GNSS for Positioning, Navigation, Timing, and Science.

G. Beutler, Astronomical Institute, Sidlerstrasse 5, CH-3012 Bern, Switzerland, gerhard.beutler@aiub.unibe.ch.

GNSS: Global Navigation Satellite Systems are designed for low-cost absolute positioning, navigation and timing on or near the surface of the Earth. The vast majority of the GNSS users is well served with meter to decimeter accuracy in positioning and time synchronization on the (sub-) microsecond level.

The United States' Global Positioning System (GPS) was (ab)used already in the early 1980s to measure "short" baselines of up to a few km with accuracies of millimeters to few centimeters. The Russian Global Navigation Satellite System (GLONASS) was developed in parallel, but due to a lack of combined or GLONASS-only receivers never received a comparable interest up to the end of the 20th century. This situation improved dramatically in the first decade of the 21st centurury. Since about 2005 the European Galileo system and the Chinese Beidou are being deployed.

Principles of Operation: GNSS are based on the (quasi-)simultaneous observation of a number of satellites. The satellites emit coherent signals in the microwave band of the spectrum on (at least two) different carrier waves. More than one carrier is required to eliminate or model ionospheric refraction effects.

The GNSS technique is interferometric in nature. Its strength lies in *relative* positioning and timing, i.e., in baseline determination and in time transfer between sites on or near the surface of the Earth. Efficient techniques were developed for relative positioning (double-difference) and for relative time transfer (common view).

Science: The GPS attracted the interest to scientists from the early 1980s onwards. Many applications like crust deformation studies over relatively short distances (Volcano surveys, dam monitoring) could be performed as soon as a sufficient number of GPS satellites was simultaneously visible for at least a part the day from the area of the survey. Towards the end of the 1980s the GPS became of interest for global science applications like monitoring plate motion. Such applications asked for analyzing longer and longer baselines. The GNSS orbit accuracy became a crucial factor in the error budget.

IGS: The requirement for precise orbits led to the creation of the International GPS Service (IGS) in 1991, which was renamed in 2005 renamed as International GNSS Service. The IGS was planned as an orbit determination service using, to the extent possible, the products of the two other space-geodetic techniques Satellite Laser Ranging (SLR) - and Very Long Baseline Interferometry (VLBI).

It was planned in particular to use the geocentric coordinates of SLR- and VLBI-sites as known in the GNSS analysis. This plan asked for the collocation of GNSS receivers with VLBI- and SLR-observatories and for a close cooperation between the GNSS and the VLBI and SLR communities. This requirement led to a rather painful, but eventually successful process.

It was also planned to use polar motion and UT1-UTC determinations from VLBI- and SLR. This plan failed (1) because the data were not available in time (originally the IGS analysis was performed within 1-2 weeks behind real-time), (2) because the time resolution of one day naturally arising in the GNSS analysis could not routinely be delivered by the two classic techniques. This is why the estimation of polar motion and length of day (lod) had to be performed within the IGS. A UT1-UTC value is still required for each day. The value is taken from the IERS Bulletin A, but originates from VLBI.

The IGS conducted a three-month test campaign in summer 1992. An observing system of about 30 globally distributed GPS receivers delivered their measurements on a daily basis to regional data centers from where they were sent to th global data centers CDDIS at GODDARD and IGN in Paris. From there the data were retrieved by a handful of IGS analysis centers, which turned out their daily products, satellite orbits & clocks, site coordinates, polar motion and lod, on a weekly basis. The 1992 test campaign, successful beyond expectation, continued on a best-effort basis after September 23, 1992 and eventually led to the official IAG service, starting operations on January 1, 1994.

GNSS Science beyond positioning and timing: The GNSS signals propagate through the Earth's ionosphere and troposphere. Originally, the atmospheric effects were considered as nuisance, but eventually led to a kind of space weather monitoring by the IGS (ionosphere maps with a 2-hour resolution) and to what is called today GNSS meteorology, which has an "Earth-fixed" branch using regional arrays of GNSS receivers and a "space-based branch" based on the occultation technique on Low Earth Orbiters.

The presentation: is scheduled for 12 minutes; material is available for at least four hours. The focus will therefore be on GNSS global science applications considering in particular the commonalities of and the complementarity between GNSS and SLR geodesy.