REPORTS FOR MISSION SELECTION
THE SIX CANDIDATE EARTH EXPLORER MISSIONS

EarthCARE - Earth Clouds, Aerosols and Radiation Explorer
SPECTRA - Surface Processes and Ecosystem Changes Through Response Analysis
WALES - Water Vapour Lidar Experiment in Space
ACE+ - Atmosphere and Climate Explorer
EGFM - European Contribution to Global Precipitation Measurement
Swarm - The Earth’s Magnetic Field and Environment Explorers
REPORTS FOR MISSION SELECTION
THE SIX CANDIDATE EARTH EXPLORER MISSIONS

EGPM –
European Contribution to Global Precipitation Measurement

European Space Agency
Agence spatiale européenne
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1. Introduction

The ESA Living Planet Programme includes two types of complementary user driven missions: the research-oriented Earth Explorer missions and the operational service oriented Earth Watch missions. These missions are implemented through the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme, where the Earth Explorer missions are completely covered by the EOEP.

Earth Explorer missions are divided into two classes, with Core missions being larger missions addressing complex issues of wide scientific interest, and Opportunity missions, which are smaller in terms of cost to ESA and address more limited issues. Both types of missions address the research objectives set out in the Living Planet Programme document (ESA SP-1227 1998), which describes the plans for the Agency’s strategy for Earth Observation in the post-2000 time frame. All Earth Explorer missions are proposed, defined, evaluated and recommended by the scientific community.

Following a call for Core mission ideas in 2000 and selection of five of the ten proposals for pre-feasibility study, three of the candidates, EarthCARE, SPECTRA and WALES, were chosen for feasibility study in November 2001. In response to a call for Opportunity mission proposals in 2001, that resulted in 25 full proposals being submitted by early 2002, three mission candidates, ACE+, EGPM and SWARM, were also chosen for feasibility study. The Phase-A studies for all six Earth Explorer candidate missions are being finalised by early 2004, forming the basis for the Reports for Mission Selection for all the six candidate missions.

The EGPM candidate mission is based on the mission proposal co-written and submitted in 2002 by a team of scientific investigators lead by Alberto Mugnai (CNR/ISAC) and Jacques Testud (IPSL/CEPT). This Report for Mission Selection was prepared based on inputs from the Mission Advisory Group (MAG) consisting of: P. Bauer (ECMWF, Reading, UK), P. Joe (Meteorological Service of Canada, Toronto, Canada), C. Kidd (University of Birmingham, Birmingham, UK), M. del Carmen Llasat (University of Barcelona, Barcelona, Spain), A. Mugnai (Consiglio Nazionale delle Ricerche, CNR, Rome, Italy) and J. Testud (now NOVIMET, Velizy, France). Parts of the Report have been prepared by the Executive based on inputs provided by the industrial Phase-A contractors. Others who, in various ways, have contributed to the Report are the members of the teams providing inputs in the context of the supporting scientific studies carried out in Europe and Canada in the frame of Phase-A.

The Report for Mission Selection for EGPM, together with those for the other five Earth Explorer candidate missions, is being circulated within the Earth Observation research community in preparation for a User Consultation Meeting at ESRIN, Frascati, Italy, in April 2004.
2. Background and Scientific Justification

2.1 Precipitation – A Crucial Geophysical Parameter

Precipitation is a key geophysical parameter. Knowledge of precipitation and its underlying processes are required in a number of research and application disciplines that are directly related to the global energy and water cycle. This includes climate diagnostics and modelling, numerical weather prediction, nowcasting, hydrological applications, oceanography, flood forecasting, transportation, agro-meteorology and water resource management. These areas are expected to have a growing socio-economic impact in the future because societal adaptation to climate change will require the prediction and management of fresh water resources.

Precipitation is a major source of energy for driving the atmospheric circulation through the storage, transport and release of latent heat associated to the precipitation formation processes. It constitutes about 75% of the heat energy of the atmosphere. The energy equivalent of precipitation at the surface is estimated to be of the order of 85 W m\(^{-2}\): this is about one third of the solar radiative energy available to the Earth’s system, and 80% of the net radiative energy at the surface. Therefore, accurate knowledge of precipitation is crucial for understanding weather and climate on all scales. In addition, precipitation is responsible for the removal of much particulate matter from the atmosphere, thus playing a key role in pollution scavenging as well as in global climate and its related changes.

![Figure 2.1: Components of the global hydrological cycle (Mean precipitation, evaporation and runoff according to Baumgartner and Reichel 1975; internal cycle according to Shiklomanov 1999).](image-url)
Figure 2.1 is a schematic representation of the global hydrological cycle, showing the role of precipitation and associated water transport. It is important to note that: (a) there is a wide degree of uncertainty (at least 10-20%) because of our inadequate knowledge of the distribution of precipitation and its variability, especially over the oceans and in remote areas; (b) a more accurate quantification of the precipitation totals over continents is needed for evaluating water storage and river flows; and (c) in mid-latitude and sub-polar climates, precipitation often falls as snow and is stored in glaciers and other solid forms that may subsequently melt at a later time, resulting in a vastly different temporal water cycle compared to that found in the tropics.

2.2 The Importance of Light Rainfall and Snowfall

The Earth has an average annual precipitation of 690 mm, of which about 5% falls as snow. There is, however, tremendous variability in both space and time. While the high precipitation rates are mainly found in a narrow band around the tropics, the occurrence and accumulation of light rain and snow is significant in the mid- to high-latitudes where frontal and stratiform precipitation systems are dominant. Figure 2.2 shows the latitudinal distribution of light rainfall (<~1 mm h⁻¹) over ocean as a proportion of total precipitation occurrence. Not only is the distribution of light precipitation very much biased towards the higher latitudes, but also the occurrence of frozen precipitation (i.e. snow) dominates polewards of 60-70 degrees. Furthermore, these regions lie outside the area observed by existing and planned space-borne radar/radiometer missions.

**Figure 2.2:** Mean zonal occurrence of oceanic light precipitation (as a percentage of total rainfall occurrence) derived from the Comprehensive Ocean-Atmosphere Data Set using ship-borne meteorological observations (1958-1991).
In central and northern regions of Europe and Canada snowfall represents a significant amount of the total precipitation. For instance, the typical average total precipitation in Canada is 535 mm per year, of which 36% falls as snow. However, there is a strong latitudinal influence and the snow proportion at the higher latitudes increases dramatically (Fig. 2.3): at Alert (~84° N), most of the snowfall is light, accounting for 90% of the total precipitation.

![Figure 2.3: Snow to total precipitation ratio for selected latitudinal locations in Canada (Ottawa ~48° N; Yellowknife ~63° N; Alert ~84° N).]

Snowmelt is a major source of water for power, irrigation and domestic supply. For example, in Sweden, about half of the national demand for energy is produced by hydropower, and around 90% of this power is generated in northern Sweden above 60° N from the melting of snow. Snow water content and the rate at which it melts is also critical to spring runoff and floods. Thus, since snowcover is derived from the accumulation of snow, detailed knowledge of the spatial distribution of snowfall is vital for several applications: these include soil-atmosphere interactions, local ecology, and building and transportation infrastructure. Conventional measurements of snowfall are difficult due to large biases induced by wind effects: a correction factor of 8 is required with daily average wind speeds of only 8 ms⁻¹ (Yang et al. 1999). In more remote regions (e.g. mountains, etc.) conventional measurements are non-existent.

2.3 Precipitation Observation and Modelling

Atmospheric (weather and climate) models attempt to reproduce the state of the atmosphere and to predict its future evolution by merging all of the available knowledge in terms of physics/meteorological laws and measured parameters. Precipitation is one of the most important predictors due to its impact on human life. However, it is the result of many interlinked physical processes such as moist convection, condensation-evaporation, nucleation, collision-coalescence, cloud-radiation interaction, and land surface processes, to name but a few. The correct representation of precipitation has significant consequences for the overall performance of the models themselves.
Due to the great variability of precipitation in space and time, insufficient knowledge of precipitation formation processes, and the lack of global measurements with the necessary detail and accuracy, model predictions and observations show significant discrepancies. For example, Figure 2.4 provides an indication that our current knowledge is unsatisfactory: there is still great variation between the zonal averages of precipitation produced by climate models.

![Figure 2.4: Multi-year zonal averages of winter time DJF precipitation (mm/day) in climate models (AMIP).](image)

More recently, questions have been raised as to whether the global water cycle is accelerating as a result of the observed global mean temperature increase. An increased rate of water cycling may impact rainfall amounts and rainfall distribution, as well as the frequency and intensity of storms. One of the greatest challenges facing mankind in an era of climatic uncertainty is the ability to detect, understand, and react to early signs that rainfall patterns may be changing.

At present, there is a conflict between the results from climate models and from available observations (e.g. the international Global Precipitation Climatology Project, GPCP): models indicate increases in global precipitation totals, paralleling global temperatures; however, these increases are not observed in reality (Fig. 2.5).

The situation is particularly complex because of the shortcomings of the global observations (especially, accuracy and coverage), and also because the modelled precipitation distribution has to be treated with caution. Unlike surface temperature projections, for which a consensus amongst forecast climate models is reached (in terms of sign rather than amplitude), precipitation forecasts do not converge across models, especially during summer and over the mid-latitudes (IPCC 2001). In addition, the effects on precipitation by anthropogenic aerosol particles should also be taken into account. These additional aerosols acting as condensation nuclei lead to clouds that are less efficient at generating precipitation and may lead to a weaker hydrological cycle.
Accurate space-based rainfall measurements would therefore play an essential role in advancing our understanding of the Earth’s water and energy cycles.

Figure 2.5: Comparison between model-derived anomalies in global mean precipitation and observations for the period 1979-2000. The model (upper graph) predicts an increasing trend while the observations (lower graph) show no obvious trends (Courtesy of NCAR and NASA/GSFC).

2.4 Quantitative Precipitation Forecasting

Quantitative forecasting of precipitation is one of the most challenging tasks for Numerical Weather Prediction (NWP). NWP models aim to provide a description of the atmosphere over periods of time ranging from a few hours (nowcasting) to a couple of weeks, at regional to global scales. The models start with a definition of the present state of the atmosphere, seeking an optimum balance between some a priori knowledge of the current conditions and information from observations. The models are then applied in three- to four dimensions (that includes the temporal development) over a short period (usually 6-12 hours). Apart from conventional observations from radiosondes, ships, buoys and aircraft, the inclusion of satellite observations has brought forward significant improvements in weather prediction skills in the recent years. While temperature and wind can be predicted rather accurately, humidity analyses and forecasts suffer from the uncertain description of moist processes in NWP models and from the scarcity of observations.

In view of the impact of climate change on the development of extreme weather, many operational weather forecasting agencies have increased their efforts for better forecasts of, for example, tropical cyclones, meso-scale convective systems, extreme
Frontal storms as well as icing and snowstorms. All of these phenomena are mainly, or in part, driven by the release of latent heat in the generation of precipitation. Figure 2.6 emphasises the discrepancies between rainfall distributions from model predictions and observations. These differences are the product of both the insufficient representation of moisture in the physics of global models, as well as the shortcomings of satellite data retrievals mainly based on infrared observations.

Figure 2.6: 1988-1999 average summer precipitation (mm/d⁻¹) from ECMWF model (upper panel) and from observational estimates (middle panel) based on the climatology of Xie and Arkin (1997). Lower panel shows difference fields (Jung and Tompkins 2003).

Precipitation is also important in the estimation of soil moisture fields, which are of primary importance in the initialisation of atmospheric models. Field and modelling studies have demonstrated that the interaction processes between the atmosphere and land are extremely important both in long-term climate simulations and short-term weather forecasting applications.
Finally, assimilation of precipitation data into meteorological models has received increasing attention in recent years, even if it cannot be directly inserted into atmospheric models: the frequent assimilation of variables directly related to the formation of precipitation and to the water cycle leads to an improvement in precipitation forecasting.

Figure 2.7 shows an example of the ECMWF operational forecast model skill in tropical cyclone track prediction. The control experiment represents the current operational model version, while the rain assimilation experiments use rain observations from the Special Sensor Microwave/Imager (SSM/I) instruments to improve the humidity analysis in the cyclone. Compared to the observed track, the rain assimilation substantially improves the track forecast.

Precipitation data is also used to validate the parameterisation of the model precipitation processes. This is done through extended case simulations where location, intensity and timing are assessed, comparison of seasonal and annual amounts. The ability of a Global Circulation Model (GCM) to correctly reproduce the diurnal cycle of clouds as well as the vertical distribution of precipitation and associated latent heating – which impacts storm evolution and climate predictions – are strong tests of the quality of the parameterisations implemented in the model.
2.5 Further Applications of Precipitation Measurements

Nowcasting and very short range forecasting applications are becoming more and more important due to their impact on many different fields: agriculture, severe convective weather, hydrology/flood forecasting, power management, disaster management (including chemical/toxic releases), traffic (road, air and sea) control, industry at large, military operations, and leisure and entertainment. Specific techniques that combine conventional meteorological data with radar and satellite information keep the end-user constantly updated on the weather status through a variety of communication channels. Timely and precise precipitation estimations with sufficient geographical coverage are at the very top of the list of parameters that are of the utmost importance for nowcasting.

Flood forecasting requires a combination of meteorological and hydrological aspects, but there is considerable difficulty associated with the quantitative aspect of precipitation measurements and forecasts. While in large catchments (>100,000 km²) upstream discharge measurements may enable the prediction of a flood, in medium sized and small (<10,000 km²) catchments rainfall measurements and forecasts are needed to predict a flood with a lead time large enough to permit civil protection measures and, therefore, to reduce the associated losses. Ten percent uncertainties in rainfall, soil moisture or storage can result in a 100% error in discharge and subsequent flood predictions.

Frequent satellite observations are of paramount importance to understand the processes for the parameterisation and refinement of models able to bridge the gap between meteorology and hydrology, and to overcome limitations associated with ground-based measurements.

Accurate measurements of precipitation are also required for improving the water resource (river/reservoirs) management of large river basins, which has a direct impact on hydro-electric power production, agricultural planning, flood and drought prediction, and potential water and food shortages. The necessary spatio-temporal scales for land applications are hourly to three hourly averages at 0.1 to 0.2 degree grid resolution.

The estimation of rainfall, together with river runoff and evaporation, is fundamental to the ocean freshwater budget assessment, which governs the evolution of the surface salinity field. The thermohaline circulation of the world’s oceans is induced by variations in density, most of which are the consequence of the different atmospheric conditions at the surface formation sites of the ocean’s water masses. Deep convection in the ocean occurs at only a few special sites in the world. One of these is Canada’s Labrador Sea, where a mid-depth water mass forms during the winter months through the process of deep ocean convection. However, the large differences in present rainfall
estimates (due to no direct measurements) over the Labrador Sea area that are shown in Figure 2.8 create great uncertainty.

**Figure 2.8:** The annual precipitation cycle (cm/month) over the Labrador Sea. The solid line is the climatology based on observations at Ocean Weather Station Bravo. The dashed line is from the Legates/MSU (microwave sounding unit) climatology. The dotted line is from the GPCP climatology. This illustrates the great disparity in precipitation observations at remote locations.

Oceanographic modelling indicates that the inclusion of precipitation reduces the buoyancy loss of the ocean by up to 50% – see, for instance, Figure 2.9. This figure also shows that the impact is greater in the winter months when most of the precipitation occurs. Greater confidence in the spatial and temporal winter precipitation fields in climatologically sensitive regions like the Labrador Seas will increase confidence in GCMs to predict the impacts of changes in ocean circulation (e.g. a shutdown of the Gulf Stream; Schwartz and Randall 2003).

**Figure 2.9:** Annual cycle of buoyancy flux over the Labrador Sea. Gain in buoyancy is associated with loss in density. The dashed line is the buoyancy flux without the precipitation contribution.
Snowfall accumulation is a key factor in understanding the hydrological cycle in mountainous regions and in mid- to high-latitude regions that experience a seasonal snow cover. Snowfall accumulation also plays a significant role in the energy balance of permafrost and the annual cycle of the active layer through its insulating effect, and in the surface radiation balance through its effect on albedo. The accumulation on sea ice and continental interiors (Antarctica and Greenland) plays an important role in the energy balance of the ice sheets, and consequently in their growth and decay.

Food security and natural resources management programmes pay great attention to agro-meteorological and agro-pastoral analyses. Food availability in many arid regions (such as the Sahel region) is mostly determined by local agricultural production, which is almost exclusively based on rain-fed crops and mostly destined for local-consumption. Therefore, the so-called ‘food-risk zones’ are those where the rain-fed cereal production is insufficient. Here, the agro-meteorological aspect, integrated with the socio-economic aspects, is a driving factor in policy making and development programmes. Another critical element is desertification. This is a tremendous threat in the medium-long term and, locally, even in the short term, when the process is accelerating or large scale population migration has occurred. Any model estimating the progress of desertification (e.g. based on soil moisture) relies heavily on precipitation estimates, which are largely inaccurate. Hence, there is an urgent need for reliable high-resolution rainfall fields and frequent observation based estimates.

2.6 The Role of the EGPM Mission for Global Precipitation Measurements

2.6.1 The Need for Observations from Space

In summary, accurate and continuous precipitation data are needed globally for a large number of environmental sciences and applications. However, ground-based precipitation measurements are sparse over land (especially, in developing countries and remote or mountainous regions) and largely missing over the oceans (Fig. 2.10). In addition, there are inherent problems in surface gauge measurements (such as wind effects) that limit their use – especially, for light snowfall, which is difficult to measure since it drifts, blows away, evaporates and melts, often before it can be measured.

It is generally recognized that satellites are the only viable means for providing the global and continuous precipitation data sets that are required. To this end, however, it would be necessary to enhance the fleet of current space-borne microwave sensors capable of measuring rainfall to achieve the temporal sampling and spatial coverage required. For instance, the semi-diurnal nature of precipitation over the tropical ocean, as well as the occurrence of strong diurnally cycled cloud systems over coastal or complex topography areas, require a three hourly sampling as a minimum. This is why the development of an international Global Precipitation Measurement (GPM) mission has been undertaken (Lin et al. 2004; Smith et al. 2004a). The current proposal highlighted in this document is to launch a European mission to address these scientific issues and to participate in GPM.
2.6.2 The Delta Provided by EGPM

As a standalone mission, EGPM will provide a crucial contribution to the accurate precipitation estimates that are required globally, since:

- It is specifically designed to detect and measure light rain and snowfall, both over land and over ocean, in mid- and high-latitude climates. This is an unprecedented characteristic that will be achieved by means of an advanced science payload that includes: (a) an innovative microwave radiometer having temperature-sounding (~50 GHz, ~118 GHz) and high-frequency window (~150 GHz) channels in addition to the standard window channels; (b) a precipitation radar having a sensitivity of better than 5 dBZ.
- Its special payload is able to provide information on precipitation microphysics that will enhance our present knowledge and understanding of all precipitation systems, including the hazardous and flash-flood producing storms, such as those along the Mediterranean coasts.
- It will contribute to nowcasting applications (especially in the Mediterranean area) by providing data within 15 minutes of acquisition.
- It will complement and enhance the coverage of operational microwave radiometers that are planned to be flown from 2008 onwards.

In addition, the innovative EGPM mission can be considered as a prototype operational mission with affordable, viable and alternative techniques for future operational precipitation missions especially designed to optimise rainfall measurements at mid-to-high latitudes, as well as to improve our nowcasting and flood forecasting capabilities.
Within the GPM constellation, the EGPM mission will:

- Provide a crucial contribution to a 3-hourly temporal sampling of the globe, a critical aspect of the measuring problem due to the rapid evolution of precipitation systems.
- Provide a lead role in understanding and interpreting measurements by other GPM components, especially over land and for light rain and snowfall.
- Extend the radar observations provided by the GPM core satellite radar to higher latitudes (i.e. poleward of 65 degrees).

In addition, the EGPM/GPM link will allow European/Canadian scientists and operational users to make use of the wealth of data collected by the GPM partners in near-real-time.
3. Research Objectives

The research objectives of EGPM can be categorized both as a standalone mission and as a significant and integral element of the GPM mission.

3.1 EGPM Objectives

The EGPM objectives are:

• To detect and measure light rain and snowfall, specifically over Northern Europe and Canada and in mid-latitude disturbances.
• To provide a significant contribution to the understanding of hazardous and flash-flood producing storms along the Mediterranean coastal regions.
• To provide accurate precipitation estimates globally.
• To improve the forecast skill of global and regional NWP and climate models by providing global data sets from which improved precipitation parameterisations can be developed and verified.
• To demonstrate the feasibility of high quality measurements of light rain and snow from space and laying the foundations for a future series of operational satellites.

3.2 EGPM - GPM Objectives

The GPM research programme aims to measure precipitation on a global basis with sufficient quality, Earth coverage, and sampling to improve prediction of the Earth’s climate, weather, and specific components of the global water cycle. The main scientific objectives of GPM can be summarized as follows:

• For Weather - to improve the accuracy of global and regional NWP models through data assimilation of precipitation measurements, with emphasis on improving the predictability of hurricanes and severe local storms, and the verification of such models with globally continuous and consistent rainfall measurements.
• For Climate - to accurately measure the global-regional variability of rainfall, relate those variations to variations in global-regional temperature, detect the presence or absence of a speculated acceleration in the global water cycle due to global temperature change, and improve global climate datasets and climate prediction through data assimilation of global rainfall measurements into global climate models (i.e. global climate reanalyses and simulation experiments).
• For the Global Water Cycle - to improve the understanding and predictability of relevant components of the Earth’s water cycle – which includes water in the atmosphere, within and on the land surface, in the oceans, and in the cryosphere – by achieving substantial accuracy improvement in basin-scale water balance across
the relevant space-time scales, with particular emphasis on improving the prediction of damaging floods and the availability of freshwater resources.

These objectives would be achieved by:

- Global spatial coverage with high rainfall estimation accuracy.
- Temporal sampling every 3 hours or less in order to improve numerical weather prediction and hydro-meteorological models through frequent data assimilation, and better forecasts of flash floods.
- Sufficient lifetime to monitor and understand long-term changes in global distribution and frequency of precipitation/latent heating, and their relationship to variations in climate.
- Efficient down-link data transmission in order to provide flash flood forecast centres with near-real time products.

These requirements would be met by the proposed EGPM mission, which would be an integral and essential component of the GPM constellation by:

- Providing global spatial coverage with high precipitation accuracy for both rain and snow; in fact, the EGPM mission is the only element of the constellation specifically designed for light rain / snow measurements.
- Providing a critical contribution to achieve the 3-hourly temporal sampling target.
4. Observation Requirements and Measurement Principle

4.1 The EGPM User Requirements

The primary goal of the EGPM mission is to address a single geophysical parameter, namely precipitation rate. To establish user requirements for EGPM, it is necessary to analyse the observational requirements of the user community. Although the user requirements can be used to steer the observational capabilities of the EGPM (and similar sensors), it should be noted that ‘there will inevitably continue to be requirements for precipitation data that exceed the data available from existing and planned systems’ (NOAA 2003).

4.1.1 Weather Forecasting

The weather forecasting community is the largest community requiring timely and large volumes of precipitation and other observations. It is required for the improvement of the description of the current atmospheric state through data assimilation techniques. This procedure is adopted for two main applications:

- Short-range and regional forecasting: simple nudging/interpolation schemes with little interaction between model physical parameterisations and observed data (e.g. better forcing for soil moisture in coupled land-atmosphere models).
- Short to longer-range global forecasting: more complex 3D/4D variational assimilation techniques with a large impact of the observations on the interaction between the observables and the full dynamical model physics.

Global precipitation measurements are also required for the better understanding of precipitation variability, better understanding of precipitation processes, the development of better parameterisation schemes in numerical weather prediction models, and for the validation of these predictions particularly in remote areas. Also, validation of the vertical profiles of precipitation would provide a stronger constraint on the parameterisation of precipitation processes.

Two organisations specifically outline the requirements of precipitation retrievals for modelling needs:

- the WMO database (WMO 2001), representative for requirements from the world meteorological and climatological community, and focused on the current and near-future status of applications, and more recently
- the requirements being consolidated in the EUMETSAT framework in the context of planning for the MSG follow-on missions, representative of European needs projected in the post-2015 timeframe (EUMETSAT 2002).
These requirements are summarised in Table 4.1, separately for ‘Global NWP’, ‘Regional NWP’ and ‘Nowcasting’. Requirements are specified in terms of four parameters: the horizontal resolution ($\Delta x$; km) of the product (not necessarily that of the instrument, which is generally better); the root mean squared error (rms) of the product (assuming that the bias is a small fraction of the error budget); the observation cycle ($\Delta t$), the time between two successive overpasses of a specific area; and the delay, being the time between the observation and availability of the product for distribution to the user.

Two measures of these parameters are provided: the ‘threshold’ (thres), which if worse than this would have no significant impact on the application, and; the ‘optimum’ (opt) value, which if better than this would be wasteful from the cost-benefit viewpoint.

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Table 4.1: User requirements for precipitation rate from WMO (top) and EUMETSAT (bottom).

The requirements specified by the WMO and EUMETSAT are very similar and only a few of the parameters differ for regional NWP and nowcasting modelling. The differences in individual values stem from the fact that the WMO requirements are intended for the more immediate near-term future: there are ‘rolling requirement reviews’ for updating them every 3 to 5 years, while the EUMETSAT tables attempt to define the requirements for the 2015-2025 timeframe, which is the planned Post-MSG (or Meteosat Third Generation, MTG) timeframe. The EUMETSAT requirements are also a result of a user consultation process and therefore represent the most desirable, rather than the achievable specifications. However, it should be noted that these requirements are applicable to all (or a combination of) observing systems, including satellite based and other instruments: the EGPM mission specific requirements would therefore not look different from these.
4.1.2 Climate Modelling

The second priority noted above relates to the seasonal to interannual timescales. Two bodies, the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS), provide requirements for the observation of the terrestrial climate. Unlike the more general specifications of the WMO and EUMETSAT noted above, these provide the same requirements for the observation of both liquid and solid precipitation (both assuming near-surface measurements): threshold values are deemed to be a spatial resolution of 10 km with an observation cycle of 6 hours, an accuracy of 0.1 mm h\(^{-1}\) and a latency of up to 5 days. Optimum values are set at 1 km, 3 hours, 0.05 mm h\(^{-1}\) and 24 hours, respectively. The values for the threshold horizontal resolution and observation cycle are achievable within the overall GPM mission.

4.1.3 Wider User Community

EUMETSAT (2002) provides additional specifications for the observation/detection of precipitation (Table 4.2). These figures are useful since they provide an indication of observance of precipitation (i.e. precipitation: no-precipitation) and the requirements for different precipitation situations.

<table>
<thead>
<tr>
<th>Application</th>
<th>Thres</th>
<th>Opt</th>
<th>Thres</th>
<th>Opt</th>
<th>Thres</th>
<th>Opt</th>
<th>Breakthrough level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observe/extrapo. Regions of Precipitation</td>
<td>50% POD</td>
<td>99% POD</td>
<td>50</td>
<td>1</td>
<td>60</td>
<td>15</td>
<td>95%/10%/10 km/60 min</td>
</tr>
<tr>
<td>Observe/extrapo. Amounts for Flooding, aviation Warnings</td>
<td>10 mm h(^{-1})</td>
<td>0.1 mm h(^{-1})</td>
<td>50</td>
<td>1</td>
<td>60</td>
<td>5</td>
<td>10 mm/h/2 km/15 min</td>
</tr>
<tr>
<td>Monitoring of convective precipitation</td>
<td>10 mm h(^{-1})</td>
<td>1 mm h(^{-1})</td>
<td>5</td>
<td>2</td>
<td>30</td>
<td>10</td>
<td>10 mm/h/3 km/15 min</td>
</tr>
<tr>
<td>Monitoring of non-convective precipitation</td>
<td>5 mm h(^{-1})</td>
<td>1 mm h(^{-1})</td>
<td>10</td>
<td>5</td>
<td>60</td>
<td>15</td>
<td>2 mm/h/5 km/30 min</td>
</tr>
<tr>
<td>Build-up of unstable snow accumulation (solid precip)</td>
<td>1 mm h(^{-1})</td>
<td>0.1 mm h(^{-1})</td>
<td>0.5</td>
<td>0.1</td>
<td>180</td>
<td>60</td>
<td>2 mm/h/5 km/30 min</td>
</tr>
</tbody>
</table>

Table 4.2: Observational requirements provided by EUMETSAT (2002) (POD = probability of detection, FAR = false alarm rate)
4.2 The EGPM Observational Requirements

A number of observational requirements for the EGPM mission (and in concert with the GPM constellation) have been devised based upon the above user requirements.

Due to the shortcomings of the conventional observing system (i.e. gauges and radar), satellite observations of precipitation are required globally, particularly over data sparse regions, such as over the oceans, unpopulated and inhospitable regions. A higher priority is, however, given to observations over Europe, mid-latitude and polar regions. The spatial resolution of the products derived from the satellite observations is commensurate with that of the meteorological models’ grid boxes and users’ applications. At present, a spatial resolution in the order of 100 km² is typical, with improvements to resolutions of the order of 10’s km² in the future. It should be noted that the sensor resolution tends to be higher than the product resolution to help mitigate beam-filling errors resulting from sub-resolution rain cells.

An important part of the whole GPM concept is the improved temporal sampling that will be provided by the mission. EGPM, together with the other GPM satellites aims to, at least, meet the threshold value for Regional NWP: a 3-hour cycle would meet European and WMO requirements (Table 4.1).

Figure 4.1: Cumulative distribution of rainfall accumulation (solid) and occurrence (dashed) plotted against rainfall intensity for Europe (United Kingdom, France, Germany and Benelux countries) and the Tropics (35° N - 35° S), as observed by surface radar and by the Precipitation Radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) spacecraft, respectively.

Figure 4.2: The cumulative distribution of snowfall amount plotted against radar reflectivity for several stations (spaced in latitude, locations indicated in brackets in the legend) in Canada and Finland.
Unlike many other meteorological parameters, precipitation is unusual in having a highly skewed intensity distribution towards zero. The dynamic range is set between 0.1 and 50 mm h⁻¹, which are seen as the intensities of rainfall that can be realistically observed over the spatial resolution of the field of view of the sensor, i.e. it is intimately linked to the spatial resolution. A smaller dynamic range for snow (solid) precipitation of between 0.1 and 20 mm h⁻¹ (water equivalent) is required.

Analysis of existing data sets shows that rainfall accumulations in the tropics are dominated by the heavier precipitation events, while at mid- to high-latitudes the occurrence and the amount of precipitation falling at lighter intensities are more significant. Figure 4.1 shows the cumulative distribution function of rainfall for two regions: in the tropics, rain intensities less than 1 mm h⁻¹ make up 55% of the occurrence but only 10% of the rain total, whilst over Western Europe these intensities occur 85% of the time resulting in 45% of the total accumulation. Figure 4.2 shows a similar plot of snowfall over several stations in Canada and Finland derived from surface radar. The data can be interpreted in terms of the wide variety of physical precipitation processes and the dependence of snowfall distribution on latitude: the most Northern station (Fort Simpson) shows a very steep distribution at relatively low reflectivities, indicating the very proficient snow processes in the near-Arctic environment. At a continental location (Woodlands), the tail at low reflectivities is indicative of a very dry environment, whereas the Eastern Canadian site (Franktown) shows the influence of moist coastal precipitation systems. The results from Finland are comparable to the Franktown results, perhaps indicating the moderating and moist environment created by the Baltic Sea.

For light rainfall, due to the minimum level detection together with the physical characteristics of light rainfall, an accuracy of better than 100% is deemed to be the best achievable. In the range 1-10 mm h⁻¹, a 50% level of accuracy is realistic, while for rain intensities above 10 mm h⁻¹ an accuracy of better than 25% is required. It should be noted that these values represent the precipitation rate accuracy for instantaneous precipitation estimates at the co-located resolution of 20 km. Temporal and spatial averaging of the precipitation estimate generally improves the overall accuracy.

The requirement for the reliability of data-delivery (the probability that errors remain within the 3-sigma band) is set at 95%: gross errors can potentially damage the objective analysis, leading to an incorrect picture of the state of the atmosphere. Experience with conventional observation systems and associated quality control in operational meteorological analysis indicate that the rate of gross errors should be only a few percent. Data-delivery on a global scale is set at 4 hours, with 2 hours required as a goal for operational meteorological use (e.g. forecast model assimilation) of the observations in the future. For climate model applications, longer delays are tolerable. To meet one of the main aims of the mission, i.e. severe storm monitoring, data delivery within 15 minutes over Europe is required for nowcasting applications.
4.3 Summary of the EGPM Observational Requirements

For a mission intended to demonstrate the capabilities of a global, pre-operational atmospheric observing system, the requirements on data quality are the most stringent and most important to achieve. Under this assumption, the horizontal resolution of observations is of the lowest priority among the requirements discussed in this section. Table 4.3 provides an overview of the requirements formulated for the EGPM mission.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Domain</td>
<td>Global</td>
</tr>
<tr>
<td>Horizontal Resolution [km]</td>
<td>20</td>
</tr>
<tr>
<td>Vertical Domain [km]</td>
<td>0 - 15</td>
</tr>
<tr>
<td>Vertical Resolution [km]</td>
<td>1 layer (surface)</td>
</tr>
<tr>
<td>Dynamic range [mm/h]</td>
<td>0.1 to 50</td>
</tr>
<tr>
<td>Precipitation rate accuracy</td>
<td></td>
</tr>
<tr>
<td>Precipitation rate &lt; 1 mm/h [%]</td>
<td>100</td>
</tr>
<tr>
<td>1 &lt; precipitation rate &lt; 10 mm/h [%]</td>
<td>50</td>
</tr>
<tr>
<td>Precipitation rate &gt; 10 mm/h [%]</td>
<td>25</td>
</tr>
<tr>
<td>Data Reliability</td>
<td></td>
</tr>
<tr>
<td>Observation cycle [hour]</td>
<td>&lt; 3 (***)</td>
</tr>
<tr>
<td>Data Delivery (global) [hour]</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>Data Delivery (Europe) [hour]</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Observational requirements for the European contribution to the Global Precipitation Measurement (EGPM) (POD = probability of detection, FAR = false alarm rate)

Notes: (*) also includes e.g. hail; (**) this is liquid water equivalent; (***) requires a GPM constellation

4.4 Measurement Principles

The remote sensing of precipitation with EGPM is based on the absorption and scattering of microwave radiation by precipitating clouds. Compared to visible/infrared wavelengths, the use of microwave radiation (here frequencies of ~10-150 GHz or
wavelengths of ~3.0-0.2 cm) has the great advantage of allowing significant penetration through rain clouds and therefore providing information on integrated precipitation liquid water and ice paths as well as hydrometeor concentration profiles. Microwave radiances are usually expressed as blackbody-equivalent brightness temperatures (TB) and radar backscatter is expressed as decibels of reflectivity (dBZ).

The technical limitation of affordable antenna sizes requires the implementation of both precipitation sensing radars and radiometers in low-Earth orbits. These observations must be available at spatial scales between 5-50 km depending on channel frequency. Both remote sensing techniques and inversion methodologies have been developed over several decades and are already being used operationally from space and in surface-based observation networks for many applications.

Existing microwave radiometers that are used for the estimation of precipitation profiles allocate channels at window frequencies that are positioned away from absorption bands/lines of water vapour and oxygen. Recently, those channels that are traditionally used for temperature and humidity profile sounding have also been exploited for cloud and precipitation sensing because of their reduced sensitivity to surface emission and their sensitivity to profile variations. Over oceans, low surface emissivity allows a large dynamical signal range to be used for the analysis of the atmospheric contribution, while over land and snow cover the surface contribution may be dominant. The use of dual-polarization channels significantly improves the delineation of cloud and precipitation information. This is because surface microwave emission is strongly polarized (over oceans) and absorption and scattering of radiation by hydrometeors depolarises this signal. Dual-polarized channels are most optimally implemented with a conical scan pattern because constant zenith angles and therefore surface emission/reflection properties are reasonably well defined.

With respect to the radiometer, the advantage of radar is its ability to control the sampled volume along the observation beam: the radial resolution is defined by the length of the pulse and is about 200 to 500 m in weather radar applications. The radar ‘reflectivity’ (Z, in mm$^6$m$^{-3}$) is proportional to the sum of the backscattering cross sections of the particles present in the observed volume, and the ‘specific attenuation’ $A$ (in dB km$^{-1}$), proportional to the attenuation cross sections of the same particles. A radar measures the ‘apparent reflectivity’ $Z_a$ (corrected for the two-way path attenuation) in each resolution cell. The retrieval of rainfall, $R$, therefore uses either a $Z$-$R$ or $A$-$R$ relationship.

Presently, the inversion of the $Z_a$ profile to derive the rain rate $R$ is most commonly used because of the heritage of the algorithms that were developed for the precipitation radar of TRMM. Among others, the technique makes use of the surface echo as a reference target to estimate the path-integrated attenuation through the full precipitation layer. Introducing a parametric particle size distribution normalization allows the $Z$-$R$ or $A$-$R$ relationships to be made independent of the size distribution
variability (Testud et al. 2001, Ferreira et al. 2001) and therefore substantially more stable. The choice of 35 GHz (Ka-band) is driven by the requirement of high sensitivity to weak rainfall and snow where little attenuation is expected.

Radar observations should be limited to near-nadir angles to avoid the contamination of lower levels with surface backscatter. The choice of three radar tracks close to nadir covering the footprint of the radiometer at the centre of the common swath is a consequence of this, as well as the restriction of the affordable antenna size.
5. Data Processing Requirements

5.1 Summary

This section presents the development status of geophysical parameter retrievals based on EGPM observations, as well as their assimilation into numerical atmospheric models. The key results of the detailed analysis that is presented in the subsequent section can be summarized as follows:

- Both EGPM radar and radiometer observation analysis methodologies are based on long-term experience and a well established framework of research and application activities shared by the global climate research, numerical weather prediction, hydrology, and related communities.

- The EGPM sensor combination strategy is embedded in the GPM synergetic algorithm development with a focus on mid- to higher latitude applications. The EGPM radar will provide crucial information on cloud structure and key mixed-phase microphysical parameters required for constraining the wide-swath radiometer algorithms.

- EGPM data will immediately be usable for numerical weather prediction (NWP) because microwave radiometric data of precipitation is already assimilated in operational or experimental mode at various national and international NWP centres.

5.2 Detailed Analysis

5.2.1 Scientific Algorithms

Passive microwave rainfall algorithms have steadily evolved from those designed for the early ESMR (Electronically Scanning Microwave Radiometer), through the SMMR (Scanning Multi-channel Microwave Radiometer) on Nimbus-7, and the SSM/I (Special Sensor Microwave/Imager) instruments flying on the DMSP (Defense Meteorological Satellite Program). A number of algorithms to retrieve precipitation rate from radiometric emission/scattering signatures (radiances or brightness temperature) have emerged that can be characterised into three classes: (a) the ‘emission type’ algorithms that use low frequency channels to detect the increased radiances due to rain emission over radiometrically cold oceans; (b) the ‘scattering’ algorithms that correlate rainfall with radiance depressions caused by ice scattering present in many precipitating clouds; and (c) the ‘multi-channel inversion’ type algorithms, which seek to invert the signal in all channels simultaneously. Algorithms based on different principles are used operationally with data from the TMI (TRMM Microwave Imager), the AMSR-E (Advanced Microwave Scanning Radiometer) and...
the SSM/I (e.g. within the Global Precipitation Climatology Project) or for rain assimilation experiments at various NWP centres.

In each case, algorithms have been optimised for the corresponding satellite sensor, and each algorithm has strengths and weaknesses related to specific applications, while none appears to be universally better than the others (e.g. Smith et al. 1998, Ebert and Manton 1998).

For the inversion of reflectivity profiles observed from space, a considerable research background is available from the heritage of algorithms that were developed for the first space-borne precipitation radar, the TRMM precipitation radar (PR). The starting point of the TRMM data processing chain is a rain type classification scheme that is based on melting layer detection (so-called ‘bright band’), the analysis of the radar reflectivity profile shape below, and the horizontal homogeneity of rain signals. The actual inversion of rain rates from radar reflectivities is constrained by the estimate of the path-integrated attenuation (PIA) that is obtained from the surface echo (Meneghini et al. 2000). However, since at low rain rates the surface echo (over both ocean and land) is subject to natural fluctuations that produce rather noisy PIA-estimates, a standard Z-R relationship without attenuation correction is applied. The retrieval may be further constrained by assumptions on microphysical characteristics such as particle size distributions.

Synergetic algorithms make use of the complementary information provided by radar and radiometer. The accurate treatment of the observation geometry is fundamental for the analysis of the probed atmospheric volume. Two basic synergetic approaches are pursued. In the first, the vertical reflectivity profile information from the radar provides the real-time calibration for the microwave radiometer-based snow and rain retrieval algorithms (e.g. Bauer et al. 2001, Di Michele et al. 2003). This is advantageous for the rain/snow estimation over land surfaces, where passive microwave sensors would rely on independent information about land surface emissivity. The second approach includes multi-spectral radiometer information of PIA at the radar observation frequency in the radar precipitation retrieval algorithms (e.g. Haddad et al. 1997). Hydrometeor contents (including cloud water), particle size distributions, particle size-density relationships and, most importantly, the vertical distribution of scatterers, are adjusted in this process.

The strengths of one instrument complement the weaknesses of the other as summarized in Table 5.1. For example, the field of view of the radiometer is not always filled with precipitation due to the small size of convective rain elements. This results in a bias (of order 40% in the tropics) and large random error in the rain rate retrieval. The radar with its high resolution can provide an estimate of the beam filling and hence be used to reduce the bias. In another example, the radiometer retrieval of precipitable water assumes a temperature and humidity profile. The freezing level from the temperature profile is used to determine the height limit of the integrated water vapour
contribution to the radiometric signal. This height can also be determined from the reflectivity profile and can hence be used to assess the model assumptions in the radiometric retrieval. Compared to convective tropical systems, northern climates are dominated by complex ice microphysics in baroclinic weather systems; the detailed radar profiles will be necessary to decode and interpret the radiometric signals. In addition, radiometric precipitation retrievals over land are very difficult because of the poor contrast between the precipitation and the land signal; therefore the vertical detail and ground clutter echo signal will be crucial in the accurate measurement of precipitation over land surfaces.

<table>
<thead>
<tr>
<th></th>
<th>Radiometer</th>
<th>Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Swath</strong></td>
<td>Broad ~1000 km</td>
<td>Narrow ~18 km</td>
</tr>
<tr>
<td><strong>Drop size distribution</strong></td>
<td>Weak sensitivity (D^4)</td>
<td>Sensitive (D^6) except in attenuation mode</td>
</tr>
<tr>
<td><strong>Cloud</strong></td>
<td>Contributes</td>
<td>Transparent</td>
</tr>
<tr>
<td><strong>Profiling</strong></td>
<td>Limited (Sounding Channels)</td>
<td>High resolution profile (a few 100 m)</td>
</tr>
<tr>
<td><strong>Land</strong></td>
<td>Strong surface emissivity effects</td>
<td>Ground clutter limited to near surface data</td>
</tr>
<tr>
<td><strong>Resolution (for given aperture) / Sensitivity</strong></td>
<td>Gain by antenna used only once</td>
<td>Better – gain is squared</td>
</tr>
<tr>
<td><strong>Inhomogeneity</strong></td>
<td>Strongly affects retrieval</td>
<td>Power law used Z-R, less affected (except in attenuation mode)</td>
</tr>
<tr>
<td><strong>Complementary strength</strong></td>
<td>Sampling</td>
<td>Physical and scientific insight, and understanding of radiometric signal; used post-mission</td>
</tr>
</tbody>
</table>

**Table 5.1: Complementary characteristics of a radiometer-radar combination (adapted from Wilheit 2003).**

5.2.2 Data Assimilation

Improvements made during the last decade to the quality of forecasts produced by operational NWP models have been the result of several factors. Computing resources have enabled improved horizontal and vertical resolutions, allowing for a better description of small-scale processes such as cloud and precipitation formation. A factor of at least equal importance has been a better specification of the initial conditions from which both deterministic and ensemble forecasts are started. The best initial state of such a model is defined within a data assimilation system that combines in an optimum sense short-range forecasts (typically between 6 and 12 hours) and meteorological observations during a 6 to 12-hour period. Based on these techniques and the increase in data, especially from satellites, forecast skill scores on large-scale dynamical fields (such as the geopotential at 500 hPa) have been significantly improved during recent years, particularly in the Southern Hemisphere (Simmons and Hollingsworth 2001).
Considering meteorological parameters quantifying the water cycle (water vapour, cloud water, rain water, soil moisture), however, the quality of both analyses and forecasts has remained rather poor, as reported at the recent ECMWF/GEWEX Workshop on Humidity Analysis (8-11 July 2002) and by Ebert et al. (2003).

The assimilation of cloud and rain affected observations can provide improved initial humidity fields that will lead to improved forecasts of clouds and rain. A major challenge for data assimilation originates from the high spatial and temporal variability of clouds and rain, whereas current systems are designed for atmospheric variables having larger spatial scales (>500 km) and lower temporal variability (>6 hours). Despite these limitations, the assimilation of precipitation observations has been under investigation during the last twenty years.

With the advent of 3D-/4D- variational assimilation systems, it has become possible to include rainfall rates in the analysis like any other kind of observation, despite the more complex cloud and rain microphysical processes that are involved. The National Center for Environmental Prediction (NCEP) has recently introduced operational assimilation of satellite derived rain rates from SSM/I and TMI in their 3D-variational system. Along the same lines, ECMWF is developing a methodology to allow the assimilation of precipitable water in rainy areas in their 4D-variational assimilation system. A number of preliminary studies (e.g. Marécal and Mahfouf 2002) have demonstrated that analyses and forecasts can be improved by assimilating such information from either retrieved rain rates (Mahfouf et al. 2003) or directly from observed microwave radiances (Moreau et al. 2003a).

Figure 5.1 shows an example of forecast errors for the 500 hPa geopotential that represents one of the key parameters of the atmospheric dynamics. In the period May 16-20, 2001, model analysis over North America was affected by an insufficient representation of several Pacific cyclones (see control experiment). By assimilating rain observations from SSM/I or TMI data, the 3-day/5-day forecast errors were substantially reduced. The better data coverage with 3 DMSP satellites led to an even larger reduction of forecast errors compared to the experiment where only TRMM TMI data was used. This proves that NWP forecasts will benefit from the highest possible frequency of observation.

5.2.3 Expected Developments

The GPM mission represents a major milestone for global precipitation monitoring: the preparation for the mission is already providing new impetus towards a common algorithm framework. The radiometers for the GPM satellite constellation are not yet fully specified, but will evolve throughout the mission preparation based upon contributions from a number of different space agencies. This imposes a number of high-level requirements upon any algorithm designed for these sensors. Any mission within GPM requires an open algorithm architecture that will allow the international community to participate in the algorithm development, its refinement, and its error
characterization. Since GPM is being designed as an ongoing cooperative concept among many agencies, algorithms are no longer designed for specific radiometers with defined frequencies, viewing geometry, spatial resolutions or noise characteristics, but must be applicable to any sensor. This requirement eliminates the sensor-specific ‘emission’ or ‘scattering’ algorithms introduced above.

A major element of EGPM (and the GPM core satellite) is the synergetic use of passive and active microwave observations. For EGPM, this synergy is crucial due to its dedication to frozen and light precipitation observation. Only EGPM and the GPM core satellite will carry radiometers and radars with different observation characteristics (frequencies, observed volume). These require some a priori information on parameters that are not directly observed, but which contribute significantly to the measurement. Therefore, a strategy for the optimised combination of the complementary observations and atmospheric models has to be developed. Figure 5.2 illustrates the co-location of the EGPM radiometer central-swath footprint with the three fixed-beam radar footprints (green and red circles).

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**Figure 5.1**: 3-day (upper panel) and 5-day (lower panel) forecast error of the 500 hPa geopotential over North America from a control experiment (solid) and when TMI (dotted) and SSM/I (dashed-dotted) rain rate retrievals are assimilated (courtesy from Mahfouf et al., 2003). The lower the error, the better the forecast, in particular between May 16-20. Note the better performance with SSM/I data due to the higher observation frequency (3 DMSP satellites vs. TRMM satellite)
Figure 5.2: Sampling geometry of the EGPM radiometer swath-centre footprint (blue circle, 20 km) together with single-beam (central green circles), and three-beam radar (green and red circles) footprints.

The logical flow of information provided by radiometer, radar and model data in a synergetic and dynamic algorithm is presented in Figure 5.3. This architecture represents the baseline for the EGPM/GPM algorithm framework. Radiometer and radar observations are combined in several steps:

1. Identification of rain-affected areas by the radar where available and by radar-calibrated radiances elsewhere.
2. Estimation of microwave background emission from clear-sky areas and interpolation to rainy areas.
3. Identification of cloud resolving model fields that match observed radar properties.
4. Optimization of key microphysical parameters (particle size distribution, particle density, freezing level) to match both radar and radiometer observations and the estimation of PIA from the radiometer.

This architecture is expected to provide hydrometer profile estimates that are superior to those obtained from either radar or radiometer alone. The algorithm will feed on, and the results will feed back into, a global and dynamic database shared with all constellation radiometers/radars in order to provide consistent retrievals.

In this synergetic algorithm, the EGPM precipitation radar will provide information on the precipitation structure and constrain the radiometer algorithm by supporting information on precipitation microphysics. This may be done by a procedure in which the radar data analysis drives a potential hydrometeor profile database or by a
variational retrieval involving microphysically consistent, single-column precipitation models (e.g. a combined radiative transfer-reflectivity-aggregation model of snow). The latter methodology represents the precursor of a simple analysis scheme as used in current NWP data assimilation, where observations from several instruments are combined with simplified dynamical physical models to produce a consistent description of the physical state of the atmosphere. Work is in progress to implement these two prototype synergetic algorithms.

**Figure 5.3:** Algorithm flowchart. Blue coloured items relate to rain-free parameter retrieval, yellow to PR profile matching, and red to the comparison of matched profiles in microwave radiance space. (Z: equivalent radar reflectivity; PIA: path-integrated attenuation; TB: brightness temperature; NR: non-raining; TMI: TRMM Microwave Imager; PR: Precipitation radar; CRM: cloud-resolving model; Do: effective mean diameter; \( \rho_{\text{ice}} \): ice particle density) Courtesy of C. Kummerow.

Future developments regarding the assimilation of precipitation in NWP systems will vastly extend the combined use of infrared and microwave satellite data in order to introduce complementary information on cloud and rain properties into the analysis. The availability of radiometric observations at lower and higher frequencies, as well as radar observations, will allow for extended options for data assimilation and
verification (e.g. assimilation of a subset of radiometer channels, validation with remaining channels and radar). Generally, the assimilation of satellite data in cloudy and rainy areas is one of the major challenges for NWP in the coming decade. A coordinated research effort regarding data assimilation systems, data retrieval techniques and modelling of cloud processes will be fostered by EGPM, both alone and within the GPM context.
6. Performance Estimation

The proposed EGPM mission will carry two instruments, namely a microwave radiometer and a radar. The EGPM radiometer has four main microwave window channels (at 18.7, 36.5, 89, and 150 GHz) positioned outside the main H2O and O2 rotational absorption bands/lines and thus receives a large signal contribution from lower atmospheric layers and the surface. In addition, sounding channels positioned near two O2 absorption bands/lines, at 50-54 and 118 GHz, penetrate the atmosphere as a function of frequency or the relative displacement with respect to an absorption line.

The proposed EGPM nadir-pointing precipitation radar has three fixed beams: it will have high sensitivity and high resolution for the detection of light rain and snow and, at the same time, be able to resolve convective storms.

Details about the technical concept can be found in the technical dossier.

Simulation studies assessing the radar/radiometer sensitivity and retrieval performance in meteorological situations that represent the primary observation target for the EGPM satellite have been carried out. In the following sections, results are presented to demonstrate that the mission proposed can meet the requirements stated in Chapter 4.

6.1 Observation Simulations

EGPM radiometer/radar observations over typical mid- to high-latitude precipitation systems are simulated with combined three-dimensional cloud-radiative transfer models. Clouds and precipitation are modelled with the non-hydrostatic cloud-resolving model of the University of Wisconsin – Non-hydrostatic Modeling System (UW-NMS) (Tripoli 1992). Mixing ratios of six different hydrometeors are computed: cloud droplets, raindrops, sleet, pristine ice crystals, snowflakes, and ice aggregates. For illustrative purposes, two scenes were chosen: (1) an October 2002 frontal system over the southern UK and the English Channel that produced light-to-medium rainfall, and (2) a January 2000 snowstorm that produced significant snowfall over the eastern coast of the United States. Details of the methodology and extended analysis of the results shown henceforth can be found in Mugnai et al. (2004). Figure 6.1 shows selected cross-sections to demonstrate the main features that could be observed by the EGPM radiometer.

For the UK frontal system over ocean, the most important signatures are:

- The three lower window frequencies (18.7, 23.8, and 36.5 GHz) are directly sensitive to liquid rainfall. Brightness temperatures (TBs) increase by up to 30 K with increasing columnar water contents. Since the water contents are rather low, this sensitivity increases with frequency.
- The higher frequency window channels (89 and 150 GHz) show increasing TBs where only cloud water is present (< 180 km), and a strong sensitivity to scattering...
by snow. TB-depressions reach 60-80 K and generally mirror the columnar snow content distribution.

- The lower frequency sounding channels (50-54 GHz) also show an emission signature in the absence of snow, while scattering occurs where the strongest snowfall is simulated (200-270 km). Where the snow contents are of similar magnitude to rain contents, signal saturation occurs, indicated by similar TBs in all channels. The 53.76 GHz channel shows little sensitivity at all because its weighting function peaks above the main cloud structure.

- The higher frequency sounding channels (118.75 GHz) show a distinct scattering feature due to snow, whose magnitude depends on the channels weighting function peak altitude. This suggests the vertical profiling capability. As for the higher window frequencies, the depression of TB follows the snow content distribution.

**Figure 6.1:** Simulated EGPM radiometer observations for the UK frontal system (a, over sea) and the Eastern US snowstorm (b, over land). From top to bottom: lower frequency window channels, higher frequency window channels, lower frequency sounding channels, higher frequency sounding channels, integrated liquid water contents (LWCs) of key hydrometeors, vertical cross-sections or rain/snow (FL: freezing level).
For the US snowstorm over land, the most important signatures are:

- While the two lower window frequencies (18.7 and 23.8 GHz) show very little sensitivity to precipitation over land, the large snow amounts produce a scattering signature even at 36.5 GHz. TB-depressions of more than 10 K are observed.

- The higher window frequencies (89 and 150 GHz) respond very strongly to scattering from snow over land. The difference between TBs at these two frequencies (between 250-320 km) can only be explained by the presence of supercooled water and small ice particles, which reduce the scattering efficiency at 150 GHz more than at 89 GHz.

- The lower frequency sounding channels (50-54 GHz) show scattering signatures that increase with decreasing weighting function peak altitude. The same feature is observed for the higher frequency sounding channels (118.75 GHz) with larger magnitudes, due to the general increase in scattering efficiency with frequency. Again, the vertical profiling capability is evident from the dependence of dynamic range on channel.

Figure 6.2 shows the simulated EGPM radar attenuated reflectivity at 35.6 GHz for the same snowstorm cross-section as shown in Figure 6.1. Also indicated are the limits of detection for 0, 5, and 16 dBZ, respectively. These results demonstrate that the chosen radar sensitivity is very important for the observation of solid precipitation. There is a significant benefit in using a sensitivity limit of 5 dBZ rather than 16 dBZ (as for TRMM Precipitation Radar) because it allows the detection of light precipitation (at distances of up to 100 km in Figure 6.2) and precipitating ice aggregates (at distances greater than 380 km). In addition, with a limit of 5 dBZ, about 1 km of the topmost cloud layer can be detected, which will affect passive microwave radiometer observations at higher frequencies.

![Figure 6.2: Simulated radar reflectivity at 35.6 GHz for the same cross-section of the Eastern US snowstorm simulation as shown in Figure 6.1. The three dotted lines correspond to three different limits of radar sensitivity (0, 5, and 16 dBZ).](image)
6.2 EGPM Radiometer Performance

The performance of the EGPM radiometer has been assessed on the basis of the geophysical variable retrieval accuracy estimation using simulated observations. The geophysical variables are the profiles of rainwater, cloud water and snow content, respectively. The assessment was carried out in two stages: (1) the quantification of the information content of the simulated observations accounting for realistic radiometric and geophysical noise; (2) the quantification of retrieval accuracy given different meteorological systems and surface types.

Experiment set-up: All results are based on meteorological events obtained from a short-range forecast that was carried out with the current operational version of the ECMWF model. Therefore, the chosen hydrometeor profiles originate from the operational cloud and convection schemes. A one-dimensional variational retrieval scheme was developed that treats single-column vectors of temperature, humidity and hydrometeor profiles. The retrieval was constrained by artificially generated first-guess state vectors of these variables, their errors, synthetic observations from the application of a multiple frequency radiative transfer model to the profiles, and an estimate of the modelling errors including the EGPM radiometric noise. The following four cases were analysed:

- A Western Canadian snowstorm, area 1, with heavy snowfall and little liquid precipitation.
- Same event, area 2, with heavy snowfall and moderate rainfall.
- Northern Atlantic front with light rain and significant snowfall.
- Scattered Florida precipitation with both light/heavy rain and snowfall.

The first two scenes are rather difficult observational situations because of the little contrast between the signal contributions from surface and atmosphere/cloud, and because of the variable surface conditions. However, they represent system types that the EGPM mission specifically focuses on, and thus constitute a benchmark test for retrieval sensitivity/accuracy.

Information content: To this end, the variability of the brightness temperatures as a result of the radiometer noise, the surface emissivity variability and the variability of the hydrometeor profiles has been investigated. For each geophysical parameter, the associated TB variability is defined as the product of the parameter’s variability and the radiometric sensitivity at the top of the atmosphere to changes in the parameter itself. The radiometric variability due to surface emissivity was computed using realistic surface emissivity values and errors obtained from combined SSM/I-ATOVS-ISCCP retrievals (Prigent et al. 1997), while that due to the hydrometeor profiles was computed using the four ECMWF model simulations for the above cases.
The results are shown in Figure 6.3, where the bars represent the total dynamic range of the signal for each EGPM radiometer channel, while the colour coding indicates the relative contribution of each component – thus allowing an estimate of the relation between the signal vs. radiometer/geophysical noise.

Figure 6.3: Contributions to total EGPM radiometric signal variability (in K) from radiometric noise (NE\Delta T; ■), surface emissivity (■), liquid (■) and frozen (■) precipitation for the selected meteorological situations. Taller bars indicate higher sensitivity and hence larger contributions.

Both the total dynamic range and its various components are highly dependent on frequency and meteorological situation. For the selected cases of shallow precipitation originating from mid-latitude systems, the total dynamic range is between 2 and 30 K; however, it may be larger for more intense systems. In detail, these results indicate that:

- The radiometer noise is small compared to the geophysical, i.e. natural, noise.
• At high latitudes and with snow covered surfaces, the window channels have to be complemented by sounding channels to overcome high geophysical noise.

• With the exception of case 1, all channels will provide crucial information to the retrievals; for snow retrievals over land surfaces, the higher frequencies and the sounding channels are most important.

• Over oceans and less variable land surfaces, the retrieval of liquid precipitation is possible; over snow-cover and for weak precipitation, only the sounding channels contain sufficient information on rain.

Retrieval accuracy: The estimation of retrieval accuracy has been performed by first generating hydrometeor profiles from the ECMWF model forecast (= the true profiles). Then, radiative transfer calculations are performed to simulate EGPM observations. Successively, the true profiles are perturbed according to realistic error structures (= the first-guess profiles). Finally, the true profiles are retrieved back using simulated observations and first-guess profiles. The retrieval accuracy is estimated from the differences between the retrieved and true profiles. Details of this retrieval methodology in the context of global modelling applications and data assimilation can be found in Moreau et al. (2003b). The surface characterization is based on the same emissivity retrievals as above.

Figure 6.4 shows the height-averaged rms (root mean square) error cumulative distribution of rain and snow retrievals for the above meteorological situations. The overlaid rms error levels of 25%, 50% and 100% indicate that, for the dynamic range of light rain rates that is covered in the simulations, the window channels do not provide accuracies better than 100%. However, the sounding channels show a much narrower distribution, with the bulk of the retrievals achieving rms errors of less than 50% for rain rates above 1 mm h\(^{-1}\). For snow retrievals, the sounding channels perform better with rms errors below 100% for practically the entire dynamic range. For snowfall rates above 1 mm h\(^{-1}\), most retrievals show accuracies better than 50%. The dynamic range of snowfall rates is rather large (0.01-20 mm h\(^{-1}\)), and therefore provides a good basis for estimating the expected global accuracy.

6.3 EGPM Radar Performance

To establish a relationship between the radar technical specifications and retrieval accuracy/detectability, a simplified precipitation model was developed. The model is characterised by a single rain layer between the surface and the freezing level (rain rate constant with altitude) and a snow precipitation layer in which the snow rate decreases with height above the freezing level. Since the radar pulse is attenuated through the rain layer, there is a lower detection limit for weak rainfall at the surface and an upper detection limit in heavy rain. While the lower limit is rather small (0.04 mm h\(^{-1}\)) due to a detection threshold \(Z_{\text{min}} = 3.5 \text{ dBZ}\), the upper detection limit may be reached for rain rates of 20-25 mm h\(^{-1}\) in the Tropics (4-5 km rain layer thickness) and of 35-55 mm h\(^{-1}\) in mid-latitudes (2-3 km rain layer thickness). For snow detection the minimum
threshold depends on the concentration of particles in the observed volume and is between 0.05 and 0.1 mm h\(^{-1}\) (melted equivalent).

In Figure 6.5, the retrieval accuracy of the near-surface rainfall rate is based on the above model cloud with a 3 km deep rain layer. Results are shown for two improved algorithms (rain profiling algorithm, RPA, and snow profiling algorithm, SPA – see Testud 2004) and for a ‘classical’ algorithm that derives rainfall rate from the relationship between the rainfall rate itself and the attenuation-corrected reflectivity for a fixed rain drop size distribution (DSD). The RPA algorithm, which is effective for rain rates > 5 mm h\(^{-1}\), uses the surface echo to estimate the path integrated attenuation.
in a formulation immune to DSD variability; the algorithm SPA, which is effective for rain rates $< 5$ mm h$^{-1}$, estimates the DSD parameters from an aggregation model.

![Rain Layer Thickness 3 km](image)

**Figure 6.5:** Relative error in the near-surface rain rate estimate for the EGPM radar, using two improved algorithms: RPA, which is effective for rain rates $> 5$ mm h$^{-1}$, and SPA, which is effective for rain rates $< 5$ mm h$^{-1}$. Results obtained with a ‘classical’ algorithm are also shown for comparison.

Employing the ‘classical’ algorithm, the relative errors remain rather large ($\geq 40\%$) over the entire range of rain rates. Including DSD-variability reduces these errors significantly: a proper combination of the improved algorithms applied to the lower and higher part of the dynamic range results in retrieval errors below 20%.

By properly modifying the precipitation model, the radar performance for near-surface snowfall rate retrieval can be evaluated. It turns out that for melted snow rates up to about 5 mm h$^{-1}$, the retrieval errors of the SPA algorithm are about 15%, while those for a ‘classical’ algorithm would be about 50%.

### 6.4 Combined EGPM Radar-Radiometer Performance

To highlight the improvement in snowfall measurement from space that would be obtained by the EGPM science payload, a series of synthetic retrievals have been performed using a profiling algorithm (Di Michele et al. 2003) for different combinations of the EGPM radiometer channels, as well as of the EGPM radar-radiometer payload. Results are shown in Figure 6.6 for the selected cross-section of the Eastern US snowstorm simulation discussed in Section 6.1.
Comparison of the four different retrievals with the ‘truth’ represented by the model simulation shows that:

- Retrievables based on the four lower window frequencies (i.e. SSM/I-like retrievals) do not provide an acceptable estimate of the snow profiles, but only a gross differentiation between them. In particular, the heaviest profiles as well as the snowfall just above the ground are greatly underestimated, while the structure of the lightest profiles is completely missed (this being a consequence of a greater impact of surface emissivity on the observed TBs).

Figure 6.6: Synthetic snow retrievals for the selected cross-section of the Eastern US snowstorm simulation. From top to bottom: (a) EGPM radiometer retrieval using only the four lower window frequencies, i.e. 18.7, 23.8, 36.5 and 89 GHz (similar to the four SSM/I frequencies); (b) as above, but using all window frequencies, i.e. adding 150 GHz; (c) as above, but using all window frequencies and the four pairs of sounding channels in 50 to 60 and 118 GHz bands; (d) combined EGPM radar-radiometer retrieval and, for comparison, (e) the model ‘truth’.
• Addition of the highest window frequency at 150 GHz largely improves the retrievals of the heaviest profiles and of the snowfall just above the ground, by helping in retrieving the columnar snow contents. Nevertheless, there are cases (near 350 km) where the snow profiles are incorrectly retrieved because the snow content is mainly associated with the upper levels rather than just above the ground – as in the model ‘truth’. In addition, retrieval of the lightest profiles is still rather unsatisfactory.

• Further addition of the sounding channels significantly improves the retrievals, because of their small sensitivity to land surface emission compared to the window channels, and because of their vertical profiling capability. In particular, retrieval of the shallow snow layer above the ground at 250-330 km is improved; the double-layer snow profiles near 350 km are better retrieved; and even the main characteristics of the lightest profiles are captured by the retrieval – except the lack of precipitating snow above the ground between 400-450 km.

• Finally, if the radiometer retrieval database is calibrated using vertical profile information obtained from radar observations, the combined radar-radiometer retrieval produces very good results in every situation. In particular, such calibration of the radiometer database can be extended to the full swath of the radiometer. The radar-radiometer combination methodology presented in Chapter 5 (Fig. 5.3) introduces the concept of a dynamical radiometer retrieval database that is constrained with radar retrievals of cloud macrophysical information (heterogeneity, freezing level height, rain and snow hydrometeor profile shape) and microphysical information (particle size distributions, particle density). This concept can be shared by both EGPM instruments, as well as between other satellites in the GPM constellation.

The improvements visible in Figure 6.6, in particular at the lowest levels, i.e. the most difficult to retrieve because of ‘shadowing’ effects due to precipitation at higher levels, have been quantified and summarised in Table 6.1.

<table>
<thead>
<tr>
<th>Liquid Water Content (LWC)</th>
<th>Bias [gm⁻³]</th>
<th>r.m.s. error [gm⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometer with channels at 18.7, 23.8, 36.5, 89 GHz</td>
<td>-0.4184 (-53%)</td>
<td>0.6771 (86%)</td>
</tr>
<tr>
<td>Radiometer with additional 150 GHz channel</td>
<td>-0.2892 (-37%)</td>
<td>0.4758 (61%)</td>
</tr>
<tr>
<td>Radiometer with further additional (sounding) channels in the 50 to 60 GHz and 118 GHz bands</td>
<td>-0.1454 (-18%)</td>
<td>0.3014 (38%)</td>
</tr>
<tr>
<td>Radar-calibrated EGPM Radiometer</td>
<td>-0.0262 (-3%)</td>
<td>0.1042 (13%)</td>
</tr>
</tbody>
</table>

**Table 6.1:** Average retrieval accuracy of the near-ground (up to 500 m) snow equivalent LWC for the four different retrievals shown in Figure 6.6. Percentage values are computed with respect to the ‘true’ average value provided by the model (0.7841 gm⁻³).
While the radiometer with channels at 18.7, 23.8, 36.5, 89 GHz already provides valuable information, the addition of the 150 GHz and, in particular, the sounding channels, significantly improve the retrieval, but only when including radar observations do the retrievals show a very low bias.

### 6.5 Summary of Results

The main results of the simulations performed can be summarised as follows.

- **The set of window frequencies** provides rain and snow retrieval accuracies over ocean that are at least comparable to those of current/near-future sensors.

- **As the sounding channels** are significantly less sensitive to surface emissivity variations than the window channels, they provide significantly more information on rainfall and snowfall over land surfaces and snow cover. Retrieval experiments show an increase in accuracy (reduction in bias and rms error) of rain and snow profile retrievals by a factor of 2 when the sounding channels are used.

  - **Light rain over ocean** can be directly sensed by the lower window channels (18.7 and 36.5 GHz) of the EGPM radiometer, as well as by the water vapour channel at 23.8 GHz.

  - **Precipitating snow over ocean** can be observed through its emission signatures at all frequencies. The retrieval problem, however, is usually more complex because oceanic snowfall melts into liquid precipitation above a sea surface with a temperature greater than 0°C.

  - **Light rain over land** is indirectly observed through the scattering of radiation by solid precipitation the higher window channels at 89 and 150 GHz, as well as at the temperature-sounding channels of the two oxygen bands near 50-54 and 118 GHz.

  - **Precipitating snow over land or snow cover** has distinct signatures at 89 and 150 GHz as well as at sounding channels. The brightness temperature (TB) depressions due to scattering and the differential signatures at the 89-157 GHz frequencies and the 54-118 GHz channel pairs carry information about whether snow is present, the vertical snow layer depth and cloud structure and snow rate as well as co-existing liquid precipitation.

- **The high frequency window channels and the sounding channels are necessary to optimise snowfall retrievals.**

- **The EGPM precipitation radar** will observe liquid precipitation between 0.04 and 20 (50) mm h\(^{-1}\). For solid precipitation the hour limit will be 0.05 mm h\(^{-1}\) (liquid water equivalent) for a depth of 3 km over both land and ocean. The upper limit is driven by attenuation in rain and varies depending on freezing level height for liquid precipitation and on scattering attenuation for solid precipitation.
• The retrieval accuracy of the EGPM radiometer meets the requirements summarized in Table 4.3. It is of the order of 100% for rain rates and snow rates below 1 mm h\(^{-1}\) (liquid water equivalent), while it is generally better than 50% for rates above 1 mm h\(^{-1}\) and significantly better if the sounding channels are utilized.

• The retrieval accuracy of the EGPM radar is significantly better than for the radiometer: less than 20% for rain and about 15% for snowfall.

• The retrieval of geophysical parameters, i.e. light rain and solid precipitation, can be significantly improved if the radar measurements are used as a constraint for the radiometer inversions in a combined radar-radiometer algorithm as shown in Figure 6.6. Bias as well as scattering can be significantly reduced in a combined (radar constraint) retrieval.

It has been demonstrated in this chapter that the mission with the technical performance detailed in the technical dossier meets the threshold requirements specified in Chapter 4, Table 4.3. In fact, its geophysical performances even approach the ‘goal’ requirements specified for light rain and solid precipitation.
7. User Community Readiness

EGPM observations are pertinent to all scientific areas related to water, land, and the atmosphere. The interrelations of these three areas results in an active user community linked to climate, weather, and hydrology.

Three widely attended GPM International Planning Workshops, held in the last three years, have demonstrated the interest and readiness of the international user community. The first GPM Workshop was held in Washington D.C. in October 2001 (NASA 2001), the second in Tokyo in May 2002 (Oki and Iguchi 2003) and the third in June 2003 at ESTEC (ESA 2003). Another is planned in the USA in June 2004.

Since EGPM and GPM represent the next evolutionary step in microwave satellite rainfall estimation, user groups, i.e. the scientific as well as the operational user communities, are very familiar with the characteristics of the data that will be provided by the mission. Further, the success of current operational and experimental missions, such as the SSM/I and sensors on-board TRMM, has led to the development of operational precipitation retrieval algorithms. Consequently, this means that the data from the mission can be fully utilised from the earliest opportunity after the launch and deployment of the satellite.

In climate diagnostics, satellite information is a key element for providing an unbiased global precipitation (including snow) climatology that includes uncertainties due to precipitation measurement and sampling errors. The current methods, often blending satellite observations with surface measurements, are crucial for detecting statistically significant global and regional precipitation trends predicted by climate change models. These observations are also important for the assessment of the global water and energy cycle and hydrological predictability, in analysing and modelling global water and energy cycles, water transports, water budget closure, hydro-meteorological processes, and in the prediction of fresh water resources. In particular, the change in these parameters and the analysis of climate-water-radiation states and the predictability of these parameters for climate are of great importance.

In terms of near-real time applications, the assimilation of satellite data for the prediction of weather and severe storms is currently receiving much attention. Techniques are currently being used to integrate satellite observations into numerical weather prediction models: the EGPM and GPM missions will contribute to improved data provision for such schemes, not only for the modelling of the atmospheric parameters, but also for providing important information on other geophysical parameters, which will in turn lead to improved parameterisation of the cloud microphysics and subsequently to better cloud resolving models and better models of radiative transfer through precipitating clouds.
Figure 7.1 shows results from global data assimilation experiments performed at ECMWF. The assimilation of rain rate observations in a global operational model framework can substantially affect model forecast skill. Panel (a) shows that the four-dimensional assimilation system produces observational impact even where no observations were present; while rain observations were assimilated only in the Tropics, increments spread to higher latitudes. Panel (b) shows the differential impact of the day two minus day one precipitation forecast. This example suggests that: (1) observations of atmospheric moisture inside and outside precipitation clear-sky are complementary; and (2) mainly affect the location of precipitation systems. While the global hydrological budget remained nearly unchanged in the experiments, the displacement of precipitation systems by assimilating rainfall observations is significant. This will have a strong impact on the forecasting of cyclone tracks, severe storm occurrences and frontal overpasses.

Work is currently progressing on the assimilation of precipitation radar observations.

**Figure 7.1:** Analysis increments of total column water vapour (TCWV, in kg m⁻²) – i.e. modification of the background TCWV state – on April 7, 2003, 00 UTC, obtained by assimilating: (a) 40N-40S SSM/I rain observations only. Panel (b) shows the impact of all moisture-related observations on the 48h-24h precipitation forecast (in mm) initialised on April 1, 2003, at 12 UTC.
The user community is currently improving algorithms for the retrieval of precipitation and its validation. The accurate retrieval of precipitation and its distribution through the atmosphere provides information on the latent heat profile, crucial to studies related to the energy budget in the atmosphere. Since TRMM, algorithm validation is receiving much attention due to the wide range of applications of rainfall products that have emerged, most of which require both rainfall and estimation uncertainty.

Moreover, the global analyses of NCEP, ECMWF and other models are used in a large number of activities for initialising regional and local meteorological and hydrological models. Thus, the benefit of rainfall data assimilation propagates to a large number of secondary users of such data. By 2007/8, several other national meteorological agencies will be operationally assimilating rainfall information. Since most of the satellite data that is used for this application already exists, the adaptation to new observing systems such as EGPM will not require many new scientific and technical developments, and can therefore directly provide a return for research and operations.

The readiness of this wide science and user community to participate in EGPM and GPM missions is also evident from the active involvement of a number of researchers in ground validation (GV) activities. The first GPM International GV Research Programme Meeting took place in Abingdon (UK) in November 2003 (Smith et al. 2004b). Figure 7.2 presents potential European contributions. Research and operational facilities include C-, X-, and L-band meteorological radars, Ka-band cloud radars, real time networked rain gauges, aircraft, ceilometers, lidars, disdrometers, multi-frequency radiometers, wind and rain-cloud profilers, and radiosondes.

![Figure 7.2: Actual and potential GPM and EGPM ground validation sites in Europe (Courtesy of DLR-DFD/IPA, Institut für Physik der Atmosphäre).](image)
Finally, there is a scientific community using, and ready to use more, precipitation data for a large range of applications, including flash flood forecasting, hydrology, civil engineering (e.g. IFNET, http://www.internationalfloodnetwork.org), news media and educational tools.
8. Global Context

8.1 The Global Precipitation Measurement (GPM) Mission

In late 2001 the Global Precipitation Measurement (GPM) mission was jointly approved by NASA and JAXA and is now in the development phase. The mission aims at improving the scientifically outstanding results obtained by the Tropical Rainfall Measuring Mission (TRMM) and extending the measurement sampling of rainfall in space and time by measuring precipitation on a global basis with sufficient quality, Earth coverage, and sampling to improve analysis and prediction of the Earth’s climate, weather, and specific components of the global water cycle. GPM will consist of two components (Fig. 8.1): an improved TRMM-like satellite (called the core satellite) in a highly inclined orbit and up to eight constellation satellites (mostly in Sun-synchronous orbits), carrying passive MW radiometers to provide global rainfall coverage at 3-hourly intervals (depending on latitude).

<table>
<thead>
<tr>
<th>Core Satellite</th>
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<tbody>
<tr>
<td>• TRMM-like spacecraft (NASA)</td>
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<td>• Η3-Α rocket launch (JAXA)</td>
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<tr>
<td>• Non-sun-synchronous orbit ~ 65° inclination</td>
</tr>
<tr>
<td>• Dual frequency radar (JAXA) K- Ka Bands (13.6-35 GHz) – 4 km horizontal resolution – 250 m vertical resolution</td>
</tr>
<tr>
<td>• Multifrequency radiometer (NASA) 10.7, 19.3, 22.7, 35, (166/183/37) GHz V &amp; H</td>
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<table>
<thead>
<tr>
<th>Constellation Satellites</th>
</tr>
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<tbody>
<tr>
<td>• Pre-existing operational experimental &amp; dedicated satellites with PMW radiometers</td>
</tr>
<tr>
<td>• Revisit time 3-hour goal at ~90% of time</td>
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<tr>
<td>• Sun-synch &amp; non-sun-synch orbits 600-900 km altitudes</td>
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<tr>
<th>Precipitation Validation Sites for Error Characterization</th>
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<tr>
<td>• Globally distributed ground validation Sites &amp; Supersites (research quality radars, up-looking GMV/DPAR-like radiometer-radar systems, dual-frequency Doppler profiler systems, rain gauge disdrometer networks, &amp; T-ρ soundings)</td>
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<tr>
<td>• Dense &amp; frequently reporting regional raingage networks</td>
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<tr>
<th>Precipitation Processing Center</th>
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<tr>
<td>• Produces global precipitation products</td>
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<tr>
<td>• Products defined by GPM partners</td>
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<tr>
<th>OBJECTIVES</th>
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<tr>
<td>• Understand horizontal &amp; vertical structure of rainfall, its macro &amp; micro-physical nature, &amp; its associated latent heating</td>
</tr>
<tr>
<td>• Train &amp; calibrate retrieval algorithms for constellation radiometers</td>
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<tr>
<th>OBJECTIVES</th>
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</thead>
<tbody>
<tr>
<td>• Provide sufficient global sampling to significantly reduce uncertainties in short-term rainfall accumulations</td>
</tr>
<tr>
<td>• Extend scientific and societal applications</td>
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</table>

**Figure 8.1:** The Global Precipitation Measurement (GPM) mission concept (Courtesy of NASA).

The core satellite is being developed under the primary GPM partnership involving NASA and JAXA, with launch planned for 2009. It is designed to measure the instantaneous 3-dimensional distribution of precipitation and its associated latent heating up to about 65 degrees latitude. High spatial resolution and rainfall retrieval accuracy will be achieved by using a dual frequency (13.6/35 GHz) imaging pulsed radar in combination with an improved radiometer similar to the TRMM Microwave
Imager (TMI). Because the core satellite will be flying in a non Sun-synchronous orbit, it will sample the diurnal variability in rainfall structure. In addition, it will serve as a calibration and reference tool for the constellation satellites, which will fill in the observational gaps of the core satellite itself. Due to the orbit of the core satellite, EGPM will produce the only available precipitation radar measurements at latitudes above about 65 degrees.

The constellation satellites include all other satellites carrying at least a passive microwave radiometer for precipitation measurement (Fig. 8.2). These satellites will generally be in near-polar, Sun-synchronous orbits, which constitute the most effective way to sample the globe with fixed repetition times. Presently planned non-GPM missions carrying microwave radiometers are the satellites of the US Defense Meteorological Satellite Program (DMSP) and of the future National Polar Orbiting Environmental Satellite System (NPOESS), which will become part of the GPM ‘constellation’. Until 2010 there will be at least two DMSP satellites in orbit with a transition to three NPOESS. A total of eight constellation satellites will be needed to achieve a 3-hourly sampling. This sampling frequency will produce time-averaged global rainfall estimates with unprecedented quality, leading to improved forecasts by climate and NWP models.

Figure 8.2: The GPM international constellation architecture (Courtesy of NASA).

8.2 EGPM Synergy with Other Projects

The EGPM will support major goals of the World Climate Programme-Water (WMO/UNESCO) and close gaps identified in the third IPCC Report. EGPM will improve our knowledge concerning the impact of climatic change on the hydrological
cycle especially in mid- to high-latitudes and over the Mediterranean region, where uncertainties are particularly large. The improved evaluation of water resources in these regions is in line with the objectives of WCP-Water and in agreement with the new Framework European Directive on Water. The application to flood forecasting at the European scale is in close agreement with the aims of the EMMA (European Multi-services Meteorological Awareness) project from EUMETNET concerning the harmonization of meteorological hazard monitoring and alerts in Europe. In addition, the WMO MEDEX (hazardous weather and climate in the Mediterranean) project, addressing cyclogenesis and severe weather in Mediterranean areas, urges the gathering of more information about the triggering, tracking and structure of convective systems over the Mediterranean Sea.

The EGPM concept fits within several international programmes, both as an individual satellite and as part of the GPM satellite constellation. EGPM adds to the satellite-based component of the Global Observing System (GOS) being developed within the newly-established WMO Space Programme. The GOS concept includes both the classical meteorological satellites programmes and research satellites that comply with WMO requirements such as: (i) relevance to WMO objectives, (ii) open data access, and (iii) reasonable level of service continuity.

EGPM would complement the coverage of microwave radiometers being flown in Sun-synchronous orbit (Fig. 8.3). These will primarily consist of the three NPOESS satellites with the Conical-scanning Microwave Imager-Sounder (CMIS): the microwave imagers of Meteor-3M and FY-3, and the microwave sounder (AMSU) of MetOp (with a coarser resolution and matching the NPOESS 09:30 orbit).

**Figure 8.3:** Fitting of the EGPM (14:30 descending) MW radiometer (swath 1050 km) in the coverage of CMIS (swath 1400 km) on NPOESS-1 (09:30 descending), NPOESS-2 (13:30 ascending) and NPOESS-3 (05:30 descending).
EGPM will be a component of GOS serving the WMO programmes, including:

- WWW (World Weather Watch)
- WCP (World Climate Programme), including the Global Energy and Water Cycle Experiment (GEWEX) with almost all of its sub-programmes – especially, the Global Precipitation Climatology Project (GPCP) – within the World Climate Research Programme (WCRP)
- AREP (Atmospheric Research and Environment Programme), including THe Observing system Research and Predictability EXperiment (THORPEX), a newly-established 10-year international research programme intended to accelerate improvements in the accuracy of 1 to 14-day weather forecasts within the World Weather Research Programme (WWRP)
- AMP (Applications of Meteorology Programme), including the Public Weather Services Programme (PWSP), which provides primary information for the public
- HWRP (Hydrology and Water Resources Programme), including the World Hydrological Cycle Observing System (WHYCOS) within the Operational Hydrology Programme (OHP)

The above examples of EGPM relevance in the global context have focused on operational applications. However, the initial motivation of the GPM mission is of a basically scientific nature. Nevertheless, since the list of international research programmes requiring precipitation data is potentially very long, no attempt will be made here to mention them all.
9. Application Potential

The concept of EGPM as part of GPM is that of a pre-operational mission already meeting a significant fraction of the requirements tabled by the operational user community as specified in Tables 4.1 and 4.2. This implies that the potential of the complete set of GPM mission elements in place has to be also considered for the application potential of the EGPM mission. Once the benefits of the complete system have been demonstrated, the overall GPM mission should be converted into an operational system run by operational agencies, i.e. in Europe by EUMETSAT. Present plans for an European Polar System (EPS) follow-on system indeed specify these operational needs (see Tables 4.1 and 4.2).

The potential for improving atmospheric forecast skill by assimilating EGPM-type microwave observations has already been demonstrated by ECMWF. The operational assimilation of SSM/I rainfall observations is in preparation, while TRMM PR data is already being assimilated experimentally (see Chapters 5 and 7).

The microwave radiometer onboard EGPM has similarities with the radiometers embarked on TRMM (TMI) and DMSP/NPOESS (SSM/I and follow-on). Similar applications as for those instruments can be expected. The methodology for the retrieval of rainfall (rates at the surface or profiles) from microwave radiometers is well established (e.g. Wilheit et al. 1994) and available from several operational centres (e.g. NOAA NESDIS, NASA, GPCC). As described in Chapter 5, the next-generation rainfall retrieval algorithms will also focus on the retrieval of precipitation-related quantities to better constrain the precipitation retrieval itself. Among those are clear-sky total column water vapour, cloud liquid and ice water paths as well as atmospheric temperature information obtained from sounding channels. Since atmospheric moisture and temperature represent a fundamental input to data assimilation in NWP applications, EGPM observations outside clouds and precipitation will complement existing meteorological satellites. The same applies for surface quantities. For example, SSM/I observations are sensitive to surface emission and therefore provide data for near-surface wind-speed estimates over ocean, detection and classification of sea-ice as well as snow cover mapping. Wind-speed information from SSM/I data has been assimilated at ECMWF since 1999. This will be continued using data from SSM/IS, AMSR, CMIS and, potentially, EGPM.

In summary, apart from applications that are directly related to precipitation, the observations of the EGPM microwave radiometer provide information on a number of fundamental quantities:

- Ocean ice properties, such as concentration and type as well as ice drift and polynya area for ice monitoring and forecasting as well as ship navigation. In climate research, the data can be used to observe long-term variations in sea-ice characteristics and the distribution and ice sheet growth and decay. In NWP
applications, these sea-ice maps allow the retrieval of surface albedo, latent and sensible heat flux between ocean and atmosphere.

- Sea surface properties, such as sea surface wind speed, sea surface temperature, latent heat exchange and oil-spills.
- Land surface properties, such as snow cover extent and flood extent for both disaster management and climate research applications. The EGPM measurements are also helpful for soil wetness monitoring and provide additional information to the current IR sensors on land surface temperature, microwave emissivity, and vegetation coverage.
- Atmospheric properties, such as water vapour, liquid water and ice profiles/columns.

A large range of additional products (rain, snow cover, water vapour, liquid and ice water, land surface temperature, wind speed, sea surface temperature, microwave emissivity) are available from various websites which are mainly TRMM or SSM/I related (e.g. NASA DAAC: http://daac.gsfc.nasa.gov/, NOAA NESDIS: http://www.nesdis.noaa.gov/, HOAPS University of Hamburg: http://www.hoaps.zmaw.de/).
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GPCP (Global Precipitation Climatology Project): http://orbit-net.nesdis.noaa.gov/arad/gpcp/.


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Acronyms

AMIP             Atmospheric Model Intercomparison Project
AMP              Applications of Meteorology Programme
AMSR             Advanced Microwave Scanning Radiometer
ATOVS            Advanced TOVS
CMIS             Conical-scanning Microwave Imager-Sounder
CRM              Cloud-Resolving Model
DMSP             Defense Meteorological Satellite Program
DSD              Drop Size Distribution
ECMWF            European Centre for Medium-Range Weather Forecasts
EMMA             European Multi-services Meteorological Awareness
EPS              European Polar System
ESMR             Electronically Scanning Microwave Radiometer
ESTEC            European Space Research and Technology Centre
FAR              False Alarm Rate
FL               Freezing Level
GCM              General Circulation Model
GCOS             Global Climate Observing System
GEWEX            Global Energy and Water Cycle Experiment
GOS              Global Observing System
GPCC             Global Precipitation Climatology Centre
GPCP             Global Precipitation Climatology Project
GPM              Global Precipitation Measurement
GTOS             Global Terrestrial Observing System
GV               Ground Validation
HWRP             Hydrology and Water Resources Programme
IFNET            International Flood Network
IPA              Institut für Physik der Atmosphäre
IPCC             Intergovernmental Panel on Climate Change
ISCCP            International Satellite Cloud Climatology Project
LWC              Liquid Water Content
MEDEX            Hazardous weather and climate in the Mediterranean
MSU              Microwave Sounding Unit
MTG              Meteosat Third Generation
NCEP             National Center for Environmental Prediction
NOAA             National Oceanic and Atmospheric Administration
NPOESS           National Polar Orbiting Environmental Satellite System
NWP              Numerical Weather Prediction
OHP              Operational Hydrology Programme
PIA              Path-Integrated Attenuation
POD              Probability Of Detection
PR               Precipitation Radar
PWSP             Public Weather Services Programme
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>RPA</td>
<td>Rain Profiling Algorithm</td>
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<tr>
<td>SSM/I</td>
<td>Special Sensor Microwave/Imager</td>
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<tr>
<td>SMMR</td>
<td>Scanning Multi-channel Microwave Radiometer</td>
</tr>
<tr>
<td>SPA</td>
<td>Snow Profiling Algorithm</td>
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<tr>
<td>TB</td>
<td>Brightness Temperature</td>
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<tr>
<td>TCWV</td>
<td>Total Column Water Vapour</td>
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<tr>
<td>THORPEX</td>
<td>THe Observing system Research and Predictability EXperiment</td>
</tr>
<tr>
<td>TMI</td>
<td>TRMM Microwave Imager</td>
</tr>
<tr>
<td>TOVS</td>
<td>TIROS-N Operational Vertical Sounder</td>
</tr>
<tr>
<td>TRMM</td>
<td>Tropical Rainfall Measuring Mission</td>
</tr>
<tr>
<td>UW-NMS</td>
<td>University of Wisconsin – Non-hydrostatic Modeling System</td>
</tr>
<tr>
<td>WCRP</td>
<td>World Climate Research Programme</td>
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<tr>
<td>WHYCOS</td>
<td>World Hydrological Cycle Observing System</td>
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<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
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<td>WWRP</td>
<td>World Weather Research Programme</td>
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</table>
EarthCARE  - Earth Clouds, Aerosols and Radiation Explorer
SPECTRA  - Surface Processes and Ecosystem Changes Through Response Analysis
WALES  - Water Vapour Lidar Experiment in Space
ACE+   - Atmosphere and Climate Explorer
EGFM   - European Contribution to Global Precipitation Measurement
Swarm   - The Earth's Magnetic Field and Environment Explorers