Upper Air Humidity observations using GPS

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Introduction
Humidity plays an important role in atmospheric processes like convection, cloud formation and precipitation, and it is highly variable in space and time. The current operational meteorological observing system relies almost entirely on radiosonde observation for upper air humidity measurements. Radiosondes are launched typically two to four times per day, leaving large parts of the day unsampled.

Ground based Global Navigation Satellite Systems (GNSS), such as the well known Global Positioning System (GPS, United States) and, in the future, Galileo (Europe), can partially fill this lack of information. Because GPS is currently the only operational GNSS we will use the term GPS in the text below. GPS signals, transmitted by a GPS satellite and received on earth are bended by the atmospheric refractivity resulting in a signal delay. When the satellite and receiver position are known an estimate of the total refractivity along the signal path can in principle be made. Refractivity depends on temperature, atmospheric pressure and humidity. When temperature and pressure are known, information on the humidity can be derived. In practice, also other unknowns such as receiver clock offsets have to be estimated.

The benefit of GPS humidity observations lies in the fact that the observations are possible in any weather situation and the observation period can be as small as 5 to 15 minutes. The deficit is that the observations are (currently) restricted to land and that an integrated quantity is observed and not a profile. Below, the method of observing upper humidity using GPS is explained. Next, some applications of GPS upper air humidity are discussed.

Method of observing upper air humidity using GPS
To accurately estimate the total delay due to the atmosphere, the positions of the GPS receivers have to be known with an accuracy of a few millimetres. This requires a fixed stable network with high-standard GPS receivers. Note that low-cost GPS receivers have a position accuracy of a few meters. In The Netherlands a network of 35 receivers is installed as a result of close collaboration, called NETPOS, between the Kadaster (the National Surveying Department of the Netherlands) and the Ministry of Transport, Public Works and Water Management. On three remote automatic weather stations operated by KNMI a GPS receiver is installed. In return KNMI has access to raw GPS time delay observations of the network. This data is available in batches of one-second values every 5 minutes with a delay of less then 2 minutes.

Surveying with GPS with an uncertainty of a few centimetres is achieved using NETPOS. All raw one-second GPS data received by the network are processed to calculate a first order atmospheric correction. For atmospheric applications a higher accuracy in positioning is needed. This higher accuracy requires estimation of several unknowns such as satellite position and receiver clock errors. By collecting and processing all raw GPS time delay observations from the network over a period of several hours this accuracy can be met. Furthermore, a network of GPS receivers with baselines longer than 1000 km, will improve the absolute accuracy of the atmospheric estimate. In Figure 1 the network of the GPS receivers used for meteorological applications is shown.

The open circles denote the sub-network used to calculate atmospheric delays every hour and the

Figure 1: GPS receiver network used for processing at KNMI. KNMI is generating two types of ZTD’s: an observation available every hour (sites denoted by open circles) and every 15 minutes (sites denoted by asterisk).
asterisks show the sub-network for real-time applica-
tions. The first product is available after 45 minutes of
the last observations and is aimed to be used in
numerical weather prediction models, while the
real-time delay is less accurate but still suitable for
nowcasting purposes.

The atmospheric delay is called the Zenith Total Delay
(ZTD) and is determined for each GPS receiver. ZTD
can be expressed as a sum of a dry and wet part, the
so-called Zenith Hydrostatic Delay (ZHD) and the
Zenith Wet Delay (ZWD). The ZHD can be approximated
using the surface atmospheric pressure\(^n\), and thus
the ZWD can be computed from the total delay by
subtraction. The ZWD is proportional to the vertically
integrated column of water vapour (IWV) over the GPS
receiver. This relation depends on the mean tempera-
ture of the atmosphere, which can be approximated
by a function of the surface air temperature\(^n\). So IWV
can be obtained from a ZTD observation.

Applications of GPS humidity observations

Atmospheric instability and GPS
In fact, ZTD is an average over time and space of the
delay of the GPS signal. The difference between
estimated ZTD mapped back on the line of sight
between the receiver and satellite and the observed
observation is called the residual signal.
This signal contains information on the state of the
atmosphere. Figure 2 shows the residual signal with
an observed elevation larger than 50 degrees mapped
to the zenith. The major systematic errors (such as
e.g. multipath signal reception) are removed from the
signal, so the remaining signal will contain only noise
and, when present, an atmospheric signature. In case
of a convective atmosphere with significant updraft
of humid air, the GPS signal will be influenced by
fluctuations of the water vapour. Spectral analysis of
a time series of one hour of GPS residual observations
is performed to calculate the power spectral density
\(P\) of the GPS signal. This parameter is compared to
a measure of buoyancy called Convective Available
Potential Energy (CAPE), which can be determined
using radiosonde observations. In Figure 3 a
scatter plot of \(P\) versus CAPE is shown for collocations
of three GPS sites and four radiosonde launch sites.
Despite the fact that the two measurements spaces
are distinct (i.e. CAPE is based on a profile at a fixed
time; \(P\) is based on a single value for the vertical
averaged over a period of an hour) the correlation is
remarkable (around 0.6). The continuous availability
of GPS estimates may help the forecaster to detect
atmospheric (in)stability\(^n\).

EUMETNET E-GVAP
KNMI participates in the EUMETNET GPS water vapour
programme (E-GVAP). This programme aims at
providing the EUMETNET partners with European GPS
delay data for use in operational meteorology. This is
done in close collaboration with the geodetic
community in Europe. EGVAP started April 2005 and is
planned for four years.
A snapshot of the locations at which GPS ZTD
estimates are measured and derived is shown in
Figure 4. Implementation of ground based GPS data
in operational NWP and nowcasting has requirements
regarding quality, homogeneity, stability, actions to
take in case of problems, extent of observation
network, etc. A key goal of E-GVAP is to gradually

![Figure 2: Residual signal of the GPS receiver for three different intervals of one hour. The middle panel shows the residual from two satellites; for the other panels only one residual was observed above 50 degrees elevation.](image)

![Figure 3: Scatter plot of Convective Available Potential Energy (CAPE) as observed by radiosonde measurements and spectral power density (P) for two periods (two weeks in November 2000 and May 2003) and three GPS sites and four radiosonde launch sites. Symbols are connected by a line when more than one GPS satellite was visible.](image)
improve the ground based GPS (near-)real time delay data to meet these requirements.

The E-GVAP-programme is based on a combination of centralised tasks, which will be carried out by the E-GVAP team, and distributed activities, which will be handled by the national met-service members in collaboration with their geodetic colleagues.

The centralised tasks include database setup and maintenance, processing of GPS data from special selected sites and quality monitoring and feedback. The distributed functions include, amongst other things, enlargement of the GPS network in areas with poor coverage in liaison with the geodetic community.

Two dimensional water vapour fields
From real time GPS IWV two dimensional water vapour fields can be generated. These fields can be used for nowcasting of convection and thunderclouds. In the example shown in Figure 5 strong lighting events occur at the edges of water vapour ridges. The possible use of these water vapour fields for nowcasting will be a topic of research for the next few years.

Expected Impact of GPS Tropospheric Slant Delays
An alternative to vertically aggregated propagation delay observations is the actual delay along the slanted path of signal propagation from satellite to receiver. The intrinsic geometrical information in these so-called ‘slant delays’ offers the possibility of improved sampling of the local refractivity of the atmosphere in the vicinity of the receiver. A disadvantage of these observations is that they are likely to contain more noise. To find out if in spite of this detriment these observations contain useful information, an impact study was conducted with simulated slant delays.

The continuous availability of GPS estimates may help the forecaster to detect atmospheric (in)stability

Figure 4: Locations in Europe with available GPS ZTD estimates. Operational sites are green; potential sites are black.

Figure 5: Example of the possible use of real time two dimensional GPS water vapour fields; a south westerly flow transported instable air which generated lightning events (black dots) in areas with a strong water vapour gradient, contoured from low values (blue) to high values (yellow).
The study comprised a System Simulation Experiment (SSE) carried out with the HIRLAM Forecasting System (HFS). The SSE is based on the Assimilation Ensemble Method (AEM), a probabilistic method originally used for the estimation of background errors\(^5\) that has been extended and applied to simulate observation impact\(^6\).

In this experiment three ensembles were generated, each defined by the set of observation types used in the ensemble:

- **Control** - The reference, incorporating all observations used in operations: SYNOP, SHIP, DRIBU, TEMP, PILOT, WINDPROF, AIREP and SATOB,
- **Denial** - As Control but without TEMP, PILOT and WINDPROF observations, a calibration experiment to determine the sensitivity of the HFS to humidity observations.
- **SDSIM** - As Control but with simulated slant delay observations added.

The ensembles consist of 4 members where each member represents an independent 14-day run of the forecasting system starting on May 2nd 2003 at 00 UTC. The model runs are performed on a 10km resolution grid with the Netherlands at the centre. The Denial ensemble is carried out to determine the sensitivity of the HFS for the input of moisture observations. For the SDSIM ensemble simulated noisy slant delay observations were generated before the experiment. They were computed from model fields of ECMWF analysis boundaries for the HFS using the HFS forward operator for GPS slant delays. In each assimilation cycle of the SDSIM ensemble on the order of 100 simulated slant delay observations are available from a GPS network mainly situated in the Netherlands. The slant delays were created using the actual GPS satellite constellation geometry at observation time.

For an ensemble with N members the RMS of N-1 independent sets of analysis difference fields is called the analysis spread and represents a measure of the uncertainty in the analysis. The difference in the analysis spread between two ensembles that differ only in the set of observation types used in the analysis gives insight in the impact of a particular observation type.

The results of the Denial experiment generally confirmed the beneficial impact of radiosondes (not shown). To illustrate the impact of slant delays the analysis spread difference between the SDSIM and the Control ensemble for surface parameters and dew point temperature at the 850, 500 and 250 hPa level is presented in the maps in Figures 6 and 7 respectively. The maps in these figures show a reduction in the spread in red which signifies positive impact. The yellow dots in and around The Netherlands in the panels represent the receiver stations in the GPS network.

For model surface fields of pressure reduced to mean sea level (PMSL), air temperature (T2m) and dew point temperature (Td2m) at 2 meter above the surface (at screen height) the impact is fairly neutral (Figure 6). The structure of the spread difference looks patchy for temperature and dew point temperature and amplitudes are small.

At 850 hPa positive impact is present around most stations of the GPS network and along the coast of Brittany (c.f. Figure 7). These structures reflect the

![Figure 6: Differences in the spread between the members of the SDSIM and Control ensemble for surface parameters PMSL, T2m and Td2m.](image)
The spread differences for dew point temperature indicate that slant delays can achieve small local improvements in the accuracy of the upper air analysis.

Outlook
In the next few years GPS ZTD observations will become available on an operational basis at European scale, also at KNMI. Applications of GPS with respect to nowcasting will be further investigated, with emphasis on convective systems. As GPS ZTD becomes routinely available the observations will be assimilated in HIRLAM. In the case of GPS slant observations more research is required, especially in the pre-processing stage of creating the observations. Implementation of realistic spatial and temporal observation error characteristics in the assimilation system of the HFS is needed, followed by impact studies with real observations on a very high resolution grid (<5km) that have to be carried out for an extended period of time to study the effects of seasonal variations in atmospheric humidity.


**Internet links**

EGVAP: http://egvap.dmi.dk

Real Time Water Vapour: http://www.knmi.nl/research/groundbased_observations/gps/real_time_IWV.html