Simulation of the Sampling Properties of the Global Precipitation Measurement Mission

by

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ABSTRACT

This study simulates and evaluates the sampling properties of the Global Precipitation Measurement Mission (GPM). The sampling quality is described in terms of the percentage of rainfall measured by ground instruments recoverable from the GPM measurements.

A specific configuration of the constellation is being used. The number of participating satellites and their individual orbital characteristics are selected and calculated. The instruments necessary for measuring precipitation on board of the satellites are selected and configured as well. Two study areas are selected, Rondonia basin in Brazil (tropics) and Ilarion basin in Greece (mid-latitudes).

Data from rain gages and radar are used. The time step of the data is disaggregated from 1 hour to 1 minute so that they will be comparable to the duration of the satellites’ contact time. The rainfall depth of every snapshot is set equal to the corresponding disaggregated values. The snapshots are then combined and rainfall events are reconstructed.

The difference between the recorded rainfall depths and the reconstructed event is generally large. In order to improve the results, several approaches are taken into consideration, including averaging the input data in time and in space.

Using point measurements from rain gages in the simulation yields poor results. Performing temporal averaging provides little improvement. However, when spatial averaging is introduced (areal precipitation), the results are generally encouraging and the percentage of under-sampled rainfall drops significantly. Comparing the results obtained from the simulation in Rondonia and in Ilarion basins, it is concluded that in mid-latitudes, the percentage of under-sampled rainfall is slightly more than that in the tropics.

Thesis supervisor: Rafael L. Bras
Title: Bacardi and Stockholm Water Foundations Professor
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"Everything changes" (Heraklitus, 490 BC)
1. Introduction

1.1. Global Precipitation Measurement Mission

The Global Precipitation Measurement Mission (GPM) is an extension of the Tropical Rainfall Measurement Mission (TRMM) launched in November 1997 by NASA and the National Space Development Agency (NASDA) of Japan. The TRMM mission has been very successful in monitoring rainfall around the tropics and the corresponding releases of latent heat. However, as its name implies, this monitoring takes place only in the tropics and cannot provide answers to fundamental questions on the global scale.

![Figure 1-1: The concept of GPM constellation. [17].](image)

An attempt has been made during the last couple of years to develop an internationally organized global scale satellite-based precipitation measurement mission. Notionally, GPM will be a constellation of satellites consisting of a mothership and
several (or as many as possible) drone satellites. The mothership satellite will initially carry one precipitation radar and a microwave imager while the drones will be equipped with a microwave imager only. The addition of other instruments is currently under consideration. The concept is illustrated in Figure 1-1.

Data assimilation from GPM products will help scientists answer persistent questions regarding the global cycle and water management. One significant hydrological question is the acceleration, or lack thereof of the global water. GPM products will hopefully aid in formulating an answer. Better estimates of area-averaged rainfall rate and accumulation and reliable predictions will also improve water management and weather forecasts. Ultimately, forecasts will significantly enhance the accuracy of flood predictions and save lives and properties.

Designing the GPM mission is difficult because of the complex logistics of the constellation and the assimilation of data from various sources, which requires contributions from many different scientific fields, thus increasing the risk of the whole project.

In order to predict and solve various issues that may appear during GPM’s operation, an extended period of simulations will take place starting from the end of the year 2002. These simulations will include existing satellites that carry suitable instruments and will preview the data collection and assimilation procedures.

1.2. Simulation Procedure

Due to the mission’s complexity, the whole simulation procedure is separated into five distinct steps.

The first step examines the number of constellation members and their individual orbit characteristics. Since the primary limiting factor is the available project budget, there is a limit to the number of satellites that can be used. In almost all configurations, the more satellites used the better the results. Hence, the analysis presented in chapter
Chapter 1: Introduction

2 estimates the maximum number of satellites that can be set in orbit considering the current budget.

The second step in chapter 3 presents the instruments for measuring precipitation. These instruments, the advanced precipitation radar and the microwave radiometer, are currently under construction. They are improved versions of similar existing instruments used in the TRMM mission and they offer better accuracy with less power consumption.

The third step, chapter 4, outlines various disaggregation methods. The ground truth data come from rain gages and radars installed in the Rondonia basin in Brazil and in the Ilarion basin in Greece. The data from the rain gages come in 1-hour time accumulations and the data from the radar come in time intervals that vary from a few minutes to half an hour. The satellites, however, spend only a few seconds above the study sites during each visit and the snapshots (measurements) they take, correspond to a few seconds of rainfall. Due to the difference in accumulation times between the ground truth data readings and the snapshots taken from the satellites, it is necessary to disaggregate the ground truth data from a 1-hour accumulation to a smaller time step that is comparable to the duration of the satellites' visits.

The constellation is set into orbit in the fourth step, presented in chapter 5 and the snapshots taken by the satellites are quantified. In particular, the measured rainfall depth of every snapshot is set equal to the disaggregated measurements taken by rain gages. In the last step, which completes chapter 5, the snapshots are aggregated and estimates of the total rainfall event depth are made.

In chapter 6, the two last steps are repeated, but instead of having the satellites measuring point rainfall, the areal precipitation over the two study areas is calculated using rain gages and is then disaggregated from a 1-hour time step to 1-minute. The satellites then take snapshots that are equal to the value of the areal precipitation and the snapshots are aggregated and compared to the original measured rainfall events.
Chapter 1: Introduction

In chapter 7, radar data are used instead of rain gages data. The spatial scale of the data is the same as in chapter 6 and the same comparisons are made.

Given the sparseness of the snapshots, a percentage of rainfall depth is lost during the snapshot aggregation process. This percentage is a measure of the hydrologic benefits of the mission and is quantified in chapters 5, 6 and 7.

Finally in chapter 8 the results from all these methods are listed and compared. Several conclusions and suggestions for further research are presented.
2. Orbits

2.1. General

The GPM constellation of satellites will consist of a mothership satellite (also known as base satellite) and a small number of drone satellites. The rest of the satellites needed to fill coverage gaps will be from other programs (co-op) provided, of course, that they have suitable instruments on board. Because of the nature of this mission, it would be financially impossible to launch and operate that many satellites a once. Therefore only a mothership and a small number of satellites (drones) will be specifically launched for this mission.

The determination of the orbit characteristics is very challenging and difficult since this constellation will be dynamic (addition and subtraction of satellites during its operation) and some of the satellites will be in defined orbits in pursuit of other objectives. The objective of the constellation is to provide global precipitation with a 3-hour revisit time. If this is not achievable, then the global coverage could be downsized to a coverage region that would extend from 70° N to 70° S latitude.

2.2. Orbit Characteristics

There is a variety of different possible orbits. Each one of them has advantages and disadvantages. For purposes of this report, three different candidates will be taken into account: the sun-synchronous, the mid-inclination and the low-inclination orbits. [1]

The sun-synchronous orbit has an approximate inclination of 98.6 degrees and has the advantage of providing samples at the same local time each day. The constant angle between the sun, satellite and observed spot on earth allows simple solar array and thermal design [6]. However, the retrograde orbit (an orbit of a satellite orbiting Earth in which the projection of the satellite's position on the Earth's equatorial plane
revolves in the direction opposite that of the rotation of the Earth) requires more launcher capability and therefore is more expensive [14]. Also, in the case of launching multiple satellites it is difficult to configure the launching patterns so that the satellites will be distributed through different ascending nodes at the same altitude.

Mid-inclination orbits (35 to 70 degrees inclination) provide short revisit intervals around the inclination latitude. However, due to the 70 degrees constraint, the polar regions are not covered at all by these satellites. It is easier to distribute multiple launched satellites to the desired orbits but they require more complex solar array and thermal design and may require periodic maneuvers to maintain the desired orbit [6].

Finally, for low-inclination orbits (up to 25 to 30 degrees inclination), the revisit intervals around the tropics (and nowhere else) are very satisfactory and the limited range of sun angles simplifies solar array and thermal design. The problem with using low-inclination orbits is that satellites with mid-inclination or sun-synchronous orbits must also be utilized in order to have coverage beyond the tropics. Since the mid-inclination and sun-synchronous orbited satellites will also cover the tropics, the result will be perfect coverage up to 30 degrees latitude but will have many gaps from 30 degrees latitude to 90 degrees latitude.

After extended simulations and optimization analyses, NASA has decided that the best solution for the GPM drones' orbits would be the sun-synchronous orbits. This decision accounts not only for the purely scientific benefits (i.e. coverage and sampling frequency) but also for the cost to benefit ratio [15].

**2.3. Optimization Procedure**

The optimization process, which involves the orbits' architecture, is basically a trade-off between coverage and resolution (see Figure 2-1 and Figure 2-2). Greatest coverage is achieved by high altitude satellites (i.e. 833 km) since the swath width will be large. However, this implies poor resolution since the resolution is the swath width divided by the number of beams that the instruments is using. Since the number of
successive beams per scan is constant for a particular instrument, the resolution is higher when the swath width is lower.

**Swath Width vs. Altitude**

![Swath Width vs. Altitude](image)

Figure 2-1: Swath width vs. Altitude (at 140 degree sector)

**Aperture size vs. Altitude**

![Aperture size vs. Altitude](image)

Figure 2-2: Aperture for footprint vs. Altitude [18]
Chapter 2: Orbits

Higher resolution, especially at low frequencies, is accomplished with low altitude satellites (i.e. 450 km). However, in the case of a higher resolution, the coverage drops significantly as the swath width is decreased from 1800 km (corresponding to 833 km altitude) to 1100 km (corresponding to 450 km altitude) as shown in Figure 2-1.

The most restrictive constraint in the optimization process is the inability to freely configure the satellite orbits. The co-operative (co-op) satellites have fixed (and different) orbits and are not optimally spaced since they are either borrowed from other missions or they will be partially utilized by the GPM constellation. Using co-op satellites in the constellation will result in coverage gaps since the original configurations of these satellites were to target specific areas of interest of the respective missions. The GPM drones, limited in number in order to keep the cost of the mission as low as possible, will not be able to efficiently fill the coverage gaps.

The total coverage varies over time when using satellites at different altitudes. The satellites will have different orbital periods. The difference in the periods changes the satellite relative phasing, so the coverage may overlap or complement (partially overlap) as shown in Figure 2-3. The phase shift period depends on this difference in the orbital periods or in other words in their altimetric difference. For example, the phase shift between a DMSP satellite and ADEOS-II is approximately 11 days.

![Figure 2-3: Complementary and overlapping coverage.](image)
It should also be noted that in order to achieve a global coverage every 3 hours using existing satellites (if they were all available for the needs of this mission) at least 10 satellites would be needed, depending on the orbital characteristics of the participating satellites.

Another requirement of the optimization process involves maintaining acceptable coverage and revisit frequencies at all times, even when a drone satellite is added or subtracted to the constellation. Since the drone satellites will be launched at different times and by different agencies, this requirement might not always be feasible.

Table 2-1: Orbital characteristics of existing co-op satellites.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Altitude</th>
<th>Inclination</th>
<th>Orbit</th>
<th>Swath</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMSP-F13</td>
<td>833 km</td>
<td>98.7°</td>
<td>Sun Synchronous</td>
<td>1400 km</td>
</tr>
<tr>
<td>DMSP-F14</td>
<td>833 km</td>
<td>98.7°</td>
<td>Sun Synchronous</td>
<td>1400 km</td>
</tr>
<tr>
<td>DMSP-F15</td>
<td>833 km</td>
<td>98.7°</td>
<td>Sun Synchronous</td>
<td>1400 km</td>
</tr>
<tr>
<td>ADEOS-II</td>
<td>803 km</td>
<td>98.6°</td>
<td>Sun Synchronous</td>
<td>1600 km</td>
</tr>
<tr>
<td>AQUA (EOS-PM)</td>
<td>705 km</td>
<td>98.2°</td>
<td>Sun Synchronous</td>
<td>1450 km</td>
</tr>
<tr>
<td>TRMM</td>
<td>402 km</td>
<td>35.0°</td>
<td>LEO</td>
<td>760 km</td>
</tr>
</tbody>
</table>

The optimization criterion or criteria can vary and should be determined from the scientific requirements. The optimal configuration in this study exists when the coverage within the region of interest for a specific time interval is maximized. Nevertheless, criteria like the minimization of the variation in coverage with time, a weighted coverage optimization (to provide best coverage in specific areas such as the tropics) or the maximization of the uncorrelated samples with the diurnal cycle could also be used.

Starting at the end of the year 2002, a simulation of a GPM configuration is planned using some of the existing satellites given in Table 2-1. The purpose of the simulation is to allow engineers to test the process by performing tests and simulations regarding data collection and assimilation. The goal is to minimize operational problems prior to the launch of the GPM mothership and drones.
2.4. Constellation

In the following two figures, the trajectories of the satellites’ orbits (Figure 2-4) and coverage (Figure 2-5) are presented for a period of 3 hours. From Figure 2-5, it is obvious that the global coverage has many gaps, but after 6 hours from the initiation of the orbits, almost 100% coverage has been achieved as illustrated in Figure 2-6. In Table 2-2 the swath characteristics of the radiometers on board of the satellites are presented.

Table 2-2: Instruments on board of the constellation’s satellites.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Instrument</th>
<th>Swath</th>
<th>Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMSP-13</td>
<td>SSM/I</td>
<td>1400 km</td>
<td>55 km</td>
</tr>
<tr>
<td>DMSP-14</td>
<td>SSM/I</td>
<td>1400 km</td>
<td>55 km</td>
</tr>
<tr>
<td>DMSP-15</td>
<td>SSM/I</td>
<td>1400 km</td>
<td>55 km</td>
</tr>
<tr>
<td>ADEOS-II</td>
<td>AMSR</td>
<td>1600 km</td>
<td>35 km</td>
</tr>
<tr>
<td>AQUA (EOS-PM)</td>
<td>AMSR-E</td>
<td>1450 km</td>
<td>36 km</td>
</tr>
<tr>
<td>TRMM</td>
<td>TMI</td>
<td>870 km</td>
<td>53 km</td>
</tr>
</tbody>
</table>

Figure 2-4: Constellation orbits in 3 hours.
Figure 2-5: Constellation coverage in 3 hours.

Figure 2-6: Constellation coverage in 6 hours.
2.5. Study Areas

In order to evaluate the products of the GPM constellation, two sites with dense networks of rain gages and disdrometers were chosen. The first site is Rondonia in Brazil (tropical), which lies within the Amazon basin. The location of the site is shown in Figure 2-7.

The second site, located in Southern Europe (mid-latitudes), is the Ilarion basin in Western Macedonia area, Greece. The location of the second site is shown in Figure 2-8. The observation of two areas in different latitudes (tropics and mid-latitudes) provides for a broad evaluation of the constellation’s efficiency in measuring precipitation.

![Figure 2-7: First Study Area: Rondonia in Amazon Basin in Brazil.](image-url)
Figure 2-8: Second Study Area: Ilarion basin in Western Macedonia in Greece.
3. Instruments

The primary instruments that will be used to measure the precipitation are the advanced precipitation radar (APR) and Microwave Imagers (TMI+). These instruments are basically updated versions of the Precipitation Radar (PR) and Microwave Imager (TMI) used in the TRMM mission. A schematic view of the scan geometries of GPM primary rainfall sensors is given in Figure 3-1.

Figure 3-1: Schematic view of the scan geometries of GPM’s primary rainfall sensors.
3.1. Advanced Precipitation Radar

The precipitation radar (PR) was the first rain radar in space. Its purpose is to provide three-dimensional structure of rainfall, particularly of the vertical distribution, obtain quantitative rainfall measurements over land as well as over ocean and improve the overall precipitation retrieval accuracy. The National Space Development Agency of Japan (NASDA) has developed the PR in cooperation with the Communications Research Laboratory, Ministry of Posts and Telecommunications.

The PR has only a Ku band, which is sufficient for measuring the rainfall in the tropics, since the rain intensities there are high in comparison to the ones expected of mid-latitudes. For the Ku band, the major parameters are summarized in Figure 3-1. The new precipitation radar, the APR, will differ slightly from the PR due to some minor improvements (better accuracy and less power consumption).

Table 3-1: The major parameters of the precipitation radar.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>13.796, 13.802 GHz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>( \leq \sim 0.7 \text{ mm/h (S/N/pulse } \sim 0 \text{ dB) } )</td>
</tr>
<tr>
<td>Swath width</td>
<td>215 km</td>
</tr>
<tr>
<td>Observable range</td>
<td>Surface to 15 km altitude</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>4.3 km (nadir)</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>0.25 km (nadir)</td>
</tr>
<tr>
<td>Antenna</td>
<td>128-element WG Planar array</td>
</tr>
<tr>
<td>Type</td>
<td>SSPA &amp; LNA (128 channels.)</td>
</tr>
<tr>
<td>Beam width</td>
<td>( 0.71^\circ \times 0.71^\circ )</td>
</tr>
<tr>
<td>Aperture</td>
<td>( 2.0 \text{ m } \times 2.0 \text{ m} )</td>
</tr>
<tr>
<td>Scan angle</td>
<td>( \pm 17^\circ ) (Cross track scan)</td>
</tr>
<tr>
<td>Transmitter/receiver</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Peak power</td>
<td>( \geq 500 \text{ W (at antenna input)} )</td>
</tr>
<tr>
<td>Pulse width</td>
<td>( 1.6 \mu\text{s } \times 2 \text{ ch. (Transmitted pulse)} )</td>
</tr>
<tr>
<td>PRF</td>
<td>2776 Hz</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>( \geq 70 \text{ dB) } )</td>
</tr>
<tr>
<td>Number of independent samples</td>
<td>64</td>
</tr>
<tr>
<td>Data rate</td>
<td>93.2 kbps</td>
</tr>
</tbody>
</table>
Chapter 3: Instruments

For the mid-latitudes, where weak rain and snow occurs (see Figure 3-3), another band has to be added to the instrument. The Ka band will operate simultaneously with the Ku band. The Ka band will have improved accuracy and will be used to measure weak rainfall and snowfall and separate snow from rain. Since this is the first time that this band will operate, its specifications will be based on preliminary requirements as shown in Table 3-2, which are subject to change.

Table 3-2: Original operational requirements of the Ka band.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>35.5 GHz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>11dBz or better</td>
</tr>
<tr>
<td>Swath width</td>
<td>20 to 40 km</td>
</tr>
<tr>
<td>Observable range</td>
<td>Surface to 15 km altitude</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>4.0 km (nadir)</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>0.25 km (nadir)</td>
</tr>
<tr>
<td>Measurable rain</td>
<td>Minimum 0.3 mm/h, Maximum 10 mm/h</td>
</tr>
<tr>
<td></td>
<td>(near surface)</td>
</tr>
</tbody>
</table>

To achieve these preliminary operational requirements of the Ka band (separation of snow and ice from rain, accurate estimation of the rain rate and the drop size distribution and computation of the effect of non-uniformity of rain drop distribution), information from both bands is needed at a given location at a given time. The radar has to use special scan patterns to combine both bands (Ka and Ku) within a single sweep.

It would be ideal to use the same scan patterns for both bands, since the target would be the same in both cases and no shifting algorithms would be necessary. However, this is not possible because the two bands operate in different wavelengths and they have different resolutions and swath widths so the scanning patterns cannot be identical within a sweep. Also, an exact match of the two beams is technically impossible. The currently proposed scan pattern is given in Figure 3-2.
Chapter 3: Instruments

Figure 3-2: Schematic view of APR conical scan.

The arrow in Figure 3-2 indicates the direction of satellite’s movement. The instrument scans from left to right and the satellite is moving from bottom to top of the figure. The result is a rotated scan at an angle $\Theta$ with respect to the plane perpendicular to the flight path.

There are 49 horizontal Ku beams (transparent circles) yielding a swath of 245 km. There are 25 Ka beams (light colored circles) as shown in Figure 3-2, yielding a swath of 125 km. The number of Ka beams is subject to change. Finally, the dark colored circles are Ka interlaced beams and should be one less in number than Ka footprints per scan. This scan pattern should not be considered final since both the instrument’s specifications and the requirements are subject to change.

Figure 3-3: Rainfall rate measured by the two PR bands.
3.2. Microwave Imager

The microwave imager (TMI+) is also an updated version of the TMI radiometer used in the TRMM mission. Ultimately, all of the satellites of the constellation including the mothership will carry it. Its swath is the one used to calculate the achieved coverage of the constellation. Co-operative satellites will probably not carry TMI but will carry other similar radiometers. Since the specifications of TMI+ (as well as its final name) are currently under consideration and this instrument will be very similar to the existing TMI, the following section describes the TMI radiometer, which is being used on board of the TRMM satellite.

The TMI (Table 3-3) is a nine-channel (frequencies) passive microwave radiometer based upon the Special Sensor Microwave/Imager (SSM/I), which has been flying aboard the U.S. Defense Meteorological Satellite Program (DMSP) satellites since 1987. The key differences are the addition of a pair of 10.7-GHz channels with horizontal and vertical polarizations and a frequency change of the water vapor channel from 22.235 to 21.3 GHz. This change off the center of the water vapor line was made in order to avoid saturation in the tropical orbit of TRMM.

Table 3-3: TMI instrument specifications.

<table>
<thead>
<tr>
<th>Channel No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Freq [GHz]</td>
<td>10.65</td>
<td>10.65</td>
<td>19.35</td>
<td>19.35</td>
<td>21.3</td>
<td>37.0</td>
<td>37.0</td>
<td>85.5</td>
<td>85.5</td>
</tr>
<tr>
<td>Polarization</td>
<td>V</td>
<td>H</td>
<td>V</td>
<td>H</td>
<td>V</td>
<td>V</td>
<td>H</td>
<td>V</td>
<td>H</td>
</tr>
<tr>
<td>Bandwidth [MHz]</td>
<td>100</td>
<td>100</td>
<td>500</td>
<td>500</td>
<td>200</td>
<td>2000</td>
<td>2000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Stability [MHz]</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Beam Width [deg.]</td>
<td>3.68</td>
<td>3.75</td>
<td>1.90</td>
<td>1.88</td>
<td>1.70</td>
<td>1.00</td>
<td>1.00</td>
<td>0.42</td>
<td>0.43</td>
</tr>
<tr>
<td>IFOV-CT [km]</td>
<td>35.7</td>
<td>36.4</td>
<td>18.4</td>
<td>18.2</td>
<td>16.5</td>
<td>9.7</td>
<td>9.7</td>
<td>4.1</td>
<td>4.2</td>
</tr>
<tr>
<td>EFOV-DT [km]</td>
<td>63.2</td>
<td>63.2</td>
<td>30.4</td>
<td>30.4</td>
<td>22.6</td>
<td>16.0</td>
<td>16.0</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Time [ms]/sample</td>
<td>6.60</td>
<td>6.60</td>
<td>6.60</td>
<td>6.60</td>
<td>6.60</td>
<td>6.60</td>
<td>6.60</td>
<td>3.30</td>
<td>3.30</td>
</tr>
<tr>
<td>#EFOVs/scan</td>
<td>104</td>
<td>104</td>
<td>104</td>
<td>104</td>
<td>104</td>
<td>104</td>
<td>208</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>Samples/beam</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Beam EFOV [km$^2$]</td>
<td>63x37</td>
<td>63x37</td>
<td>30x18</td>
<td>30x18</td>
<td>23x18</td>
<td>16x9</td>
<td>16x9</td>
<td>7x5</td>
<td>7x5</td>
</tr>
<tr>
<td># EFOVs/scan</td>
<td>26</td>
<td>26</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>104</td>
<td>104</td>
<td>208</td>
<td>208</td>
</tr>
</tbody>
</table>
The TMI antenna is an offset parabola, with an aperture size of 61 cm (projected along the propagation direction) and a focal length of 50.8 cm. The antenna beam views the earth surface with a "nadir" angle of 49°, which results in an incident angle of 52.8° at the earth’s surface. The TMI antenna rotates around a nadir axis at a constant speed of 31.6 rpm. The rotation draws a "circle" on the earth’s surface, as shown in Figure 3-1. Only 130° of the forward sector of the complete circle is used for taking data. The rest is used for calibrations and other instrument maintenance purposes.

The altitude of the satellite (i.e. 350 km) and the 130° scanned sector yield a swath width of approximately 760 km. During each complete revolution that corresponds to a scan period of 1.9 seconds, the subsatellite point advances a distance of 13.9 km [9]. Since the smallest footprint (85.5-GHz channels) size is only 6.9 km (down-track direction) by 4.6 km (cross-track direction), there is a "gap" of 7.0 km between successive scans. However, this is the only frequency where there is a small gap. For all lower frequency channels at this particular altitude, footprints from successive scans overlap the previous scans. As the altitude increases, the gap will increases and this will occur in lower frequency channels as well.

TMI+ will require an increase in power and mass due to the demands of higher performance. Hence engineers and scientists are working to find a better implementation of the TMI. The new instrument will be based on the same operating principles as the existing TMI, will carry the same functionality and provide measurements with the same accuracy (or ideally even better), but it has to be lighter and consume less power. Furthermore, the updated version of the TMI will correct some accuracy problems that were revealed during TRMM’s operation.
Chapter 4: Rainfall Disaggregation

4. Rainfall Disaggregation

Two disaggregation methods are presented in this chapter. First, Huff's rainfall distribution curves is a simple regional rainfall disaggregation method [8]. Although this method is not used directly during the simulation process, several of the concepts are used in the second method, the Beta Distribution disaggregation method.

4.1. Huff Rainfall Distribution Curves

Huff [8] analyzed the significant storms in 11 years of rainfall data recorded by the State of Illinois. The data were represented in a non-dimensional form by expressing the accumulated depth of precipitation \( P_t \) (i.e., at time \( t \) after the start of rainfall) as a fraction of the total storm depth \( P_{tot} \) and plotting this ratio as a function of a non-dimensional time \( t/t_d \).

![Dimensionless Huff rainfall coefficients](image)

**Figure 4-1:** Dimensionless Huff rainfall coefficients for all four different quartiles.
Chapter 4: Rainfall Disaggregation

<table>
<thead>
<tr>
<th>( t/t_d )</th>
<th>( P_t/P_{tot} ) for Quartile</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>0.05</td>
<td>0.063</td>
<td>0.015</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>0.10</td>
<td>0.178</td>
<td>0.031</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>0.15</td>
<td>0.333</td>
<td>0.070</td>
<td>0.072</td>
<td>0.055</td>
<td>0.055</td>
</tr>
<tr>
<td>0.20</td>
<td>0.500</td>
<td>0.125</td>
<td>0.100</td>
<td>0.070</td>
<td>0.070</td>
</tr>
<tr>
<td>0.25</td>
<td>0.620</td>
<td>0.208</td>
<td>0.122</td>
<td>0.085</td>
<td>0.085</td>
</tr>
<tr>
<td>0.30</td>
<td>0.705</td>
<td>0.305</td>
<td>0.140</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>0.35</td>
<td>0.760</td>
<td>0.420</td>
<td>0.155</td>
<td>0.115</td>
<td>0.115</td>
</tr>
<tr>
<td>0.40</td>
<td>0.798</td>
<td>0.525</td>
<td>0.180</td>
<td>0.135</td>
<td>0.135</td>
</tr>
<tr>
<td>0.45</td>
<td>0.830</td>
<td>0.630</td>
<td>0.215</td>
<td>0.155</td>
<td>0.155</td>
</tr>
<tr>
<td>0.50</td>
<td>0.855</td>
<td>0.725</td>
<td>0.280</td>
<td>0.185</td>
<td>0.185</td>
</tr>
<tr>
<td>0.55</td>
<td>0.880</td>
<td>0.805</td>
<td>0.395</td>
<td>0.215</td>
<td>0.215</td>
</tr>
<tr>
<td>0.60</td>
<td>0.898</td>
<td>0.860</td>
<td>0.535</td>
<td>0.245</td>
<td>0.245</td>
</tr>
<tr>
<td>0.65</td>
<td>0.915</td>
<td>0.900</td>
<td>0.690</td>
<td>0.290</td>
<td>0.290</td>
</tr>
<tr>
<td>0.70</td>
<td>0.930</td>
<td>0.930</td>
<td>0.790</td>
<td>0.350</td>
<td>0.350</td>
</tr>
<tr>
<td>0.75</td>
<td>0.944</td>
<td>0.948</td>
<td>0.875</td>
<td>0.435</td>
<td>0.435</td>
</tr>
<tr>
<td>0.80</td>
<td>0.958</td>
<td>0.962</td>
<td>0.935</td>
<td>0.545</td>
<td>0.545</td>
</tr>
<tr>
<td>0.85</td>
<td>0.971</td>
<td>0.974</td>
<td>0.965</td>
<td>0.740</td>
<td>0.740</td>
</tr>
<tr>
<td>0.90</td>
<td>0.983</td>
<td>0.985</td>
<td>0.985</td>
<td>0.920</td>
<td>0.920</td>
</tr>
<tr>
<td>0.95</td>
<td>0.994</td>
<td>0.993</td>
<td>0.995</td>
<td>0.975</td>
<td>0.975</td>
</tr>
<tr>
<td>1.00</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The study area and storm duration for which the distributions were developed vary considerably, with \( t_d \) ranging from 3 to 48 hours and the drainage basin area ranging from 25 to 1000 km² (10 to 400 mi²). The distributions are most applicable to Midwestern regions of North America and regions of similar rainfall climatology and physiography.
Chapter 4: Rainfall Disaggregation

The storms were grouped into four categories depending on whether the peak rainfall intensity fell in the 1st, 2nd, 3rd or 4th quarter (or quartile) of the storm duration. In each category, a family of curves was developed representing the 90th, 80th, 70th, etc., percentile. The average of all the storm events in a particular category (e.g., 1st quartile) is represented by the 50% exceedence curve. An “average” storm for each category was estimated in dimensional form. Table 4-1 shows the dimensionless coefficients for each category (quartile) expressed at intervals of 5% of $t_d$.

The first quartile curve is generally associated with relatively short duration storms in which 62% of the precipitation depth occurs in the first quarter of the storm duration. The fourth quartile curve is normally used for longer duration storms in which the rainfall is more evenly distributed over the duration $t_d$ and is often dominated by a series of rain showers or steady rain or a combination of both. The third quartile has been found to be suitable for storms on the Pacific seaboard.

To use the Huff distribution, the only parameters that should be specified are the total depth of rainfall $P_{tot}$, the duration $t_d$ and the desired quartile. The curve (Figure 4-1) can then be scaled up to a dimensional mass curve and the intensities obtained by discretizing the mass curve for the specified time step, $t$.

4.2. Beta Distribution

The reason for not using Huff’s method in this research is that it is regionally dependent. The beta distribution, however, has no regional dependence and can be easily parameterized to take the shape of any rainfall event.

The beta distribution is given by the following equation:
Chapter 4: Rainfall Disaggregation

\[ f(x) = \begin{cases} \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} x^{a-1} (1-x)^{b-1}, & \text{if } 0 \leq x \leq 1; \ a, b > 0 \\ 0, & \text{otherwise} \end{cases} \tag{4.1} \]

where \( \Gamma \) is the gamma function

\( a \) and \( b \) are positive constants

Depending on the values of the factors \( a \) and \( b \), a different algorithm may be used to produce the variates from the equation above. There are four distinct cases, assuming \( a \) is always greater than \( b \):

- **\( a < 0.5 \):** Johnk’s algorithm is used [3]. This generates the beta variate as

  \[ \frac{u_1^{1/a}}{u_1^{1/a} + u_2^{1/b}} \tag{4.2} \]

  where \( u \) and \( u \) are uniformly distributed random variates.

- **\( b > 1 \):** The algorithm BB given by Cheng [2] is used. This involves the generation of an observation from a beta distribution of the second kind by the envelope rejection method using a log-logistic target distribution and then transforming it to a beta variate.

- **\( a > 1 \) and \( b < 1 \):** The switching algorithm given by Atkinson [1] is used. The two target distributions used are \( f_1(x) = b x^b \) and \( f_2(x) = a (1 - x)^{b-1} \), along with the approximation to the switching parameter of \( t \), given in the following equation:

  \[ t = \frac{1-b}{1+a-b} \tag{4.3} \]

- **In all other cases:** Cheng’s BC algorithm [2] is used with modifications suggested by Dagpunar [3]. This algorithm is similar to Cheng’s BB, used when \( b > 1 \), but is tuned for small values of the constants \( a \) and \( b \).
The key to using the beta distribution is determining the parameters $a$ and $b$. If these two parameters are somehow chosen, then it is fairly easy to implement one of the above mentioned algorithms and generate variates that follow the beta distribution.

### 4.3. Disaggregation Procedure

Consider a 6-hour rainfall event, measured by a rain gage, presented in Table 4-2 and Figure 4-2. Following a concept similar to Huff’s classification, every rainfall event is divided into four time intervals (see Figure 4-3), provided that its duration is at least 4 hours. For each one of the four intervals, the accumulated rainfall depth is calculated using the original 1-hour measurements available from ground instruments (see Table 4-3). The location of the maximum accumulated depth of the storm is determined to be in the $1^{st}$, $2^{nd}$, $3^{rd}$ or $4^{th}$ time interval or in the $1^{st}$, $2^{nd}$, $3^{rd}$ or $4^{th}$ category just like in Huff’s classification.

Table 4-2: The hourly rainfall depths of a 6-hour rainfall event.

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Rainfall depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.7</td>
</tr>
<tr>
<td>2</td>
<td>10.2</td>
</tr>
<tr>
<td>3</td>
<td>14.8</td>
</tr>
<tr>
<td>4</td>
<td>9.1</td>
</tr>
<tr>
<td>5</td>
<td>3.6</td>
</tr>
<tr>
<td>6</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Chapter 4: Rainfall Disaggregation

Figure 4-2: A 6-hour rainfall event measured by a rain gage.

Figure 4-3: The four generated intervals.

From Table 4-3, this particular rainfall would be characterized as second category, since its accumulated rainfall depth has its peak in the second quartile.
Chapter 4: Rainfall Disaggregation

Table 4-3: The accumulated rainfall depth in each interval.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Starting time (h)</th>
<th>Ending time (h)</th>
<th>Rainfall depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>1.5</td>
<td>10.8</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>3.0</td>
<td><strong>19.9</strong></td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>4.5</td>
<td>10.9</td>
</tr>
<tr>
<td>4</td>
<td>4.5</td>
<td>6.0</td>
<td>2.9</td>
</tr>
</tbody>
</table>

In order to obtain a suitable continuous representation (disaggregation) for the particular event the beta distribution is fitted to the event. An iterative algorithm is used with the following restrictions to fit the beta distribution to the storm at hand:

- The peak should be in the second time interval (for this example)
- In every interval of the disaggregated event, the accumulated rainfall depth should have the same value as the original event

In the first iteration, two arbitrary positive values are selected for coefficients $a$ and $b$. Depending on these values, the appropriate equation (see section 4.2) is applied and the beta distribution is generated. The resulting beta curve is compared to the data and checked for the above two restrictions. If the restrictions are not met, two new parameter values will be chosen and the comparison is repeated until the desired shape is obtained (see Figure 4-4).

In the special case where the duration of an original event is less than four hours, the above algorithm cannot be directly used since the location of the peak cannot be unambiguously determined. A statistical method of determining the classification of these events is then introduced, as shown in Table 4-4. The values in Table 4-4 are arbitrarily selected.
Chapter 4: Rainfall Disaggregation

Figure 4-4: Disaggregation using the iterative algorithm.

For example, consider an event that lasted for two hours. During the first hour it had a total rainfall depth 1.4 mm, and during the second hour it had 2.6 mm. According to Table 4-4, (3rd row because the duration is 2 hours and the peak occurs during the second hour) the algorithm will yield a storm of type 3 with a probability of 60% or 4 with a probability of 40%. In the case of 50 2-hour events the algorithm produces 30 events of curve type 3 and 20 of curve type 4 on average.

Table 4-4: Curve analysis for event with less than 4 hours duration.

<table>
<thead>
<tr>
<th>Duration (h)</th>
<th>Peak</th>
<th>Curve Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>2 (50%) or 3 (50%)</td>
</tr>
<tr>
<td>2</td>
<td>1h</td>
<td>1 (40%) or 2 (60%)</td>
</tr>
<tr>
<td>2</td>
<td>2h</td>
<td>3 (60%) or 4 (40%)</td>
</tr>
<tr>
<td>3</td>
<td>1h</td>
<td>1 (80%) or 2 (20%)</td>
</tr>
<tr>
<td>3</td>
<td>2h</td>
<td>1 (10%) or 2 (60%) or 3 (30%)</td>
</tr>
<tr>
<td>3</td>
<td>3h</td>
<td>2 (20%) or 3 (80%)</td>
</tr>
</tbody>
</table>
5. **Simulation With Rain Gages Input Data**

5.1. **Rondonia Basin**

Many different events were analyzed from the period of December 20\textsuperscript{th} 1998 to March 22\textsuperscript{nd} 1999 from 40 different rain gages in the Rondonia basin. The distribution map of the rain gages network is shown in Figure 5-1.

There are four distinct regions where the network density is high. The purpose of this spatial distribution of the rain gages is for calibrating a rain gage with others that reside in its immediate vicinity. It also serves the purpose of operating some rain gages at a given time while other rain gages malfunction or are under maintenance.

![Figure 5-1: The locations of the 40 rain gages in Rondonia.](image-url)
Chapter 5: Simulation With Rain Gages Input Data

In Figure 5-2, the number of rain gages that were in operation on a particular day is graphically presented. For each day of the mentioned period, the number of rain gages that reported a measurement was counted and represented with a bar. The bar size is proportional to the number of stations. A complete bar indicates that all stations were operational. The only period when all 40 rain gages reported measurements of the rainfall was between January 28th and February 15th 1999 as shown in Figure 5-2.

The recorded events are treated as separate when there is an interval of no-rainfall that lasts for 6 or more hours. The gaps in the rain gages’ measurements, are caused by operational issues and do not indicate periods of no rainfall.

![Figure 5-2: Data integrity of the measurements taken from rain gages (Rondonia).](image)

5.2. Ilarion Basin

A period of three months of hourly rainfall measurements taken by 41 rain gages, between December 20th 1998 and March 22nd 1999, is available for the Ilarion basin (Figure 5-3). All 41 rain gages were in operation during that period. The distribution of the rain gages is even throughout the basin and its neighboring areas, unlike the distribution in Rondonia basin (see Figure 5-4).
Chapter 5: Simulation With Rain Gages Input Data

Figure 5-3: Ilarion basin digital elevation model (DEM).

Figure 5-4: The locations of the 41 rain gages in Ilarion.
5.3. Satellite Measurements

The procedure that was used during the simulation is separated into four steps. The first step is the complete disaggregation of all events captured by each rain gage. For the Rondonia basin, 40 different time series of disaggregated rainfall were computed, using data from 40 installed rain gages with a time step of 1 minute.

During the second step, the gaps of each time series were filled with zeros so that they have a common temporal start (December 20th, 1998) and end (March 22nd, 1999). Zeros were not only placed in the beginning and in the end of each series, but also in between, where no measurements were present. For example, the 40th rain gage in Rondonia, measured 15 distinct events, from January 28th 1999 through February 15th 1999. This sample of 19 days was extended with the addition of zeros to the beginning and to the end in order to reach the common temporal start and end (total of 80 days).

In the third step, the satellites were flown above the locations of the rain gages using the Satellite Tool Kit (STK) software. The access reports (contact time and duration) from STK were used in the simulation software in order to obtain the actual snapshots over the locations of each rain gage. Each snapshot is graphically represented as a vertical line in all following graphs that refer to the constellation’s observations.

The results are not time independent, as shown in Table 5-1 and in Figure 5-6. For example, if the first snapshot had been taken at 140 min (Figure 5-6) instead of 1 min, then the peak of the rainfall event would have been included among the snapshots and the aggregation would yield a completely different, better, result. Nevertheless, if we average all events instead of examining one particular event, then the results will be time independent.
An example of an 11-hour event of 68.4mm total accumulation is given in Figure 5-5, disaggregated with the Beta distribution. The disaggregation time step is 1 minute. If the first satellite makes contact at the beginning of the event (base hour 00:00), then we will have 4 contacts in total (not from the same satellite) equal to 174 seconds in total. During this contact time, 0.151 mm of rainfall is measured as shown in Table 5-1.

Table 5-1: Measurements taken during the event from the constellation.

<table>
<thead>
<tr>
<th>Hour (base 00:00)</th>
<th>Contact (sec)</th>
<th>Measurement (mm) *</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>42.5</td>
<td>0.033</td>
</tr>
<tr>
<td>04:33</td>
<td>38.4</td>
<td>0.075</td>
</tr>
<tr>
<td>07:15</td>
<td>50.1</td>
<td>0.041</td>
</tr>
<tr>
<td>10:49</td>
<td>43.2</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Chapter 5: Simulation With Rain Gages Input Data

Figure 5-6: Snapshots (vertical lines) taken by the satellites during 11-hour event.

Figure 5-7: Snapshots that underestimate the total rainfall accumulation.
In the last step, the snapshots were used to generate a possible rainfall. The simplest way to accomplish this is by using a linear interpolation between two successive snapshots. This usually underestimates the total rainfall depth (see Figure 5-7). However, it may overestimate it if the peak or a point near the peak is one of the snapshots (as in Figure 5-8), although this is rather rare due to the sharp shape of the rainfall curve.

### 5.3.1. Defining a Radius of Increase

Estimating total rainfall depth from the limited snapshots is very difficult and likely inaccurate. To improve the results, information from surrounding rain gages can be used, trying to exploit the fact that in the tropics, for example, the rainfall intensities correlate at a distance of up to 40 km [10].
One approach is to increase the observation radius from a point to 50 km and fill in some gaps by adding snapshots taken from satellites that were also flying within the 50 km radius during a particular event.

The number of snapshots that can be used to fill gaps can vary from 0 to 9, and depends primarily on the event duration and the number of rain gages that are located within 50 km radius from the reference rain gage.

Using an example to illustrate the effect of an increase in radius of influence, Figure 5-9 depicts a 20-hour event with 40.1 mm total rainfall depth, as it was measured by the rain gages.

The rainfall event was disaggregated (Figure 5-10). The solid curve is the equivalent (to the event presented in Figure 5-9) disaggregated rainfall event with 1-minute time step. The vertical lines represent snapshots taken by satellites that flew above the rain gage. In Figure 5-10, the five vertical lines represent five snapshots taken at different times over the same location by not necessarily the same satellite.

In Figure 5-11, snapshots taken by satellites that flew within a 50 km radius from this rain gage during the particular event are added. The additional snapshots are designed as dashed lines. Each one of the snapshots contains exactly 1 minute accumulated rainfall depth. The value of this depth is determined from the intersection of the snapshot with the disaggregated event.

In twenty hours, only two snapshots were added (7 snapshots in total) which did not improve much the aggregation process, not to mention the error introduced by using rainfall measurements that occurred up to 50 km from the reference point. When we performed a linear interpolation using the 5 snapshots we obtained 8 mm aggregated rainfall. When we performed the same procedure with the 7 snapshots we obtained approximately 10 mm. Even though the relative difference between the two methods is of the order of 25%, both events significantly underestimate the total accumulated depth, which in this example is 40.1 mm.
Chapter 5: Simulation With Rain Gages Input Data

Figure 5-9: The original 20-hours long rainfall event (1 hour time step).

Figure 5-10: The disaggregated event and the satellites’ snapshots (vertical lines)
Figure 5-11: The snapshots added by increasing the observation radius.

Table 5-2: Effect of radius on the aggregated rainfall event (Rondonia).

<table>
<thead>
<tr>
<th>Radius (km)</th>
<th>Contacts</th>
<th>Measured (mm)</th>
<th>Aggregated (mm)</th>
<th>Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event 1: Duration 11 hours, total accumulated depth 68.4 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>0.3</td>
<td>4.2</td>
<td>93.9</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
<td>0.8</td>
<td>11.3</td>
<td>83.5</td>
</tr>
<tr>
<td>75</td>
<td>5</td>
<td>0.8</td>
<td>11.3</td>
<td>83.5</td>
</tr>
<tr>
<td>100</td>
<td>7</td>
<td>1.4</td>
<td>15.7</td>
<td>77.0</td>
</tr>
<tr>
<td>Event 2: Duration 2 hours, total accumulated depth 8.3 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>50</td>
<td>1</td>
<td>0.1</td>
<td>0.9</td>
<td>98.7</td>
</tr>
<tr>
<td>75</td>
<td>2</td>
<td>0.2</td>
<td>1.6</td>
<td>97.7</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>0.2</td>
<td>1.6</td>
<td>97.7</td>
</tr>
</tbody>
</table>

Table 5-2 shows for two different rainfall events the effect that an increased radius has on the aggregation. According to the results, even if we use a radius of
100km, which is extremely large, the loss of the accumulated depth will be reduced by only 10% to 30%.
6. Simulation With Areal Precipitation

6.1. Rainfall Aggregation

The methods introduced thus far to reproduce original rainfall events from instantaneous snapshots taken by satellites have not been very successful. The snapshots over rainfall measurements taken by rain gages are not enough for aggregating the original rainfall event, even in the case where an area of 100 km radius is considered around each rain gage. Therefore, the concept of the areal precipitation is introduced. This method significantly increases the contact time from seconds to minutes, since the Rondonia basin has dimensions of approximately 200x150 km.

For this method, the digital elevation models (DEMs) of the study areas are needed. With the aid of ArcView/ArcInfo GIS the following shape files were constructed:

- Rondonia tract boundaries, with raw data obtained from IBGE (Brazilian Geographic and Statistics Institute) [12].
- Rondonia county boundaries, with raw data obtained from IBGE (Brazilian Geographic and Statistics Institute) [12].
- The locations of the rain gages in Ji-Parana basin (located in the East part of the Rondonia basin). The coordinates of the rain gages locations were obtained from raw ASCII files publicly available from NASA’s web site.

The three layers described above, were combined and over imposed in ArcView GIS, after converting them to the same projection and unit system. The result is shown in Figure 6-1.

The DEM (digital elevation model) of the basin was used to generate the hydrograph network of the basin, the various sub basins and the Thiessen polygons. The raw data for the whole South America were obtained from the GTOPO30 project, available from the USGS web site [13].
The boundaries shown in Figure 6-1 are political and should not be confused with the actual physical boundaries. If the South America DEM is combined with the political boundaries of the Rondonia County, then it is possible to downscale the DEM to the county (see Figure 6-4). With the DEM information in hand, the Hydrologic Modeling extension was used in ArcView GIS to generate the stream network.

The Hydrologic Modeling extension was used to compute the accumulated flow, the slopes, the sub basins and finally the stream network in the basin. The user must provide some input parameters in order to complete the modeling. These parameters influence the way the upstream drainage and the slopes are computed.
Chapter 6: Simulation With Areal Precipitation

The simplest case, in 1-D space, is to use only two cells to derive a local slope (by comparing their elevations) as shown in Figure 6-2A. Using only two cells to derive the slopes produces a more detailed output since it takes into account even the slightest fluctuations in elevation (see Figure 6-2B). This detailed output is not always desired, however, since it is computationally expensive and is not of great importance to the interests of this project. Therefore, more cells were used in the computations and average local slopes were obtained (Figure 6-2C, where four cells are used instead of two).

![Figure 6-2: Effect of the number of cells used in the slope calculation (1D).](image)

In 2-D space, the same concepts apply. If the extension is permitted to use only the neighboring cells to determine the slopes (Figure 6-3A), then a very complicated flow pattern is derived (and unrealistic). A clearer pattern is obtained once the average slope from the surrounding cells is computed (Figure 6-3B).

![Figure 6-3: Effect of the number of cells used in the slope calculation (2D).](image)

In this work, 8 neighboring cells (forming a 3x3 square) are used in order to calculate the average slope from a cell. Using the average slope, the potential flow
direction is obtained. The choice of parameters is rather arbitrary and a comparison of
the output digital map with another non-digital map is necessary to evaluate the success
of the digital product.

For a minimum number of 80,000 cells to generate a sub basin (that is a sub
basin cannot have less than 80,000 cells of 1x1 km size), the hydrologic modeling
extension delineated 3 sub basins (see Figure 6-5) and plotted the stream network.
However, from Figure 6-1 it is apparent that the installation of the rain gages is not
uniformly distributed in the basin, but they are concentrated in its Northeast side.
Therefore, attempting to create Thiessen polygons for the whole basin (all three sub
basins) would cause accuracy problems since there will be one sub basin with no rain
gages and the two other sub basins will have a highly uneven distribution of them. For
this reason, a smaller study area is considered.
Chapter 6: Simulation With Areal Precipitation

Figure 6-5: The 3 sub basins generated from the hydrologic modeling extension.

Figure 6-6: The downscaled area (left map) and its original location (right map).

The new smaller area with dimensions of approximately 200x160 km, is shown on the left map in Figure 6-6. Its location with respect to the Rondonia basin is shown
on the right map in Figure 6-6. The Thiessen polygons will be calculated and applied only in this area, where the distribution of rain gages is relatively uniform.

### 6.2. Thiessen Polygons

The Thiessen polygons for the study area shown in Figure 6-6 were calculated using ArcView GIS. According to the Thiessen method, each rain gage is connected with straight lines to the two most proximate rain gages creating triangles. From every side of the triangle the perpendicular bisector is drawn. The vertices of the polygons are then defined as the intersections of two such perpendicular bisectors or a bisector with the boundary condition (here, the limits of the study area).

![Example of Thiessen polygons.](image)

There are two approaches to handle data gaps and different operation times of the rain gages. The first is to complete the gaps of the measurements by correlating data from rain gages and using the autocorrelation formula in order to estimate the missing measurements. The second is to use only those rain gages in operation at each particular time. In this case, the Thiessen polygons will change with time. The second approach was followed and an example of a set of polygons created on January 5th at
06:00 is shown in Figure 6-7. For each set of Thiessen polygons, the area of each polygon was used together with the actual measurements corresponding to each polygon in order to derive the areal precipitation:

\[ P = \frac{A_1P_1 + A_2P_2 + \ldots + A_NP_N}{A_1 + A_2 + \ldots + A_N} \]

where \( N = 1, 2, \ldots, \) number of rain gages in operation at the same time.

### 6.3. Areal Precipitation

The areal precipitation calculated from Thiessen polygons as described in section 6.2 is disaggregated following the same procedure described in section 4.2. Thus from rainfall of 1-hour time step intervals we obtain areal rainfall of 1-min time step intervals. The areal precipitation as calculated from the rain gages data starts on 12/21/1998 and ends on 03/20/1999, which makes a total of 90 days of data (approximately 3 months).

Table 6-1: Some properties of the areal precipitation data set (Rondonia).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of records</td>
<td>2160</td>
</tr>
<tr>
<td>Starting date</td>
<td>12/21/1998</td>
</tr>
<tr>
<td>Ending date</td>
<td>03/20/1999</td>
</tr>
<tr>
<td>Number of events</td>
<td>84</td>
</tr>
<tr>
<td>Total accumulated depth (mm)</td>
<td>594.2</td>
</tr>
<tr>
<td>Longest event (h)</td>
<td>51</td>
</tr>
<tr>
<td>Event with most accumulated depth (mm)</td>
<td>42.3 (in 16h)</td>
</tr>
</tbody>
</table>

With the assumption that 6 hours with no rainfall defines separate events, 84 distinct rainfall events were recorded. Table 6-1 summarizes and presents some properties of the areal precipitation data set for the Rondonia basin and Table 6-2 for the Ilarion basin.
Table 6-2: Some properties of the areal precipitation data set (Ilarion).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of records</td>
<td>2160</td>
</tr>
<tr>
<td>Starting date</td>
<td>12/21/1998</td>
</tr>
<tr>
<td>Ending date</td>
<td>03/20/1999</td>
</tr>
<tr>
<td>Number of events</td>
<td>52</td>
</tr>
<tr>
<td>Total accumulated depth (mm)</td>
<td>320.7</td>
</tr>
<tr>
<td>Longest event (h)</td>
<td>16</td>
</tr>
<tr>
<td>Event with most accumulated depth (mm)</td>
<td>25.4 (in 8h)</td>
</tr>
</tbody>
</table>

### 6.4. Satellite Measurements in Rondonia

The satellites in the simulation were flown over the study areas during the period of three months of data mentioned in section 6.3. The contact times were rounded to the nearest whole minute (i.e. an 88 seconds contact time was rounded to 1 minute and 104 seconds to 2 minutes) and the assumption that the satellites can actually measure the areal precipitation during their contact with the study areas (instead of an instantaneous snapshot of a point rainfall) was adopted.

The footprint of the instrument is simulated with a circle. In reality, it is a 135 degrees arc, which is stretched spatially in a direction parallel to the satellite’s direction, due to the satellite’s orbital velocity. As the satellite moves, the far left and far right points of the arc have a spatial difference $\Delta s$ equal to the ratio of the satellite’s orbital velocity divided by the time required by the microwave imager to move its pointing head from the one side of the arc to the other (135 degrees angle). The difference between the real footprint and the one used in the simulations is shown in Figure 6-8.
Chapter 6: Simulation With Areal Precipitation

Figure 6-8: Used (left) and actual (right) satellite footprint.

For the three-month study period, the orbits of the satellites were simulated and the measurements that the satellites would have taken were collected (see Table 6-3). DMSP-F13 satellite does not access the Rondonia Basin.

Table 6-3: Contacts made by the satellites of the constellation (Rondonia).

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Encounters</th>
<th>Average contact time (min)</th>
<th>Total contact time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMSP-F13</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DMSP-F14</td>
<td>268</td>
<td>8.1</td>
<td>2166</td>
</tr>
<tr>
<td>DMSP-F15</td>
<td>272</td>
<td>8.0</td>
<td>2179</td>
</tr>
<tr>
<td>ADEOS-II</td>
<td>247</td>
<td>7.7</td>
<td>1914</td>
</tr>
<tr>
<td>AQUA (EOS-PM)</td>
<td>213</td>
<td>6.1</td>
<td>1294</td>
</tr>
<tr>
<td>TRMM</td>
<td>190</td>
<td>3.0</td>
<td>572</td>
</tr>
</tbody>
</table>

For the period of 90 days that we have data, there are 90x24x60=129600 records of areal precipitation, each corresponding to 1 min time step. From these records, only 7880 were recorded by the satellites (6.1% of the total records). Since there are data for 3 months, there are three monthly time steps, the first from 21st December 1998 to 20th January 1999, the second from 21st January 1999 to 20th February 1999 and the third from the 21st February 1999 to the 20th March 1999.
Chapter 6: Simulation With Areal Precipitation

If no aggregation is performed, then from the 594.2 mm of total areal precipitation, only 46 mm of rainfall are recorded which corresponds to 8% of the total precipitation. However if we perform a linear interpolation between two successive measurements we account for up to 75% rainfall, a dramatic increase from the aggregated 1h and 3h rainfall from isolated rain gages that was discussed in section 5.3.

It is noted that these results may be an overestimation of reality due to the simplification of the footprint pattern (the footprint shape was exaggerated) and by rounding the contact durations upwards. The results of the analysis above are shown in Table 6-4.

Table 6-4: Measured areal precipitation statistics by the GPM constellation (Rondonia).

<table>
<thead>
<tr>
<th>Time Period</th>
<th>(Active) Encounters</th>
<th>Total precipitation (mm)</th>
<th>Measured Precipitation (mm)</th>
<th>Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total for 3 months</td>
<td>(454) 1190</td>
<td>594.2</td>
<td>441.7</td>
<td>25.7</td>
</tr>
<tr>
<td>1st month</td>
<td>(158) 397</td>
<td>258.2</td>
<td>170.6</td>
<td>33.9</td>
</tr>
<tr>
<td>2nd month</td>
<td>(139) 399</td>
<td>148.3</td>
<td>112.6</td>
<td>24.1</td>
</tr>
<tr>
<td>3rd month</td>
<td>(157) 394</td>
<td>187.6</td>
<td>158.7</td>
<td>15.4</td>
</tr>
</tbody>
</table>

6.5. Satellite Measurements in Ilarion

For the same study period, the contacts made by the satellites over the Ilarion basin are presented in Table 6-5. The TRMM satellite does not access the Ilarion basin at all. The measured areal precipitation statistics are shown in Table 6-6.
Table 6-5: Contacts made by the satellites of the constellation (Ilarion).

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Encounters</th>
<th>Average contact time (min)</th>
<th>Total contact time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMSP-F13</td>
<td>255</td>
<td>7.7</td>
<td>2045</td>
</tr>
<tr>
<td>DMSP-F14</td>
<td>239</td>
<td>7.8</td>
<td>1876</td>
</tr>
<tr>
<td>DMSP-F15</td>
<td>286</td>
<td>8.1</td>
<td>2205</td>
</tr>
<tr>
<td>ADEOS-II</td>
<td>221</td>
<td>7.7</td>
<td>1756</td>
</tr>
<tr>
<td>AQUA (EOS-PM)</td>
<td>213</td>
<td>6.1</td>
<td>1294</td>
</tr>
<tr>
<td>TRMM</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6-6: Measured areal precipitation statistics by the GPM constellation (Ilarion).

<table>
<thead>
<tr>
<th>Time Period</th>
<th>(Active) Encounters</th>
<th>Total precipitation (mm)</th>
<th>Measured Precipitation (mm)</th>
<th>Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total for 3 months</td>
<td>(376) 1214</td>
<td>326.7</td>
<td>233.9</td>
<td>28.4</td>
</tr>
<tr>
<td>1st month</td>
<td>(144) 405</td>
<td>126.9</td>
<td>94.7</td>
<td>25.4</td>
</tr>
<tr>
<td>2nd month</td>
<td>(125) 407</td>
<td>115.1</td>
<td>77.0</td>
<td>33.1</td>
</tr>
<tr>
<td>3rd month</td>
<td>(107) 402</td>
<td>84.7</td>
<td>59.4</td>
<td>29.9</td>
</tr>
</tbody>
</table>
7. Simulation With Radar Data

7.1. SPOL Radar

The SPOL radar was developed by NCAR/ATD laboratories. After a testing period which ended in 1996, it was installed in Rondonia Basin and was operating between January 10th 1999 and February 28th 1999. Until January 15th there are significant gaps in the recorded data since several tests and calibrations were performed. Hence, the time period between January 10th and January 15th was ignored. For the remaining period of the 44 days, the SPOL radar was sweeping an area of 70,000 km², 4 to 7 times per hour.

Figure 7-1: The ground instrumentation in Rondonia. [0]

In Figure 7-1, a schematic view of the ground instrumentation in Rondonia basin is presented. The SPOL radar has a radius of roughly 150 km. Measurements are given
in cells 3 km x 3 km. Hence, the area is divided in 100x100 cells. The whole analysis was performed in areal averages as well.

**7.2. Data Processing**

Since both the number of the radar snapshots during one hour and the intervals between them vary, the first step in processing the radar measurements is to average them in time. This was accomplished by taking a weighted average of all measurements belonging to a particular hour using the following formula:

\[
M = \frac{M_1 t_1 + M_2 t_2 + \ldots + M_N t_N}{t_1 + t_2 + \ldots + t_N}
\]

where
- \( M_i \) is the measurement corresponding to a particular snapshot
- \( t_i \) is the average duration time of the snapshot
- \( N \) is the number of snapshots within an hour
- \( M \) is the average measurement corresponding to that hour

To calculate the average time between two successive radar snapshots, the scheme shown in Figure 7-2 was used. In this particular example, the SPOL radar took four snapshots between 12:00 and 13:00. This method does not take into consideration the snapshots taken before or after the hour that is been averaged.

![Figure 7-2: Conceptual scheme for the average duration time calculation.](image)

This averaging takes place in all 10,000 grid cells, thus producing 10,000 values of mean rainfall rate per hour for all 44 days in which the SPOL radar was in full operation.
Finally, for the same reasons mentioned in section 4.2, the rainfall was disaggregated using the Beta distribution into one-minute time steps.

7.3. Satellite Measurements

Following a similar approach as in the rain gages simulation, the satellites forming the constellation were set in orbit for the whole period of the 44 days. The visitation frequency over a grid varied in time, but it was usually not less than every 7 hours. Each time a satellite was over a grid, it was assumed that its snapshots contained the value of the 1 minute disaggregated rainfall rate, although the duration of the visit was only a few seconds.

By compiling all the snapshots taken by the satellites over each grid, an aggregation was performed, using linear interpolation as shown in section 5.3. Since the observed accumulated rainfall depth over each grid is known for every event, the sum of all events yields the total observed accumulated rainfall depth. The comparison of the rainfall observed by the satellites \( P_{\text{OBS}} \) and the rainfall measured by the SPOL radar \( P_{\text{MEAS}} \) is the percentage of the actual rainfall that is measured by the satellites over a grid as shown in the following equation (over the whole study period):

\[
P(\%) = 100 \frac{P_{\text{MEAS}} - P_{\text{OBS}}}{P_{\text{MEAS}}}
\]

Figure 7-3 presents the measured rainfall by the SPOL radar for each grid cell. The maximum rainfall depth for all grid cells is 891.6 mm. This number is divided by 10, creating 10 classes starting from 0 and counting with intervals of 89.16 mm. The color in each grid cell, represents the class in which the total accumulated rainfall of the particular grid falls in. The darkest color, for example, represents grid cells where the total accumulated rainfall was between 0 and 89.16 mm and the lightest is where the total accumulated rainfall was between 802.44 and 891.6 mm.
Figure 7-4 shows the values of $P$ (percentage of estimated rainfall) for each grid cell. The legend of colors represents percentages ranging from 10% to 90% in 10% intervals. For example the first color is used when the value of the observed rainfall is between 0 and 10%. The mirror image of these results is presented in Figure 7-5, where instead of the values of $P$, the values of $1-P$ (the percentage of precipitation lost) have been plotted. Using this figure, it is easier to identify the cells with the greater rainfall loss (lighter color). On average, 60-80% of the total rainfall is being measured by the constellation of the satellites.

Figure 7-3: Rainfall in each grid cell as measured by the SPOL radar.

The results as shown in Figure 7-4 or Figure 7-5, depend primarily on four factors. The first is the visitation frequency over each cell, which varies according to the location of the cell within the grid. The second factor is the duration of the contact. The more often and the more time the satellite spends over a grid cell, the better the results.
The third factor is the frequency of rainfall in each cell. The more often it rains, the more accurate are in general the aggregated rainfall events (see section 5.3). The final factor is the actual rainfall pattern. If, for instance, the rainfall rate is constant, the aggregated event would have the same accumulated rainfall depth with the real event while if we had instantaneous high and low peaks the accuracy could drop to the order of 0%.

![Figure 7-4: Percentage of rainfall observed by the satellites.](image-url)
Figure 7-5: Percentage of rainfall that was not observed by the satellites.
8. Conclusions

8.1. Rain Gages

The results that were obtained using point measurements obtained by disaggregating rain gages data from 1 hour to 1 minute were not satisfactory. The percentage of rainfall lost with this method varied from 40% to 70%, which is not an acceptable value.

Further attempts to improve these results by increasing the influence radius and using 3-hour accumulated precipitation depths had little impact on the results. In the best of the cases, an improvement of 30% was achieved.

The percentage of lost rainfall drops drastically when the point measurements are substituted with areal precipitation (see Table 8-1 for Rondonia and Table 8-2 for Ilarion). The reason for this is that almost all snapshots contain a non-zero value as it is rare that there is an hour with no precipitation over a 200x160 km area.

Table 8-1: Percentage of rainfall depth lost using areal precipitation data (Rondonia).

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total for 3 months</td>
<td>25.7</td>
</tr>
<tr>
<td>1st month</td>
<td>33.9</td>
</tr>
<tr>
<td>2nd month</td>
<td>24.1</td>
</tr>
<tr>
<td>3rd month</td>
<td>15.4</td>
</tr>
</tbody>
</table>

Comparing the two study areas, the percentages of rainfall depth lost in the Ilarion basin were higher than in Rondonia basin. The rainfall frequency in Ilarion basin is lower than in Rondonia basin (also shown in Table 6-4 and Table 6-6). Therefore, relatively larger no-rainfall intervals in Ilarion basin followed by events with short duration caused many satellite snapshots to measure zero rainfall and those who did measure rainfall often missed the peaks.
Table 8-2: Percentage of rainfall depth lost using areal precipitation data (Ilarion).

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total for 3 months</td>
<td>28.4</td>
</tr>
<tr>
<td>1st month</td>
<td>25.4</td>
</tr>
<tr>
<td>2nd month</td>
<td>33.1</td>
</tr>
<tr>
<td>3rd month</td>
<td>29.9</td>
</tr>
</tbody>
</table>

8.2. Radar Data

Using radar data instead of data from rain gages, produces slightly better results. For the total period where radar data were available, the total measured precipitation was around 80% (compared to the 75% that was obtained from spatially averaged rain gages’ data).

The reason for this is that radar data have smoother peaks than area data produces from point measurements. The more constant the rainfall rate the more precipitation that is measured.

8.3. Further Research

There are several simplifying assumptions made in this analysis, which in general tend to overestimate the observed precipitation. One of them is the shape of the footprint of the instrument used (see Figure 6-8). Another simplification is the upwards rounding of the contact durations. By removing these assumptions from future analyses, a better virtual product will be produced.
The rainfall disaggregation and the snapshot aggregation methods used in this analysis are relatively simple models. It would be interesting to investigate into the impacts of more sophisticated models on the results of the simulation.

Using the virtual product obtained in this or in a similar research, the evaluation of a GPM configuration can be done through hydrologic processes. Instead of comparing the measured rainfall with the original rainfall in order to assess the effectiveness of the constellation, it is possible to compare a hydrologic variable produced using real data and virtual data. A way to accomplish this, is to calculate the water budget in a basin using ground truth precipitation and precipitation obtained by the satellites. By comparing the differences between the two sets of produced results, another estimation of the scientific value of a specific GPM configuration can be acquired.

Using more test sites with sufficient ground networks (rain gages, disdrometers and radars) in different latitudes will also be very helpful. Especially interesting will be areas with large intervals of no precipitation and areas with low precipitation rate.

Finally, the current thesis uses one possible configuration in terms of number of satellites, orbital characteristics and instruments on board. Changing these parameters will affect the results. A sensitivity analysis of these parameters would be a logical first step in such an attempt and would certainly reveal more candidate configurations.
References

References

15. GPM White Paper, National Aeronautics and Space Administration, March 2002 (draft).
17. Precipitation.org web site http://www.precipitation.org/

TRMM LBA Web Site http://olympic.atmos.colostate.edu/lba_trmm/
A. Appendix A

A.1. Introduction

This computer program was created in order to facilitate and speed up the processing of large volume of rain gages rainfall measurements and radar snapshots. Most procedures discussed in chapters 4 through 7 are included in this algorithm.

The program is capable of importing unlimited number of data files that contain hourly rainfall from rain gages or hourly rainfall from radars. It can disaggregate all the rainfall events into smaller time steps (i.e. 1 minute) using various disaggregation methods. Using satellite data files that describe the contact time and duration of each contact for every satellite belonging to the constellation, the program calculates the snapshots and aggregates rainfall events from them.

Finally it computes the percentage of rainfall that has been observed during the simulation period to the total rainfall recorded by the ground instrumentation. All the above procedures can be graphically displayed and the results can be exported to text (ASCII) files.

The program uses all Windows interface conventions like keyboard shortcuts and multi level menus. Its requirements are a Windows 95 or better operating system with 16 MB Ram and 800x600 16-bit color display.

A.2. Interface

In Figure A-1 the program’s main interface is shown. There are four distinct areas, the menu bar, the input files list, the information panel and the feedback panel. The menu bar contains all the commands available in the program and information of their shortcuts.
The input files list presents all the currently loaded input files (rain gages or radars). The information panel shows information about a specific loaded input file and it is triggered each time the user clicks on a file located in the input files list (see Figure A-2).

Finally the feedback panel shows information about the procedure that was executed or displays meaningful error messages during or after an operation. The highlighted message is the last in precedence and the messages are chronologically sorted from first to last.

Figure A-1: The program’s main interface.
A.3. File Menu

The file menu (Figure A-3) pops up whenever the user clicks on the File located at the menu bar. It contains all input and output operations that can be performed.

- New Project: starts a new project and clears all memory and matrices.
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- **Open Project**: loads an existing project, which is a project saved by the GPM Data Simulator. Valid project files have the `.gsp` file extension.

- **Save Project**: saves a currently opened project for future reference. The default project extension is `.gsp`.

- **Save Project As**: saves a currently saved project under a different name. If the project has not been saved yet, then this menu has no difference from the Save Project menu.

- **Empty Temporary Files**: to conserve disk space, this option wipes out temporary files that are no longer needed or that can be easily generated again from the program if needed at a later time.

- **Special Batch**: this command is for debugging purposes and should not be used.

- **Export Station Data**: when the input files are rain gages, this command generates a text (ASCII) file that contains the information requested by the user through a special form shown in Figure A-4. The “Export” button will be enabled once the user checks some of the available options and chooses a target file name by pressing the button “Browse”.

![Export Station Data](image)

Figure A-4: Export rain gages data to an external file dialog box.
Appendix A

The structure of the generated ASCII file is simply the column headers in the first row and the data in the following rows. The number of rows that follow the column headers is equal to the number of rain gages that are present (i.e. one row for each rain gage). Fields are separated with a TAB character which makes the files equivalent to the Tab Delimited format in Excel. A part of this file is presented below:

<table>
<thead>
<tr>
<th>No</th>
<th>Filename</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Period(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LBA0001.accu</td>
<td>-62.13339</td>
<td>-10.76519</td>
<td>21/12/1998 to 20/03/1999</td>
</tr>
<tr>
<td>2</td>
<td>LBA0040.accu</td>
<td>-62.86886</td>
<td>-10.29833</td>
<td>21/12/1998 to 20/03/1999</td>
</tr>
</tbody>
</table>

> **Recent files list**: here might be more menus present before the Exit menu and after the Export submenu, with no particular names but full file paths instead. These correspond to recently opened projects and if clicked, the projects mentioned there are automatically loaded. In Figure A-3 for example, the test.gsp project will be loaded.

> **Exit**: this command terminates the program. In the case that there are unsaved changes, a prompt appears suggesting that the user should save any changes prior to closing the program. The user can then save, not save or cancel the exit command.

A.4. **Edit Menu**

The edit menu is invoked once the user click on edit located in the menu bar. The commands included here are related to importing data, the feedback panel (called debug window) and to some customization options.

> **Input Rain gages Data**: a dialog box shows up (Figure A-6) prompting the user to select the folder where the rain gages files are located. This is the way to import radar data after converting them to the file format used for rain gages by hand, using an external application or using the tools provided with this application.
The format of the data files is described here:

http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/TRMM_FE/lba/gauge_2a56.shtml

These data files should not be moved, as each time the project starts it will be looking for them at the location where they were previously stored. If moving the files is imperative the whole procedure of importing them should be repeated.

- **Satellite Contact**: a dialog box shows up making possible for the user to manage the data files that contain information about the contact (visitation
Appendix A

frequency and duration) of the satellites. These files must be simple ASCII files and follow a specific structure. The first few records of such a file are listed below:

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Day</th>
<th>Month</th>
<th>Year</th>
<th>Start Time</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMSP-F15</td>
<td>21</td>
<td>12</td>
<td>1998</td>
<td>00:08 38</td>
<td>577</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>12</td>
<td>1998</td>
<td>01:44 577</td>
<td>602</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>12</td>
<td>1998</td>
<td>12:51 602</td>
<td>608</td>
</tr>
</tbody>
</table>

The first record is used as an identifier and must be unique. It is case insensitive (TRMM is the same with Trmm). Each following row represents a contact information record and has five distinct fields (none of them optional) separated with Tabs (Tab delimited in Excel). The three columns are the day, the month and the year of the contact, the fourth is the time when the contact started (in a HH:MM format, where HH varies from 00 to 23) and the fifth column is the contact duration in seconds.

![Contact Times dialog box](image)

Figure A-7: The satellite contact times dialog box.

The format specifications of this file has been engineered in such a way that it is fairly simple to produce them using STK and a spreadsheet. The filename and the extension of the actual file are both unimportant. After saving the project, the filenames
Appendix A

are for archive purposes only and they can be moved, since the necessary information is stored in side the project file.

By clicking the “Add” button, a file browse standard dialog box shows up and you can select any file locally or remotely stored that contains contact information. By clicking on the satellite’s name and the button “Remove” it is possible, at any given time, to remove the information from the project.

Useful information can be retrieved and viewed for each satellite file separately, by clicking on the name of the satellite. In the frame “Details” information such as the number of records imported and the average contact time will be displayed.

➢ **(Debug Window) Clear**: clears the feedback panel.
➢ **(Debug Window) Time stamp**: inserts a time stamp (date and time) for future reference if the contents of the panel are exported.
➢ **(Debug Window) Export**: exports the contents of the feedback panel to a plain ASCII file for reference or bug reports.
➢ **Options**: displays the options dialog box, which serves as a visual interface that sets the user preferences. You do not have to restart the program for the changes to take effect.

The **events** frame sets the number of hours with no rainfall that separate two different events. The default value is 6, but any number of hours between 1 and 48 (2 days) can be used. Two non-zero rainfall measurements that are separated from a number of zero measurements, which is less than the number defined here, will be treated as one event.

The **export** format can be used to create comma or tab (default) delimited files when data are exported. The reason for wanting to do something like this has to do with the post-processing external application. Spreadsheets usually support both types.
Appendix A

The **miscellaneous** frame offers two options, the first is to hide the debug window (feedback panel), which will slightly accelerate the program’s execution and simplify its interface and the second is to force secondary windows (not the main interface window) to stay on top of other windows (belonging to the same or other Windows applications).

![Options dialog box](image)

Figure A-8: Options dialog box.

### A.5. Analysis Menu

The analysis menu includes all commands related to presenting the input data and processing them. These commands are available after the user imports any amount of data using the *Edit Menu* as described in A.4.

- **Station Distribution Map**: displays a graphical view of the rain gages (or radar) locations. The projection used is a standard Cartesian map with the latitude coordinate on the vertical axis and the longitude coordinate on the horizontal axis. An example of this view is shown in Figure A-9.
The location of each rain gage is marked with a circle of radius that varies according to the slider’s position (in Figure A-9 it is set equal to 6). Setting this value has only a visual effect on the view, as the centers of the circles remain centered at the exact rain gage location at any value selected.

- **Data Integrity Check**: in the case where the operational period of the rain gages varies, this option can be used to display a view of all data available at a particular day within the operation period. There are two possible settings, the complete graphic data availability check and the complete arithmetic data availability check. The first check displays the results graphically while the second shows the actual number of rain gages that were in operation during a particular day.

- **Rainfall disaggregation**: through this dialog box, the rainfall can be disaggregated from 1 hour time step to less (from 1 minute to 30 minutes) using
either Huff’s rainfall distribution curves (see 4.1) or Beta distribution (see 4.2). The dialog box is presented in Figure A-10.

![Rainfall Disaggregation Dialog Box](image)

**Figure A-10: Rainfall disaggregation dialog box.**

You can disaggregate one rain gage at a time by clicking on the drop down list located at the top of the dialog box or disaggregate all rain gages by clicking on *Batch Process*. The disaggregation method can be changed using the *Change* button and selecting the desired method (as in Figure A-11).

![Select Disaggregation Method](image)

**Figure A-11: Selection of disaggregation method.**
If Huff's method is selected, then the *Configure* button will be enabled and further adjustments of the method's properties can be done by pressing it (Figure A-12). For example, if the First [1/4] selection is chosen, then from all four curves, the first one will be used to disaggregate all rainfall events.

![Configure Huff's Method](image)

Figure A-12: Configuration of Huff's method.

- **Event Browser**: Presents graphically all the original rainfall events (with 1 hour time step) as shown in Figure A-13.

![Event browser](image)

Figure A-13: Event browser.
By pressing *Next* and *Previous* buttons, the next and the previous rainfall event are presented respectively. If instead of the hourly accumulation of rainfall, the accumulated view is needed (cumulatively adding all previous hourly rainfall depths) then the *Accumulate* option should be checked. Clicking on the *Disaggregated...* button, this dialog box closes and the Disaggregated Event Browser pops up.

- **Disaggregated Event Browser**: works in a similar way as the Event Browser, but instead of presenting the original rainfall events it shown the disaggregated events. This dialog box will not work until the rainfall disaggregation procedure has been performed.

![Disaggregated events browser...](image)

Figure A-14: Disaggregated Event Browser.
Figure A-15: Disaggregated Event Browser (Accumulation view).

- **Rainfall Measurement Report:** This option sets the satellites into orbit and monitors their snapshots over all rain gages. For this, the contact times must be provided (via the *Edit Menu*). Clicking on this menu results in the processing status panel shown in Figure A-16.

Figure A-16: Processing status panel.
Depending on the number of data entered and the number of satellite contacts, the whole procedure might last from seconds to several hours. Usually for 40 rain gages and 6 satellites the whole duration does not exceed 5 minutes. For radar with one month data and 6 satellites it can takes approximately 4 hours. Once the procedure is finished the results are displayed in a new window as shown in Figure A-17. By pressing the Save button, it is possible to export the results to a text file.

Column Encounters refers to the number of contacts made by all satellites over the particular rain gage when the rainfall recorded by the rain gage was non-zero. In brackets is the total number of contacts made by the satellites. The total precipitation refers to the total recorded precipitation over the operation period by the rain gage. What was directly recorded by the satellites during the same period, is written in the Directly Measured column. The Interpolated column refers to the rainfall depth that was calculated after interpolating (whenever possible) between snapshots that were falling in the same event. Finally, in the last column the percentage of interpolated rainfall to the total precipitation is given.

<table>
<thead>
<tr>
<th>File Used</th>
<th>Encounters</th>
<th>Total Prec (mm)</th>
<th>Directly Measured (mm)</th>
<th>Interpolated (mm)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>197 [1190]</td>
<td>897.1</td>
<td>56.4</td>
<td>636.2</td>
<td>70.9</td>
</tr>
<tr>
<td>S2</td>
<td>186 [1190]</td>
<td>818.5</td>
<td>53.3</td>
<td>449.6</td>
<td>54.9</td>
</tr>
<tr>
<td>S3</td>
<td>153 [1190]</td>
<td>677.8</td>
<td>43.3</td>
<td>389.8</td>
<td>57.5</td>
</tr>
<tr>
<td>S4</td>
<td>185 [1190]</td>
<td>737.4</td>
<td>39.9</td>
<td>405.8</td>
<td>55</td>
</tr>
<tr>
<td>S5</td>
<td>184 [1190]</td>
<td>860.7</td>
<td>39</td>
<td>413.8</td>
<td>48.1</td>
</tr>
<tr>
<td>S6</td>
<td>188 [1190]</td>
<td>710.1</td>
<td>33.2</td>
<td>368.6</td>
<td>51.9</td>
</tr>
<tr>
<td>S7</td>
<td>193 [1190]</td>
<td>772.5</td>
<td>56.2</td>
<td>541</td>
<td>70</td>
</tr>
<tr>
<td>S8</td>
<td>154 [1190]</td>
<td>679.7</td>
<td>24.2</td>
<td>331.1</td>
<td>48.7</td>
</tr>
<tr>
<td>S9</td>
<td>187 [1190]</td>
<td>737.4</td>
<td>39.7</td>
<td>392.5</td>
<td>53.2</td>
</tr>
<tr>
<td>S10</td>
<td>181 [1190]</td>
<td>723.7</td>
<td>29.7</td>
<td>335.9</td>
<td>46.4</td>
</tr>
<tr>
<td>S11</td>
<td>183 [1190]</td>
<td>798.6</td>
<td>33</td>
<td>411.8</td>
<td>52.2</td>
</tr>
<tr>
<td>S12</td>
<td>194 [1190]</td>
<td>797.4</td>
<td>33.8</td>
<td>378.3</td>
<td>47.4</td>
</tr>
<tr>
<td>S13</td>
<td>185 [1190]</td>
<td>775.7</td>
<td>41.8</td>
<td>455.7</td>
<td>58.8</td>
</tr>
</tbody>
</table>

Figure A-17: Simulation results window.