# Proposal for
# The second EUMETNET GNSS Water Vapour Programme
# (E-GVAP-II)

# June 2008

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# Proposal for the 2nd EUMETNET GNSS Water Vapour Programme (E-GVAP-II)

## Summary page

Title of Programme E-GVAP-II

Objectives

- Make the European ground based near real time GNSS zenith total delay and water vapour network continue to function operationally.
- Expand network.
- Improve homogeneity and quality of GNSS ZTD product.
- Connect to EUCOS and WIS.

Program responsible member and working team

- Selection procedure to be recommended by PB-OBS and decided by Council.
- The current E-GVAP team, consisting of DMI (resp. member), Het Koninklijk Nederlands Meteorologisch Instituut (KNMI), and UK Met Office (METO) is willing to continue.

| | |
|---|---|
| Starting date | 1 April 2009. |
| Duration of programme | 4 years and 9 months. |
| Cost over four years | 565,250 Euros. |
| Cost of first year | 119,000 Euros. |
| Date of proposal | June 2008 |

# Proposal for the 2nd EUMETNET GNSS WV Programme (E-GVAP-II)

# 1 Executive summary

## 1.1 Introduction and background

The current E-GVAP programme (hereafter called E-GVAP-I), run under the EUMETNET grouping of ENMSs, has been a very successful programme over the last 3 ¼ years. Europe now has an operational system for extracting meteorological data from GNSS signals, and this data are now used operationally in European NWP systems. It offers improvements to customer service, through improved forecasts from improved analysis of the state of the atmosphere. The primary variable derived using this system is the zenith total delay (ZTD), related to the water vapour content in the atmosphere. Traditionally there has been a lack of water vapour measurements at high horizontal resolution - E-GVAP has offered a valuable additional and complementary source of water vapour data. Case studies have shown that the data are also highly useful for now-casting, but operational use have not yet been taken up. While the quality of data from this system is in general high enough for assimilation into NWP systems, it is clear that much can still be done to improve the quality, in particular,

- By harmonising production across the networks
- By improving quality control and data monitoring.

Detailed background material, about the relevant science, history and E-GVAP-I achievements and technical aspects can be found at Annex A.

The original plan was to transfer the programme into EUCOS by the end of E-GVAP-I. However, this has not been possible due to differing priorities for EUCOS and limited EUCOS resources. The EUCOS plans for a *central data hub* would perhaps lead one to the conclusion that this would be a good time to integrate E-GVAP. However, the central data hub will not become available soon, and in view of the emerging WIS it seems a better and more robust idea to prepare the GNSS observing system for integrating into WIS. Following this logic, the E-GVAP dataserver + monitoring facility would become a DCPC for the VGISCs, that will be installed at DWD, Met Office and Météo France in the coming years.

The soft- and hardware used by the different EUMETNET observing programmes are often very different, depending upon the environments under which the programmes have evolved. This has made it much cheaper to develop the systems, but makes it very costly to unite them on a common computer platform. For many of the programmes, including E-GVAP, it will be cost effective to maintain existing facilities, if possible, for production and active monitoring. It will further keep the data “close to the experts”, which is necessary as long as one is in a stage where corrective actions will sometimes need to be taken, to cure problems with poor data.

## 1.2 Purpose

This proposal is presented to PB-OBS on behalf of EUMETNET Council in order that the next phase of the E-GVAP programme can be considered. It is hoped that PB-OBS will endorse the proposal and offer a positive recommendation to EUMETNET Council.

## 1.3 Summary of the Proposal

Building upon the results from the current programme, E-GVAP-II will take actions to improve and coordinate future operational processing of ground based (gb) GNSS zenith total delay and integrated water vapour on both the European and National scales. The exchange of data established under E-GVAP-I shall continue.

Activities will be designed to improve data quality and homogeneity by identifying superior processing techniques in collaboration with the geodetic community, and by introducing active quality control that can withhold poor data if problems are identified for a given site or processing centre. Important for this will be the "supersites" being invented now in E-GVAP-I, as well as comparison against NWP data. An attempt shall be made by the processing centres to use estimates of "satellite orbits and clocks" better suited for near real time processing.

E-GVAP-II will prepare for the emerging WIS and European VGISC, making the E-GVAP server/monitoring facility a DCPC working in close collaboration with the EUCOS team to enable implementation in the EUCOS programme.

E-GVAP-II will track the benefits of ground based GNSS measurements in their use by NWP systems and now-casting. These benefits can then be used to promote the use of the data.

The costs of the programme are expected to be 89.250 Euros for the first 9 months, and 119,000 Euros per year for the following four years.

The management and coordination of the programme shall be decided after the EUMETNET Council has decided whether to proceed and a programme decision has been made. At this point any changes required by Council can be made along with a call for a Responsible Member.

## 1.3 Key points for PB-OBS to consider

- Recommendation of E-GVAP-II proposal to Council.
- Recommendation to Council whether to make new call for responsible member.

# 2. Programme

## 2.1 Objectives of the programme

During E-GVAP-I substantial progress in developing a network of surface based GNSS water vapour measurements suitable for operational meteorology has been made. The number of sites is high and increasing. The majority of the E-GVAP-I goals has been successfully reached (and there is still about ¾ year of the programme left). Two met institutes now use NRT GNSS data in their operations, more will follow in 2008. The majority of the E-GVAP-I goals has been successfully reached (and there is still about ¾ year of the programme left).

Yet, for a number of reasons the "system" should not be "handed over" to operations and non-experts in the near future: The data quality should be made more homogenous, which requires close ongoing collaboration with the geodetic side. The ability to detect and withhold erroneous data via a central facility should be explored and a system that performs this task should be installed.. This requires that the data are kept "close to the experts" during this phase. The data density is lacking in a few member states, and should increase during the next phase.

The facilities to "take over" the observing system will change in the coming years, with the emerging WIS and EUCOS central data hub, neither of which exists at present. Formal arrangement should be made with EUCOS about the implementation, which will be done in the proposal for a continuation of the EUCOS programme.

The main objectives of the E-GVAP-II programme are of two types. The first type is ensuring continuation of the current data delivery. The other will focus on improving the products and preparing implementation in the emerging common European distribution system for meteorological observations.

1. Ensure the system built up in E-GVAP-I is maintained and continue to run, to make available for assimilation and now-casting data from the sites currently available in E-GVAP-I beyond March 2009.
2. Continue the established, fruitful close collaboration with the geodetic community. Thereby increase the number of sites, in particular in regions with poor coverage and data, and increase the homogeneity and quality of the NRT ZTDs.
3. Further and improve the construction of IWV maps and animations for use in now-casting.
4. Ensure that data server and data monitoring facilities have backups in case of failure, minimising the risk of a complete lack of ZTD/IWV data.
5. In collaboration with the geodetic community, and possibly EUMETSAT, attempt to improve quality and security of access to so-called "satellite orbit and clock estimates", which are used in the data processing by the processing centres.
6. Set up methods for monitoring that enable near real time detection and subsequent withhold of certain types of incorrect NRT ZTD data.
7. Formalise and improve the use of the "supersites" introduced in E-GVAP-I for monitoring of system stability and errors.

8. Collaborate closely with the EUCOS team, both regarding future implementation of E-GVAP into EUCOS, and regarding construction of the planned "EUCOS portal" for access to EUMETNET programme observational data.
9. Convince EUMETNET members using E-GVAP data to become members of E-GVAP.
10. Follow the development of the WIS and VGISC. Prepare for the E-GVAP data monitoring and distribution system to become a DCPC relative to the WIS.
11. To co-ordinate the meteorological exploitation of national sources of GNSS data by cost-effective agreements and provide meteorological support for expansion of GNSS observing networks.
12. To report on the progress of water vapour /zenith total delay data assimilation research and promote the use of GNSS water vapour measurements in operational meteorology by the provision of suitable teaching material and documentation
13. Follow and report on the developments in the field of assimilation of slants and gradient. Enable and encourage production and distribution of gradients and slant delays via E-GVAP facilities.
14. To explore the possibilities for long-term central archiving of both raw (RINEX) and processed(ZTD) data for off-line research and potential future re-processing for climate applications.

## 2.2 Programme Details

The three project expert teams have proven highly useful in E-GVAP-I and will maintained:

1 **Expert team on data processing and standards**
[Dealing with quality issues associated with GNSS data processing]

2 **Expert team on promoting use of the observations**
[Including liaison with data assimilation and observing system experiments, and with other water vapour network users]

1 **Operational liaison groups for gb GNSS ZTD/IWV observations**
[Managing the interaction between meteorologists and the wider GNSS sensing community]

The programme management (PM) will set up the agreements with the NMS who will provide the support to enable the individual project teams to function. The programme management will provide the necessary project co-ordination and organize the half-yearly plenary meetings. The PM will work under the guidance of PB-OBS, providing progress reports on the defined work packages.

# 3. Organisation

## 3.1 Programme team

The programme shall be coordinated by a responsible member. The responsible member is to make agreements with one or more facilities that can run a data-hub and perform timeliness monitoring and active quality control. Council may choose to re-tender a responsible member for this programme when it considers the next phase.

In E-GVAP-I, DMI, METO and KNMI work as a programme team, with DMI as coordinator, METO running data-hub and monitoring, and KNMI doing quality control. These three institutes are willing to continue as a programme team for E-GVAP-II. In parts of the proposal tasks are assigned to DMI, KNMI and METO following this scheme. New agreements which institute is to do what must be made if a new responsible member selected and new programme team formed.

The overall management of the programme will be handled at meetings taking place every six months. Each NMS sends a representative to these meetings and sponsors its own delegate who is responsible for the national meteorological coordination with the operators of the national GNSS sensor network

### 3.2 Expert teams

Three expert teams who will be responsible for assigned tasks within the project will support the programme. It has proven beneficial in E-GVAP-I to have the expert teams on data processing and data usage meet. The joint meetings will be continued. The expert team meetings have to be financed by the programme as they will contain many members from the geodetic side, not funded for this type of work by other means.

### 3.3 Reporting

The PM will provide regular progress reports to PB-OBS, following the half yearly plenary meetings, and will include specific results from expert meetings. Data availability and quality will be continuously measured at the server and monitoring facilities, and summarized on a monthly or quarterly basis.

### 3.4 Risk assessment

While the overall risk of the programme is low, certain aspects are not in the hands of the programme team. This includes the evolution of the network density in specific regions, the production of an improved satellite orbit and clock product, and the non E-GVAP specific elements of the implementation into EUCOS and alignment with the WIS and VGISCs.

### 3.5 Programme duration, next (EUCOS) programme phase

In the very unlikely scenario that the necessary components for implementation into EUCOS and the WIS & VGISC system are in place faster than expected, the transfer to EUCOS should take place more early and E-GVAP-II terminate as an independent, optional programme.

Prior to final implementation in EUCOS a new separate E-GVAP programme proposal and a call for tender should be made.

## 4. Work breakdown

### 4.1 Programme management

The PM will be responsible for the management of the programme and the three expert teams. A web site plus an FTP server will facilitate communication between participants**.** The PM will organize the half yearly plenary meetings. The PM will provide the necessary support for the expert meetings to be held. The PM will in all case cooperate with the local organizer of the meetings.

Thus, the PM has to perform the following tasks:

- Set up working and reporting procedures.
- Monitor the progress, initiate corrective actions as necessary.
- Preparation of meetings, administration for the meetings, minutes, etc. (in liaison with EUMETNET CO)
- Function of a web site for publicity and project documents
- Management of the project budget
- To supervise liaison with the GNSS sensing community
- To liaise with bodies such as WMO and the user community
- Extract radiosonde data for EUREF-EUMETNET data exchange.
- Produce DMI-HIRLAM NWP ZTD estimates for use in the E-GVAP-II monitoring of GNSS ZTD data quality.
- Assist KNMI in development of quality controlling algorithms.
- Delivery of the final report

## 4.2 Data hub, monitoring and quality control.

The data hub, monitoring, and quality control is split between the two E-GVAP partners KNMI and METO. They have expertise in these fields from doing this work successfully in E-GVAP-I.

- The data hub will become part of the operational environment at METO, ensuring automatic backups and minimised downtime.
- The monitoring of timeliness and in-consistencies in ZTD data files is/will be done at METO. Files with inconsistent data will not be BUFR encoded and distributed. IWV maps will be made at METO. Experimentation with use of IWV maps in short time forecasting will be done at METO.
- Quality control of ZTDs is/will be done at KNMI by comparison of GNSS ZTDs, NWP forecast ZTD and other observations, such as radiosonde data. Further comparisons will be done between processing centres by use of the supersites which all centres have to process. In case systematic errors are detected the monitoring facility will, via the data server, prevent further spreading of data from the processing centre in question until the problem has been solved. Statistics will be made for verification purposes. In the end this will become automated. DMI will assist by production of DMI-HIRLAM ZTD estimates and by assisting in the development of quality control algorithms.

## 4.3 Expert team on gb NRT GNSS data processing and standards

The expert team meetings are vital, not only for identifying and agreeing on best processing practices, but also to maintain a high level of encouragement and dedication among the processing centre people (recall that most of them receive no economic benefits from their processing, and do not on a regular basis see the effect of their work on the forecasts.). The purpose of this expert team is:

- Update the monitoring and reporting practices for feedback to GNSS data processing centres and GNSS stations operators as necessary.
- Report on progress in the development of near real time processing of zenith total delay
- Report on the success and errors of various data processing techniques, and recommend those methods considered sufficiently reliable to meet the accepted data requirements.

- Agree on minimum processing standards for E-GVAP processing centres.
- Attempt to make available improved (faster updates) estimates of satellite orbits and satellite clock offsets, for use in the near real time processing. Preferably in collaboration with other relevant agencies, such as IGS and/or EUMETSAT GRAS SAF.
- Report on progress in development of real-time processing of ZTD, of inclusion of additional GNSS systems (GLONASS, Galileo), and of the developments concerning reliable estimation of ZTD gradients, slant delays and double difference residuals (another “version” of slant delays).
- Report on usefulness of meteorological data in validation of GNSS processing, and in GNSS processing itself.
- Monitor and report on the progress in developing the GNSS water vapour sensing network

## 4.4 Expert team on gb GNSS data usage in meteorology

The team shall consist of experts in the usage of gb GNSS data in NWP and now-casting. Members shall be selected such that, if possible, all operational NWP models/data assimilation systems utilised by the members are covered by an expert. An expert in tomography reconstruction of the water vapour fields from ZTD/IWV estimates should be included.

The purpose of this expert team is:

- Update user requirements for processed data, in the light of ongoing data assimilation experiments, changes in resolution, and assimilation cycling frequency of NWP models
- Identifying errors and other things that might be harmful to successful operations.
- Regularly compile reporting practices to be followed by processing centres regarding updates of their processing, changes in network, addition of extra GNSS stations, etc.
- Review progress with data assimilation techniques suited to improve the use of gb GNSS water vapour measurements in numerical weather prediction and the results of associated observing system experiments.
- Support the development of improved data displays for results from the European networks.
- Report on the developments of the use of real time measurements in now-casting by combining GNSS IWV with other sources, such as wind-profiler data and Meteosat Water Vapour imagery.
- Report on the developments of the use gb GNSS observations for real time forecast verification
- Report to GNSS processing centres about data usage, outcome of data selection algorithms, biases, and other things that might help identify good and poor processing practices, and encourage processing centres to improve products in a friendly competition.
- Report on the use of GNSS measurements as a component of future meteorological Integrated Observing Systems.
- Make documentation introducing meteorologists to gb GNSS ZTD and IWV data, origin of errors, and examples of the use of observations for meteorological operations and research

- Report on the developments regarding use ZTD gradients or slant delays in NWP data assimilation.

## 4.5 Liaison groups for collaboration with the geodetic community

The purpose if the liaison groups is to ensure good collaboration with the geodetic community, both the European and national level, and to make formal agreements about data exchange, securing the NRT GNSS ZTD data for the future. In E-GVAP-I it has been found beneficial to operate with a small liaison group for the European level, and to have a somewhat larger expert team on data processing, the meetings of which then covers a significant part of the liaison work. In addition E-GVAP representatives must be partaking in important meetings for the geodetic society, such as the yearly EUREF symposium. This is much appreciated by the geodetic community, and has proven a very important way of establishing new contacts and maintaining old. Finally liaison travel money shall include ad hoc help to NMS in the phase of establishing contacts and agreements with national GNSS site owners or processing centre, and inclusion of representatives from new processing centres in the expert team meetings, to provide effective guidance in proper processing and ease their set up, leading to faster inclusion of data from regions with poor coverage.

These groups should have the following tasks:

- Encourage collaboration between geodetic and meteorological communities.
- Agree an operational processing policy for a European scale regional network using data from sensor sites where raw GNSS data are freely available.
- Agree on the national level on an operational processing policy for data from national GNSS sites where the real time GNSS data cannot be made freely available on a European scale.
- Seek collaboration with other GNSS meteorology programmes, such as the EUMETSAT GRAS SAF.
- Identify what services meteorologists can provide to the GNSS sensing community, which may mitigate the operational costs of the GNSS sensing network.
- Identify which meteorological data are of importance to the GNSS geodetic society and review data exchange of meteorological data. Make documentation helping geodesists to understand and use exchanged meteorological data.
- Develop policies whereby facilities associated with the deployment of surface GNSS sensors (e.g. sensor sites, communications) can be shared between meteorologists and the GNSS operators, thus reducing costs to meteorologists.
- Agree a method of identifying sensor sites unambiguously, acceptable to both geodetic and meteorological communities (which use different naming conventions).
- Provide support for the establishment of operational data processing centres, especially in areas where the network coverage is currently poor.
- Provide recommendations for design of GNSS networks for regional NWP and now-casting purposes.
- Maintain close collaboration with EUCOS a plan for long term financial and administrative support of the GNSS water vapour network.

# 5. Financial costs per year

## 5.1 Budget

| | |
|---|---|
| Project manager 0.5 year per year | 43.0 k€ |
| Contract to support hub/central processing + quality control facility | 51.0 k€ |
| Expert team and liaison meetings | 15.0 k€ |
| Project Travel | 10.0 k€ |
| Total | 119.0 k€ |

This is 10.0 k€ lower than the yearly budget of E-GVAP-I.

If continuing with the current team these will be spilt as:

| | | |
|---|---|---|
| Project manager 0.5 year per year | 43.0 k€ | DMI |
| Contract to support hub/central processing | 25.5 k€ | MetO |
| Contract to quality control facility | 25.5 k€ | KNMI |

## 5.2 Example of budget split-up

For illustration is below listed approximate membership contributions. It is based on the current E-GVAP-I members. More members will reduce the price of each member. The precise amount will change slightly when the GNP numbers on which the split-up is based are updated.

| **Member** | **Euros** |
|---|---|
| Belgium | 5545 |
| Croatia | 439 |
| Denmark | 3671 |
| Finland | 2845 |
| France | 31656 |
| Iceland | 200 |
| Ireland | 2160 |
| Netherlands | 8924 |
| Norway | 3991 |
| Spain | 14692 |
| Sweden | 5219 |
| Switzerland | 6167 |
| United Kingdom | 33591 |
| Total | 119000 |

# Annex A

# Briefing on science, history and E-GVAP-I

## A.1 Science

Global Navigation Satellite System (GNSS) radio signals interact with the atmosphere of the Earth. The signals slow down and bend, when passing from a GNSS satellite to a ground based (gb) receiver, causing a delay of the signals compared to a no atmosphere situation. The delay results in errors when using GNSS signals for positioning. The largest effect is from the Ionosphere, but this part is easily subtracted, due to its dispersive (frequency dependent) nature, and the fact that the GNSS satellites emit at two frequencies. The remainder of the delay is due to the neutral atmosphere, near the surface of Earth. For geodesists this delay is a noise term, which must be corrected for. For meteorologists it is an important observation, because it contains information on the total water vapour and mass of the atmosphere along the signal path.

The delay caused by the neutral atmosphere is estimated and corrected for, by in the processing of GNSS data fitting the observed GNSS data to a model which includes a delay term, along with many other terms that must be estimated simultaneously. Mapping functions are used to transform from the slant delays at different lower elevation angles to zenith. The mapped delay is called zenith total delay (ZTD). The ZTD estimated can be considered a specially weighted average of the delays toward the individual satellites. The ZTD is typically given as a distance, corresponding to the actual delay multiplied by the speed of light, equal to the apparent extra distance the signals have been travelling.

The ZTD can be divided into two terms. The first term is the zenith hydrostatic or zenith dry delay (ZHD), which is proportional to the pressure at the GNSS receiver site. The second term is the zenith wet delay (ZWD), which is proportional to the integrated water vapour (IWV) above the GNSS site, and which depends weakly on the temperature and humidity profile above the site. The ZHD is of the order 2 m at sea surface, while ZWD varies between 0 and about 0.5 m. The split up requires extra information, e.g. a measured or calculated pressure.

It is the sensitivity to water vapour, hence the ZWD, which makes GNSS ZTD observations interesting to NWP and now-casting. NWP models are quite good at predicting ZHD, but poor at predicting ZWD. For the moment most of the humidity information assimilated in NWP models comes from radiosondes, which have a poor coverage, both horizontally and time wise. Gb GNSS near real time (NRT) ZTDs have time resolutions of about 15 min (it depends on the parameters of the data processing, the observational data used in the GNSS data processing for ZTD calculation are typically obtained every 30 seconds). The spatial resolution varies significantly. In some countries and regions it is higher than one site per 30 km, in other significantly lower.

Currently the NRT GNSS data processing aims at producing good quality ZTDs. As the ZTD is an average, each receiver station typically seeing 8 or more individual GNSS satellites, some information about the inhomogeneity of the atmosphere surrounding the receiver site is lost in the processing. In the future more GNSS satellites will become available. For the moment the Russian GLONASS system is being renewed, and many of the European GNSS receiver sites are being equipped with hard- and software enabling use of also GLONASS signals, on top of the signals from the well known US GPS satellites. In the future the European Galileo system will further enhance the number of satellites. As this happens, it will become possible to produce high quality estimates of the variations in delays toward different directions around each receiver site. This could be in the form of so-called gradients of ZTD, or in the form of slant delays (the individual delays toward each satellite).

Already today slant delays have been produced and assimilated in scientific projects, as for example the TOUGH project. As a result software exists today in the official HIRLAM code for assimilation of GNSS slants delays. Production and use of gradients or slant enlarge the information content, but are for the moment still research topics.

## A.2 History

GNSS meteorology started in the nineties.
In Europe production and use of ground based GNSS ZTD/IWV data have been studied in a number of scientific projects, such as WAVEFRONT (1996-1999) COST716 (1998-2004), MAGIC (??-??), and TOUGH (2003-2006). The main conclusions from those projects were

- It was indeed possible to produce GNSS ZTD in NRT, fast enough while still being accurate enough for use in regional NWP, based on GNSS data from existing GNSS sites.
- It was possible to assimilate the data in NWP models
- The use of the GNSS ZTD data appeared to have a positive impact on NWP forecasts, although this was not objectively proven.

## A.3 E-GVAP-I

Based on these results the E-GVAP-I proposal was made, to move from a test phase to an operational GNSS observing system producing NRT ZTDs and IWVs useful in operational NWP and now-casting.

E-GVAP-I started April 1´st 2005 and runs for 4 years, to March 2009. Currently 13 EUMETNET members are members of E-GVAP-I (Belgium, Croatia, Denmark, Finland, France, Iceland, Ireland, Norway, Netherlands, Sweden, Spain, Switzerland, United Kingdom).

E-GVAP-I has been successful in establishing and maintaining a good working relation ship with the geodetic community. This is a backbone of the GNSS observing system being established, as it is based, with a few exceptions, on the use of data from existing GNSS sites, owned by national geodetics institutes and private firms. Otherwise the price of the observing network would be formidable, as the price of a single receiver installation is about 30.000 euros, which further requires geodetic expertise for processing.

Today 13 centres are processing NRT GNSS ZTD data for E-GVAP. Three of the processing centres are located at met offices (KNMI, METO, SMHI). The processing of GNSS data is complex, there is a long way from the original time measurements of arriving GNSS signals at a receiver to the ZTD. In this way ZTD observations differ strongly from all conventional meteorological observations. The data can be processed in different ways, many of which under the right conditions produce ZTDs of sufficient quality. However, different processing methods are subject to different problems if something fails. And the computation costs of adding more GNSS sites is related to the processing method. In E-GVAP-I a number of the processing centres therefore run two processing chains. One for production, and one for experimentation and improving. The processing chain is not at present in its final state and will change when the GALILEO system becomes operational.

The exchange of data is now in many cases governed by memorandums of understanding (MoUs). Most recently an MoU was made between EUREF (an inter European body in GNSS geodesy, somewhat like EUMETNET) and EUMETNET, about access to GNSS data from the so-called EPN sites, which are used to construct the European part of the reference frame of the Earth, to which all the GNSS observations are tied in the processing of the data.

On their site some of the geodetic institutes are interested in meteorological data, and according to the MoU EUREF members can get access to such data as part of the data exchange. For a geodetic institute to acquire the meteorological data they must first sign a document saying that the data are only for scientific or educational use, and provide name and address of a responsible person.

Today E-GVAP-I collects and distributes data from more than 800 sites, as can be seen in Figure 1.

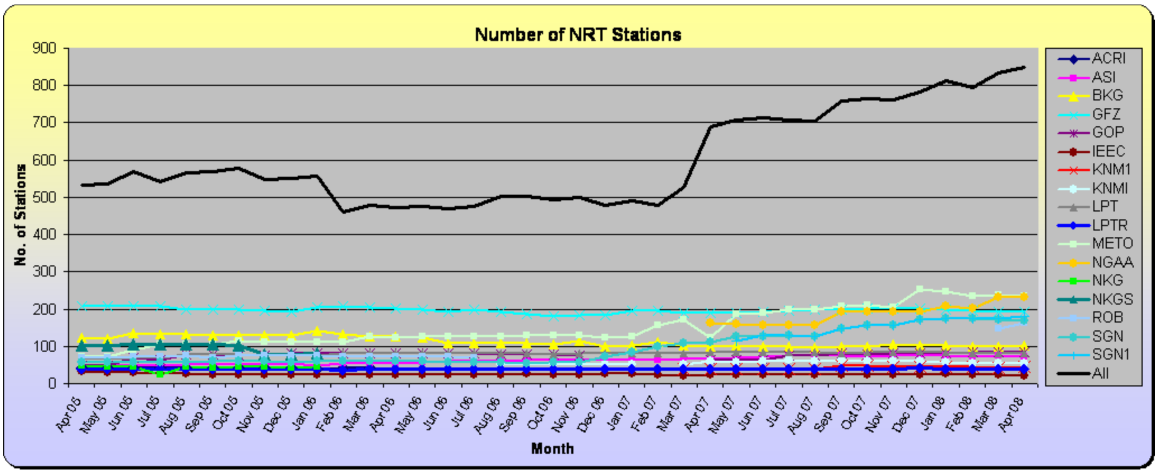


Figure 1. Number of sites with NRT ZTDs as function of time. (By Dave Offiler, METO)

The time for the NRT ZTDs to arrive is for the majority of the processing centres good enough to enable assimilation, even in regional models with short cut-off times, as shown in figure 2.

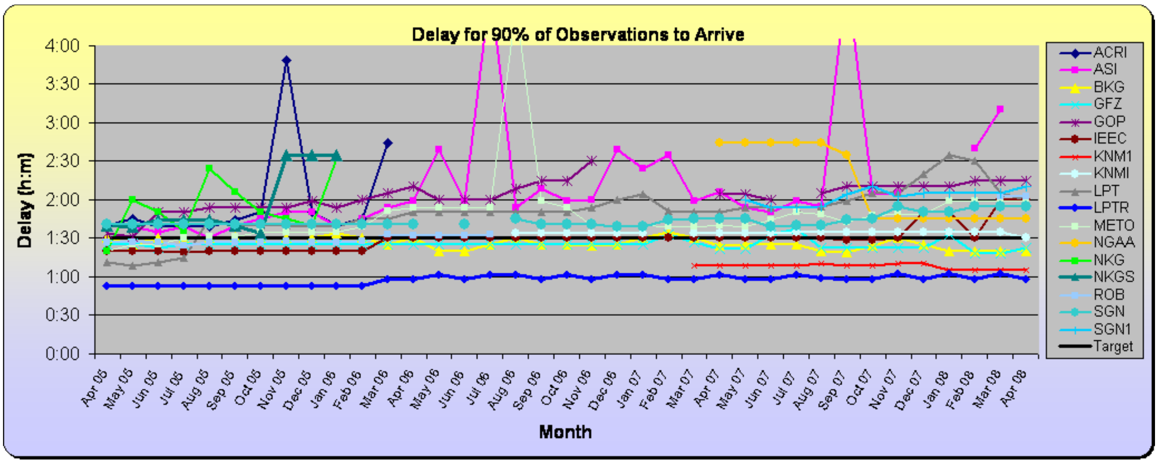

Figure 2. Time at which 90 percent of data from different processing centres have arrived at database at METO. (By Dave Offiler, METO).

The spatial distribution of the ZTD data varies significantly from region to region. Looking at figure 3 it should told that this side of summer many more stations will appear from Finland, Norway and Iceland. Very recently data have started to become available from platforms in the North Sea. And recently IGE from Spain has started to process Spanish GNSS data, which will gradually lead to an increase in the density of Spanish sites.

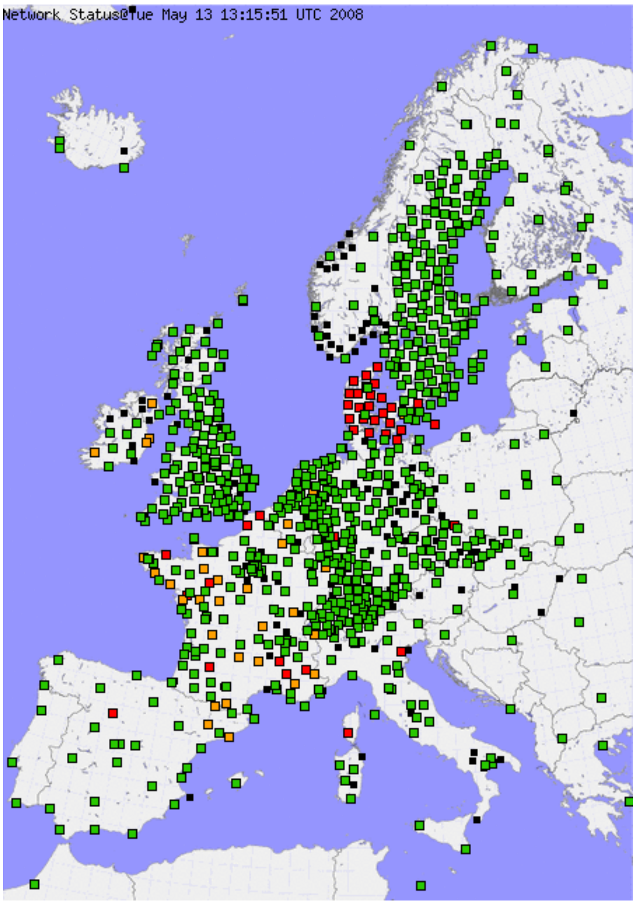

Figure 3. Map from E-GVAP-I monitoring page (By Siebren de Haan, KNMI).

The current dataflow for processing and use of GNSS ZTD an IWV observations is shown in figure 4.

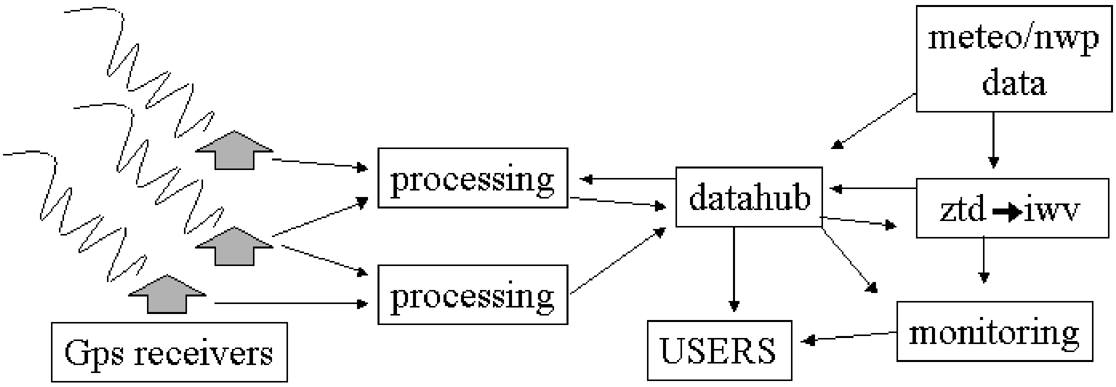


**Figure 4**: Schematic dataflow of GNSS water vapour observations.

In E-GVAP-II the results of the continuous monitoring shall be made able to stop distribution of ZTD data from the datahub if the data are found to be erroneous.

## A.3.1 Usefulness and quality of observations

Today two E-GVAP-I members assimilate E-GVAP ZTDs in their operational models.
Météo France assimilates since September 2006 E-GVAP ZTDs in both the global Arpege, the regional Aladin model, and since April this year also in their non hydrostatic mesoscale model Arome (which will be having a resolution of only 2.5 km). UK Met Office uses E-GVAP ZTDs in their regional model NAE and mesoscale model UK4. Both institutes have documented a positive impact from their use of GNSS ZTD observations. This is the best proof of usefulness that one can get.

A number of additional E-GVAP-I members are expected to start operational assimilation during 2008, e.g. DMI, KNMI, and other HIRLAM countries. These institutes have been comparing the ZTD data to the NWP models for an extended time, to create the necessary statistics for assimilation, and have made impact experiments which vary between positive and neutral impact.

In addition DWD has recently started to work on assimilation of IWV in their regional model.

Based on the monitoring it can be determined that the quality of the ZTDs wary between the processing centres and from site to site. Different meteorological institutes apply quite different pre-processing techniques to deal with this. At METO a white-list for processing centres is used, i.e. only data from selected processing centres are allowed to enter the NWP model. At Météo France the selection is based on a statistical study of the site and processing centre offsets, so that in principle all processing centres and all sites can be selected (though a given site only once). This is followed by a thinning, depending on the resolution of the NWP model. The approach by DMI is close to that of Météo France, whereas KNMI uses an approach close to that of METO.

The use of GPS data for now-casting purposes is still under research. Currently, case studies show that there is a relation between onset of thunderstorms and the two-dimensional distribution of water vapour.

## A.3.2 Supersites

During E-GVAP-I it became clear that for successful inter-comparison of the large number of processing centres a number a few sites should be processed by all processing centres. Subsequently a set of so-called supersites were selected. These sites are collocated with other upper air humidity observations for comparison. Currently, the majority of the supersites are processed by all processing centres and forming thereby an ideal data source for quality control. In the figure below the locations of the supersites are shown.

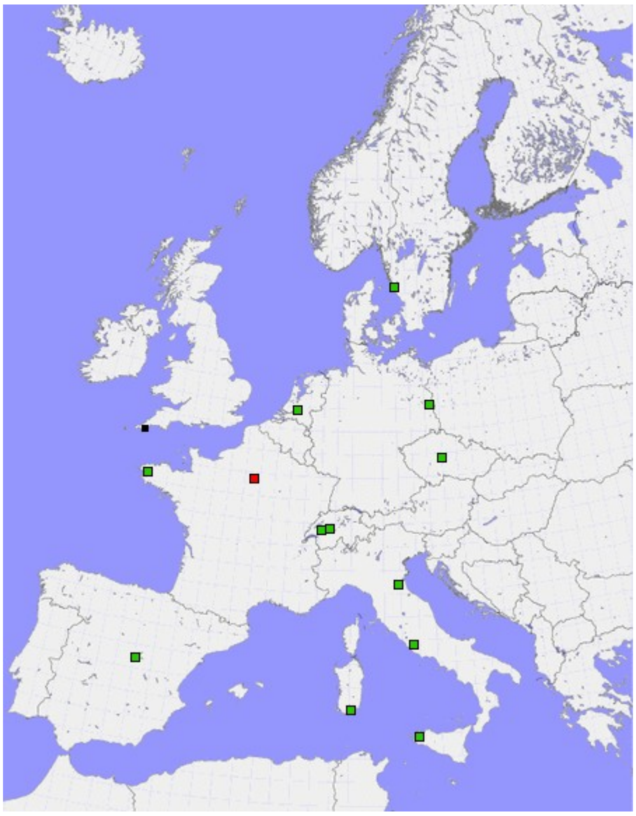

**Figure 5**: Location of SuperSites in Europe.

## A.3.3 E-GVAP-I and the future

While the quality of E-GVAP-I NRT ZTDs is in general high enough for use in data assimilation, it is clear that much can still done to improve the quality. Both regarding production of a more uniform ZTD product from the processing centres, and regarding removal of (some of) the in-correct ZTDs by E-GVAP monitoring.

Recently an incident in France, where a GNSS site owner moved a GNSS sites 40 m without noticing the SGN processing centre, resulted in incorrect ZTDs for a large number of sites processed by SGN. The fault was not caused be SGN, and the nature of it was something that one cannot guard perfectly against. Some of the incorrect data could be detected by the NWP assimilation systems, but not all. However, with the proper form of active monitoring it will be possible to discover and withhold such data, as long as all data pass a central facility controlled by E-GVAP experts. While the above case was particularly grave, all centres now and then deliver incorrect data for one or more sites, or for entire networks. Also many of these more isolated incidents can be discovered and withheld, when the proper software has been developed. In this regard the introduction of the supersites is very important, as they allow for real time monitoring and comparison of the overall performance of all involved processing centres.

According to the E-GVAP-I plan the programme was to transfer into EUCOS by the end of E-GVAP-I. However, a similar action item has never been implemented among the EUCOS action items. Further EUCOS has recently been going through a period with lack of resources and correspondingly less possibility of doing extra work. It is not possible to implement E-GVAP in EUCOS in the remainder lifetime of E-GVAP-I, nor via a short extension of E-GVAP-I.

The plans for a *central data hub* under EUCOS appeared a natural time to transfer from E-GVAP-I to EUCOS. However, the central data hub will not become available soon, and in view of the emerging WIS it seems a better and more robust idea to prepare the GNSS observing system for that. In that case the E-GVAP dataserver + monitoring facility in common becomes a DCPC for the VGISCs, that will be installed at DWD, METO and Météo France.

During the planning of the EUCOS central data hub it has become clear that the soft- and hardware used by the different EUMETNET programmes are entirely different, depending upon the environments under which the programmes have evolved. This has made it much cheaper to develop the systems, but makes it very costly to unite them on a common computer platform. For many of the programmes, including E-GVAP, it will be cost effective to maintain existing facilities if possible for production and active monitoring. It will further keep the data “close to the experts”, which is necessary as long as corrective actions will sometimes need to be taken, to cure problems with poor data.

At the drafting meeting for the central data hub primo March at DWD, it was agreed between the EUCOS team, the other programme managers and the programme manager of E-GVAP-I, that the best solution would be to make a proposal for an E-GVAP-II project.

## A.4 References, further reading

E-GVAP homepage: http://egvap.dmi.dk.

Poli et al, *Forecast impact studies of zenith total delay data from European near real-time GPS stations in Météo France 4DVAR*, Jour. Geo. Res., vol 112, D06114, 2007.

TOUGH project results: http://tough.dmi.dk,
*COST 716 Final report*. http://www.oso.chalmers.se/~kge/cost716.html
A comprehensive set of articles on the production and use of meteorological GNSS data worldwide can be found in a special volume of the Journal of the Japanese Society of
Meteorology (volume 82, 2004), entitled Application of GNSS remote Sensing to Meteorology and Related Fields, eds. Anthes et al.

http://www.swisstopo.ch,
http://www.geodaf.mt.asi.it/html/GPSAtmo/ground.html.

# Annex B

## Programme Time table

The programme is planned to start on April 1'st, 2009 and to last for 4 years and 9 month.

Plenary meetings at 6 month intervals

Expert teams on data processing and data usage to have joint meetings. Teams to meet once a year, more often if PM decides otherwise.

Liaison meetings in connection with expert team meetings, EUREF yearly symposium, and on an ad hoc basis as necessary.

### B.1 Milestones

**April 2009 to Dec 2009**

- Setup of liaison group and the two expert groups
- Formalisation of contacts to EUCOS, including how to make in common a route map for implementation of E-GVAP into EUCOS.
- Establish contacts to people responsible for the development of the WIS and VGISC.
- Extension of networks in Spain and Portugal.
- First version of software capable of stopping automated distribution of delay data which the monitoring has found to be incorrect.
- Definition of common, minimum requirements to processing as regards problems with access to data from individual sites, and to satellite orbit and clock estimates.
- Establishment of an agreed set of User Requirements appropriate to a fully-operational environment, to be updated during E-GVAP-II as appropriate to changing external drivers and user needs.
- Reports from expert, liaison and E-GVAP teams.
- Establish contacts with non-European Suppliers and Users with the objective of mutual data exchange globally.

**Year 2010**

- Arrangement with facility(ies) which can process GNSS data which might become available in Europe, but are not processed already by current GNSS processing centres.
- Reports from expert, liaison and E-GVAP teams.

**Year 2011**

- Workshop on the production and use of gb GNSS delay data. In connection with expert team meeting or an international conference.
- Reports from expert, liaison and E-GVAP teams.

**Year 2012**

- A review/discussion of the future route for European ground based GNSS observations for meteorology
- Draft proposal for the future of E-GVAP.
- Reports from expert, liaison and E-GVAP teams.
- Nominal start of operations under EUCOS

**Year 2013**

- Review of processing, utilisation, and impact of ground based GNSS data at European meteorological services.
- Workshop on the production and use of gb GNSS delay data. In connection with expert team meeting or with international conference.
- Reports from expert, liaison and E-GVAP teams.
- Final report
- Formal hand-over of operations to EUCOS

# Annex C

## Programme team details of current E-GVAP team.

### **C.1 DMI**, programme management

DMI is the national centre for operational meteorology, climate monitoring, research of the atmosphere, covering the processes from the troposphere to the ionosphere and magnetosphere. About 400 people work at DMI.

DMI partake in the HIRLAM corporation and is heavily involved in the development of the HIRLAM data assimilation system and its ability to utilise GNSS observations and also to validate such data.

DMI has a broad expertise in the field of GNSS meteorology, both ground and space based, and has been/is involved in the following GNSS projects: MAGIC, COST716, TOUGH, CLIMAP, ACE, GODANS, ØRSTED, WATS, ACE+, METOP/EPS, GNSSOS/NPOESS.
DMI was coordinator for the TOUGH project (scientific project on improving the use of ground based GNSS data). DMI is coordinator and host of the GRAS-SAF (data processing and distribution of GNSS radio occultation data from coming METOP EUMETSAT satellite).

Further details on DMI at www.dmi.dk

**CV for Henrik Vedel, programme manager**

Date of birth: 1958-04-29
Nationality: Danish
Education: 1987: Cand scient (masters) in physics and mathematics, Niels Bohr Institute, Univ. of Copenhagen, Denmark.
1991: PhD in physics, Niels Bohr Institute, Univ. of Copenhagen.
Career: 1987-1991, PhD stipend at SARC foundation
1991, guest researcher, NORDITA
1992, postdoc, University of Victoria, Canada
1993-94, research assistant, University of Victoria, Canada
1995-1997, postdoc, Theoretical Astrophysics Centre, Denmark
1998-2007, research scientist, DMI.
2008- present, senior research scientist, DMI.

Specialities, general: Data assimilation, NWP modelling, hydrodynamics, statistics.
Specialities, specific: -Development of software for assimilation of GNSS data in NWP and for validation of GNSS data against met.data.
- Running impact studies for GNSS data in NWP, using both GNSS ZTDs and slants.
- Partaking in former EU GNSS project MAGIC
- Project coordinator for EU GNSS project TOUGH (15 partners, see

http://tough.dmi.dk for info on TOUGH).
- Member of working group 3 of former COST716
- Partaking in former Danish Research Council GNSS project GODANS
- Partaking in the former ACE scientific pre-study (GNSS radio occultation).
- Involved in EUMETSAT project to enable assimilation of GNSS occultation data with HIRLAM.

## C.2 **KNMI**, quality control and monitoring.

KNMI is the Royal Netherlands Meteorological Institute for operational meteorology, climate monitoring, atmospheric and seismologic research. Currently, about 500 people are working at KNMI.

KNMI is also part of the HIRLAM consortium and is a lead center in NWP model verification. Within COST716 KNMI chaired Working Group 3 “Applications” and hosts the website for the demonstration campaign of COST716 and TOUGH. The COST716 final workshop was hosted by KNMI in December 2003. KNMI has been/is involved n the following GNSS projects: COST716, TOUGH, CLIMAP and METOP/EPS.

CV for Siebren de Haan, responsible for quality control and monitoring:

Date of Birth: 1968-06-05
Nationality: Dutch
Education: Masters in Mathematics State University Groningen, 1986-1992
Post Master Course Applied Mathematics University of Technology Eindhoven, 1995-1997
May 2008: Phd : “Meteorological applications of a surface network of GPS receivers”

Career: 1998-present: satellite observation scientist

Specialities: Assimilation of satellite derived sea surface temperatures
Sea Ice detection using the ERS scatterometer
Member of WG3 of former COST716
“webmaster” of COST716/TOUGH demonstration website
Development of Software for conversion of ZTD to IWV
National project : ”Reconstructing 3D water vapour using GNSS slant observations”
Visiting Scientist for the GRAS-SAF “Global fields from GNSS Radio Occultation observations”
Real-time and near real-time GPS processing

## C.3 **METO**, data hub, IWV maps, monitoring, BUFR encoding.

The Met Office is the UK's National Meteorological Service, with large computing facilities and extensive activities in weather and ocean forecasting and in climate research and prediction. Detailed information on activities of the Met Office is available at http://www.metoffice.com

In the context of GNSS meteorology, the Met Office is/has been involved in: WAVEFRONT, COST-716, TOUGH, E-GVAP WATS, ACE, ACE+ and the GRAS SAG. It is a leading member in the EUMETSAT GRAS SAF (1999-2012), principally responsible for development of the portable Radio Occultation Processing Package (ROPP) software deliverable. It is planned that ROPP be extended to cover support for gb GNSS.

The Met Office assimilation system operationally incorporates Radio Occultation data (GRAS, COSMIC, CHAMP, GRACE-A) into its global NWP model, and E-GVAP ZTD data into its regional and UK models.

The Met Office has supported the data hub and monitoring for wind profiler and Doppler weather radar for the WINPROF project. Within COST -716 Dave Offiler established the THORN server to collect data centrally during COST-716 and TOUGH. In E-GVAP-I the server was updated. The Met Office collect the uploaded ZTD files from the server and encode them into the WMO-standard BUFR format, which are injected onto the GTS for use by other NWP centres globally. Data flow and quality monitoring and performed daily with monthly summary reports, and results presented via the E-GVAP monitoring site hosted by KNMI. Under G-GVAP-II, this system will be made more robust by making use of operational servers and with additional quality control applied to the BUFR encoding stage.

Development of further UK facilities within E-GVAP-II will be managed by. John Nash and Jonathan Jones under the authorisation provided by the Head of Observations, Gill Ryall. Dave Offiler will be conducting the monitoring work at METO and control BUFR encoding, and Gemma Bennitt will be responsible for data assimilation.

John Nash is manager of the Upper Air team, Development, and co-chairman of the CIMO Upper Air OPAG. Jonathan Jones is a member of the Met Office Upper Air Team responsible for the development of near real time GNSS water vapour processing for the UK Met Office.

(The abbreviation METO is used, because “METO” is the acronym used for UK Metoffice as regards GNSS ZTD products.)

# Annex D

## Acronyms

| | |
|---|---|
| AMSU | Advanced Microwave Sounding Unit |
| BUFR | Binary Universal Format for the Representation of data (WMO) |
| COST-716 | European Co-operation in the field of Scientific and Technical Research, Action 716 |
| DCPC | Data Collection and Production Centre |
| EUCOS | EUMETNET Composite Observing System |
| EUREF | European Reference Frame, IAG reference frame sub-commission for Europe. |
| Galileo | Global Positioning System (Europe) |
| gb | ground based |
| GISC | Global Information System Centre |
| GLONASS | Russian/Soviet pendent to GPS. |
| GNSS | Global Navigation Satellite System (Generic: GPS, GLONASS, Galileo) |
| GPS | Global Positioning System (USA) |
| GRAS SAF | GNSS Receiver for Atmospheric Sounding Satellite Application Facility |
| GTS | Global Telecommunication System |
| HIRS | High Resolution Infrared Sounder |
| HIRLAM | High Resolution Limited Area Model |
| IAG | International Association of Geodesy. |
| IGS | International GNSS Service. |
| IWV | Integrated water vapour. |
| MAGIC | Meteorological Applications of Global Positioning System Integrated Column Water Vapour Measurements in the Western Mediterranean (EU project) |
| NMS | National Meteorological Service |
| NRT | Near-real time |
| NWP | Numerical weather prediction. |
| RMDCN | Regional Meteorological Data Communications Network |
| TOUGH | Targeting Optimal Use of GPS Humidity Observations in Meteorology (EU project) |
| VGISC | Virtual GISC |
| WAVEFRONT | Water Vapour Experiment For Regional Operational Network Trials (EU project) |
| WIS | WMO Information System |
| WMO | World Meteorological Organisation |
| ZTD | Zenith total delay (and zenith tropospheric delay, two names for the same property) |