Title Page

Targeting Optimal Use of GPS Humidity Measurements in Meteorology

TOUGH

A RESEARCH and TECHNOLOGICAL DEVELOPMENT PROJECT
Submitted to Energy/Environment and Sustainable Development

Theme 7.2.1 Generic Earth Observation Technologies:
Introduce scientific results into new or existing applications

Theme 7.2.2 Generic Earth Observation Technologies:
Improve the exploitation of earth observation data

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Content list

1. Project Summary

Knowledge of the atmospheric distribution of water vapour is of key importance in weather prediction and climate research. It is tightly coupled to processes like energy transfer, precipitation, and is an important greenhouse gas. However, currently there is lack of knowledge about the actual humidity field, both due to a shortage of observations and a sub optimal handling of humidity in the data assimilation systems, which are used to make estimates of the actual atmospheric field. Such fields are used to start numerical weather prediction models and for climate monitoring. Global Positioning System (GPS) signals are particularly sensitive to water vapour. The main purpose of this project is to develop and refine methods enabling the use of GPS data from existing European GPS stations in numerical weather prediction models, and to assess the impact of such data upon the skill of weather forecasts.

The GENERAL OBJECTIVES for the project are to improve the use of GPS data for numerical weather prediction and climate monitoring. This shall be done by innovation of new techniques and methodologies enabling proper correction of error sources identified in previous work, as well as by initiating use of the more detailed information available in the form of the individual delays between each receiver and the GPS satellites visible to it, rather than the single average type delay used by current methods. In the project we will:

- Carry out research to optimise the assimilation of ground-based GPS in numerical weather prediction models. This research will include a proper modelling of the GPS measurement errors and application of more advanced assimilation techniques. Each step/component in the optimisation of the assimilation techniques will be verified by impact studies.
- Develop methods for use of GPS slant delays in numerical weather prediction. Use of slants will enhance the amount of information available from each ground station.
- Running a research mode data collection, by co-ordinated pre-processing and distribution of ground-based GPS measurements from Europe through a few European processing centres in support of the proposed data assimilation research efforts. The data processing centres will provide pre-processed data from subsets of the total European network, and each subset of the data should have comparable error characteristics. These error characteristics will be documented through comparisons of data from stations included in several of the network subsets (network overlap).
- Investigate the benefit of using ground-based GPS-data in numerical weather prediction using the improved assimilation software through extended parallel data assimilation and forecast experiments, with and without ground-based GPS measurements, covering all four seasons.

After the project, the resulting methodologies can be utilised by European weather forecast agencies at large, and the results help pave the road for a future co-ordinated, operational European GPS moisture observation system. The exploitation of this new source of Earth Observation data is expected to benefit in particular the prediction of precipitation. In the longer run it will benefit also climate monitoring. When the Galileo satellites are launched the amount of observations of this type will increase and some of the error sources can be more easily controlled.

2. Scientific/Technical Objectives and Innovation

The main purpose of this project is to develop and refine methods enabling the use of Global Positioning System (GPS) data from existing European GPS stations in numerical weather prediction models, and to assess the impact of such data upon the quality of weather forecasts. After the project, the resulting methodologies can be utilised by European weather forecast agencies at large, and the results help pave the road for a future co-ordinated, operational European observation system. The exploitation of this new source of Earth Observation data is expected to benefit in particular the prediction of precipitation.

Weather forecasting of today is strongly dependent on the application of numerical weather prediction (NWP) techniques. Starting from initial states representing the atmosphere at a certain time, numerical models are integrated forward in time to obtain the future state of the atmosphere. The initial atmospheric states, the quality of which are of crucial importance to the quality of the forecasts, are obtained from the time history of observations through a process that is generally referred to as *atmospheric data assimilation*. Thousands of observations are required for the determination of the state variables of the atmospheric models, the most important ones being vertical profiles of wind, temperature and moisture, in addition to the pressure at the surface of the earth.

Throughout the history of NWP, the observation and model initialisation of the moisture has been treated with less care than the other variables. The moisture initialisation has generally been carried out without coupling to the initialisation of temperature, surface pressure and wind. Only radiosonde observations of atmospheric moisture profiles have been available, and these observations are often not representative of the scales of motion described by the models and are also affected by observational errors. Remote sensing observations and modern data assimilation methods, based on e.g. variational techniques, have the potential of bringing the moisture field initialisation to a more advanced state.

The measurement of the atmospheric delay of radio signals from navigation system satellites, such as the GPS, offer an opportunity for the NWP community to get access to high quality atmospheric moisture information from already established networks of GPS ground stations. The atmospheric delay of GPS radio signals is due to the sensitivity of atmospheric refraction to atmospheric pressure, temperature and moisture. The total delay of the radio signals between a GPS satellite and a GPS ground station is essentially dependent on the total atmospheric mass, i.e. the pressure at the surface, and the columnar atmospheric moisture content. Provided the surface pressure can be determined from another source of information, e.g., an NWP model, the delay of the GPS signals provides a unique source of information related to the atmospheric moisture content. Normally the GPS data processing results in a single delay measure, reflecting the average properties of the atmosphere around the site. More advanced techniques, which determines the delay between the site and each GPS satellite on the sky are being introduced – thereby enhancing the information content by nearly a factor ten.

The utilisation of data from GPS ground stations for numerical weather prediction, and also for climate monitoring and research, is the subject of the COST Action 716 (Exploitation of Ground-based GPS for Climate and Numerical Weather Prediction Analysis). Several of the members of COST 716 Action have furthermore contributed to EC-funded MAGIC (Meteorological Applications of GPS Integrated Water Vapour Measurements in the Western Mediterranean) Project. Considerable progress has been achieved both within COST 716 and within the MAGIC project. The quality of the data has steadily been improved and the extraction techniques work in near real time and are approaching operational status in Europe. COST 716 data assimilation tests for the June 2000 period using Central and Northern European model integration areas have indicated significant bias (systematic observation error) problems between the GPS total zenith delay measurements and model predictions. Preliminary results from MAGIC assimilation show a neutral impact in the overall statistics over 2 weeks of data, but indicate positive impact for rapidly evolving localised storm systems or in situations where the humidity field is not dominated by large-scale dynamics. Thus, GPS delays are potentially very useful to meteorology, but further research is needed before the GPS data can be used in an optimal way to the benefit of numerical weather prediction. It is based on these promising results that 7 meteorological institutes now join forces in this project in order to optimise the methods by which GPS data can be utilised in NWP models. In total 15 institutes will partake in the project, seven of which will process the GPS data into zenith delays do research on improving such processing.

The GENERAL OBJECTIVES for the present project proposal are to improve the use of GPS data for numerical weather prediction and climate monitoring. This shall be done by innovation of new techniques and methodologies enabling proper correction of error sources identified in previous work, as well as by initiating use of the more detailed information available in the form of the individual delays between each receiver and the GPS satellites visible to it, rather than the single average type delay used by current methods.

Considering the experiences and the achievements from the COST 716 Action and from the MAGIC Project, these general objectives may be stated more precisely through the following verifiable sub-objectives:

- Carry out research to optimise the assimilation of ground-based GPS in numerical weather prediction models. This research will include, for example, a proper modelling of the GPS measurement errors and application of more advanced, 4-dimensional, assimilation techniques. Each step/component in the optimisation of the assimilation techniques will be verified by impact studies.
- Develop methods for use of GPS slant delays in numerical weather prediction.
- Running a research mode data collection, by co-ordinated pre-processing and distribution of ground-based GPS measurements from Europe through a few European processing centres in support of the proposed data assimilation research efforts. This work will be closely linked with the COST 716 Action. The data processing centres will provide pre-processed data from subsets of the total European network, and each subset of the data should have comparable error characteristics. These error characteristics will be documented through comparisons of data from stations included in several of the network subsets (network overlap).
- Investigate the benefit of using ground-based GPS-data in numerical weather prediction using the improved assimilation software through extended parallel data assimilation and forecast experiments, with and without ground-based GPS measurements, covering all four seasons. Special emphasis will be devoted to the verification of precipitation forecasts.
- Promote the idea of an operational utilisation of ground-based GPS measurements to the numerical weather prediction community in Europe.

State of the art in GNSS observations of water vapour

The raw GNSS data consist of ranging measurements from visible navigation system satellites such as the Global Positioning System (GPS). If the positions of the satellites and receivers are precisely known, the ranging measurements can be used to detect delays due to the atmosphere. This is possible since the propagation speed of the radio signals is sensitive to the refractive index of the atmosphere, which is a function of pressure, temperature and humidity, and the ionospheric electron content. The ionospheric delay is dispersive and can be removed using observations on two frequencies. The remaining accumulated delay for a raypath is the integral of the refractivity along the trajectory of the ray through the atmosphere

$$d = 10^{-6} \int_l N dl \quad \text{where} \quad N = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

The refractivity N is described as a function of temperature T, the partial pressure of dry air P_d, and the partial pressure of water vapour e and constants, k_1, k_2, and k_3, which have been determined experimentally (Smith et al 1953, Thayer 1974, Bevis et al 1994). Small scale horizontal variations may be neglected, to first order, so that observations at all satellite elevation angles can be mapped to a single zenith delay value which can then be transformed to integrated water vapour with auxiliary information on the surface pressure field (Bevis et al 1992).

Since the concept was initially proposed, the quality of the data has steadily improved through several major efforts, for example the EC projects MAGIC (Haase et al 2001, Vedel et al 2001) and WAVEFRONT (Dodson et al 1999), and NEWBALTIC (Emardson et al 1998), and the U.S. ARM (Gou et al 2000), GPS/STORM (Rocken et al 1995), CORS (Fang et al 1998), and CLIMAP(Haas et al 2001),

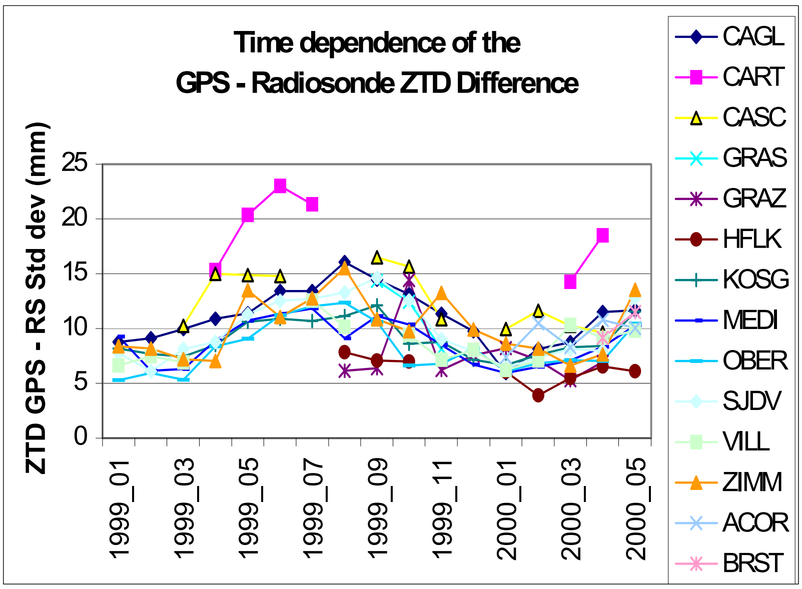


Figure 1 Time dependent behaviour of the standard deviation of the GPS-radiosonde ZTD difference over a 1.5 year time period in the Mediterranean area.

MAGIC (Meteorological Applications of GPS Integrated Column Water Vapour Measurements in the Western Mediterranean) was a 3-year research project financed in part by the European Commission to develop the tools necessary for the meteorological users to integrate the GPS derived humidity products into their numerical weather prediction models, and test these models in severe storm situations. In the project, a prototype system for deriving and validating robust GPS integrated water vapour (IWV) and zenith tropospheric delay (ZTD) data sets was developed, both in post-processing and near-real-time mode. An extensive a database of 1.5 years of ZTD data is available for more than 50 sites in Spain, France, and Italy. The database has been validated through continuous comparisons with radiosondes. The comparison shows differences with a standard deviation on the order of 10 mm ZTD (see fig. 1) or the equivalent error in IWV of 1.6 kg/m^2. The continuous comparison with independent data sets demonstrated that there are long-term differences that require further investigation, especially for climate applications. Continuous comparisons with HIRLAM NWP fields show a standard deviation of 17 mm ZTD or 2.7 kg/m$^{2.}$ A higher standard deviation for the HIRLAM fields than radiosondes indicates that there is significant information contained in the GPS observations that is unknown to the NWP model, and hence the potential to improve the model.

State of the art in meteorological data assimilation

The European weather services have invested scientific development efforts over the past 5-10 years into a new generation of data assimilation based on variational techniques. The 3-dimensional versions of these assimilation schemes (3D-Var) have recently been introduced operationally (Lorenc et al 1999, Gustafsson et al 2001). One of the advantages of these variational data assimilation schemes is the possibility to utilise observed quantities with complicated, e.g. non-linear, relations to the forecast model variables. Thus it is, for example, possible to directly assimilate the atmospheric delay data as measured at the ground-based GPS stations. Early trials to assimilate simulated ground-based GPS measurements with simplified variational data assimilation schemes were carried out by the Mesoscale Meteorology group at the National Centre for Atmospheric Research (NCAR), Boulder, USA (Kou et al 1996, de Pondeca et al 2000). The main limitation of these early NCAR trials with variational data assimilation of GPS data was the lack of a background error, thus the forecast errors were not described properly and therefore the assimilation became sub-optimal. The more mature variational data assimilation schemes developed by European weather services for operational purposes included proper background error constraints. The meteorological services involved in the COST 716 Action and the MAGIC Project developed and tested 3D variational methods for the assimilation of ground-based GPS data. Assimilation tests were carried out for a 2 weeks period in June 2000. The overall large scale statistical impact on forecasts of temperature, wind, and humidity fields was neutral for the GPS ZTD data set, which was not unexpected given the number of GPS ZTD observations compared with conventional observations. However, rainfall forecasts for specific case studies were improved, especially in localised regions of high precipitation (see fig 2, next page). This was a very encouraging result, that was undetectable in the overall statistics, but has the potential to have a significant socio-economic impact, since these intense short duration high precipitation events are a principal cause of weather related damage in the Mediterranean region.

On the other hand, COST 716 data assimilation tests for the same June 2000 period and for Central and Northern European model integration areas have indicated significant bias (systematic observation error) problems associated with the GPS Total Zenith Delay measurements. These bias problems were temporarily avoided by introduction of Bias Reduction Algorithms**,** based on a comparison between GPS measurements and forecast model data. The origin of the problem is yet not clear, however. Simulation studies ([1]) and results from trials to model the spatial correlation of GPS observation errors (2) support the possibility of slowly varying and horizontally correlated observation errors associated with the GPS measurements.

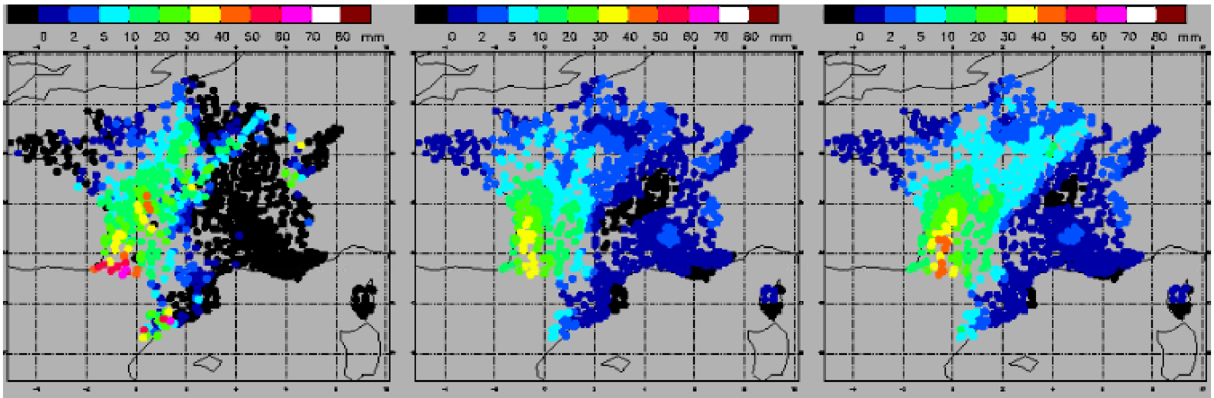


Fig 3a. Observed precipitation 2000 06 09, 12 to 24 UTC

Fig 3b. Predicted precipitation 2000 06 09, 12 to 24 UTC, no GPS data in data assimilation.

Fig 3c. Predicted precipitation 2000 06 09, 12 to 24 UTC, with GPS data in data assimilation.

Figure 2 (left panel) observed 12 hour accumulated precipitation for an event the 9 June 2000 which produced high rainfall in the Pyrenees and north-eastern Spain, (centre panel) forecast precipitation without GPS data, (right panel) forecast precipitation with GPS data.

European geodesists and meteorologists have joined forces in the COST 716 Action on "Exploitation of ground-based GPS for climate and numerical weather prediction application", with participation from 17 European countries. A benchmark data collection, near-real time processing, data distribution and data assimilation test was successfully carried out for a two-week period in June 2000. A near-real time data collection, processing and distribution exercise is continuously ongoing from April 2001 until February 2002. A working group (WG4) on the design of an operational ground-based European GPS network for meteorological purposes has started its activities.

Innovation by the present project proposal

The innovative elements of the present project proposal include

- Optimisation of the 3 dimensional assimilation of ground-based GPS data by a proper modelling of observation error biases and spatial/temporal correlation
- Development of 4-dimensional assimilation to utilise the temporal resolution of the GPS data.
- Processing, validation and assimilation of GPS slant delays.
- Development of methods for assimilation of GPS slant delays in 3 dimensional data assimilation
- Investigation of the optimal use of the GPS data in meteorology by extended parallel data assimilation and forecast experiments distributed over all seasons, by objective and subjective verification.

3. Project Workplan

a) Introduction

The main objectives for the present project proposal are to improve the use of GPS data for numerical weather prediction and climate monitoring. This will be done by innovation of new techniques and methodologies enabling proper correction of error sources identified in previous work, as well as by initiating use of the more detailed information available in the form of the individual delays between each receiver and the GPS satellites visible to it. In order to make the required progress to meet the objectives, research efforts and technical developments over a wide range of problem areas need to be carried out. This research and development require active participation from the geodetic and the meteorological communities. To get an initial overview of the required efforts, we here mention a few **scientific and technical key problems** that will be solved:

- The pre-processing of the raw GPS measurements will be handled by a number of Processing Centres. In order to meet the future operational timeliness requirements from the numerical weather prediction community, algorithms for near-real-time pre-processing will be introduced. Furthermore, this pre-processing will be carefully co-ordinated and monitored in order to guarantee the meteorological community a homogeneous data set, with stable and known (documented) error characteristics.

- Early trials to assimilate ground-based GPS data have indicated that these data may be affected by systematic observation errors (error biases) as well as spatially and temporally correlated observation errors. Significant efforts will be devoted in the present project to (a) increase our understanding of the origin of these observation errors; (b) eliminate these errors to the extent possible and (c) model the characteristics of the observation errors. Realistic statistical models of the observation errors are needed for an optimal assimilation of the data.

- It is foreseen that the most significant impact of ground-based GPS measurement will be possible only through application of 4-dimensional assimilation techniques. First of all, GPS data have a high temporal resolution. More important may be that GPS data provides information mainly on the atmospheric moisture. In order to derive atmospheric pressure, temperature and wind fields that are consistent with the moisture field as seen by the GPS data, the forecast model must be utilised in the assimilation process. This is exactly what is done in 4-dimensional data assimilation. Two forms of 4-dimensional data assimilation, namely 4 dimensional variational data assimilation (4D-Var) and nudging, will be applied in the present project in order to maximise the impact of GPS data.

- The ground-based GPS data provide information only about the vertical integrated atmospheric moisture content. In order improve the vertical distribution of the observed water vapour during the assimilation process, the GPS data assimilation will be supplemented in the present project with assimilation of moisture measurements from surface stations.

- Ground-based GPS information has so far been utilised in the form of Zenith Total Delay (ZTD) data. Each ZTD data value is obtained through a mapping from a number of slant delay measurements. It is expected that the meteorological data assimilation would benefit from a direct assimilation of slant delays. The explicit mapping to zenith delays, which may introduce unnecessary errors, is avoided and information on horizontal gradients may also become possible to extract.

- To assess the impact of the ground-based GPS data, and the best way in which to process and use such data, three types of studies will be carried out. First, cases of significant weather events will be selected. Data assimilation experiments will be conducted to assess the impact of the data on these cases. Special attention will be given to short range precipitation forecasts, as we expect that most additional information from the data should be in humidity. Secondly, data assimilation experiments using different data assimilation systems will be conducted for long periods (e.g. a month) and for all seasons, in order to draw general conclusions on the operational use of the data. Forecasters and other end-users will evaluate the quality of the resulting weather forecasts, produced with and without the GPS data.

The scientific and technical work of the proposal has been divided into 7 basic work-packages WP 3000 – WP 9000, the content of which is briefly described below. These basic work-packages have been further sub-divided into sub-work-packages, described with details later in this section. Three additional work-packages involve **Project Management (WP 1000)**, **User requirements (WP 2000)** and **Exploitation and dissemination (WP 10000)**.

Modelling of observation error characteristics for data assimilation (WP 3000)

Data assimilation for NWP (Numerical Weather Prediction) optimally estimates the atmospheric state using observation information. The observed values always contain observation errors. In case these errors are un-correlated between different observations, more plentiful observations lead to a more accurate state estimate. Observation error correlation generally implies reduced information content of the observations. Use of more observations does not in this case improve, but degrade the quality of the state estimate, unless the error correlation is properly accounted for.

In static data assimilation schemes, such as 3D-Var (3-dimensional variational assimilation), observations are used from one instant close to the analysis time. Serially correlated observations errors from one station, i.e. temporal observation error correlations, do not play any role in this case. Horizontal error correlations, i.e. observation error correlations between stations at one instant, need to be accounted for by error modelling in order to obtain an optimal state estimate. In temporally extended data assimilation schemes, such as 4D-VAR, observations are used at appropriate time over a data-window. In this case also temporal correlations of observation errors need to be accounted for.

Mean observation errors, i.e. error biases, need a specific treatment of bias reduction. Generally it is very difficult, however, to distinguish the slowly varying horizontal observation error correlation from the mean observation errors, or from the systematic errors of the NWP model. Comparison of ground-based GPS measurements with forecast model data and with radiosonde data have revealed that the GPS measurements may be affected by error biases. Early data assimilation experiments have indicated that it is necessary to apply bias reduction algorithms in order to avoid detrimental effects of these error biases on, for example, precipitation forecasts. Ideally, these error bias problems should be avoided by applying remedy actions as close as possible to the source of the information, e.g. at the GPS station or by improving the pre-processing algorithms. It is foreseen, however, that the need for bias reduction schemes will remain. Statistical comparison between GPS observations and model data will be applied to design the bias reduction algorithms.

The design of the ground-based GPS measurements and pre-processing systems implies theoretically the measurements to be affected by spatially correlated errors. Simulation studies by Jarlemark et al. (2001) and studies of empirical spatial correlations by Stoew et al. (2001) support this theory. These studies suggest that the length scale of the GPS observation error correlation may be significantly larger than the length scale of the forecast error. This separation of length scales can possibly be utilised for a determination of the spatial (horizontal) correlation of GPS observations errors from innovation vectors, i.e. the differences between GPS observations and the model data. Other observations of the atmospheric moisture could in principle serve as references for the estimation of the GPS observation errors, but the limited spatial resolution and relatively poor quality of radiosonde moisture measurements do not make this approach meaningful. It will furthermore be investigated whether the observation error and forecast error contributions to the spatial correlation of the GPS data innovation vectors can be separated through a modelling of the forecast error correlation by simulation techniques, based on ensemble assimilation experiments.

With the introduction of 4-dimensional variational data assimilation (4D-Var), several observations from the assimilation window, for example a 6 hour period, and from the same station may be utilised. Experiences from the 4D-Var assimilation of surface observations have shown that the sensitivity of the assimilation to systematic observation errors may become critical and that models for the temporal correlation of observation error need to be specified (Järvinen et. al., 1999). Models for the temporal correlation will alternatively be developed from innovation vectors, i.e. differences between GPS observations and model data, or from differences between GPS observations and high quality radiosonde observations.

The efficiency of the developed bias reduction schemes and the developed models for spatial and temporal observation error correlation will be tested through data assimilation and forecast experiments.

Development and testing of 4-dimensional data assimilation techniques (WP 4000)

It is foreseen that ground based GPS observations due to their high time resolution, and due to the use of the forecast model in the assimilation will have the highest impact when assimilated using 4D-Var assimilation systems. 3D-Var assimilation systems are currently in operational use by DMI, MetO, and SMHI, while 4D-Var assimilation systems are under development.

The 4D-Var assimilation schemes will be developed to handle GPS observations in an optimal manner. Since GPS observations mainly are related to the moisture variables of the forecast model, it is important to include condensation and precipitation processes in the 4D-Var schemes. This requires mathematical formulations, called parameterization, of these processes and their computer codes in nonlinear, tangent linear and adjoint forms. In most of the state of the art NWP models, these schemes are highly nonlinear and non-differentiable. Therefore, they often need to be simplified or regularized in mathematical formulations before the development of the tangent linear and adjoint schemes needed by 4D-Var.. The application of 4D-Var to GPS data will be tested and validated through case studies and through data impact studies, covering at least ten days.

DMI and MetO expect to apply complete 4-dimensional variational data assimilation (4D-Var) schemes for their operational NWP forecast models, while LAQ will apply a simplified 4-dimensional assimilation based on nudging to a mesoscale forecast model (MM5) and compare this with 3D-Var assimilation.

Optimisation of GPS and surface humidity assimilation (WP 5000)

The ground-based GPS measurements of Zenith Total Delay (ZTD) in principle only provide information on the vertically integrated water vapour in the atmosphere above the GPS stations. In case no other water vapour information is available, 3-dimensional variational data assimilation (3D-Var), for example, will use statistical knowledge only to distribute the observed information in the vertical. It was shown by Kuo et al. (1996) in an observing system simulation study that more information on the vertical distribution of water vapour could be retrieved by adding humidity observations from surface stations. This possibility to improve the utilisation of ground-based GPS measurements will be investigated by running a 3D-Var data assimilation and forecast experiment over one month with and without 2 meter relative humidity observations.

This shall be done by INM and SMHI. The variational data assimilation system to be applied by these two project partners already includes preliminary observation operators based non-linear, tangent-linear and adjoint versions of the post-processing for 2 meter relative humidity. These observation operators will be upgraded to be consistent with the latest version of the forecast model and complemented with models for observation error statistics.

Development of methods for assimilation of slant GPS delays (WP 6000)

Instead of deriving zenith quantities, GPS signal delay and integrated water vapour can also be measured along slant paths from ground-based receivers to GPS satellites. By using not only the zenith delay of a receiver but also the slant delays the number of observations will increase by roughly a factor ten. By applying variational algorithms a three-dimensional water vapour field can be retrieved from slant observations, at least from a dense network of receivers. Furthermore, the horizontal resolution of the retrieved water vapour field will also profit from this larger amount of observations.

The derivation of zenith and slant GPS delays from GPS observations involves several assumptions about the atmospheric structure. In particular, assumptions about atmospheric homogeneity and receiver multipath when observing satellites are at low elevation angles (close to the horizon) influence the results. The multipath must be carefully modelled as a function of receiver environment while the atmospheric model used for the mapping must be carefully chosen in cases of atmospheric inhomogeneities. Even when estimating only slant delays, mapping functions are still needed in order to separate receiver clock errors from atmospheric delays. Traditionally, mapping functions are empirical functions derived from multi-year averages of radiosonde data. A new approach is to derive the mapping function directly from NWP model output. This could result in a significant improvement of IWV measurements for low elevations. Pre-processing of raw slant delays before assimilation will be investigated, using additional input from NWP analysis. This will help to discriminate site dependent effects (multipath, antenna phase center variations) and receiver clock errors from atmospheric delays. It can also be used to derive intermediate quantities such as ZTD, horizontal gradients, scale height and or timing information, which could be used as an alternative to assimilating slant delays. Currently used software will be modified, if necessary, and additional modules to estimate slant delays and model multipath will be developed. Furthermore, mapping procedures based on forecast model input will be developed and tested by one weather service, KNMI, and a geodetic institute, TUD.

In order to obtain realistic results the error biases and correlations of the GPS slant measurements must be modelled. Observations for a network of ground-based receivers will be simulated from a 3-D water vapour field and used for assimilation trials. The goal of these simulations is to test our software and to estimate the capability of a network of GPS receivers to reconstruct refractivity field inhomogeneities at different scales. In addition we need to determine an optimal discretisation and interpolation scheme of the refractivity field to be used for the processing of observational data. The retrieved fields will be validated against water vapour radiometer measurements during the CLIWANET campaign.

The natural first step towards using slant-delay measurements in NWP assimilation is to properly evaluate them against the model counterparts. For this task an appropriate observation operator[1] is needed. The zenith delay observation operator is simple to develop, as the observation geometry is relatively straightforward and similar to the NWP model geometry. The slant-delay observation operator, in contrast, requires a model profile along a slanted path with unknown intersections with the model levels. Once the problem of interpolating the model variables on a slanted path is solved, the associated delay calculation problem can be fairly easily solved.

A demonstration version of a GPS slant delay observation operator will be developed by FMI and KNMI in co-operation, and this observation operator will be adapted to the HIRLAM three-dimensional variational data assimilation system. The operational NWP model of KNMI will be used for impact studies with a resolution of at least 10 km x 10 km. The performance of the assimilation of these slant delays will be investigated by conducting observation system simulation experiments (OSSE). Impact studies will be performed with the analysed water vapour fields, obtained from the GPS data of a dense GPS network (Observation System Experiment, OSE). DMI will perform assimilation tests using the software developed by KNMI and FMI.

Impact studies and extreme case studies (WP 7000)

DMI will monitor the operational forecasts and information about the actual weather in order to identify periods and areas in which the forecasts are particularly poor, or in which "special" weather occurred in areas with good coverage of GPS stations partaking in the project. For the selected cases, each participating institute will carry out extensive, full-scale data assimilation experiment. Month long assimilation experiments will be carried out for each of the four seaasons. Standard statistical methods will be used for objective verification. Analyses and forecasts with and without the ground-based GPS data will be verified against observations and analyses. Special attention will be given to short range forecasts of moisture, clouds and precipitation. Forecasters will participate with subjective verification of the forecasts.

[1] An observation operator is an algorithm which calculates the estimate of an observable given a NWP atmospheric state.

One of the objectives of the EUCOS program of EUMETNET is to increase the cost-efficiency of the European observing system while staying at the same overall cost. It is proposed to replace some radiosonde stations by AMDAR aircraft soundings. Comparing with radiosondes, one of the drawbacks of the current AMDAR is the lack of humidity information. The ground-based GPS ZTD data could provide useful complementary humidity information that allows this cost-redistribution with less negative effect on numerical weather predictions. A well documented EUCOS observation period will be selected, see e.g. Amstrup (2000), and the impact of replacing radiosonde data with combined AMDAR/GPS data will be studied.

GPS ZTD data provision and monitoring (WP 8000)

Currently GPS data is available from regional geodetic networks under pre-existing agreements with regional processing centres. In past research methodology has been developed to process the data to retrieve atmospheric properties. This methodology will be used in demonstration mode in this project, to allow the users to gain experience using the EO products in their NWP application. The GPS data will be retrieved from the sites and quality checked. The refractive delays in the GPS signals will be calculated and then geometrically mapped to the zenith delay (ZTD. For a period of at least one year this will be done in near real time (NRT), as necessary for operational NWP. These products will be used by NWP groups, which are developing ZTD assimilation algorithms. The data will also be further processed to remove the hydrostatic component of the delay based on surface pressure measured at the site. This non-hydrostatic, or "wet" delay will then be transformed to integrated water vapour. These products will be used by NWP users, which are developing nudging assimilation systems.

Each regional data processing centre will be responsible for retrieving the GPS data, processing the data, and transferring the data to the project ftp site in NRT. In processing the data, the centres will include stations from a common reference network in their solutions to provide a means for cross-checking the quality of the data and to ensure that the reference frames used are consistent. Similar products that are available from organisations outside the consortium that cover other regions will also be made available to the meteorological users.

The first 3 months are to be used to improve the raw data flow as necessary, to verify the robustness of the processing system and to make any adjustments to the processing concerning the station distribution, following the recommendations of the work-package leader and a **processing committee**. During these 3 months and the following 21 months, the products will be provided continuously to the users as a demonstration prototype system. 6 months into the project quality control standards will be implemented.

Radiosonde observations can be used as an important independent data set for validating GPS ZTD data both on a daily basis and on long term statistics. The quality of the radiosondes is high, but the temporal and spatial resolutions sometimes lead to problems. NWP analyses and forecasts, on the other hand, can be used as another source of data with a uniform resolution in 4 dimensions. The database will contain radiosonde data, NWP data and precipitation data that is collected for validating the short term precipitation forecasts.

GPS ZTD system research (WP 9000)

In previous work developing the methodology and its validation, it was established that the GPS ZTD and IWV products are of a quality comparable or superior to existing data sources available to the NWP user community. In particular, the products were shown to be in overall good agreement with radiosondes (less than 10mm of delay). However, the products occasionally had epochs of unexplained poor data quality. In addition, long spatial and temporal signals in the residuals from radiosonde and NWP comparisons have been detected. This work-package will investigate the source of these errors and contribute new techniques to the methodology implemented in the demonstration processing.

Most of the GPS software packages provide the standard deviation of the estimated Zenith Total Delay (ZTD) parameter as an estimate of the quality of the solution. The standard deviation is a formal measure of quality computed from the inverse of the normal matrix. As a measure of quality it is seriously flawed because it does not take into account the actual quality of the observations, it is unaware of important errors such as multipath, and it assumes the orbits (and sometimes satellites clocks) are perfect. The standard deviation is always too optimistic and cannot be used to model the errors during the assimilation into NWP. A new quality indicator for the ZTD will be developed and tested. The new indicator will be computed from the estimated least squares residuals by using variance component estimation techniques, taking into account the degree of freedom over the domain of the ZTD parameter.

The strength of ground-based GPS is certainly not its absolute accuracy. Because of its sensitivity to signal multipath effects, varying the elevation angle cut-off limits - or using different schemes for down-weighting low elevation angle observations - will typically have a significant impact on the estimated ZTD value. A constant bias over decades is in principle not a problem but if there are variations at the time scales of years it will influence both NWP models and long term climate monitoring. We will use long time series (> 5 years) of independent radiosonde and microwave radiometer data to study these effects and believe that a correct assessment can be made at the 5-10 mm level in ZTD. Very-Long-Baseline Interferometry (VLBI) is another method, which will be used. Several European VLBI sites, e.g., Wettzeell, Matera, and Onsala, are co-located with important GPS sites in the IGS network, where data are publicly available. The VLBI estimates of ZTD are obtained from the same type of estimation technique as in GPS but due to the large directional antennas used the multipath effect is in practise eliminated. VLBI observations are, however, not continuous, but 24-hour observing sessions bi-weekly or monthly for more than five years provide a sufficient data base.

GPS tropospheric zenith delay is correlated with the site co-ordinates, especially with the vertical one. For meteorological applications there is no need to estimate them when processing GPS data, but, in order to derive the 'best' possible ZTD estimates, there is a need to know site co-ordinates with a certain level of accuracy. Generally they are obtained averaging daily station estimates over a longer period of time. So even for pure meteorological applications there is the need of station co-ordinates monitoring. Of course, they are related to the terrestrial reference frame (TRF) in which they have been computed. The changing of TRF could introduce biases into the GPS ZTD and IWV products. Furthermore constrains to the reference frame are also induced by fixing the GPS orbits (IGS orbits are given in a TRF) during the data reduction, what is commonly done when regional network are considered. Therefore it is an interesting question to understand how to deal with the biases related to the reference frame, even for climate investigations. Furthermore, the geodetic reference frame is always being improved. There are occasionally slight changes which can lead to offsets in the long term trend of GPS ZTD. The influence different reference frames have on GPS ZTD estimates will be evaluated and a methodology for dealing with updates to the reference frame will be established. It will be verified that differences between processing centres estimates for the reference IGS stations are not due to orbit errors, co-ordinate errors or reference frame errors. Guidelines for verifying the quality of GPS ZTD and IWV data will be established by examining repeatability of co-ordinates and these guidelines will be implemented in the GPS ZTD and IWV processing.

Results from the EC MAGIC project showed that the difference between GPS ZTD and radiosondes increased in magnitude in high humidity regimes, producing a seasonal signal in these differences. These signals limit the ability to separate a climatic signal from the noise in the of GPS ZTD products. Biases correlated with seasonal signals due to systematic differences in actual and modelled vertical structure will be investigated as well as noise sources in the radiosonde and GPS ZTD data that could have a seasonal variation.

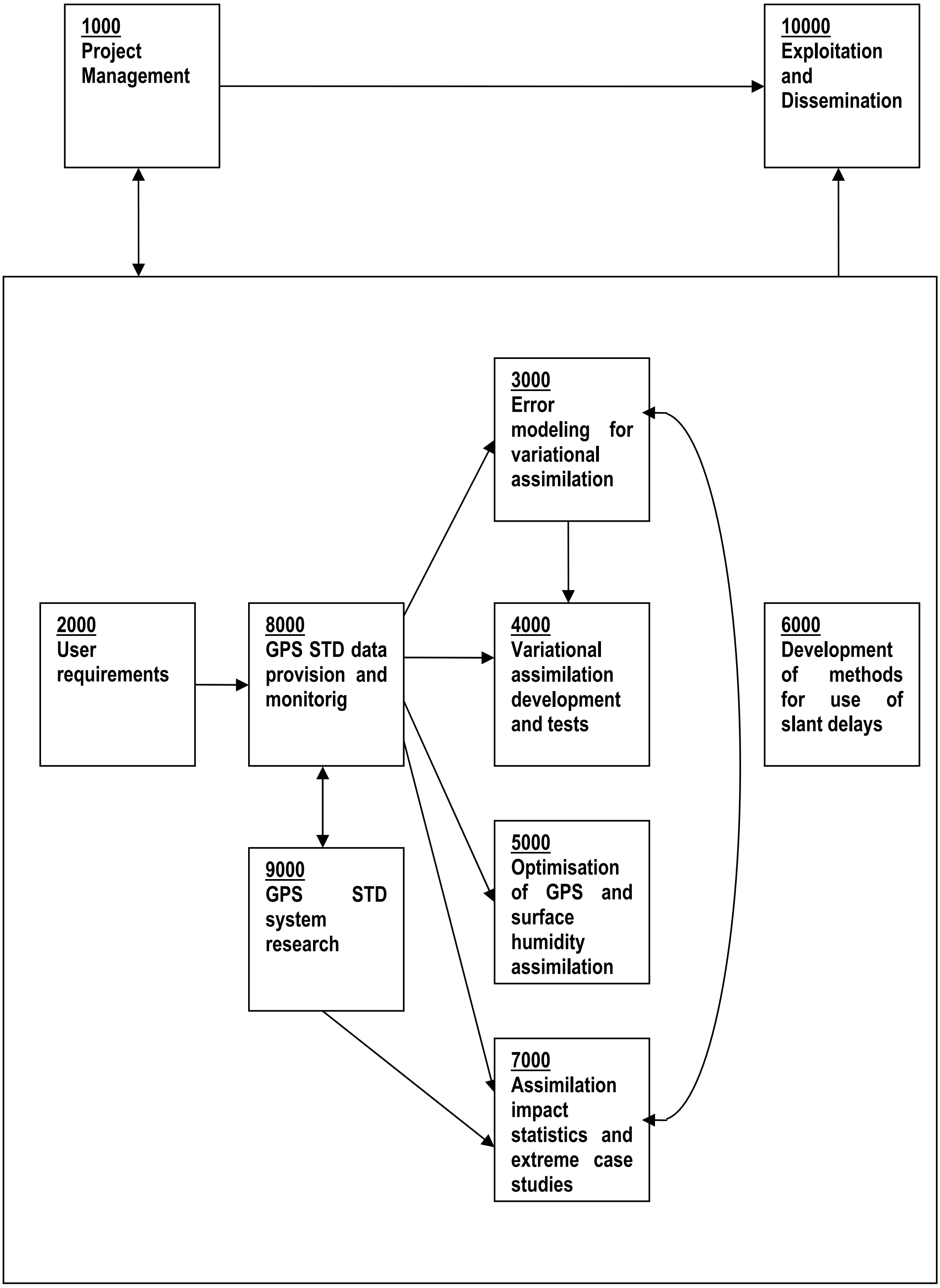
The International GPS Service (IGS) has developed a method for combining ZTD solutions from different processing centres by removing a bias between processing centres and averaging the results. The same method is applied for the 12 analysis centres of the EUREF Permanent GPS Network (EPN). Typical for IGS and EUREF is, that almost all stations are processed by at least three processing centres. In our distributed network, only a subset of stations will be common among processing centres, but these can be used to verify that there are no offsets. The batch type of processing used by IGS and EUREF will be converted into a Kalman filter approach that can be used in near real-time applications. The differential biases between the analysis centres will be modelled for the stations in common. Special techniques for the detection, identification and adaptation of outliers and biases will be used. Algorithms will be developed and tested and possible refinements will be investigated. For example, the NRT combination could be further combined with bias reduction algorithms (using output from NWP analysis) to model absolute biases. TUD will also develop automated methodology for a regional combination of solutions following the EUREF model, in order to provide the best integrated product from the regional products. They will aid in the implementation of this methodology at the processing centres.

b) Project planning and time table

WP#	Wpname	Start	End	Year 1	Year 2	Year 3
1000	**Management**	**00**	**36**			
1100	Overall Management	00	36			
1200	Scientific Coordination	00	36			
1300	Data supply co-ordination	00	36			
1400	Meeting preparation and participation	00	36			
2000	**User Requirements**	**00**	**03**			
3000	**Error Modelling for variational assimilation**	**00**	**24**			
3100	Bias reduction schemes	00	24			
3200	Modelling of spatial error correlation	00	24			
3300	Modelling of temporal error correlation	00	24			
4000	**Variational assimilation development and tests**	**00**	**36**			
4100	Develop and optimise 4Dvar assimilation	00	33			
4200	Mesoscale data assimilation development and tests	00	36			
5000	**Optimisation of GPS/surface humidity assimilation**	**00**	**36**			
5100	Refining methods of surface humidity assimilation	00	24			
5200	Testing combined GPS / surface humidity assimilation	24	36			
6000	**Development of methods for use of slants delays**	**00**	**36**			
6100	Slant delay retrievals	00	30			
6200	Slant delay validation and observation error studies	06	24			
6300	Observation operator development	00	18			
6400	Assimilation tests	18	36			
7000	**Assimilation impact statistics / extreme case studies**	**00**	**36**			
7100	Co-ordination of case studies and compiling results	00	36			
7200	Case studies and extensive impact studies	06	30			
7300	EUCOS scenario impact studies	00	24			
8000	**GPS ZTD data provision and monitoring**	**00**	**36**			
8100	Product quality monitoring and reporting	00	36			
8200	NWP User GPS ZTD/IWV data server maintenance	00	36			
8300	Regional GPS ZTD data production	00	36			
8400	Furnishing continuous radiosonde and NWP output	00	36			
8500	Validation database development and maintenance	00	36			
8600	User validation and feedback	03	33			
9000	**GPS ZTD System Research**	**00**	**30**			
9100	Robust quality indicators	00	09			
9200	Long term bias elimination	00	30			
9300	Co-ordinate system biases	00	24			
9400	Biases correlated with seasonal signals	00	24			
9500	Optimal combination of regional solutions	00	09			
10000	**Exploitation and dissemination**	**00**	**36**			

Table 1 Project planning and timetable.

c) Graphical presentation of the project's components



WP1000 two-way interacts with all WP´s in the large box. All these provide input to WP10000.

d. Work package descriptions

d_1. Work package list

WPNO	Wpname	PM	Leader	Start	End
1000	**Management**	**37**	**DMI**	**00**	**36**
1100	Overall Management	12	DMI	00	36
1200	Scientific Co-ordination	2	DMI	00	36
1300	Data supply co-ordination	8	ACRI-ST	00	36
1400	Meeting preparation and participation	15	DMI	00	36
2000	**User Requirements**	**1**	**MetOffice**	**00**	**03**
3000	**Error Modelling for variational assimilation**	**38**	**FMI**	**00**	**24**
3100	Bias reduction schemes	4	SMHI	00	24
3200	Modelling of spatial error correlation	25	FMI	00	24
3300	Modelling of temporal error correlation	9	DMI	00	24
4000	**Variational assimilation development and tests**	**24**	**MetOffice**	**00**	**36**
4100	Develop and optimise 4Dvar assimilation	12	MetOffice	00	33
4200	Mesoscale data assimilation development and tests	12	LAQ	00	36
5000	**Optimisation of GPS and surface humidity assimilation**	**13**	**SMHI**	**00**	**36**
5100	Refining methods of surface humidity assimilation	3	SMHI	00	24
5200	Testing combined GPS and surface humidity assimilation	10	INM	24	36
6000	**Development of methods for use of slants delays**	**42**	**KNMI**	**00**	**36**
6100	Slant delay retrievals	10	TUD	00	30
6200	Slant delay validation and observation error studies	8	KNMI	06	24
6300	Observation operator development	15	KNMI	00	18
6400	Assimilation tests	9	KNMI	18	36
7000	**Assimilation impact statistics and extreme case studies**	**73**	**DMI**	**00**	**36**
7100	Co-ordination of case studies and compiling results	1	DMI	00	36
7200	Case studies and extensive impact studies, including validation by forecasters.	68	DMI	06	30
7300	EUCOS scenario impact studies	4	DMI	00	24
8000	**GPS ZTD data provision and monitoring**	**97**	**ACRI-ST**	**00**	**36**
8100	Product quality monitoring and reporting	3	ACRI-ST	00	36
8200	NWP User GPS ZTD/IWV data server maintenance	2	MetOffice	00	36
8300	Regional GPS ZTD data production	84	ACRI-ST	00	36
8400	Furnishing continuous radiosonde and NWP output	3	DMI	00	36
8500	Validation database development and maintenance	3	ACRI-ST	00	36
8600	User validation and feedback	2	MetOffice	03	33
9000	**GPS ZTD System Research**	**21**	**Chalmers**	**00**	**30**
9100	Robust quality indicators	3	TUD	00	09
9200	Long term bias elimination	7	Chalmers	00	30
9300	Co-ordinate system biases	3	ASI	00	24
9400	Biases correlated with seasonal signals	5	ACRI-ST	00	24
9500	Optimal combination of regional solutions	3	TUD	00	09
10000	**Exploitation and dissemination**	**2**	**DMI**	**00**	**36**

Table 2 Work package list and personnel resources. Note that only the work package leader is listed, though the person-months resources are include all participating partners.

Workpackage / partner personnel resource matrix

The following table gives the number of person-months allocated to each work package for each partner.

	Workpackage	DMI	SMHI	Met Office	INM	LAQ	KNMI	FMI	ACRI-ST	Chalmers	NMA	ASI	IEEC	LPT	GOP	TUD	Total
1000	**Management**	11.5	2	0.5	0.5	0.5	0.5	0.5	7.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	27
2000	**User requirements**	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0.5
3000	**Error modelling for variational assimilation**	2	11	0	0	0	0	7	0	12	0	0	0	0	0	0	32
4000	**4-dimensional assimilation development and tests**	5	0	5.5	0	10	0	0	0	0	0	0	0	0	0	0	20.5
5000	**Optimisation of GPS and surface humidity assimilation**	0	6	0	9	0	0	0	0	0	0	0	0	0	0	0	15
6000	**Development of methods for use of slants delays**	3	0	0	0	0	17	9	0	0	0	0	0	0	0	6	34
7000	**Assimilation impact statistics and extreme case studies**	12	0	14	18	14	0	0	0	0	0	0	0	0	0	0	58
8000	**GPS ZTD data provision and**	2	0	2	0	0	0	0	12	4	7.5	6.5	11	8	9	0	62

	monitoring																
9000	**GPS ZTD system research**	0	0	0	0	0	0	0	0	9	0	3	0	0	0	5	17
10000	**Exploitation and dissemination**	1..5	1	0.5	0.5	0.5	1.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	10
Total by Partner		37	20	23	28	25	19	17	20	26	8.5	10.5	12	9	10	11	276

Table 3 Work package / partner personnel resource matrix

d_2. List of Deliverables

Due date is the first day of the month corresponding to T0 + the month number.

Type refers to the nature of the deliverable using one of the following codes:
Re = Report; **Da** = Data set; **Eq** = Equipment; **Pr** = Prototype; **Si** = Simulation;
Th = Theory; **De** = Demonstrator; **Me** = Methodology; **Co** = Code; **O** = other

Dissemination level uses one of the following codes:
PU = Public
RE = Restricted to a group specified by the consortium (including the Commission Services).
CO = Confidential, only for members of the consortium (including Commission Services).

PPC refers to all Associated contractors, which are processing centres, PACRI through GOP
PNWP refers to all contractors who are NWP meteorological agency users, DMI through FMI

D 1	**kickoff meeting minutes**	**DMI 00 Re CO**
D 2	**kickoff meeting minutes**	**DMI 03 Re PU**
D 3	**1st project meeting minutes**	**DMI 06 Re CO**
D 4	**semi-annual progress report - report 1**	**DMI 06 Re CO**
D 5	**2st project meeting minutes**	**DMI 12 Re CO**
D 6	**annual progress report - report 2**	**DMI 12 Re PU**
D 7	**3st project meeting minutes**	**DMI 18 Re CO**
D 8	**Semi-annual progress report - report 3**	**DMI 18 Re CO**
D 9	**4st project meeting minutes**	**DMI 24 Re CO**
D 10	**annual progress report - report 4**	**DMI 24 Re PU**
D 11	**5st project meeting minutes**	**DMI 30 Re CO**
D 12	**Semi-annual progress report - report 5**	**DMI 30 Re CO**
D 13	**final project meeting minutes**	**DMI 36 Re CO**
D 14	**final report - report 6**	**DMI 36 Re PU**
D 15	**user requirements document**	**MetO 03 Re PU**
D 16	**Bias reduction scheme**	**SMHI 12 Co+Re PU**
D 17	**Impact of Bias reduction scheme on assimilation**	**SMHI 24 Co+Re PU**
D 18	**Development of spatial error correlation model**	**FMI 18 Re PU**
D 19	**Report on spatial error correlations**	**Chalmers 24 Re PU**
D 20	**Impact of spatial error correlation model**	**SMHI 30 Re PU**
D 21	**Development of temporal error correlation model**	**SMHI 18 Re PU**
D 22	**Report on temporal correlations**	**Chalmers 18 Re PU**
D 23	**Impact of temporal error correlation model in 4D-Var**	**DMI 30 Re PU**
D 24	**HIRLAM 4DVAR results**	**DMI 33 Re PU**
D 25	**MetO model 4DVAR results**	**MetO 30 Re PU**
D 26	**4DVAR software (GPS-specific forward operator)**	**MetO 33 Re PU**
D 27	**Report on MM5 GPSPW nudging**	**PLAQ 12 Re PU**
D 28	**Report on MM5 GPSPW 3DVAR**	**PLAQ 24 Re PU**
D 29	**Report on MM5 GPS-ZTD 3DVAR**	**PLAQ 36 Re PU**
D 30	**Surface moisture observation operator**	**SMHI 12 Co+Re PU**
D 31	**Surface moisture impact study**	**SMHI 24 Co+Re PU**
D 32	**Impact of surface humidity obs. on GPS data assim.**	**INM 36 Re PU**
D 33	**Software for slant delay retrieval/multipath mapping.**	**TUD 18 Co+Re PU**
D 34	**3 month test dataset.**	**TUD 12 Data PU**
D 35	**2 month data set from period of interest.**	**TUD 24 Re PU**
D 36	**Software for direct mapping function approach.**	**TUD 30 Co+Re PU**

D 37	**Slant delay validation and observation error report**	**KNMI 24 Co+Re PU**
D 38	**3Dvar Slant delay observation operator implementation**	**FMI 12 Co PU**
D 39	**Initial evaluation of the observation operator**	**FMI 18 Re PU**
D 40	**Impact assessment of moisture on HIRLAM forecasts**	**KNMI 36 Re PU**
D 41	**Impact study of assimilation of slant delays.**	**DMI 36 Re PU**
D 42	**Selected cases for first year**	**DMI 13 Re PU**
D 43	**Selected cases for second year**	**DMI 25 Re PU**
D 44	**Comparison of case studies**	**DMI 32 Re PU**
D 45	**DMI assimilation results**	**DMI 30 Re PU**
D 46	**INM assimilation results**	**INM 30 Re PU**
D 47	**PLAQ assimilation results**	**PLAQ 30 Re PU**
D 48	**MetO assimilation results**	**MetO 30 Re PU**
D 49	**comparison of different assimilation methods**	**DMI 30 Re PU**
D 50	**selected EUCOS IOP assimilation impact results**	**DMI 24 Re PU**
D 51	**start of monthly GPS ZTD IWV quality reports**	**ACRI-ST 06 Re PU**
D 52	**Project database web site**	**ACRI-ST 06 web PU**
D 53	**data exchange formats**	**MetO 03 Re PU**
D 54	**support software**	**MetO 06 Co PU**
D 55	**Initial delivery of GPS ZTD IWV products**	**PPC 04 Da PU**
D 56	**GPS ZTD IWV valid. reports**	**PPC 24 Re PU**
D 57	**Final GPS ZTD IWV system evaluation**	**PPC 30 Re PU**
D 58	**Radiosonde data specification document**	**DMI 03 Re PU**
D 59	**HIRLAM output specification document**	**DMI 03 Re PU**
D 60	**Start of delivery European radiosonde data**	**DMI 03 Da PU**
D 61	**Start of delivery HIRLAM analyses/forecast**	**DMI 03 Da PU**
D 62	**Validation data sets with web site access**	**ACRI-ST 12 Da PU**
D 63	**start delivery of monthly monitoring/validation report**	**MetO 06 Re PU**
D 64	**monitoring and validation performance summary**	**MetO 33 Re PU**
D 65	**quality indicator algorithm**	**TUD 09 Me PU**
D 66	**Biases in ZTD**	**Chalmers 30 Re PU**
D 67	**GPS ZTD and reference frame correlations**	**ASI 24 Re PU**
D 68	**GPS ZTD IWV seasonal bias report - northern climate**	**Chalmers 33 Re PU**
D 69	**Regional Combination methodology and report**	**TUD 09 Me+Re PU**
D 70	**Project web site**	**DMI 03 Other PU**
D 71	**Project Publicity brochure**	**DMI 04Other PU**
D 72	**User workshop proceedings**	**KNMI 24 Re PU**
D 73	**GPS Data Recommendations for European NWP**	**PNWP 36 Re PU**
D 74	**Final project publisity brochure**	**DMI 36 Other PU**

D 75	**TIP**	**ALL 36 Re**

Table 4 List of project deliverables

The annual reports will follow the FP5 guidelines at http://www.cordis.lu.eesd.manage.htm, and eventual further guidelines provided by the EC Scientific Officer.

d_3. Workpackage Descriptions

WP 1000 - Management

Start date: 0
End date: 36
WP leader: DMI
Total person months per participant (including sub-workpackages): DMI 12, PSHMI 2, ACRI-ST 7.5, and all other partners 0.5

- Overall project management will be carried out by DMI.
- Scientific co-ordination will be carried out by SMHI and will assure the progress of the scientific workpackages concerning development of new techniques and methods for NWP assimilation.
- Data supply co-ordination will be carried out by ACRI-ST who is responsible for assuring the delivery and quality of all the GPS ZTD products that are used as inputs to the scientific and assimilation workpackages.
- Meeting preparation and participation will be carried out by all partners to assure timely reporting of results.

The detailed descriptions are provided in the sub-workpackages below.

WP 1100 - Overall Management

Start date: 0
End date: 36
WP leader: DMI
Person months per participant: DMI 10

WP objectives:
The overall project management and co-ordination will be carried out by DMI, which will be the single contact point of the project for EC and external communication.

Methodology/Work Description:
- Interface with scientific co-ordinator, data-supply co-ordinator and work-package managers
- Maintain communication tools (email, personnel directory, internal web site)
- Maintain the external project web site
- Ensure high level communication link with users
- High level quality assurance and verification of deliverables
- Define high level standards, distribution and access for deliverables
- Monitor high level action items and schedule.
- Overall meeting co-ordination and recording of minutes and action item list
- Compilation of annual reports
- Ensure communication with EC and delivery of reports and minutes
- Financial co-ordination
- Make formal requests to outside organisations for required additional data on behalf of the consortium.

Deliverables:

Deliverable title		Resp. Partner	DelivDate	Type	DissemLevel
D 1	kickoff meeting minutes	DMI	00	Re	CO
D 2	kickoff meeting minutes	DMI	03	Re	PU
D 3	1st project meeting minutes	DMI	06	Re	CO
D 4	semi-annual progress report - report 1	DMI	06	Re	CO
D 5	2st project meeting minutes	DMI	12	Re	CO
D 6	annual progress report - report 2	DMI	12	Re	Pu
D 7	3st project meeting minutes	DMI	18	Re	CO
D 8	Semi-annual progress report - report 3	DMI	18	Re	CO
D 9	4st project meeting minutes	DMI	24	Re	CO
D 10	annual progress report - report 4	DMI	24	Re	Pu
D 11	5st project meeting minutes	DMI	30	Re	CO
D 12	Semi-annual progress report - report 5	DMI	30	Re	CO
D 13	final project meeting minutes	DMI	36	Re	CO
D 14	final report - report 6	DMI	36	Re	Pu

WP 1200 – Scientific Co-ordination

Start date: 0
End date: 36
WP leader: DMI
Person months per participant: SMHI 1.5, DMI 1.5

WP objectives:
Oversee the research tasks of the project, establish priorities for case studies.

Methodology/Work Description:
- Interface work package managers.
- Review schedule monitoring and advise on work plan adjustments where necessary.
- Contribute to progress meeting agendas.
- Aid in compilation of meeting minutes and annual reports.
- Call additional group working meetings when necessary.

WP 1300 – Data supply co-ordination

Start date: 0
End date: 36
WP leader: ACRI-ST
Person months per participant: ACRI-ST 7

WP objectives:
Oversee the data exchange and maintenance.

Methodology/Work Description:
- Correspond with partner representatives to establish detailed data requirements for each workpackage and for establishing a Project Dataset Description
- Co-ordinate smooth exchange of data
- Correspond with leaders of data provision sub-workpackages and assure the delivery of the data required for the efficient execution of the project
- Manage additional requests for data as they evolve following the progress of the project.
- Co-ordinate the GPS ZTD processing committee.
- Act as the single contact point between the user meteorological agencies, and the GPS ZTD processing centres as a unit.

WP 1400 - Meeting preparation and participation

Start date: 0
End date: 36
WP leader: ALL
Person months per participant: All participants- 0.5 PM

WP objectives:
Meeting participation.

Methodology/Work Description:

- Provide individual participant progress reports 2 weeks before meeting to co-ordinator.
- Provide hard copy of transparencies presented at the meeting.
- Participate in meetings.
- At end of project provide recommendations for European use/processing of GPS delay data (PM resources are shared with workpackage 10000 dissemination and exploitation).
- Each NWP participant will contribute to the recommendations in the 1 month prior to the final meeting in a 2 page report format with the following indicative headings:
    - Background description of operational NWP system at their agency
    - Description of methodological approach for using GPS ZTD or delay data developed and tested in the project
    - Short summary of tests and extreme cases
    - One illustrative figure
    - Conclusions on perspectives at the national level and European level
- Each processing centre and non-NWP partner will contribute to the recommendations in the 1 month prior to the final meeting in a 2 page report format with the following indicative headings:
    - Summary description of their implementation of the GPS ZTD IWV system including improvements brought about by the WCHAL000 research activities and recommendations for future processing systems.
    - Summarised evaluation of validation activities with mention of any remaining problem areas.

Deliverables:
Deliverables are the progress reports that are provided in the semi-annual and annual reports in WASI00, and the final recommendations report in WPNMA000 and are not listed again here.

WP 2000 – User Requirements

Start date: 00
End date: 03
WP leader: MetO
Total person months per participant: MetO 0.5 PM

WP objectives:
Define User Requirements for NWP and specify project Q/A requirements.

Methodology/Work Description:
- Establish User Requirements for near-real time GPS data for operational NWP purposes *(User Workshop, Questionnaire, WMO UR documents)*
- Define quality assurance and quality control procedures for project network data deliverables *(in consultation with processing centres)*

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 15 user requirements document	MetO	03	Re	Pu

WP 3000 – Error modelling for variational assimilation

Start date: 0
End date: 24
WP leader: FMI
Person months per participant: DMI 2, SMHI 11, FMI 7, Chalmers 12

WP objectives:
Data assimilation for NWP (Numerical Weather Prediction) optimally estimates the atmospheric state using observational information. The observed values always contain observational errors. In case these errors are un-correlated between different observations, more plentiful observations lead to a more accurate state estimate. Observation error correlations generally imply reduced information content of the observations. Use of more observations does not in this case improve, but degrade the quality of the state estimate, unless the error correlations are properly accounted for.

In static data assimilation schemes, such as Optimum Interpolation (OI) or 3D-VAR (3-dimensional Variational), observations are used from one instant close to the analysis time. Serially correlated observations errors from one station, i.e. temporal observation error correlations, not play any role in this case. Horisontal error correlations, i.e. observation error correlations between stations at one instant, need to be accounted for by error modelling in order to obtain an optimal state estimate. In temporally extended data assimilation schemes, such as 4D-VAR, observations are used at appropriate time over a data-window. In this case also temporal correlation of observation errors need to be accounted for.

Mean observation errors, i.e. biases, need a specific treatment of bias correction. Generally it is very difficult, however, to distinguish between the slowly varying horizontal observation error correlation from the mean observation errors, or from the systematic errors of the NWP model.

Methodology/Work Description:
The detailed descriptions are provided in the sub-workpackages below.

WP 3100 – Bias reduction schemes

Start date: 0
End date: 24
WP leader: SMHI
Person months per participant: SMHI 3

WP objectives:

- To develop and test schemes for reducing the effect of observational error biases in ground-based GPS measurements.

Methodology/Work Description:

Comparison of ground-based GPS measurements with forecast models data and with radiosonde data have revealed that the GPS measurements may be affected by systematic errors (error biases). Early data assimilation experiments have indicated that it is necessary to apply bias reduction algorithms in order to avoid detrimental effects of these error biases on, for example, precipitation forecasts. Ideally, these error bias problems should be avoided by applying remedy actions as close as possible to source of the information, e.g. at the GPS station or by improving the pre-processing algorithms. It is foreseen, however, that the need for bias reduction schemes will remain. Statistical comparison between GPS Zenith Total Delay measurements and the operational SMHI HIRLAM model will be carried out for at least one year of data, to include possible seasonal variations, and for data from a network distributed all over Europe, to include possible geographical variations. Data compiled by the GPS data producers within the project will be utilized. Various predictor variables that might explain systematic differences between modelled and measured data will be investigated, for example geographical position, season, time of the day, tropospheric temperature and moisture content. Furthermore, the possibility to use an adaptive bias reduction algorithm based on Kalman filtering will be investigated.

The efficiency of the developed bias reduction scheme will be tested through data assimilation and forecast experiments with and without application of the bias reduction scheme.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 16 Bias reduction scheme	SMHI	12	Co+Re	Pu
D 17 Impact of Bias reduction scheme on assimilation	SMHI	24	Co+Re	Pu

WP 3200 – Modelling of spatial error correlation

Start date: 0
End date: 24
WP leader: FMI
Person months per participant: Chalmers 8, SMHI 6, FMI 7

WP objectives:

- To develop and test models for the spatial correlation of ground-based GPS observation errors to be applied in variational data assimilation.

Methodology/Work Description:

The design of the ground-based measurement and pre-processing system implies theoretically the measurements to be affected by spatially correlated errors. Simulation studies by Jarlemark et al. (2001) and studies of empirical spatial correlations by Stoew et al. (2001) support this theory. These early studies suggest that the length scale of the GPS observation error correlation may be significantly larger than the length scale of the forecast error. This separation of length scales can possibly be utilised for a determination of the spatial (horizontal) correlation of GPS observations errors from innovation vectors, i.e. the differences between GPS observations and the model data. Other observations of the atmospheric moisture could in principle serve as references for the estimation of the GPS observation errors, but the limited spatial resolution and relatively poor quality of radiosonde moisture measurements do not make this approach meaningful. It will furthermore be investigated whether the observation error and forecast error contributions to the spatial correlation of the GPS data innovation vectors can be separated through a separate modelling of the forecast error correlation by simulation techniques, based on ensemble assimilation experiments.

The efficiency of the developed spatial error correlation model will be implemented and tested through data assimilation and forecast experiments with and without application of the spatial error correlation model. The implementation of the spatial error correlation may cause coding design difficulties, since the present design of computer codes for operational variational data assimilation schemes does, in principle, not allow for such spatially correlated errors.

Since the errors in the ZTD estimates from the GPS data are strongly correlated with the errors in the estimated site positions in the local vertical coordinate, we will also investigate the spatial error correlation of these residuals in the vertical site positions using both archived GPS data and near real-time data acquired within the proposed project. The point is that the true site position is significantly less variable than is the true ZTD. It is, therefore, in this case much easier to separate the signal from the error for long time series of data. Here we can also assess possible differences in spatial error correlation using the post processed and the near real time processed GPS data.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 18 Development of spatial error correlation model	FMI	18	Re	Pu
D 19 Report on spatial error correlations	Chal	24	Re	
D 20 Impact of spatial error correlation model	SMHI	30	Re	Pu

WP 3300 – Modelling of temporal error correlation

Start date: 0
End date: 24
WP leader: DMI
Person months per participant: DMI 2, SMHI 2, Chalmers 4,

WP objectives:

- To develop and test a model for the temporal correlation of ground-based GPS observation errors in 4-dimensional variational data assimilation

Methodology/Work Description:

With the introduction of 4-dimensional variational data assimilation (4D-Var), several observations from the assimilation window, for example a 6 hour period, and from the same station may be utilised. Experiences from the 4D-Var assimilation of surface observations have shown that the sensitivity of the assimilation to systematic observation errors may become critical and that models for the temporal correlation of observation error need to be specified (Järvinen et. al., 2000). Furthermore, due to the coding design of variational data assimilation schemes, it may be easier to implement models for the temporal correlation of errors, rather than models for the spatial correlation of errors. Models for the temporal correlation will alternatively be developed from innovation vectors, i.e. differences between GPS observations and model data, or from differences between GPS observations and high quality radiosonde observations.

The efficiency of the developed temporal error correlation model will be implemented and tested through data assimilation and forecast experiments with and without application of the spatial error correlation model.

As in WP3200 we will also make use of existing and new time series of vertical position estimates. The temporal correlation - or decorrelation with time - will be studied. Studies indicate so far decorrelation times of the order of 2-4 days. We will based on results from more extensive studies try to separate the observed temporal variations in the ZTD, estimated using GPS data, into the decorrelation of the signal (ZTD) and the GPS error.

Deliverables:

	Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 21	Development of temporal error correlation model	SMHI	18	Re	Pu
D 22	Report on temporal correlations	Chalmers	18	Re	Pu
D 23	Impact of temporal error correlation model in 4D-Var	DMI	30	Re	Pu

WP 4000 – Variational data assimilation development and tests

Start date: 0
End date: 33
WP leader: METO
Total person months per participant: DMI 5, MetO 5.5, PLAQ 10

WP objectives:

Methodology/Work Description:
The detailed descriptions are provided in the sub-workpackages below.

WP 4100 – Develop and optimise 4DVAR assimilation

Start date: 0
End date: 33
WP leader: METO
Person months per participant: DMI 5, METO 5.5

WP objectives:

- Enable assimilation of ground based GPS data into 4DVar data assimilation systems.
- Investigate impact of ground based GPS data when assimilated using 4DVar data assimilation systems.
- Capability for operational assimilation of GPS data in 4DVAR.

Methodology/Work Description:
It is foreseen that ground based GPS observations due to their high time resolution will have the highest impact when assimilated using 4DVar assimilation systems. At both DMI and the Met Office, a 3DVar assimilation system is currently in operational use and 4DVar versions are under development.
The operators enabling assimilation of ground based GPS observations in 4DVar shall be tested. Secondly a number of case studies shall be performed, in which 4DVar assimilation of GPS data is compared to simulations based on 3DVar analyses.

- Develop, implement and test methodology for 4DVAR assimilation of GPS data
- Undertake assimilation/forecast impact studies using 4DVAR with realistic domain configurations and over at least a 10 day period.
- Optimise 4DVAR assimilation with feedback from impact studies, ready for fully operational use of GPS data.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 24 HIRLAM 4DVAR results	DMI	33	Re	Pu
D 25 MetO model 4DVAR results	MetO	30	Re	Pu
D 26 4DVAR software (GPS-specific forward operator)	MetO	33	Re	Pu

WP 4200 – Mesoscale data assimilation development and tests

Start date: 0
End date: 36
WP leader: PLAQ
Person months per participant: PLAQ 10

WP objectives:

- Development of GPS ZTD assimilation software for the 3DVar assimilation system for the mesoscale NWP model MM5.
- Investigate the impact of assimilation of GPS PW into the MM5 at high resolution using different assimilation techniques: nudging and 3DVAR.

Methodology/Work Description:
Recent work showed the impact of the assimilation of GPS precipitable water (PW) into high resolution weather forecasts (Faccani et al., in preparation) for a few cases using the nudging technique. It is desirable to test this technique operationally and compare it with a more accurate assimilation technique such as 3DVAR. Therefore, during the first period the GPS PW will be assimilated through nudging, in the mean time the 3DVAR system will be implemented and the assimilation will be carried out using the 3DVAR only. A comparison with the nudging will be performed for a few selected cases. The GPS ZTD assimilation technique will be developed for fully operational use.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 27 Report on MM5 GPSPW nudging	PLAQ	12	Re	Pu
D 28 Report on MM5 GPSPW 3DVAR	PLAQ	24	Re	Pu
D 29 Report on MM5 GPS-ZTD 3DVAR	PLAQ	36	Re	Pu

WP 5000 – Optimisation of GPS and surface humidity assimilation

Start date: 0
End date: 36
WP leader: SMHI
Total person months per participant: SMHI 6, INM 9

The detailed descriptions are provided in the sub-workpackages below.

WP 5100 – Refining methods for surface humidity assimilation

Start date: 0
End date: 24
WP leader: SMHI
Person months per participant: SMHI 3

WP objectives:

- To develop observation operators, including observation error modelling and quality control algorithms, for assimilation of moisture information (2 meter relative humidity) from surface stations (SYNOP) in variational data assimilation.

- To test the impact of using moisture information from surface stations in variational data assimilation.

Methodology/Work Description:
The variational data assimilation system to be applied by Partners SMHI and INM already includes preliminary observation operators based non-linear, tangent-linear and adjoint versions of the post-processing for 2-meter relative humidity from an earlier version of the forecast model. These observation operators will be upgraded to be consistent with the latest version of the forecast model and complemented with models for observation and representativity errors. A data assimilation and forecast experiment will be carried out over a period of 2 weeks to test the impact of 2-meter relative humidity observations.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 30 Surface moisture observation operator	SMHI	12	Co+Re	Pu
D 31 Surface moisture impact study	SMHI	24	Co+Re	Pu

WP 5200 – Testing combined GPS and surface humidity assimilation

Start date: 24
End date: 36
WP leader: INM
Person months per participant: INM 9, SMHI 3

WP objectives:

- To test the impact of using humidity information from surface stations in combination with ground-based GPS information

Methodology/Work Description:

The ground-based GPS measurements in principle only provide information on the vertically integrated water vapour in the atmosphere above the GPS stations. It was shown by Kuo et al. (1996) in an observing system simulation study that more information on the vertical distribution of the moisture could be retrieved by adding humidity observations from surface stations. This possibility to improve the utilisation of ground-based GPS measurements will be investigated by running a 3D-Var data assimilation and forecast experiment over one month with and without 2-meter relative humidity observations.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 32 Impact of surface humidity obs. on GPS data assim.	INM	36	Re	Pu

WP 6000 – Development of methods for use of slant delays

Start date: 0
End date: 36
WP leader: KNMI
Total person months per participant: KNMI 17, TUD 5, FMI 9, DMI 3

WP objectives:
To develop methods to retrieve slant delays from ground based GPS with acceptable accuracy, to prove that the slant delays can be exploited with acceptable accuracy to (re)construct 3D fields of water vapour from integrated (1D) measurements through variational techniques, either using slant delays directly or intermediate products, and to develop methods to use the improved knowledge of atmospheric water vapour and its temporal and spatial variability over the GPS network area in NWP.

Methodology/Work Description:
Instead of obtaining zenith quantities, IWV can also be measured along a slant path from a ground-based receiver to a GPS satellite. By using not only the zenith delay of a receiver but also the slant delays the number of observation will increase by roughly a factor ten. A slant delay on its own has a two dimensional character. However, by applying variational algorithms a three-dimensional water vapour field can be retrieved from slant observations from a network of receivers. Furthermore, the horizontal resolution of the retrieved water vapour field will also profit from this larger amount of observations.
The use of variational analysis methods allows obtaining three-dimensional water vapour distributions from the atmospheric delays along the line of sight between all satellites and receivers. The technique of deriving slant path delays from a GPS receiver network will be investigated and errors and spatial and temporal correlation will be characterised. Because GPS atmospheric delay values are available covering time intervals ranging from minutes to hours the knowledge about the temporal and the spatial distribution of atmospheric water vapour will be greatly improved. Numerical weather prediction (NWP) should profit from a better description of the water vapour distribution and its error structure, especially with respect to forecasting precipitation and cloud cover.

The detailed descriptions are provided in the sub-workpackages below.

WP 6100 – Slant delay retrievals

Start date: 0
End date: 30
WP leader: TUD
Person months per participant: TUD 5, KNMI 3

WP objectives:
Develop and test methods to calculate unbiased slant delays and/or intermediate products for use in NWP assimilation, and provide a 3-month dataset for validation and assimilation tests.

Methodology/Work Description:
The derivation of zenith and slant GPS delays from GPS observations involves several assumptions about the atmospheric structure. In particular, assumptions about the atmospheric homogeneity and receiver multipath when observing satellites at low elevation angles (close to horizon) influence the results. The multipath must be carefully modelled as a function of receiver environment while the atmospheric model used for the mapping must be carefully chosen in cases of atmospheric inhomogeneities. Even when estimating only slant delays, mapping functions are still needed in order to separate receiver clock errors from atmospheric delays. Traditionally, mapping functions are empirical functions derived from multi-year averages of radiosonde data. A new approach is to derive the mapping function directly from NWP models. This could result in a significant improvement of IWV for low elevations. Pre-processing of raw slant delays before assimilation will be investigated, using additional input from NWP analysis. This will help to discriminate site dependent effects (multipath, antenna phase centre variations) and receiver clock errors from atmospheric delays, but it can also be used to derive intermediate quantities such as ZTD, horizontal gradients, scale height and or timing information, which could be used as an alternative to assimilating slant delays.

- TUD will modify currently used software, if necessary, and develop additional modules to estimate slant delays and model multipath
- TUD will carry out the processing of raw GPS data and compile a 3-month dataset for a small but dense network for assimilation and validation purposes
- TUD will compile a dataset for a 2 week test period corresponding to a period of interest because of dynamical storm system activity
- KNMI will develop a procedure to compute direct mapping function from HIRLAM
- TUD and KNMI will test the direct mapping function approach, and develop and test the pre-processing approach

Deliverables:

Deliverable title		Responsible Partner	Delivery Date	Nature	Dissem. Level
D 33	Software for slant delay retrieval/multipath mapping.	TUD	18	Co+Re	Pu
D 34	3 month test dataset.	TUD	12	Data	Pu
D 35	2 week data set from period of interest.	TUD	24	Data	Pu
D 36	Software for direct mapping function approach.	TUD	30	Co+Re	Pu

WP 6200 – Slant delay validation and observation error studies

Start date: 6
End date: 24
WP leader: KNMI
Person months per participant: KNMI 6

WP objectives:
Validation of slant delays, and assessment of the observational errors and correlations.

Methodology/Work Description:
In order to obtain realistic results the errors and correlation of the GPS slant WV must be modelled first. Observations for a network of ground-based receivers will be simulated from a 3-D water vapour field and used for assimilation trials. The goal of these simulations is to test our software and to estimate the capability of a network of GPS receivers to reconstruct refractivity field inhomogeneities at different scales. In addition we need to determine an optimal discretisation and interpolation scheme of the refractivity field to be used for the processing of observational data. The retrieved fields will be validated against water vapour radiometer measurements during the CLIWANET campaign.

These modelled assumptions and the errors and correlation introduced will be studied with the aim at deriving a valid mapping model with sufficient accuracy for the considered applications. The subsequent derivation of slant water vapour follows this new strategy and will be tested on a 3-month dataset of slant delays.

Deliverables:

Deliverable title	Responsible Partner	Delivery Date	Nature	Dissem. Level
D 37 Slant delay validation and observation error report	KNMI	24	Co+Re	Pu

WP 6300 – Observation operator development

Start date: 0
End date: 18
WP leader: KNMI
Person months per participant: KNMI 4, FMI 9

WP objectives:
To develop a slant delay observation operator for NWP.

Methodology/Work Description:
The actual GPS signal delays are measured on slant-profiles of the atmosphere. The aim in the NWP variational data assimilation is to make use of the measurements close to the raw data format with little data pre-processing. The natural first step towards using slant-delay measurements in NWP is to properly evaluate them against the model counterparts. For this task an appropriate observation operator is needed. The zenith delay observation operator is simple to develop, as the observation geometry is relatively straightforward and similar to the NWP model geometry. The slant-delay observation operator, in contrast, requires a model profile along a slanted path with unknown intersects with the model levels. Once the iterative problem of interpolating the model variables on a slanted path is solved, the associated delay can be fairly easily solved.

- FMI will develop a demonstration version of observation operator in co-operation with the expertise of the KNMI
- FMI, together with KNMI, will adjust a three-dimensional variational data assimilation system of for the HIRLAM-model for assimilation of (simulated) slant delays. Special attention will be paid to the selection of sources of data that can constrain the solution(s) (e.g. Meteosat WV, radiosonde and other satellite methods).
- FMI will make the initial evaluation of the functionality of the observation operator against the slant-delay measurements

Deliverables:

Deliverable title	Responsible Partner	Delivery Date	Nature	Dissem. Level
D 38 3Dvar Slant delay observation operator implementation	FMI	12	Co	Pu
D 39 Initial evaluation of the observation operator	FMI	18	Re	Pu

WP 6400 – Assimilation tests

Start date: 18
End date: 36
WP leader: KNMI
Person months per participant: KNMI 4, DMI 3

WP objectives:
To test the performance and study the impact of assimilation of slant delays in NWP.

Methodology/Work Description:
At KNMI, the NWP model HIRLAM (High Resolution Limited Area Model) will be used for the impact studies with a resolution of at least 10km x 10km over a 10 day period, using a three-dimensional variational data assimilation system of HIRLAM, adjusted by KNMI for assimilation of (simulated) slant delays. The performance of assimilation of these slant delays will be investigated by conducting observation system simulation experiments (OSSE):Simulated slant delay observations can be retrieved from a ECMWF nature run. The basic elements of an OSSE are a state-of-the-art data assimilation system, a nature run "truth" and a database of simulated observations. The later includes both simulated observations of conventional meteorological systems, comparable to the operational network, and simulated slant delay observations. All simulated observations, including the simulated slant delay observations, will be constructed such that the error characteritics are realistic. Assimilation of these simulated observations will be conducted with HIRLAM 3DVAR. These observations are added to the commonly used observations to asses the impact of the extra moisture information. The nature run and observation database are available for ECMWF members.

Impact studies will be performed with the analysed water vapour fields, obtained from the GPS data of a dense GPS network (Observation System Experiment, OSE). In addition, GPS data can be combined with wind profiler data to investigate the impact of the combination of these observations.

- KNMI will perform observation system simulation experiments using 3D moisture fields.
- DMI will perform assimilation tests and study the impact of assimilation of slant delays using the assimilation software developed by FMI and KNMI.
- KNMI will provide an assessment of the impact of added moisture information on the HIRLAM forecast quality

Deliverables:

Deliverable title	Responsible Partner	Delivery Date	Nature	Dissem. Level
D 40 Impact assessment of moisture on HIRLAM forecasts	KNMI	36	Re	Pu
D 41 Impact study of assimilation of slant delays.	DMI	36	Re	Pu

WP 7000 – Assimilation impact statistics and extreme case studies

Start date: 0
End date: 36
WP leader: DMI
Person months per participant: DMI 12, MetO 14, INM 18, PLAQ 14

WP objectives:
The objective is to carry out extensive tests of the impact in weather forecasting models of integrated water vapour data (IWV) or zenith tropospheric delay data (ZTD) derived from GPS in order to have a large statistical sample which can provide a scientific basis for future decisions of meteorological agencies concerning establishing a European GPS ZTD/IWV observation system.

Methodology/Work Description:
Comprehensive assimilation tests, which are the primary objective of the project are defined as 3-4 weeks of assimilation with and without GPS ZTD/IWV per season for 3 years, and the detailed analysis of 10 interesting cases per year. The tests are carried out by 4 European meteorological institutes, and analyses of the results are provided by all 7 meteorological institutes involved in the project.

Note that in the MAGIC project, the data processing system was developed and tested and run for 2.5 years, with continuous validation. Assimilation algorithms were implemented and tested on a limited data set which was enough to provide encouraging results, especially concerning the impact on precipitation forecasts. A more complete investigation is needed, in particular with assimilation tests during all seasons, and detailed investigation of the remaining error sources.

The detailed descriptions are provided in the sub-workpackages below.

WP 7100 – Co-ordination of case studies and compiling results

Start date: 0
End date: 36
WP leader: DMI
Person months per participant: DMI 1

WP objectives:

- To select periods and areas for which case studies should be made by project partners doing data assimilation and running NWP forecasts (incl. DMI). A selection will be done separately for each of the two first project years.
- To compare outcome of case studies.

Methodology/Work Description:
Monitor the operational forecasts and information about the actual weather at particular locations in order to identify periods and areas in which the forecasts were particularly poor, or in which "special" weather occurred in areas with good coverage of GPS stations partaking in the project.

Compare outcome of case studies performed by project partners.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 42 Selected cases for first year	DMI	13	Re	Pu
D 43 Selected cases for second year	DMI	25	Re	Pu
D 44 Comparison of case studies	DMI	32	Re	Pu

WP 7200 – Extensive assimilation tests

Start date: 6
End date: 30
WP leader: DMI
Person months per participant: DMI 9, METO 14, INM 18, PLAQ 14

WP objectives:

- Document the impact of ground-based GPS data on NWP data assimilation and forecast systems
- Compare the different assimilation methods used by TOUGH participants

Methodology/Work Description:
Each participating institute will carry out extensive, full-scale data assimilation experiments, for at least one month for each of the four seasons. Standard statistical methods will be used for objective verification. Analyses and forecasts with and without the ground-based GPS data will be verified against observations and analyses. Special attention will be given to the short-range forecasts of moisture, cloud and precipitation.

This will involve:

- Optimisation of initial capability for assimilation of GPS data, including implementation of any necessary bias correction scheme (based on results from WP 6000)
- Parallel, quasi-operational, assimilation in demonstration mode for a period of at least one month.
- Generation of individual case studies of regional interest for detailed study. There will be a target of 4 cases per year, where suitable cases can be identified. Cases will be biased towards more extreme events and/or where current operational models give poor guidance on an event.
- Objective verification of assimilation on analyses and short-period forecasts
- Subjective verification by forecasters.
- Comparison and appraisal of the different assimilation methods

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 45 DMI assimilation results	DMI	30	Re	Pu
D 46 INM assimilation results	INM	30	Re	Pu
D 47 PLAQ assimilation results	PLAQ	30	Re	Pu
D 48 MetO assimilation results	MetO	30	Re	Pu
D 49 Comparison of different assimilation methods	DMI	30	Re	Pu

WP 7300 – EUCOS scenario impact studies

Start date: 0
End date: 24
WP leader: DMI
Person months per participant: DMI 2

WP objectives:

- A dataset necessary for running EUCOS scenario impact studies
- A report on the impact of ground-base GPS ZTD data on selected EUCOS scenario

Methodology/Work Description:
One of the objectives of the EUCOS program of EUMETNET is to increase the cost-efficiency of the European observing system while staying at the same overall cost. It is proposed to replace some radiosondes by AMDAR aeroplane soundings. Comparing with radiosondes, one of the drawbacks of the current AMDAR is the lack of humidity information. The ground-based GPS ZTD data could provide useful complementary humidity information that allows this cost-redistribution with less negative effect on numerical weather predictions.

- DMI will select a well documented EUCOS observation period; e.g. Amstup (2000).
- DMI will perform data assimilation experiments for the proposed EUCOS scenario with and without the ZTD data. The impact of ZTD data of the data assimilation system will be assessed by traditional methods with emphasis on precipitation verification

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 50 selected EUCOS IOP assimilation impact results	DMI	24	Re	Pu

WP 8000 – GPS ZTD data provision and monitoring

Start date: 0
End date: 36
WP leader: ACRI-ST
Total person months per participant: DMI 2, MetO 2, ACRI-ST 12, Chalmers 4, PNMA 7.5, ASI 7.5, IEEC 11, LPT 8, GOP 9

WP objectives:
Ensure delivery of quality checked GPS ZTD IWV data for use in the assimilation tests.

Methodology/Work Description:
Currently GPS data is available from regional geodetic networks under pre-existing agreements with regional processing centres. In past research, in part funded by the EC MAGIC project, methodology has been developed to process the data to retrieve atmospheric properties. This methodology will be used in demonstration mode in this project, to allow the users to gain experience using the EO products in their NWP application.

The GPS data will be retrieved from the sites, transformed to RINEX format if necessary, and quality checked. The refractive delays in the GPS signals will be calculated and then geometrically mapped to the zenith delay (ZTD). This will be done in NRT continuously for at least one year. Further data will be provided in NRT or in lumps for case studies on a best effort basis. The products will be used in this form by NWP users that are developing ZTD assimilation algorithms. The data will also be further processed to remove the hydrostatic component of the delay based on surface pressure measured at the site. This non-hydrostatic, or "wet" delay will then be transformed to integrated water vapour. The products will be used in this form by NWP users that are developing nudging assimilation systems.

Each regional data processing centre will be responsible for retrieving the GPS data, processing the data, and transferring the data to the project ftp site in NRT. In processing the data, the centres will include stations from a common reference network in their solutions to provide a means for crosschecking the quality of the data and to ensure that the reference frames used are consistent. Similar products that are available from organisations outside the consortium that cover other regions will also be made available to the meteorological users (Germany in particular).

The first 3 months are to be used to improve raw data flow as necessary, verify the robustness of the processing system and make any adjustments to the processing concerning the station distribution, following the recommendations of the workpackage leader ACRI-ST and the processing committee. During this 3 months and the following 21 months, the products will be provided continuously to the users as a demonstration prototype system. 6 months into the project the quality control standards derived in the WPNMA000 will be implemented. During the final 6 months a final evaluation of the dataset as a whole will be carried out by each processing centre.

The detailed descriptions are provided in the sub-workpackages below.

WP 8100 – Product quality monitoring and reporting

Start date: 0
End date: 36
WP leader: ACRI-ST
Person months per participant: ACRI-ST 3

- ACRI-ST will monitor the quality of the data and report to the meteorological users each month with an automatically generated summary report on the quality.
- ACRI-ST will establish an archive for reporting significant changes to any site or processing system.
- ACRI-ST will establish a mirror site to the NWP user data exchange site for backup purposes.
- ACRI-ST will monitor the network status (active sites) daily.
- ACRI-ST will disseminate this information to partners on the project database web site.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 51 start of monthly GPS ZTD IWV quality reports	ACRI-ST	06	Re	Pu
D 52 Project database web site	ACRI-ST	06	web	Pu

WP 8200 – Maintain facilities for data exchange for NWP users

Start date: 0
End date: 36
WP leader: METO
Person months per participant: METO 1

WP objectives:
Provide and maintain facilities for data exchange, especially of near-real time data for NWP users.

Methodology/Work Description:
- Provide infrastructure facilities for file exchange (e.g. private project ftp server, GTS/RMDCN)
- Lead on data formatting and dissemination standards, both within the project and externally (especially WMO)
- Provide and maintain supporting software (e.g. BUFR encoder/decoder)

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 53 data exchange formats	MetO	03	Re	Pu
D 54 support software	MetO	06	Co	Pu

WP 8300 – Regional GPS data production and validation

Start date: 0
End date: 36
WP leader: ACRI-ST
Person months per participant: Chalmers 4, PNMA 7.5, ASI 6.5, IEEC 11, LPT 8, GOP 9, ACRI-ST 6

WP objectives:
Provide GPS ZTD data continuously for a period of at least one year of near-real time quality for NWP users. These data are to be used for the seasonal assimilation experiments and quasi operational assimilation experiments in wFMI200. Further GPS ZTD data on a best effort basis, to be used for case studies.

Methodology/Work Description:

- All processing centres will elect one person to participate on the GPS ZTD processing committee deciding the final geographic distribution of the products, and decide on the routine implementation of procedure refinements developed in the GPS ZTD processing research workpackage.
- All processing centres will document their implementation of the GPS ZTD IWV system at T0 + 3 months in the format specified by ACRI-ST. This will also be included as an appendix to the annual GPS ZTD IWV validation reports and the Final GPS ZTD IWV system evaluation report.
- All processing centres will document their implementation of the updates to the GPS ZTD IWV system taking into consideration the processing quality improvements derived in WCHAL000.
- ACRI-ST will process data from French and western Mediterranean stations.
- Chalmers will process data from Sweden and Denmark.
- PNMA will process data from Norway and other Scandinavian countries.
- ASI will process data from Italy
- IEEC will process data from Spain
- LPT will process data from Switzerland and other Alpine countries
- GOP will process data from central European countries
- Other stations not included on the list above will be processed by one of the centres following agreement of the PGZPC (GPS ZTD processing committee)
- All processing centres will process data from the core IGS reference sites
- All processing centres will deliver the data to the MetO database.
- All processing centres will report any significant changes to any site or processing system to the archive established by ACRI-ST.
- All processing centres will carry out continuous validation at the data supply side against radiosonde and model data.
- All processing centres will report on the validation activities of their centre in each of the first 2 annual reports
- All processing centres will provide an evaluation of their results for the entire duration of the demonstration in a contribution to the final evaluation report.

Note: PGZPC refers to the PGZPC GPS ZTD Processing Committee and includes a representative from each processing centre.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 55 Initial delivery of GPS ZTD IWV products	PPC	04	Da	Pu
D 56 GPS ZTD IWV validation reports	PPC	24	Da	Pu
D 57 Final GPS ZTD IWV system evaluation	PPC	30	Re	Pu

WP 8400 – Furnishing continuous radiosonde and NWP output

Start date: 0
End date: 36
WP leader: DMI
Person months per participant: DMI 2

WP objectives:
To provide

- Continuous radiosonde observations (every 12 h) over Europe throughout the project.
- HIRLAM NWP output (every 5 min) for all GPS stations processed in the proposed project.

Methodology/Work Description:
Radiosonde observations can be used as an important independent data set for validating GPS ZTD data both on daily basis and on long-term statistics. The quality of the radiosondes is high, but the temporal and spatial resolutions sometimes lead to problems. NWP analyses and forecasts, on the other hand, can be used as another source of data with uniform resolution in 4-dimensions. The importance of having continuous radiosonde and NWP output as references for GPS data monitoring has been demonstrated during the MAGIC project.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 58 Radiosonde data specification document	DMI	03	Re	Pu
D 59 HIRLAM output specification document	DMI	03	Re	Pu
D 60 Start of delivery European radiosonde data	DMI	03	Da	Pu
D 61 Start of delivery HIRLAM analyses/forecast	DMI	03	Da	Pu

WP 8500 – Validation database development and maintenance

Start date: 0
End date: 36
WP leader: ACRI-ST
Person months per participant: ACRI-ST 3

WP objectives:
Make accessible to all project participants the data necessary for validating the quality of the GPS ZTD IWV products and the forecasts.

Methodology/Work Description:
The database will contain the radiosonde and NWP data provided in WPACRI400, and the precipitation data that is collected for validating the short-term precipitation forecasts.

- Maintain the validation database; assure acquisition, compilation, and access to precipitation data provided by met agencies for validation case studies.
- Compile format specifications for each data set
- Maintain a catalogue of access information and location for each data set.
- Describe the project data sets and maintain them in a Project Dataset Description
- Update the Project Dataset Description at 6-month intervals.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 62 Validation data sets with web site access	ACRI-ST	12	Da	Pu

WP 8600 – User Validation and Feedback

Start date: 3
End date: 33
WP leader: METO
Person months per participant: METO 1

WP objectives:
Continuous monitoring and validation against NWP

Methodology/Work Description:
- Develop and implement on-line (automatic) monitoring /validation and reporting systems.
- Continuously monitor incoming near-real time data for timeliness and reliability with standard statistics reported at least daily.
- Regular (at least daily) validation of incoming GPS data against NWP model equivalent parameters, using standard statistical methods.
- Production of monthly reports and summary report of whole demonstration period.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 63 start delivery of monthly monitoring/validation report	MetO	06	Re	Pu
D 64 monitoring and validation performance summary	MetO	33	Re	Pu

WP 9000 – GPS ZTD system research

Start date: 0
End date: 30
WP leader: Chalmers
Total person months per participant: Chalmers 9, ASI 3, TUD 5

WP objectives:
Carry out basic research on the source of un-modeled errors in the GPS ZTD IWV products, and increase the robustness and quality of the products with new methodology.

Methodology/Work Description:
In previous work developing the methodology and its validation, it was established that the GPS ZTD IWV products are of quality comparable or superior to existing data sources available to the NWP user community. In particular, the products were shown to be in overall good agreement with radiosondes (less than 10mm of delay). However, the products occasionally had epochs of unexplained poor data quality. In addition, long spatial and temporal signals in the residuals from radiosonde and NWP comparisons have been detected. This workpackage will investigate the source of these errors and contribute new techniques to the methodology implemented in the demonstration processing.

- The detailed descriptions are provided in the sub-workpackages below.

WP 9100 – Robust quality indicators

Start date: 00
End date: 09
WP leader: TUD
Person months per participant: TUD 2.5

WP objectives:
Increase the robustness and quality of the products by developing an improved quality indicator.

Methodology/Work Description:
Most of the GPS software packages provide the standard deviation of the estimated Zenith Total Delay (ZTD) parameter as an estimate of the quality of the solution. The standard deviation is a formal measure of quality computed from the inverse of the normal matrix. As a measure of quality it is seriously flawed because

- It does not take into account the actual quality of the observations,
- It is unaware of important errors such as multipath, and
- It assumes the orbits (and sometimes satellites clocks) are perfect.

The standard deviation is always too optimistic and cannot be used to model the errors during the assimilation into NWP.

A new quality indicator for the ZTD will be developed and tested. The new indicator will be computed from the estimated least squares residuals by using variance component estimation techniques, taking into account the degree of freedom over the domain of the ZTD parameter.

- TUD will develop robust quality indicators dependent on the number of data and degrees of freedom of the geodetic solution
- TUD will distribute the algorithms to be implemented by all processing centre in the first revision of the processing system.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 65 quality indicator algorithm	TUD	09	Me	Pu

WP 9200 – Long term bias elimination

Start date: 0
End date: 30

WP leader: Chalmers
Person months per participant: Chalmers 7

WP objectives:

- Determine and characterise biases in the estimated ZTD time series from ground-based GPS data.
- Provide recommendations on how to eliminate the sources of the biases.

Methodology/Work Description:
The strength of ground-based GPS is certainly not its absolute accuracy. Because of its sensitivity to signal multipath effects, varying the elevation angle cut-off limits - or using different schemes for down-weighting low elevation angle observations - will typically have a significant impact on the estimated ZTD value. A constant bias over decades is in principle not a problem but if there are variations at the time scales of years it will influence both NWP models and long term climate monitoring.

We will use long time series (> 5 years) of independent radiosonde and microwave radiometer data to study these effects and believe that a correct assessment can be made at the 5-10 mm level in ZTD. Very-Long-Baseline Interferometry (VLBI) is another method which will be used. Several European VLBI sites, e.g., Wettzeell, Matera, and Onsala, are co-located with important GPS sites in the IGS network, where data are publicly available. The VLBI estimates of ZTD are obtained from the same type of estimation technique as in GPS but due to the large directional antennas used the multipath effect is in practise eliminated. VLBI observations are, however, not continuous, but 24-hour observing sessions bi-weekly or monthly for more than five years provide a sufficient database. .

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 66 Biases in ZTD	Chalmers	30	Re	Pu

WP 9300 Co-ordinate system biases

Start date: 00
End date: 24
WP leader: ASI
Person months per participant: ASI 3

WP objectives:
Investigate biases introduced into the GPS ZTD IWV products related to reference frames and establish a methodology for ensuring consistency among processing centres concerning reference frames.

Methodology/Work Description:
GPS tropospheric zenith delay is correlated with the site co-ordinates, especially with the vertical one. For meteorological application there is no need to estimate them when processing GPS data, but, in order to derive the 'best' possible ZTD estimates, there is the need to know site co-ordinates with a certain level of accuracy. Generally they are obtained averaging over a longer period of time daily station estimates. So even for pure meteorological application there is the need of station co-ordinates monitoring. Of course, they are related to the terrestrial reference frame (TRF) in which they have been computed, and the changing of TRF could introduce biases into the GPS ZTD IWV products. Furthermore constrains to the reference frame are also induced by fixing the GPS orbits (IGS orbits are given in a TRF) during the data reduction, how is commonly done when regional network are considered. Therefore it is an interesting question to understand how to deal with the biases related to reference frame, even for climate investigations. Furthermore, the geodetic reference frame is always being improved, there are occasionally slight changes which can lead to offsets in the long-term trend of GPS ZTD.

- The influence different reference frames have on GPS ZTD estimates will be evaluated.
- ASI will establish a methodology for dealing with updates to the reference frame
- ASI will verify that differences between processing centres estimates for the reference IGS stations are not due to orbit errors, or co-ordinate errors or reference frame errors.
- ASI will establish guidelines for verifying the quality of GPS ZTD IWV data by examining repeatability of co-ordinates and lead the implementation of these guidelines in the GPS ZTD IWV processing.

Deliverables

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 67 GPS ZTD and reference frame correlations	ASI	24	Re	Pu

WP 9400 Biases correlated with seasonal signals

Start date: 0
End date: 24
WP leader: Chalmers
Person months per participant: Chalmers 2

WP objectives:
Determine the reason for seasonal biases in the GPS ZTD IWV products.

Methodology/Work Description:
Results from the EC MAGIC project showed that the difference between GPS ZTD and radiosondes increased in magnitude in high humidity regimes, producing a seasonal signal in these differences. These signals limit the ability to separate a climatic signal from the noise in the of GPS ZTD products.

- Chalmers will investigate the seasonal component of long term.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 68 GPS ZTD IWV seasonal bias report	Chalmers	33	Re	Pu

WP 9500 Optimal combination of regional solutions

Start date: 00
End date: 09
WP leader: TUD
Person months per participant: TUD 2.5

WP objectives:
In a distributed network processing approach, a method is required for ensuring the results from the processing centres are compatible.

Methodology/Work Description:
The International GPS Service (IGS) has developed a method for combining ZTD solutions from different processing centres by removing a bias between processing centres and averaging the results. The same method is applied for the 12 analysis centres of the EUREF Permanent GPS Network (EPN). Typical for IGS and EUREF is, that almost all stations are processed by at least three processing centres.

In our distributed network, only a subset of stations will be common among processing centres, but these can be used to verify that there are no offsets. Also, IGS and EUREF operate in post-processing mode.

The batch type of processing used by IGS and EUREF will be converted into a Kalman filter approach that can be used in near real-time applications. The differential biases between the analysis centres will be modelled for the stations in common. Special techniques for the detection, identification and adaptation of outliers and biases, developed at TUD, will be used. Algorithms will be developed and tested.

- Two possible refinements will be investigated
  1. Extension or combination of the NRT combination with bias reduction algorithms (using output from NWP analysis) to model absolute biases,
  2. The use of error correlation models to provide analysis centre dependent corrections for stations that are not in common.

  Both of these additional investigations are related to other workpackages in this proposal.

- TUD will develop automated methodology for a regional combination of solutions following the EUREF model, in order to provide the best integrated product from the regional products. They will aid in the implementation of this methodology at the processing centres at To + 9 months.

Deliverables:

Deliverable title	Resp. Partner	DelivDate	Type	DissemLevel
D 69 Regional Combination methodology and report	TUD	09	Me+Re	Pu

WP 10000 – Exploitation and dissemination

Start date: 0
End date: 36
WP leader: DMI
Person months per participant: DMI 1.5, KNMI 1.5, all other partners 0.5

WP objectives:
Facilitate the exploitation of research results by partners within the consortium and increase the potential user community outside the consortium through the dissemination of projects results. Co-ordinate interactions with complementary European and international scale initiatives.

Methodology/Work Description:
Scientific and technical exploitation of project results within the consortium is covered in specific work-packages with those objectives. However, for the long-term exploitation of GPS data, it is necessary to co-ordinate with internal and external users at the European level. This work-package carries out the necessary dissemination activities to accomplish these long term objectives, including co-operations with the ongoing COST 716 action (Exploitation of ground-based GPS for climate and numerical weather prediction applications, with the ongoing COST 720 action (Integrated Ground Based Remote Sensing Stations for Atmospheric Profiling), with IGS working groups and with EUMETNET. TOUGH will provide research results to these actions and organisations necessary for drawing conclusions and supporting recommendations at an European scale.

- Disseminate project results via the project web site
- Compile database of users and potential users
- Organise a user workshop in collaboration with an international conference
- Participate in European and international actions to support European and global observing systems
- Maintain an exploitation plan consistent with the needs of users within the consortium and with a perspective towards a wider user community
- Represent the project to the main European level users and organisations, e.g. EUMETNET, EUMETSAT
- Represent the project to the national level users, i.e. meteorological agencies
- Presentation of the project level results at international conferences
- At end of project provide recommendations for European use/processing of GPS delay data (PM resources are shared with workpackage 1400 meeting preparation and participation).
- Compile a comprehensive report with recommendations for European use of combined GPS delays network data for numerical weather prediction.
- Each NWP participant will contribute to the recommendations in the 1 month prior to the final meeting in a 2 page report format with the following indicative headings:
  - Background description of operational NWP system at their agency
  - Description of methodological approach for using GPS ZTD or delay data developed and tested in the project
  - Short summary of tests and extreme cases
  - One illustrative figure

    - Conclusions on perspectives at the national level and European level
- Each processing centre and non-NWP partner will contribute to the recommendations in the 1 month prior to the final meeting in a 2 page report format with the following indicative headings:
    - Summary description of their implementation of the GPS ZTD IWV system including improvements brought about by the WCHAL000 research activities and recommendations for future processing systems.
    - Summarised evaluation of validation activities with mention of any remaining problem areas.

Deliverables:

Deliverable title		Resp. Partner	DelivDate	Type	DissemLevel
D 70	Project web site	DMI	03	Other	Pu
D 71	Project publicity brochure	DMI	04	Other	Pu
D 72	User workshop proceedings	KNMI	24	Re	Pu
D 73	GPS Data Recommendations for European NWP	PNWP	36	Re	Pu
D 74	Final project publisity brochure	DMI	36		Pu
D 75	TIP	PALL	36		Other

4. Contribution to Objectives of Programme/Call

The proposed project contributes specifically to Objective 1 and Objective 2 of Key action "7.2 Development of generic Earth observation technologies".

Objective 1: "Introduce scientific results into new or existing applications", and Objective 2: "Improve the exploitation of Earth observation".

Measurements from an existing network of ground-based GPS stations, developed mainly for geodetic purposes and available with very minor additional costs, are utilised for numerical weather prediction purposes (Objective 2). This is a new application of existing geodetic measurements, and it will allow numerical weather prediction centres to specify the initial moisture field with an accuracy and detail that has not been possible in the past. Improved and more detailed forecasts are expected, in particular of precipitation.

Furthermore, the utilisation of ground-based GPS measurements in numerical weather prediction has been made possible through the introduction of advanced data assimilation schemes like 3- and 4-dimensional variational data assimilation (3D-Var and 4D-Var), that have been developed through significant scientific efforts over the past 5-10 years (Objective 1).

5. Community added value and contribution to EU policies

European (and global) dimension of the problem

The operational numerical weather prediction models that provide European citizens with 1-2 day forecasts cover approximately a quarter of the globe, even for the limited area regional models such as HIRLAM. These models require, particularly for rainfall prediction, a dense, evenly distributed and accurate observation of the water vapour field. The global NWP models that provide boundary conditions for the operational models require improved observations as well. This means that resolving problems with deficiencies in the observing system for European users requires European scale efforts.

Co-operative initiatives have existed for some time for radiosonde and other observation networks, as well as for atmospheric remote sensing from space. The ground-based GPS data offer the advantage of an existing station network and existing data processing capabilities. It is necessary when considering using GPS as an atmospheric remote sensing source that the data collection and data processing efforts are shared between European member states so that the observation system is dense enough to have significant impact. In particular for detailed rainfall forecasts during the warm season with the next generation mesoscale NWP models, a station density of approximately 30 km is required. Furthermore, a carefully co-ordinated European GPS data processing effort is necessary in order to guarantee a homogenous and well documented data quality. Furthermore, a carefully coordinated European GPS data processing effort is necessary in order to guarantee a homogenous and well documented data quality. Therefore, the contribution that GPS data can make to resolving the problem also requires European scale efforts.

European added value for the consortium

The objectives proposed in TOUGH benefit by carrying out the research as a collaborative effort at the European level. Bringing together a strong international group of people working on similar problems will increase the efficiency of the development. Problems will need to be tackled in terms of NRT delivery, orbit determination, stability of reference frames, and understanding of noise sources that require international co-operation. The joint efforts of the geodetic and the meteorological communities in the present proposal will give added value in the form of improved data quality for both of these communities. By using the GPS information, the meteorologists will be able to improve the quality of the modelling output products, and these improved products can help the geodetic community to improve their data processing (feedback loop) and products for geodetic applications.

The expertise in making the GPS observations and retrieving parameters of meteorological interest is found in different countries than the infrastructure support and techniques for the assimilation activities. The proposed collaborations between trans-national partners will increase the efficiency and capabilities of the consortium. The size of the consortium is optimum. The NWP agencies are working in pairs or small groups to resolve critical assimilation problems, benefitting by multiple approaches. The group of NWP agencies working on assimilation is a large enough critical mass to have a good sampling of the expected benefits at a European scale. The group of GPS ZTD data processing partners is large enough to ensure an extensive European scale data set, with a higher level of coordination to assure good communication. As a result, good examples of pan-European efforts for developing the Earth Observation programs will be created.

Contribution to European Union policies

The consortium contributes to the development of techniques necessary for assimilation and exploitation that are consistent with European priorities:

- Testing the impact of GPS observations in the context of the EUMETNET Composite Observing System furthers its objectives of optimizing the cost effectiveness of the non-spaceborne observing system.

The means for developing the GPS ZTD system into an operational Earth Observation system is consistent with the European level policies for cooperation in meteorological observations. This is discussed in more detail in section C9.

- Developing assimilation algorithms and testing the impact of GPS ZTD systematically on large datasets is critical input to the objectives set out in the European COST Action COST 716 "Exploitation of Ground-based GPS for climate and numerical weather prediction Applications" which requires assimilation tests that would otherwise be based on a very limited set of test cases.

World Meteorological Organization (WMO) has assessed satellite capabilities for NWP and climate monitoring purposes (WMO, 1998; WMO, 2000). The WMO has given a priority to higher resolution observations of humidity. The WMO has concluded that such observations are an important input, not only to numerical weather prediction, but also to the Global Climate Observing System (GCOS).

- The refining of techniques for new humidity observations will contribute to the evolution of European policies on the regional and global climate change by testing the detection limits of the new observation techniques.

6. Contribution to Community social objectives

Improving the quality of life and health and safety

- Daily forecasts and warnings of severe weather situations become a vital asset for many areas of life and activities for public and industrial businesses with an ever-increasing economical importance.
- The use of accurate and timely weather information, both actual and forecast, is essential for the operation of air transport. As air traffic grows, new aeronautical systems are being developed in order to optimise aircraft operation and thus to ensure a high level of safety and in particular in the meteorological area.

The humidity observations are expected to make the significant improvements in weather prediction for European citizens. The most improvement should come in precipitation forecasts of European models. Therefore the public should benefit most importantly from more reliable warnings that are especially useful for the prediction of floods, increasing the safety of European citizens.

Improving employment prospects and development of skills in Europe

TOUGH makes no direct contribution to employment prospects in Europe.

TOUGH makes an important contribution to the development of skills in Europe:

- There will be many of the activities in the next five years in research disciplines related to GPS systems and the use of the future European GALILEO system. Public uses of precise satellite time and positioning information together with a growing commercial market made it clear that modern highly developed countries need access to such skills. TOUGH project will contribute to develop such skills.
- One of the major error sources in precise global time and position information is the contribution from atmospheric phenomena. TOUGH research results will increase the ability of European users to use GPS information.
- Modern numerical weather prediction systems and climate research activities rely more and more on satellite Earth observations. TOUGH will develop skills in Europe in the most forefront data assimilation theories and applications related to GPS information.
- TOUGH reinforces the development of state of the art and innovative GPS techniques at the higher education level that will be directly and indirectly transferred to increase the skills of the European workforce.

Preserving and/or enhancing the environment

Water vapour structure plays a very important role in environment forecast and monitoring. TOUGH will improve knowledge of the water vapour structure by providing complementary observation data and by improving data assimilation systems.

A better understanding of the water vapour structure has also important implications for climate change researches. TOUGH will start to investigate the long term error characteristics of GPS measurements, which will be a stable independent data source for climate monitoring.

7. Economic development and scientific and technological prospects

Economic benefits

There are short-term economic benefits due to increasing the cost-effectiveness of the European observing systems. For example, the objectives of the EUCOS programme are to increase the cost-efficiency of the European observing system over the continents while staying at the same overall cost. This is proposed by replacing radiosondes with AMDAR airplane soundings, however the AMDAR soundings do not contain humidity information. The ground-based GPS ZTD data will provide supplementary humidity information that allows this cost-redistribution with less negative effect on the forecasts. Thus the cost-effectiveness of the GPS observations are very beneficial to end users at the European level as well as at the level of the national meteorological agencies.

There are long term economic benefits from the improvement in NWP, in particular for forecasting of severe weather, as the ground-based GPS data are expected to improve the humidity analysis and lead to better forecasts for humidity and precipitation. The improved weather analyses and forecasts deliver benefits to the European public, to aviation, and to the fishing and shipping industries, both in terms of safety (meteorological hazards and dangers detection and avoidance) and cost effectiveness (e.g., improved flight profile and conduct).

Strategic impact

Strategic impact for Europe
The investment in the research for developing methodologies to exploit the GPS observations will place Europe in a leading position on the international scene in this domain. Current research in the U.S., for example, does not have the equivalent density of potential observations, nor the breadth of experience with different assimilation approaches. These are key to successful exploitation of the data.

Strategic impact for meteorological agency users of project results
Improvement of weather prediction quality will add to the competitiveness of meteorological agencies that supply services to the European public, to aviation and to marine transport industries.

Strategic impact for TOUGH partners
Participation in the project will help the research institutes involved to remain at the forefront of their respective fields.

Exploitation plans

There are three general types of research results emanating from the TOUGH research that are planned for exploitation:

- Validated observation data sets
- Assimilation algorithms for ground-based GPS data necessary for exploitation in NWP
- Reports on the effectiveness of the observation techniques, on which decisions regarding the implementation of the observing systems can be based.

Six national meteorological centres have already been included as participants in the consortium. These are the DMI, FMI, KNMI, INM, SMHI, and the UK Met Office. The plan for exploitation within the project is well defined .

Ground-based Zenith Total Delay (ZTD) data will be exploited by DMI, FMI, SMHI, KNMI, INM, and the Met Office within the project. The development that has taken place in previous projects such as the EC project MAGIC and COST 716 has resulted in a ZTD-component that could be included into operational data assimilation systems, and pre-operational exploitation is expected to occur at the meteorological centres involved in TOUGH during the lifetime of the project. The ZTD data will also be exploited as a source of validation data, and will be exploited for climate research by DMI and other climate users outside the project.

Slant refractive delays from dense arrays will be exploited by KNMI, TUD, FMI and DMI. The emphasis is on the assimilation capability for slant delays in some form. This will make the data much more exploitable to general users.

The conceptual exploitation plan for the TOUGH project is illustrated in the following diagram.

During the project
Exploitation plans for the period during the project include, for example, cooperation with the ongoing COST 716 action *Exploitation Of Ground Based GPS For Climate And Numerical Weather Prediction Applications*. The COST 716 action provides organisational support for making recommendations at an European level, while TOUGH will contribute research results to support COST recommendations at a European scale, and gain from a larger user perspective.

Short term exploitation plan
For the short and long-term exploitation of GPS data in an operational manner, it is necessary to co-ordinate with internal and external users at the European level. In the short term, TOUGH is expected to contribute to recommendations for defining an operational system in

the context of EUMETNET following guidelines established by WMO. TOUGH assimilation impact results provide key input for the definition of the future operational system.

TOUGH reports on assimilation tests and the developed algorithms will provide key input for decisions on operational implementation of GPS ZTD data assimilation within the meteorological institutes at the national level.

Long term exploitation plan
The long term exploitation plan involves the implementation of an operational GPS ZTD network most likely based on an approach defined by EUMETNET. It also involves the actual implementation of the developed assimilation algorithms in the operational forecasts. Further exploitation, particularly for mesoscale situations, will evolve as the operational GPS ZTD network densifies. Results from the mesoscale assimilation tests carried out in TOUGH will contribute to the evolution of future high resolution exploitation of the GPS ZTD data. The techniques developed in TOUGH for understanding and reducing long term biases are critical for long term exploitation of the data for climate studies.

Dissemination strategies

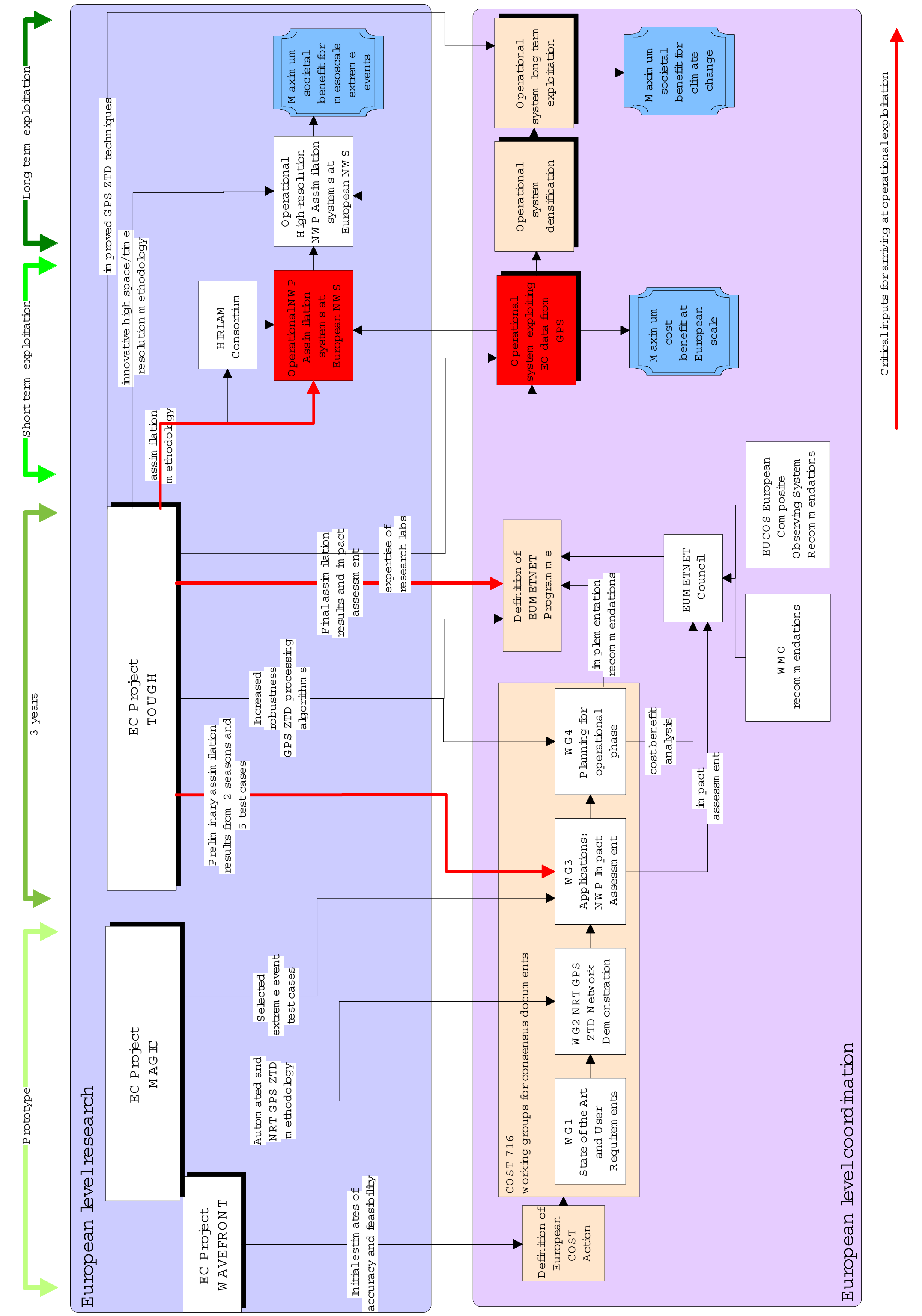
The objective of the dissemination strategies are to facilitate the exploitation of research results by partners within the consortium and increase the potential user community outside the consortium through the dissemination of project results. The TOUGH consortium, and the DMI and KNMI in specific WP 10000 activities, will co-ordinate interactions with complementary European and international scale initiatives.

Assimilation algorithms and methodology are an important result that will also be disseminated to users outside the consortium. This will take place in exchanges with the HIRLAM consortium, of which five partners are members. It will also take place through presentations at European and international conferences.

Results in forms of scientific papers and reports, particularly those from impact studies, will be disseminated to users outside the consortium to promote further exploitation of the data and aid decision-making on future network design.

The detailed dissemination plan includes:
- Disseminate project results via the project web site
- Organise a user workshop in collaboration with an international conference
- Participate in European and international actions to support European and global observing systems
- Represent the project to the main European level users and organisations, e.g. EUMETNET.
- Represent the project to the national level users, i.e. meteorological agencies
- Present the project level and workpackage level results at international conferences
- Compile a comprehensive report with recommendations for European use of combined GPS network delay data for numerical weather prediction at the end of project.

Graphical description of exploitation plan.



8. The consortium

The consortium is a well-balanced group of organisations that cover the extensive domains of expertise required for the project success, from geodesy to meteorology. The consortium includes EO data suppliers (academic and private researchers), and EO data users (the NWP agencies). The complementary expertise of the partners is expected to be a major benefit to the consortium and allow rapid progress towards the project objectives.

No.	Loc	Partner Name	Expertise	Role in Consortium
DMI	DK	DMI, Danish Meteorological Institute	National met service, expertise in operational numerical weather prediction, atmospheric and ionospheric research, satellite remote sensing	**End User** Project co-ordination. Development of assimilation methodology and impact studies in NWP. Production of validation data sets.
SMHI	SE	SMHI, Swedish Meteorological and Hydrological Institute	National met service, expertise in operational numerical weather prediction, atmospheric and hydrological research.	**End User** Scientific co-ordination. Development of assimilation methodology.
METO	UK	MetOffice, UK Met Office	National met service, expertise in operational numerical weather prediction, atmospheric research	**End User** User requirements, development of assimilation methodology and impact studies in NWP. Validation of GPS data.
INM	ES	INM, Instituto Nacional de Meterología de España	National met service, extensive activities in weather and ocean forecasting and in climate research and prediction	**End User** Assimilation, especially concerning combined use of GPS and surface humidity data.
LAQ	IT	LAQ, CETEMPS University of L'Aquila	Centre for research on heavy precipitation events associated with the facility for operational weather prediction	**End User** Assimilation, especially applied to mesoscale heavy precipitation events
KNMI	NL	KNMI, Koninklijk Nederlands Meteorologisch Instituut	National met service, expertise in operational numerical weather prediction, atmospheric research	**End User** Development of assimilation methodology, validation and testing for slant delays.
FMI	FI	FMI, Finnish Meteorological Institute	National met service, expertise in operational numerical weather prediction, atmospheric research.	**End User** Development of assimilation methodology for slant delays. Error correlations.
ACRI-ST	FR	ACRI-ST Sciences de la Terre	Private research SME, expertise in GPS atmospheric research, remote sensing and satellite sensor simulator development.	Data supply co-ordination, processing of GPS data into ZTD and IWV, providing and maintaining databases, seasonal GPS ZTD error correlations.
CHAL	SE	Chalmers University of Technology	University with research expertise in water vapour radiometry and precise applications of GPS	Processing of GPS data into ZTD and IWV. Research in removal of long-term biases.
NMA	NO	NMA, Norwegian Mapping Authority	National agency for geodesy, cartography and geographic information	Processing of GPS data into ZTD and IWV.
ASI	IT	ASI, Italian Space Agency Centre for Space Geodesy	National space agency with expertise in space geodesy, Precise applications of GPS.	Processing of GPS data into ZTD and IWV, error studies related to reference frames.
IEEC	ES	IEEC, Institut d'Estudis	Private foundation whose	Processing of GPS data into

		Espacials de Catalunya	activities are related to spatial technology and scientific research of and from space; expertise in precise applications of GPS	ZTD and IWV
LPT	CH	LPT, Swiss Federal Office of Topography	Government organisation for geodesy, topography, cartography and the controlling of the real estate cadastre; expertise in precise applications of GPS	Processing of GPS data into ZTD and IWV
GOP	CZ	GOP, Research Institute of Geodesy, Topography and Cartography - Geodetic Observatory Pecný	Branch of the national geodetic survey, experimental research in geodetic astronomy, gravity field variations, satellite geodesy, precise applications of GPS	Processing of GPS data into ZTD and IWV
TUD	NL	TUD, Delft University of Technology, department of Geodetic Engineering	University with expertise in the development of theory and data analysis for GPS and precise applications of GPS	Derivation of slant delays, development of quality indicators, optimal combined solution.

Co-operation between Research Institutes and End Users

The research institute and end user members of the consortium have worked together on previous projects. This gives confidence in the strength of the collaboration which is important for the success of the project. Because of these existing relationships, the consortium is assured of successful collaboration and effective transfer from data suppliers to users despite its large size.

For example:

IEEC and ACRI-ST have worked as suppliers of validated data and methodology to the end user DMI in the MAGIC project for exploiting ground-based GPS ZTD data in NWP and climate.

Chalmers, ASI, IEEC, LPT, and GOP have worked as suppliers of validated Earth Observation data derived from GPS to end users in the COST 716 Action. The COST 716 action objectives are to promote the transition of ground-based GPS meteorology to the pre-operational stage. DMI, SMHI, and UK Met Office have collaborated through discussions of preliminary assimilation tests for COST 716. All partners have been involved in COST 716 and have developed close, constructive working relationships that cross interdisciplinary boundaries through that involvement. This previous collaboration has also established a larger end user community for the products developed in the previous EC research projects.

IEEC and Chalmers have worked as suppliers of validated data to end user UK Met Office in the EC WAVEFRONT project for demonstrating the accuracy of ground-based GPS data.

IEEC, DMI, and UK Met Office have worked together in the EC CLIMAP which began pilot tests on the feasibility of delivering NRT GPS ZTD data.

DMI, SMHI, INM, KNMI, and FMI are all members of the HIRLAM consortium. These groups already have experience collaborating on model development. This existing collaboration will assure that assimilation techniques that are developed in TOUGH will be exploited by a larger community.

Chalmers, ASI, IEEC, LPT, NMA, TUD and GOP have a history of cooperation established in the context of EUREF (European Reference Frame) and the IGS (International GPS Service) for geodetic research.

No.	Name	WAVEFRONT	CLIMAP	MAGIC	COST716	CLIWANET
1	DMI		X	X	X	
2	SMHI				X	X
3	MetO	X	X		X	
4	INM				X	
5	LAQ					
6	KNMI		X		X	X
7	FMI				X	
8	ACRI-ST			X	X	
9	Chal	X			X	X
10	NMA				X	
11	ASI			X	X	
12	IEEC	X	X	X	X	
13	LPT				X	
14	GOP				X	
15	TUD				X	

9. Project management

Management structure

Co-ordinator - CO

The overall project management and co-ordination will be carried out by DMI, who will be the single point of contact for the project for the European Commission and external communication. DMI will be responsible for the technical direction of the activities, and overall quality assurance.

Co-ordination group leaders

The co-ordination group leaders are responsible for assuring effective communication among a group of tasks and verifying that progress is being made to attain the high level objectives of the group of workpackages. There are 2 groups with designated leader:

- Scientific co-ordination – DMI assisted by SMHI
- Data supply co-ordination – ACRI

The main priority of the groups is to assure that the output project products conform to the specifications. If necessary the group leaders will meet with their group at more frequent intervals than the 6-month project progress meetings and will deal with detailed data exchange issues. Co-ordination group leaders are responsible for input to the progress meeting agenda for issues concerning the progress of the group. The co-ordination group leaders will be responsible for all aspects of project management at the group level, including schedule monitoring, quality assurance, and direct interactions with the user participants in the project. The group leader will provide minutes of any individual group meetings to the consortium.

Steering committee

DMI will lead a steering committee made up of the NWP workpackage leaders that will be responsible for refining the definition of the actions to be taken by the consortium as a whole in order to effectively carry out the work, when these actions are not defined in the proposal, or need to be defined in more detail. The actions will be approved by the lead scientist of all partner organisations that are concerned by the action. The steering committee will meet at the 6 months project progress meetings, and more frequently when necessary. Reports of the actions of the steering committee will be made at the progress meetings, and minutes will be provided by the steering committee to all partner lead scientists.

GPS ZTD Processing Committee

The GZPC will be made up of one representative from each of the GPS data processing centers that are involved in the proposal. Under the guidance of ACRI-ST, they will be responsible for approving consensus decisions regarding processing and delivery of the GPS ZTD products to the consortium partners.

Work package leaders

Work package leaders are responsible for the work defined in the work package descriptions, including the work of other organisations also involved in the work package. They are accountable to the group co-ordinator, project co-ordinator for the deliverables of the work package.

Lead scientists

The lead scientist at each organisation is responsible for communication between the consortium and individual members of the team from the organisation. The lead scientist is responsible for the delivery of the deliverables assigned to their organisations. The lead scientist will assure that financial/administrative issues concerning the organisation are handled correctly by the financial/administrative officers at the organisation.

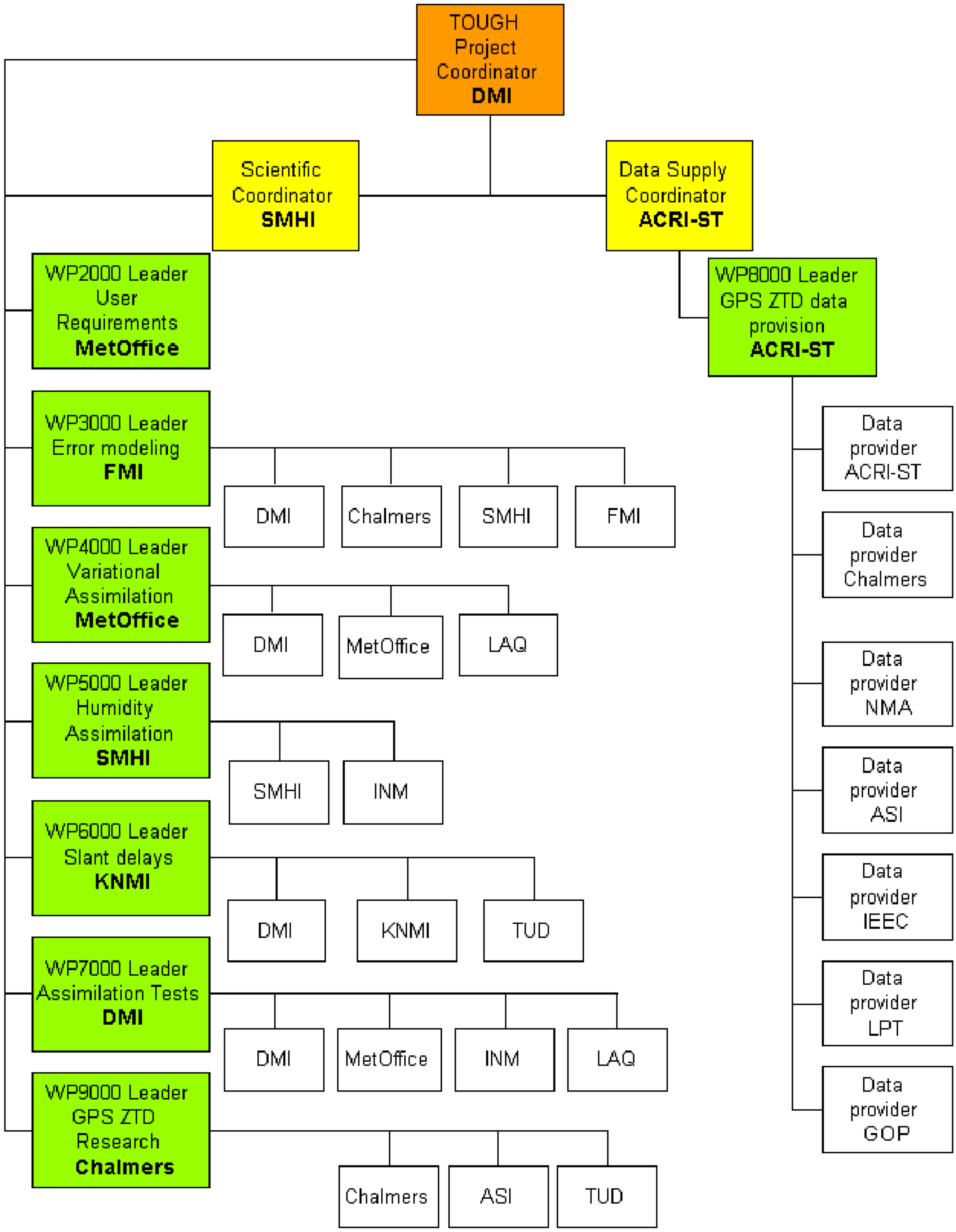


Figure 3 Management structure.

Communication and Quality Plan

Good communication among project participants, project monitoring, and quality control will be assured through the following elements:

- **Email lists** - email will serve as the primary means of communication with separate lists established for organisation lead scientists; all research personnel including user partners institute administrative/financial officers; EC technical contacts; EC financial contacts external user groups. The lists will be maintained by the CO.
- **Personnel directory** - a project personnel directory will be maintained by the CO, and will be available on the project web site.
- **Project web site** - the web site will serve for internal distribution of documents and communication concerning the project as well as for external distribution of project results. The site will be maintained by the CO with links to individual participants web sites. The internal web site will have password security to protect restricted deliverables.
- **Ftp sites** - each participant will maintain an ftp site, either protected or anonymous, accessible by the consortium members for the exchange of electronic information.
- **Partner web sites** - each participant will maintain a web site, with at least part of the web site with public access, for the dissemination of electronic information.
- **Deliverables** - deliverables made available electronically, where possible, before the end of the working day of the due date. All documents must be made available with in PDF irrespectable of their original format.
- Datasets will be provided with electronic access, described on the web site, with detailed format specifications provided, and a reference algorithm description provided for processed data. They will be verified by the group co-ordinators and then posted to the project web site by the CO.
- **Dataset deliverables** - will be provided with electronic access, described on the web site, with detailed format specifications provided and where necessary will conform to the standards consistent with the needs of the consortium. A reference algorithm description will be provided for processed data. Updates or changes to datasets or processing will be documented in a file associated with the deliverable and accessible via the web. The deliverables will be verified by the group co-ordinators and then posted (or their links will be posted) to the project web site by the CO.
- **Scientific papers and presentations in conferences** - papers will be the primary means of communication of theoretical project results. Quality control is automatically provided by peer review. Copies of submitted papers relevant to the project objectives will be provided to the CO. Copies of relevant abstracts for scientific conferences will be provided to the CO for posting on web site.
- **Geographical results** - deliverables containing geographical results (maps, databases, data sets) will also contain a description of their format, and where necessary, will conform to standards (to be determined) consistent with the needs of the consortium. Electronic versions will be provided to consortium participants on request, in agreement with the distribution access defined for the deliverable. They will be verified by the group co-ordinators and then posted to the project web site by the CO.
- **Annual reports** - annual reports will be compiled by the CO as contract deliverables to the EC. Participants will submit their individual annual reports 2 weeks before the date cost statements are due or the annual meeting. The report will have a self-contained scientific report section and an administrative section describing the status of programmed activities, the internal schedule and budget updates and modifications. The compiled report, with an executive summary prepared by the co-ordinator, will be delivered 2 weeks after the meeting. The scientific part of the annual report will be for public dissemination. Annual reports from each participant are on the order of 10 pages.
- **Semi-annual reports** - Participants will submit their individual semi-annual reports 2 weeks before the semi-annual meeting. It will have a self-contained high-level technical report section and an administrative section describing the status of programmed activities

internal schedule and budget updates and modifications. The compiled individual semi-annual reports will be delivered 2 weeks after the meeting. Semi-annual reports are on the order of 2 pages.

- **Meetings** - there will be 7 meetings: Kick-off, and six progress meetings at 6-month intervals. The group co-ordinators will submit items for the agenda and the CO will post meeting agendas 1 month before the meeting, distribute minutes 1 week after the meeting with action items, and review status of action items 2 weeks after the meeting. Participants are required to send at least one representative to the meeting. Participants are required to prepare slides to present their progress, which will be distributed to all participants. Persons from outside the consortium may be invited to the meetings after approval by the steering committee.
- **Security** - security and restricted distribution, where applicable, of project results will follow the description in deliverable list, and will be formalised among partners at a future meeting.
- **Representation to the EC** - The project co-ordinator, DMI, has the authority to represent the consortium to the EC. Others may represent the consortium by approval of the project co-ordinator. All communication with the EC will take place through the project co-ordinator DMI.
- **Quality assurance** - The Group coordinator is responsible for assuring that each project deliverable satisfies the requirements in terms of content as well as quality. In addition, specific workpackages 7100, 8100, 8600, and 9100 specifically assure the scientific quality of project deliverables.

Risk assessment, alternatives

In general the risk of the project work packages is low. The main dependency between the work packages is the delivery of data from WP8000 to most of the scientific WP´s. Whereas there may be holes in the stream of data from a GPS data provider now and then, it is extremely unlikely GPS data at large will not be available throughout the project.

WP4000 – There is a risk that MetO will not have the necessary basic 4DVar data assimilation system available in due time.

In case a sub work package can not be carried out the selected alternative will be to allocate the resources to case and impact studies (WP7000) and development and test of slant delay assimilation software (WP6000).

Milestones and Project Schedule Monitoring

Seven meetings and six milestones are defined for progress monitoring of the project:

Milestone	Meeting / review	Required Participants
M00	Kick-off	All
M06	Progress Meeting 1	All
M12	Progress Meeting 2	All
M18	Progress Meeting 3	All
M24	Progress Meeting 4	All
M30	Progress Meeting 5	All
M36	Progress Meeting 6 / Final review	All

The milestones have been defined in common with the project meetings to facilitate discussion and review of project results by the entire consortium. Deliverables have been associated with the milestone immediately following the project phase in which they are generated in order to facilitate management.

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