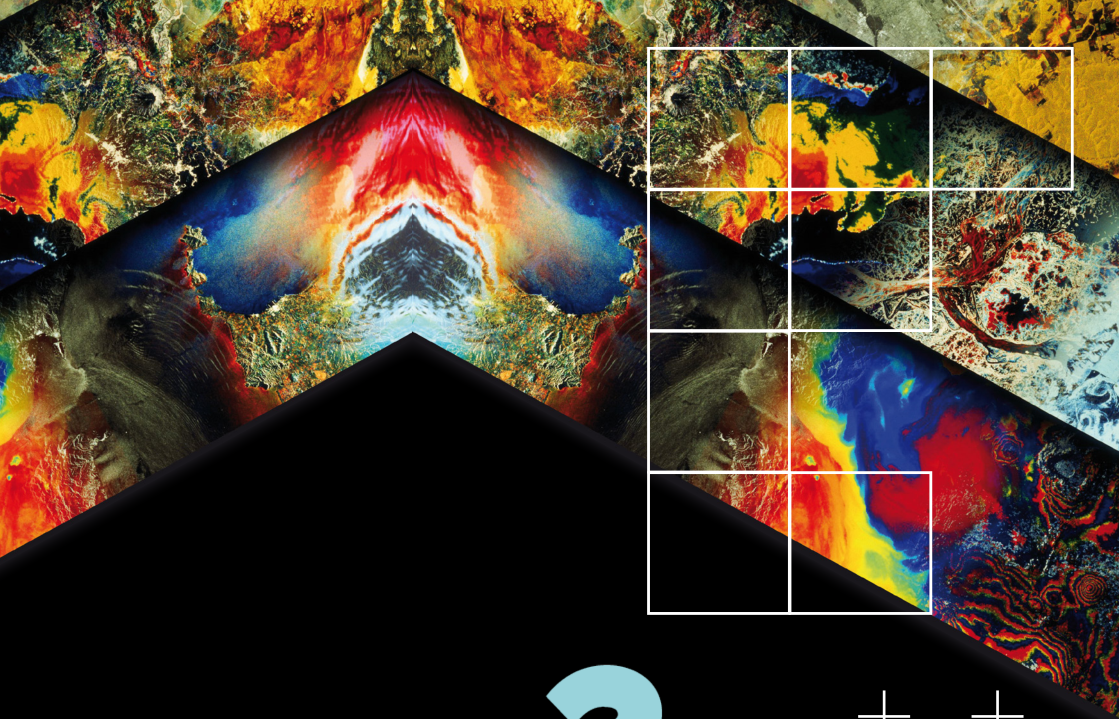

Gfg^2®

GNSS for Global Environmental Earth Observation

Gfg^2®

SEVENTH FRAMEWORK PROGRAMME

THIS BOOKLET IS produced within the Gfg^2 project, a three year coordination action, funded by the 7th Framework Program of the European Commission under the Environment theme. Its mission is to better assess the value of Global Navigational Satellite Systems (GNSS) for Global Environmental Earth Observation (GEEO) and GEOSS.

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Introduction

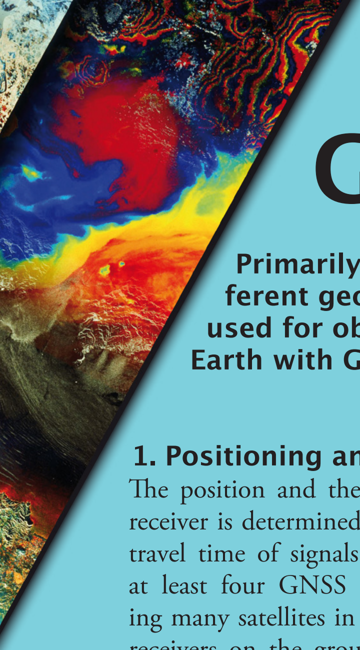
GLOBAL NAVIGATIONAL Satellite Systems (GNSS) is likely to form an even more important infrastructure in everyday life in the future compared to today. The first operational system, the American Global Positioning System (GPS), is today well known to the society.

What is less known is that in addition to determining a position with an accuracy of a few metres, GNSS have already proven to be powerful for observations of interesting physical parameters highly relevant for research in Earth sciences. The purpose of this booklet is to give a few examples from the wide range of GNSS applications related to observations of our planet.

These observations are made using different geometries. The GNSS satellites are orbiting the Earth at an altitude just above 20 000 km, meaning approximately two revolutions around the globe in 24 hours.

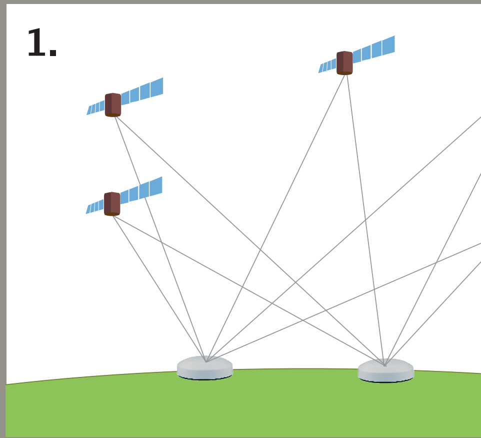
However, there is considerable freedom for the location of GNSS receivers. They can be installed on the Earth's surface, or flown onboard aircrafts or even satellites. These geometries are introduced on the next two pages, followed by examples of different kinds of Earth observations. At the end there is a short list of scientific papers, which have provided inspiration and material for this publication.

Contents



Geometries for

Primarily four different geometries are used for observing the Earth with GNSS signals.

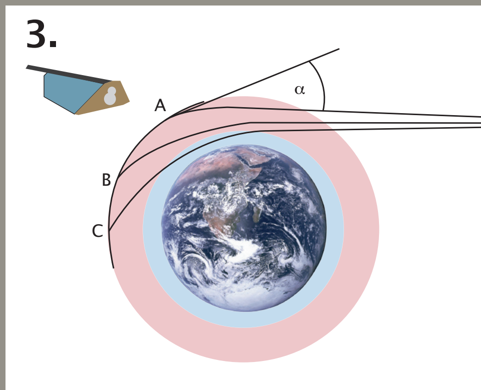


1. Positioning and timing

The position and the time of a GNSS receiver is determined by measuring the travel time of signals transmitted from at least four GNSS satellites. By having many satellites in the sky and many receivers on the ground favourable geometries are obtained and very accurate positioning and timing can be realized.

2. Atmospheric remote sensing from the ground

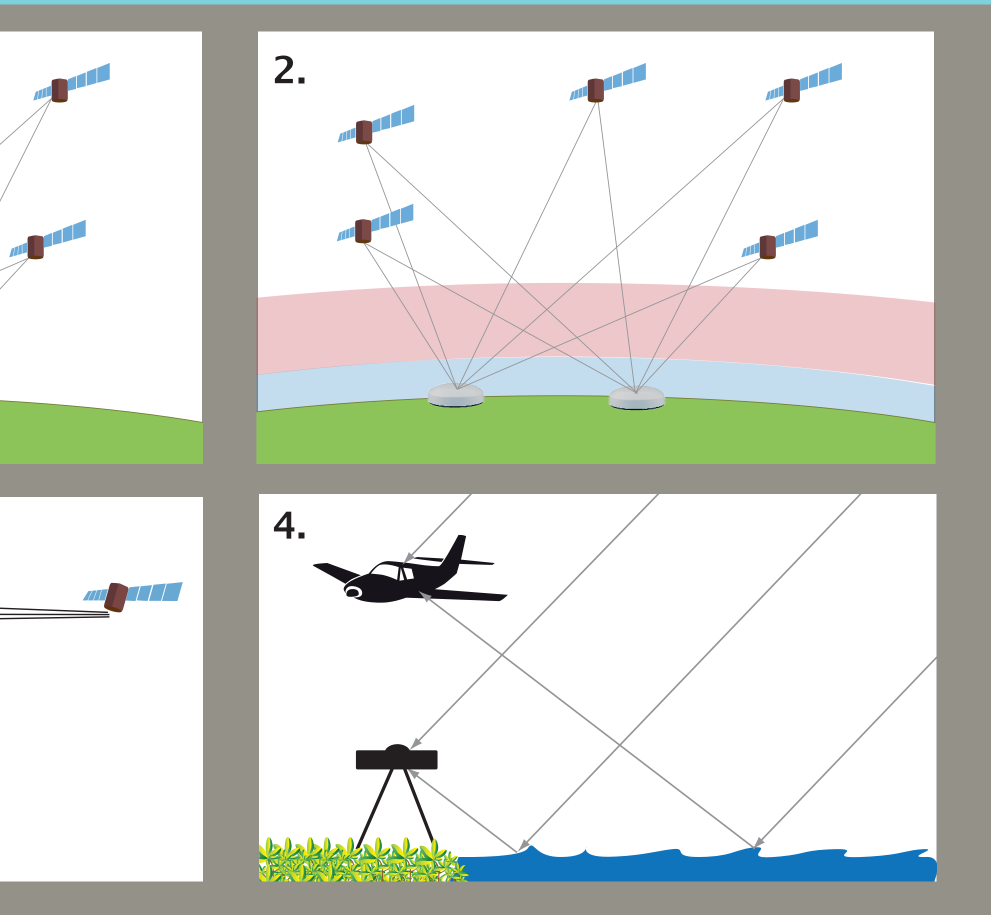
GNSS signals travelling through the atmosphere are delayed (compared to the speed of light in vacuum). The ionosphere, from roughly 80 kilometres to 1000 kilometres height, contains free electrons. The number of free electrons can be measured by using GNSS signals at two frequencies. In the neutral atmosphere, ranging from the ground up to the ionosphere, the amount of water vapour can be measured when satellite signals are received from satellites at many different elevation angles, thereby travelling through the water vapour layers along paths of different lengths.



3. Atmospheric remote sensing by occultations

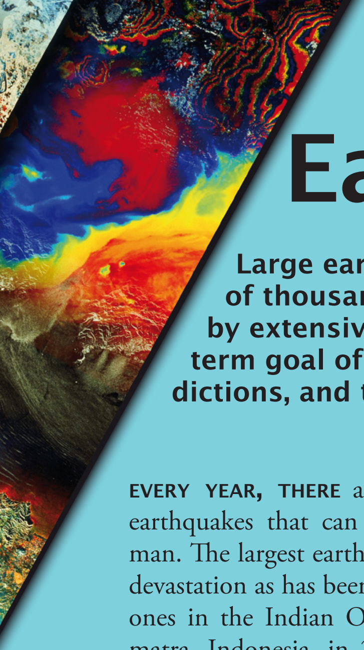
By placing GNSS receivers on satellites in low earth orbit (LEO) the atmosphere can be remotely sensed on a global scale. The technique is referred to as radio occultation. The bending angle α of the signal path from the transmitting GNSS satellite to the LEO satellite is the fundamental observable. Vertical profiles of electron density, temperature, and water vapour can be derived from a time series of bending angles.

Earth observations



4. Distance and/or characteristics of reflecting surfaces

Reflecting surfaces and objects can be observed by combining direct and reflected GNSS signals. Several cases exist. The receiver can use one antenna for both signals, or an optimized antenna for each signal, depending on the application. The antenna can be fixed at a certain height above the ground where the reflected signal will provide information about changes in e.g. snow cover, vegetation, or nearby sea level. It is also possible to place the receiver in an aircraft or even a LEO satellite in order to study reflections from larger areas, such as the surface of the ocean.

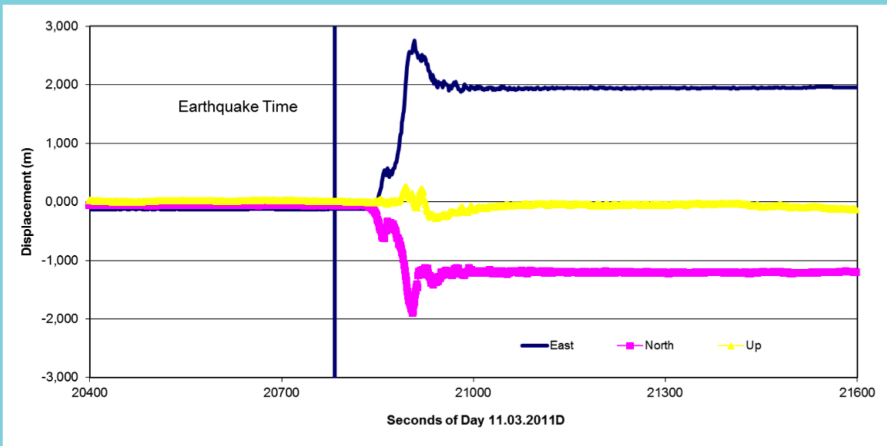


Earthquakes and

Large earthquakes have the potential to kill hundreds of thousands of people. By monitoring crustal motions by extensive GNSS networks, researchers have the long term goal of being able to make accurate earthquake predictions, and thereby saving many lives.

EVERY YEAR, THERE are about 100,000 earthquakes that can be felt by a human. The largest earthquakes cause total devastation as has been evident from the ones in the Indian Ocean close to Sumatra, Indonesia, in 2004 and the Tohoku earthquake east of Honshu, Japan, in 2011. Earthquakes have been studied a long time by seismometers but during the last couple of decades the actual motions are monitored by extensive GNSS networks in many regions of the world (see figure below). The motivation is to obtain a better understanding of earthquakes, with the long term goal to possibly be able to make accurate predictions.

The San Andreas' fault in California is a good example of a region with a GNSS network that has grown during the last 10–20 years. Of course GNSS is often just one of several different types of sensors. For example, the Plate Boundary Observatory in the USA is a network of geodetic and strain instrumentation that



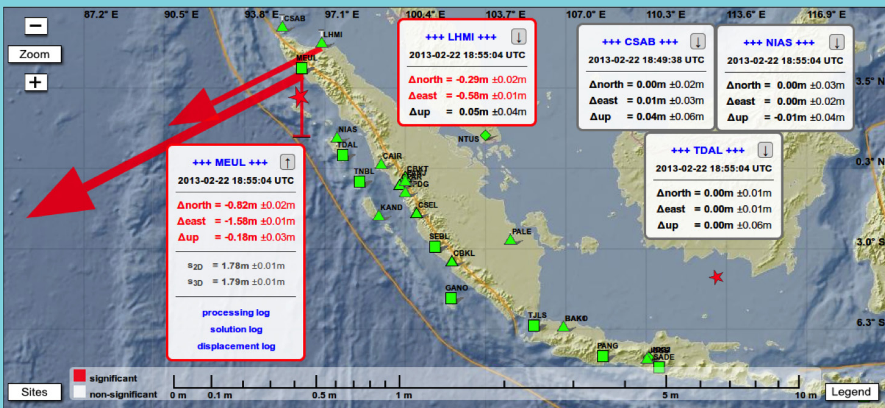
Station displacement estimated from high-rate GPS data induced by the Tohoku Mw 9.0 earthquake in Japan in March 2011. Such results of displacement and seismic waveforms can be provided in real-time with an accuracy of a few centimetres.

Courtsey of M. Ge, GFZ

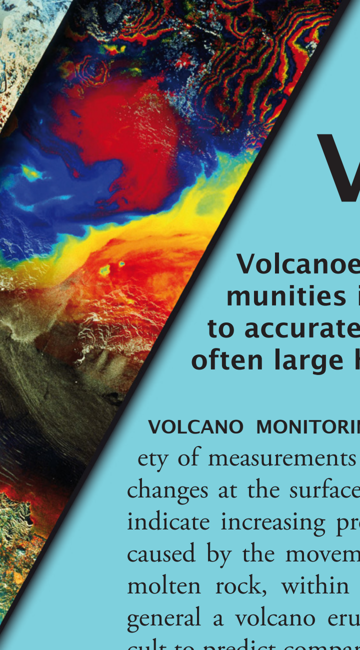
tsunamis

is imaging fast and slow deformation in the lithosphere – that is the Earth's crust and upper portion of the mantle – along the western United States and Alaska.

An automatic system for the near real-time determination and visualization of ground motions, and deformations of the Earth's surface concurrent with seismic activity, was developed by the German Research Centre for Geosciences (GFZ) within the project German Indonesian Tsunami Early Warning System (GITEWS). The system is capable of delivering 3D-displacement vectors for locations with GNSS equipment in the vicinity of an earthquake's epicentre with a delay of only a few minutes. These vectors can help to assess tectonic movements caused by the earthquake, which must be known for reliable early warning predictions, e.g. concerning the generation of tsunami waves. To this end a so-called Ground Tracking System (GTS), that is a system with GNSS receivers on the ground for monitoring the motions of the Earth's crust, has been integrated in the Indonesian Tsunami Early Warning System and is in operation at the national warning centre in Jakarta since November 2008. The graphics below is a screenshot from one of the GTS operator screens in Jakarta. It displays GNSS-derived, co-seismic displacements related to the Sumatra-Andaman earthquake which generated the devastating tsunami of the 25th December 2004.



The GTS and most of the shown GNSS-stations (triangles = GITEWS real-time reference stations, squares = tide gauges with GNSS) were installed after 2005 and thus simulated GNSS-data were used in this figure (i.e. timestamps of 2013 — data from A. Babeyko, GFZ). Lateral and vertical displacement components are displayed as arrows and bars, respectively. Courtsey of C. Falck, GFZ



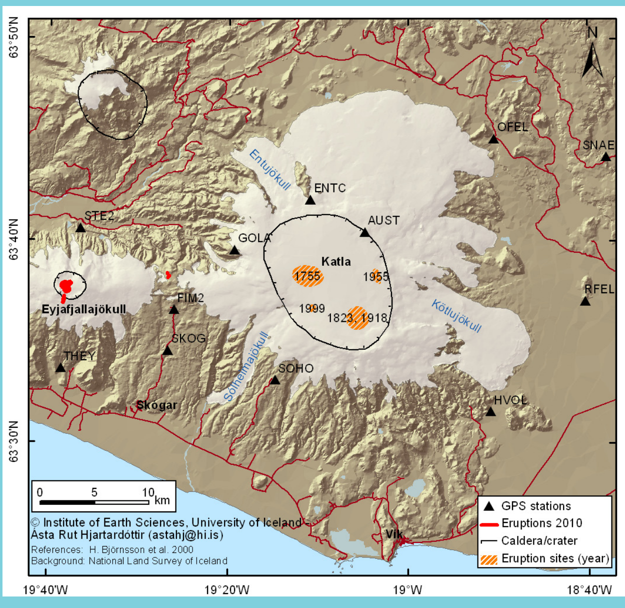
Volcanoes and

Volcanoes and landslides are a serious threat to communities in specific regions. GNSS networks contribute to accurate predictions which hopefully can reduce the often large human and economic losses.

VOLCANO MONITORING involves a variety of measurements in order to detect changes at the surface of a volcano that indicate increasing pressure and stresses caused by the movement of magma, or molten rock, within or beneath it. In general a volcano eruption is less difficult to predict compared to earthquakes. Nevertheless, history has shown that there is a certain degree of surprise involved. In Europe, there are two areas that have been studied for a long time – Iceland (and its volcanoes) and the Etna volcano on the island of Sicily in Italy. In fact, a lot of active volcanoes world wide are equipped with GNSS networks.

Another major technique to map the topography of volcanoes and detect ground deformation is the interferometric synthetic aperture radar (InSAR). In this case it is a great advantage to include a number of GNSS sites in the area covered in order to achieve a 3D calibration of the map.

LANDSLIDES ARE MORE widespread than any other geological event and have high ranking among the natural disasters in terms of casualties and economic damages. Deforestation and constructions of new settlements and infrastructures, as direct consequences of population growth, and the increasing frequency of extreme meteorological events, due to the global climatic changing, could lead to more severe and more frequent impact on human life,



GNSS/GPS monitoring stations on the Katla volcano on Iceland.

landslides

health, and activities in the near future. Risk reduction generally comes through countermeasures, both structural and non-structural, that directly act on the developing process or tend to reduce the effects on the fabric of the city and of the environment.

Nevertheless countermeasures often showed to be insufficient especially if carried out on disruptions that have dimensions, kinematics and morpho-evolutive conditions that are hard to stabilize. In these cases there are basically two options: the relocation of the element at risk or the surveillance of the evolution of the instability process by means of a monitoring system. The monitoring therefore represents a powerful tool to control the area as well as to manage the emergencies coming from hydrogeological instable phenomena.

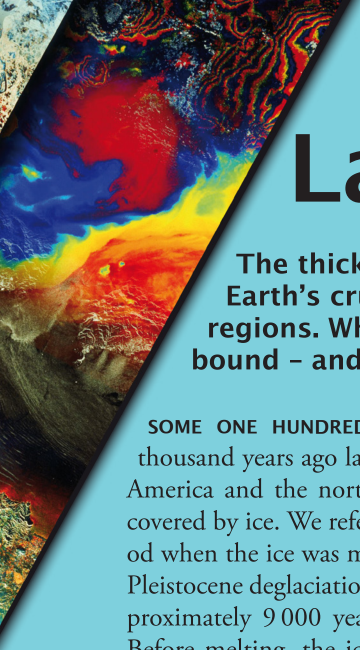
The Tessina landslide in the Eastern Italian Alps, threatening the small village of Funes, after the event of 1992. The landslide has reached a total longitudinal extension of 3 km and a maximum width of about 500 m, with a volume of involved material estimated to about 7 millions of m^3.

Courtsey of CNR-IRPI, Padua, Italy

LANDSLIDE AND VOLCANO monitoring systems share a range of aspects. A network of GNSS receivers is installed in and around the hazardous area. Landslides may be of different types. Some are more or less in continuous motion whereas others suddenly occur without warning. Obviously the latter type is the most likely to cause severe damage.

Important parameters to study in order to characterize a landslide are the type of soil and clay, and the variations in the ground water content. GNSS observations are normally complemented by such measurements together with classic geodetic measurements, by means of theodolites, inclinometers, and electronic distance metres, as well as terrestrial and aerophotogrammetric analyses.

Examples of existing GNSS networks installed to study landslides are found in the Dolomites in Italy, the Eastern Pyrenees in Spain, and San Juan Mountains in Colorado, USA.



Land uplift after

The thick ice of the latest glacial period pressed the Earth's crust hundreds of metres downwards in some regions. When the ice melted, the land started to re-bound – and is still lifting.

SOME ONE HUNDRED thousand to ten thousand years ago large areas in North America and the north of Europe were covered by ice. We refer to the time period when the ice was melting away as the Pleistocene deglaciation which ended approximately 9 000 years before present. Before melting, the ice sheet was up to four kilometres thick which implied that the Earth's crust was pressed downwards by several hundred metres. The uplift, or postglacial isostatic adjustment, is still going on and is illustrated by the interesting aerial photograph below showing the coastline at a small village on the Swedish east coast. A number of boathouses, built in the middle of the 18th century, are now far away from the water.

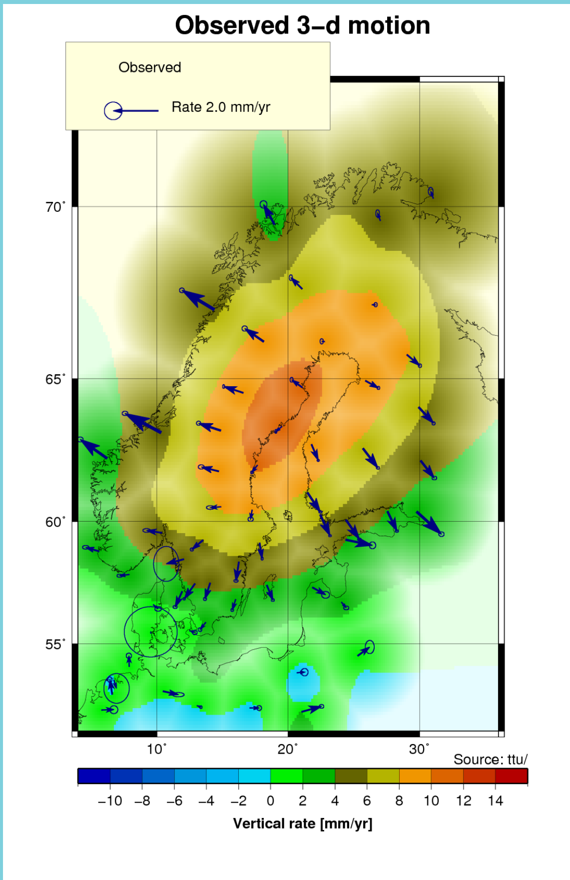
The location of the coastline is a combined effect of the dynamics of the crust and the sea level. In the 18th century the prevailing theory for the observed changes in the coastline was that the sea water was moving away. There were several, more or less brave, theories for where the water went. Observations along the coast line contributed to arrive, about one hundred years later, to a conclusion about what was actually happening: the crust of the Earth was rebounding after the rapid – by geological time scales – disappearance of the ice masses.

MEASUREMENT OF GEODETIC positions of stations on the earth crust using GNSS provides a unique method to infer mo-

Boathouses, built in the middle of the 18th century, on the island of Brämön just south of the city of Sundsvall on the east coast of Sweden. Due to the land uplift the houses are now far away from the water. © Lantmäteriet

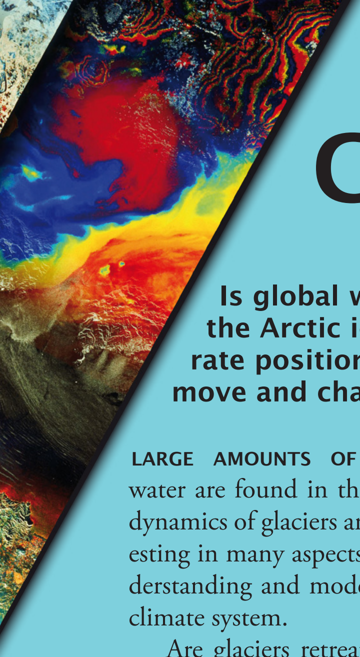
the latest ice age

Observed land uplift in Fennoscandia. The basis for the plot comprises 14 years of GPS data, daily solutions for positions, from which constant rates of change have been estimated. The uplift is colour coded and the horizontal rates are denoted by arrows. Courtsey of H.-G. Scherneck, Chalmers



tion with respect to the gravity centre of the earth. The figure to the right depicts the results obtained for the glacial isostatic adjustment of Fennoscandia, i.e. the region made up by the Scandinavian peninsula, Finland, Karelia and the Kola peninsula.

Notably, if we know the motion of the solid crust, we can correct tide gauges for their changing vertical position and thus infer change of sea volume in absolute terms. The basis for the plot comprises 14 years of GPS data, daily solutions for positions, from which constant rates of change have been estimated. The precision of the vertical rates at the stations with the longest history of operation is 0.2 millimetres per year. It is also interesting to study the horizontal motion of the sites, which are directed away from the center of the uplift. Although it is an expected result that can be predicted with geophysical methods by combing models for the ice distribution and melting with a viscosity profile of the Earth's crust and upper mantle, these motions were first detected by the GNSS technique.



Glacier and sea

Is global warming melting our glaciers and causing the Arctic ice cover to shrink? GNSS provides an accurate positioning tool for investigating how the ice masses move and change.

LARGE AMOUNTS OF the Earth's fresh water are found in the form of ice. The dynamics of glaciers and sea ice are interesting in many aspects related to the understanding and modelling of the Earth climate system.

Are glaciers retreating? Is their total mass decreasing, and if so, at which rate? What is happening to the ice in the Arctic, both to sea ice and the Greenland ice sheet? The Greenland ice volume amounts to about 3 million km^3 which would cause global sea level to rise by more than 7 metres if it all would melt. These questions can be addressed by using GNSS as an accurate positioning tool.

In order to study the dynamics of large outlet glaciers, a research experiment was carried out during the summers of 2006-

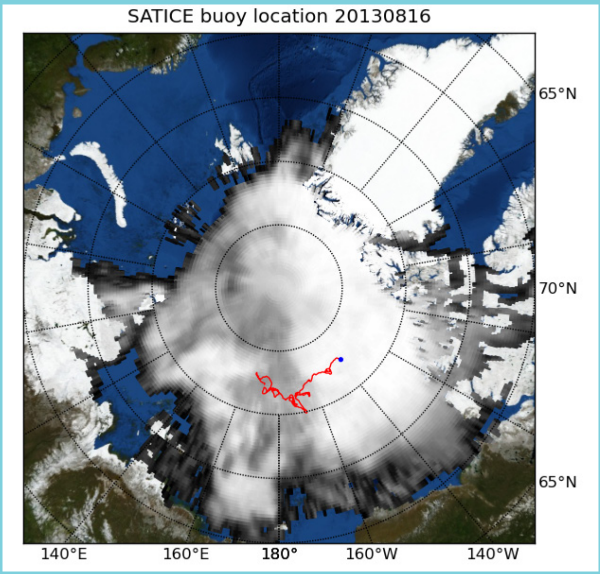
Right: The deployment of a SATICE buoy. Courtsey of P. Elosegui, P. Hwang, SATICE Project

Below: Installation of a GNSS receiver on the Helheim glacier on Greenland. Note the red flag that was used in order to be able to find the station and retrieve the data fifty days later. Courtsey of M. Nettles, L. Stearns, SERMI Project

ice motions

2010 on Helheim glacier and Kangerdlugssuaq glacier, in southwest Greenland. Overall, close to 100 GNSS sites were deployed on the glaciers' surface over 5 years (see photo, preceding page).

The GNSS position estimates revealed the extensional character of these fastest moving glaciers, with speeds that can increase from about 10 meters a day at the glacier head to about three times faster at the terminus, where the glacier calves the large icebergs that fill the fjord. Most significantly, these GNSS results also detected step-like changes in speed that coincided with glacial earthquakes – corresponding to calving events – also detected as tsunami waves in the fjord and by a nearby seismometer.



The motion of one of the SATICE buoys from August 2012 until August 2013. Courtsey of P. Elosegui, M. Olsson, SATICE Project

AN EXAMPLE OF research on the dynamics of the sea ice is the project "Arctic Ocean sea ice and ocean circulation using Satellite Methods" (SATICE). It is the first high-rate, high-precision positioning experiment on sea ice in the Arctic.

The project uses buoys equipped with sensors of several physical parameters, such as temperature of air and water, air pressure at sea level, relative humidity, snow depth, and ice thickness. The buoys are also equipped with cameras and GNSS equipment. The installation of a buoy on the ice is shown in one of the photos in the preceding page.

Each buoy continuously collects GNSS data for 3-dimensional positioning. All the data are sent via a satellite link to a central computer in near-real time, where the data are processed to estimate the time-varying buoy positions. Time-varying positions result from sea ice drift (see figure above) as well as ice deformation, fracture, thickness variations, ocean tides, ocean dynamics, among others.

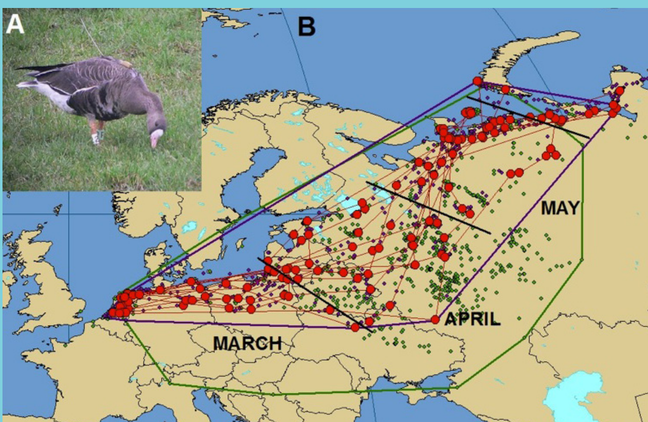
Tracking birds

Little is known about migrating animals. Uncovering their life cycles can help us to understand and predict how infectious diseases carried by migrating species can spread over the world.

TRACKING WILD, MIGRATING animals is a difficult job. For instance, European storks breed in northern Europe and spend the winter in Africa, migrating 10 000 kilometres each season. Being an effective tracker requires inventiveness, endurance and investments in equipment and time. In the past, tracking was mainly carried out to study migration, animal distribution, and habitat choice. But recently developed high-resolution GNSS tracking equipment allows more complex questions to be investigated.

There are several reasons for tracking migrating species. The most obvious is the conservation of migrating species as has been agreed in the Convention for the Protection of Migratory Species. On the other hand, wild species can carry diseases such as avian influenza, swine fever, or West Nile fever, influencing the global spread of diseases and triggering anxiety of the public and policy makers. Being able to track the animals means that their behaviour can be better understood or that their live cycle can be mapped. By understanding the movements of the host animals, we can understand and predict how diseases can spread over the world.

SEVERAL RESEARCH PROJECTS use and develop GNSS animal tracking equipment and analysis tools for studies of animal movements and for more sophisticated behavioural research on wild and domestic animals. In one study, 30 white fronted geese were equipped with GNSS transmitter collars in the pe-



Recordings of white fronted goose in 2006–2008. Red dots represent GNSS positions, while green dots represent additional metal ring recordings. Courtsey of www.blessgans.de

and mammals

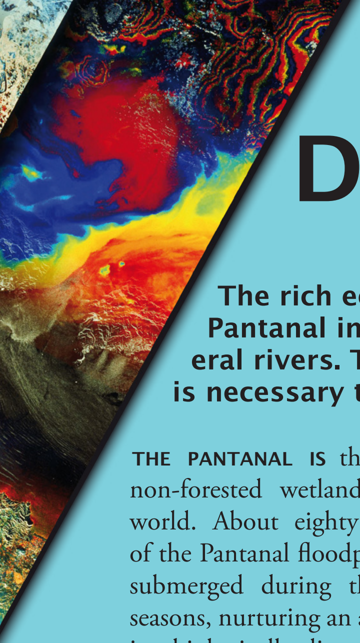
Tracking of a domestic cow with a Lotek collar in the E-track project.
Courtsey of www.project-e-track.eu

riod 2006–2008. The transmitters sent GNSS locations to satellites every other day. During the three years, 13 complete migration tracks were recorded as can be seen in the left-hand figure.

The E-track project makes use of GNSS collars and the European Geostationary Navigation Overlay Service (EGNOS) that provides higher accuracy locations than conventional GNSS tracking. This is combined with fast sampling in order to achieve both high spatial and temporal resolution, which is often required when attempting to track animal behaviour in the field. In 2012 newly developed Lotek collars using EGNOS correction were tested in an open field with nine cows, see figure above.

The collars performed well and were set at an interval of one location each minute or once every two seconds. Behavioural observations were carried out at the same time to correlate movement patterns with behavioural patterns. In 2013 the analysis showed that behaviour of the cattle could be successfully predicted on the basis of the location data of the cattle obtained with the GNSS collars, and that speeds and movement angles can be used as indicators for predicting behaviour.

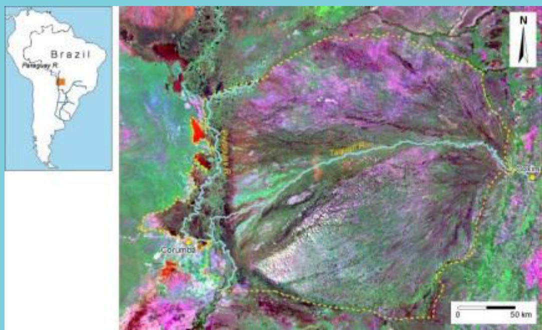
IN THE FUTURE, further developments of exciting geolocating tools may for example help in fighting poaching by enabling tracking of endangered species and studying their movements into high poaching risk areas. Additional spin-off applications in other domains may have even larger societal impact such as in animal management in agriculture. It might also provide new opportunities for crowd control in festivals or soccer matches, and for more efficient mass transportation and logistics at airports and train stations. However, in case such societal applications are being developed, then also new legal and ethical aspects will have to be developed in line with the innovation strategy.



Digital elevation

The rich ecosystems in the world heritage wetlands of Pantanal in Brazil are dependent on the flooding of several rivers. To understand disturbances that take place, it is necessary to gain insight in where water flows and why.

THE PANTANAL IS the largest non-forested wetland in the world. About eighty percent of the Pantanal floodplains are submerged during the rainy seasons, nurturing an astonishing biologically diverse collection of aquating plants and an extremely diverse fauna. The Pantanal is surrounded by the high plateau of the Cerrado, where at present intensive agriculture takes place.



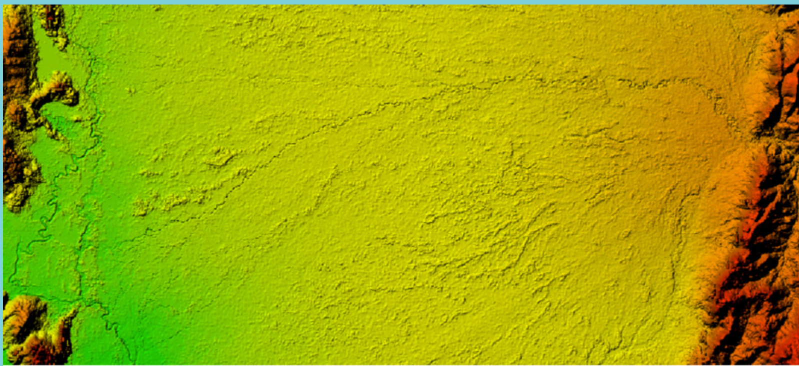
Location of the Pantanal. Courtesy of R. Jongman, Alterra, Wageningen UR

Cerrado and Pantanal have a sensitive relationship as all Pantanal rivers have their origin on the Cerrado. Disturbances upstream have impacts downstream. Knowledge about the system functioning can prevent conflicts downstream. In order to be able to make a distinction between natural river processes and external, man-induced effects one must understand where water flows and why.

River and overland water flow are depending on altitudinal differences.

The Pantanal is a UNESCO World Natural Heritage Site, the largest non-forested wetland in the world – about the size of the UK. It is the home of alligators, pumas, jaguars, giant otters and hundreds of fish species, many of them migrating. Courtesy of R. Jongman, Alterra, Wageningen UR

model for wetlands



Courtesy of R. Jongman, Alterra, Wageningen UR

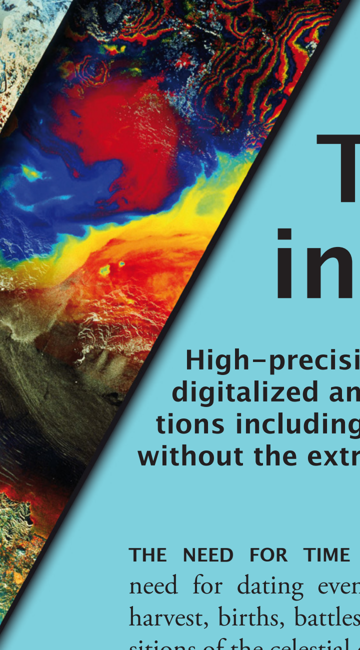
The final digital elevation model of the Pantanal.

Therefore one needs a digital elevation model (DEM) – a three-dimensional representation of a terrain's surface – for insight in water flows. But how to make a model of a landscape that is flat as a pancake and sparsely inhabited? Or, how can we model the system and measure changes in river bank height of centimetres over a distance of 500 kilometres?

THE PROJECT OF creating a digital elevation model of the Pantanal took place in 2003 and 2004. Remote sensing satellite images from international and national projects were already available. Elevation data was among others acquired from GTOPO30, a digital elevation model of the world, and from the Shuttle Radar Topographic Mission (SRTM). The vertical resolution had an absolute accuracy of better than 16 metres (90 % confidence level).

The results had to be validated during a field campaign to correct the model derived from the SRTM. However, it was not possible to prepare a base and a rover station for real time accurate position measurements. Therefore, use was made of a GPS post-processing service, Scripps Orbit and Permanent Array Center. Solution quality depends largely on the availability and proximity of the nearest three base station data and the availability of precise satellite orbits and clock corrections. For validation, two known geodetic points were recorded – one in Enschede in the Netherlands and one in Corumbá, Brazil.

At the time of this project, GPS was the only available navigation satellite system. Future systems such as Galileo will provide additional signals resulting in a higher accuracy of the three-dimensional positions, which means that the technology will be even more attractive for researchers. This would be a step forward in land management, although quality assurance and quality control procedures will still be needed.



Timing infrastructure

High-precision timing is indispensable in today's highly digitalized and globalized society. Many high tech applications including Earth observations would hardly be possible without the extremely accurate timing provided by GNSS.

THE NEED FOR TIME emerged with the need for dating events. Seasons, seed, harvest, births, battles, catastrophes, positions of the celestial objects were events that regulated the evolution of civilizations in ancient times. Far from weakening this dependency, our contemporaries are making it stronger and pushing it to astonishing limits of precision; protocols for time transfer by computer networks, air traffic control, stock exchange, space navigation, satellite systems, mobile phones and security systems make us time-dependent today.

The use of GNSS receivers in time comparisons, introduced in the 1980s, was a major improvement in the construction and dissemination of timescales. The method consists of using the signal broadcast by GNSS satellites, which contains timing and positioning information. It is a one-way method, the signal being emitted by a satellite and received by specific equipment installed in a laboratory. For this purpose, GNSS receivers have been developed and commercialized to be used specifically for time and frequency transfer.

As a result of GNSS receiver hardware development and improvements in data

EXAMPLES OF GNSS TIMING IN TELECOM

- Switched telephone networks use GNSS timing as primary reference clock.
- Cellular telephone systems use microsecond timing to synchronize cell sites in order to allow seamless switching.
- The channel access method CDMA requires microsecond timing and uses GNSS to coordinate time between base stations.
- Network Time Protocol (NTP) is used to synchronize computers to the millisecond level and is available in all operating systems.
- IP based applications such as streaming audio and video.
- Precise Timing protocol providing sub-microsecond timing across a facility.

processing and modelling, the uncertainty of clock synchronization via GNSS receivers fell from a few hundreds of nanoseconds at the beginning of the 1980s to one nanosecond today.

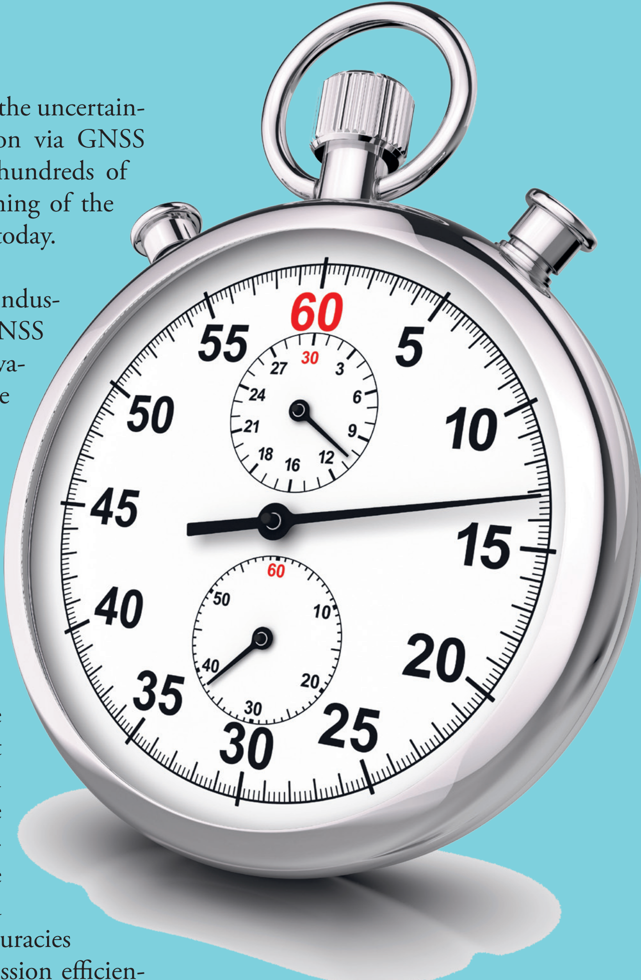


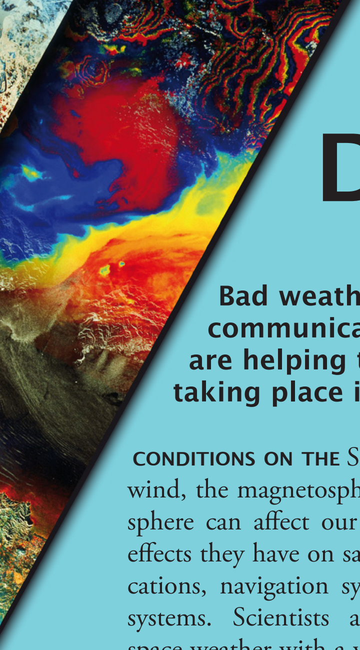
Photo: Shutterstock

THE TELECOMMUNICATION industry makes wide use of GNSS timing for supporting a variety of applications, see the fact box. Most of the approximately 500 000 cellular base stations in operation around the globe are provided with embedded GNSS equipment.

Timing is important also in transmission of electrical power – the phase of the alternating current has to be synchronized in the world power grid since large phase errors may result in equipment damage and power outages, and already small phase inaccuracies reduces the power transmission efficiency. Historically, phase synchronization has been accomplished by adjusting the phase at local power generating plants to match the overall grid phase.

GNSS based phase synchronization equipment is starting to be installed globally. Its higher timing accuracy results in higher efficiency in power transmission, fewer black outs, and better fault isolation. Power line fault isolation is often accomplished using GNSS timing to measure the distance to a break in a power line, which greatly reduces the time to find the break and to restore service.

In finance, with billions of transactions per day and the emergence of fully automated computer trading, precise timing of trades is critical. An inaccurate time stamp could result in either an unfair advantage being gained or in loss of revenue. Today, time stamp traceability requirements are at the level of one second, and within a few years millisecond timing will be required to support high speed computer trading.



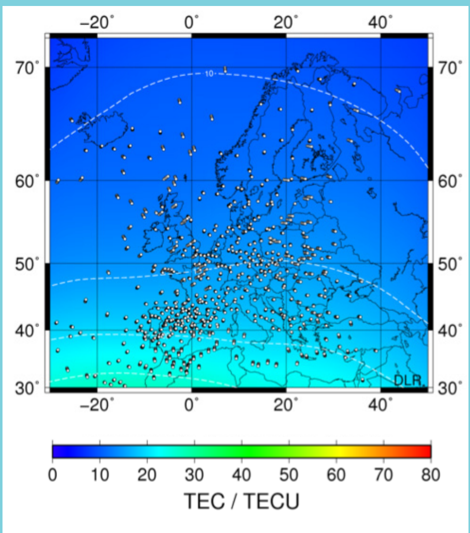
Dynamics of the

Bad weather in the ionosphere may severely disturb our communication, navigation, and power systems. GNSS are helping the scientists to understand the processes taking place in the ionosphere.

CONDITIONS ON THE Sun and in the solar wind, the magnetosphere, and the ionosphere can affect our lives through the effects they have on satellites, communications, navigation systems, and power systems. Scientists are now studying space weather with a wide range of tools in order to learn more about the physical and chemical processes taking place in the upper atmosphere and beyond. One such tool is the use of GNSS signals.

The signals from GNSS satellites travel through the ionosphere on their way to the receivers on or near the Earth's surface. The free electrons populating this region of the atmosphere affect the propagation of the signals, changing their speed and direction of travel. By processing the data from dual-frequency GNSS receivers, it is possible to calculate how many electrons the signal encountered along its travel path. This measure is referred to as the total electron content (TEC), which tells us how active the ionosphere is. It is defined as the number of electrons in a vertical column with a cross-sectional area of one square metre. A network of ground-based receivers can be used to provide a map of the TEC above the stations. The TEC normally varies smoothly between day and night – it increases as the Earth's dayside atmosphere is ionized by the Sun's extreme ultraviolet radiation, while the TEC on the nightside is reduced by chemical recombination.

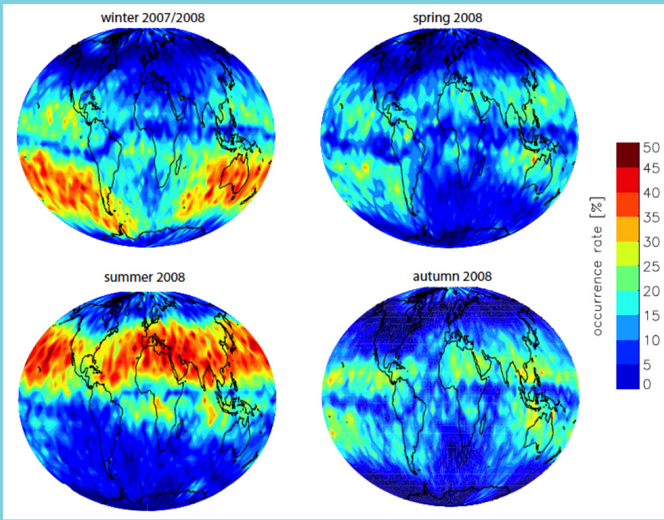
However, just as the lower atmosphere, the ionosphere can experience



The total electron content (TEC) over Europe derived from ground-based GNSS-data. The results are expressed both in TEC units (1 TEC = 10^{16} electrons/m^2). The white circles denote the piercing point of the radio link between the satellite and the GNSS ground station at 400 km height.

Courtsey of N. Jakowski, DLR (link on p. 31)

ionosphere

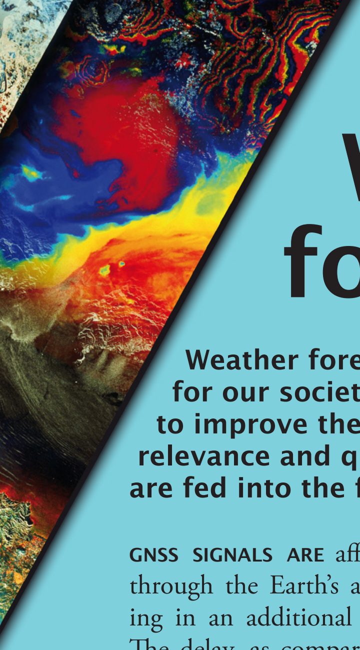


Global maps of the occurrence of ionospheric disturbances in 2008 (in the so called sporadic E-layer), derived from space-based GNSS radio occultation measurements using satellites. The distribution depends on the season with maximum occurrence at the respective summer hemisphere. Courtsey: C. Arras, GFZ

stormy weather. Smooth variations in total electron content are then replaced by rapid fluctuations, and some regions experience significantly higher or lower TEC values than normal. Today, GNSS is extensively used to study solar storms and adding to the understanding of the Earth-Sun environment.

GNSS ARE POWERFUL for studying space-weather phenomena when data are processed in a way that emphasizes the spatial and temporal variability of the medium. Continued monitoring of space weather using GNSS will further enhance our understanding of the dynamic processes taking place in the ionosphere and their effects on communications and navigation, electric power grids, and other technological systems.

A topic related to GNSS observations and earthquakes is the possibility that changes in the atmosphere take place above earthquake locations. It has been argued by some scientists that both increased infrared emission due to electrical fields caused by radon emanation, as well as unusual high variability in the TEC has been observed *before* large earthquakes, but others do not find the evidence convincing. Less controversial is that TEC variations have been observed *after* the occurrence of a large earthquake, caused by acoustic and gravity waves that propagate from the earth surface upwards into the atmosphere. Of course, if ionospheric variability could be used to predict earthquakes it would be extremely useful. For the time being we can only conclude that more research is needed.



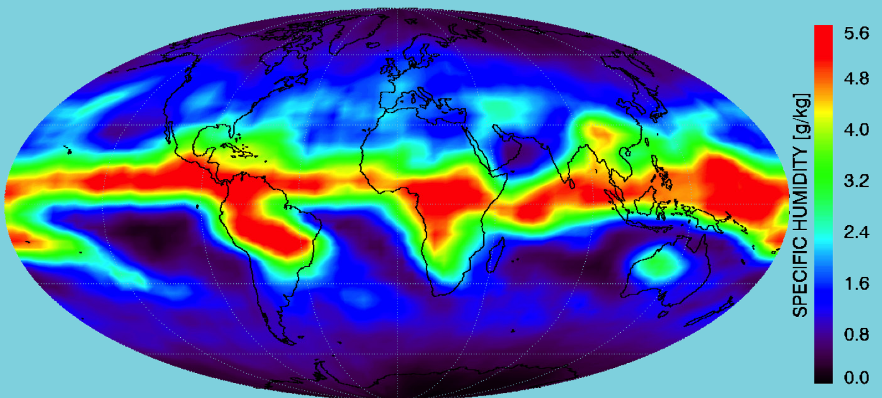
Weather forecasts

Weather forecasts are becoming more and more important for our society and there is a continuous research effort to improve their quality. Of fundamental importance is the relevance and quality of the meteorological observations that are fed into the forecast models.

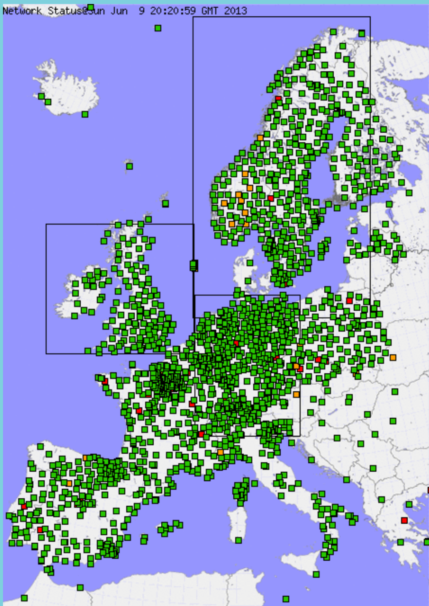
GNSS SIGNALS ARE affected as they pass through the Earth's atmosphere, resulting in an additional signal path delay. The delay, as compared to undisturbed signal propagation in vacuum, depends mainly on air pressure, temperature and water vapour. The GNSS radio occultation technique provides profiles of temperature, and in combination with other data also water vapour profiles, at the locations of the occultations. For the ground-based GNSS networks the integrated water vapour above each individual GNSS station can be estimated.

Generally, the middle troposphere is most appropriate for humidity investigations using GNSS occultations. This is because the quality of the occultation data is reduced in the low troposphere where the attenuation of the signal is larger, especially in the tropics. In the upper troposphere there are very low amounts of humidity meaning that the effect on the signal is too small to be clearly detected.

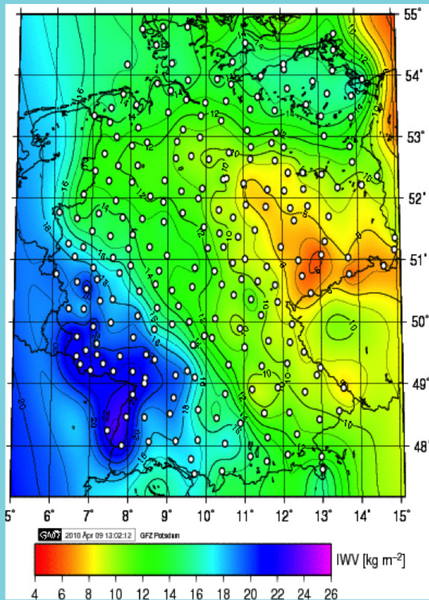
Humidity profiles from occultations provide unique data for the investigation



Monthly mean for October 2006 of the global distribution of specific humidity at the 600 hPa pressure level, at an altitude of about five kilometres. Derived from GNSS radio occultation measurements. Courtesy of S. Heise, GFZ



The present European network of GNSS stations used in weather forecasting. Courtesy of the E-GVAP programme (link on p. 31)



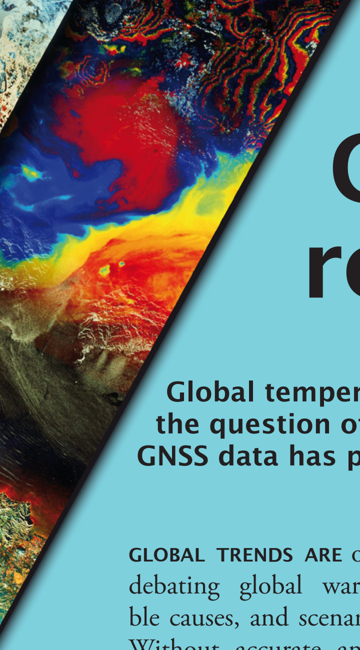
The water vapour content over Germany derived from ground-based GNSS stations. Courtesy of G. Dick, GFZ

of short, medium or seasonal term water vapour distribution on a global scale. The left-hand figure gives such an example.

AN EXAMPLE OF radio occultation observations of temperature is given in the next spread on climate observations. However, given that the data processing can be done in close to real time, improved temperature observations globally have provided significant improvements in operational weather forecasting.

The idea of also using ground-based GNSS to measure water vapour in the atmosphere was, like many other scientific discoveries, a side effect. When measuring movements of the Earth's crust, researchers became experts in calculating and taking into account the influence of the atmosphere which is introducing a delay of the time of arrival of the received signal. The main reason for variations in this delay is the amount of water vapour along the signal's propagation path.

Since 2005 the European weather services run the project E-GVAP in which many organisations collaborate in data acquisition and analyses. The present network of stations providing data in near-real time, typically within 2 hours, is shown above to the left. The entire data set is then available to all the participating weather services to improve regional weather forecasts. The figure above to the right depicts a distribution of the water vapour content over Germany based on GNSS data. These reconstructions contribute to the investigations of various atmospheric processes like convection and precipitation.



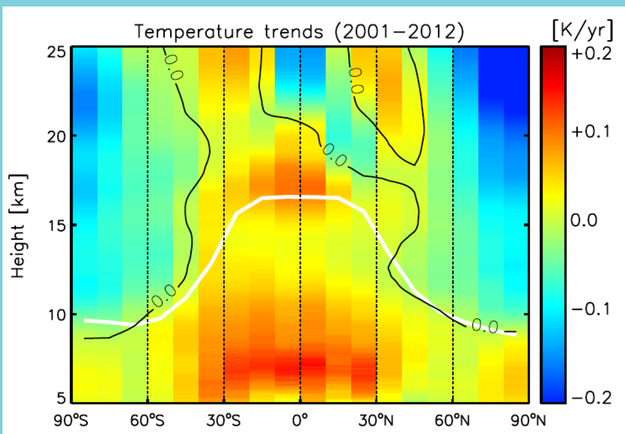
Climate research

Global temperature trends are important when it comes to the question of global warming. During the last few years, GNSS data has proven its potential for climate monitoring.

GLOBAL TRENDS ARE one big issue when debating global warming, the possible causes, and scenarios for the future. Without accurate and stable observations of what is actually going on questions about the future become more difficult. During the last few years several studies have demonstrated the potential of both ground-based and radio occultation GNSS data for climate monitoring.

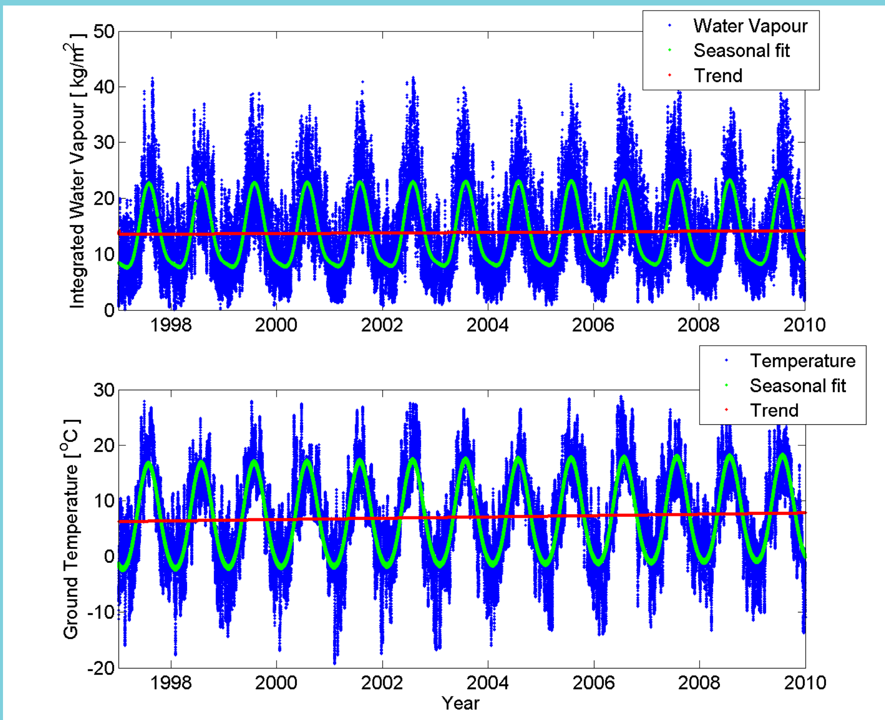
The radio occultation data enable the possibility for a very accurate determination and detailed temporal and spatial monitoring of the temperature structure in the upper troposphere and lower stratosphere. The figure below demonstrates a warming of the upper troposphere and a cooling of the lower stratosphere. The strength of the radio occultation technique for climate research lies in the ability to generate climate benchmark data of temperature and water vapour, as mentioned in the weather forecast section. The benchmark data can also serve as a reference data set for other climate observations with the steadily growing temporal coverage of the data set.

Ground-based GNSS receiver stations measure the atmospheric water vapour content above the antenna. Ac-



Temperature trends in the upper troposphere and lower stratosphere (5–25 km) derived for the period 2001–2012. The resolution in height and latitude is 100 metres and 10°, respectively. The solid white line denotes the mean tropopause height. Courtesy of T. Schmidt, GFZ curate measurements of water vapour in the atmosphere are in general difficult and costly to carry out with high temporal and spatial resolution over long time. The GNSS technique is therefore a promising tool. As continuously operating receivers are increasing in numbers the spatial resolution will continue to improve. Many countries today have networks with typical baseline lengths of 50–200 kilometres. An example of a time series of water vapour is shown below.

Finally, it needs to be stressed that the climate is characterized by averages and trends of atmospheric parameters over long time. The weather is naturally very variable and the common practice is to use 30 year averages in climate research. This means that the GNSS technique has not yet acquired sufficient data in order to calculate the first data point. On the other hand, the results demonstrated so far are very promising, in the sense that they seem to be able to provide stable time series, without drifting measurement errors over very long time.



The water vapour content and the temperature at the ground for 14 years at the GNSS site Onsala in Sweden. The blue dots are hourly observations. Modelling a linear trend (red lines) and seasonal components (green lines) gives a trend for the water vapour content and the temperature of 0.5 kg/m^2/decade and 1.1 °C/decade, respectively.

Courtesy of T. Ning, Chalmers

Snow depth, vegetation, and soil moisture

In most GNSS applications, reflected signals are undesired since they disturb the measurements. Reflected GNSS signals are however not all bad – they can be very useful for measuring snow depth, vegetation, and soil moisture.

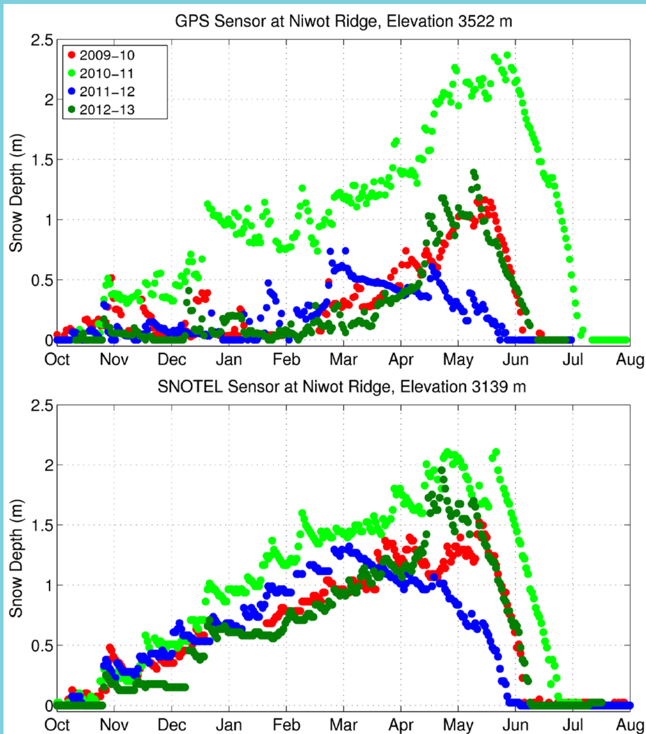
THE VAST MAJORITY of all continuously operating ground-based GNSS networks are designed in order to minimize the effect of possible reflected signals into the antenna of the receiver. This is motivated by the desire to reach the highest possible accuracy for measurements of three dimensional positions and the water vapour content above the site.

Nevertheless, some reflections will always be present, and for a certain application it is possible to optimize an installation in order to obtain favorable reflections from the land surface. The goal is to exploit these reflections to derive parameters like snow depth, soil moisture content, and the development of vegetation.

Although the reflection geometries are often more complicated to describe theoretically, compared to reflections in sea and lake surfaces (see next two pages), it has been shown that information on snow depth can be retrieved. The traditional method to measure snow depth is by inserting measurement sticks into the snow, which is rather time consuming. Therefore, if snow depth can be obtained as an additional product from many already existing GNSS stations a

A GNSS station for observations of the snow depth at Niwot Ridge near Boulder Colorado, USA.

Courtesy of K. Larson, Univ. of Colorado

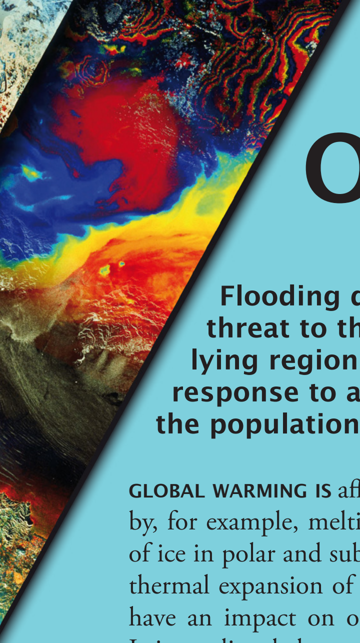


Snow depth results from Niwot Ridge from GPS data (top) and a nearby traditional sonic sensor (SNOTEL) for four consecutive winter seasons. Courtesy of K. Larson, Univ. of Colorado

lot of new information on the water cycle will be available. Hence, more reliable forecasts of the water supply can be made. An example from a site near Boulder, Colorado is given in the figures to the left and upper right.

AN ASSESSMENT OF the possibilities to retrieve information on the development of vegetation and soil moisture was made using a measurement campaign from March to September 2010, thereby covering a full crop growing season, near Florence in Italy. Correlations between different reflection coefficients for different combinations of signal polarization, were seen for both the plant water content and the soil moisture content. It was concluded that reflected GNSS signals can be used to study soil moisture, in the upper first centimeters of the soil, and the development of vegetation over the growing season.

A GNSS installation for vegetation and soil moisture measurements. Courtesy of A. Egido, Starlab



Ocean and lake

Flooding due to rising global sea levels poses a serious threat to the millions of people living in coastal and low-lying regions. Monitoring and understanding the local response to a global sea level rise is crucial to the safety of the population in these areas.

GLOBAL WARMING IS affecting the sea level by, for example, melting of large masses of ice in polar and subpolar regions, and thermal expansion of seawater. This will have an impact on our human society. It is predicted that more than 300 million people in coastal and low-lying areas will be directly affected by flooding from sea level rise by the end of the 21st century. Another measure is that more than 50 percent of the world's population live within 60 kilometres of the coast. Monitoring and understanding the local hydrodynamic and meteorological response to a global sea level rise is therefore crucial for the safety of the population in these affected areas.

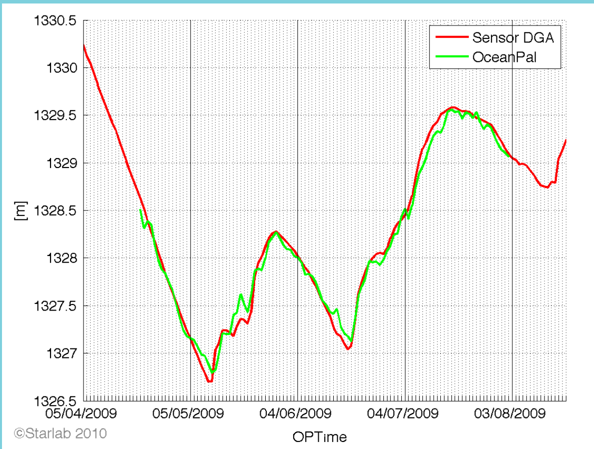
The traditional way to observe sea level is with tide gauges, which results in measurements relative to the Earth's crust. The Earth's crust is, however, continuously moving and in order to fully understand sea level change processes, measurements of sea level in relation to the Earth's centre of gravity are necessary. A way to separate the sea level observation into local sea surface height and local land surface height, and to relate both of them to the Earth's center of mass, can by realized by the use of GNSS.

DIFFERENT techniques exist. The least costly is to use a single GNSS installation

An experimental station for assessing the accuracy of GNSS-based sea level observations. The station uses two receivers and two antennas, one up-looking for direct signals, and one down-looking for reflected signals. Note that the height of the antennas is adjustable in order to study different geometries. Courtesy of G. Elgered, Chalmers.

levels

at the coastline, close to the sea, that uses GNSS signals that are reflected off the sea surface. From the observed variability in the signal-to-noise ratio of the signal from a specific GNSS satellite, caused by the interaction between the direct and the reflected signal, it is possible to calculate the vertical distance to the sea level. The temporal resolution of this technique is limited to approximately half an hour, depending on the geometry of the installation – that is the visibility of open sea seen from the GNSS antenna – and the number of GNSS systems to be used.



GNSS measurements (OceanPal®) of the level of the Laja Lake, Chile, from April to August 2008. The results are compared to independent traditional measurements by the Chilean Water Management Agency (DGA). Courtesy of A. Egido, Starlab

The temporal resolution can be improved if two separate antennas are used with receivers that track the phase of the GNSS signal. These kind of installations allow to derive sea level from traditional geodetic phase data analysis. One such installation is shown in the photograph in the left-hand page.

OBSERVATIONS WITH another system, called OceanPal®, have been made at the Laja Lake, in the Bio-Bio region, Chile in 2008. These results are shown in the graph above together with independent measurements by the Chilean Water Management Agency (DGA). The level of the lake has its maximum during the summer after the melting season. During this period of time, the agreement between the two measurement techniques was better than 5 centimetres.

The application of using GNSS for sea and lake level measurements is rather recent. Most of the results so far are obtained using GPS data only. It is expected that the accuracy will be improved significantly when also the signals from GLONASS and Galileo satellites are used since that will mean additional favourable geometries of the observations.

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