DATUM CONTROL AND LEVELING

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Lecture Overview

• Introduction
• Tidal Datums
• Benchmarks
• Leveling: Some basic principles
• Geodetic Fixing Of Tide Gauge Benchmarks
Introduction (1/7)

*What do provide the measurements made by a tide gauge?*

Relative Movement of the sea level with respect to the land.
Are Sea and Land Levels constant over long periods of time?

Neither the Sea Level nor the Land Surface are constant or fixed over long periods of time.

Why?

There are vertical movements of the land associated with:

- Co Seismic Activity
- Glacial Isostatic adjustment
- Plate Tectonics

Natural Processes

- Ground water pumping
- Natural gas extraction

Human Activities
Introduction (3/7)

“Important issues to do with long term sea level trends”
(e.g. Woodworth 2006, in *Phil. Trans. R. Soc.*)

- Vertical land motion at tide gauges
  - Stockholm: Post-glacial rebound
  - Nezugaseki: 1964 earthquake
  - Bangkok: Ground water pumping
  - Manila: Sedimentation

- Challenges
  - Rates in sea-level change: ~1-2 mm/yr
  - **Standard errors several times smaller to be useful in these studies!**

- Motivation for GPS reprocessing
  - To use the best available data and most accurate models *to reduce errors in the estimates of coordinates*
  - To use them all over the data span (models, parameterization…) in order *to derive consistent sets of station coordinates, and to limit spurious signals in their time series*
High precision Global Positioning System (GPS) geodesy is now a powerful new tool for the Earth sciences. It has revolutionized global and regional geodesy and research into crustal motion and deformation.
Introduction (6/7)

GPS velocities at TG... How well do they work?

Introduction (7/7)

To understand sea level changes properly, the different sea level and land vertical movements have to be decoupled.

How it could be done?

By
- Careful definition of the tide gauge datums
- Local leveling procedures
- Making independent measurements of changes in the land levels, using modern geodetic techniques
Tidal Datums
Tidal Datums

Brief definition:

Vertical reference for reckoning heights (or depths) that corresponds to a particular phase of the tide.
Tidal Datums

Every station has its own local tide gauge datum, defined by the zero of its tide staff.
Current Atlantic, Caribbean, and Gulf of Mexico DARTs
Tidal Datums
Applications to nautical charting hydrography

Heights are referred to MHW

Soundings are referred to MLLW
Tidal Datums

Tidal datum begins with a tide staff or a sensor leveling point

And ends with a tidal bench mark

NOTE: Other Tidal Datums (MHW, MLW, MSL) and values (Highest & Lowest Observed) not shown for clarity.
Tidal Datums: Multiple Pressure Transducer Systems

- It uses absolute pressure sensors
- It is the difference C-A which gives sea level
- The flat part of the B-A curve is immune to any problems with datum offsets or instrument drift
- The B-A curve is overlaid onto the C-A curve
  - the intersection of the flat line with the full curve defines the datum of the full curve

Extremely accurate system with automatic datum control.
Tidal Datums: Single Pressure Transducer Systems

- Two problems:
  - Determine the effective level to which one attempts to measure sea level
  - To monitor if it changes over a long period

- By using tide staff measurements at regular intervals, it should be possible to fix that datum of what could be a good quality sea level time series to approximately centimetre accuracy.

Difficulty of establishing a datum and of monitoring changes in the effective datum.

PVC Hydraulic 50 mm

PVC Conduit 32 mm

Stainless Steel Clamps
Tidal Datums (Summary)

- Sea level data are collected using a variety of technologies.
- Regardless of the collection technique, sea level data must be related to a stable datum.
- Redundant instrumentation allow to maintain very precise vertical levels.
- Appropriate processing procedures can supply sea level data that are accurately related to a datum at the millimeter level.
- To relate water levels to the solid earth, we need a *tidal datum*.
- For sea level observations, a land benchmark is used as the primary reference point.
Benchmarks
Benchmarks

- A Benchmark (BM) is a clearly marked point located on a stable surface, such as exposed rock, a quay wall or a substantial building.

- When a BM is on a horizontal surface, it normally takes the form of a round-headed brass bolt.

- Common practice is to use as a BM a disk made of brass, bronze, or aluminum alloy, diameter (3”), stamped with an appropriate inscription and individual identifying information.

- Unambiguously documented in the tide gauge metadata.

Two principal qualities desired in benchmarks:

- Permanency
- Certainty in identification
The tide gauge benchmark for the SEAFRAME at Port Vila known as "Van 14", installed by the Royal Australian Navy. The benchmark is the small knob on which the hammer is resting. A raised mark at the top of the knob is the precise level. A chunk of concrete below the benchmark fell off during a recent earthquake.

The primary bench mark is a disk set flush in a 5.5 m (18 ft) x 4.9 m (16 ft) concrete patio, 38 m (126 ft) NW of the NW corner of the white 2-story house (Keene residence), 3.81 m (12.5 ft) west of the east face of the patio, and 1 m (3 ft) north of the south edge of the concrete patio.
Benchmarks

• It is recommended a minimum of five within a few hundred metres, or at most one kilometers, of the tide gauge.

• These should be connected individually by high-precision leveling.

• It is desirable, although not essential, that all BM be tied into a country’s national leveling network.
Tide Gauge Benchmark (TGBM)

• The main benchmark for the gauge.
• It serves as the datum to which the values of sea level are referred.
• If necessary, redefinition of the TGBM is possible

How is the TGBM chosen?

Some criteriums:

- Stability
- Security
- Distance
GPS Benchmark (GPSBM)

- Is another special mark chosen from the local network of BM.
- It serves as the reference mark for GPS measurements.
- It should be connected to the TGBM by leveling.

**TGBM and GPSBM can be defined using the same mark?**
Gauge Contact Point (CP)

• The CP is a type of ´Benchmark´, which must be connected to the TGBM.

• Is a vertical reference mark, associated with the gauge itself.
  - Conventional float and stilling well gauges
  - Acoustic gauges
  - Radar gauges
  - ´B´ gauges
Leveling
Leveling

• For vertical control purposes we need High-precision leveling.

• All the marks must be connected by leveling at regular intervals (at least annually).

• On unstable ground, more frequent leveling may be necessary.

Next slides were taken from the presentation made by Tilo Schöne at the ODINAFRICA/GLOSS Sea Level Training Course – Oostende, Belgium; 13-24 Nov 2006.

Some new slides were included

The original presentation can be downloaded from the website: http://www.pol.ac.uk/psmsl/powerpoint/
How to:
Some Basic Principles for Leveling

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Lecture Overview

• Equipment
• Introduction to Leveling
• Observation, Field Notes, and Computation
• Errors and their effects
Equipment
Equipment

• Level Instrument
• Tripod
• Staff/Pole
• Change plate (German: Frog/Frosch)
• Pole staff bubble (bull eye)
• Marker
Equipment: Level Instrument

• Automated Levels
  – Easy to use (not power!)
  – Needs experience
  – Robust even in hostile environment

• Digital Levels
  – Push-button technique
  – No reading errors, special staff
  – Readings are stored and analyzed digitally
Automated Levels (Compensator)

Bull Eye

Pendulum

Tribrach

Courtesy: Deumlich, Vermessungskunde
Digital Levels

• Uses Barcode staffs
• Internal storage of data
  – Download to the computer
  – Automated height computation + adjustment
  – No feeling for quality anymore
  – You frequently need power plugs
Equipment

- Level Instrument
- Tripod
- Staff/Pole
- Change plate (German: Frog/Frosch)
- Pole staff bubble (bull eye)
- Marker
Equipment: Tripod

• Wooden design or aluminum
  – From “easy to sit” to “ops, this is high”
Equipment

- Level Instrument
- Tripod
- Staff/Pole
- Change plate (German: Frog/Frosch)
- Pole staff bubble (bull eye)
- Marker
Equipment: Staff/Pole

- Wood, aluminum, fiberglass
- Graduated in feet or meters
- INVAR type for high precision leveling
Equipment

- Level Instrument
- Tripod
- Staff/Pole
- Change plate (German: Frog/Frosch)
- Pole staff bubble (bull eye)
- Marker
Equipment: Change Plate

- For long survey lines
- Allows change of instruments
  - Best is a metal change plate
  - Screws e.g. at fences
  - Sharp stones or nails
- Beware of dark colors
Equipment

• Level Instrument
• Tripod
• Staff/Pole
• Change plate (German: Frog/Frosch)
• Pole staff bubble (bull eye)
• Marker
Equipment: Bubble

- Keep the pole upright
  - Any tilt will disturb your readings
Equipment

- Level Instrument
- Tripod
- Staff/Pole
- Change plate (German: Frog/Frosch)
- Pole staff bubble (bull eye)
- Marker
Survey Markers

• Gives you a fixed point
  – Should be of good quality
  – Should be long-term
  – Preferable in bedrock, settled buildings, or bridges
  – Do not use fences or walls
Introduction to Leveling
Some Basic Definitions

• **Level surface (e.g. the geoid)**
  – A water surface with no motion
  – Gravity gradient is the normal to the level surface
  – The Instrument’s Bubble is in the normal (!)

• **Horizontal surface**
  – At the instruments axis, the *horizontal* surface is tangent to the *level* surface
  – Over short distances (<100 m) the horizontal surface and the level surface will coincide
  – For long leveling lines the effects of the gravity field must be considered
Basic Principle of Leveling

• Measures height differences between points
  – Along a line
  – Several points from one occupation

\[
\Delta h = bs - fs
\]
Definitions

• **Back sight (BS)**
  – The *first* reading from a new instrument standpoint (i.e. take the height to the instrument)

• **Fore sight (FS)**
  – The *last* reading from the current instrument station (i.e. give the height to a benchmark)

• **Intermediate sight (IS)**
  – Any sighting that is not a back sight or fore sight
Reading a Staff

- Read the [m], [dm] & [cm]
- Estimate the [mm]

- Check yourself for frequent used numbers (2/3) or (7/8)
Basic Rules for Leveling

- Always start and finish a leveling run on a Benchmark (BM or TGBM) and close the loops
- Keep fore sight and back sight distances as equal as possible
- Keep lines of sight short (normally < 50m)
- Never read below 0.5m on a staff (refraction)
- Use stable, well defined change points
- Beware of shadowing effects and crossing waters
Observation, Field Notes, and Computation
How to: A sample loop

New Benchmark NB1

New Benchmark NB2

Tidal Hut TH
How To: Field Notes

<table>
<thead>
<tr>
<th>Back</th>
<th>Inter</th>
<th>Fore</th>
<th>Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1327</td>
<td></td>
<td></td>
<td>TH</td>
</tr>
<tr>
<td>2365</td>
<td>3982</td>
<td>NB1</td>
<td></td>
</tr>
<tr>
<td>2347</td>
<td>0986</td>
<td>NB2</td>
<td></td>
</tr>
<tr>
<td>3753</td>
<td>3724</td>
<td>NB1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1101</td>
<td></td>
<td>TH</td>
</tr>
</tbody>
</table>
- **Misclosure Error**

Misclosure = $\Delta H_{SOLL} - \Delta H_{IST}$
An acceptable misclose?

- Small misclosures in closed level loops are expected because of the accumulation of random errors and can be adjusted.
- If the misclosure is large, the loop (or part of it) must be repeated.
- Misclosures can also result from errors in published BM levels and from BM instability.
Testing the misclose

• The amount of misclosure acceptable using a specific instrument and survey line length

• For our example, a *first order, class I* leveling standard is adopted (according to National Ocean Survey, U.S. Coast and Geodetic Surveys) *…

\[
\text{misclosure} \leq 4 \sqrt{s} \text{ mm}
\]

• where \( s \) is the length of the line in km

*Dependent on your country’s rules and the instrument used*
Our example

- The misclosure is +1 mm
- The length of the loop is 0.4 km
- Acceptable error is
  \[ 4 \sqrt{0.4} = \pm 2.5 \text{ mm} \]
- The misclosure of +1 mm is within the limit
- Mean error for NB1 = \( \frac{2.5}{2} \sqrt{0.4} \)
How to: **Simple adjustment of level circuits or lines**

• Making a complete circuit probably it will close with a difference in elevation. The difference is the error of running the circuit or line of levels, called the *error of closure*. The problem arises of determining errors for intermediate points and adjusting their elevations accordingly.

• The appropriate correction to the observed bench mark is directly proportional to the distance of the bench mark from the point of beginning or to the number of instrument setups since the point of beginning.

If $E_c$ is the error of closure of a level circuit of length $L$

and $a, b, \ldots, n$ are the respective distances from the point of beginning

then $C_a, C_b, \ldots, C_n$ are the respective corrections to be applied

\[
C_A = -\frac{a}{L} E_c; \quad C_b = -\frac{b}{L} E_c; \quad \ldots; \quad C_n = -\frac{n}{L} E_c
\]
An example: Loop Closure

The length of the loop is 4.7 km

What is the permissible error?

National Ocean Survey, U.S. Coast and Geodetic Survey
Specifications for vertical control: Maximum closures Loop

<table>
<thead>
<tr>
<th>First Order</th>
<th>Second Order</th>
<th>Third Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>Class II</td>
<td></td>
</tr>
<tr>
<td>4 \sqrt{K}</td>
<td>5 \sqrt{K}</td>
<td>6 \sqrt{K}</td>
</tr>
<tr>
<td>8.6 mm</td>
<td>10.8 mm</td>
<td>13.0 mm</td>
</tr>
<tr>
<td>Class I</td>
<td>Class II</td>
<td></td>
</tr>
<tr>
<td>8 \sqrt{K}</td>
<td>12 \sqrt{K}</td>
<td></td>
</tr>
<tr>
<td>17.3 mm</td>
<td>26.0 mm</td>
<td></td>
</tr>
</tbody>
</table>
An example: Level Loop Adjustment

The length of the loop is 4.7 km
Accepted elevation BM 20 = 10.365 m
Final elevation BM 20 = 10.358 m
Closure Error = + 0.007 m

The allowable error for a first-order, class I is 8.6 mm

<table>
<thead>
<tr>
<th>Point</th>
<th>Distance from BM 20 (km)</th>
<th>Obs. elevation (m)</th>
<th>Correction (m)</th>
<th>Adjusted elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM 20</td>
<td>0.0</td>
<td>10.365</td>
<td>0.0</td>
<td>10.365</td>
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<tr>
<td>BM 201</td>
<td>0.8</td>
<td>12.102</td>
<td>+0.001</td>
<td>12.103</td>
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<tr>
<td>BM 202</td>
<td>2.4</td>
<td>16.418</td>
<td>+0.004</td>
<td>16.422</td>
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<tr>
<td>BM 203</td>
<td>3.0</td>
<td>14.320</td>
<td>+0.005</td>
<td>14.325</td>
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<tr>
<td>BM 20</td>
<td>4.7</td>
<td>10.358</td>
<td>+0.007</td>
<td>10.365</td>
</tr>
</tbody>
</table>
How to: Three-Wire Leveling

• The recording of three readings at each sighting enables the surveyor to perform a relative precise survey while utilizing ordinary levels
<table>
<thead>
<tr>
<th>STA</th>
<th>B.S.</th>
<th>DIST</th>
<th>F.S.</th>
<th>DIST</th>
<th>ELEV</th>
<th>DESC.</th>
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<tbody>
<tr>
<td>BM 17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>186.2830</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.825</td>
<td>1.775</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>+</td>
<td>0.725</td>
<td>10.0</td>
<td>1.673</td>
<td>10.2</td>
<td>+0.7253</td>
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<tr>
<td></td>
<td>0.626</td>
<td>9.9</td>
<td>1.572</td>
<td>10.1</td>
<td>187.0083</td>
<td></td>
</tr>
<tr>
<td>/3</td>
<td>2.176</td>
<td>19.9</td>
<td>5.020</td>
<td>20.3</td>
<td>-1.6733</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+0.7253</td>
<td></td>
<td>-1.6733</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TP1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>185.3350</td>
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<td>1.750</td>
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<tr>
<td></td>
<td>0.571</td>
<td>12.7</td>
<td>1.620</td>
<td>13.0</td>
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<td>1.713</td>
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<td></td>
<td>+0.5710</td>
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<td>-1.6200</td>
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<td>TP2</td>
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<td></td>
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<td></td>
<td>184.2860</td>
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<tr>
<td>STA</td>
<td>B.S.</td>
<td>DI ST</td>
<td>F.S.</td>
<td>DI ST</td>
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<td>DESC.</td>
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<tr>
<td>TP2</td>
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<td></td>
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<td></td>
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<td></td>
<td>-2.4263</td>
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<tr>
<td>BM201</td>
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<td>182.9777</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+2.4143</td>
<td>61.5m</td>
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<td>62.9m</td>
</tr>
<tr>
<td>Σ</td>
<td></td>
<td></td>
<td>+2.4143</td>
<td>61.5m</td>
<td>-5.9176</td>
<td>62.9m</td>
</tr>
</tbody>
</table>

Arithmetic Check: 186.283 + 2.4143 – 5.7196 = 182.9777
Errors and their effects

(many, but only a few addressed)
Errors in leveling, e.g.

- Collimation, Parallax
- Change point / staff instability
- Instrument or Benchmark instability
- Refraction
- Uncalibrated staff or levels
- Reading, booking, or computation errors
- Fore- and backsight distances different
Systematic and Random Errors

- Earth curvature
- Refraction
- Collimation errors
Effect of Earth Curvature

\[(r + \Delta h)^2 = r^2 + s^2\]
\[\Rightarrow \Delta h \approx s^2/(2r)\]

<table>
<thead>
<tr>
<th>Distance (s) in m</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect ((\Delta h)) in mm</td>
<td>0,008</td>
<td>0,03</td>
<td>0,2</td>
<td>0,8</td>
<td>80</td>
</tr>
</tbody>
</table>

Refraction

Mean Gradient: 0.2 °C / m

Collimation error

-Occurs when the line of sight (as defined by the lens axis and cross-hairs) is not horizontal
-Leads to an incorrect staff reading
Instrument test: Nähbauer

\[ a_1' = a_1 + e \]
\[ b_1' = b_1 + 2e \]
\[ \Delta h = a_1 - b_1 \]
\[ \Delta h_1 = a_1' - b_1' = a_1 - b_1 - e = \Delta h - e \]

With \( \Delta h_1 + e = \Delta h_2' - e \)

\[ e = \frac{\Delta h_2' - \Delta h_1}{2} \]
Instrument test: Peg

(a) Error in 30 m

(b) Error in 60 m
EXAMPLE
What is the error in the line of sight for the level used to take the following readings?

Solution
First setup: Rod reading at A, \( a_1 = 1.075 \)
           Rod reading at B, \( b_1 = 1.247 \)
           True difference in elevations = 0.172

Second setup: Rod reading at A, \( a_2 = 1.783 \)
               Rod reading at B, \( b_2 = 1.946^* \)

               Apparent difference in elevation = 0.163
               Error (\( \Delta e_2 \)) in 60 m = 0.009

This is an error of -0.00015 m/m. Therefore, the collimation correction (C factor) = +0.00015 m/m.
Summary
Procedure of leveling

1. The instrument must be check before use! (see lecture)
2. The instrument and level must be stable settled-up
3. The bubble tube must be leveled before the reading
   - Beware of sun exposure (will wander)
   - Ensure the instruments pendulum is in-limit
4. The instrument must be set up in the middle between two staffs
   - Prevents curvature effects
   - If impossible, use the same distances, but opposite for the next readings
5. You must not use the parallax screw between the backsight and foresight readings
Procedure of Leveling

6. Readings must be taken 30-50 cm above the ground
   • Surface refractions
   • Beware also of temperature gradients (inside/outside buildings) !!!!

7. Staff should be set up vertically

8. A change plate should be used

9. Leveling must be done in two opposite directions but the same line (beaware of gravity gradients)

10. Staff should be calibrated, especially if INVAR

11. Be careful when crossing rivers (large water surfaces)
   • Use “same-time” (mutual) observations
   • Repeat it during different times of the day
An Unhappy Surveyor

... having a 2 centimeter difference
Geodetic Fixing Of Tide Gauge Benchmarks

• Advances in modern geodetic techniques have provided new methods for fixing bench marks

• Space Geodetic Techniques*
  – GPS, (GLONASS, GALILEO)
  – DORIS
  – (SLR, VLBI)

• Absolute Gravity measurements provide collateral evidence of crustal movements

• The space geodesy measurements can be used to fix into a geocentric reference frame the GPSBM, which should be connected to the TGBM by leveling

• As a result, sea level measurements can be compared with altimetric sea levels

*Stable Reference / Reference Frame is needed
Geodetic Methods

- Altimetry
- InSAR
- Gravity
- Absolute Gravity
- Tide Gauge
- Leveling
- Geoid

$h$

$W = W_0$
Space Geodetic Techniques

Microwave Techniques:

- **Global Positioning System (GPS):** USA
- **Global Navigation Satellite System (GLONASS):** Russian Pendant
- **GALILEO:** future European satellite navigation system
- **DORIS:** French doppler satellite tracking system
GPS (Introduction)

- Technique has been established as a scientific tool since around 1993
- GPS is now the most common technique for point monitoring
- Scientific organization (IGS/GGOS/IAG) is providing a high quality service (provision of orbits, clocks, point coordinates and velocities) (see http://igscb.nasa.jpl.gov)
- GPS is a multi-purpose sensor
GPS with Choke Ring Antenna

Satellite Communication

Meteo-Sensor

Solar Power

Floating TG and Pressure TG are complementing the setup
GPS inside

2-Frequency Geodetic Receiver
Sampling 1Hz to 30sec
IGS-GPS network and cGPS@TGs

**IGS network:**
- Geographically balanced
- Some clustering in populated areas
- Optimized point distances
- Strict requirements on latency (minutes to a few days)

**cGPS@TG:**
- Sites along coastlines
- Many clusters in Europe, Japan, USA
- Short GPS baselines, sometimes multiple receivers at one site
- Many remote and manually operated sites
GPS: Recommendations

• Each long-term and reliable tide gauge should be equipped with continuous GPS
• If (for practical or budgetary reasons) impossible, establish a pillar for regularly repeated GPS campaigns
• For studies involving sea level, it is recommended that a dual-frequency receiver should be installed directly at the tide gauge
• The GPSBM and GPS antenna need to be levelled to the TGBM at least annually
GPS: Recommendations

- Dual frequency receivers and Choke Ring Antenna
- 30 Sec sampling (1Hz if hazardous area)
- Short latency for data transmission
- No obstructions around, use safe places, and no radio interference
- Prevent multipath, e.g. from roofs, walls or the pillar itself
- Leveling benchmark at the GPS pillar and regular leveling to other benchmarks
TIGA
Tide Gauge Benchmark Monitoring Pilot Project of the IGS
op.gfz-potsdam.de/tiga
TIGA Pilot Project

• Initiated in 2001

• Goals are
  – Establish, maintain and expand a global cGPS@TG network
  – Compute precise station parameters for the cGPS@TG stations with a high latency
  – Reprocess all previously collected GPS data at cGPS@TG stations, if possible back to 1993
  – Promote the establishment of links to other geodetic sites which may contribute to vertical motion determination (DORIS, SLR, VLBI, AG)