Global Navigation Satellite System (GNSS) at Tide Gauge Installations in the South Atlantic Ocean

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Overview

• Global Navigations Satellite Systems (GNSS)
• Tide Gauges
  – Relative and geocentric sea level
• South Atlantic Ocean work
• Tristan da Cunha

Tide board installation at King Edward Point Research Station, South Georgia Island in 2014.
Global Navigation Satellite Systems (GNSS)

- **GPS (Global Positioning System)**
  - US, operated since 1980
  - Most widely used GNSS, ubiquitous to modern society

- **GLONASS (Globalnaja Nawigazionnaja Sputnikowaja Sistema)**
  - Russian, operated since 1982
  - Full constellation in 1996, dropped to just 7 satellites in 2002, full constellation since October 2011

- **Galileo**
  - European, with two validation satellites in orbit since 2005 and 2008
  - Currently 18 satellites (ok: 14)

- **BeiDou (BDS)**
  - Chinese, with a first validation satellite on orbit since 2007
  - Currently 15 satellites

- **Others (QZSS, IRNSS, …)**
Global Positioning System (GPS)

- Supports an unlimited number of receivers capable of tracking the signals of all satellites simultaneously in view (usually between 4 and 12)
- Revolutionized positioning and high-precision applications in geodesy and geophysics
- Largest benefit through the establishment of networks of continuously recording stations

This enabled Applications such as:

- GNSS geocentric satellite positions for the entire day (accurate to few cm)
- GNSS satellite clock corrections (accurate to a few ten picoseconds)
- Mean receiver coordinates per day (accurate to a few mm)
- Position of the Earth’s rotation axis on the Earth’s surface
- Length of day (daily estimates, accurate to a few microseconds)
- Tropospheric zenith delays for all stations (which in turn allow GPS to estimate the total water vapour content over the station - provided station pressure and temperature are available) with high time resolution
- time and (in particular) frequency transfer between time laboratories (sub-nanosecond accuracy)
GNSS Segments

- Provide position information
- Global coverage
- 3 Segments
  - Space segment: Satellites
  - Control segment: Control & Monitoring stations
  - User segment: Receivers (multiple uses)
Error sources for GNSS observations

- Orbit errors: error in position of the satellite in the orbit
- Clock errors: lack of synchronization between transmitter and receiver clocks
- Signal delay in Earth’s atmosphere: due to difference in refractivity
- Receiver environment: multipath, receiver noise
IGS Tracking Network
Regional and National GNSS Networks

EUREF Tracking Network

Teferle et al (2009)

ACT (2011)
### Details of repro2 at BLT

<table>
<thead>
<tr>
<th>Software</th>
<th>Bernese GNSS Software Version 5.2 (BSW5.2)</th>
</tr>
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<tr>
<td>Satellite Systems</td>
<td>GPS</td>
</tr>
<tr>
<td>Elevation cutoff angle</td>
<td>deg and elevation dependent weighting</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>Ionospheric-free linear combination (L3) including 2\textsuperscript{nd} orders corrections</td>
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<tr>
<td>Antenna PCV</td>
<td>IGS absolute elevation and azimuth dependent PCV igs08.atx file</td>
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</table>
| Troposphere       | 1. GMF and DRY GMF mapping for the a priori values and while estimating hourly ZWD parameters using WET GMF  
                       2. VMF mapping for the a priori values and ZWD estimate using WET VMF |
| Troposphere Gradients | Chen Herring for tropospheric gradient estimation |
| Conventions       | IERS2010                                  |
| Ocean tides       | FES2004                                   |
| Gravity Field     | EGM2008                                   |
| Ambiguity Resolution | Resolved to integers up to 6000 km using different techniques depending on the baseline length |
| Datum             | No-Net-Rotation (NNR) and No-Net-Translation (NNT) with respect to IGb08 |
| Network           | Upwards 450 stations                      |
| Time period       | 1994 to 2015                              |
| Data              | Double-differenced phase and code observations |
Aberdeen

Station: aber
Rate = 15.8 ± 0.1 mm/yr
WRMS = 1.6 mm

Station: egu09
Rate = 14.7 ± 0.1 mm/yr
WRMS = 1.4 mm

Station: AG
Rate = 1.9 ± 0.2 mm/yr
WRMS = 4.3 mm

Location: Aberdeen

Images showing the location of the stations and the graphs representing the deformation rate and the WRMS values for each station.
The ITRF2008 Network

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The ITRF2008 network comprises 934 stations located at 580 sites, with 463 sites in the northern hemisphere and 117 in the southern hemisphere. The ITRF2008 combination involves 84 co-location sites where two or more technique instruments were or are currently operating and for which local ties are available. Figure 1 illustrates the full ITRF2008 network where we superimposed the VLBI, SLR and DORIS sites co-located with GPS. In fact all the 84 co-location sites comprise permanent GPS stations, except two sites: Dionysos (Greece) where DORIS and an old mobile SLR were co-located, and Richmond (Virginia, USA) where VLBI, SLR and DORIS systems were co-located.

2.2 Local ties in co-location sites

The local ties used in the ITRF2008 combination are provided in SINEX format with known measurement epochs, and 63% of them are available with full variance covariance information. Most of the local ties used in the ITRF2005 combination are used here with some updates, e.g., Tahiti (GPS, SLR, DORIS), Tsukuba (GPS, VLBI), Herstmonceux (GPS, SLR), Medicina and Noto (GPS, VLBI), Greenbelt (GPS, VLBI, SLR, DORIS), Maui/Haleakala (GPS, SLR), San Fernando (GPS, SLR), Onsala (GPS, VLBI).

ITRF2008:
934 Stations
580 Sites
463 N. Hem.
117 S. Hem.
84 co-location Sites

Accuracy:
Origin: 1 cm
Scale: 1.2ppb

Altamimi et al. (2011)
Classical Float Tide Gauge

Introduced in the 1830s and used in many ports around the world by the late 19th century.
Float Gauge at Holyhead, UK

Float gauges are still important components of GLOSS and can be made into digital gauges with the use of encoders.
Radar tide gauge provided by NOC and UNESCO to Alexandria
BGAN-enabled Tide Gauges
Welcome to the Permanent Service for Mean Sea Level (PSMSL)

Please read news items on changes to combined MTL and MSL records and flags.

PSMSL is the global data bank for long term sea level change information from tide gauges and bottom pressure recorders.

About Us:
Learn about PSMSL, contact us, read news items and annual reports.

Data:
Obtain and submit tide gauge and bottom pressure data.

Products:
Browse the data set via GoogleEarth or obtain derived products, view regional commentaries and author archives.

Training & Information:
A wide variety of FAQs, training and software documentation, information on non-oceanographic signals in tide gauge records (e.g., glacial isostatic adjustment, atmospheric pressure, etc.)

Links:
Links to other networks and programs, as well as international sea level contacts.

www.psmsl.org
1987: 27000 station-years of data
2014: 61000 station-years of data

www.psmsl.org
Datum Control of the Tide Gauge

• The first essential step for any installation is to ensure that the tide gauge is providing good *Relative Sea Level* data.

• It is not enough to have a gauge provide ‘sea level’ without knowing what that level is relative to.

• The sea level should always be expressed relative to the tide gauge *Contact Point*, the level of which is subsequently determined relative to the *Tide Gauge Bench Mark (TGBM)*.

• The TGBM is considered to be the most stable BM near to the gauge, but GLOSS standards require about 5 other ancillary marks to as to check the TGBM’s stability.
Whatever the type of gauge – they have to be calibrated and levelled to local benchmarks

Benchmarks

A set of at least 5 benchmarks near to the gauge is required by GLOSS standards, of which one will be the main Tide Gauge Benchmark (TGBM). The 5 are needed to check the stability of the TGBM.

These should be levelled regularly (e.g. annually) and their levels should be documented by means of ‘RLR diagrams’, with the information passed to PSMSL etc.

In many ways the benchmarks are more important than the tide gauges themselves!
Relative Sea Level

- We now have a tide gauge to measure the level of the sea relative to the TGBM on land.
- This is called Relative Sea Level and (when averaged over months and years) is the same as the Mean Sea Level archived by the PSMSL.
Land Level as well as Sea Level Changes

• A problem is that Relative Sea Level can contain information on land level change as well as true sea level change
• The land could be submerging (e.g. Bangkok) or emerging (e.g. Sweden) relative to the centre of the Earth at a rate faster than sea level itself is changing
• So we also need to monitor the land level changes using modern geodetic techniques – this will give us Geocentric Sea Level
Mean Sea Level (MSL) Records from PSMSL

- **Stockholm - Glacial Isostatic Adjustment** (GIA; sometimes called Post Glacial Rebound or PGR): Site near Stockholm shows large negative trend due to crustal uplift.
- **Nezugaseki - Earthquakes**: This sea level record from Japan, demonstrates an abrupt jump following the 1964 earthquake.
- **Fort Phrachula/Bangkok - Ground water extraction**: Due to increased groundwater extraction since about 1960, the crust has subsided causing a sea level rise.
- **Manila - Sedimentation**: Deposits from river discharge and reclamation work load the crust and cause a sea level rise.
- **Honolulu - A 'typical' signal** that is in the 'far field' of GIA and without strong tectonic signals evident on timescales comparable to the length of the tide gauge record.

(PSMSL, 2015)
Geocentric Sea Level

• For science we would like to adjust the sea level measured by the gauge for the effects of land movements.

• One way to do this is to monitor the vertical movement of the TGBM (or a BM near to it) using GNSS (GPS).

• In practice the GPS may be installed exactly at the tide gauge or some distance from it. In the latter case, the GPS BM must be included in the regular levelling to the TGBM and included in the BM diagram.
GPS at a Tide Gauge

• GPS at a tide gauge consists of a receiver (computer) connected by a cable to the GPS antenna, which is a measured height above the GPS BM.

• The receiver can be connected by phone or internet

• GLOSS requires Continuous (Permanent) GPS installations (CGPS)

• GPS data from tide gauges are collected and analysed by SONEL www.sonel.org.
GPS at a Tide Gauge

GPS Station elsewhere for monitoring land movements

GPS satellite

GPS Station close to Tide Gauge

Precise Level

Tide Gauge

TGBM

MSL
Trimble Net R9 GNSS receiver

Suitable receivers are available from several manufacturers

This is connected by modem to a telephone, or to a satellite system such as BGAN so the GPS data gets to a data centre.
GPS

Quelles stations GPS ?

Les stations GPS pour lesquelles vous trouverez des données dans SONEL sont signalées sur une carte dynamique (cliquable). Il s’agit surtout de stations GPS permanentes co-localisées avec des marégraphes, mais aussi des stations GPS importantes pour la réalisation d’un repère terrestre géocentrique stable et précis.

Number of stations displayed: 495

List of stations
A TECHNICAL FORUM ON CONTINUOUS GPS POSITIONING OF TIDE GAUGES

INTRODUCTION
BACKGROUND
CASE STUDIES
MEETING ARCHIVES

brought to you by the
CGPS@TG Working Group
Tide gauge and GPS in Tasmania
Tide gauge and GPS in USA
Tide gauge and GPS in Norway
Tide gauge and GPS in Indonesia
GPS at UK tide gauges

Lerwick, Aberdeen, North Shields, Lowestoft, Sheerness, Dover, Portsmouth, Newlyn, Liverpool, Stornoway

Antenna
Monitoring Vertical Land Motions at Tide Gauges

- Tide gauges (TG) measure local sea level.
- Vertical land motions (VLM) are determined from CGPS and AG at or close to the tide gauge.
- The change in sea level decoupled from VLM can be inferred.
9 Sea Level Stations

Real time telemetry:
- Ascension Island
- Saint Helena
- Port Stanley
- Tristan
- Vernadsky (Faraday)
- Rothera
- Gibraltar

Delayed mode data:
- Signy

St. Helena and Tristan recently re-built after storm damage

2016/2017 (with ULUX)
2016/2017 (with ULUX)
2013/2014 (with ULUX)
terminated
(with Ukraine)
Regional Continuous GNSS Stations
The continuous GNSS Station KEPA

GNSS antenna and mast...good sky view on top of Brown Mt.

Solar power system, enclosures with batteries and electronics, structural frame, radio antenna, weather station.
Levelling: Monitoring Height Changes Locally

Figure 6: Network of TGBM at KEP research station. Existing TGBM (UKHO-HD-9798 and UKHO-ISTS-061) are in yellow and new TGBM (KEPGO-KEP-001 to KEPGO-KEP-004) in red. Dashed line shows the path of levelling work carried out during February 2013: from the tide gauge on the jetty (1) past the boatshed (2), over the grass area south to the food (3) and coal (4) stores, between Discovery House (5) and Carse House (6) and to the satellite tower (7).
Survey at Brown Mountain
We love Brown Mountain !?=`+”*
Survey at KEP
Tristan da Cunha

- GNSS station installation
- Pressure and radar tide gauge installation
- Establish a TGBM network
- Measure all geodetic ties to 1mm accuracy between all BMs (GNSS, DORIS and TGs)
The ITRF2008 Network

**Table 1**

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The GPS submitted solution represents a large part of the first reprocessed solution by the IGS and covers the time period 1997.0–2009.5 (Ferland 2010; Ferland and Piraszewski 2008). Note that a very small portion of GLONASS observations were used by some IGS ACs that contributed to the reprocessing effort. For the first time the DORIS contribution is a combined time series involving seven ACs and covers its full observation history, using data from all available satellites except Jason-2 (Valette et al. 2010).

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![ITRF2008 Network](image)

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- 580 Sites
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- 84 co-location Sites

Accuracy:
- Origin: 1 cm
- Scale: 1.2ppb
Co-location of Instruments

- None of space geodetic techniques is able to provide all the parameters necessary to completely define a TRF
  - VLBI strength (orientation), SLR strength (geocentre), GPS strength (crustal movements)

- To define an accurate ITRF (Source GGOS 2020):
  - < 1 mm reference frame accuracy
  - < 0.1 mm/yr stability

- Measurement of sea level is the primary driver improvement over current ITRF performance by a factor of 10-20.

- The co-location of different and complementary instruments is crucial for several reasons:

- Without co-location sites and highly accurate local tie information, it is impossible to establish a unique and common global reference frame (TRF) for all major space geodetic techniques to answer key geophysics science questions.
Co-location of Geodetic Techniques

Hartebeesthoek Radio Astronomy Observatory (HartRAO)

Abstract

HartRAO is the only fiducial geodetic site in Africa, and it participates in VLBI, GNSS, SLR, and DORIS global networks, among others. This report provides an overview of steps taken during 2009 towards the repair of the 26-m radio telescope and the conversion of the 15-m Karoo Array Telescope (KAT) prototype to a radio telescope capable of performing geodetic VLBI tasks.

1. Geodetic VLBI at HartRAO

Hartebeesthoek is located 18 km northwest of Johannesburg just inside the provincial boundary of Gauteng, South Africa. The nearest town, Krugersdorp, is 6 km distant. The telescope is situated in an isolated valley which orders protection from terrestrial radio frequency interference. HartRAO uses a 70 meter equatorially mounted Cassegrain radio telescope built by Blaw Knox in 1970. The telescope was part of the NASA deep space tracking network until 1994 when the facility was converted to an astronomical observatory. The telescope is collocated with an ILRS SLR station (MOBLAS), an IGS GNSS station (HRAO), and an IDS DORIS station (HBMB) at the adjoining Satellite Application Centre (SAC) site.

Figure 1: HartRAO fiducial site for geodetic techniques of VLBI, GNSS, and SLR (Credit: M. Gaylard)
Summary of Geodetic Measurements at/near a Tide Gauge
Thank you for your attention!
Acknowledgements

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  – University of Nottingham, Nottingham, UK
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