Overview of VLBI

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1. The Importance of Reference Frames

Modern geodetic techniques are expected to provide the observational basis for the systematic investigation of a wide range of scientific questions including, among others:

- the motions, tectonic and otherwise, of the Earth's crust on local, regional, continental, and global scales.
- the rotational dynamics of the Earth.

In general, scientific investigations of these phenomena proceed by the precise determination of the position vectors and their time dependence of observation locations on the Earth's surface. These determinations are carried out to a high precision (often as high as parts in 10^9 to parts in 10^{10}) by a variety of geodetic techniques over many decades. In an effort to advance our understanding of many important geophysical phenomena it is often essential that high precision data sets, realized by various geodetic techniques and acquired at times that are decades (and eventually even centuries) apart, be merged, analyzed, and interpreted in a coherent and self-consistent manner. In general this sort of data analysis requires the combination of vector (and possibly tensor) quantities, directly or indirectly, derived from the geodetic measurments. In combining high precision vector and tensor quantities it is essential that the components of the vector and the elements of the tensor are **referred to a common set of fundamental basis vectors or a common fundamental reference frame lest the procedure yield mathematically illogical and physically meaningless results**. When very high precision geodetic measurments are being analyzed in this fashion it is essential to find a solution to the question of a common fundamental reference frame.

In order to serve the purpose required of it in the context of modern geodesy, such a common fundamental reference frame must:

- be realizable to a precision of the order of parts in 10^{10}
- be reproducible to a precision of the order of parts in 10^{10} over time scales of centuries or longer

2. Candidate Fundamental Reference Frames

Historically fundamental geodetic reference frames (Terrestrial Reference Frames) were attached to the surface of the Earth. Such frames of reference were of course rotating and their use in dynamical applications required a precise measurment of the rotation vector of the reference frame. This required continuous monitoring of the Earth's rotation since the rotation vector was time varying as a result of a variety of geophysical phenomena. In the modern context the rotational motion of the tectonic plates of the Earth, at rates of the order of $\pi/2$ per 10^8 years or roughly parts in 10^8 per year, renders this frame unstable on the times scales of interest and precludes the use of the Earth's surface as a candidate for such a fundamental reference frame.

The practice of successful navigation at sea also imposed a requirement for the establishment of a fundamental reference frame on the sky. The Celestial Reference Frame was defined by the equator, ecliptic, and pole of rotation of the Earth and was realized by the estimates of the celestial coordinates of stars in the Milky Way Galaxy. In the modern context the rotation of the Milky Way Galaxy at rates of the order of 2π per 3×10^8 years or roughly parts in 10^8 per year combined with the chaotic proper motions of stars renders this frame unstable on the time scales of interest and precludes the use of the Milky Way Galaxy as a candidate for such a fundamental reference frame.

Other inadequate candidates for the definition of a fundamental reference frame include the orbital planes of passive compact satellites such as "Lageos" or "Starlette". These objects are buffeted by the solar wind, are perturbed by the tidal forces of the Sun and Moon, are subjected to the gravitational accelerations of time varying harmonics of the Earth's gravity field, and are subjected to the gravitational accelerations of unknown high order harmonics of the Earth's gravity field.

The orbital planes of active satellites such as GPS and GLONASS are even less suitable for the definition of a fundamental reference frame. Active satellites suffer from all the drawbacks of passive compact satellites and have in addition the complications of large drag effects on solar panels, orbital maneauvers imposed by ground controllers, and angular momentum dumps imposed by ground controllers.

The present-day solution to the definition of the **fundamental reference frame** has been found by retreating from the Earth to the edges of the known Universe and adopting a cosmological frame of reference defined by a large number (400 to 600) of "bright" quasars and Active Galactic Nucleii (AGNs) whose relative positions on the celestial sphere are estimated by Very Long Baseline Interferometry (VLBI) measurements with an internal precision of the order of 0.1 to 0.2 milli-arc seconds or a few parts in 10^{10}. This suite of cosmological objects define what is referred to as the International Celestial Reference Frame (ICRF). The ICRF has been adopted by both the IUGG and the IAU as constituting the **fundamental reference frame** for astronomy, astrophysics, geodesy, and geophysics. The ICRF is tied to the Equatorial or Dynamical Reference Frame defined by the Vernal Equinox and the North Celestial Pole (NCP) with high (0.2 to 1.0 milli-arc second) precision, largely as a result of the intrinsically high precision of VLBI measurements, but with low (100 to 200 milli-arc second) accuracy, limited largely by the uncertainties in the location of the Equinox and NCP within the Dynamical Frame.

3. VLBI Basics

The fundamental geodetic VLBI observable, τ_{obs} also known as the signal "delay", is the differential time-of-flight, between two VLBI antennas located on the Earth's surface, of broadband microwave "noise" signals emanating from quasars or other cosmological radio sources. This is an observable which depends only on **fundamental physics**, namely a realization of the atomic second and a clock synchronization convention.

The VLBI signal delay τ_{obs} is measured by amplifying, downconverting in frequency, and digitally sampling, the quasar signal at each antenna site with electronic signal processing devices whose time, frequency, and phase information is derived coherently from an on-site atomic frequency standard, usually a hydrogen maser. Figure 1 shows the basic geometry of VLBI and the equipment used.

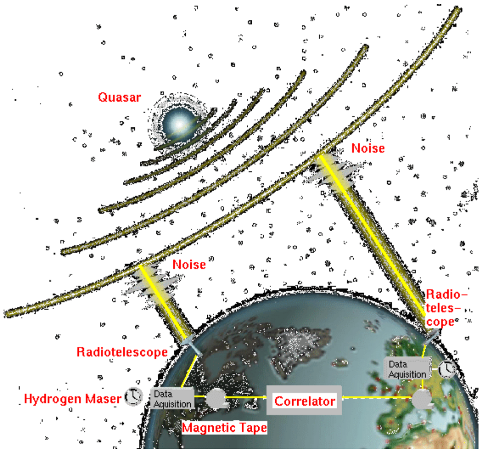

Figure 1. VLBI concept. (Original drawing by John Hazen, modified by Hayo Hase.)

The digitally sampled quasar signals are recorded, along with precise station time information, by a broad bandwidth digital data recorder and the recorded tapes are subsequently delivered to a special purpose VLBI correlator facility for cross correlation processing. Cross correlation processing of VLBI data requires continual and precise compensation, before multiplication, for the changing differential time-of-flight and changing differential Doppler shift imparted to the microwave signals by the rotation of the Earth during the entire period of coherent integration. The relative delay at which the peak of the cross correlation function is found yields a value of τ_{obs}.

As in all correlation functions, the width of the central maximum of the VLBI cross correlation function is inversely related to the bandwidth of the signals being cross correlated. The precision with which the value of the signal delay τ_{obs} may be measured is given by $\delta\tau_{obs}$ and is related to the effective bandwidth B_{eff} of the cross correlated signal by

$$\delta\tau_{obs} = \frac{1}{SNR \cdot B_{eff}} \tag{1}$$

where SNR refers to the signal-to-noise ratio observed on the interference fringes and B_{eff} refers to the **effective bandwidth** of the recorded VLBI signals. In geodetic VLBI systems it is customary to increase the effective bandwidth of the recorded signals beyond the limitation imposed by simple considerations of the maximum bit rate and the Nyquist Sampling Theorem by recording a number of widely spaced, relatively narrowband, RF signal channels; separately filtered from the broadband quasar noise signal. In this way geodetic VLBI systems function by observing the microwave analog of **optical white light interference fringes** with the attendant very small tolerance on relative delay. As a typical example we shall consider $B_{eff} = 700$ MHz, $SNR = 50$, and $\delta\tau_{obs} = 28$ picoseconds which corresponds to about 8 millimetres of light travel distance. Modern VLBI systems routinely measure the signal delay τ_{obs} to a few tens of picoseconds.

The VLBI signal delay measured at the correlator, τ_{obs}, while dominated by the differential time-of-flight of the quasar microwave signal between the radio observatories, does contain other significant contributions that require attention. In general we may express the signal delay τ_{obs} as a sum of many terms

$$\tau_{obs} = \tau_g + \tau_{clock} + \tau_{inst} + \tau_{trop} + \tau_{ionos} + \tau_{rel} + \cdots \tag{2}$$

where, for example

- τ_{clock} is a contribution to the signal delay arising from the mis-synchronization of the reference clocks at each observatory

- τ_{inst} is a contribution to the signal delay arising from the propagation delays through on-site cable runs and other instrumentation
- τ_{trop} is a contribution to the signal delay arising from the propagation delays through the non-ionized portions of the Earth's atmosphere.
- τ_{ionos} is a contribution to the signal delay arising from the propagation delays through the ionized portions of the Earth's atmosphere.
- τ_{rel} are special and general relativistic corrections to the classical geometric delay τ_g

All of these terms, with the exception of τ_{rel}, are to be considered from a geodetic VLBI perspective to constitute small nuisance terms corrupting the classical geometric delay τ_g. The effects of all of these terms, including τ_{rel}, must be accounted for and then removed by one of several methods:

1. direct computation from known physics, (τ_{rel})
2. direct calibration (τ_{inst})
3. least squares estimation by modelling, possibly with the aid of locally measured input parameters, (τ_{atmos}, τ_{clock})
4. direct removal by physical processes (τ_{ionos})

The classical geometric delay, τ_g is defined implicitly by

$$\tau_g(t) = \frac{1}{c}\hat{s} \cdot [\vec{r}_2(t) - \vec{r}_1(t + \tau_g(t))] \tag{3}$$

where $\vec{r}_1$ and $\vec{r}_2$ are the geocentric (or solar system barycentric) position vectors of the radio observatories and $\hat{s}$ is a unit vector in the direction of the source of radiation as seen from the origin of the geocentric (or solar system barycentric) frame. Repeated determinations of $\tau_g(t)$ by the sequential observation, in rapid succession, of many radio sources $\hat{s}_k, k = 1, 2, 3, \cdots$ results in a data set sufficient to overdetermine the VLBI vector baseline $\vec{b} = \vec{r}_2 - \vec{r}_1$. This data set is analyzed by standard non-linear least squares methods to yield a high precision estimate of the VLBI vector baseline, Earth orientation parameters (precession, nutation, polar motion, UT1), station clock errors, as well as other quantities such as radio source positions etc that pertain to the VLBI observation technique. The Earth orientation parameters are referred to the non-rotating [1] cosmological frame of the ICRF.

The ICRF is often described (erroneously) as constituting the "best definition of an intertial frame" for the purposes of physics and astronomy. While the ICRF is an essential aspect of the definition of an inertial frame, this wording suggests that the ICRF can be used to define a "global inertial frame". This is an error and is a practice that should be discouraged. A desciption of the ICRF that is in accord with relativistic physics would require the recognition that global inertial frames do not exist. Local inertial frames however do exist and require for their definition a "local standard of rest" that is provided by a state of free-fall and a "standard of non-rotation" that

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[1] The adoption by the IUGG and IAU of the ICRF defined by VLBI and the use of the ICRF to define a standard reference frame for the geodetic application of VLBI to the measurment of Earth orientation parameters is based on an assumption that the Universe at large is non-rotating. Our present day understanding of modern physics persuades us that this is likely to be the case. Kurt Gödel has shown that if the Universe at large is rotating then there exist closed, time-like world lines and it would be possible to travel into one's past; a feat generally considered impossible.

is provided by the ICRF. The geocenter and the solar system barycenter are both in a state of free-fall and are both suitable origins for a local inertial frame and both are used in the reduction of VLBI observations. The **essential role** of the ICRF in both cases is to provide the requisite "standard of non-rotation" required to establish the inertial reference frame.

The present-day repeatability of vector baseline determinations by VLBI techniques, between radio observatories equipped with state-of-the-art VLBI systems, is of the order of a few millimetres on baselines up to several thousand kilometers. A global network of geodetic VLBI observatories carrying out routine VLBI measurments provide an **essential contribution** to the definition of the International Terrestrial Reference Frame (ITRF) defined by a number of geodetic control points, many but not all of which, are co-located with geodetic VLBI antennas, whose positions and velocities within the ITRF are continually monitored.