VLBI Correlation for Navigation on Earth and in Space

by Irene Reichl (VSC Research Center)
translated from German

Navigation systems can only be as accurate as their reference system. Satellites circle steadily in their orbits, while the Earth spins once slightly faster, once slightly slower. Weather, winds, jet streams, or changes in the Earth's core result in rotational fluctuations. If the Earth rotates one millisecond faster than assumed, this leads to a position deviation of 50cm at the equator and at least 5km on Mars. Surely, agencies like ESA and NASA have a strong interest in the most accurate terrestrial reference frame possible.

But how exactly can such a reference frame be determined? Like already in the Old Stone Age or in the better documented antiquity, the answer is found while studying the universe.

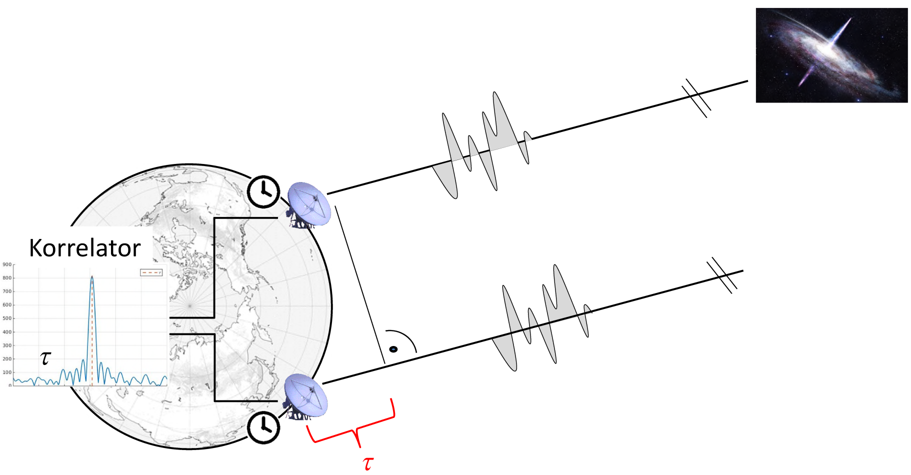
Quasars - the fixed points in space as terrestrial reference

Quasars (quasi-stellar radio source) are the active parts of galaxies on the edge of the observable universe which emit point-like broadband radio waves. Unlike stars that we can see with the naked eye and whose proper motion is non-negligible, quasars are located much farther from the Earth and their locations appear as fixed and stable. Moreover, radio waves always penetrate the Earth's atmosphere, whereas visible light is blocked by bad weather alone.

From the noise of the quasar to the terrestrial reference frame

There are about 50 telescopes stationed around the globe capturing radio waves from quasars for geodetic purposes. Locations equidistant from a quasar receive the same quasar noise at the same time. Therefore, a station closer to this same quasar records a signal shifted by the travel time between the two stations in this spatial direction. This fact is exploited in that way that the measurement time series from two different stations are aligned to determine this time shift.

Just as a straight line can be drawn more accurately the farther apart the base points are, the same principle applies to the measurement accuracy of connected telescopes on Earth. Their accuracy improves with larger distance (baselines). In the early days, when stations were still physically connected by cables, there was a tight limit on the maximum distance between them. With the use of atomic clocks, this limitation has fallen and the distances became larger, hence the name Very Long Baseline Interferometry (VLBI). Internationally, all the centres are interlinked, with NASA operating the coordination centre of the International VLBI Service for Geodesy and Astrometry.



The radio waves from a quasar about one billion light-years away reach the Earth as a plane wavefront. If objects are at different distances from the quasar, they are reached by the wavefront with a certain time difference τ. The latter is calculated in the correlator by shifting the two signals against each other until the correlation maximum is found. © Johannes Böhm

Observation precisely planned with VieSched++

To calculate the three-dimensional coordinates and velocity vectors of the terrestrial reference frame, several hundred quasars are being observed in different spatial directions. As the Earth rotates, measuring stations are always facing different quasars. Which stations will observe the same quasars at the same time within a 24h measurement campaign is carefully planned with help of the scheduling software VieSched++.

Six correlators worldwide, including the Vienna Center for VLBI

There are approximately two to three 24-hour measurement campaigns per week with data volumes up to about 200-300 TB. Transferring the data and correlating them requires enormous hardware and Internet-bandwidth resources, so that only a few centres worldwide, so-called correlators, have the technical capabilities to do this, including the MIT Haystack Observatory, the Washington Correlator, the Bonn Correlator Center, the Tsukuba VLBI Correlator, the Shanghai VLBI Correlator, and the Vienna Center for VLBI.

Close cooperation between Vienna Scientific Cluster and Vienna Center for VLBI

The data reach the Vienna Center for VLBI via the web. "To achieve a high transmission bandwidth," Jakob Gruber explains, "a parallel server process runs on the VSC login nodes, waiting for the data from the radio telescope stations." At the moment, we achieve up to 10 GBit/s. "It takes one to two weeks to transmit a 24h measurement campaign from about eight stations," says Johannes Böhm. "If I had one wish, it would be an Internet transmission rate of 100 GBit/s to transfer the measurement campaigns in real time." Such a high bandwidth is currently being tested between stations in Sweden, Germany, Spain and Austria.

Johannes Böhm: "We are in the fortunate position to be supported by the VSC and to be able to draw on their know-how." © EuroCC Austria

One petabyte superfast data storage

The received data are stored in a one-petabyte superfast parallel file system acquired specifically for this purpose. Despite that, after three to four measurement campaigns with 200 to 300 terabytes each, the storage would already be full. However, hundreds terabytes of measurement data can be deleted after the correlation. Only the considerably smaller result files are kept and made available to the public in the framework of the open data policy.

International networking helps overcome breakdowns

The storage is sufficient for regular operation, but there is always a risk of interrupted internet connection, as happened recently due to a defective Atlantic submarine cable. The data from the radio telescope in Hawaii had to be physically fed to the MIT Haystack Observatory and from there transmitted to the other correlators over the Internet. In such cases, the data from the same measurement campaign must continue to be stored by the individual correlators until all the data are available and the analysis is complete.

Correlation of large amounts of data on HPC systems of the VSC

Once the data are available, they are correlated using a community code. "The VSC helps us to efficiently compile the community code for the specific hardware and create optimised job scripts for the VSC," adds Jakob Gruber. "What you get from the calculations are the transit time differences to each radio telescope for each observed quasar." These result files which only weigh a few Megabytes can subsequently be further processed by other programmes, such as the Vienna VLBI and Satellite Software (VieVS), on the user's laptop.

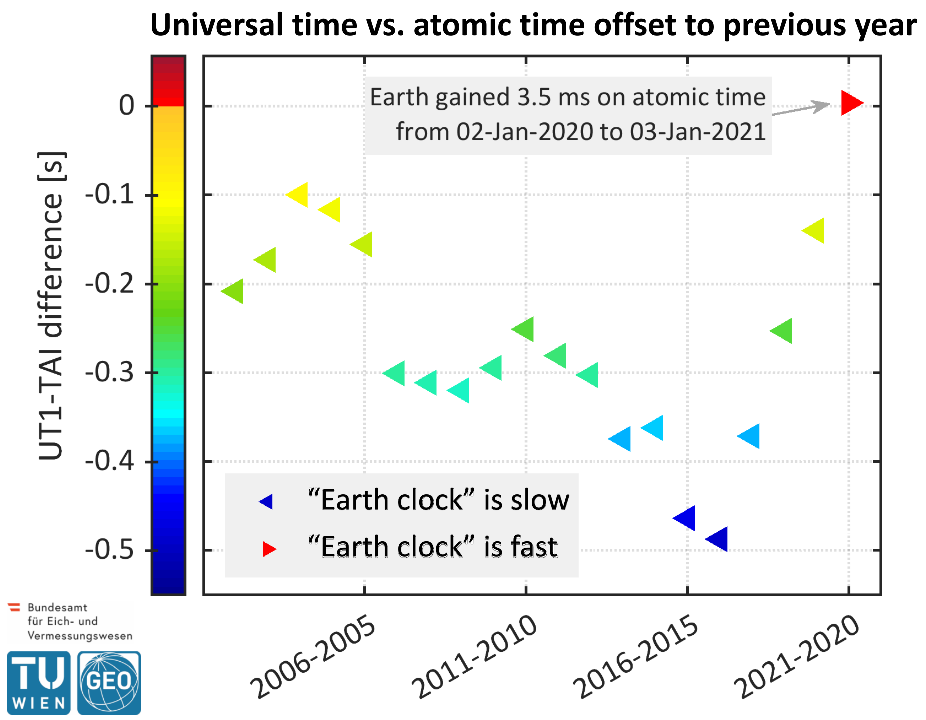
VieVS determines geodetic parameters for plate tectonics and sea level

VieVS, developed by the VLBI research group, calculates, for example, the motion of the Earth's rotation axis, the length of day, and a reference frame for the Earth and space. The terrestrial reference frame, with a station accuracy of at least 0.3 mm per year, is a prerequisite for observing plate tectonics as well as the sea level rise, which is currently about three millimeters per year.

Geophysical phenomena are reflected in variations of the Earth's rotation parameters

Atmospheric rearrangements change the Earth's moment of inertia and thus affect its speed of rotation, comparable to a water diver turning faster in a squat somersault than in a stretch somersault. The weather and especially variations in the jet streams are thus reflected in tiny variations in day length. Remarkably, the Earth is now spinning faster again, even though it is slowed in the long term by the Moon.

"This development has already lasted longer than could be explained by fluctuations caused by the weather, which is why there are speculations about processes in the Earth's core as the underlying cause," says Johannes Böhm with caution, "because almost no one dares to make a statement about a possible origin of this phenomenon in the Earth's core." Sigrid Böhm, also of the Department of Geodesy and Geoinformation, is researching how climate change might affect the Earth's rotation in the coming decades and centuries. VLBI observations over the last four decades provide a very valuable dataset for this purpose to validate the models.



Time can be measured as a strictly elapsed duration for which the most accurate clocks, called atomic clocks, are used. This is what we call atomic time. Time can also be derived from the rotation of the Earth, called universal time (UT1). UT1 and atomic time (TAI) are not synchronous, because the Earth does not always need the same time for a complete rotation around its own axis or around the Sun. The figure shows the divergence of the two “times” at the beginning of the year during the last two decades — a result of the VLBI's in-house analysis.

"The graph also illustrates the current continuing trend — lately," Sigrid Böhm explains, “the Earth has often been rotating faster than the corresponding duration of a nominal day.” © Sigrid Böhm

Vienna Center for VLBI:
https://www.vlbi.at

International VLBI Service for Geodesy and Astrometry:
https://vlbi.org

Vienna VLBI and Satellite Software:
https://vievswiki.geo.tuwien.ac.at

“The Earth is spinning faster” (“Die Erde dreht sich schneller”, TU Wien News, in German):
https://www.tuwien.at/tu-wien/aktuelles/news/news/die-erde-dreht-sich-schneller

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