Yann Kempf, BASI-P1
2007/2008
Introduction to Geophysics 1

The use of VLBI as an investigation tool in geodesy

In this paper, I will present the technique known as VLBI (Very Long Baseline Interferometry). I will first give an overview, explaining how VLBI is working and how scientists set it up. Then I will focus on the application of VLBI to geodesy. Finally we will see what results VLBI can yield, with an example taken from a publication.

I. What is VLBI?

The term '**VLBI**' is obviously an acronym, which is in fact standing for '**V**ery **L**ong **B**aseline **I**nterferometry'. Let's explain each of these components separately.

Interferometry is a technique that relies on combining two or more telescopes to enhance the power and the resolution by studying the interference produced when the light beams are added up.
The power is of course a factor of the collecting surface, which logically increases if mirrors or dishes are added.
The more important thing is the improvement of the resolution, because it is a function of the diameter for a single telescope, or a function of the separation between the combined telescopes in an interferometer. [See Appendix] It is clear that it is way easier (and cheaper!) to build two separate small telescopes to simulate a scope with the resolving power of a much larger one, than to actually build this enormous monster telescope.
When doing interferometry, one seeks to align the waves received in the two (or sometimes more) telescopes, usually so that, by the superposition principle, when in phase, their constructive interference produces one stronger wave.
This way, fainter sources can be observed, and mapped with greater detail. [1]

The **baseline** is a key factor in interferometry. It is the distance that separates the individual telescopes from each other, as seen from the observed object. It is the only factor that affects the resolution power of the array for any given wavelength. [See Appendix]

In interferometry, and especially in radioastronomy, the **long**er your baseline is, the better are the results you get. [See Appendix] This led to the building of large telescope arrays. One famous example is the Very Large Array (VLA), located near Socorro, New Mexico, USA. It combines 27 radio antennae in a Y-shaped configuration, each of which is 25 m in diameter. They are set on rails, and can be placed as far apart as to simulate a 36-km-diameter dish. [2]

Finally, the V stands for **very** long baselines, i.e. ranging from tens to thousands of kilometers. This is achieved by setting up networks comprising radiotelescopes across countries, continents, and even, why not, further out. Many examples exist, among them the MERLIN network in England, the EVN in Europe, the NRAO's VLBA. JAXA is even planning to launch a radiotelescope satellite, thus effectively expanding a baseline into space over several tens of thousands of kilometers. [3]

II. How does VLBI work?

First of all, of course, a network of radiotelescopes has to be set up to be able to carry out VLBI observations. It can be a fully dedicated installation, like the Very Long Baseline Array

(VLBA) which is a network of ten identical remote-controlled 25-meter antennas scattered about the United States [2]. On the other hand, a VLBI network can be put up by using already existing facilities simultaneously. There are many larger radiotelescopes that are being operated by research agencies, universities or laboratories across the planet (Jodrell Bank, UK; Nancay, France; Effelsberg, Germany; Arecibo, Puerto Rico; a.m.o.) [3], which, when combined into a VLBI network, provide easily very long baselines.

The main point in interferometry is to observe a same object at the same time from various locations to be able to combine the signals crest-to-crest, thus creating the interference patterns sought after.
But the simultaneous combination of the signals can hardly be achieved at once when the individual stations are located up to several thousand kilometers apart. To tackle this issue, the incoming signal is recorded on magnetic tapes, along with a very accurate time-keeping signal from a high-precision atomic clock. Of course the clocks must all have been synchronised before. These tapes are then collected at a central facility where they are played back in a machine called a 'correlator'. It shifts the playback slightly iteratively, until ultimately the signals are perfectly aligned in order to produce the long-expected interference fringes.
During the process, not only have the scientists acquired the enhanced observations radioastronomers are looking for, but there is also an extremely interesting piece of information which comes almost as a 'by-product'; the exact time delay between the reception of the signal at the various locations. And as the speed of light is known and finite, this gives the radial distance between the antennae with respect to the radio source, as well as the length of the baseline after a little basic geometry.

When they perform VLBI for the sake of radioastronomy, scientists observe any type of objects. But there is one type of objects in particular that is used when the aim is ultimately geodetic measurements, usually they choose so-called quasars or QSOs (Quasi-Stellar Objects). Scientists take quasars because their signal is random or at least highly variable on the timescales considered. Moreover, quasars are very remote (they actually belong to the furthest objects observed from Earth), which implies that any parallax problems that could be an issue for closer objects because of the widespread observing points are easily negligible. This means that QSOs provide observers with a fixed, non-moving, stable and reliable radio source with a unique signal; the perfect target for the kind of measurements that are needed.

III. How is it used for geodetic purposes?

Once the correlator processed the tapes recorded at radiotelescopes in various locations which observed the same object at the same time, one exactly knows the timeshift in the arrival time of the signal at the locations, and by extension the relative positions of the stations (i.e. the baselines) with a high accuracy.

Geodesists use radiotelescopes in VLBI networks to determine the positions of each station relatively to each other in the network, as the processing is done in pairs. By taking these measurements on a regular basis, usually several observing campaigns a year, one can produce a time series of the baselines between the stations. When these series are processed, it is easy to compute variation rates of the baselines, and from that, adding a bit more of processing, geodesists can determine the tridimensional motions of the stations.

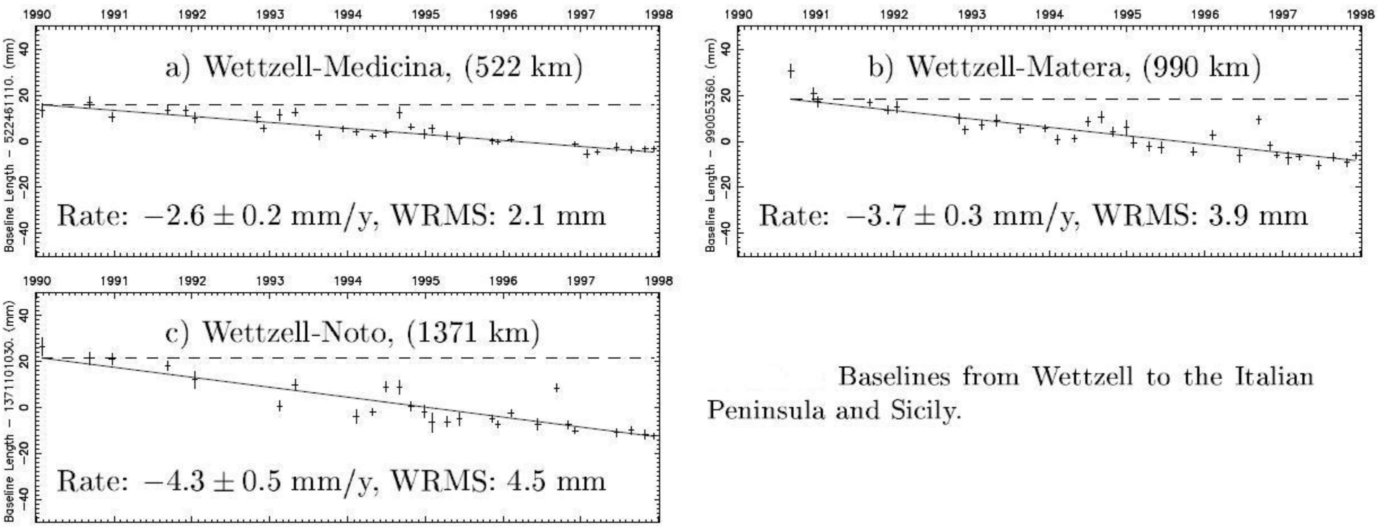
The theory is really neat, but before they can actually have reliable baseline data, scientists have to cope with many problems at various levels, which have direct or indirect influence on the quality and the overall usability of the collected data.
When not using a dedicated network, researchers rely on radiotelescopes that are each run separately and independently of each other by a different institution. The attribution of observing time is, as for any observing facility, done by the own scientific committee at each

observatory. Therefore it is quite difficult to obtain observing time, at many observatories and simultaneously, two conditions that are fundamental for any VLBI data to be produced.
There are also various hardware issues that come into account when the goal is to obtain an accuracy way below 1 cm. Changes in hardware, like the installation of new bearings, heavily influence the data as they can change the position of the antenna by many centimeters. The mechanical response of the hardware to weather, including thermal expansion, wind, precipitations, might also induce unwanted variability.
Further up, the atmosphere plays a fundamental role as well physically, influencing the signal as it travels through its many different layers. All the effects, like atmospheric refraction or delaying of the waves, which vary with the terrestrial and space weathers, need to be subtracted for each location, either using observations or models.
Geophysical factors are of fundamental importance too when aiming at high goals like those. Small-scale effects in time and space need to be taken care of for each observatory. Oceanic, crustal and atmospheric tides, atmospheric pressure load varying with the weather [4], water load from precipitations, all these kinds of phenomena can have cm- to dm-scale effects on the position of the individual telescopes. Therefore they must be carefully modelled to be subtracted from the data before actually studying the time series.

IV. Example of results

In this part I will present an example of results yielded by VLBI. It is mainly based on Haas & Nothnagel, 1998 [5]. The EVN (European VLBI Network) is the network that has been used for the measurements presented in this paper. It is a set of 10 radiotelescopes scattered all over the continent, from Spain to England, from the Crimean Peninsula to the Svalbard Archipelago, over Italy, Germany and Sweden.

Once all of the previously mentioned issues have been addressed, one gets a time series for each baseline, i.e. the spatial distance from one station to another within the network during the time span studied. This easily provides by simple computation the drift rates for each baseline. The following plots show this type of data. I chose those for their clear trend, which is quite big and does not, of course, exist for every baseline.



Baselines from Wettzell to the Italian Peninsula and Sicily.

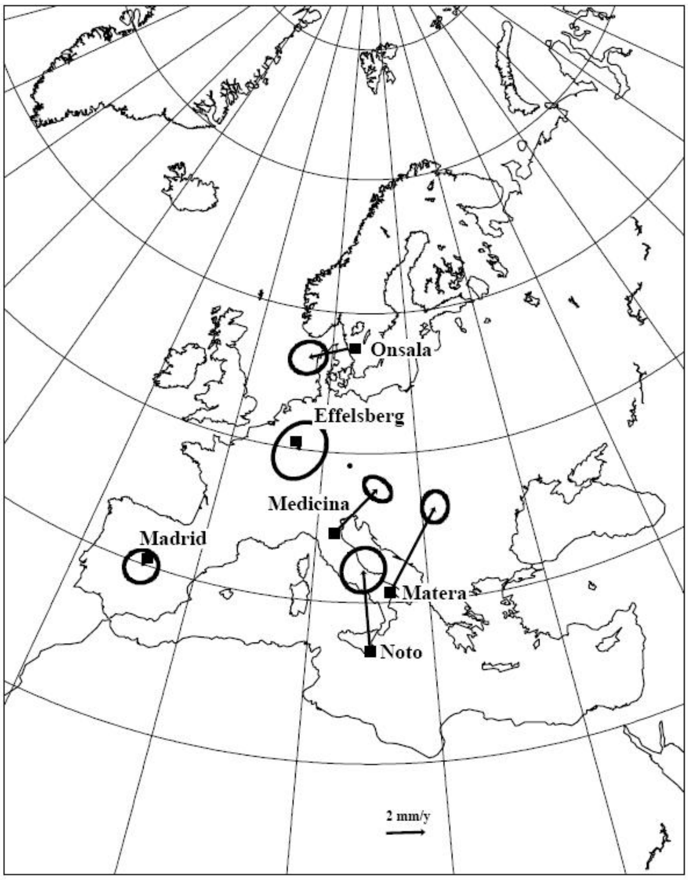
It is already valuable information, but the stations are not floating in free space, hence it is useful to link this set of data to the actual positions of the antennae on the surface of the Earth. By choosing a reference station within a network, a full relative motion model can be made, whith very high accuracies. This is achieved by determining the coordinates of that reference point. Proceeding from there, it is possible to compute the coordinates for each station. After that, the coordinates are converted from cartesian to ellipsoidal, the latter system being devised so that it fits best the Earth's surface. From the drift expressed in such coordinates, one can extract tridimensional drifts in two horizontal directions (North and East) and one ellipsoidal height component, which comes in most handy when considering the motion of a place located on the surface of our globe.

The following table gives these components for 6 stations that have produced reliable data during the study.

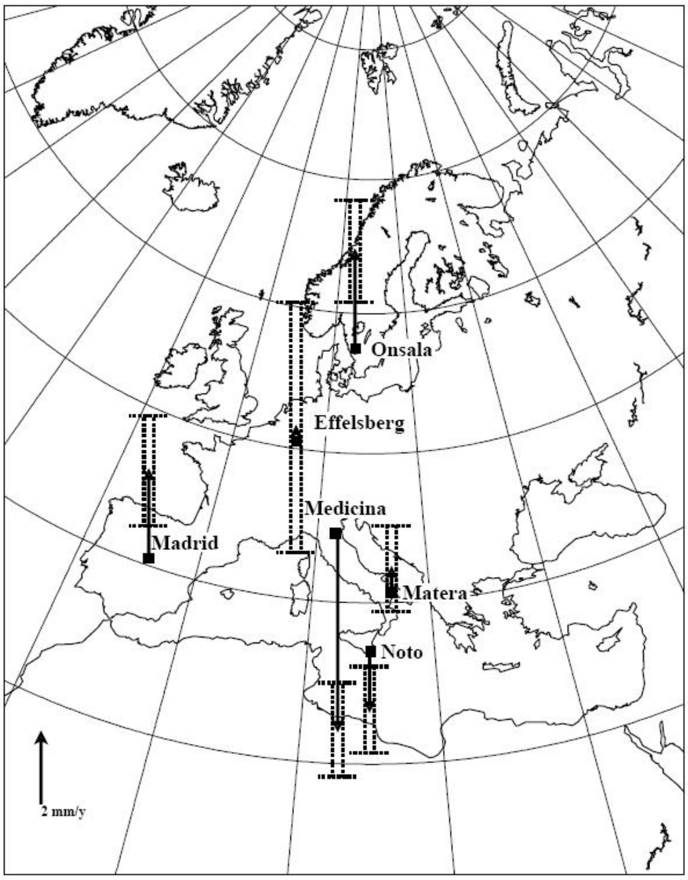
Horizontal and vertical velocities with their standard deviations of six stations in the network.

Station	East [mm/y]	North [mm/y]	Height [mm/y]
Effelsberg	$+0.3 \pm 0.6$	-0.5 ± 0.5	$+0.1 \pm 3.2$
Madrid	-0.2 ± 0.4	-0.5 ± 0.3	$+2.3 \pm 1.4$
Matera	$+2.4 \pm 0.3$	$+4.3 \pm 0.3$	$+0.6 \pm 1.1$
Medicina	$+2.1 \pm 0.3$	$+2.4 \pm 0.2$	-4.9 ± 1.2
Noto	-0.4 ± 0.4	$+4.2 \pm 0.5$	-1.4 ± 1.1
Onsala	-1.9 ± 0.4	-0.5 ± 0.3	$+2.6 \pm 1.3$

Of course, this has only been the observational and computational parts of the work so far. To make the data a bit more eloquent, at least visually, geodesists can easily make maps showing all these results, as shown below.



Horizontal site motion



Vertical site motion

And then do the geophysics really begin, since these fine results have of course to be interpreted.

This study set the location of Wettzel (D) as the reference point, and its coordinates were chosen in a system that sets Europe as the reference plate, i.e. as being motionless among all tectonic plates.
As the horizontal motions of Effelsberg and Madrid demonstrate, the Eurasian plate is not moving with respect to itself at least in Western Europe, that is it is not subject to any strong deformation under any strain.
On the other hand, the Italian stations show in their horizontal motions that they are located on a piece of plate that is experiencing complex deformations because it is neither fully belonging to the Eurasian plate, nor is it part of the African plate that is still ramming into Europe. Being squashed between both, it is put under complex strain.
The vertical motions also give interesting clues to geophysical processes happening. The fact that the station of Medicina is subsiding at a high rate can be related to ground water and gas extraction in the Po valley. The uplift of Onsala in Sweden is one more proof for the so called post-glacial rebound of the whole of Northern Europe. Having been relieved from the heavy ice sheet that covered most of it during the last ice-age, Northern Europe's land masses that were depressed now rise at a fast pace to reach again isostatic equilibrium.

V. Conclusion

Very Long Baseline Interferometry is a technique that can be used very effectively for geodetic purposes, as it provides sub-cm accuracies in the determination of the positions of individual stations, allowing for very good measurements and observations to be made across wide distances, as well as regularly over long time spans, using non-dedicated facilities that are therefore easier and cheaper to maintain.

VI. Appendix : Resolving power [6]

For a circular mirror or objective, the resolving power in radian is given by: $\alpha=\frac{k*\lambda}{D}$, where λ is the wavelength, D the diameter and k a numerical constant. Astronomers are looking for the smallest possible α, which is the smallest angular size their instrument will be able to resolve. The first way is of course to increase D, which can be done either by building larger instruments, or by combining more instruments into an interferometer, where then the distance between the instruments, called the baseline, replaces the diameter D.
The radiofrequencies have the longest wavelengths in the electromagnetic spectrum, ranging from centimetric to kilometric order. This explains why very large arrays, thus yielding accordingly long baselines, are needed in radioastronomy to reach resolutions of any interest for today's research in astrophysics and cosmology.

VII. Sources

- 1 : Resolving the Faces of Stars, Sky & Telescope, February 2007
- 2 : National Radio Astronomy Observatory (http://www.nrao.edu/)
- 3 : Max-Plank Institut für Radioastronomie, Bonn (http://www.mpifr-bonn.mpg.de/ public/angela/main.html)
- 4 : Study of the atmospheric pressure loading signal in VLBI observations, L. Petrov, J.-P. Boy, 2003 (http://arxiv.org/abs/physics/0311096)
- 5 : Crustal motion in Europe determined with geodetic Very Long Baseline Interferometry, R. Haas & A. Nothnagel, 1998 (http://citeseer.ist.psu.edu/198428.html)
- 6 : Astronomy 1, Lecture by John Simmons, WS 2007/2008, Luxembourg University
- Astronomical Optical Interferometry, B. Tubbs, 1997/2002 (http://www.geocities.com/capecanaveral/2309/page1.html)