E-GVAP
The EIG EUMETNET GNSS Water Vapour Programme, phase III

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Introduction.

Global Navigation Satellite System (GNSS) signals are sensitive to molecules in the atmosphere; in particular water vapour, which is a key greenhouse gas, and via condensation leads to cloud formation and precipitation, which releases of about half the energy that drives atmospheric motions.

In GNSS positioning the atmospheric influence is a noise term. Estimating the size of it, is to meteorology an important observation, because there is a strong lack of humidity observations. A fact becoming becoming more important, now operational high resolution numerical weather prediction (NWP) models reach scales the traditional meteorological observing system do not resolve properly.

The main purpose of E-GVAP is to provide ground based GNSS observations for use in operational meteorology in near real time (NRT), and to further the use of such data in both NWP and general weather forecasting. E-GVAP is based on a close collaboration between geodesy and meteorology. There are currently 18 national met-offices as members of E-GVAP, and they collaborate with 17 GNSS analysis centres (ACs), taking care of the collection and processing of the GNSS data. The majority of the ACs are geodetic institutions, a few are met-offices. Each AC itself collaborate with a multitude of GNSS site and data owners regarding access to the RINEX data used for the processing. The is a tophat MoU between EUREF and EUMETNET, and the EPN sites are the backbone of the E-GVAP observing system. In addition a tophat MoU has been made between EUPOS and EUMETNET. Local, national networks helps to improve spatial resolution - which is very important in regard to short lived phenomena with low predictability, such as severe precipitation.

Scientific basics

The refractivity, N, responsible for the slowdown and bending of the GNSS radio waves, is related to the properties of the tropo- and stratosphere as, see e.g. Bevis at al, **Jour. Appl. Met**, vol 33, p. 379, 1994.

$$N = R_d k_1 \rho_d + R_w \rho_w (k_2 + k_3/T) = \frac{p}{T}\frac{1}{1+q(1/\epsilon-1)}\left(k_1 + \frac{q}{\epsilon}\left(k_2 - k_1/\epsilon + \frac{k_3}{T}\right)\right), \qquad (1)$$

Here ρ means density, subscripts d and w refer to dry air and water vapour, R to the gas constant. The k's are constants determined empirically. p is pressure, T temperature, q specific humidity, and ϵ the ratio of the molecular weight of xx to xx. The first form shows refractivity is strongly related to the density of the molecules, the second that refractivity is directly related to the variables pressure, specific humidity and temperature of typical NWP models.

The GNSS data processing performed results in an estimate of the Zenith Total Delay, ZTD. It corresponds to the integral of refractivity over height in the vertical, $\int N\delta z$. The ZTD can be split into two parts,

$$ZTD = ZHD + ZWD, \qquad ZHD \approx 2.276810^{-5}\frac{p_a}{c(\theta_a, h_a)}[m/hPa], \qquad ZWD = \frac{R_d}{\epsilon g_s(\theta)}\sum_{i=1}^{N} q_i\left(k' + \frac{k_3}{T_i}\right)\Delta p_i \qquad (2)$$

The so-called hydrostatic delay, ZHD, is closely approximated by the "Saastamoinen formula", in which it depends solely on the pressure at the GNSS antenna, p_a, and a function c close to unity, which varies slowly with latitude and altitude. The wet delay ZWD depends mainly on the humidity and weakly on temperature, the summation is done over the layers of the NWP model. g_s is the local gravitational acceleration, using the surface value and its approximate variations with latitude is sufficient for meteorological usage of the data. $k' = k_2 - k_1/\epsilon$. Typical values of ZHD near msl is order 2 meters, whereas ZWD varies between 0 and 0.5 m. NWP models are much superior in predicting ZHD relative to ZWD, hence the ZTD provides mainly humidity information to models.

E-GVAP data

The current E-GVAP data coverage is shown in figure 1. There is a focus on Europe, but also processing of global data, and data exchange with NOAA, because of global NWP models.

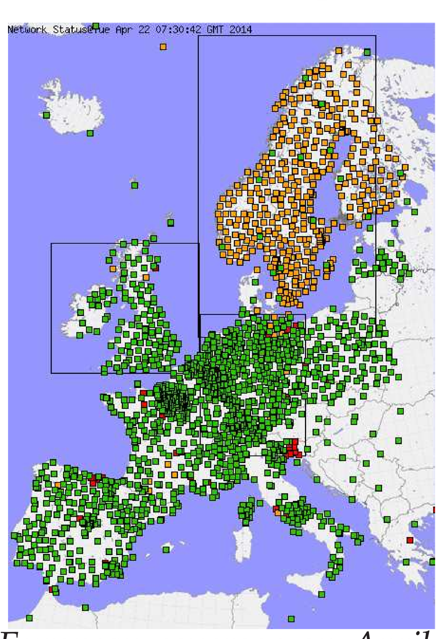

Fig 1a. European coverage on April 22 2014. Each square represents a GNSS site. Color according to latency.

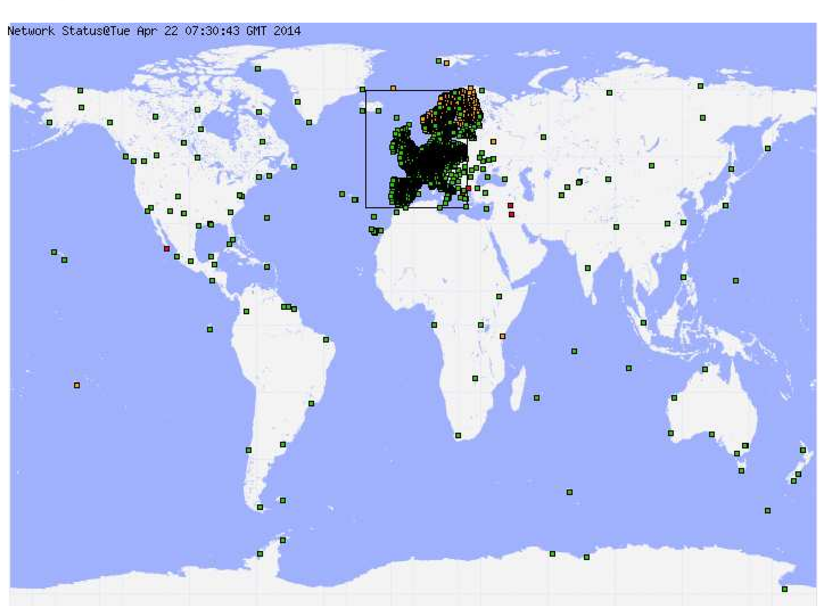

Fig 1b. Global coverage on April 22 2014. Note that due to a transient lack of NOAA data, about 300 sites are missing in North America on the map

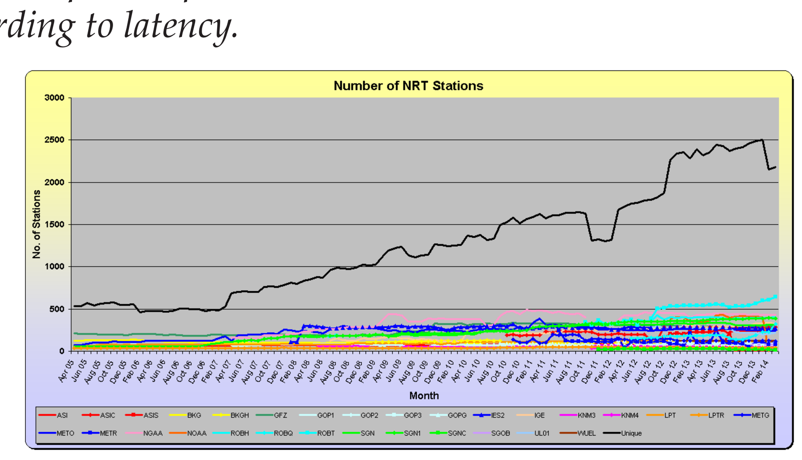

Fig 2. Number of unique GNSS sites versus time.

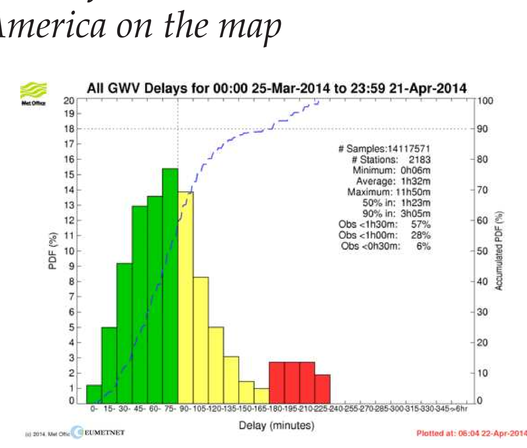

Fig 3. Histogram of "age of data" upon arrival in 15 min. bins. For all data, including experimental.

The number of contributing GNSS sites is gradually increasing. We are constantly interested in adding extra sites. With regard to high resolution NWP, we are not near saturation in any area. There is a currently a goal of data being available within 90 min. Since the uploads are hourly, and contain data with different valid times within the hourly bin, there is data of different ages from the same site within each file. The future high resolution NWP models will require faster access to data - which on the E-GVAP side requires changes of data formats, file naming, and processing strategies. It will be a gradual process to achieve that, but already today some of the ACs run close to real-time processing, with delays of only of the order 5 minutes.

GNSS data are highly useful for climate monitoring purposes, due to the long term stability of the observing system (which is essentially based on clocks). A particular aspect, however, is that the quality of the processing improves with time during the first hours and days. For this reason data processed in near real-time mode (like in E-GVAP) or in real-time mode, should not be used for climate monitoring. For this purpose, one should use post-processed data, preferably from sites with a long history

It is mainly ZTD which is used in data assimilation, but NWP models using nudging assimilation instead use integrated water vapour (IWV), which can be found from ZWD. However, the E-GVAP ZTDs are also used to produce animated 2D sequences of the IWV field over Europe (and subdivisions thereof). These are useful in *n*ow-casting to aid a forecaster in certain situations. The animations can been seen via the E-GVAP homepage. Today E-GVAP data are assimilated operationally by Meteo France, UK Metoffice, KNMI, and DMI. The assimilation increases the skill of the NWP forecasts. It is expected that a number of European met-services will follow this year. Some of them are presently running assimilation of E-GVAP data in test mode.

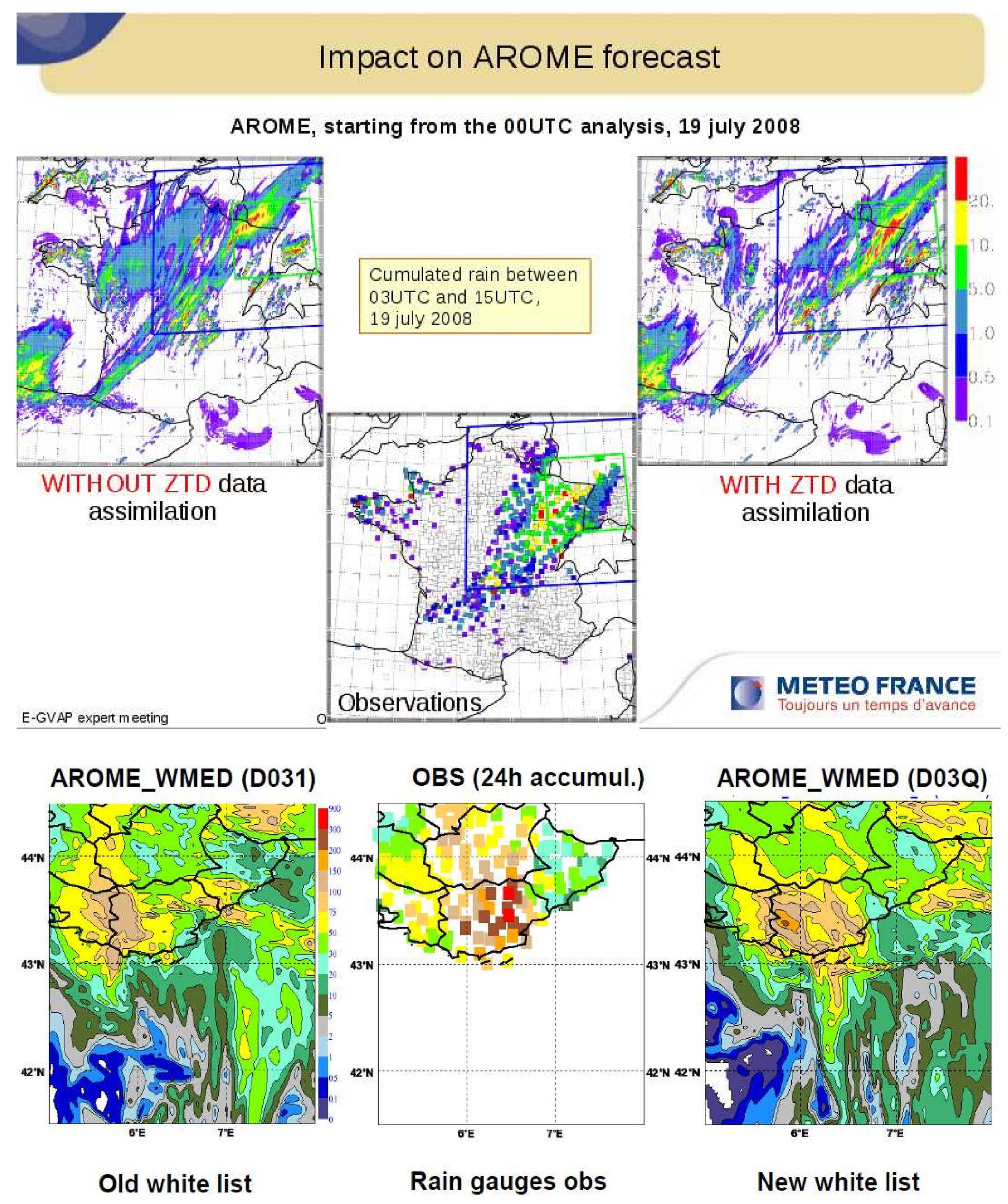

Fig 4. Impact of ground based GNSS ZTDs (from Patrick Moll, Meteo France).

Figure 4 provides an example of the impact of ground based GNSS ZTD observations. In the upper three figures one notice how the GNSS data correctly reduce the precipitation in NW France and increase it in the East. In the lower three figures it is seen how increase of the GNSS network by about a factor four (old versus new white list) improves the forecast. Due to the physics of the atmosphere the variables of NWP models are strongly interrelated, for this reason assimilation of a certain property can benefit many properties of an NWP model. Which is also found to be the case with ground based GNSS data.

AC acronym	Institute
ASI	e-geos/Telespazio, Italy
BKG	Federal Agency for Cartography & Geodesy, Germany
GFZ	Helmholz Centre Potsdam, GFZ German Research Centre for Geosciences
GOP	Geodetic Observatory Pecny, Czech Republic
IES	Institue of Engineering, Surveying and Space Geodesy, Univ. of Nottingham, UK
IGE	Instituto Geografico National, Spain
IRE	Met Eireann, Republic of Ireland
KNMI	Royal Meteorological Inst. of the Netherlands
LPT	SwissTopo, Switzerland
METO	UK Met Office, UK
NGAA	Chalmers Technical University and Swedish Meteorological and Hydr. Inst., Sweden
NOAA	National Oceanic and Atmospheric Administration, USA
ROB	Royal Observatory of Belgium
SGN	Institut Geographique National, France
SGOB	Satellite Geodetic Obs., IGCRS, & Dept. of Geodesy and Surv., TU Budapest, Hungary
ULO	University of Luxembourg, Faculty of Science and Communication
WUEL	Wroclaw Univ. of Environemental and Life Sci., Inst. of Geodesy and Geoinform., Poland

Participating analysis centers

E-GVAP members: National metoffices of Belgium, Croatia, Denmark, Finland, France, Hungary, Iceland, Ireland, Luxemburg, Netherlands, Norway, Portugal, Serbia, Slovak Republic, Spain, Sweden, Switzerland, United Kingdom.

Outlook

E-GVAP is now in phase three, running 2013-2017. The main focus will be on extending the network. Enabling sub-hourly data exchange, in order to facilitate rapid update, high resolution NWP. And to introduce active quality control (AQC), that on the fly can detect the rare case where many ZTDs are simultaneously in error and prevent usage.

E-GVAP has two expert teams, one on data processing and one on data usage. They meet once a year. While E-GVAP cannot fund other peoples participation in these meetings, they are open, providing a possibility for starting new collaborations or general knowledge sharing or learning.

There is great potential for improving the gb GNSS products for meteorology. For example by estimating and using also **ZTD gradients**, or switching to production and usage of **slant delays** or **residuals**. Likewise the use of **tomography** to create 3D water vapour fields. The EU Cost Action GNSS4SWEC (Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate) focusing on such topics has just started. See the corresponding poster here at EGU in this session. E-GVAP will collaborate closely with GNSS4SWEC.

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