G51A-02 0825h

Measuring Seismic Surface Waves with 1-Hz GPS

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Large earthquakes can cause seismological instrumentation to saturate or 'clip', even hundreds to thousands of kilometers away from the epicenter. In cases where seismological instruments fail to record ground motion, high-rate GPS data can serve as a replacement for these missing seismic data. We present an analysis of 1-Hz GPS data collected after the 2002 November 3 M7.9 Denali Fault earthquake. A significant number of seismic instruments clipped during this earthquake. An initial analysis demonstrated that surface waves could be observed on 1-Hz GPS instruments as far away as Colorado Springs, CO. In this study we add data from over 20 GPS receivers recording at 1-Hz in Canada and the western United States. Horizontal displacements exceeded 30 cm at some of these sites. We also investigate techniques for reducing GPS-specific errors. If available, 1-Hz GPS data collected in days before and after the earthquake are used to estimate and remove GPS errors, significantly improving 1-Hz GPS precision. Also, the impact of receiver mixing and ambiguity resolution performance is assessed.

G51A-03 0840h

Gps Real Time Monitoring of Active Volcanoes: Experience During the 2002-2003 Eruption of Stromboli (Aeolian Islands, Italy) and Data From Etna Network.

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In this work we present the data from the real time GPS network "SciaraDat", installed after a tsunami wave-creating flank collapse on the western slope of Stromboli volcano. The utility of this monitoring tool is demonstrated with emphasis on the clear relationship between GPS data and volcanological phenomena. Moreover, data from the 2001 Etna eruption, postprocessed with the epoch-by-epoch algorithm, demonstrate the importance of the instantaneous positioning approach for both scientific and civil defence communities related to the potential danger of a volcanic eruptions.

G51A-04 0855h

Real-Time High-Rate Upgrades of SCIGN Sites

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We are in the process of upgrading sites of the Southern California Integrated GPS Network (SCIGN) to real-time (1 sec latency), high-rate (1 Hz) operations, and have completed the upgrades for more than 25 sites. The normal operation for most of the network includes 30-second sampling with data downloads every 24 hours. The purpose of the upgrades is twofold: (1) to provide data rates useful for measuring strong ground motions to complement traditional seismic instruments in the event of a medium to large earthquake and data latencies useful for seismic response, risk mitigation, and rapid earthquake model determinations based on coseismic displacements; (2) to provide real-time access to high-rate data to surveyors, GIS professionals, structural engineers, transportation engineers and others requiring access to precise positioning and navigation information, under the umbrella of the California Spatial Reference Center (CSRC). We report on the status of upgrades in three sub-networks, each with a distinct focus: (1) the Orange County Real Time Network in collaboration with the County of Orange Public Facilities and Resources Division, (2) the Parkfield region in collaboration with the USGS and UC Berkeley's NCEDC and (3) the Riverside County Real Time Network in collaboration with the Riverside County's Department of Transportation and Flood Control and Water Conservation District. In the latter sub-network, we are developing a real-time displacement meter that will integrate broadband seismic and GPS measurements. We highlight achievements and lessons learned from these upgrades and assess whether it is feasible and desirable for the Earthscope project to pursue a similar approach.

G51A-05 0910h

Streaming GNSS Data over the Internet: The EUREF-IP Ntrip Broadcaster

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The global Internet can be used for the real-time collection and exchange of GNSS data, as well as for broadcasting derived differential products. The EUREF community decided in June 2002 to set up and maintain a real-time GNSS infrastructure on the Internet using stations of its European GPS/GLONASS Permanent Network EPN. A pilot project was established called EUREF-IP (IP for Internet Protocol). This real-time GNSS data service uses a new dissemination technique called "Networked Transport of RTCM via Internet Protocol" (Ntrip). Ntrip stands for an HTTP application-level protocol streaming GNSS data over the Internet. Currently about 110 data streams are available through EUREF-IP Ntrip Internet Broadcaster. This paper introduces the EUREF-IP Ntrip Broadcaster with its available real-time data streams from different networks. It focuses on positioning accuracy as well as on data latency, monitoring aspects and standardization.

G51A-06 0925h

GFZ HR/LL GPS Ground station networks and their use

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The contribution presents GFZ's global and local High-Rate and Low-Latency GPS networks. The global HR/LL network was established, in collaboration with JPL, to support the CHAMP and GRACE POD activities and the radio occultation experiment on both missions. The GFZ sub-network is composed of 13 continuously tracking stations, generating 15-min 1 Hz GPS data files and transmitting them to GFZ every 15 minutes. Eight stations contribute to the Galileo mission preparations. Since early 2003 eight HR sites are streaming GPS data in real time. Three of them take part in the IGS Real-Time Prototype Network. GPS HR/LL network for deformation monitoring is an example of local HR/LL GPS array. This 1 Hz network was installed on Popocapetel volcano end of 1999. For the calibration of satellite altimetry, an autonomous 10 Hz GPS-Buoy was developed by GFZ and is operating in the North Sea. The presentation describes shortly the three systems and discusses issues such as: data performance, real-time data aspects and quality monitoring. Application results from ultra-rapid CHAMP/GRACE orbit processing, radio-occultation routine processing, buoy monitoring and volcano monitoring in geodesy, geophysics and meteorology will be presented.

G51A-07 0940h

Utilizing Site-Specific Antenna Phase Center Calibration Maps for Reducing the Noise in the GPS Vertical

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The Global Positioning System has emerged as a leading tool in the field of geodesy. GPS observations have been shown to be a useful geodetic tool for such applications as monitoring post-glacial rebound and calibrating satellite altimeters to study sea level change. We have been analyzing data from 40 GPS sites near tide gauges for the purpose of developing vertical crustal motion estimates, which are subsequently used in the calibration of satellite altimeter measurements. However, site-specific errors such as multipath have limited the positioning accuracy, especially in the vertical. To combat these site-specific errors, antenna phase center calibration maps were developed by averaging the residuals over the time series of each point-positioned GPS site into bins 2 x 5 degrees in elevation and azimuth. No elevation cut-off was used for the purpose of exploring the effects of the maps on observations made at very low elevation angles. This was done separately for pseudorange and carrier phase. In addition, each antenna used at a given site had a unique map. This technique was iterated upon several times, using every day in the time series, until the variations were sufficiently captured. It will be shown that the antenna phase center calibration maps dramatically reduced the elevation dependence of the point-positioned solutions, especially between 0 degree and 10 degree elevation cut-offs. For example, at MacQuarie Island (MAC1), the difference in estimated trends over the 0 - 10 degree elevation cut-offs varied by as much as 3.5 mm/yr without using the calibration maps, whereas the maximum difference with the maps was 0.5 mm/yr over the same range. Also, there was a significant reduction in the vertical repeatibility of 1 - 2 mm in most cases. A list of new estimated trends at approximately 40 sites, as well as a thorough analysis of the associated errors will be shown.

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G51B MCC: Level 1 Friday 0830h

Advanced Tropospheric Sensing Methods and Accuracy of Tropospheric Information Determined by Space Geodetic Techniques II Posters *(joint with A)*

Presiding: **Y Bar-Sever,** Jet Propulsion Laboratory, California Institute of Technology**; H Schuh,** Vienna University of Technology

G51B-0025 0830h POSTER

The Tropospheric Products of the International GPS Service

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The International GPS Service (IGS) produces several tropospheric products that are based on combined contributions from several IGS Analysis Centers. These products contain time series of total zenith delay from a large subset of the IGS network of ground-based GPS receivers. The IGS has recently adapted a new method for the derivation of the combined tropospheric products. In this paper we describe this method and assess its benefits. Each product consists of time series of total zenith troposphere delay at 5 minute intervals from a set of IGS ground sites. Total zenith delay values are estimated with the precise point positioning approach, using the IGS combined GPS orbit and clock solutions, and Rinex files generated by each site. Presently there are two types of IGS tropospheric products: "Final", and "near real time (nrt)". The Final product is based on the IGS "Final", and most precise combined GPS orbit and clock products, and on daily Rinex files, and has a latency of approximately 10 days after the data is collected. The NRT product is based on the IGS ultra-rapid GPS orbit and clock products, and on hourly Rinex files. The latency is up to three hours after data has been collected. We compare this new approach for generating the IGS combined tropospheric products

with the previous approach, which was based on explicit combination of total zenith delay contributions from the Analysis Centers. The new combination approach enables the IGS to rapidly generate high accuracy and high reliability total zenith delay time series for many hundreds of sites, increasing the utility of the products to weather modelers, climatologists, and GPS analysts. We discuss issues of accuracy, quality control, and utility of the new products.

G51B-0026 0830h POSTER

Accuracy assessment of IGS zenith tropospheric delays

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When traversing the non-ionized part of the Earth's atmosphere, GPS signals are affected by spatio-temporal variations of the refractive index, which induce a propagation delay usually known as tropospheric delay. In high-precision applications of space geodetic techniques such as GPS, this delay can be estimated along with other geodetic parameters of interest. Since 1997, the International GPS Service (IGS) has been combining estimates of zenith tropospheric delays provided by different analysis centers for a large number of stations distributed worldwide. This atmospheric product is of great interest in GPS applications to Meteorology and climate studies. To assess the accuracy of this product, we have compared zenith delay estimates at about 80 IGS stations with ray-tracing estimates obtained from weather balloons launched near the GPS sites. In this presentation, we will describe the method we used to compare these estimates and will discuss the impact of distance between the balloon launch site and the GPS site on the assessment of quality of zenith delay estimates from the latter. For the best cases, our assessment indicates an overall accuracy of 1 cm or better for this IGS product.

G51B-0027 0830h POSTER

Tropospheric Parameters Determined by VLBI Within the IVS

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In April 2002 the IVS (International VLBI Service for Geodesy and Astrometry) set up the Pilot Project - Tropospheric Parameters, and the Institute of Geodesy and Geophysics (IGG), Vienna, was put in charge of coordinating the project. Seven IVS Analysis Centers have joined the project and regularly submitted their estimates of tropospheric parameters (wet and total zenith delays, horizontal gradients) for all IVS-R1 and IVS-R4 sessions since January 1st, 2002. The individual submissions are combined by a two-step procedure to obtain stable, robust and highly accurate tropospheric parameter time series with one hour resolution. The internal accuracy of the combined wet zenith delays is between 2 and 4 mm. The zenith delays derived by VLBI are compared with those provided by the International GPS Service (IGS). At sites with co-located VLBI and GPS antennas the short-term variabilities of the GPS and VLBI derived zenith delays generally show a good agreement but biases are found between the results of the two techniques. Possible reasons for these biases are discussed. Since July 1st, 2003, within the IVS the tropospheric parameters are determined as operational products. The presentation also includes the VLBI CONT02 campaign of 15 days of continuous observing in the second half of October 2002.

G51B-0028 0830h POSTER

A Comparison of ERS-2/ENVISAT and TOPEX/JASON-1 Tropospheric Zenith Wet Delay Measurements with Estimates from Offshore GPS Data.

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The accuracy of estimated atmospheric path delay due to water vapour derived from GPS data is often assessed by comparing GPS estimates with those derived from other sensors including radiosondes and ground based Microwave Radiometers (MRs). However, this is not always a convenient or cost effective approach. In this work we adopt an alternative approach utilising data from the MRs present on the altimetric satellites ERS-2, ENVISAT, TOPEX and JASON-1 which pass almost directly overhead a number of continuously recording GPS receivers located on oil platforms in the northern North Sea. This coincidence removes the main obstacle preventing such studies over land; namely background surface heat emissions which contaminate the MR tropospheric delay measurements. We use the GIPSY/OASIS II GPS processing software with a tuned tropospheric delay estimation strategy to process daily solutions and estimate tropospheric Zenith Wet Delay (ZWD) at 5 minute intervals as a random-walk parameter. Precise ZWD estimates, at the time of satellite overpass of the oil platforms, are derived at the repeat period of the altimetric satellites. Early results from 40 ERS-2 overpasses spanning a four year period show good agreement between GPS and MR, with a mean fit of <10mm.

G51B-0029 0830h POSTER

Upper Tropospheric and Stratospheric Radio Occultation Retrieval. A Validation Study Based on Data From CHAMP, ENVISAT Instruments, Radiosondes, and NWP Analyses

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Current Global Navigation Satellite System (GNSS) radio occultation (RO) retrieval techniques generally yield excellent results on refractivity, geopotential height (or pressure), and temperature in the upper troposphere and lower stratosphere. Above 30 km, throughout the upper stratosphere, the errors of retrieved atmospheric profiles increase significantly. The retrievals can still be fairly accurate in the upper stratosphere, however, if one uses adequate high-altitude initialization and statistical optimization techniques invoking background data (e.g., from climatologies). Simulation studies showed that sensible use of independent background data has the ability to significantly reduce retrieval errors, especially biases, in the upper stratosphere (e.g., mean temperature biases < 0.25 1 K in the 30 to 40 km height domain). Results of these studies will be summarized. They make clear that, in particular, care is required not to introduce eventual biases from the background data into the retrieval results. In this study we focus on investigating the stratospheric RO retrieval performance, especially regarding temperature, when applying different high altitude initialization/statistical optimization schemes and different kinds of background information to CHAMP RO bending angle data. Atmospheric data products generated by the operational CHAMP processing system at GeoForschungsZentrum Potsdam (GFZ) and data products from the IGAM/CHAMP processing chain will be extensively validated with correlative data from ENVISAT instruments (MIPAS, GOMOS), radiosondes, and global NWP analyses (ECMWF analysis fields). Additionally, a new temperature product generated from the precise pointing data of the GOMOS steering front assembly will be introduced and used in the validation study. The validation results will be discussed with emphasis on the matter of upper stratospheric temperature biases in RO data.

G51B-0030 0830h POSTER

GPS Water Vapor Tomography Based on Accurate Estimations of the GPS Tropospheric Parameters

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The Global Positioning System (GPS) is now a common technique for the retrieval of zenithal integrated water vapor (IWV). Further applications in meteorology need also slant integrated water vapor (SIWV) which allow to precisely define the high variability of tropospheric water vapor at different temporal and spatial scales. Only precise estimations of IWV and horizontal gradients allow the estimation of accurate SIWV. We present studies developed to improve the estimation of tropospheric water vapor from GPS data. Results are obtained from several field experiments (MAP, ESCOMPTE, OHM-CV, IHOP,...). First IWV are estimated using different GPS processing strategies and results are compared to radiosondes. The role of the reference frame and the a priori constraints on the coordinates of the fiducial and local stations is generally underestimated. It seems to be of first order in the estimation of the IWV. Second we validate the estimated horizontal gradients comparing zenith delay gradients and single site gradients. IWV, gradients and post-fit residuals are used to construct slant integrated water delays. Validation of the SIWV is under progress comparing GPS SIWV, Lidar measurements and high resolution meteorological models (Meso-NH). A careful analysis of the post-fit residuals is needed to separate tropospheric signal from multipaths. The slant tropospheric delays are used to study the 3D heterogeneity of the troposphere. We develop a tomographic software to model the three-dimensional distribution of the tropospheric water vapor from GPS data. The software is applied to the ESCOMPTE field experiment, a dense network of 17 dual frequency GPS receivers operated in southern France. Three inversions have been successfully compared to three successive radiosonde launches. Good resolution is obtained up to heights of 3000 m.

G51B-0031 0830h POSTER

The Influence of Atmospheric Water Vapor on High-precision GPS Positing Determination

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We utilize the measurements collected by the Global Positioning System (GPS) receivers established as continuously operating reference stations by Central Weather Bureau and I.T.R.I/CMS of Taiwan to investigate the impact of atmospheric water vapor on high-precision positioning determination. The surface meteorological measurements that were concurrently acquired by co-located instruments include temperature, pressure and humidity data. To obtain the influence of the baseline length on the proposed impact study, two baselines are considered according to the locations of the permanent GPS sites. The length of the shorter baseline is about 26 km, while the other is about 118 km. The results of the baseline determination for both 2-hr and 24-hr periods, and hence 3-D coordinates were compared for the cases with and without a priori knowledge of surface meteorological measurements. The preliminary finding based on two weeks measurements is that the surface meteorological measurements have a significant impact on the positioning determination for the longer baseline case, but a negligible impact for the shorter baseline case. The inclusion of the surface meteorological measurements introduces a negative bias of 6 mm to the baseline determination for the longer baseline cases.

G51B-0032 0830h POSTER

Compensating atmospheric distortions in SAR interferograms using continuous GPS time series of Zenith Wet Delay estimates

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Spatial heterogeneity of the wet component of atmospheric refractivity causes distortions in radar interferograms. Integrated refractivity along the radar line-of-sight is proportional to total excess path length of of the radar signal propagating through the random 3D refractivity field, and this extra delay can contribute significantly towards the observed phase in radar interferograms. This additional component of interferometric phase can cause erroneous interpretation of useful signal information in interferograms, particularly with respect to crustal deformation studies where the ground displacement signal is on the order of the noise component. In this report, we analyze the residuals of a topography-corrected, deformation-free radar interferogram in terms of atmosphere-induced excess path delays. Furthermore, we leverage Zenith Wet Delay (ZWD) estimates from continuous Global Position System (GPS) stations operating in the same area to model the atmosphere phase screen in the radar interferogram. This modeling is performed via ordinary kriging, which takes advantage of the spatial covariance characteristics of the ZWD field known from Kolmogorov turbulence theory. The theory predicts the spatial covariance of the isotropic three-dimensional refractivity random field. For our modeling purposes, we derive the corresponding form of spatial covariance for the projection of this field onto the two-dimensional plane of the radar interferogram. The performance of our modeling efforts is gauged by computing the Power Spectral Densities (PSD) before and after subtraction of the observed phase screen with our model. Our results indicate that such minimum estimation variance modeling produces smooth estimators that track well large spatial wavelength trends. Thus, these models reduce power in only low-frequency bands, from 0.1 cycles/km to 1 cycle/km, of the PSD by almost one order of magnitude. The resulting model, however, reduces overall rms of atmosphere phase noise by about 50%. To improve the performance of the atmosphere phase screen modeling, we consider incorporating more data from each continuous GPS station in the form of time series of ZWD estimates centered around the interferogram observation times. Furthermore, we appeal to the Kolmogorov-Taylor model of a “frozen-in” atmosphere which provides a relationship between theoretical temporal covariance to correlations in the spatial domain, due to movement of the atmosphere column by wind with an average velocity, to relate temporal wet delay observations to predictions of atmosphere phase delay at unsampled spatial locations.

G51B-0033 0830h POSTER

Simulations of Troposphere Scintillation Impacts on Water Vapour Retrieval Using the Satellite-to-Satellite Measurements

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The radio occultation technique is using signals from the Global Positioning System (GPS) to measure phase and amplitude changes caused by the atmosphere. The observations are done from low Earth orbiting (LEO) satellites. The retrieved vertical profiles of the refractive index are used to extract the information of temperature, pressure, and humidity as a function of height in the troposphere and stratosphere. In order to improve the separation of the contributions of water vapour and temperature in the lower troposphere, without using external data, the ESA Earth Explorer satellite mission ACE+ will actively sound the atmosphere using LEO-to-LEO signal transmission at three frequencies around the 22 GHz water vapour absorption line (10, 17, and 23 GHz). The new and novel observations will focus on measuring amplitude and phase at the different frequencies in order to resolve the main terms for intensity changes in the received signals. The combination of the three frequencies removes the effect of liquid water droplets in clouds from the process of estimating the profile of tropospheric water vapour. The transmission of coded signals between LEOs (with similar signal structure as GPS) is the key observable for monitoring the global distribution of atmospheric water vapour. In the lower troposphere, where water vapour is abundant, the less strongly absorbed 10 and 17 GHz signals are employed. Transmitted power and receiver antennae gains are sized to achieve a worst-case moisture concentration of 20 g/kg at the bottom of the troposphere in the tropics. In the upper troposphere, where the moisture concentration can be lower by 4 orders of magnitude, the overriding consideration is detecting the relatively weak effect with sufficient precision in order to achieve accurate moisture measurements. We will present end-to-end simulations of the measurements, consisting of a forward propagation of the signals and a retrieval theory for the estimated complex refractivity profiles, to assess the importance of phase and amplitude fluctuations in relation to troposphere scintillations for the accuracy of the method. The new simulation tool consists of forward full wave signal propagation in two dimensions through a large set of phase screens placed in the fluctuating medium between the transmitter and the receiver. The received LEO-LEO phases and amplitudes are used to estimate the complex refractivity profile by applying the Full Spectrum Inversion theory and a fitting transform solution based on the complex fields of all three probing frequencies.

G51B-0034 0830h POSTER

Observation of the Antarctic Sudden Stratospheric Warming of September 2002 using GPS Radio Occultation Technique

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The vertical resolution and global coverage of GPS radio occultation (GPSRO) measurements of temperatures in the stratosphere makes it an ideal tool to study the appearance and evolution of sudden stratospheric warmings (stratwarms). Additionally, the nearly polar orbits of the CHAMP and SAC-C satellites that carry GPSRO sensors give excellent coverage in the polar regions where sudden stratwarms occur. In this poster, we analyze the Antarctic sudden stratwarm event of September 2002 using the combined data from both satellites.

G51B-0035 0830h POSTER

Diurnal signatures of atmospheric water vapor observed by GPS receivers on Taiwan

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In light of the tremendous potential of GPS in atmospheric and geodetic research and education, National Science Council (NSC) of Taiwan initiated a project to set up a 200 GPS sites network in year 2000. Major funding to support the network comes from Central Weather Bureau (CWB), Department of Interior, Academic Sinica, and NSC. Up to date, there are in total more than 100 GPS sites are completed. In this paper, we present the diurnal signatures of atmospheric water vapor observed by the GPS receivers. Atmospheric water vapor is a key variable in the atmospheric radiation budget and global hydrological cycles. Traditionally, its diurnal variation is primarily examined using the observations from radiosonde soundings, which are typically launched twice daily and, hence, insufficient to capture the representative characteristics of the diurnal water vapor variation. Recently, the GPS observations that provide continuous measurements of atmospheric water vapor were used to study its diurnal variations in USA. In this contribution, we investigate the diurnal variation of water vapor based on GPS observations in Taiwan whose climatology dramatically differs from that in the Northern America. The differences are primarily due to the fact that Taiwan is located in the boundary of the sub-tropical and tropical regions with much more abundant of water vapor in the atmosphere in addition to its fast changing topography surrounding by the oceans. The GPS data that are used for the current study are mainly obtained from the dense network supported by the Central Weather Bureau. The diurnal variations of the water vapor are described and quantified by sinusoidal functions. The characteristics of diurnal water vapor variation and semi-diurnal variations are then discussed.

G51B-0036 0830h POSTER

Monitoring the Water Vapour Content of the Atomsphere using the Austrian GNSS Reference Station Network

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GPS has become an important tool both in navigation and in precise point positioning. One of the nuicance parameters limiting the accuracy of point determination is the water vapor content of the troposphere. On the other hand meteorologists are interested in the wet component of the troposphere as a valuable tool for Numerical Weather Prediction and Climate Studies. Therefore GPS offers a low cost monitoring of water vapor with high temporal resolution. We make use of continuous measurements of the GPS/GLONASS reference station network in Austria, which currently consists of about 27 sites with a mean distance of 50 km. The total zenith path (TZPD) delays for 2 weeks in 2002 (May and August 2002) with an anticipated huge difference in the water vapour content were calculated. Subsequently the results are compared to contributions of different processing centers of the COST-716 project (Exploitation of Ground Based GPS for Climate and NWP) and with zenith path delay estimates provided by the IGS. Based on the observed atmospheric pressure field the Zenit Wet Delay has been separated from the TZPD estimates. As meteorologists need the water vapor within less than two hours, special attention is paid to the availability, reliability and especially on the quality of the satellite orbits used for the network calculations. For this reason we try to use rapid ephemeris instead of the IGS final orbits, whereby we make a quality control of the rapid orbits. If one or more satellites show poor quality or if one satellite is missing at all we include the broadcast ephemeris information instead.

G51C MCC: 2010 Friday 1020h

Advancing the Cutting Edge of Geodesy II: Dynamics of the Earth

Presiding: **O de Viron,** Royal Observatory of Belgium**; G Blewitt,** Nevada Bureau of Mines and Geology and Seismological Laboratory

G51C-01 1020h INVITED

Seasonal Crustal Deformation in Japan and its Interannual Variation

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A dense array of GPS is useful to study seasonally changing load through periodic components in crustal movements. In this paper I review observed and predicted seasonal crustal movements in the Japanese Islands, where both nationwide dense GPS array and meteorological sensor network are available. From comprehensive evaluation of various sources contributing to seasonal signals, the largest factor in Japan is found to be snow, weighing over 1000 kg per square meter in some regions. This is followed by various kinds of loads on the land area, such as atmosphere, soil moisture and dam, and non-tidal ocean loads also cause certain seasonal signatures. Seasonal crustal deformations are calculated by synthesizing all these seasonal load changes, some of which are directly measured meteorologically and others are inferred through models. They are compared with real data observed by the dense GPS array in Japan, and they agreed fairly well. The seasonal signals observed by GPS also include artifacts, such as scale changes due possibly to atmospheric refraction, and atmospheric delay gradients. We often discuss subtle crustal deformation signals, e.g. those associated with silent earthquakes, isolating them by removing secular and periodic components. Understanding seasonal signals and their interannual variability is crucial in removing these unwanted signals. Amplitudes of seasonal signals in Japan were suggested to have increased in 2000, and I discuss its causal relationship with the increase in snow depths in the 1999/2000 winter.