Realization of terrestrial and celestial reference systems using space geodetic observations

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During the last 30 years a global network of stations equipped with instruments for high precision observation of artificial Earth satellites and very distant radio sources has been established. Some of the satellites are carrying payloads, for example radar altimeters, where the application requires that the radial component of the satellite orbit must be determined to a precision of five cm or better. Another example with very high requirements for the orbit precision, is SAR (Synthetic Aperature Radar) interferometry that can be used for the determination of small vertical movements at the surface of the Earth.

The determination of high precision satellite orbits require that a set of differential equations must be established and solved in a well defined reference system. Actually, two reference systems are needed. One "fixed" to the Earth's crust and rotating with the Earth (the terrestrial reference system), and one "fixed" to the celestial sphere (the celestial reference system). The relative orientation between the two reference systems is represented by five Earth orientation parameters (EOP). The most important applications of these reference systems are of cause positioning and navigation both at the surface of the Earth and in space.

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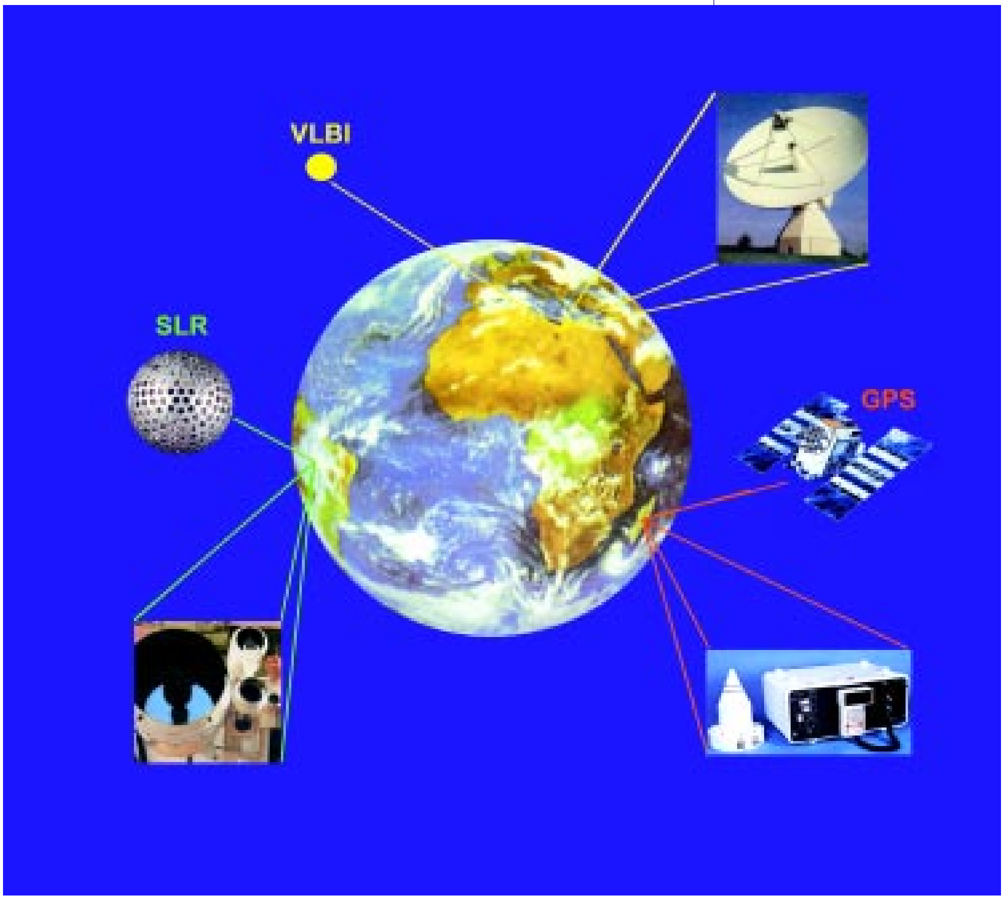
Realization of reference systems

Let us think that one specific point or reference marker is selected for each station in the global network. Furthermore, assume that these points are the vertices of a terrestrial polyhedron. In the same manner, assume that the directions of very distant radio sources on the celestial sphere are the vertices of a celestial polyhedron. Due to tectonic motion, post-glacial rebound and other geophysical phenomena, the terrestrial polyhedron will deform in time. In extreme cases the relative motion of the vertices can reach up to 20 cm per year. Also the celestial polyhedron suffer from deformations but the deformation rate is several orders of magnitude smaller than for the terrestrial polyhedron and can therefore be neglected for a time interval of a few decades. Deformation is in practice given by velocity components of the vertices. Given the coordinates of the vertices we have implicitly given the direction and scale of each of the three axes of a reference frame. Given the velocities we have implicitly given how the direction of the axes and their scale changes with time. *A reference frame, either terrestrial or celestial, is realized by the specific numbers given in a table of coordinates for the vertices and valid for a certain reference epoch.* In addition we need velocities for the motion of these vertices in time so that it is possible to calculate the instantaneous position at any epoch. The velocities can be considered as a model for the motion of the vertices.

The method used for the calculation of coordinates and velocities of the vertices of the terrestrial polyhedron, and coordinates of the vertices of the celestial polyhedron, and the EOP series, is based on the analysis of high precision



observations towards artificial Earth satellites and radio sources (space geodetic observations). The most important types of space geodetic observations come from Very Long Baseline Interferometry (VLBI), Global Positioning System (GPS), and Satellite Laser Ranging (SLR).

VLBI is a technique where pairs of radio telescopes, with a typical antenna diameter of 20 meter, measure the difference in arrival time of signals at X- and S-band frequencies from very distant radio sources. The two frequencies are used for the removal of most of the influence of the ionosphere on the signal propagation. The precision of the best observations is typically 20-30 picoseconds corresponding to 6-10 mm in range. The number of VLBI stations is around 30 and the observations are taken in session of 24 hours where typically 3 to 10 of the stations participate. The International VLBI Service for geodesy and astrometry (IVS) organization is responsible for the overall coordination of the use of the VLBI network.

GPS is a US military satellite system consisting of 24 satellites. There are two types of GPS observations, the pseudorange observations with a precision at the dm level or worse, and the phase observations with a precision at the one-mm level but with an unknown integer number of wavelengths. The two frequencies of the GPS observations are in the L-band. Presently more than 300 high precision globally distributed GPS receivers are operated on a continuous basis. The International GPS Service (IGS) organization is responsible for the coordination of the global GPS tracking network.

The SLR stations measure the total range from a transmitting laser at the surface of the Earth to retroreflectors onboard a satellite and back to the laser pulse detector at the backplane of a telescope. The measurement precision ranges from a few mm for the best stations to some dm for the worst stations. The number of laser stations is approximately 30. The International Laser Ranging Service (ILRS) is responsible for the overall coordination of the SLR network.

Each type of observation is analyzed using very complicated software systems designed specifically for that technique. Actually, several scientific organizations have developed their own software for the analysis of one of the types of space geodetic observations. The principle behind any of the software packages is the following: The individual observation is compared to a corresponding theoretically calculated observation based on a model accounting for all known effects including a model for the motion of the station and the satellite involved in the observation. The total model is expressed in terms of model parameters like orbital elements, station coordinates and velocities, radio source coordinates, EOP, gravitational coefficients, and lots of other secondary parameters. Corrections to the a priori values of the model parameters are estimated so that the difference between the actual observations and the theoretically calculated "observations" are minimized in a least squares sense. Usually, only a subset of the model parameters are estimates but in many cases the number of solve-for parameters is at the level of 1000 or higher. If for example GPS observations are analyzed approximately 1500 second order

Space geodetic observations from VLBI, GPS and SLR play a key role in the realization of terrestrial and celestial reference systems.

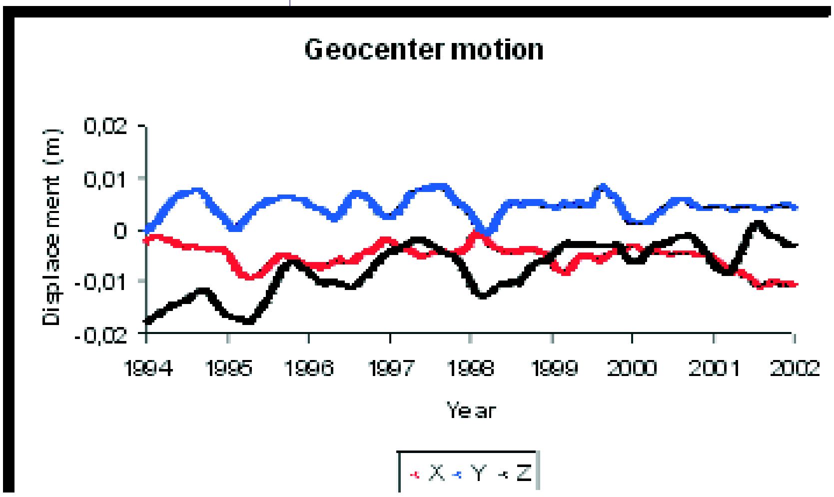


Fig. 1. Coordinates of the instantaneous center of mass of the Earth relative to the MRF-2000 reference frame. Calculated by the GEOSAT Software using VLBI, GPS and SLR observations.

differential equations must be solved numerically. In any case the analyses require hours of computation time even on the newest powerful computers.

The observations are usually analyzed in batches of one day. The result from each day is a state vector containing the parameter estimates for that day and a corresponding covariance matrix giving the precision and correlation of the parameter estimates. In fact, each daily solution is an individual realization of the terrestrial and celestial polyhedrons including consistent estimates of the EOP giving the relative orientation of the two polyhedrons. A second software system combines the daily polyhedrons and EOP's for a time interval of many years to one average terrestrial polyhedron including deformation in terms of velocities, one average celestial polyhedron and a series of EOP's. The migration of the instantaneous center of mass of the Earth including the atmosphere and oceans, felt by the satellite, is simultaneously determined relative to the slowly deforming average terrestrial polyhedron. Several scientific organizations, including Forsvarets forskningsinstitutt, produce such analyses. Finally, the average polyhedrons and corresponding EOP series of each technique are combined into a technique-independent terrestrial polyhedron and its deformation with a corresponding EOP series.

This last combination is performed by the International Earth Rotation Service (IERS) on the basis of analysis results from a number of organizations including Forsvarets forskningsinstitutt. IERS is responsible for the development and maintenance of terrestrial and celestial reference frames and the EOP's. It is clear that the estimated numbers for the terrestrial and celestial reference frames depend on the applied analysis model. Using a slightly different model will give other values for the coordinates and the velocities. The concept of a reference system is introduced in order to account for this. *A reference system is defined as the reference frame plus the models applied in the analysis for the estimation of the numbers of the reference frame table.*

The concept of a reference system is vital since the model part of the realization tells the user how the reference system can be applied in practice. Therefore, if a user wants to find very precise coordinates and velocities for his own GPS receiver in the IERS realization of the terrestrial reference system, he or she must analyze data from this GPS receiver simultaneously with observations from some of the GPS receivers used in the realization of terrestrial reference using the same analysis model as was used in the IERS realization of the terrestrial reference frame. The IERS estimates of the EOP must furthermore be used in the analysis. Similarly, if the user wants to determine the orbit of a satellite in the IERS realization of the celestial reference frame, he or she needs to include a subset of the tracking stations in the IERS terrestrial reference frame relevant for the tracking technique for that specific satellite. The analysis model must be the one applied for the generation of the IERS reference frames. The IERS model is described in the IERS Standards. The IERS Standards are improved at an interval of some years by the leading experts of each model component. The next edition is expected at the end of year 2002.

Present and possible future contributions from Forsvarets Forskningsinstitutt

Data from independent techniques can in principle be combined using two different strategies. The analysis strategy presently being used by the analysis centers including the IERS is the following: The different types of observations are processed separately using analysis software developed specifically for each technique. The results at the arc level for a specific technique are combined into a global technique-dependent solution. With an *a posteriori combination* (APOST) of all technique-dependent global solutions a multi-technique global solution is established.

It has been observed that the internal consistency of the analysis results within each individual technique is typically almost one order of magnitude better than the external consistency between the different techniques when APOST is applied. The author has developed a more general strategy where the different types of data are combined at the observation level with one consistent model and one consistent strategy. The results at the arc level are combined into a global solution accounting for all correlations within each arc. We call this strategy *the a priori combination* (APRI) *method.*

There are several advantages with the APRI method: 1) One set of estimates can be determined for the technique-independent parameters. 2) The combination of independent and complementary information from different types of observations will reduce the parameter correlations and lead to more accurate results. 3) The proposed method will make it possible to detect and study possible technique-dependent systematic errors and biases. 4) The estimated satellite orbital elements, radio source coordinates, and nutation parameters will be realized in a long-term stable celestial reference frame realized primarily by the radio sources. GPS and SLR will contribute directly in the determination of nutation and UT1 and not only be used to estimate the rate of change of these parameters. 5) All estimates of geodetic and geodynamic parameters will in principle be given in one single realization of the terrestrial reference frame. This is especially interesting since a terrestrial reference frame realized by VLBI alone is almost free of gravity effects while reference frames realized by the satellite techniques certainly are dependent on gravity effects. 6) It is often seen that results from the analysis of VLBI data to some degree suffer from variations in the VLBI network geometry. This problem is greatly reduced with the inclusion of SLR and GPS data in the analyses. 7) The combined analysis of VLBI, GPS, and SLR can be used to estimate (and validate) the eccentricity vectors between the different antenna phase centers within each colocated station.

The GEOSAT software for analysis of any type of space geodetic observations, and developed by Forsvarets forskningsinstitutt since 1984, is the only existing software worldwide with the APRI capability. For that reason Forsvarets forskningsinstitutt has been apointed as a Combination Research Center (CRC) for IERS. The main goals are to study the advantages listed above and to investigate the potential of the APRI method as a candidate method to be used by IERS for future realizations of the terrestrial and celestial reference systems. Forsvarets forskningsinstitutt is also analysis center and technical development center for IVS and associate analysis center for ILRS.

The results are very promising as can be seen from Fig.1, which shows the x-, y-, and z-coordinates of the Earth's instantaneous center of mass relative to the ITRF-2000 reference frame and calculated by the GEOSAT software. A small but not negligible inconsistency between the IERS EOP series and the ITRF-2000 has recently been detected using GEOSAT. Presently, Forsvarets forskningsinstitutt are performing analyses to determine the absolute position of the phase center of the transmitter antennas of the individual GPS satellites using a combined VLBI, GPS and SLR analysis. With GPS data alone it is only possible to determine the phase center relative to one of the GPS satellites and not absolutely which is possible with the GEOSAT software. The present knowledge of the phase center position is uncertain to at least one meter! We hope to estimate the phase center with an uncertainty of some cm. The consequence of errors in the location of the phase center is that the meter realized by GPS will have an error of up to 15 parts per billion corresponding to an error of almost 10 cm in the height component of the receiver coordinates. This is important for high precision applications of GPS. FFI has demonstrated that the combined analysis of VLBI, GPS and SLR data with the APRI method improves the EOP estimates by up to 100 % compared to an individual analysis of any of the data types. For good arcs the EOP's can be estimated with a precision of 50 micro arc seconds corresponding to 1.5 mm at the surface of the Earth.

The GEOSAT software is continuously improved with implementation of the newest available model components. We plan to prepare the GEOSAT software for applications to space probes in the solar system. One such application is the Rosetta mission where a space probe will orbit around a small comet and where the gravity field of the comet is to be determined along with the orbits of the comet and the space probe. Another possibility is to develop a mini-version and ultra-effective autonomous version of GEOSAT for orbit determination and orbit prediction and to be flown onboard a low Earth orbiter like the proposed Norwegian NSAT-1 satellite.