TRACKING PLATE TECTONICS WITH VERY LONG BASELINE INTERFEROMETRY

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1 Introduction

1.1 Geodesy

Geodesy is the science of accurate positioning on Earth. It only makes sense to measure positions within a carefully defined reference frame. The International Terrestrial Reference Frame is used for this purpose. The Earth rotates (often in a "jerky" fashion), and the rotation axis precesses and wobbles. So, measuring and maintaining the reference frame is not easy - but very important. The economic benefit to the Australian economy of precise positioning systems (defined as systems providing a position accuracy of at least 2 cm) will be between 7.8 and 13.7 billion dollars by the year 2020 (ACIL Allen Consulting, 2013). Think of autonomous trains / trucks / tractors, GPS watches etc. etc. Such position measurements require a reference frame accurate to no worse than a few millimetres.

Tackling major environmental challenges also requires a highly accurate reference frame. Examples include measuring the strain field of the Australian tectonic plate, needed for seismic hazard reduction; and tracking changes in global sea level (rising at a rate of about 3 mm/year). In 2015, the United Nations General Assembly adopted a resolution on the importance of accurate geodetic reference frames to global economy and sustainable development.

There are four main techniques which are used to measure positions on Earth. The best known is Global Navigation Satellite Systems (GNSS, of which GPS is the most widely-used). However, GNSS cannot function on its own as it is not sensitive to changes in the Earth's rotation - the orbits of GPS satellites will change if Earth's gravitational field and/or rotation changes, but we will be none the wiser. Similar problems affect other satellite-based techniques, Satellite Laser Ranging and Doppler Orbitography.

Observations by radio telescopes of distant radio wave-emitting quasars provides a unique way of constraining the Earth's place in space. Known as Very Long Baseline Interferometry (VLBI), this method is unique in not relying on observations of Earth-bound satellites. Instead, VLBI observes radio-loud quasars so distant that they are effectively fixed on the sky. Because of this, VLBI provides the only way of measuring both Earth positions and earth rotation simultaneously. All other geodetic techniques, including GPS, rely on VLBI to provide this information.

An international VLBI program, coordinated as part of NASA's Crustal Dynamics program, has been running since the 1980s. It provided the first clear evidence that the Earth's continents are moving *right now*, consistent with the plate tectonic theory. Until then, our evidence was historical, e.g. similarity in continent shapes, and in flora and fauna. The Hobart 26-metre telescope at Mt Pleasant, Cambridge, has been participating in global VLBI observations since 1990.

1.2 Very Long Baseline Interferometry

1.2.1 Basic principles

The idea of Very Long Baseline Interferometry (VLBI) is to use observations of the same astronomical object (usually a quasar) at two or more telescopes. The quasar will appear to "twinkle" over time, because of several possible reasons: it can get brighter and fainter due to variations in its energy output; and movement of clouds both in the Earth's atmosphere and intergalactic space move can intercept some of the radio light coming from the quasar. Observing over a sufficiently long time (typically about 5 minutes), these variations will be *correlated* at the two telescopes looking at the same quasar. We can then find the time delay τ between quasar signals arriving at the first and second telescope, and use the speed of light (which is known to high precision) and elevation angle of the telescope to find the distance $\mathbf{b}$ between the telescopes, using trigonometry:

$$\tau = t_2 - t_1 = -\frac{\mathbf{b}.\mathbf{s_0}}{c} = -\frac{b\cos\theta}{c} \tag{1}$$

where θ is the angle of the telescope from the ground (if the telescope points straight up $\theta = 90$ degrees and there is not time delay), and b is the straight-line length between telescopes.

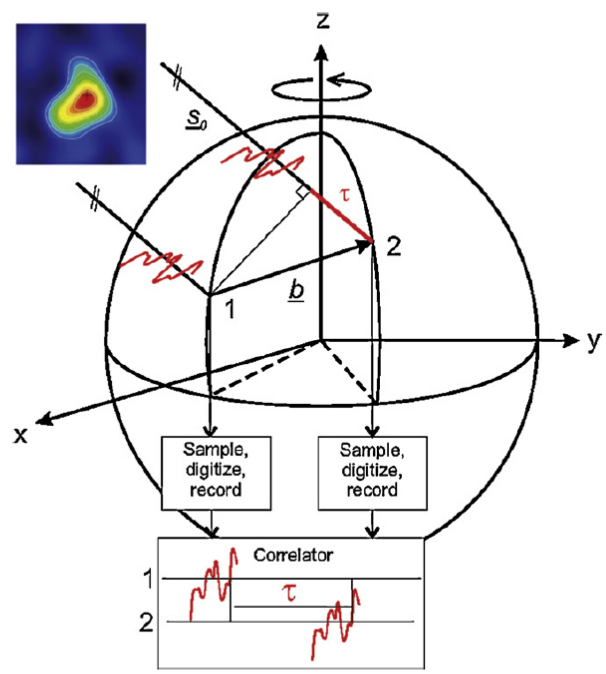

Figure 1: VLBI geometry. Radio signals from a distant quasar arrive at one telescope earlier than at the other. Using the speed of light, the observed time delay τ can be converted to a baseline length b between the telescopes. From Schuh & Behrend (2012).

The recorded time delays are very small (fractions of a second), and very accurate clocks are needed to provide accurate time stamps, and therefore correlation of the signals. These clocks are Hydrogen masers, which are stable to approximately one second in 30 million years (Allen standard deviation of $\sim 10^{-15}$).

1.2.2 Analysis

To extract signals of interest (i.e. positions of stations on Earth, and of quasars in the sky), the cross-correlated signals need to be corrected for many effects. These are corrected using either known physics and/or calibration observations. Main factors are as follows.

Effects of geometry, physics and celestial bodies

- Geometric delay, as in Equation 1, must also compensate for the fact that the Earth is rotating while the signals are arriving - and hence the path length of the quasar signal changes.

- Light travels at the speed of - surprise, surprise - light, and hence we need to use relativity to calculate its path.
- Tides from celestial bodies, chiefly the Moon, Sun and Jupiter, can introduce position changes up to 55 cm. These need to be corrected, using known locations of these objects. A secondary effect is that these tides also cause movement of the oceans and atmosphere, which then also pull on the solid Earth and change the positions further.
- The fact that quasars are not perfect point sources (instead, these are black holes with jets) introduces errors at the level of a few millimeters.

Instrumental effects

- Every station runs its own high-precision maser clock, and these clocks are not synchronized very well between stations (it's hard!)
- Electronics (cables, hardware) at each station introduces extra delays in the signal path that need to be accounted for.

Effects of Earth's atmosphere

- Earth's troposphere delays signal arrival, as waves travel slower than in the (almost) vacuum of intergalactic space. This effect can be up to 2 metres.
- Earth's ionosphere also delays these signals, but differently to the troposphere - ionospheric delays are frequency-dependent, which actually makes getting rid of them quite easy: we simply observe at two frequencies (2.3 GHz and 8.4 GHz), and use the lower frequency observations to correct the higher frequency ones we are actually interested in.
- Pressure of the Earth's atmosphere changes substantially between day and night. This pushing down by air on the solid Earth can change station positions by as much as 1-2 cm, and needs to be corrected. Yes, you read that right!

Some of these effects are corrected using known physics. Examples include geometry, relativistic corrections, and even the effects of tides and quasar jets.

Instrumental effects are usually "calibrated out", by using a test observation that measures the parameter of interest. For example, having cables run from the top of the telescope (where the quasar signal arrives) to the control room introduces an extra time delay, which we calibrate by injecting a "fake" signal and measuring how long it takes to travel to the top of the telescope and back.

Some of these effects are very hard to measure, and instead we resort to compiling lots of observations and treating these sources of error as "noise" that can be "averaged out", using something like least-squares fitting. These parameters include tropospheric delay and clocks, and to some extent the ionosphere (which is corrected using observations at two widely spaced radio frequencies).

The end result is a time series of station positions, and how these change over time - giving station velocities, as shown in Figure 2.

2 Additional resources

NASA links:

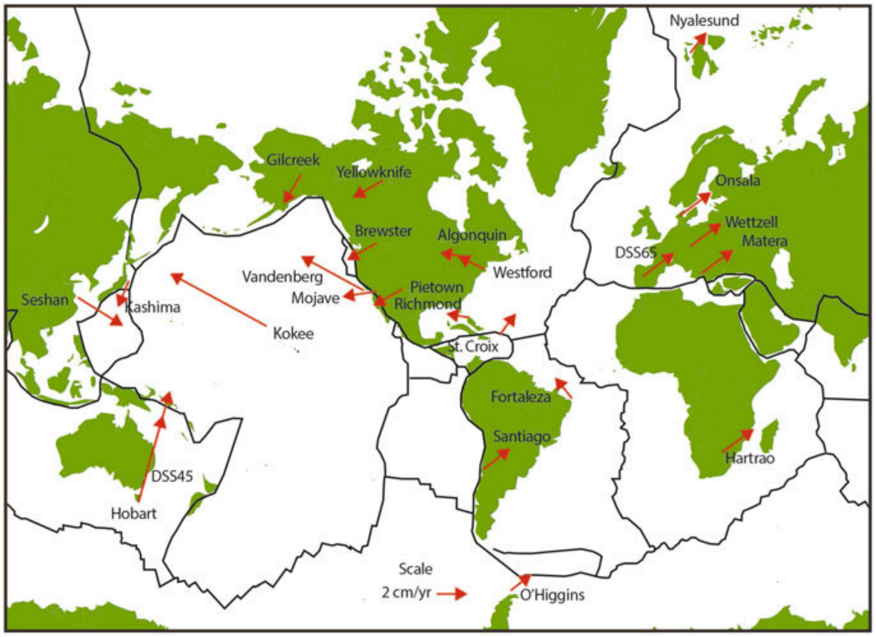

Figure 2: Telescope motion as captured by VLBI. Arrows show velocity vectors; large arrows mean faster motion. From Whitney et al. (2014).

- Space geodesy : https://space-geodesy.nasa.gov/science_and_applications/science_and_applications.html
- Geodetic VLBI website : https://space-geodesy.nasa.gov/techniques/VLBI.html
- Past and present Crustal Dynamics Programs: https://cddis.nasa.gov/Programs/Historical_Programs.html#DOSE
- Cool videos : https://space-geodesy.nasa.gov/multimedia/videos/videos.html . Specifically VLBI: https://space-geodesy.nasa.gov/multimedia/videos/vlbi_quasars/VLBIQuasarsVideo.html

Baseline length time series : http://www.ccivs.bkg.bund.de/EN/Quarterly/VLBI-Baseline/vlbi-baseline_node.html

3 The data

3.1 Raw data

Figure 3 shows an example of the raw time series of data. In this uninspiring figure, the x-axis shows time channels (small fractions of a second). The primary data streams are shown in blue and green, and these look just like noise. That's because in astronomy our signal is always much, much weaker than the background. What saves us is the fact that signal is *correlated* (i.e. it adds up as we observe for longer), while noise is random (i.e. it cancels out). The purple curve shows how the signal strength increases with time (left to right), while the noise (red curve) stays the same. Once sufficient signal-to-noise is achieved in each observations, we are ready to cross-correlate data from two telescopes and calculate our time delays.

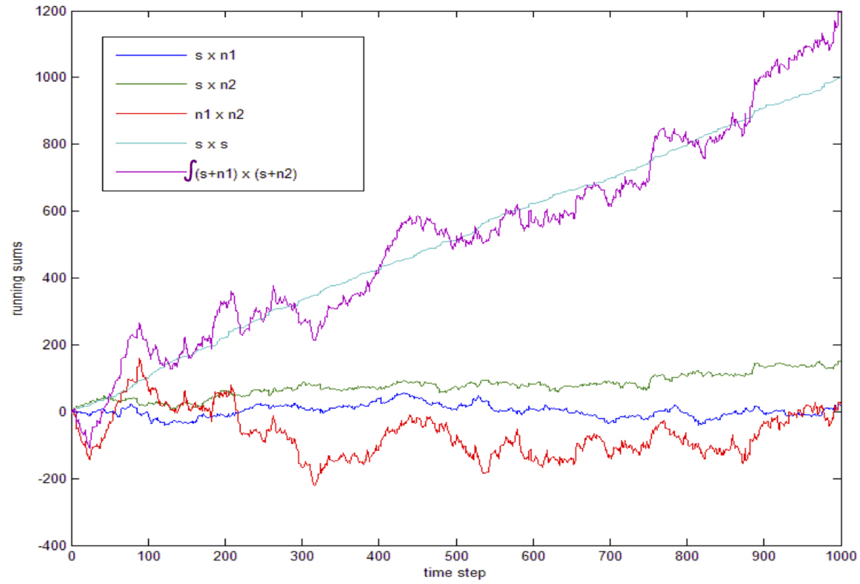

Figure 3: Time series of weak, noisy signals at a radio telescope. As more data is collected, signal adds up (purple) while the noise (red) stays constant. From Roger Capallo.

3.2 Changing baseline lengths

Processed baseline time series are tabulated and used to construct a Terrestrial Reference Frame. In this process, known as "Least Squares Adjustment", initial guesses for station positions are moved around until the greatest consistency of all the measurements (i.e. distances between all possible pairs of telescopes) is achieved. Distance between each pair of telescopes (known as a "baseline length") is usually measured to an accuracy of about 1 cm.

The spreadsheet "Baselines_Mar19'.xlsx" provides a compilation of baseline lengths over ≥ 25 years for several strategically chosen (for reasons that will become clear in Section 4) baselines. To make things interesting for students, most of the baselines have been chosen to include the Hobart 26 metre telescope at the Mt. Pleasant Radio Observatory at Cambridge.

The selected stations (see Figure 4) are:

- Indo-Australian plate: Hobart26 (Tasmania), Yarragadee (Western Australia)
- North American: Westford (Massachusetts, Eastern USA)
- Pacific: Kokee Park (Hawaii)
- South American: Fortaleza (Eastern Brazil), Concepcion (Chile)
- African: Hartebeesthoek (South Africa)
- Antarctic: Syowa (operated by Japan)
- European: Wettzell (Germany), Badary (Siberian Russia), Seshan (China)

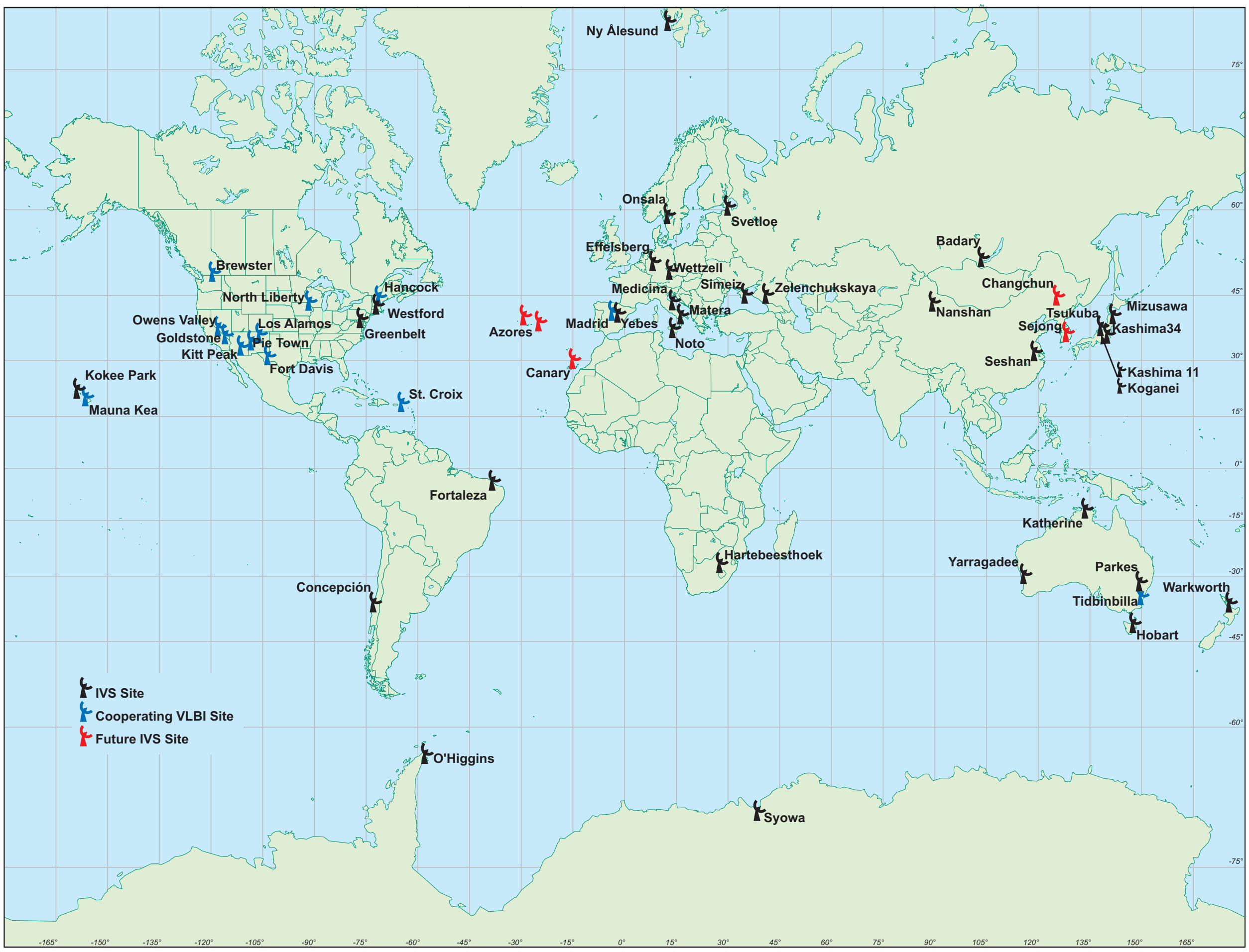

Figure 4: Distribution of international VLBI stations.

4 Suggested investigations

The suggested tasks below have been designed in order of increasing complexity. I hope they facilitate data-led discovery of what the Earth's tectonic plates are doing, and encourage the students to investigate further the questions raised by the data.

The tasks require basic familiarity with Excel spreadsheets, specifically the ability to make a scatter plot of baseline length against time (Column B vs Column C in each tab of the provided Excel spreadheet). This can be done by highlighting both columns, then selecting "Insert", then "Scatter".

In some cases, a line of best-fit needs to be made. This can be done by right-clicking on one of the data points in the plot, and selecting "Add trendline", then "Add equation to chart". The slope of the equation (A in $y = Ax + B$) is the rate (in metres per year) at which the separation between two stations changes.

Note: the uncertainties on individual baseline measurements (Column D of Excel spreadsheet) are ignored in the following analysis, for simplicity. In reality, all baseline length measurements are weighted by the inverse of this value, i.e. measurements with smaller uncertainty carry more weight. Given the sheer amount of excellent data available, ignoring the uncertainties does not change any of the results below - but (time permitting) discussing measurement uncertainty in class could (should!) be useful.

1. Tectonic plates are moving, right now!
   - Plot baseline length vs time for Hobart - Kokee Park.
   - Question: Why is the length changing over time? What can you conclude about the relative motion of the Australian and Pacific tectonic plates?
2. Intra-plate stability.
   - Plot baseline length vs time for Hobart - Yarragadee.
   - Question: Why is the length *not* changing over time?
3. Earthquakes.
   - Plot baseline length vs time for Hobart - Concepcion.
   - Question: What happens in February 2010?
   - Question: What can you say about the rate at which the distance between telescopes is changing? What do you think it means?
4. Mid-Atlantic ridge.
   - Plot baseline length vs time for two baselines: Fortaleza - Hartebeesthoek and Westford - Wettzell.
   - Question: Do you notice any similarities between their behaviour? Looking at the map, why do you think that may be?

For students who work through the above tasks quickly, there are two further "challenge" questions.

1. Where is Tasmania going?

- Question: Using a set of baselines, determine whether Tasmania is moving North or South.

2. The size of the Earth.

    - Question: Using the baseline length of Yarragadee - Seshan and your knowledge of trigonometry, can you calculate the radius of the Earth? Hint: these stations are at approximately the same longitude (see “StationCoordinates” tab in the Excel spreadsheet).