GNSS Meteorology on Moving Platforms

Advances and Limitations in Kinematic Water Vapor Estimation

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Research vessel Alkor *(above). Oil-recovery Vessel* Bottsand *(right).*

Over the years, researchers have advanced the use of GPS receivers to measure water vapor content in the troposphere and model its effects on signal propagation. However, these techniques typically employ stationary GPS receivers. This column describes a method for measuring water vapor by GPS receivers on moving platforms and determining the associated atmospheric effects .

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Although GNSS is primarily designed for positioning, navigation, and timing applications, it can also be used to determine a quantity that is of major interest for meteorologists and climate researchers, namely, integrated water vapor. This gas plays a critical role for the energy balance of our atmosphere and is actually responsible for approximately 62 percent of the natural greenhouse effect. Consequently, the distribution of water vapor, as well as its spatial and temporal behavior, is important for climate predictions and weather forecasts.

Whilst GNSS-based integrated water vapor monitoring has become a well-established technique in static networks of reference stations, only very few efforts have yet been carried out to employ this method on moving platforms such as ships and aircraft. In this article, we will address kinematic water vapor estimation with GPS in kinematic mode. The results presented in this article feature the successful retrieval of vapor on the open sea via very long baselines for the first time. We will also outline the limitations inherent in the current use of GPS alone and the outlook for future benefits from a combination of GPS and Europe's new Galileo system.

Basic Methodology

Many GNSS users wonder how it is possible to determine a meteorological quantity such as water vapor from geometric measurements as obtained by a satellite navigation system.

The key to understand the basic methodology can be illustrated by having a closer look on the observation equation used for precise positioning, that is, the carrier phase observation:

$$\phi_A^i = \frac{S_A^i + c\cdot(\delta t_A - \delta t^i) - \delta S^i_{A[ION]} + \delta S^i_{A[TROP]}}{\lambda} - N_A^i + \varepsilon_\phi$$

in which $\phi_A{}^i$ is the carrier phase measurement in cycles to satellite i as observed at station A. S is the geometric distance, c the speed of light, and λ the wavelength of the carrier. N is the carrier phase ambiguity term and ε denotes the noise. The receiver and satellite clock errors (δt_A and δt^i) will be eliminated by double differencing of observations between two stations and two commonly viewed satellites in the in-house software package PrePos GNSS Suite, which was used for this study. The ionospheric propagation delay $\delta S_{[ION]}$ can, in principle, be removed by combination of measurements sampled on two different frequencies (the so-called "ionosphere-free linear combination").

Even after these computations, however, it becomes evident that the tropospheric path delay $\delta S_{[TROP]}$ is still present. Approximate tropospheric propagation delay models are employed in normal navigation applications to derive this term as a correction. In GNSS meteorology, we do the opposite: Our goal is to derive a precise estimate of $\delta S_{[TROP]}$.

Figure 1 illustrates the simplified processing chain: In the first step, GNSS measurements and precise orbit data constitute the only basic dataset needed. These data are preprocessed (cycle-slip detection, correction of Earth tides, antenna phase center corrections, etc.). Afterwards, we carry out parameter estimation employing either a Kalman filter or a least-squares adjustment procedure. The remaining two steps are needed to derive integrated water vapor from the tropospheric propagation delay estimate $\delta S_{[TROP]}$. Firstly, we must separate the total path delay into a hydrostatic and a wet component, as follows:

$$\delta S^i_{A[TROP]} = m\left(\varepsilon^i_A\right)_{[HYD]}\cdot ZHD_A + m\left(\varepsilon^i_A\right)_{[WET]}\cdot ZWD_A$$

The right-hand side of this equation shows that propagation delays are normally modeled in the zenith direction and converted into slant direction using a mapping function m, which is basically dependent on the elevation angle ε. The simplest

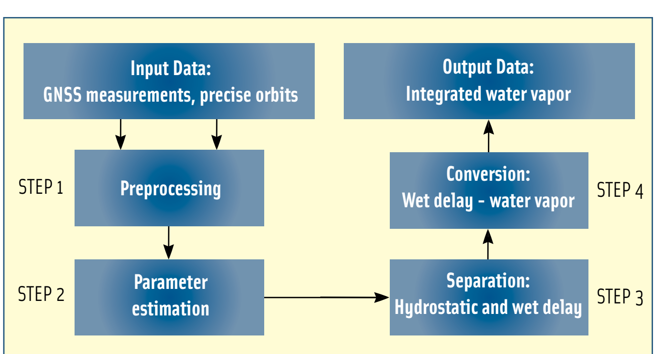

FIGURE 1 Processing chain for GNSS-based integrated water vapor determination.

mapping function is 1/sin ε, but it is by far too inaccurate for this application.

Today, several precise mapping functions are available, accurate down to elevations of 10° at least. These functions are separately given for hydrostatic and wet delays. The zenith hydrostatic delay *(ZHD)* itself can be accurately computed from relatively simple models given knowledge of pressure at the antenna site. The zenith wet delay *(ZWD)*, however, is very much influenced by water vapor, and we can establish a relation between this component and the integrated water vapor *(IWV)*:

$$\frac{ZWD}{IWV} = 10^{-6}\cdot R_w\cdot\left(k_2' + \frac{k_3}{T_M}\right)$$

where R_w is the specific gas constant for water vapor and k_2', k_3 are refraction constants. Finally, the weighted mean vapor temperature of the atmosphere (T_M) is

$$T_M = \frac{\int_{H_0}^{\infty}\frac{e}{T}\cdot Z_w^{-1}\cdot dH}{\int_{H_0}^{\infty}\frac{e}{T^2}\cdot Z_w^{-1}\cdot dH} \qquad \text{or}$$

$$T_M \approx a_0 + a_1\cdot\cos\left[2\pi\cdot\frac{DoY - DoY_W}{365.25\,[days]}\right] + a_2\cdot T_0$$

with e being the partial water vapor pressure, T the dry temperature, $Z_w{}^{-1}$ inverse compressibility of wet air (close to 1.0), dH the differential height increment and H_0 the surface height.

Unfortunately, the mean temperature requires knowledge of the atmospheric profile, but it is possible to establish a relation between the surface dry temperature T_0 and the mean temperature T_M that can be expressed as a seasonal function plus a linear term with $a_{0,1,2}$ denoting empirically determined (and site-specific) coefficients. As a rule of thumb, the ratio *ZWD/IWV* is approximately 6.0 to 6.5 (with *ZWD* in millimeters and *IWV* in kg/m²).

In summary, we can conclude that GNSS-based water vapor estimation requires knowledge of pressure and temperature. However, if these pieces of information are missing, the total tropospheric delay can be directly assimilated into numerical weather models and still serves a beneficial function.

The Challenge of Moving Platforms

Today, we can state that integrated water vapor contents can be successfully retrieved from the GNSS phase measurements in static networks (reference stations) with an accuracy in the range of 0.5 to 1.0 kg/m². IWV estimation on moving platforms such as ships, in contrast, has only rarely been investigated in detail thus far.

Nevertheless, the scientific community would benefit from using this method on ships (or even aircraft) because normally a lack of atmospheric measurements exists in sea-covered regions – and those represent two-thirds of the earth's surface. Space-borne radiometers serve as an important data source for these regions, but a surface-based GNSS system could provide substantial value with respect to the calibration of these sensors.

Actually, kinematic vapor determination is considerably more complicated. In the *static* case, the GNSS antennas will not alter their location. Thus, the number of unknowns is rather limited: 3 coordinate components and usually 12 to 24 troposphere parameters are estimated in a data batch covering a single 24-hour day. The number of tropospheric delay parameters depends on the selected smoothing interval.

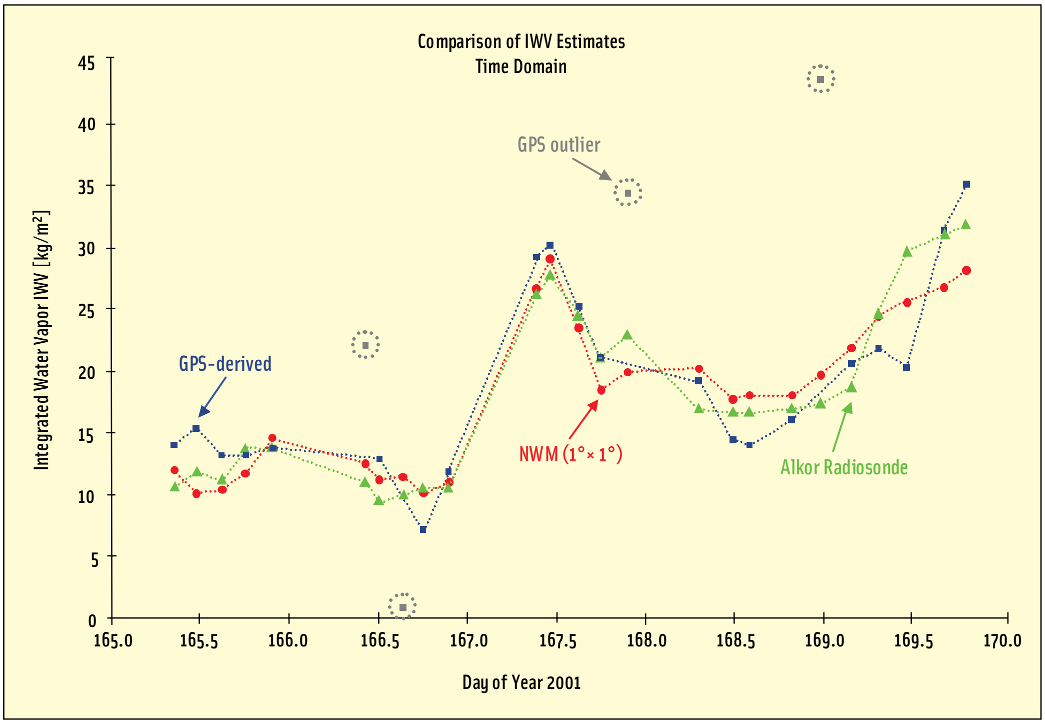

FIGURE 2 Comparison of GPS-, radiosonde and weather-model (NWM) derived water vapor samples during the Alkor experiment.

Things are different in the *kinematic* case: The position of a ship, for instance, is varying continuously. Consequently, a new location vector must be determined epoch-to-epoch, which leads to a "loss of geometrical strength" in terms of parameter estimation compared to the static case. This problem particularly affects the ambiguity parameters (number of full cycles), which are additional unknowns when precise carrier-phase measurements need to be processed.

Whereas these parameters show a relatively quick convergence in static scenarios, this process is emphasized far less in the kinematic mode. Furthermore, baselines to the surrounding reference stations are often rather long in this kind of application such that ambiguity fixing becomes problematic, and cycle slip correction is often rather critical in kinematic scenarios. Nevertheless, the following sections will demonstrate that it is possible to derive integrated water vapor samples from GPS receivers onboard of ships.

GNSS Meteorology Experiments

Kinematic experiments were conducted in the Baltic Sea within the scope of the BALTIMOS project aiming to validate a coupled climate model for the Baltic region. Firstly, GPS measurements of geodetic quality were collected with dual-frequency receivers of geodetic quality on research vessel *Alkor* (pictured here) during two measurement campaigns.

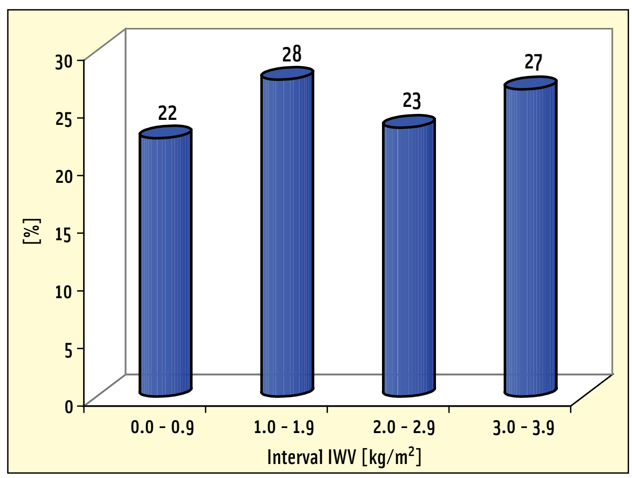

FIGURE 3 Probability statistics of discrepancies between the GPS-derived water vapor samples and the reference data from the numerical weather model (NWM).

The importance of these experiments is related to the fact that radiosondes were regularly launched by a partner group from the Institute of Meteorology (University of Hamburg) delivering refractivity profiles with high accuracy and vertical resolution. These data allow the derivation of the integrated water vapor contents fully independently from GPS and serve a good job for the verification of the GPS-derived water vapor estimates.

Secondly, a receiver was installed on the oil recovery vessel *Bottsand* (see accompanying photo) in 2001 and operated continuously through the year 2002 until the beginning of 2003. This twin hull ship participates in depollution campaigns in the Baltic Sea. Funded by the German Bundesländer (federal states) with access to the Baltic Sea, the

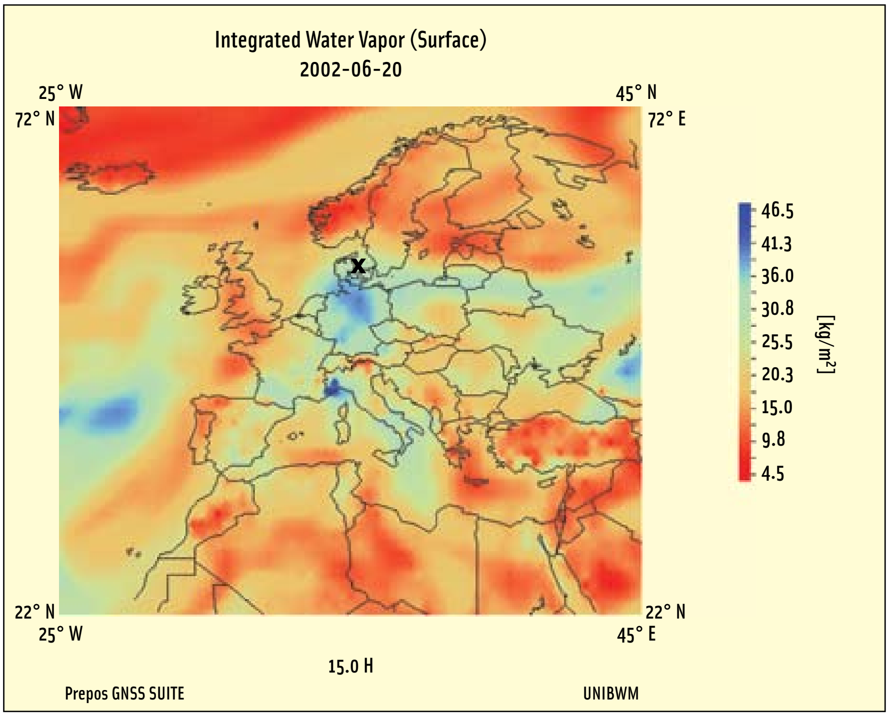

FIGURE 4 Distribution of water vapor over Europe on 20 June 20, 2002, (location of Bottsand is marked by a cross).

Bottsand is operated by the Federal German Navy.

The primary motivation to place a GPS receiver on this vessel is linked to the fact that the *Botttsand* also regularly cruises these waters in the region between its home harbor Warnemünde near Rostock and Kiel/Lübeck so that frequent measurements of the integrated water vapor component in this region of the Baltic Sea could be taken.

Cruises of the RV *Alkor*

The measurement campaigns were conducted in June 2001 (days of year 165 to 169) during which the vessel took position at a dedicated grid point of the climate model in the Baltic Sea at latitude 56.0° N and longitude of 18.7° E. Several surrounding IGS and EUREF reference stations were used for both precise position determination of the ship and water vapor estimation. The smallest baselines were those to RIGA (170 km) and LAMA (Olsztyn, Poland, 270 km). Other reference stations in use were ONSA (Onsala, 440 km) and POTS (Potsdam, 540 km).

The difference between GPS-derived integrated water vapor and high-resolution radiosonde data was better than or equal to around 3 kg/m^2 in about 50 percent of the experiments. Unfortunately, the GPS-IWV turned out to be out of bounds in some cases; these outliers are marked in **Figure 2** by dotted circles. However, omission of the GPS outliers in the time series leads to a reasonably good agreement with the reference data coming from a 1°×1° numerical weather model (U.S. National Oceanic & Atmospheric Adminstration's National Centers for Environmental Prediction Global Data Assimilation System) as well as the high-quality radiosonde data. All major trends in the evolution of IWV during these few days are correctly mirrored in the individual time series from the three different data sources.

Results from the *Bottsand*

A total of 120 experiments derived from voyages of the *Bottsand* from 2001 to 2003 brought acceptable results. GPS results were considered to be "acceptable" if the difference to the reference data (in this case only from the numerical weather model since no radiosonde data were available) was less than 3.9 kg/m^2. **Figure 3** illustrates these differences and their probability and also reveals that 60 of these successful experiments show a discrepancy of less than 2.0 kg/m^2. For more details on these cruises please refer to the report by this author and E. Krueger cited in the Additional Resources section.

A water vapor content of 2 kg/m^2 corresponds to an error in zenith wet delay of about 1.3 centimeters, which is a good result for kinematic GPS applications considering the rather long baseline lengths to the reference stations. The smoothing interval was around 1.0 to 1.9 hours in 80 percent of the successful experiments, but even some short-term data batches (10% of the cases) as short as only 0.4 to 0.9 hours showed a good agreement.

Figure 4 portrays the distribution of water vapor (referenced to the surface) over Europe during one of the *Bottsand* experiments on June 20, 2002, with a humid front approaching the Baltic Sea where the vessel was located (at black cross). The integrated water vapor contents measured with the GPS array deviated by 2 kg/m^2 from the prediction of the weather model in this case.

Conclusions

The preceding results indicate that the integrated water vapor content of the troposphere can be successfully derived from GNSS measurements on moving platforms such as ships. Generally speaking, the outcome of the experiments presented here is encouraging for future research in this field. An accuracy (standard deviation) of 3.9 kg/m^2 or better was achieved in 50 percent of the experiments, and the accuracy was even below 2.0 kg/m^2 in 25 percent of the experiments.

However, we still have much room to enhance the accuracy in the future if we recall that the comparable figure for static networks is around 0.5 to 1.0 kg/m^2, 100 percent of the time. Clearly, kinematic water vapor estimation is still a field that needs improvement. Three major limitations place a burden on current efforts to derive IWV on ships with data from GPS alone:

1) The number of available GPS satellites is often limited to around five

to eight. This is fully sufficient for most navigation applications because — in theory — only four satellites are needed for a three-dimensional position fix. For the particular requirements of kinematic water vapor estimation, however, we would benefit from using as many satellites as possible in order to augment the carrier phase ambiguity estimation process. Furthermore, geometry-dependent error terms could be reduced with more satellites in view.

2) Carrier phase measurements are prone to cycle slips, which will inevitably occur in case of obstacles interrupting reception of satellite signals, but cycle slips may also stem from other causes — ionospheric scintillations and strong multipath effects on the signals, for instance. The longer that we can maintain continuous carrier phase tracking of the GPS signals without any cycle slip, the more stable the GPS IWV solution will become.
3) Signals on more than one frequency could be beneficial, particularly in terms of the ambiguity resolution process. Currently, the GPS signals on the second frequency (the P/Y-code on L2) are particularly prone to cycle slips because this signal is encrypted and must be decoded by complicated correlation processes, which leads to a loss of signal power and thus increases the probability of cycle slips.

Fortunately, the availability of new open signals at GPS and GLONASS L2 frequencies, transmitted by the GPS Block IIR-M and GLONASS-M satellites now being launched, as well as the planned availability of additional open signals on Europe's Galileo GNSS, will help to overcome most of the limitations currently present. Galileo will be interoperable with GPS in major aspects. This will effectively add a second constellation of satellites to the existing ones, greatly resolving nowadays problems with respect to geometry.

Finally, new signals are expected both for GPS and Galileo that use a data-free channel and will significantly lower multipath. This means a better carrier-to-noise ratio and, thus, a smaller probability for cycle slips. These new signals will also enable new methods for quick and efficient carrier phase ambiguity resolution.

Without doubt, GNSS meteorology will greatly benefit from the innovations in satellite navigation.

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Manufacturers Credits

The GPS receivers used in the research described in this article were 4000SSE receivers from **Trimble Navigation Ltd.**, Sunnyvale, California, USA.

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Torben Schüler received his diploma in geodesy and cartography from the University of Hannover in 1998. Afterwards, he joined the Institute of Geodesy and Navigation (University FAF Munich) as a research associate, earned a doctorate, and is now head of the GNSS/INS Laboratory at the same institute. His major research work is focused on precise GNSS positioning, including atmospheric and, in particular, tropospheric delay modeling. Schüler was heavily involved in the development of the standard tropospheric correction model for the Galileo satellite navigation system now being deployed.

"Working Papers" explore the technical and scientific themes that underpin GNSS programs and applications. This regular column is coordinated by **Prof. Dr.-Ing. Günter Hein**, a member of the European Commission's Galileo Signal Task Force and organizer of the annual Munich Satellite Navigation Summit. He has been a full professor and director of the Institute of Geodesy and Navigation at the University FAF Munich since 1983. In 2002, he received the United States Institute of Navigation Johannes Kepler Award for sustained and significant contributions to the development of satellite navigation. Hein received his Dipl.-Ing and Dr.-Ing. degrees in geodesy from the University of Darmstadt, Germany. Contact Professor Hein at <Guenter.Hein@unibw-muenchen.de>. IG