

Engineering of the Global Precipitation Measurement System

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¹²*Abstract*—Global Precipitation Measurement (GPM) is an international effort to improve climate, weather, and hydrological predictions through more accurate and more frequent precipitation measurements. GPM will be conducted through an international partnership led by the National Aeronautics and Space Administration (NASA) of the United States and the National Space Development Agency (NASDA) of Japan, with other organizations and countries providing additional data streams and scientific analysis. Measurements will be made with a constellation of Earth observing satellites and a global ground validation program. NASA will provide two spacecraft to the constellation, the Core and the Constellation spacecraft. For instrumentation, NASA will provide a conical-scanning, polarization-sensitive, multi-frequency microwave radiometer termed the GPM Microwave Imager (GMI) for both the Core and Constellation satellite. NASA will also provide the mission operations for the two spacecraft, two ground validation “Supersites,” and the Precipitation Processing System (PPS) needed to assimilate all of the various data streams and produce the products. NASDA will provide the Dual-frequency Precipitation Radar (DPR) for the Core spacecraft, the launch of the Core spacecraft, and a data stream from the GCOM-B1 spacecraft.

This paper presents the engineering of the NASA portion of GPM from scientific objectives to viable system design. GPM’s six elements, (1) the flight instruments, (2) the Core spacecraft, (3) the Constellation spacecraft, (4) the mission operations system, (5) the ground validation system, and (6) the PPS, must operate together and within the political environment of partnerships in order to achieve the science objectives. Decisions on topics such as autonomy, Internet Protocol, Virtual Direct Broadcast, and orbits affect multiple elements across the mission. Advances in system

engineering tools and techniques will enable a more cost-effective development effort. As GPM approaches its Preliminary Design Review (PDR) and the start of implementation, we take a look at the current system design, how we arrived here, and where we plan to go.

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1. INTRODUCTION

Our industrial society, with its reservoirs for drinking water and its hydroelectric plants for electricity, “relies on the fact that water will fall from the sky.”[1] Yet our current ability to measure precipitation is amazingly imprecise. We sample rain over land with about 40,000 rain gauges, which together have a total surface area smaller than a football field, and we cover only a few countries with a patchwork of radars that can easily be off by a factor of two. Precipitation over the 70% of Earth covered by ocean is barely touched by the ground-based measurements.

The Tropical Rainfall Measuring Mission (TRMM) has been demonstrating, since its launch by NASA and NASDA in 1997, the benefits of rain measurement from space. TRMM’s Ku-band Precipitation Radar (PR) and Microwave Imager (TMI) make active and passive microwave measurements which penetrate clouds and directly sample the rain processes within. TRMM has shown the benefits of including precipitation measurements in hurricane-track

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forecasts (see Figure 1). The mission has demonstrated a substantial improvement in the accuracy and consistency of rainfall estimation in the tropics. Recent work has begun to merge passive microwave measurements from other missions such as Aqua and the Defense Meteorological Satellite Program (DMSP) with the active and passive measurements from TRMM to create a more complete picture of rain across Earth.

GPM will build on the work of TRMM and extend the science from understanding tropical rainfall to using that understanding to improve climate, weather, and hydrological forecasts on a global basis.

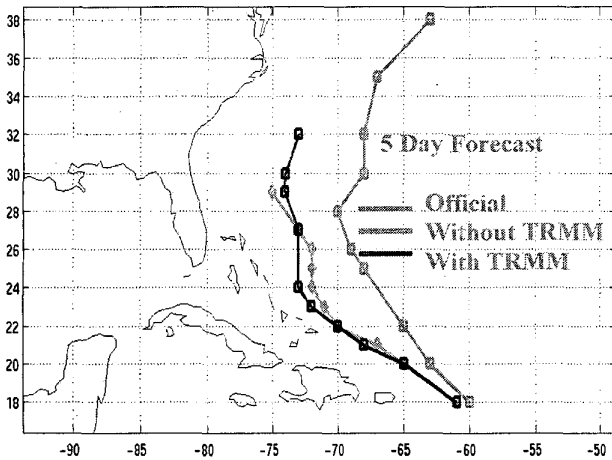


Figure 1: Impact of TRMM data on Hurricane Bonnie forecast [2]

2. THE SCIENCE

The mission of NASA’s Earth Science Enterprise (ESE) is to “Develop a scientific understanding of the Earth System and its response to natural and human-induced changes to enable improved prediction of climate, weather, and natural hazards for present and future generations.” GPM is an ESE-sponsored mission; thus, its purpose and goals directly reflect those of its parent organization. GPM’s science objectives are to improve mankind’s ability to predict three factors vital to life on Earth: the climate, the weather, and the availability of flood/fresh water resources. GPM will accomplish these objectives by providing more frequent and more accurate sampling of Earth’s precipitation. These scientific data will be used to increase our understanding of Earth’s climate, weather, and water cycle, which, in turn, will allow us to further comprehend and predict global changes and their effects.

GPM will improve ongoing efforts to predict climate by providing global measurement of precipitation, its distribution, and physical processes. This information is a key indicator of the global water cycle and its response to climate change. GPM will increase the accuracy of weather

and precipitation forecasts by providing more accurate measurement of precipitation rates and latent heat release. These key inputs are needed by computer models to produce better weather predications. GPM’s frequent and complete sampling of Earth’s precipitation will enable better prediction of flood hazards and improved management of life-sustaining activities dependent upon fresh water.

GPM has the potential to enable advancements in a vast number of disciplines that affect the world’s citizens: flood and drought prediction, soil system science, agriculture planning, water supply planning, forest management, civil engineering, water resources management, and even military operations. Additional information on the science is available in Smith, et al [3].

3. GPM ARCHITECTURE

GPM’s measurements fall into three categories: microphysics measurements, sampling measurements, and error characterization measurements. Microphysics measurements will be made from space with a Dual-frequency Precipitation Radar (DPR); a number of microwave radiometers will sample precipitation from various spacecraft, and the errors will be characterized through instrumentation on the ground and comparison of flight measurements. Figure 2 shows the GPM architecture. The Core Spacecraft will provide the microphysics measurements and the critical calibration reference for the other microwave radiometers. The constellation, which includes the Constellation Spacecraft and other partner spacecraft, will sample the precipitation globally multiple times in a day. The mission operations center will control the NASA spacecraft through the Tracking Data Relay Satellite System (TDRSS). All the data from the spacecraft and the ground validation system will be processed by the Precipitation Processing System (PPS) and sent to distribution centers around the world.

Flight Instruments

The objectives of GPM require that two types of measurements be made: near-global measurements of rainfall, and three-dimensional measurements of cloud structure and precipitation (including drop-size distributions). These measurements can best be performed using two different types of instruments; a passive microwave radiometer, the GMI, and an active radar, the DPR.

The GMI is a conical-scan, passive microwave radiometer that will be used for rainfall measurement. NASA will procure two nearly identical GMI instruments from industry—one instrument to be placed on the Core Spacecraft, and the other on the NASA-provided Constellation Spacecraft. Although the vendor for GMI has not been selected at this time, the instrument’s design will most likely incorporate substantial heritage from a previous

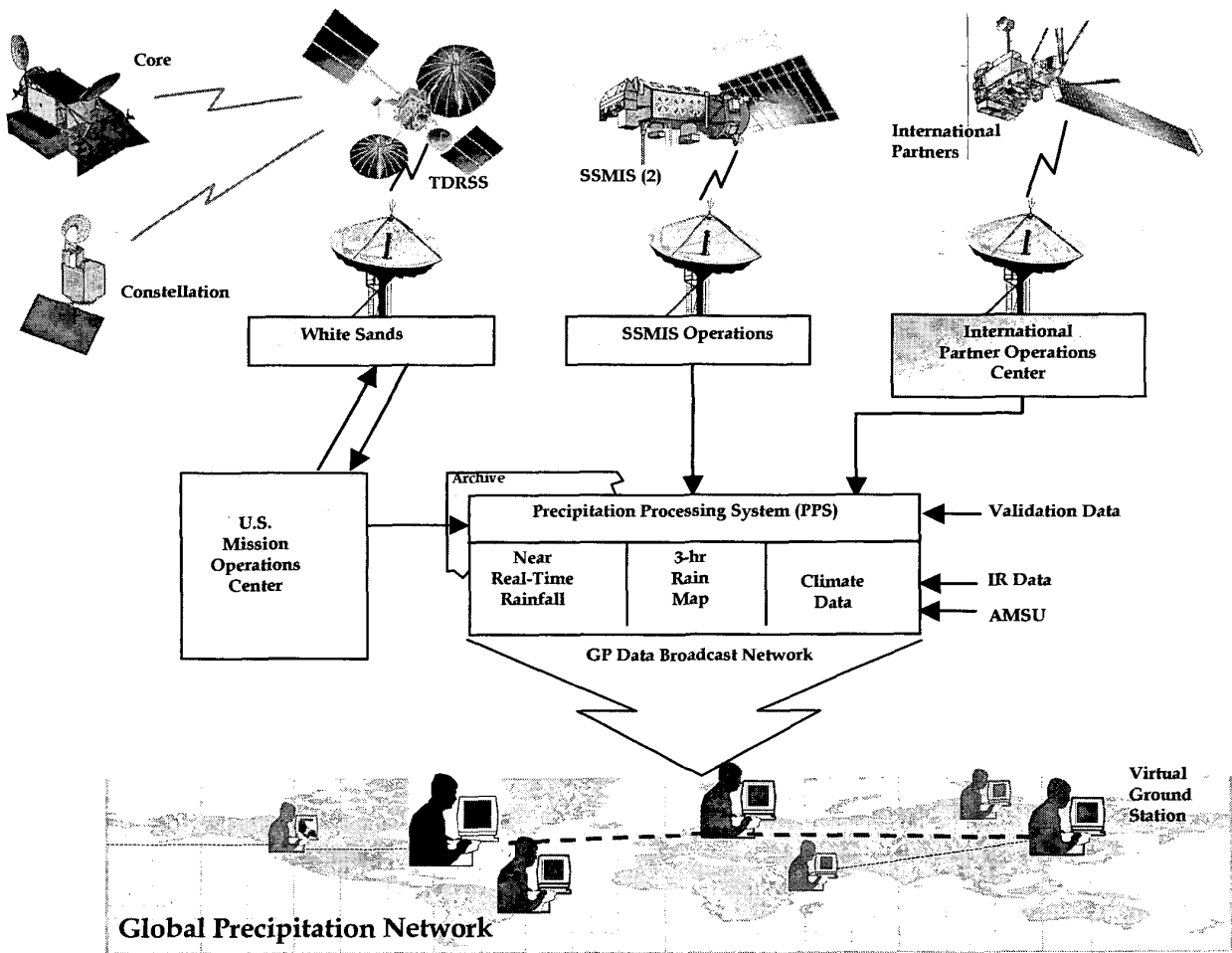


Figure 2: GPM Mission Architecture

design (i.e. SSM/I, TMI, SSMIS, or CMIS) (refer to Figure 3). This heritage will benefit GPM by reducing the technical risk, time required for design and fabrication, and procurement cost. GMI will be designed to make simultaneous measurements in several microwave frequencies (e.g., 10.7, 19.3, 23, 37, 89 GHz), giving the instrument the capability to measure a variety of rainfall rates and related environmental parameters. Additional, higher frequency measurement channels (150-165 and 183 GHz) are under consideration in order to provide increased sensitivity for the measurement of light rains frequently found at Earth's higher latitudes; a decision concerning the inclusion of these additional measurement channels will be made as part of the procurement process.

The notional design for GMI includes an offset parabolic reflector of approximately 1.0 meters in diameter, which rotates about the instrument's vertical axis. The antenna will point at an off-nadir look angle of $\sim 49^\circ$, providing a ground measurement swath of ~ 800 km from side-to-side centered along the ground-track of the Core spacecraft (see

Figure 4). The speed of rotation has not been firmly established, but most heritage systems have used a

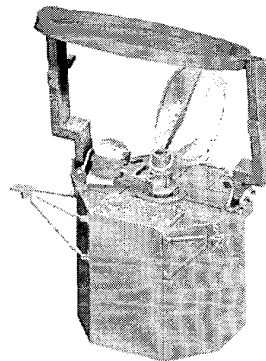


Figure 3: GMI-Type Instrument

rotational rate of about 32 rpm. During each 2-second revolution measurements will be made over $\sim 130^\circ$ scan sector centered on the spacecraft velocity vector. The remaining 230° of the antenna rotation will be used to perform a hot and a cold calibration and other housekeeping functions. The instrument will thus be calibrated once per scan, or about every two seconds, at both ends of its measurement range, thus providing well-calibrated, highly accurate measurements. The rotating mass of the instrument generates momentum which must be compensated either by the instrument or by the spacecraft. The current concept is for the instrument to provide its own momentum compensation, by integrating a separate momentum wheel assembly. GMI is expected to have a mass of about 80 kg. The electronics enclosure should be on the order of $0.5 \times 0.5 \times 0.5$ m, supporting a reflector of ~ 1.0 m in diameter.

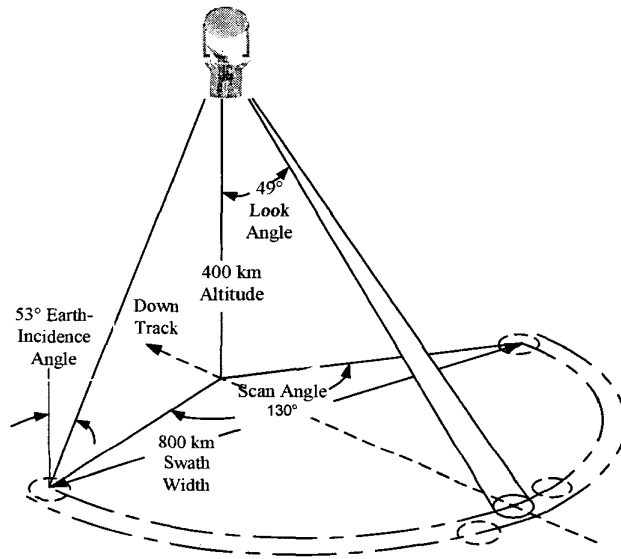


Figure 4: Illustration of GMI Scan Geometry

In addition to the two microwave radiometers being procured by GPM, additional microwave radiometers will be operated during the GPM era by other U.S. Government agencies and foreign space programs. These instruments will provide the frequent global rainfall measurements that are discussed in the constellation section below. The availability of these instruments is a result of their versatility; when properly configured, they can be used to infer a wide variety of phenomena, such as atmospheric moisture and temperature profiles, soil moisture and sea surface temperature. The microwave radiometer's versatility has made it an instrument of choice for a variety of measurement programs, including environmental remote sensing and weather forecasting. Microwave radiometers will be used during the GPM era on several satellites supporting these programs. GPM has initiated the planning

and coordination needed so that the measurements made by the instruments will be available to assist GPM in meeting its objectives for frequent, global measurements of rainfall.

The detailed measurements of cloud structure and precipitation characteristics will be made with the DPR. This instrument will be provided to GPM by NASDA (Figure 5). The DPR will be comprised of two, essentially independent radars. One radar will operate in the Ku-Band (13.6 GHz) and is referred to as PR-U. The other radar will operate in the Ka-Band (35.55 GHz) and is referred to as PR-A. By measuring the reflectivities of rain at two different radar frequencies, it is possible to infer information regarding rain rate, cloud type and its three-dimensional structure, and drop-size distribution. The design approach for both radars is based upon the TRMM PR design, updated as necessary to incorporate new technologies, and modified for operation at the specified frequencies. Like the PR, each of the DPR radars will use a 128-element active phased array. The two radars are designed to provide temporally matching ground footprints with the same spatial size and scan pattern. Careful physical alignment of the radar antennas will be required on the spacecraft to ensure co-alignment of the beams is achieved on-orbit. The DPR will have a 245 km wide ground swath, comprised of 49 footprints, each 5 km in width. The DPR's mass is estimated to be 660 kg. The antenna for the PR-U will be $2.4 \times 2.4 \times 0.5$ m in size, and the PR-A $1.0 \times 1.0 \times 0.5$ m. Additional instrument information is available in Flaming [4].

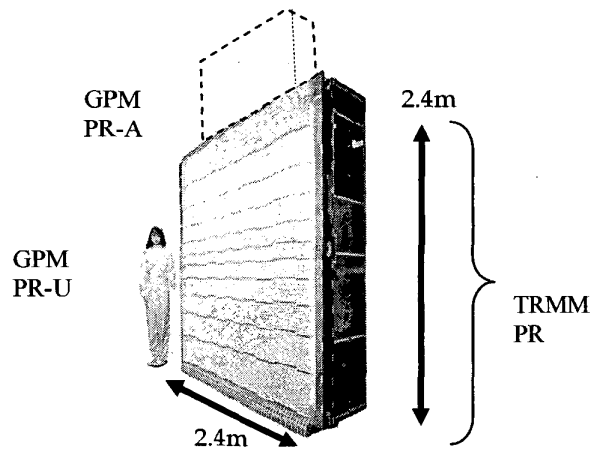


Figure 5: GPM DPR Similar to TRMM PR, But With Added GPM PR-A

Core Spacecraft

The Core Spacecraft will provide microphysics measurements of drop-size distribution and latent heat release in storms, and it will provide a calibration reference for microwave radiometer instruments throughout the GPM constellation. The spacecraft will fly in a 400 km circular

orbit, which is low enough to provide 5 km resolution with the radar. The orbit inclination will be 65 degrees, which will enable the Core Spacecraft orbit to cut across the orbits of the constellation spacecraft, sample the latitudes where nearly all precipitation occurs, and sample different times of day. In this orbit, the spacecraft will cover 91 percent of Earth's surface, sampling the area where 97 percent of the planet's rainfall occurs. The Core Spacecraft data will be returned essentially continuously over a low-rate Tracking and Data Relay Satellite System-Demand Access System (TDRSS-DAS) link.

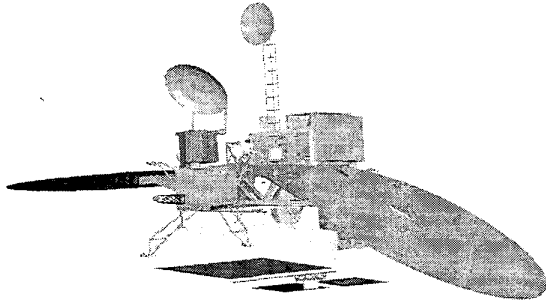


Figure 6: Core Spacecraft Concept

The Core Spacecraft will carry two instruments—the DPR and the GMI, described in the previous section. The GMI will passively measure global rainfall with a much larger “footprint” than the DPR. By comparing the information from the two instruments on the Core Spacecraft, scientists will be able to obtain accurate data algorithms and will be able to calibrate data from the additional satellites in the GPM constellation.

Inclusion of these two instruments on the GPM Core Spacecraft imposes certain constraints on the spacecraft design. The DPR, in particular, will require significant power to function (approximately 570 watts, nearly half of the 1200 watts required to power the entire spacecraft). Therefore, the Core Spacecraft's solar array panels must be large to gather the solar energy required for the mission. Also, the Core Spacecraft must fly at a fairly low altitude (400 km) to maximize the signal strength of its radar instruments. The combination of a large solar array panel area and the relatively dense atmosphere found at this altitude will cause a significant drag on the Core Spacecraft. The more drag a spacecraft encounters, the more fuel it must expend to maintain its orbit. Therefore, a design where the spacecraft will experience minimal drag is preferred. In addition, the GMI cold space calibration field of view must face away from the sun for the instrument to function properly, further complicating the spacecraft design.

Given the Core Spacecraft's science requirements and their corresponding constraints, GPM engineers performed a series of trade studies to optimize the design of the spacecraft. To minimize drag, the Core Spacecraft's solar array panels will not track the sun. They will remain fixed, facing edge-on in the direction of the spacecraft's velocity vector. As the spacecraft's orbit precesses around Earth, operators will rotate (or “yaw”) the satellite 180 degrees every 36 days to ensure that one side of the spacecraft faces away from the Sun. This maneuver is expected to take 20 minutes for each rotation, and will not significantly impact the amount of time the spacecraft's instruments will be available for science observations. The solar array facing the Sun will be canted at a 20-degree angle to increase the panel surface area facing the Sun, maximizing that panel's capacity to collect energy. Figure 6 shows the current concept of the Core Spacecraft.

In addition, the Core Spacecraft will employ a distributed onboard computer architecture, taking advantage of the substantial computational capabilities that are available at a reasonable cost in the present day. The Core Spacecraft will utilize three separate computer systems (each with a backup) to perform guidance, navigation, and control functions; command and data handling functions; and power system functions. Each of the computer systems will consist of similar hardware, with customized software and interface cards enabling it to perform specialized tasks. This distributed architecture will be cost effective, since each of the major subsystems can be independently developed and tested, while minimizing non-recurring engineering expenses for components.

GPM engineers are currently examining potential options for the Core Spacecraft data bus—the system that will control onboard communications among the subsystem computers. Available alternatives include the MIL-STD-1553 bus and an Ethernet data bus system. While the MIL-STD-1553 data bus is a proven performer in the space environment, the faster data rate transfer of the Ethernet bus (10 Mbps, compared to 1 Mbps for the 1553) along with the standardized data protocols it employs (such as Internet Protocol, Transmission Control Protocol, and User Datagram Protocol) make it a more attractive choice for the Core Spacecraft. Ethernet has not been used in high-reliability space-based applications, however, and it will require significant effort and cost to develop an Ethernet data bus system that can withstand the rigors of space. NASA technology programs have been funding Ethernet development, making it a possible option for GPM. GPM will continue to investigate Ethernet technology as it matures, and will make a final decision on the data bus design prior to the Preliminary Design Review (PDR), currently scheduled for the fall of 2003.

Constellation

The GPM constellation will consist of a collection of

spacecraft providing microwave radiometer data streams. This constellation will greatly improve sampling of Earth's precipitation. Most of these spacecraft will be dedicated to other missions, with GPM partners providing the data streams for use in the GPM science data processing. NASA will contribute one Constellation Spacecraft dedicated to the overall constellation. This spacecraft will carry the GMI instrument.

Since most of the constellation satellites will be in Sun-synchronous (polar) orbits, the data can be downlinked once per orbit without violating latency constraints (although some outreach users would prefer more frequent access to the rainfall images). Like the Core Spacecraft, the NASA-provided Constellation Spacecraft will use TDRSS-DAS continuously, reducing data latency to ~2 minutes.

The GPM constellation is not an orthodox constellation like GPS or Iridium, where all spacecraft are controlled by a single organization and maintain a fixed relationship. GPM's constellation will actually be a collection of spacecraft, most with missions independent of GPM. Many of the spacecraft are Sun-synchronous, but their altitudes and orbital periods differ. For example, the DMSP spacecraft orbit at 833 km, while GCOM-B1 will orbit at 802 km. The different orbital periods cause the ground tracks to move with respect to each other, oscillating between overlapping coverage and missed coverage.

Some spacecraft will be dedicated to GPM, and a big challenge for the designer is the optimization of the orbits

for those spacecraft, given the varying coverage of the other existing spacecraft. Even finding a figure of merit for optimization is difficult. The objective of the GPM constellation is the reduction of precipitation estimate errors by more frequent sampling. A simple measure of average revisit time disguises the difference between sampling uniformly across a day and sampling twice as often over only half a day. Worst-case revisit time emphasizes the gaps in coverage, but since many locations will eventually have one large gap, this metric does not tell us much about coverage over longer periods. To overcome these shortcomings, GPM has been utilizing a "binning statistics" figure of merit, where the day is divided into 8 three-hour bins for each of thousands of equal-area pixels across the globe, and we count how many of those bins any spacecraft sees at least once.

Figure 7 shows the increasing coverage provided by additional spacecraft within the GPM constellation. The Core Spacecraft samples only 12% of the globe's 3-hour bins, but adding two DMSP spacecraft, GCOM-B1, and the NASA Constellation Spacecraft bring the total coverage to 70%. The green curve on the chart shows the average revisit time vs. number of spacecraft in the constellation. The average time between samples for any given point for the Core Spacecraft alone is over 24 hours, but adding the four other spacecraft brings the average time down to 3 hours. Note that these results are averaged over time and space, masking the fact that some regions have better sampling and some regions have worse on any given day. Also, additional spacecraft can have a much bigger impact

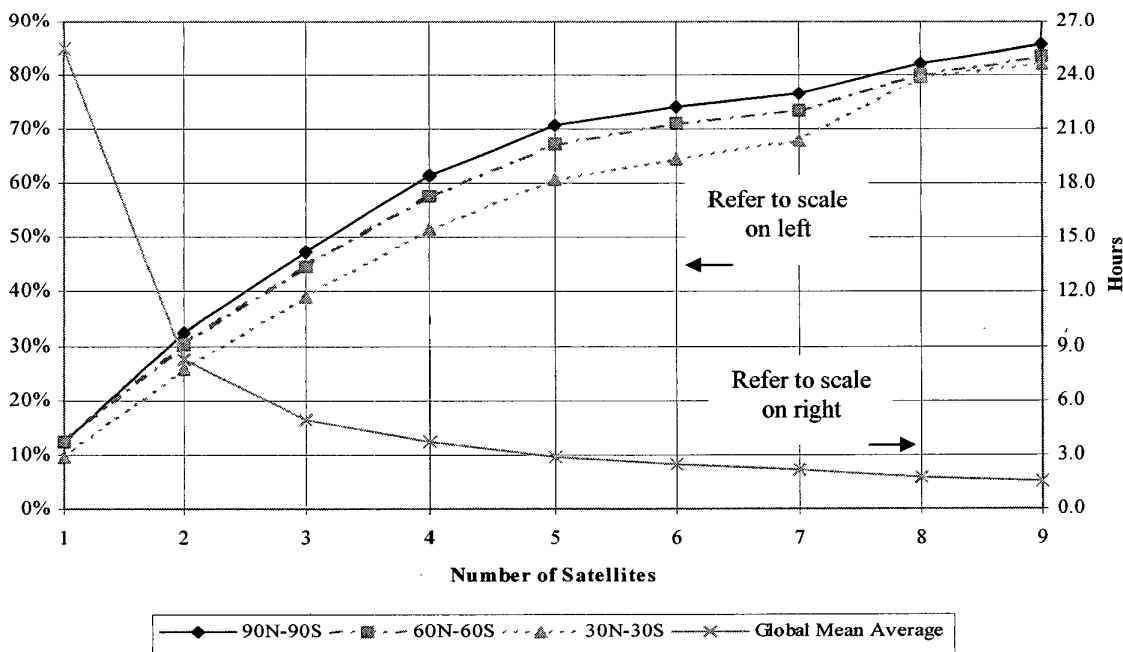


Figure 7: Percent of 3-hr Bins Sampled and Global Mean Revisit Time vs. Number of Satellites in the Constellation.

on some regions than on the global average. Some of this effect can be seen with the addition of a low-inclination spacecraft such as the eighth satellite in the plot. The percent of bins over $\pm 30^\circ$ shows a much more dramatic change than the global plot ($\pm 90^\circ$).

Mission Operations System

The mission operations for NASA's GPM spacecraft will be routine, automated, and low risk. The instruments will be on all of the time, with infrequent interruptions for calibrations. The spacecraft will perform most functions autonomously, including orbit determination and station keeping. The spacecraft will be in contact with the ground almost all of the time, reducing the operations risk by minimizing the time required to recognize and respond to an anomaly.

Both spacecraft will communicate continuously with the ground through the TDRSS. The communications will be interrupted briefly for handovers from one Tracking and Data Relay Satellite (TDRS) to another. A standard protocol will be used to retransmit any missing data. The Mission Operations Center (MOC) will provide the PPS with near real time data, 3-hour data sets, and 24-hour data

sets (refer to Figure 2).

The MOC will monitor both the Core and the NASA Constellation Spacecraft and generate the commands for any spacecraft activities. The operations center will only be staffed 40 hours per week during normal operations. At other times, automated systems will page an on-call operator in the event of a problem. The MOC will coordinate the instrument operations with the instrument teams.

GPM spacecraft operations will be simple. There will be very few activities to schedule and the activities will not conflict with one another. The standard protocol will allow the data to be delivered autonomously. Orbit maneuvers will be performed several times per year – often enough to maintain this expertise but not so often as to be a burden on operations. The two NASA spacecraft will not interact operationally with each other or with other partner spacecraft.

Ground Validation System

Ground Validation (GV) is an integral and critical element of GPM. The products of GV will be quantitative estimates

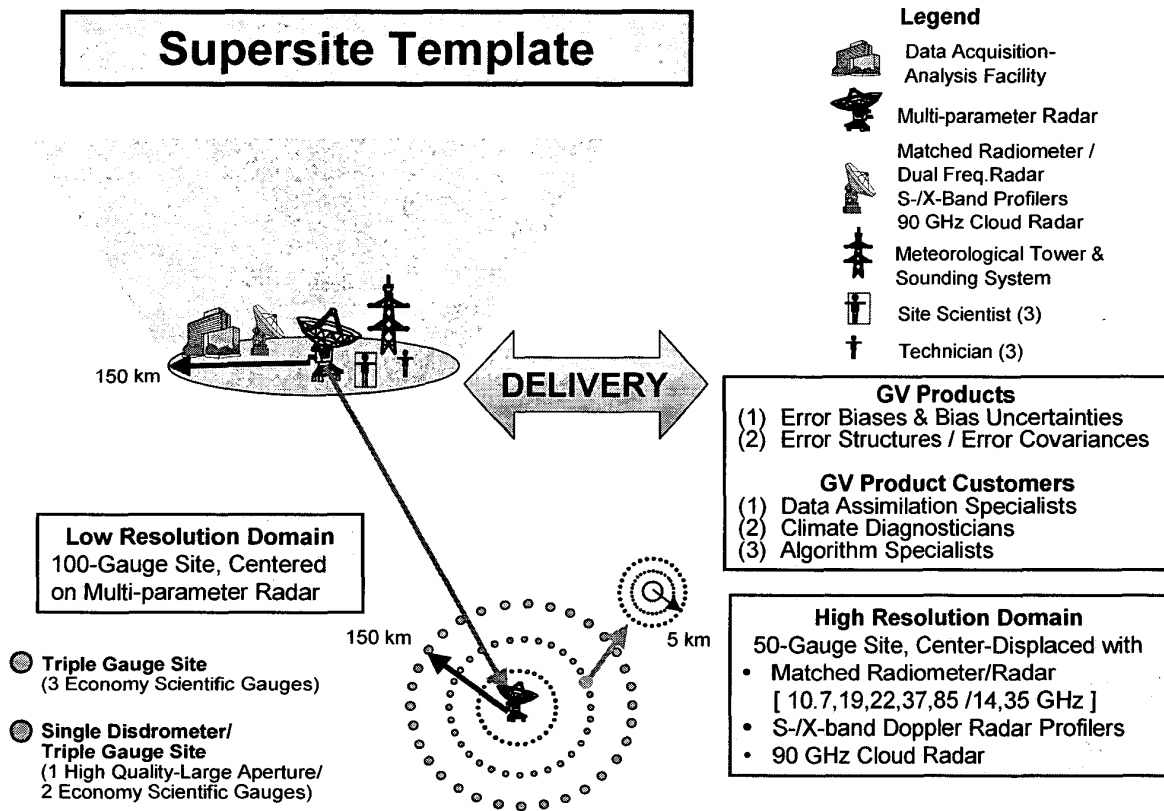


Figure 8: The Ground Validation Supersite is a Key Primary Component to the Routine Product Program

of systematic and random error on the satellite retrievals. GV will also characterize the spatial and temporal structure of the error, as well as other patterns in the error. By providing quantitative error products to the Earth Science communities, the GV program will provide increased credibility and utility to the GPM space-borne products.

GPM will build upon the heritage of the TRMM GV program by understanding and implementing well the complex lessons for success. The GPM GV program is composed of two distinct subprograms: (1) a Routine Product Program (RPP) and (2) a Focused Measurement Program (FMP). The following provides a brief description of each program.

Routine Product Program (RPP)—The RPP will be a continuous program providing, as products, validation answers on a regular and timely basis to the scientific community through the PPS. The primary elements of the RPP are the Supersite facility and the Regional Rain Gauge Network. Figure 8 provides a template as to how the Supersites will be instrumented and operated and how they will respond to the GPM validation customers. The Supersites will become operational two years prior to GPM Core launch and will continue operation through mission life. NASA will site, equip, operate, and maintain two of the Supersites and one Regional Rain Gauge Network. One Supersite will be within a tropical oceanic climate, while the second will be within a mid-latitude continental regime. Since the two NASA Supersites and the single Rain Gauge Network will be insufficient to provide measurements over all climatic regimes and meet the Mission's spatial and temporal requirements, NASA is seeking domestic and international partners to provide additional GV sites. Specifically, NASA is seeking partnerships to provide up to eight additional Supersites and up to five additional Regional Rain Gauge Networks.

The choice of instrumentation for the Supersites is dictated from the required GV products. Figure 8 provides some of the likely candidates for Supersite instrumentation. Two products are expected from the Supersite operations. These products are in the form of error characteristics and will consist of (1) bias and bias uncertainty factors that are a slow function of space, time, and rain rate, and (2) local-domain space-time error covariance structures. The first product, error bias, will be produced from a dual-frequency radar and radiometer instrument, channel-matched to that of the GPM primary space-borne instruments. The ground-based radar/ radiometer is proposed to survey the resolution volume of the space-borne instruments during overpass events. The second product, error structure, will be produced from a multi-parameter (i.e., polarimetric) volume-scanning radar and a network of rain gauges and disdrometers. In these measurements, exact calibration of the polarimetric radar and gauge network will not be necessary. The important aspect will be the underlying space-time resolution and structure provided by the

observations.

There will be three primary customers of the GV Supersite activities: (1) Data Assimilation Specialists, (2) Climate Diagnosticians, and (3) Algorithm Specialists. Data Assimilation Specialists study how to best assimilate satellite-derived precipitation measurements into environmental prediction models including General Circulation Models (GCM), Numerical Weather Prediction (NWP) models, Limited Area Models (LAM), and Hydrological models. The second customer type, Climate Diagnosticians, try to understand the veracity of trends and variations found in their models. The GV Supersite products will be in the form of validation answers, consisting of error characteristics of the retrievals, to these two customers. The third customer, Algorithm Specialists, is interested in improving the accuracy of satellite-derived products through improved algorithms. The Supersite will assist the algorithm specialists through testing and validation of assumptions within the physical models, which form the basis of the algorithms.

Successful implementation of the Supersites depends upon effective and timely communication between the Supersite research scientists and the PPS. Effective communication is particularly important for the algorithm specialists who need reliable and near-real-time alerts when a Supersite produces a significant deviation between the rain rates it observes and what is provided by an over-flying satellite. Firstly, the PPS supplies the Supersite with data from the recent satellite overpass. The GV Supersite scientists generate a comparison (with some scientific insight) between their ground observations and that of the satellite. These answers are communicated back to the PPS, which then communicates to the Algorithm Specialists what the problems are, as they occur, along with the relevant data sets that describe and explain the problem.

Focused Measurement Program (FMP)— The FMP will consist of a diverse mix of research and experiments, each dedicated to a focused objective. Some experimental programs of the FMP will explore climatological and meteorological phenomena not represented by the Supersites. Other experimental programs will possess demonstrational objectives to validate instrumentation suites or data product algorithms. The FMP will emphasize research activities addressing GPM GV risk factors, as the risks are identified. It is expected that GV risk reduction from the focused program will ultimately improve the operational products of the RPP Supersites. Focused activities will span a range of complexity from experiments involving a few researchers with ground-based instrumentation to field campaigns involving research aircraft and ships and a diverse complement of researchers and personnel. Regardless of the complexity, the objectives of the FMP experiments will be limited and specific. In contrast to the RPP, the FMP will provide products in a non-routine but deliberate timeframe. FMP activities will

commence as early as 2004. Experiments and research will continue in the years prior to GPM Core Spacecraft launch and throughout the mission lifetime.

Precipitation Processing System

The PPS will be responsible for the production and distribution of GPM mission data. The process will begin with ingest of satellite data from the GPM MOC, GPM mission partner data centers, and ancillary data sources. This data will then be processed into the various types and levels to produce the standard product set determined and approved by the GPM science team.

The PPS must take into consideration the fact that GPM will not be put into place as a one-time deployment of the complete final array of space and ground elements, but will evolve from demonstrations using existing assets and the time-phased addition of dedicated and contributed elements. In addition, the PPS must accommodate variation in assets and data streams, without requiring major changes in essential equipment or processes, as GPM partners join or leave the program over time.

TRMM, Aqua, and two DMSP satellites currently in orbit carry a set of instruments suitable to demonstrate the data gathering and calibration functions of the GPM Core Spacecraft and three constellation spacecraft respectively. A demonstration ground validation and calibration site is planned for 2004 to work with TRMM over-flights, thereby providing ground validation data. ADEOS-II data should also be available after its launch in late 2002. The TRMM Science Data Processing System is being upgraded to accept the additional spacecraft and ground data. This configuration will be capable of demonstrating each aspect of the PPS—world-wide data gathering, ground calibration, data correlation, and multi-asset operations—well before the full-up system is deployed in the 2005-2007 timeframe.

The PPS will produce three distinct kinds of products. On a very timely basis (as data come into the GSFC processing system) a global precipitation map available to all via web access will be updated with the latest satellite data. Every three hours, the best instrument data available will be combined and quality-controlled to create a three-hour global precipitation product with error characterization that can be used in weather modeling and forecast improvement. A key driver in this type of precipitation product will be to provide the best quality product as close to the actual data collection time as is feasible. These products will be available to designated users within 20 minutes of the collection of the last data bit in the product. The third type of product will be a climate research quality product where timeliness is less of a driver than the accuracy. These products will be the best satellite data stream and ancillary data stream (including data from GPM ground validation sites) available. These climate research quality products will be released within 48 hours of receipt of the necessary

data input.

Products will be generated through three levels. Level 1 will be the calibrated, geo-located, instrument values at the instrument field of view. Level 2 will maintain the instrument footprint orientation but will convert instrument values to physical parameters, the key parameter for the mission being precipitation rate. Level 3 products will aggregate the level 2 physical parameters into different time-space grid orientations. This level will provide the key climate research quality products produced by GPM. Figure 9 provides an example of a level 2 product of vertical hurricane (Floyd) structure as well as surface rain-rates derived from the PR on TRMM. An improved version of this TRMM instrument will be part of GPM and an analogous product will likely be part of the standard data products. All GPM data products will be available to users via the GSFC DAAC or regional data distribution centers provided by mission partners (refer to Figure 2).

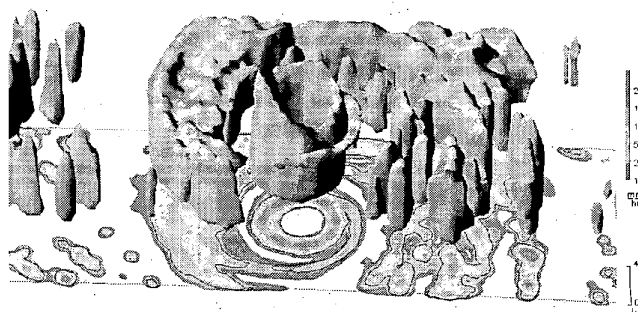


Figure 9: Hurricane Floyd Data Product

4. TRADE RESULTS

Several major decisions have impacted the mission architecture of GPM. Among these, the constellation configuration, the use of Internet Protocol, and the use of TDRSS-DAS service for virtual direct broadcast are innovative approaches to classic system engineering problems.

Constellation Configuration

As explained earlier, the GPM constellation will really be a collection of spacecraft from different organizations with different primary objectives. The original concept for GPM was a true orthodox constellation of eight spacecraft plus the Core, with Sun-synchronous orbits three hours apart around the globe. These nine spacecraft would have required at least five different orbital planes (one for the Core and four for the Sun-synchronous spacecraft, with two spacecraft in each plane). Because of the low nodal precession rate for polar orbits, a large amount of time (or fuel) would have been required to move a pair of spacecraft to a different plane, so practically, GPM would have needed five launches. Even if the Constellation Spacecraft were

small, simple, and inexpensive, the launch costs made the idea of an orthodox constellation impractical. Fortunately, a number of missions are flying, or plan to fly, microwave radiometers with frequencies suitable for rain retrieval, and NASA is actively pursuing partnerships with the organizations sponsoring these missions.

Internet Protocol

The GPM mission will use an Internet Protocol (IP) stack as the data format for all return link and forward link space-ground data transmissions. The protocol stack supports guaranteed delivery of data across the space-ground link. This approach represents an advancement in the current state-of-practice for data communications between spacecraft and ground assets, which are currently based on the Consultative Committee for Space Data Systems (CCSDS) recommendations. The use of IP for GPM should offer the following operational benefits for the mission:

- a. End-to-end data routing from the spacecraft to the ultimate end user of the data can be easily accomplished via the IP address inserted into the spacecraft data stream.
- b. Use of a guaranteed-delivery IP will eliminate the need for a level zero processing function within the ground system to remove communications artifacts and reassemble the spacecraft data stream in its original format for delivery to users.
- c. The management of the spacecraft's on-board Solid State Recorder (SSR) will be greatly simplified, and much more automated than the SSR management for many currently operational missions. IP will allow identification and retransmission of selected portions of spacecraft data without operator intervention.

A key feature of the IP design on GPM for return link telemetry communications is the use of the Multicast Dissemination Protocol (MDP) as the file transfer protocol. MDP is a "selective negative-acknowledgement" protocol and allows the queuing of protocol directives for later transmission, enabling the GPM spacecraft to operate with asynchronous command and telemetry links and still provide guaranteed data delivery. The protocol identifies only those portions of file transfers that were not successfully received in the ground system during downlink operations. Protocol directives identifying these incomplete file segments, and acknowledging files successfully received, will be stored within the ground system and uplinked to the GPM spacecraft every 3 hours. Once the missing segments from a file are received, the complete file will be delivered to the PPS for further processing and distribution. Files within the GPM spacecraft's SSR will be automatically deleted when successfully received on the ground by the autonomous transmission of file acknowledgements.

GPM proposes to use standard protocols such as File Transfer Protocol (FTP) and Transmission Control Protocol (TCP) for command uplinks. Use of these protocols will enable the guaranteed delivery of commands from the ground system to the spacecraft when full-duplex communications are available and should simplify operational activities associated with command verification from current methods. By using the User Datagram Protocol (UDP), "blind" commands can be sent from the ground system to the spacecraft during emergencies or safe-mode situations, where return link communications may be unavailable.

Virtual Direct Broadcast

Initial plans for GPM included a direct broadcast transmitter for real-time reports to local sites as the spacecraft flew over, just as the National Oceanic and Atmospheric Administration (NOAA) polar weather satellites carry a UHF direct broadcast transmitter. With this configuration, the spacecraft would have required an S-Band transmitter to downlink all of the data once per orbit. By using a TDRSS-DAS link continuously, GPM will no longer require a UHF transmitter and will enable global access to all of its precipitation data with less than five minutes delay. As it is collected, the science data will be relayed through a TDRS, through NASA's Space Network, and to the MOC, where the data files will be reassembled and forwarded to the PPS for distribution over the Internet. DAS uses the multiple access capability of TDRSS, where several spacecraft can use the same frequency at the same time through code division multiple access and beamformers, so the cost is less than scheduling access once per orbit through the dedicated TDRSS service.

The primary disadvantages of utilizing TDRSS-DAS involve the antenna and the low data rate. Because of the long distance to the TDRS, the GPM spacecraft must carry a high-gain antenna. This antenna must be pointed and it must have a clear view of the zenith hemisphere. The data rate with DAS must remain below 300 kbps due to system limitations. The instruments on the GPM Core spacecraft will nearly fill this bandwidth so we must carefully allocate data rate.

5. SYSTEM ENGINEERING PROCESS

Fundamentally, system engineering is a method of solving problems which are too complex for a single individual to tackle. A problem is divided into a number of smaller problems, each of which is handled by a different person. The system engineer decides how to divide the effort so that the individual pieces can be brought back together in the end to solve the original problem. In something as complex as a space flight mission, this process occurs at multiple levels as the mission is broken down into elements, subsystems, components, and circuits. Different engineers look at the problem differently, and each engineer who

works on the project brings his own perspective and bias. As the engineers define the project in more and more detail, they discover that initial solution ideas cannot work, so they make changes along the way. Communication between individuals is never perfect, so there are misunderstandings which must be discovered and corrected. It is a huge challenge to assemble a functioning system that accomplishes the original objectives.

In order to effectively utilize multiple engineers working in parallel on different elements of a system, the system engineer defines requirements for each of the elements in such a way as to ensure margin at the places where the elements interact. The system engineer could require that the power system produce exactly the amount of power that he estimates the other components will consume, but it is more efficient during the early design to require the power system to produce extra power so that the solar array will not require a redesign if some other subsystem engineer decides he needs another watt of power. This requirements-driven process is the standard method for the engineering of aerospace systems, but the margin is an inherent inefficiency. System engineers are constantly looking for ways to reduce excess margins without increasing the development and operations risk.

In the past, engineering was a very manual function. Documents carried the design for each element, subsystem, and component, and the only link between information in documents was in the mind of the engineer. But engineering has changed dramatically over the last decade as computer technology has brought substantial capability to the desktop. Electrical circuit and mechanical drawings now exist in electronic form, with the drawings linked to each other and to extensive part libraries. Automated tools take the electronic drawings and faithfully produce the final products, eliminating the possibility of a human misreading a document. Computers have greatly reduced the effort and scrutiny needed to go from schematic to routing to board fabrication.

A similar revolution in automation has started to impact system engineering, and GPM is investigating ways to take advantage of that capability to better manage the system engineering data. We have selected the System Level Automation Tool for Enterprises (SLATE) from EDS as the primary tool for the GPM system engineering effort. Our customized SLATE database is our primary repository for requirements, risks, and trade studies.

SLATE allows the GPM team to store its data in a hierarchical structure, so that the organization of information matches the system's block diagrams. The engineering team breaks the system up into smaller pieces, and the data structure matches that breakdown. All the data is in one location, so everyone works with the same configuration.

Engineers assign requirements to physical or functional blocks within the system, and they link requirements to other defining and complying requirements. Validation of the design (where the engineers ensure that we have designed the right system) is greatly simplified by the ability to autonomously trace the level 1 requirements to the elements and subsystems and search for unlinked requirements. SLATE is no substitute for the knowledge and experience of an engineer, but the tool provides a method to capture and retrieve information reliably, so that we do not have to depend on a single person to maintain all of the relationships.

We also store information about GPM risks and trade studies in the SLATE database. We have defined special object types, which enable us to link risks and trade studies to the requirements and architecture elements within the system. A risk frequently involves the possibility of not meeting a particular requirement, and the mitigation of a risk may result in a new requirement. GPM's database captures these relationships. Similarly, trade studies lead to additional requirements, and the linkages in our database help us document how the engineers developed the design.

6. FUTURE WORK

The GPM Mission Confirmation Review is scheduled for late 2003. We must complete a PDR and an independent assessment before NASA Headquarters will give the go-ahead to implement the mission. The design work has moved from the mission level to the element and subsystem level, with only small modifications occurring to the mission configuration, as the element and subsystem engineers refine their designs.

The mission-level engineering team will spend substantial effort over the next year defining the engineering process. We must set up our SLATE database to capture verification information as the system is built and tested. As components are tested in parallel prior to integration, we will have a single repository to capture the actual performance information, with roll-ups of mass, power, and other budgets available with the click of a button. SLATE will also enable us to easily produce status review charts, resulting in a savings of valuable engineering time.

7. CONCLUSION

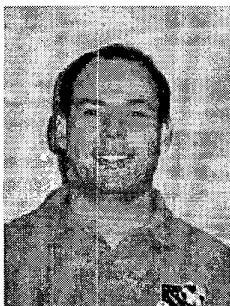
The engineering work on GPM is just beginning. With a year of formulation complete and another year to go before the PDR, much of the mission architecture and top-level requirements are defined. The details of the elements are beginning to take shape. The engineering team is considering not only the products, but also the process necessary to create a cost effective and successful mission. Ensuring that the instruments, Core Spacecraft, Constellation Spacecraft, Mission Operations System, Ground Validation System, and Precipitation Processing

System all work together to produce an effective Global Precipitation Measurement is a challenging task. Automated tools will simplify this task, enabling engineers and scientists to deliver better climate, weather, and hydrological forecasts for everyone.

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Timothy Rykowski/GSFC Code 581 is the GPM Ground System Manager, and is responsible for the specification, design, and development of all systems necessary to provide space-ground communications and mission operations for the NASA-provided GPM spacecraft. Mr. Rykowski has been employed at GSFC since 1983, and was most recently the Project Manager for the Earth Observing System (EOS) Data and Operations System (EDOS), which currently provides the return link and forward link processing capabilities for the Terra and Aqua missions within the EOS program.



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