would ensure that the low rain rate measurement requirement would be met.

The proposed radar, discussed later, is expected to have a dynamic range of about 0.5 to 50 mm/hr. The data would complement the radiometer data in two senses. First, at the rain extremes the radar will provide a more reliable rain rate measurement, albeit over a much reduced swath; and second, when sufficient data have been collected, they will provide a basis for improving the radiometric algorithms.

3.3.3 Rain Over Land

The microwave emissivity of dry land is of the order of 0.95 ± 0.05. Thus, the brightness temperature of land surfaces appears warm when viewed from space. The presence of either rain or soil moisture will depress the brightness temperature measured over land. In the case of scattering and absorption by liquid hydrometeors, the decrease in the brightness temperature is modest and comparable to the decrease due to the soil moisture that would remain after a rain event. However, if the radiances are measured at an angle with respect to nadir, the radiances from rain are un-

polarized, whereas those from moist soil are polarized. Thus, polarization information might be used to discriminate between precipitation and moist soil.

At high rain rates there is generally enough ice in the upper layers of the storm to produce large decreases ($>100°$) in the brightness temperature at high frequencies (>70 GHz). This effect greatly enhances the capability of mapping rain over land and, if both polarizations are measured, the rain can be discriminated from the background effects even if the rain fills only a small portion of the field of view.

As with dynamic range considerations, the radar measurements complement the radiometric measurements by providing improved measurements of rainfall over land within their limited swath and by providing a basis for improving the radiometric algorithms.

3.3.4 Height of the Rain Column

Absorption-mode passive microwave measurements provide a very good estimate of the total attenuation along the view path between the spacecraft and the ocean surface. Essentially all of this attenuation occurs within the rain column. One needs an estimate of the attenuation path length (rain column height) to estimate the rain intensity. Past attempts have used a climatology of the freezing level ($0°C$ isotherm) as a proxy for this rain layer thickness with limited success. Although coincident soundings could provide a better estimate of the freezing level than climatology, the freezing level is still a poor proxy for the rain layer thickness in the tropics where warm rain processes are common.

Unfortunately, passive techniques alone cannot determine this degree of freedom. The rain layer thickness parameter can, however, be determined from the active measurement as noted in the subsequent section on active microwave. Although this layer thickness could be determined on a pixel-by-pixel basis only within the limited portion of the radiometer swath covered by the radar, a climatology could be developed on this overlap region that would be usable throughout the radiometer data set and, for that matter, any radiometer data set from other spacecraft.

3.3.5 Surface Effects

The dielectric constant and the roughness of the surface have some effect on the upwelling radiance. Over land surfaces this restricts the use of absorption mode measurements for rainfall estimation. Over the ocean the surface emissivity has a token variability due primarily to the wind's roughening the surface but also due to variations in temperature and salinity. Under most circumstances, this variability is much less of a problem than the non-precipitating cloud problem in determining the low rain rate measurement threshold.

3.3.6 Vertical Distribution of Liquid Water

In addition to measurements of the total rainfall, climate models need information on the vertical distribution of the latent heat released. Information on the vertical distribution of liquid water in the form of rain drops is a zero-order approximation to this, as mentioned earlier. Radar would provide the most direct measurement although information on the vertical extent of the precipitation layer is also possible using passive techniques if appropriate channels in the 60, 118, or 183 GHz regions are used.

3.3.7 Inhomogeneities Within a Radiometer's Field of View

The field of view (FOV) of spaceborne microwave radiometers is by necessity large, and the radiation sensed by such instruments represents the integration of the microwave radiation over the FOV. Unfortunately, considerable spatial variations in precipitation can exist within such a FOV and the effect of these spatial inhomogeneities on the radiation sensed by such an instrument needs to be addressed.

The problem that these inhomogeneities create, when considering the development of a rainfall retrieval scheme based on microwave radiation transfer algorithms, can be illustrated by considering the following issues:

1. How are the satellite radiance data, which represent integrations of the radiance over the FOV of the instrument, related to the (average) rainfall within the FOV? Since the relationship between rainfall intensity and radiance at 19.35 GHz derived from one-dimensional (1-D) (slab cloud) radiative transfer theory is nonlinear and is concave downwards, direct use of the 1-D theory would produce a systematic underestimate of the rainfall intensity.

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2. The second issue that is pertinent to the FOV problem is generally overlooked and concerns the extent to which the algorithms based on the 1-D theory are relevant descriptors of the transfer of microwave radiation through an atmosphere that is intrinsically three-dimensional (3-D) with finite-sized clouds in the horizontal. Both of these issues need to be addressed in assessing the likely effects of FOV on rainfall retrieval schemes based on radiative transfer.

3. A third issue concerns the effects of storms at different parts of their life cycles in the FOV. The effect of FOV will be to contribute some sort of bias to the estimation of rainfall, which will probably not be constant. Thus, it is important to assess the nature of such a bias and its effect on rainfall retrieval. In doing so it will prove useful to consider the following steps:

   a. The need for some form of statistical distribution estimate (such as a pdf) of the rainfall that is likely to exist within the FOV.

   b. Given these statistical descriptions of rainfall on a scale smaller than the FOV, some way of incorporating these statistics into the radiative transfer models has to be developed, or at least these statistics must be used to estimate some sort of error in the retrieval scheme. Recent 3-D radiative transfer theories suggest that such statistical information appears explicitly in the description of attenuation. The possibility of such a connection between the physical radiative transfer processes and the statistical description of the medium should be investigated further and offers some real promise.

   c. Information such as that derived from IR and visible radiometers as configured for AVHRR or from the spaceborne radar is, or will be, available on a much smaller scale than is possible with the microwave radiometers. Such data may provide a useful way of characterizing the inhomogeneities within the FOV of the microwave radiometers and thus possibly can be used in the retrieval schemes. The way in which such data provides sub-FOV information about precipitation needs to be considered further, especially within the context of step 2. To ensure more continuity in the smaller scale visible information, it is important to consider adding a nighttime visible sensor as part of the AVHRR configurations.

3.3.8 Virga

Errors due to rain that evaporates before reaching the surface are inherent in any remote sensing technique which cannot determine the height of the hydrometeors all the way down to the surface. This includes passive microwave, visible, and infrared radiometers from space, as well as ground-based radar except at rather short ranges. This evaporation process causes significant vertical redistribution of heat energy and has a strong influence on mesoscale dynamics. This phenomenon can be easily discriminated from actual rain by the radar measurements directly for that part of the FOV viewed by the radar swath and potentially inferred over extended areas surrounding the FOV.

3.4 Active Microwave

A two-frequency (~ 15 and ~ 35 GHz) radar is proposed for TRMM. To attain a desired field of view approximately 4 km from an altitude of 300 km requires an antenna dimension of approximately 100 wavelengths. Antenna cost and size constraints rule out wavelengths longer than about 3 cm (i.e., frequencies lower than X-band). A reasonable choice for the lower frequency of a dual-frequency radar appears to be between 10 and 16 GHz (X-band to Ku-band). For the selection of a higher frequency, several considerations are relevant: (1) sensitivity at low rainfall rates, (2) moderate-to-high attenuation for the application of dual-wavelength methods, (3) an attenuation/rain rate relationship that is relatively insensitive to fluctuations in the drop size distribution, and (4) the capability to distinguish between frozen and liquid hydrometeors. Most of these criteria are satisfied by the choice of a frequency near 35 GHz, despite loss of sensitivity (through excessive attenuation) at intense rainfall rates. The spaceborne radar sensor has the potential to provide a number of important geophysical parameters related to the full characterization of precipitation on a global basis. These include:

1. Mapping of rainfall rate
2. Altitude of the melting level (radar bright band) and associated rain heights
3. Mean estimated rain rate and liquid water content
4. Precipitation rate profile as a function of altitude

3.4.1 Principles

The interaction of radar waves with rain particles consists of scattering (including backscatter) and attenuation. The

extent of scattering and attenuation strongly depends on the radar wavelength, the rain rate, and the particle size distribution. By measuring the amount of radar signal backscatter and/or rate of attenuation as a function of path length through the rain region, detailed information about the rain properties can be derived. Broadly speaking, the backscatter measurements are strongly dependent on the details of the rain drop size distribution (DSD), but the attenuation measurements may be very closely related to the rain intensity with greatly reduced dependence on the DSD.

The various methods for making spaceborne radar measurements of rain may be classified as follows:

1. Backscatter method
2. Attenuation coefficient method
3. Drop size distribution method
4. Surface reference method

While these methods may use one or more frequencies, two frequencies have been proposed to enhance significantly the measurement accuracy over that of just a single frequency. The principle of each method is described with particular emphasis to its applicability to spaceborne measurements. Table 1 briefly summarizes the advantages and disadvantages of each of these techniques. It should also be emphasized that the measurement capability may be significantly enhanced if more than one method is used.

Table 1.
Comparison of Radar Precipitation Measurement Techniques

Technique	Advantages	Disadvantages
Backscatter	Simple; straightforward data reduction; allows measurement of precipitation layer thickness and melting level height; allows profiling at lower frequencies, lighter rain rates	Is based on an empirical reflectivity-to-rain-rate relation; requires absolute calibration of the radar; ambiguity may be introduced by the melting region
Attenuation Coefficient	Empirical relationship; is subject to less error than the backscatter technique; does not require absolute calibration	If one frequency is used, rain-rate homogeneity in altitude has to be assumed over selected intervals; is based on difference in power that requires higher measurement accuracy; more computationally intensive than the previous method; limited capability at very high and very low rain rates
DSD	Provides a fundamental parameter: rain drop size distribution; requires absolute calibration on one channel	Assumes reflectivity ratio at the two frequencies is constant; same disadvantages as the previous method
Surface Reference	At 35 GHz gives path-averaged rain rates; absolute calibration is not required	Changes in surface characteristics will introduce errors; limited capability at very high and low rain rates; computationally intensive for profile determination; bright band may introduce a bias

The *backscatter technique* is based on measuring the radar returns from contiguous range bins and relating these echos to the corresponding rain rates. This technique can be implemented using nonattenuating frequencies (below 5 GHz) or attenuating frequencies (above 5 GHz for low rainfall rates). With this approach, the top of the precipitation region (and therefore its thickness) and the height of the melting level (which usually shows as a bright return) can be determined at the attenuating frequency, whereas the entire rain profile may be determined at the nonattenuating fre-

quency. The radar reflectivity-height profile may be converted to a rain rate-height profile using an empirical relation in which an average DSD is assumed.

In the *attenuation coefficient method,* the returns from successive range intervals are used to determine the attenuation of the signal. Assuming uniformity over predefined range intervals and an average drop size distribution, the attenuation profile is converted to a rain rate using an empirical relation. In the particular case of the 35 GHz region, the attenuation coefficient is directly related to the rain rate with very little dependence on the DSD. When a second, lower frequency is used, a less-stringent restriction is introduced as compared to the homogeneous assumption for a single frequency.

In the *DSD method,* both the backscatter and attenuation measurements at two frequencies are used as inputs to a model that would allow the estimation of rain rate. With the assumption of uniform reflectivity, the DSD can also be estimated. A second alternative to this method is to employ two attenuating wavelengths.

In the *surface reference technique,* the surface echo is measured through the rain layer and compared to the same measurement over the same or a similar area when no rain is present. This may be implemented by using a reference library for land echoes collected throughout the mission or, in the case of the ocean, by comparing surface echoes from neighboring regions. The resulting ratio gives a measure of the total attenuation through the rain layer, which in turn can be related to the mean rain rate. Better accuracy is possible when two frequencies are used.

3.5 Visible and Infrared Techniques

Visible and infrared techniques derive rainfall estimates from satellite imagery through relationships between radiances and rainfall and/or through cycles of cloud growth and dissipation. There is a wide variety of schemes for the estimation of rainfall from visible and infrared data (Atlas and Thiele, 1981; Barrett and Martin, 1981). Of the visible and infrared techniques, life history methods (based on cloud growth models and geostationary satellite data) have given useful results mainly over land surfaces in the tropics where convection is dominant. Elsewhere, cloud-indexing techniques (evaluating probable precipitating clouds basically by cloud type and cloud area) have been necessary to provide rainfall estimates from areas not covered with geostationary imagery, or which are dominated by stratiform rain cloud systems. Again, few such studies have been carried out over oceans partly due to the greater problems of calibration and verification, but more fundamentally to the low scientific priority attached to such activities until recently. However, provided that the best of the existing techniques were calibrated in a suitable way, there is no fundamental reason why visible and infrared methods should not contribute greatly to global rainfall estimates, supplementing the more focused tropical rainfall measurements proposed here.

Unfortunately, visible and infrared techniques do not cope well with the finer details of the meso-and local-scale instantaneous rainfall patterns and processes prevalent within the tropics. The accuracy of estimates is sensitive to the resolution of image data. Coefficients often prove to be markedly dependent on region and season. Because of the functional complexity which usually is required to achieve acceptable accuracies, few techniques have achieved widespread use. Other problems with visible and infrared techniques include difficulties of precisely defining rain/no rain boundaries, assessing low intensity rainfall, and evaluating very high intensity rain events when the cloud system is stratiform or mixed stratiform and cumuliform.

3.5.1 AVHRR

The operational NOAA Advanced Very High Resolution Radiometer (AVHRR) that is proposed for TRMM contains two channels in the visible part of the spectrum and four channels in the infrared. Since the operational AVHRR is a general purpose instrument flown in a polar orbit, some modifications are desirable to enhance its performance in measuring rain in an orbit of lower altitude and inclination.

The fundamental channels for implementing visible and infrared rain techniques are visible (in the 0.5 to 0.7 micrometer range) and thermal infrared (near 11 micrometers). These are part of the operational AVHRR. Other channels are of potential value to TRMM. These include channels in the 1.6, 6.7, and 15 micrometer regions, as well as a nighttime reflectance channel.

A 1.6-micrometer channel (or pair of channels) could be used during the daytime to distinguish between ice and supercooled water clouds. Observations from a 6.7-micrometer channel could be combined with observations from the primary visible and infrared channels to type clouds and, with observations from the 11-micrometer channel, to measure the heights of the tops of cirrus. From two channels on the short wavelength side of the 15 micrometer CO_2 absorption band, by means of differential atmospheric transmission and cloud effects, the heights of clouds in the middle and upper troposphere could be measured.

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A highly sensitivity nighttime reflectance channel, such as that flown successfully by the Defense Meteorological Satellite Project (DMSP), would enable visible techniques to be used around the clock.

Because TRMM would fly at just over 1/3 of the orbital altitude of NOAA satellites, the potential exists for much higher spatial resolution with no compromise in sensitivity. The 500-m spatial resolution could reveal aspects of cloud structure that would be important to implementing microwave as well as visible and infrared algorithms.

The width of the swath of the AVHRR can be changed by adjusting the scan angle. To help model microwave sensor response and encircled energy effects, it would be highly desirable to have AVHRR coverage across a swath which on each edge is two microwave pixels broader than that of the passive microwave instrument.

3.6 Sensors and Algorithms Panel: Conclusions and Recommendations

Although the basic principles of both active and passive microwave remote sensing are well known, there are many issues that can impact the accuracy of the measurements. These issues must be understood much better in order to limit their negative impact on the expected results of the mission. The most effective way to accomplish this is through a series of well-designed ground-based and airborne experiments with radars, radiometers, and independent precipitation physics measurements. A variety of aircraft platforms will be required to operate in the appropriate range of meteorological conditions. These experiments need to be designed and evaluated in a framework of cloud dynamical-microphysical models related to cloud radiative models. The contribution of these models will increase sharply in the next decade as cloud populations acted upon by mesoscale inhomogeneities and boundaries become a reality in the next generation of cloud models.

3.6.1 Summary of Panel Findings

- The three-instrument approach (passive microwave, radar, and VIS/IR) is the effective way to make the needed measurements.
- The single-channel ESMR is not adequate to measure high rain rates, so a multifrequency addition such as an SSM/I or SMMR is intended. However, if it can be managed within cost constraints, the most feasible technical approach recommended would be design and development of a multifrequency microwave instrument specifically tailored to the tropical rainfall mission concept.
- A dual frequency ($\sim$15 and $\sim$35 GHz) radar as originally proposed is considered appropriate for the mission. However, continued studies are needed to consider a variety of technical design options, including precise selection of frequencies.
- The visible/infrared radiometer (e.g., AVHRR) should have a minimum of two channels, one for the thermal infrared and one for the visible reflected light. Additional channels such as the 1.6 micron for liquid/ice discrimination and a nighttime visible sensor would be useful as well.
- Relevant analytical and algorithm development studies to estimate rainfall using available VIS/IR, passive microwave, and radar data, should be pursued, using models as an inherent part of the approach.
- An airborne sensor development program and experimental activities to investigate instrumentation concepts and to verify the interpretation algorithms should be conducted.
- A series of ground-based and airborne (VIS/IR/microwave) experiments should be carried out in conjunction with planned large-scale experiments such as EMEX, Florida Deep Convection Experiment, ISCCP, ISLSCP, STORM and planned shuttle experiments while making maximum use of past data such as FACE, COHMEX, etc.

4. GROUND TRUTH

4.1 Introduction

The spaceborne facilities proposed to be employed in TRMM to measure the amount and vertical structure of tropical precipitation are indirect and will utilize certain previously untested observational technologies. Therefore, it is essential to conduct a careful calibration (or "ground truth") program in parallel with the design and execution of the mission. Briefly, the objectives of the ground truth program are:

- To provide ground-based measurements of tropical rainfall on the time and space scales of interest to TRMM (i.e., from the nearly instantaneous active and passive microwave sensor's "footprint size" up to $5°$ by $5°$ squares on the time scale of a month).
- To verify the vertical distribution of hydrometeors in locations of tropical precipitation. This objective is needed to verify TRMM measurements of vertical precipitation structure with radar and to test the physical bases of the TRMM radiometric techniques for interpreting net upwelling microwave radiation in terms of surface rainfall rate.
- To improve and test the cloud models used in the TRMM algorithms.

The planning of a ground truth program for TRMM, summarized in Figure 32, is particularly challenging because accurate measurement of precipitation at the Earth's surface is itself a very difficult problem. Even simple rain gage measurements on land are affected by wind, local terrain, and proximity to buildings and other obstacles. Over oceans, only ships and buoys provide platforms for gages. These platforms are not only scarce and characterized by the same problems as land sites, but they have the added problems of pitch and roll and contamination by sea spray.

In addition to the basic difficulties of measuring rain at a point on the Earth's surface, the precipitation measurements must be carefully designed to be representative. Precipitation is highly variable in time and space. Nearly all precipitation, whether associated with tropical clouds, extratropical cyclones, midlatitude thunderstorms, hurricanes or orography, is organized on the mesoscale and consists of a combination of intense, highly localized convective showers and more widespread stratiform precipitation (Houze, 1981; Houze and Hobbs, 1982). Determination of rainfall over areas of the sizes of interest to TRMM must take this natural variability into account. The ground truth program is therefore challenged to provide a measurement strategy that will yield accurate areal precipitation amounts while properly accounting for the natural variability of rainfall.

The most frequently used method for areal measurement of rainfall other than rain gages is radar. Radars are excellent for indicating the detailed horizontal and temporal variability of precipitation and for indicating vertical structure. They are generally less accurate than gages in obtaining instantaneous point measurements of rainfall. However, averages of large numbers of point values of rain rate derived from radar agree well with averages of data from gages. (Recently Austin and Geotis [personal communication] obtained agreement to about 10 percent error in the rainfall totals obtained in 375 simultaneous rain gage and radar measurements.)

In addition to using gages and radars, rain amounts can be inferred from mass, heat, and moisture budgets derived from rawinsonde data. In one technique, convective cloud outflow at the surface is related to rainfall. Previous work (Ulanski and Garstang, 1978a, 1978b, 1978c; Cooper et al., 1982, Doneaud et al., 1982, 1983; Watson et al., 1981; Watson and Blanchard, 1984) has demonstrated that low level velocity fields measured on a space scale of about 10 km and a time scale of about 1 per minute can provide reliable estimates of the surface divergence fields. Integration of the surface divergence yields vertical velocity. The downward vertical velocities can then be integrated over time and space to obtain estimates of the downward mass transport. Downward mass transport, in turn, can be directly related to rainfall. To obtain rain amounts over much larger areas, numerous investigators have inferred surface fluxes of precipitation (ususally as a residual) from budgets calculated from upper air soundings describing a large volume of the atmosphere. (See, for example, the GATE studies, such as Brummer, 1978; Albright et al., 1981; Frank, 1979.) This budget method is one of the few techniques that can provide an estimate of rainfall amount on the largest scales of interest to TRMM.

The ground truth program for TRMM should include the use of rain gages for accurate instantaneous point values of rainfall and radars for spatial and temporal distribution of precipitation and accurate longer-term average rain amounts. Also, budget techniques should be employed. However, because of the inherent limitations of these traditional methods, other technologies should also be sought to supplement and enhance the ground truth program to maximize its accuracy. Section 4.2 outlines a strategy for the ground truth program to be conducted during TRMM, in which both traditional and new techniques are used. Section 4.3 discusses the pre-mission phase of the program.
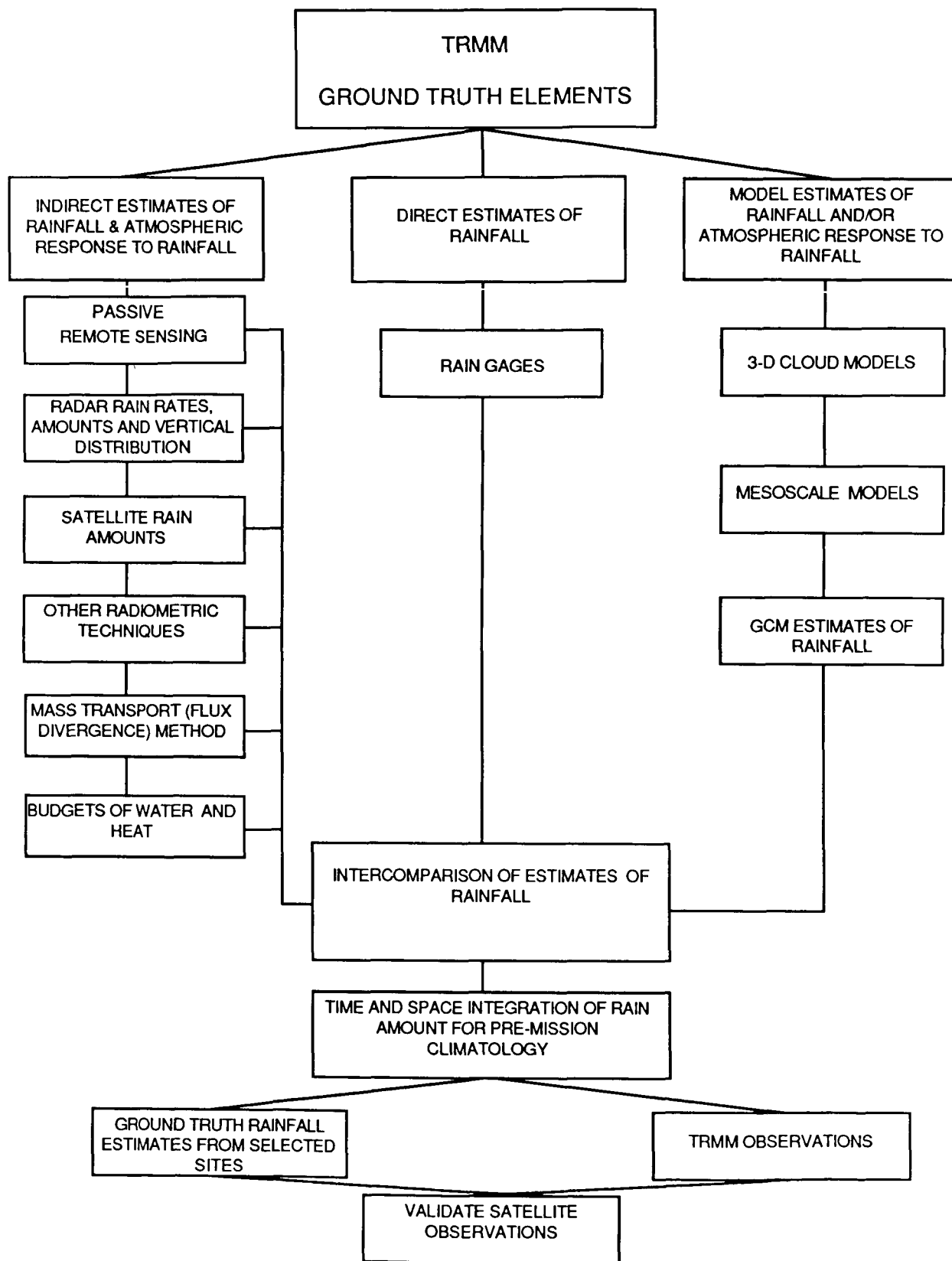
Figure 32. Ground truth planning elements to support a tropical rainfall mission.

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4.2 Mission Ground Truth Strategy

4.2.1 Design of a basic ground truth module

Since the objective of TRMM is to measure rainfall around the circumference of the Earth in tropical latitudes, ground truth sites should be located at several representative points in low latitudes. At these sites, instrumentation should be established for the accurate determination of instantaneous surface precipitation rates over areas corresponding to the size of the TRMM footprint, as well as average amounts over larger areas (e.g., 10^5 km^2 corresponding to the TRMM-averaging box size) and longer time periods (e.g., one month). In addition to the rainfall amount, the horizontal variability, time variation, and vertical distribution of the precipitation should be determined in detail throughout a representative volume of the atmosphere surrounding the ground truth site.

Since no single technique appears to be adequate for determining the amount and structure of precipitation in a volume of the atmosphere, an observational module consisting of a combination of instruments will have to be designed for each site. Only by employing several techniques at a given site can the desired accuracy be achieved. For example, each module may be developed around a radar located on a coastline. Disdrometers should be employed to determine the raindrop-size spectrum characteristics required to calibrate the radar reflectivity measurements. A high-density network of rain gages located over the land would check the calibration of the radar measurements and allow them to be applied over the sea with confidence. By employing a network of surface, boundary-layer, and upper-air observations (possibly using profiler techniques) throughout the region covered by the radar, an independent measure of the net precipitation in the region could be obtained through analysis of the water vapor budget of the region. In addition to these standard techniques, new technologies should be applied within the observational module. At least four technologies appear promising:

1. *Multiple polarization radar.* This capability could add some precision to the measurement of precipitation rate by radar and would help distinguish liquid from ice in vertical profiles of the precipitation structure.
2. *Attenuation measurements.* Attenuation of horizontally propagating microwave and visible/infrared radiation is strongly related to the intensity of intervening precipitation (Crane, 1985; Ulbrich and Atlas, 1985). Measurement of this attenuation promises to be an accurate way of determining mean rain rates over large areas.
3. *Doppler radar.* Doppler instrumentation on the radar at the ground truth site would allow the vertical air motion in the precipitation regions to be sampled. By a regular program of intermittent observation over a long period of time (e.g., several years), a single Doppler radar at a ground truth site could accumulate a statistically meaningful sample of the vertical air motions at that location. Vertically pointing measurements could provide snapshots of convective motions sampled at random, while tilt-sequence vertical azimuth display (VAD) scans obtained at random in stratiform precipitation areas could provide samples of the vertical motions in those regions. From these statistics, the typical vertical motion profiles in convective and stratiform precipitation regions could be derived. These profiles, in turn, would be closely related to the vertical distribution of diabatic heating in the precipitation areas.
4. *Submerged hydrophones.* An experimental technique for measuring rain over the ocean consists of suspending a hydrophone on a long line below the sea surface. The acoustical signal from the raindrops striking the water can be detected and related to surface rainfall rate. This technique could provide independent measurements of the precipitation rate over the oceanic region covered by radar.

An observational module simultaneously employing most, if not all, of the various techniques discussed above should be able to provide the required ground truth at a single site. Several independent estimates of the rain rate can be obtained from some combination of radar, rain gages, water vapor budget, mass transport, microwave or visible/IR attenuation, and hydrophones, depending on whether over land or ocean, with the desired accuracy. Estimates could be both for point measurements and for longer-term averages. In addition, the horizontal and temporal variability and vertical distribution of the precipitation would be determined.

4.2.2 Locations of ground truth modules

Ground truth modules consisting of the mix of instruments described above should be located at climatologically representative points in tropical latitudes. These points should be on coastlines and in locations where the operation of a sophisticated data network is feasible. Some locations that have been suggested are:

1. *Darwin, Australia (12°S).* This station experiences heavy rains during the Southern Hemisphere summer. At

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this time of year, the latent heat released in tropical cloud systems in the "maritime continent" region north of Australia constitutes the atmosphere's greatest heat source. Planetary-scale monsoonal and tropical east-west circulations are driven by this heating. A high quality meteorological station, including a radar, is maintained by the Australian Bureau of Meteorology in Darwin.

2. *Madras, India (12°N).* This station experiences significant precipitation during the transition between Northern Hemisphere summer and winter regimes. The India Meteorological Department maintains a meteorological station with a digital radar in Madras.

3. *A Western Pacific Island (e.g., Kwajalein, 8°N).* This station is representative of the intertropical convergence zone of the Pacific Ocean. A meteorological station including a digital weather radar is located there. However, to develop a climatological rainfall record, a recording system will have to be added.

4. *Panama (9°N).* This area is representative of the intertropical convergence zone. A rain gage network is maintained in the region by the Panama Canal Commission.

5. *Florida (24 to 30°N).* Florida has a semitropical climate with considerable rainfall. The experimental site expected to be located in the Kennedy Space Center vicinity for TRMM premission ground truth studies will be within the area covered by TRMM and should continue as a key mission site. Other instrumentation such as NEXRAD and automated mesonet meteorological stations will be in place to meet Air Force and NASA objectives in addition to that proposed to meet TRMM objectives described in 4.3.2 below.

4.2.3 Field experiments

The ground truth modules described in Section 4.2.1, and located during TRMM at sites such as those suggested in Section 4.2.2, should be operated throughout the mission. At selected times during TRMM, the modules could be enhanced by the addition of further instrumentation, which would be operated in the mode of an intensive field experiment. The primary platforms to be added to the basic observational module during these experiments would be aircraft and additional ground-based Doppler radars for multiple Doppler radar analysis of individual storms, as opposed to the statistical data obtained by the single Doppler radars operated for long periods of time at the ground truth sites. These platforms would add a host of supplementary measurements that would allow the dynamical, thermodynamical, and microphysical structure of the precipitating cloud systems to be documented in detail on a case-by-case basis.

4.3 Pre-mission Ground Truth Strategy

As discussed, the TRMM mission ground truth objectives are to determine the three-dimensional structure of tropical precipitation and to measure rainfall amounts on the various horizontal scales relevant to TRMM (i.e., from the nearly instantaneous active and passive microwave sensors "footprint size" up to 5° by 5° squares on the time scale of a month). To obtain these measurements, a variety of technologies will be employed. To determine how well these methods (some previously untested) will work, a carefully planned pre-mission experimental program must be carried out. The following experiments are considered essential:

4.3.1 Rainfall measurement comparison for spaceborne radar/radiometer techniques

It is envisioned that the studies of the physics of rainfall measurement using the active and passive microwave techniques to be used during the mission will require ground-based rainfall measurement techniques suitable for observations over restricted areas and for short times. Unfortunately, at the present time there are no generally accepted accurate remote sensing ground-based techniques for nearly instantaneous rain measurements although many candidates exist and have been proposed. The immediate goal must be to identify the best techniques from among the candidates. To do this, conduct small-scale measurements consistent with the most accurate direct measurement of rain by gages that is possible. The use of a microwave attenuation link as a beginning is strongly recommended. Following the microwave link research the next step would be to identify those remotely sensed quantities that are most suited for accurate rain measurements over at least limited areas. Measurements over small areas will facilitate eventual intercomparisons with potential radar rain measurement parameters. The use of submerged hydrophones should be tested to determine their usefulness for comparisons over ocean areas.

Once limited-area measurements using microwave link techniques are possible, it is anticipated that, for TRMM intercomparisons, multiple-parameter radars will play an essential role because of the capability of radars for cost-

effective measurements over substantial areas. Radars will ultimately have to be used both for ground-based intercomparisons and for subsequent mission measurements as well. For pre-mission experiments it will be desirable to use a multiple-polarization Doppler radar, perhaps with multiple-frequency capabilities. Such a radar could offer several potential parameters for rainfall measurement for comparisons with the derived microwave link measurements, for comparison with available rain gage measurements, and for comparison among each other. Once the best radar parameters have been selected, they will be used to make rainfall measurements as accurately as possible over substantial areas for pre-mission and mission research.

4.3.2 Accurate rainfall measurements on various scales for mission comparisons

The most critical requirement of the pre-mission ground truth program is to establish that rainfall amounts can be determined with the required accuracy in the range of time and space scales relevant to the experiment. To achieve this objective, it is proposed that a comprehensive multiscale observational array of rain gages and other instrumentation be established in southern Florida, centered on the NASA Kennedy Space Center (KSC) (Figure 33). The proposed array builds on facilities already in place or proposed for KSC.
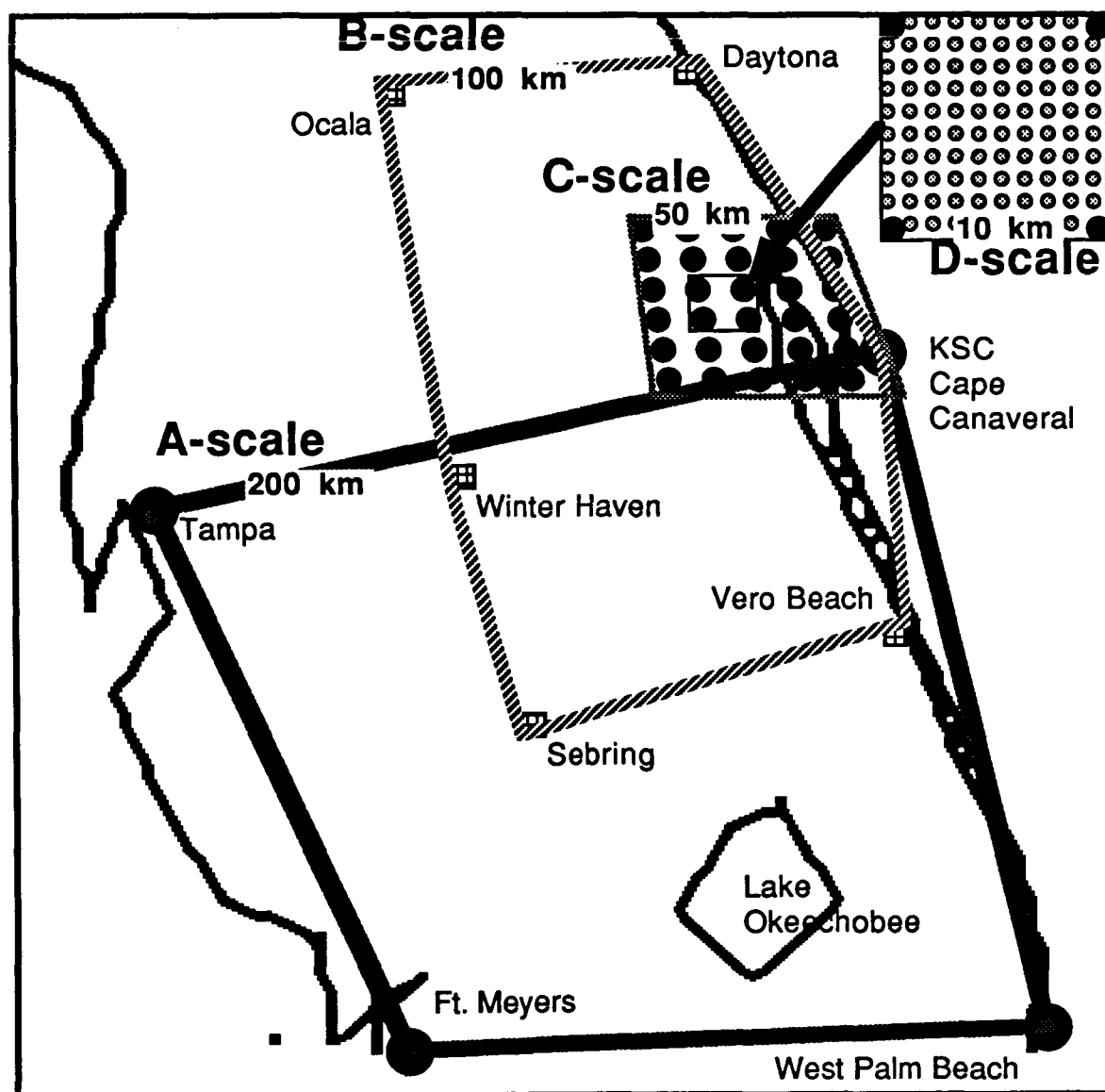

Figure 33. Proposed ground truth observation grid for Florida site.

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A transportable, multiparameter, polarization diversity, coherent radar should be suitably located to scan at low elevation angles over the rain gages. Depending on availability, initial short-term measurements may be made using one of the only two suitable radars currently in existence (CP-2, CHILL). However, long-term radar studies must be conducted to investigate the accuracies of the rainfall estimates derived from the various radar parameters as functions of temporal and spatial averaging. The information would be used to determine the cost effectiveness of alternative radar systems for deployment during the mission. It is recommended that an advanced dedicated radar be acquired for mission ground truth studies and support. Such a dedicated radar could also provide useful information for mass transport measurements and for determining hydrometeor state as a function of altitude. This radar should also be transportable so that it could be used as a calibration standard for the global TRMM ground truth network.

The Florida site is also expected to incorporate attenuation links, disdrometers, augmented sets of rain gages, automated mesonet units, and possibly, upward-looking radiometers and Doppler radars.

As another means of estimating rainfall, it is suggested that the mass transport technique be carred out for the 10 by 10 km (D) scale and the 50 by 50 km (C) scale. Estimates by this technique, on these scales, can then be compared with other indirect radiometric and radar measurements over the same space scales.

Explicit calculations based on radar-observed echo distributions should be made in conjunction with actual observations of the surface velocity fields. The purpose of such calculations is to determine how well outflow can be calculated from radar reflectivity. Successful estimates of radar-based outflow can then be used to provide an integrated estimate of precipitation that is not dependent on direct measurement of the velocity fields.

It is also proposed that water and heat budgets be calculated for the 200 by 200 km (A) scale and 100 by 200 km (B) scale illustrated in Figure 33. Rawinsonde measurements taken 4 times in 24 hours would provide the required input for the A scale. The B-scale network provides measurements at the 10-m level, which will not allow budgets to be calculated but will permit time integration around the 100 by 100 km area to obtain surface divergence and mass transport.

Comparisons between the budget-estimated precipitation for the 200 by 200 km region can then be made with the best estimate of area/time rainfall obtainable from the other techniques. If the budget calculations prove to be useful, then consideration can be given to using budget methods as a valuable ground truth foundation for TRMM.

The budget estimates developed for the site can then be extended to cover larger and more remote (ocean) areas that lend themselves to budget estimates (e.g., Gulf of Mexico, Bahamas-Greater Antilles, Caribbean Sea).

The estimates of rainfall obtained by these techniques provide the basis for an intercomparison of rainfall amount on the time and space scales of interest. This intercomparison depends in large part on the adequacy of the data set. Ground truth experiments should be conducted over a sustained period of time to accumulate adequate statistics. This period should not be less than 3 years and preferably should continue for 5 years prior to the mission.

The pre-mission strategy should also include a parallel modeling effort that is intimately related to the ground truth program and indeed to the overall TRMM mission, which in part is designed to improve the capabilities of these numerical models. Three-dimensional cloud models currently being tested at the Goddard Laboratory for Atmospheres should be used in an interactive mode with the proposed observations to arrive at model estimates of: (a) convective cloud/complex(s) rainfall, and (b) the vertical distributions of liquid water for convective cloud complexes.

4.4 Ground Truth: Recommended Implementation Strategy

A strategy for accomplishing the end objectives of a sound mission ground truth program requires the following activities:

a. *Development of a primary standard.* The proposed key elements of the primary standard are: a two-frequency microwave attenuation link (path length approximately 200 m); a visible and IR attenuation link if feasible; high-precision "rate" rain gages; disdrometers; high-precision vertical and horizontal anemometers; upward-looking microwave radiometers; and a Doppler radar if possible.

b. *Development of transfer standards.* The second proposed phase will be to transfer the primary standard technology to a large-area array. Because of extensive meteorological instrumentation already in place, the vicinity of the Kennedy Space Center, Florida has been suggested. Long microwave attenuation links (10 to 30 km) perhaps in a circular pattern are proposed along with the temporary use of one of the National Science Foundation (NSF)-supported multiparameter radars (e.g., NCAR CP-2 radar). The multiparameter radar, calibrated with the microwave attenuation links, would then become the large-area transfer standard. The array would also contain rain gages and Doppler radar and possibly upward-viewing radiometers. Rainfall amount

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over the area could also be derived indirectly through flux divergence analysis (i.e., downward mass transport of air in precipitating convective systems). This will require several Portable Automated Mesonet Systems (PAMS) in the array. For ocean ground truth, it is proposed to upgrade and digitize at least one island station radar (e.g., Kwajalein). Attenuation links on oil rigs in the Gulf of Mexico and the possible use of submerged hydrophones for acoustic determination of rainfall should also be investigated.

c. *Development of the mission ground sites.* The next phase would be the calibration and/or deployment of grid-size ground truth systems in representative regions for the flight mission. It is anticipated that for grid-size statistics, available weather radars and associated conventional equipment can be, for the most part, calibrated well enough with the transfer standards. However, it may be necessary to increase standard meteorological measurements, perhaps using PAMS, in some regions to estimate total rainfall through mass transport/heat budget analysis over the area, if that technique proves feasible.

d. *Field experiments.* Field experiments, which are an integral part of research associated with a flight project such as that proposed here, cannot be adequately assessed at this time because of their multipurpose nature and dependence on many other sequential factors. In most, if not all cases, pre-mission field experiments will serve a multiplicity of research and mission development objectives (i.e., aircraft flights for radar and radiometer instrument/system development, algorithm development and testing, physical process studies of rainfall initiation and distribution characteristics and, not least, the development of primary and transfer standards leading to establishment of large area ground truth for the mission. *During the mission,* carefully designed field experiments will be necessary to assess, understand, and possibly enhance the 3-year data set that is to be developed. Both for time advantage and to conserve resources, an important task will be to identify related experiments being planned for other projects and research efforts that can be augmented or influenced in such a way as to help meet mission requirements and NASA's precipitation research efforts (e.g., the Equatorial Mesoscale Experiment (EMEX), Florida Deep Convection Experiment, etc.).

The measurement of precipitation from space is an extremely difficult problem under the best of circumstances, thus validation (and possibly calibration) of the space measurements is crucial to a successful mission. Therefore, substantial project resources will be required for the entire ground truth program.

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APPENDIX A

List of Acronyms

1-D	One-dimensional
3-D	Three-dimensional
AGU	American Geophysical Union
AMEX	Australian Monsoon Experiment
AMMS	Advanced Microwave Moisture Sounder
AVHRR	Advanced Very High Resolution Radiometer
CHILL	Transportable multiparameter polarization diversity coherent radar
COHMEX	Cooperative Huntsville Meteorological Experiment
CP-2	Transportable multiparameter polarization diversity coherent radar
DMSP	Defense Meteorological Satellite Program
DSD	Drop Size Distribution
EMEX	Equatorial Mesoscale Experiment
ENSO	El Nino/Southern Oscillation
ESMR	Electrically Scanning Microwave Radiometer
FACE	Florida Area Cumulus Experiment
FOV	Field of View
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
IFOV	Instrument Field of View
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
ITCZ	Intertropical Convergence Zone
IWC	Ice Water Content

KSC	Kennedy Space Center
LWC	Liquid Water Content (total)
MIT	Massachusetts Institute of Technology
MONEX	Monsoon Experiment
MP	Marshall-Palmer drop size distribution
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	The next meteorological radar
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OLS	Operational Line Scanner
PAMS	Portable Automated Mesonet System
pdf	Probability Density Function
RWC	Rainfall Water Content
SMMR	Scanning Multichannel Microwave Radiometer
SPCZ	South Pacific Convergence Zone
SSM/I	Special Sensor Microwave Imager
STEP	Stratosphere Troposphere Exchange Program
STORM	Stormscale Operational and Research Meteorology
TOGA	Interannual Variability of the Tropical Oceans and Global Atmosphere
TRMM	Tropical Rainfall Measuring Mission
UCLA	University of California, Los Angeles
VAD	Velocity Azimuth Display
WCRP	World Climate Research Programme

Monday, November 18, 1985

Registration	8:00
Welcome and Introductory Remarks John Theon, NASA Headquarters	8:30

SCIENCE REQUIREMENTS/OBJECTIVES

Tropical Rain Mission Goals/Challenges G. North, NASA/Goddard Space Flight Center	9:00
Climate Modeling/Diagnostic Requirements P. Webster, Pennsylvania State University	9:30
Tropical Rain Systems/Observation and Modeling J. Simpson, NASA/Goddard Space Flight Center	10:00
Break	10:30
Tropical Rainfall Mission Impact on Hydrology P. Eagleson, Massachusetts Institute of Technology	10:45
Discussion—Morning Sessions	11:15
Lunch	11:30

INSTRUMENT/ALGORITHM/DATA SYSTEM CONCEPTS

Payload Rationale and Microwave Retrievals T. Wilheit, NASA/Goddard Space Flight Center	1:00
Radar Precipitation Measurements from Space J. Goldhirsh, Johns Hopkins University (APL)	1:30
The RRL Precipitation Measurement Program N. Fugono, RRL, Tokyo, Japan	2:00
Visible/Infrared Inference of Rain J. Weinman, Univeristy of Wisconsin	2:30
Passive Microwave Precipitation Measurements R. Spencer, Marshall Space Flight Center	3:00
Break	3:30

*This is the agenda of the Workshop that provided the basis for this report.

GROUND TRUTH/PRE-LAUNCH EXPERIMENTS

Ground Truth Strategies   3:45
*R. Houze, Univ. of Washington (A. Jameson-substituting)

Quantitative Measurements of Rain   4:15
D. Atlas, University of Maryland

Proposed Pre-mission Shuttle Experiments   4:45
G. Wilson, Marshall Space Flight Center

C. Elachi, Jet Propulsion Laboratory   5:10

Discussion and Comments   5:30

<u>Attendees Provide Preference for Panel Participation</u>

Ice Breaker   6:00

Tuesday, November 19, 1985

Plenary Session: Establishment and Charge of Panels   8:30

Working Panels Meet—Short Presentations   9:00

Lunch   11:30

Working Panels: Discussion; Writing   1:00

Plenary Session: Update   4:30

Wednesday, November 20, 1985

Working Panels: Final Versions   8:30

Lunch   11:30

Plenary Session: Summing Up

Panel 1:   Summary, G. North   1:00
Panel 2:   Summary, T. Wilheit   1:30
Panel 3:   Summary, *R. Houze (A. Jameson, Acting Chairman)   2:00

Final Discussion on Major Issues,   2:30
   Policy Considerations, Etc.

Concluding Remarks, J. Theon   3:30

Adjourn   4:00

*In Absentia

APPENDIX C
WORKSHOP PARTICIPANTS

Philip Arkin	NOAA
David Atlas	University of Maryland
Eric Barrett	University of Bristol
Maurice Blackmon	NCAR
David Bowles	Utah Water Research Lab
Rafael Bras	MIT
V. N. Bringi	Colorado State University
Richard Carbone	NCAR
Bill Cleary	ORI, Inc.
Robert Crane	Dartmouth College
Thomas Crowley	National Science Foundation
Guisseppi Dalu	National Research Council (Italy)
Paul Davis	RDS
Peter S. Eagleson	MIT
Charles Elachi	JPL
Jay Fein	National Science Foundation
Gerald W. Felde	AFGL/LYS
R. Ferraro	RDS/NOAA
Noboyoshi Fugono	Radio Research Laboratory (Japan)
Michael Garstang	University of Virginia
Catherine Gautier	Scripps Institute of Oceanography
Julius Goldhirsh	John Hopkins/Applied Physics Lab
Reynold Greenstone	ORI, Inc.
Norman Grody	NOAA
V. K. Gupta	Utah State University
Barry Hinton	University of Wisconsin—Madison
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15. Supplementary Notes

16. Abstract Tropical rainfall data are crucial in determining the role of tropical latent heating in driving the circulation of the global atmosphere. Also, the data are particularly important for testing the realism of climate models, and their ability to simulate and predict climate accurately on the seasonal time scale. Other scientific issues such as the effects of El Nino on climate could be addressed with a reliable. extended time series of tropical rainfall observations. A passive microwave sensor is planned to provide information on the integrated column precipitation content, its areal distribution, and its intensity. An active microwave sensor (radar) will define the layer depth of the precipitation and provide information about the intensity of rain reaching the surface, the key to determining the latent heat input to the atmosphere. A visible/infrared sensor will provide very high resolution information on cloud coverage, type, and top temperatures and also serve as the link between these data and the long and virtually continuous coverage by the geosynchronous meteorological satellites. The unique combination of sensor wavelengths, coverages, and resolving capabilities together with the low altitude, non-Sun-synchronous orbit provide a sampling capability that should yield monthly precipitation amounts to a reasonable accuracy over a 500- by 500-km grid.

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