How to deal with non-linear station motions?

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Current station parameterization (coordinates and velocities) to realize long-term reference frames can only cover secular station motions (caused, e.g., by plate tectonics, post-glacial rebound, etc.)
Unmodeled effects like atmospheric or hydrological loading cause **periodic signals** in coordinate time series. Available models are still not accurate enough.
Episodic effects (e.g., local hydrological effects or post-seismic deformation) can neither be covered by linear station velocities nor by periodic signals.
Strategies to deal with non-linear station motions

- **Modeling**
  - improved modeling of global geophysical fluids (atmosphere, oceans, hydrology, etc.) that are mainly responsible for periodic station motions
  - ideal solution, long-term objective

- **Parameterization**
  - set up parameters like annual and semi-annual sine functions for the station coordinates (besides linear station velocities)
  - interim solution

- **Sampling**
  - estimation of epoch reference frames in addition to multi-year reference frames
  - only possibility to approach episodic effects
Parameterization

Only necessary, as long as (loading) models have deficiencies and, therefore, an interim solution, but...

- calls attention to the general problem
- gives feedback to the modeling approach
- helps to categorize stations with respect to sub-annual stability
- interesting as regards the necessary datum constraints

So far, only **indirect estimates** from final coordinate time series for the periodic signals available. Direct estimation important, as other parameters could absorb parts of the signal.
Significance of (semi-)annual station motions

Derived from differences between epoch and multi-year reference frames (combined GPS, SLR and VLBI solutions; 1994-2006; 335 stations with 528 sets of positions)
Reduction of station RMS

<table>
<thead>
<tr>
<th>Reduction of height RMS</th>
<th>Percentage of stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 1 mm</td>
<td>38%</td>
</tr>
<tr>
<td>&gt; 2 mm</td>
<td>14%</td>
</tr>
<tr>
<td>&gt; 3 mm</td>
<td>4%</td>
</tr>
</tbody>
</table>
Hofn (Iceland):

- time series of differences between epoch (ERF) and multi-year reference frames (MRF)
- trends probably due to deficiencies in the velocity estimates of the MRF
- semi-annual signal not always significant
- strong annual signal in the up component
- different amplitudes for consecutive intervals, but good phase agreement
(Semi-)annual station motions (2)

Yakutsk (Russia):

- strong annual signal in the up component
- annual signals not able to cover episodic effects contained in the horizontal components
Sampling

- **epoch-wise combination** of different space geodetic techniques (GPS, SLR, VLBI)
- epoch reference frames (ERFs) only contain station positions (no velocities!)
- **datum realization**:  
  - origin: SLR  
  - orientation: NNR (GPS)  
  - scale: SLR/VLBI
- adequate number of **local ties** per epoch necessary
Different sampling rates
(1 d, ..., 28 d): compromise between datum stability and the possibility to sample short-term effects.
## Epoch vs. multi-year reference frames

<table>
<thead>
<tr>
<th>Parameterization</th>
<th>ERF</th>
<th>MRF</th>
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<tbody>
<tr>
<td>Parameterization</td>
<td>$X(t_i)$</td>
<td>$X(t_0), \frac{dX}{dt}$</td>
</tr>
<tr>
<td>Stability</td>
<td>short-term</td>
<td>long-term</td>
</tr>
<tr>
<td>Non-linear station motions</td>
<td>frequently sampled</td>
<td>suppressed</td>
</tr>
<tr>
<td>Station network</td>
<td>sparse</td>
<td>dense</td>
</tr>
<tr>
<td>Number of local ties</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Latency (e.g., after earthquakes)</td>
<td>few epochs</td>
<td>$\geq 2.5$ years</td>
</tr>
</tbody>
</table>
Summary

- Stations currently parameterized with coordinates and corresponding velocities for TRF computations
- Station velocities cover secular station motions, but neither periodic nor episodic effects
- Parameterization of (semi-)annual station signals can serve as an interim solution, as long as geophysical fluid models are imperfect
- (Semi-)annual signals are significant; the amplitude of the up component exceeds the cm level for about 15% of the stations
- Epoch reference frames (ERFs) can sample both periodic and episodic effects
- Sampling rate is a compromise between datum stability and the temporal resolution of the station motion
- ERFs are available with short latency (e.g., after earthquakes)