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Abstract	Natural hazards and climate change are of major concern to the society. Huge losses are reported in recent years. It is widely believed that modern GNSS technologies are effective in hazard monitoring and climate change detection and modelling. Considering the limitations of current accuracy and reliability, sophisticated strategies and models have to be developed. We introduce and overview recent GNSS activities at GFZ in this field, including ground and satellite based atmospheric sounding, reflectometry and GNSS seismology. In addition we summarize recent hardware developments, where new robust on-site hardware systems combining GNSS receiver and other sensors (e.g. seismic sensors and weather sensors) are developed. The main focus of our contribution is recent results of GNSS analysis software developments for real-time applications, where multi-technique (e.g. SLR and GNSS) and multi-system (e.g. GPS and GLONASS) data source can be handled uniquely. The software can run in real-time as well as post-processing modes, and precision of several mm for ground surface deformation can be achieved. We overview the ground and spaced based GNSS atmosphere researches based on the estimation and assimilation of atmosphere parameters, which are among those parameters estimated from our GNSS software. Related projects, applying these new developments, are also introduced.

Keywords (separated by '-')	Natural hazards monitoring - Climate change - Hardware development - EPOS-RT - Atmosphere modelling

Chapter 12
GNSS Activities for Natural Disaster Monitoring and Climate Change Detection at GFZ – An Overview

J. Chen, M. Bender, G. Beyerle, G. Dick, C. Falck, M. Ge, G. Gendt, S. Heise, M. Ramatschi, T. Schmidt, R. Stosius, and J. Wickert

Abstract Natural hazards and climate change are of major concern to the society. Huge losses are reported in recent years. It is widely believed that modern GNSS technologies are effective in hazard monitoring and climate change detection and modelling. Considering the limitations of current accuracy and reliability, sophisticated strategies and models have to be developed. We introduce and overview recent GNSS activities at GFZ in this field, including ground and satellite based atmospheric sounding, reflectometry and GNSS seismology. In addition we summarize recent hardware developments, where new robust on-site hardware systems combining GNSS receiver and other sensors (e.g. seismic sensors and weather sensors) are developed. The main focus of our contribution is recent results of GNSS analysis software developments for real-time applications, where multi-technique (e.g. SLR and GNSS) and multi-system (e.g. GPS and GLONASS) data source can be handled uniquely. The software can run in real-time as well as post-processing modes, and precision of several mm for ground surface deformation can be achieved. We overview the ground and spaced based GNSS atmosphere researches based on the estimation and assimilation of atmosphere parameters, which are among those parameters estimated from our GNSS software. Related projects, applying these new developments, are also introduced.

12.1 Introduction

Natural hazards are of major concern to the society. DMISCO (Disaster Management International Space Coordination Organization) stated: From 1994 to 2003 there were more than 300 major natural disasters on average each year, impacting more than 100 countries, killing over 50,000 people, affecting nearly 260

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million people and causing economic damage totaling US$ 55 billion each year (GeoForschungsZentrum Potsdam). In 2008, the Wenchuan earthquake in China caused 69,225 known deaths, 17,939 people are listed as missing, and 374,640 injured (Xinhua News Agency).

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For more than 10 years now, global and regional GPS/GNSS (Global Navigation Satellite System) networks have demonstrated their potential for detecting plate tectonic movements, strain and stress accumulation. During the mega-earthquake off Sumatra in December 2004 a dense network of GPS stations in Thailand demonstrated the capability for the detection and the closed monitoring of dynamic processes during a rupture process (GeoForschungsZentrum Potsdam).

To achieve the real-time deformation detecting and monitoring with GNSS, the following tasks are most challenging:

- the design and development of a new series of multi-parameter stations running unattended and autonomously for long periods,
- the development of new and automated GPS/GNSS software systems allowing real-time data analysis and self-detection of events, and
- the development and test of new data communication strategies for high-rate and high-volume data.

We present the latest progress at GFZ in the above tasks. Sections 12.2 and 12.3 introduce the developments of sensor stations and its application in Indian Ocean Tsunami early warning system. Section 12.4 shows the progress of GNSS reflectometry for surface deformation monitoring. The structure and applications of the newly designed GNSS software are discussed in Section 12.5.

Climate changes can also be monitored and detected by GNSS technologies. Crossing the atmosphere, GNSS signals experience propagation, which can be modelled by atmosphere parameters. These parameters are among the various estimated parameters of GNSS data analysis and are assimilated in atmosphere modelling thereafter. Recent years we see big progresses of atmosphere modelling in GNSS meteorology and atmospheric sounding, which improve our understanding of climate mechanism enormously. We summarize our climate change monitoring related activities in ground and space based GNSS atmospheric sounding in Section 12.6.

12.2 GNSS Sensor Station Developments

The geodetic branch (Department 1) at GFZ has a strong background in the field of geodetic sensor system operation such as SLR (Satellite Laser Ranging), PRARE (Precise Range And Range Rate Equipment) and instruments on satellites (e.g. onboard ERS-2, CHAMP, GRACE, TerraSAR-X). This includes the operation of sensor networks and the development of task and environment adapted sensor stations with small series manufacturing. Some examples for GFZ-developed sensor

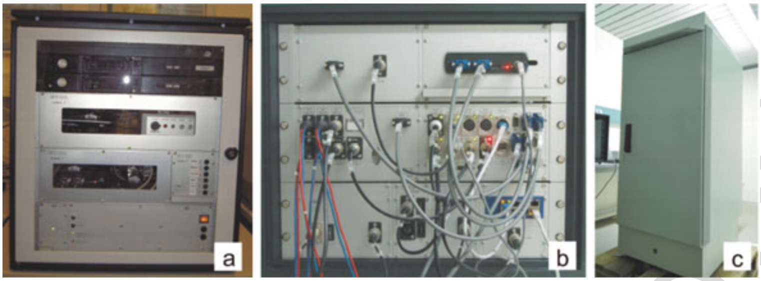

Fig. 12.1 (**a**) GNSS sensor station used for GFZ-operated global network locations, following a "no moving parts" and "off the shelf" components design philosophy. (**b**) GNSS sensor station with low power consumption and service friendly design developed for the GITEWS project. (**c**) Outdoor box with special passive cooling design

stations are shown on Fig. 12.1. All mentioned station designs have been tested in a climate chamber to ensure a reliable performance under all considerable climate conditions.

The station type on Fig. 12.1a was developed for the globally distributed, GFZ-operated GNSS sensor station network. It reflects findings from many years of global network operation with respect to remote hardware control, monitoring, failure recovery and repairs at remote locations. Nearly all integrated devices are "off the shelf" components with standard dimensions (Falck et al. 2008). They have been selected for long term operation but may be easily replaced after years by "off the shelf" components of a later generation. The construction has no moving parts (e.g., solid state hard disks, no fans) and produces no noise. An UPS (uninterruptible power supply) is integrated as well as a fold-out keyboard, mouse and monitor panel. Advanced remote monitoring and control devices allow failure detection and recovery, largely independent from local operators. The resulting key feature of this station type is the high level of reliability and redundancy.

Another example of a GFZ developed GNSS station design is the RTR (real-time reference) station as used for the GNSS component of the Indonesian Tsunami Early Warning System INATEWS (see next chapter). Special requirements from the field of operation are taken into account. Most important was to support the easiness of low level service works and the capability to handle frequent mains power outages enduring from seconds to days. The electronic components are installed in service-friendly modules, connected through front side cables. Even "off the shelf" components have their own extra cases to allow easy replacement in case of a malfunction. A set of rechargeable batteries is placed next to the indoor rack or inside the outdoor rack and allows a system operation of more than 2 days, independent of mains power.

Both station types (Fig. 12.1a and b) are based on a 19-inch rack mount construction housed in either regular indoor or weatherproof outdoor racks (Fig. 12.1c). The selected outdoor rack is a double wall construction, allowing passive cooling (no fans) without any kind of open window between electronics and environment. The outdoor rack was not developed at GFZ, but identified as an important component for long term field installations.

A special software package with a modular concept has been developed. It was initially used for global network stations and adapted for the GITEWS RTR stations. The software supports several GNSS receiver types of various manufacturers as well as different meteorological sensor stations. It is capable of combining real time data streaming with file based transfer to keep the communication bandwidth low. An integrated monitor checks the status of the sensor station regularly. Automatic software updates are possible without interruption of normal operation. This software package is an essential precondition for near real-time and real-time applications.

12.3 GNSS-Based Component for Tsunami Early Warning Systems

GNSS technologies offer a high potential to support tsunami early warning systems. After the Tsunami event of 26th December 2004 the German government initiated the GITEWS project (German Indonesian Tsunami Early Warning System) to develop a tsunami early warning system for Indonesia. The new developed GNSS-based component utilises on- and off-shore measured GNSS data and is the first system of its kind that was integrated into an operational early warning system. Figure 12.2 shows the GNSS-component operator desk at the Indonesian Tsunami Early Warning Centre INATEWS at BMKG Jakarta, inaugurated on November, 11th 2008.

The new GNSS-based system covers all aspects from development, manufacturing and installation of sensor station hardware, real-time data transfer issues, a new developed automatic near real-time data processing and a graphical user interface for early warning centre operators including training on the system (Ramatschi et al. 2008). GNSS sensors are installed on buoys, at tide gauges and as real-time RTR stations, either stand-alone or co-located with seismological sensors. The GNSS data are transmitted via satellite links to the warning centre, where they are processed in a near real-time data processing chain.


Photo: C. Falck, GFZ

Fig. 12.2 GNSS operator desk at the Indonesian Tsunami Early Warning Centre

There are two modes of data processing, the normal mode and the tsunami mode. The latter is selected as soon as a potentially tsunami relevant event was detected by the warning centre (strong earthquake, increased sea level at tide gauge, etc.). The first step in tsunami mode is the processing of data from the real-time reference stations. Then the system processes data of the 10 most relevant sensors (e.g. located nearest to the earthquake location) in 2 min intervals. In normal mode data of all sensors are processed in 5 min intervals, to allow a continuous sensor performance monitoring.

For sensors on land the data processing delivers deviations from the sensor location mean coordinates. Deviations with significant higher values than the normal noise level are regarded as land mass movements which can occur, e.g., due to strong earthquakes. This ground motion (plate tectonics) information is a valuable source for a fast understanding of an earthquake's mechanism with possible relevance for a potential following tsunami. It is also important to know displacements for locations with tide gauge sensors to separate real, tsunami caused sea level changes from apparent, displacement caused sea level changes which moved the tide gauge sensor.

For GNSS data measured on a buoy the processing (single baseline solution with one on land GNSS station as reference) delivers coordinates as well. Only the vertical component is of interest as it corresponds to instant sea level heights. Deviations to the mean sea level height are an indicator for a passing tsunami wave. By this means, ground motion and sea level height monitoring, the GNSS system supports the decision finding process whether most probably a tsunami has been generated or not.

The GUI (graphical user interface, see displays on Fig. 12.2) of the GNSS-based system supports both, a quick view for all staff members at the warning centre (24 h/7d shifts) and deeper analysis by GNSS experts. The GNSS GUI system is implemented as a web-based application and allows all views to be displayed on different screens at the same time, even outside the warning centre. This is part of the concept and supports the teamwork between warning centre staff on duty or on standby and sensor station maintenance staff.

12.4 GNSS Reflectometry

GNSS reflectometry (GNSS-R) is a promising new approach proposed by Martín-Neira (1993) that uses GNSS signals reflected from the earth to derive information about the height and the condition of the reflecting surface. It can be used in an altimetric and a scatterometric manner to measure surface height as well as wind speed, wind direction, soil moisture or sea ice extend, among others. The usability of GNSS-R has been demonstrated in several ground-based, air-borne and space-borne experiments. Code based and phase based GNSS-R approaches have to be distinguished. In code based GNSS-R the reception delay between the direct and the reflected GNSS signal is measured, which is similar to radar altimetry. Additionally the reflected signal contains information about the scattering characteristic, which can be related to surface roughness. For the phase based approach coherent reflections are necessary. These can be obtained at grazing angle geometries, which are common also in radio occultation measurements (Beyerle and Hocke 2001). The phase interference between direct and reflected GNSS signals can be interpreted as height variation (Helm 2008). Compared to conventional measurement techniques GNSS-R has a variety of advantages. In contrast to monostatic methods like radar altimetry a GNSS-R receiver aboard a low earth orbiting (LEO) satellite receives GNSS reflections from many directions simultaneously so that GNSS-R can be regarded as multistatic (Fig. 12.3). This results in an increase of spatial and temporal resolution needed to observe mesoscale features. The GNSS signals are freely available and are used as signals of opportunity. Considering the planned installation of Galileo and forthcoming systems the number of GNSS satellites and therefore the number of reflected signals is going to increase dramatically within the next decade. Their availability will be continuous over a long time, because they are used commercially. GNSS-R is a passive measurement technique with a low energy budget. This allows the building of small and affordable GNSS-R satellites, especially when commercial-off-the-shelf (COTS) GNSS receivers could be used. The GFZ has carried out ground-based experiments with a modified COTS JAVAD receiver called GNSS Occultation, Reflectometry and Scatterometry (GORS) receiver and has demonstrated its capability to measure lake surface height at centimeter accuracy (Helm et al. 2008). When installed on small satellites within a constellation this technique is believed to be applicable as a global tsunami early warning system. A feasibility study of GFZ shows that a Sumatra like tsunami (Fig. 12.3) would be

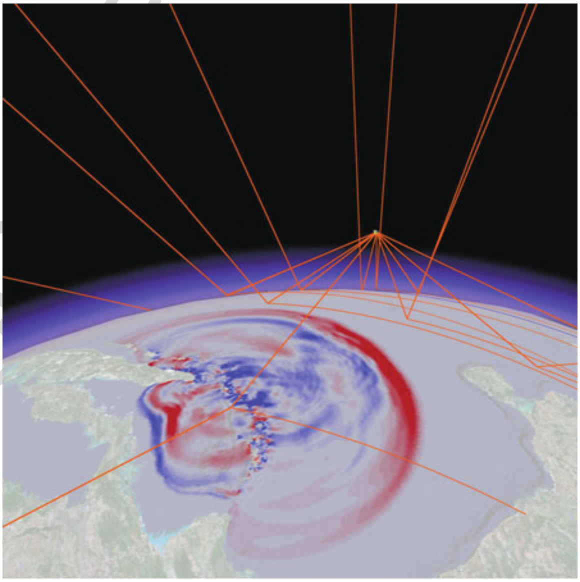

Fig. 12.3 Simulation of GNSS-R signal paths and reflection tracks during a tsunami event off-shore Indonesia

detectable within 17 min with a GNSS-R Walker-constellation of 18 satellites at 900 km altitude and 60° inclination (Stosius et al. 2008).

12.5 GNSS Seismology

Based on the expertise on GNSS software development, a newly-designed software package, EPOS-RT (Earth satellite Positioning and Orbit determination System in Real-Time) (Chen et al. 2008, 2009; Ge et al. 2008; Rothacher et al. 2008), is being developed at GFZ for data analysis of various applications, such as real-time deformation monitoring (Network solution mode) and providing service for applications based on PPP (Precise Point Positioning, PPP mode). Figure 12.4 shows the system structure of EPOS-RT. There are three main parts: data communication, processing kernel, and product service. Processing kernel is the main processing unit where observation modelling, parameterization and estimation are encoded. Data communication deals with input and output data. Service part manages and broadcasts products from processing kernel to users.

Various tests and investigations were carried out. In PPP mode, satellite clocks are estimated first, where a comparable precision can be achieved compared to IGS final clocks.

Using the estimated satellite clock and corresponding satellite orbits, ground surface deformation monitoring was carried out. During the Mw7.8 Chile earthquake, on DoY 318, 2007, we analyzed GPS observations at station TALA, 100 km away from the epicenter. Figure 12.5 shows the kinematic PPP results in east component, which is the main deformation at this station. The top plot shows the time series for the whole day, where we see a sudden offset at 15:42 UTC, 1 min after the earthquake hit Tocopilla town. The bottom plot shows the deformations during 20 min before and after the earthquake epoch.

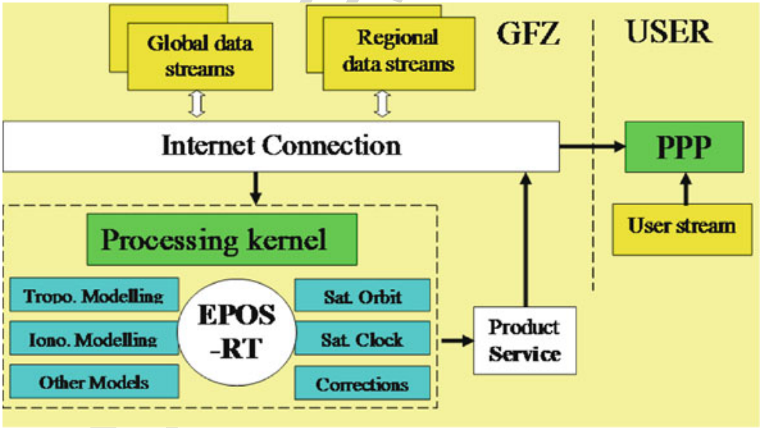

Fig. 12.4 System structure of EPOS-RT

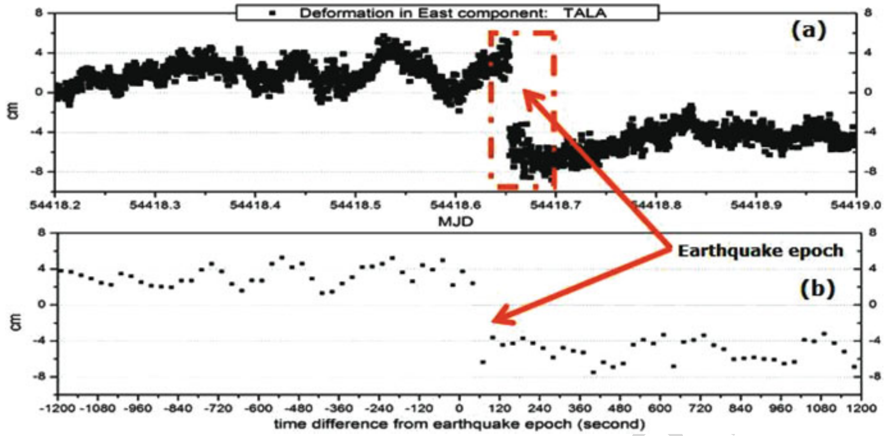

Fig. 12.5 Coordinate changes of TALA during Chile earthquake 2007. (**a**) Daily PPP solution, displacement of ∼8 cm at East component is observed. (**b**) Coordinate changes of East component during the period 20 min before and after the earthquake epoch

Network solution mode is the second solution mode of EPOS-RT. Making use of the data from the European real-time GNSS network (baselines range from 100 km to 420 km), Fig. 12.6 shows real-time monitoring of the station BZRG, in Bolzano, Italy over 2 days. The system initializes within around 20 min and ambiguity fixing starts thereafter. The real-time coordinate precision is better than 1.3 cm in horizontal components and around 4 cm in height.

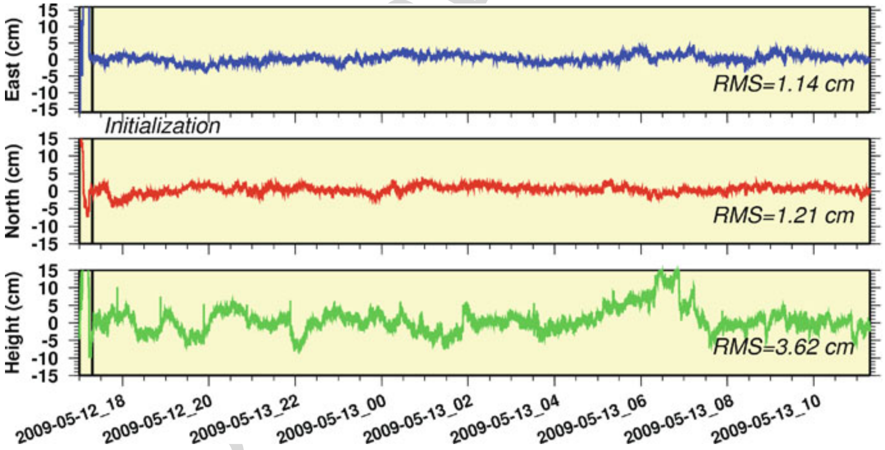

Fig. 12.6 Coordinates differences compared to IGS weekly combination of station BZRG in Italy, where RMS refers to IGS coordinates

12.6 GNSS Atmospheric Sounding

12.6.1 Ground-Based GNSS Meteorology

Crossing the atmosphere, GNSS signals experience a propagation delay depending on constitution of the ionosphere (electron density) and neutral atmosphere (pressure, temperature, water vapor). The neutral atmosphere related zenith path delay (ZPD) above each GPS ground station is a standard product of routine GPS data processing and the humidity induced part of ZPD provides a valuable source of vertically integrated water vapor (IWV) information. Regarding the key role that water vapor plays in the Earth's atmosphere system and the high temporal and spatial variability of water vapor, GPS IWV observations are important for both numerical weather prediction (e.g. Gendt et al. 2004) and climatological investigations (e.g. Nilsson and Elgered 2008). The GPS-based IWV observation technique is characterized by several advantages in comparison to the traditional observing systems: independence on sensor calibrations and therefore long-term stability, all-weather capability, high accuracy and low cost. Based on its global network observations (currently more than 300 stations), the IGS provides ZPD data starting from February 1997. To convert ZPD to IWV meteorological information are normally required, but currently only a limited number of IGS stations are equipped with meteorological sensors. To solve this problem, an analysis technique based on ECMWF (European Centre for Medium-Range Weather Forecasts) analysis data has been developed at GFZ (Heise et al. 2009). Figure 12.7 gives a general view on IGS IWV results derived at GFZ. Good agreement for most of the stations is seen compared to ECMWF.

The globally available GPS data sets are refined by regional observations, e.g. for Europe (http://egvap.dmi.dk/) or Germany. The GFZ operates a near real-time analysis center processing about 300 German GPS stations in addition to the IGS

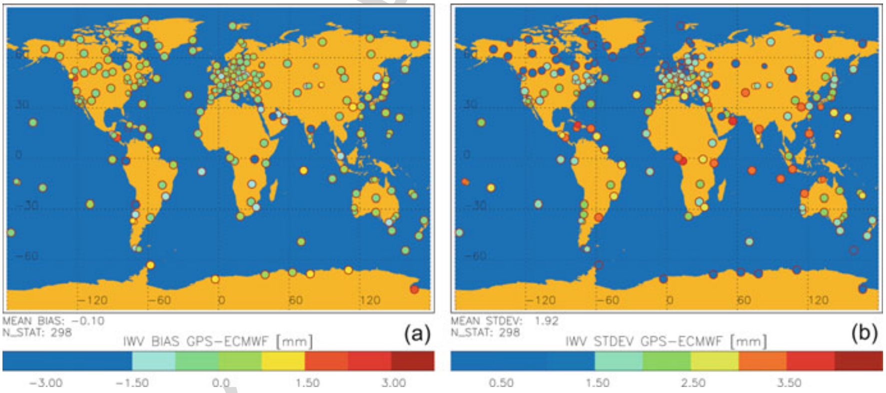

Fig. 12.7 GPS IWV results from 2007 in comparison with ECMWF: (**a**) bias, (**b**) standard deviation

and EUREF networks. The EPOS GPS processing package is used to analyze ZPD, IWV and slant delay data at hourly intervals. EPOS is based on a least-squares adjustment of zero-differenced phase and range observations and can either run in PPP or network mode. The Saastamoinen model and the Global or Niell mapping functions are used to apply tropospheric corrections. The un-modelled part of the slant path delay is adjusted for each individual observation to consider local atmospheric inhomogeneties. To estimate the IWV, additional meteorological observations are required. The IWV data are available with a temporal resolution of 15 min (Fig. 12.8) and give detailed information about the water vapor distribution above Germany. Furthermore, the slant delays along the satellite-station links are analyzed with a temporal resolution of 2.5 min (Bender et al. 2008). These data provide valuable information about the spatial water vapor distribution. 3D water vapor fields are reconstructed either by using the GPS water vapor tomography (Troller et al. 2006) or by assimilating the slant data to a numerical weather model (Zus et al. 2008).

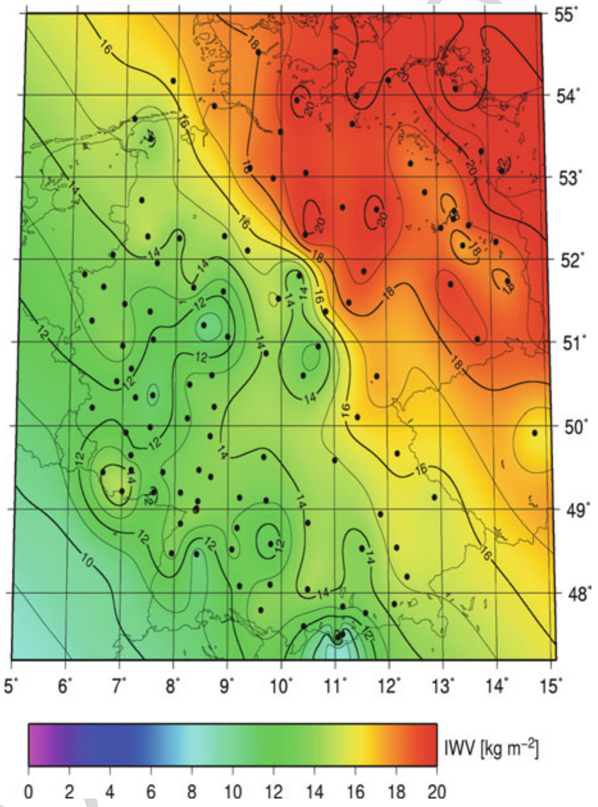

Fig. 12.8 Near real-time IWV distribution above Germany at 1 May 2008, 0:00 UTC. The stations providing data at that time are marked with *black circles*

12.6.2 Spaced-Based Atmosphere Sounding

The availability of GPS radio signals has introduced a new promising remote sensing technique for the Earth's atmosphere. The GPS based radio occultation (RO) exploits these signals received onboard a Low Earth Orbiting (LEO) satellite for atmospheric limb sounding. The GPS signals are influenced by the atmospheric refractivity field resulting in a time delay and path bending of the signal. The atmospheric excess phase is the basic observable that is measured with millimetric accuracy. This is the basis for precise refractivity and temperature profiles (Wickert et al. 2007, 2009; Wickert and Jakowski 2007).

The tropopause layer is one of the key regions of the atmosphere with links to the stratosphere-troposphere exchange as well as climate research. Global mean tropopause height shows an increase in re-analyses and radiosonde observations during the last decades. Tropopause height changes are caused by different forcing mechanisms. One mechanism leading to an increase of the tropopause height is a warming of the troposphere and a cooling of the lower stratosphere. Thus, the tropopause height could be considered as a parameter for the detection of climate change processes and therefore the continuous identification and monitoring of the tropopause height is an important goal in climate research.

The most important data source for the determination of tropopause parameters are radiosonde data whereas model analyses suffer from lower vertical resolution. Despite good vertical resolution of radiosonde measurements a global coverage is impossible. GPS RO enables precise refractivity and temperature profiles with high vertical resolution (< 1 km in the tropopause region). The GPS RO technique requires no active calibration, is weather independent, and the occultations are almost uniformly distributed over the globe. Another important characteristic is the long-term stability of the system, e.g., the CHAMP RO experiment provides data continuously since mid-2001. For the determination of the tropopause different definitions and concepts exist. Here the classical definition of the World Meteorological Organization (WMO) for the first lapse rate tropopause (LRT) derived from a temperature profile is used.

Figure 12.9a shows zonal mean first (dotted) and last (solid) LRT heights derived from CHAMP for the period 2001–2007 for different seasons. The tropopause has a strong meridional structure (LRT1). In the tropics (30°S–30°N) the tropopause height is nearly constant. In the deep tropics (10°S–10°N) LRT1 reaches mean values of about 16.5 km. The strongest gradients in the tropopause height occur between 30° and 60° on both hemispheres with mean heights decreasing to 8–10 km (Schmidt et al. 2005). Usually a second tropopause (LRT2) is observed in the extra-tropics during the winter months (Schmidt et al. 2006).

For the first LRT from the CHAMP data between May 2001 and December 2007 a trend analysis was performed showing a global trend of about +6.6 m/year (Fig. 12.9b). This value is in excellent agreement with trend results derived from longer radiosonde data sets (Schmidt et al. 2008).

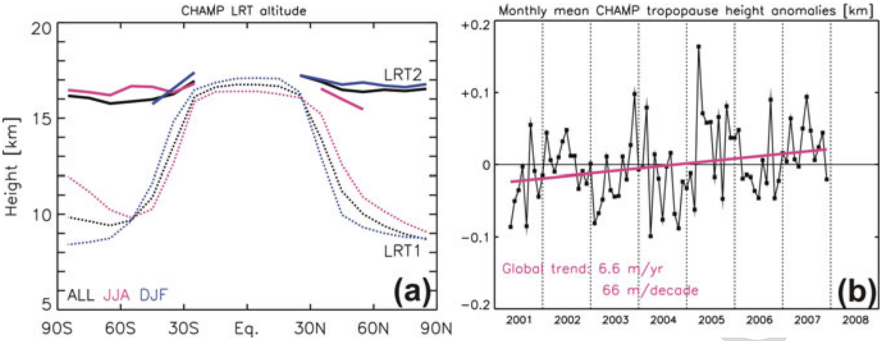

Fig. 12.9 (**a**) Zonal mean first (*dotted*) and last (*solid*) LRT heights derived from CHAMP for the period 2001–2007 for different seasons (June–August, JJA; December–February, DJF; and global). (**b**) Monthly global mean CHAMP tropopause height anomalies (2001–2007) and the according linear trend (6.6 m/year)

12.7 Summary

We briefly introduced several GFZ activities related to GNSS based hazard and climate monitoring. These activities are related to ground and satellite based atmospheric sounding, reflectometry, GNSS seismology and corresponding hardware developments. The introduced results underline the ability of GPS, in future extended by Galileo, to be used as a powerful tool for remote sensing to detect natural disasters and climate change related information of the systems Earth.

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Chapter 12

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