Frequent epoch reference frames instead of instant station positions and constant velocities

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Motivation: ITRF kinematics based on station velocities

- The International Terrestrial Reference Frame (ITRF) provides station coordinates for an instant of time (epoch date) and constant velocities for interpolating or extrapolating the station coordinates at a particular date (instant of time), e.g. for satellite tracking, point positioning, navigation, ...

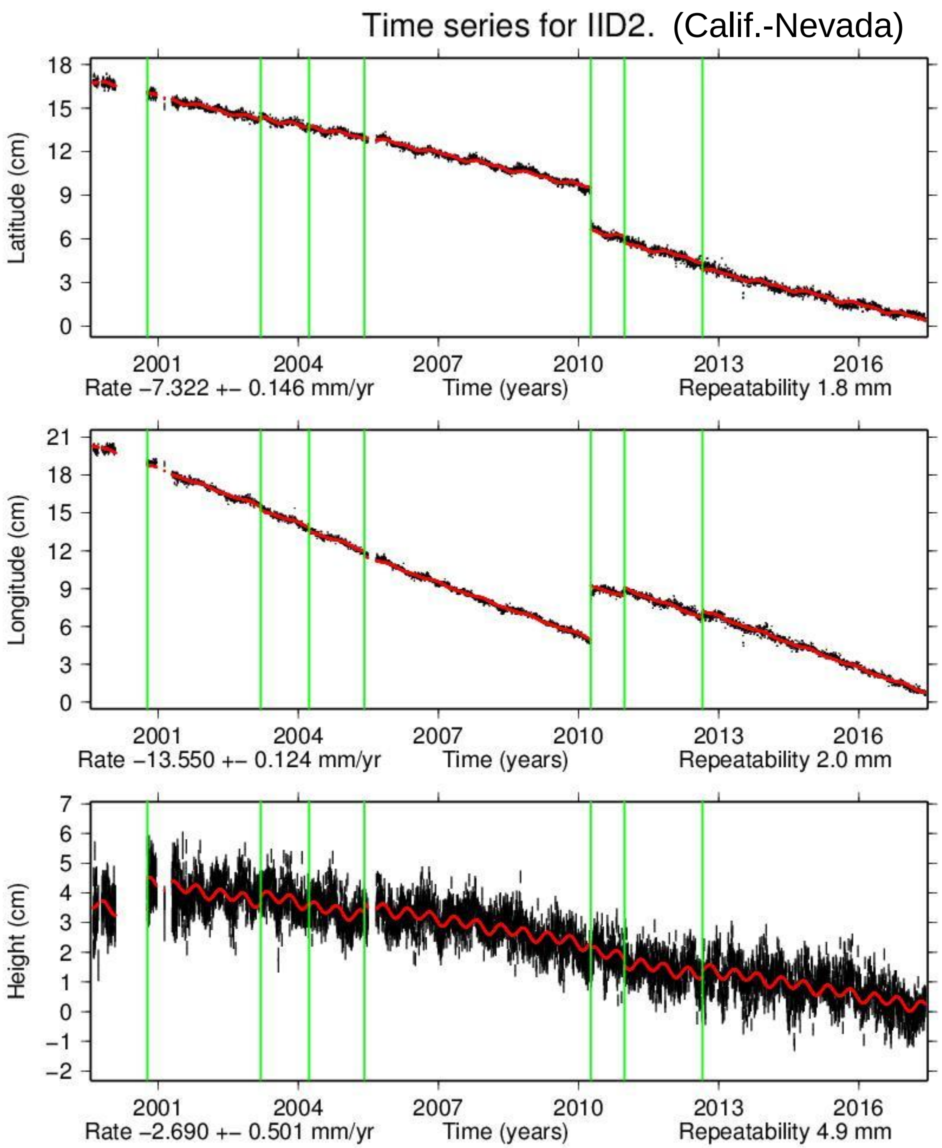
- The basic reason for adopting this procedure was that station coordinate changes were assumed to be mainly due to crustal movements caused by tectonic motions, which are constant over long time intervals.
  [At the beginning of the ITRF-series (1989) velocities were taken from the geophysical plate model AM0-2 (Minster and Jordan 1978)].

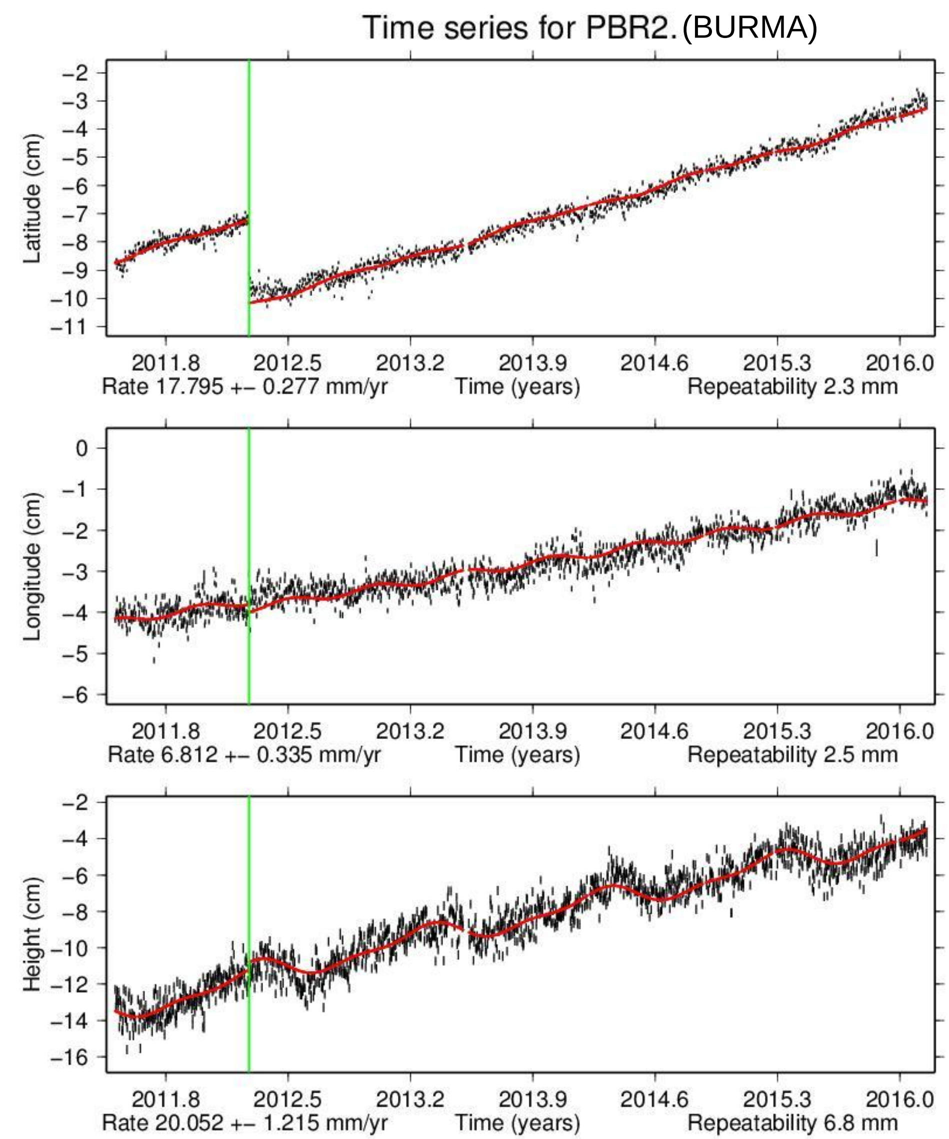
- Time series of station coordinates demonstrate today many non-constant velocities due to various reasons:

  - abrupt co-seismic dislocations (at the time of an earthquake);
  - abnormal post-seismic velocities (after an earthquake);
  - non-linear environmental effects (at any time);
  - instrumental (antenna) changes.

Examples of dislocations in station position time series

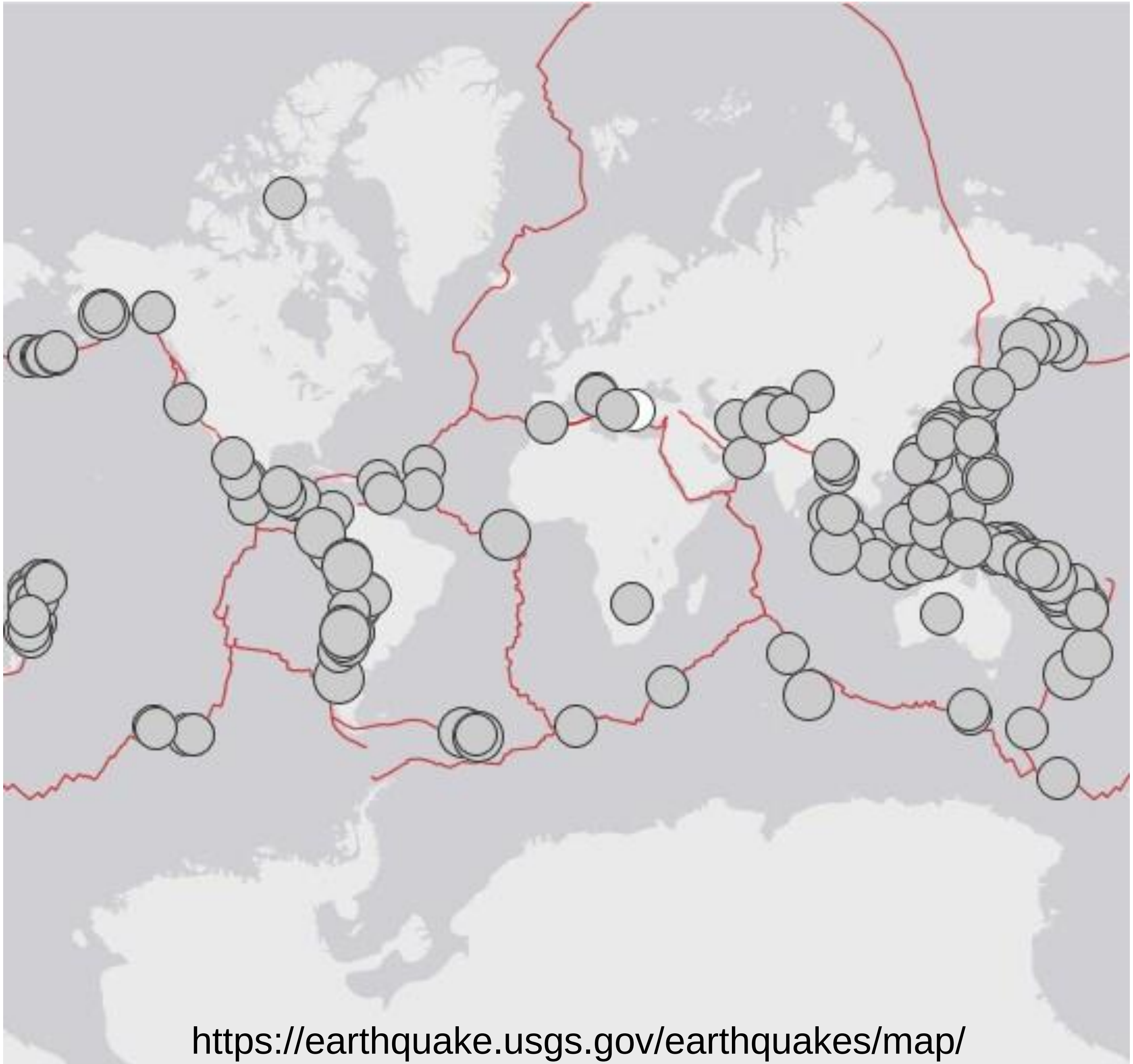
1. Abrupt co-seismic dislocations (caused by large earthquakes)





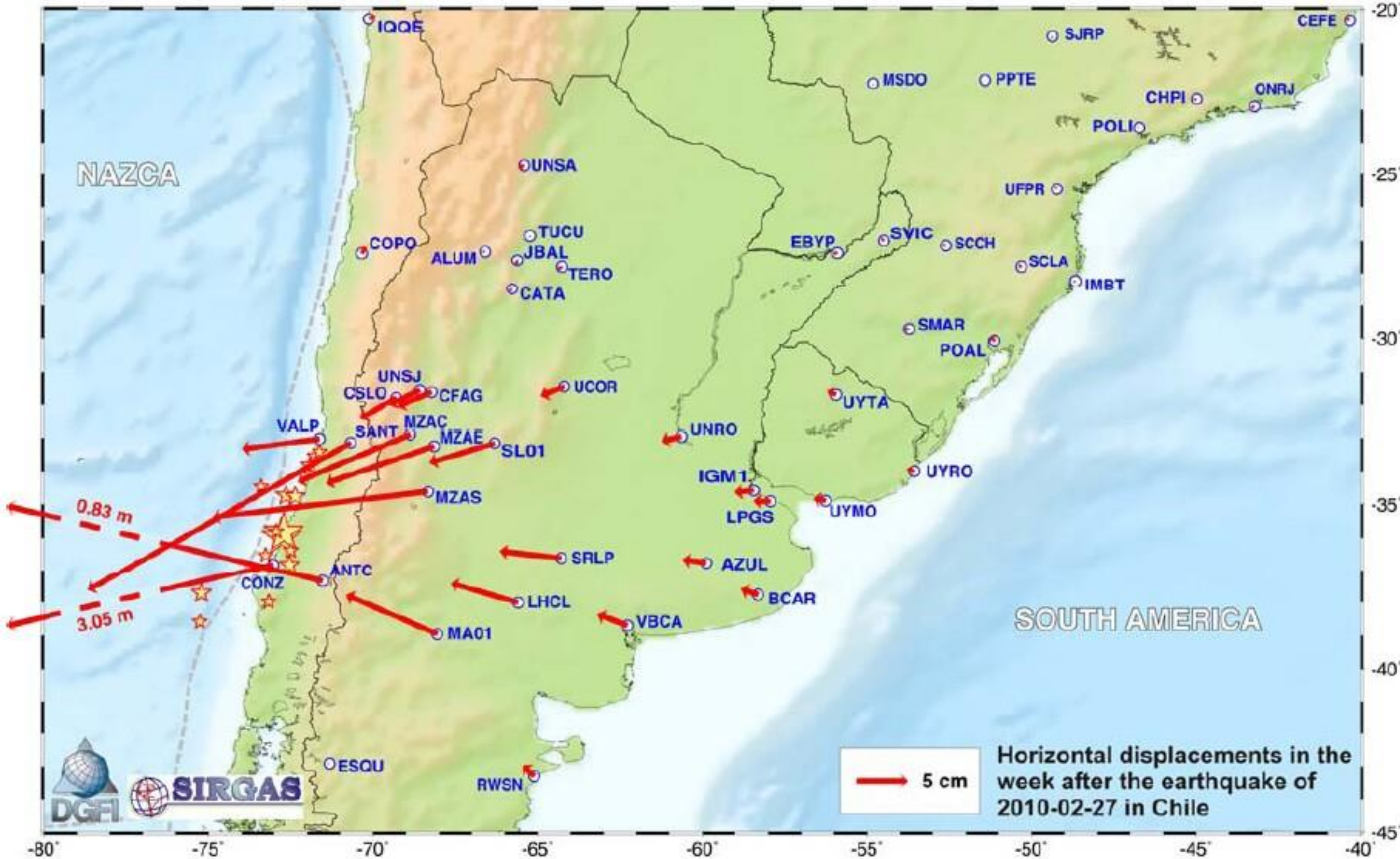
https://sideshow.jpl.nasa.gov_post_series.html

Earthquakes M > 6 over two years time interval



From 2015-07-01 until 2017-06-30 we had **265** earth-quakes M > 6.0 causing significant deformations of the Earth’s crust; not only close to the epicentre, but **extended over very large regions**.

Dislocations after the Maule (Chile) earthquake 2010



Significant displacements over more than 1300 km (Sánchez et al. 2013)

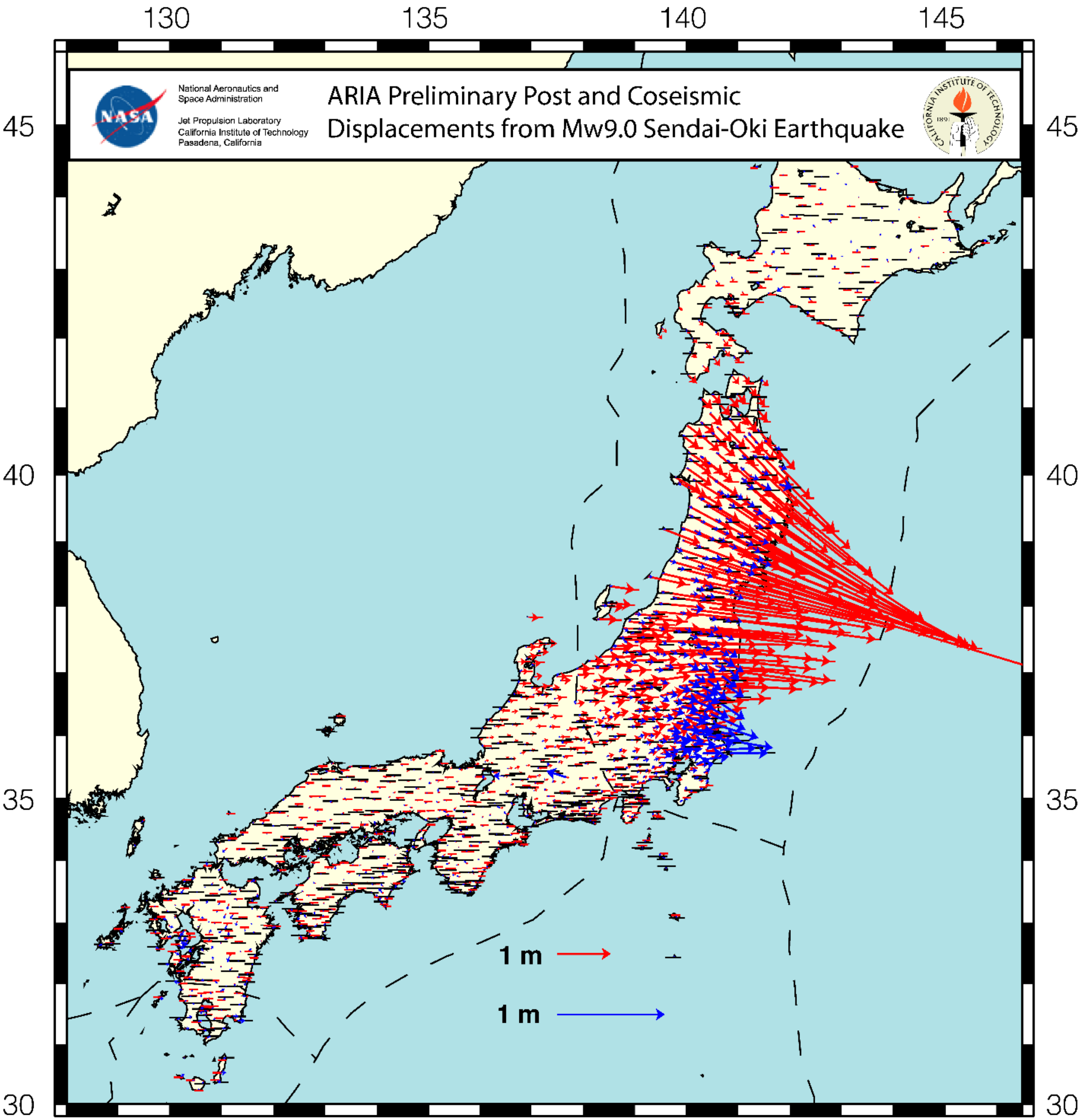
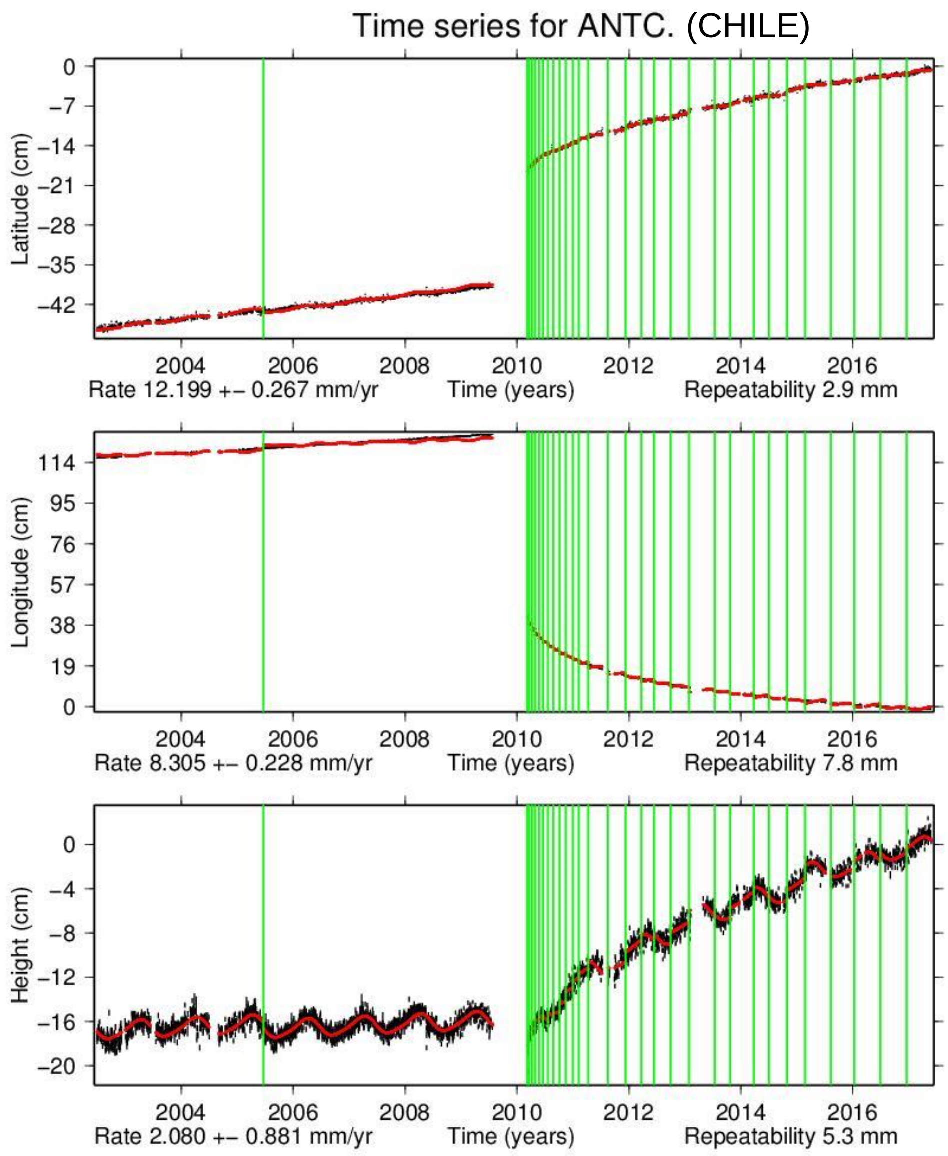


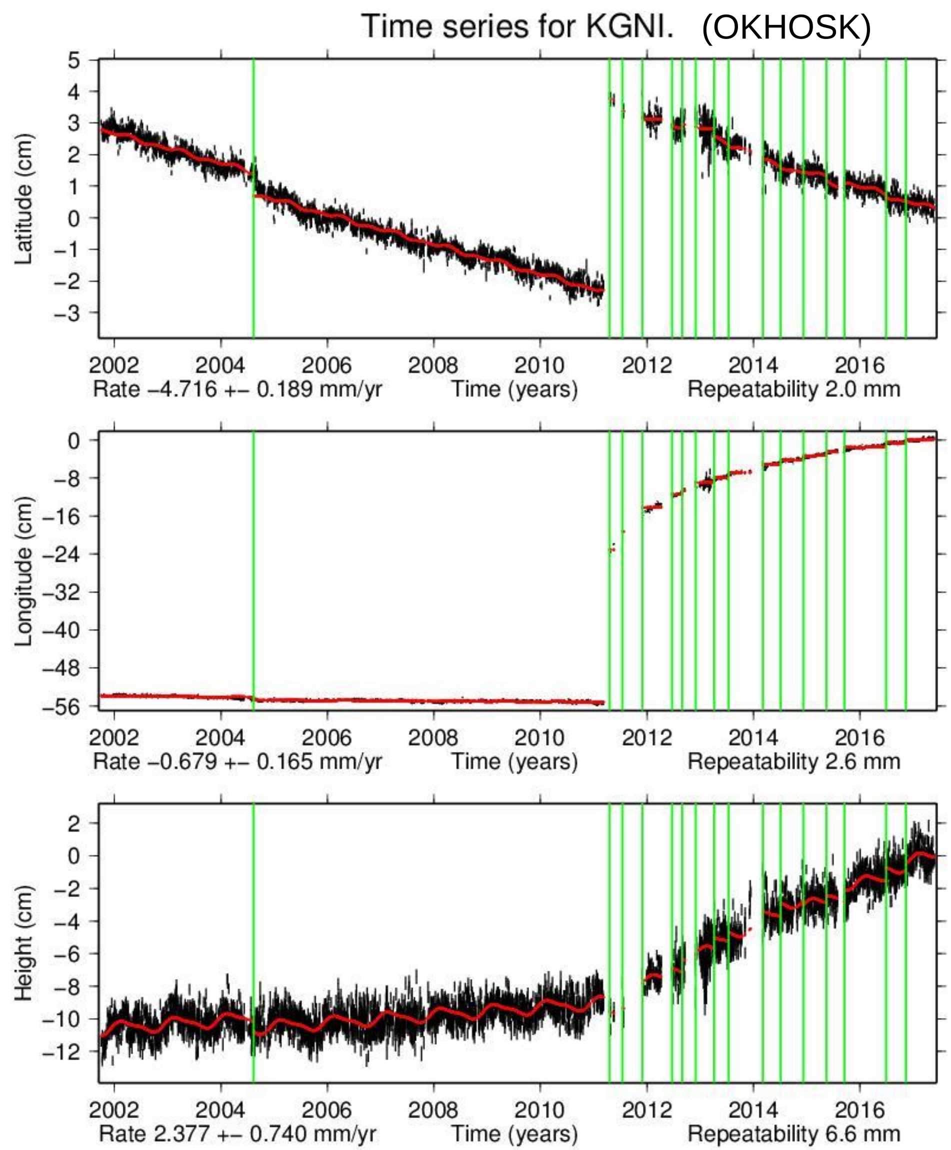
Figure shows horizontal displacements based on ARIA verion 0.3 position estimates for GEONET stations. Coseismic displacement is shown in red, and first 8 hours of postseismic motion is shown in blue, including motion caused by aftershocks. Bars at end of vector show 95% error estimate. Solutions courtesy of ARIA team at JPL and Caltech (email aria@jpl.nasa.gov or aria@caltech.edu). All original GEONET RINEX data provided to Caltech by the Geospatial Information Authority (GSI) of Japan.

Dislocations after the Tohoku (Japan) earthquake 2011

Examples of abnormal velocities in station time series

2. Abnormal velocities after earthquakes

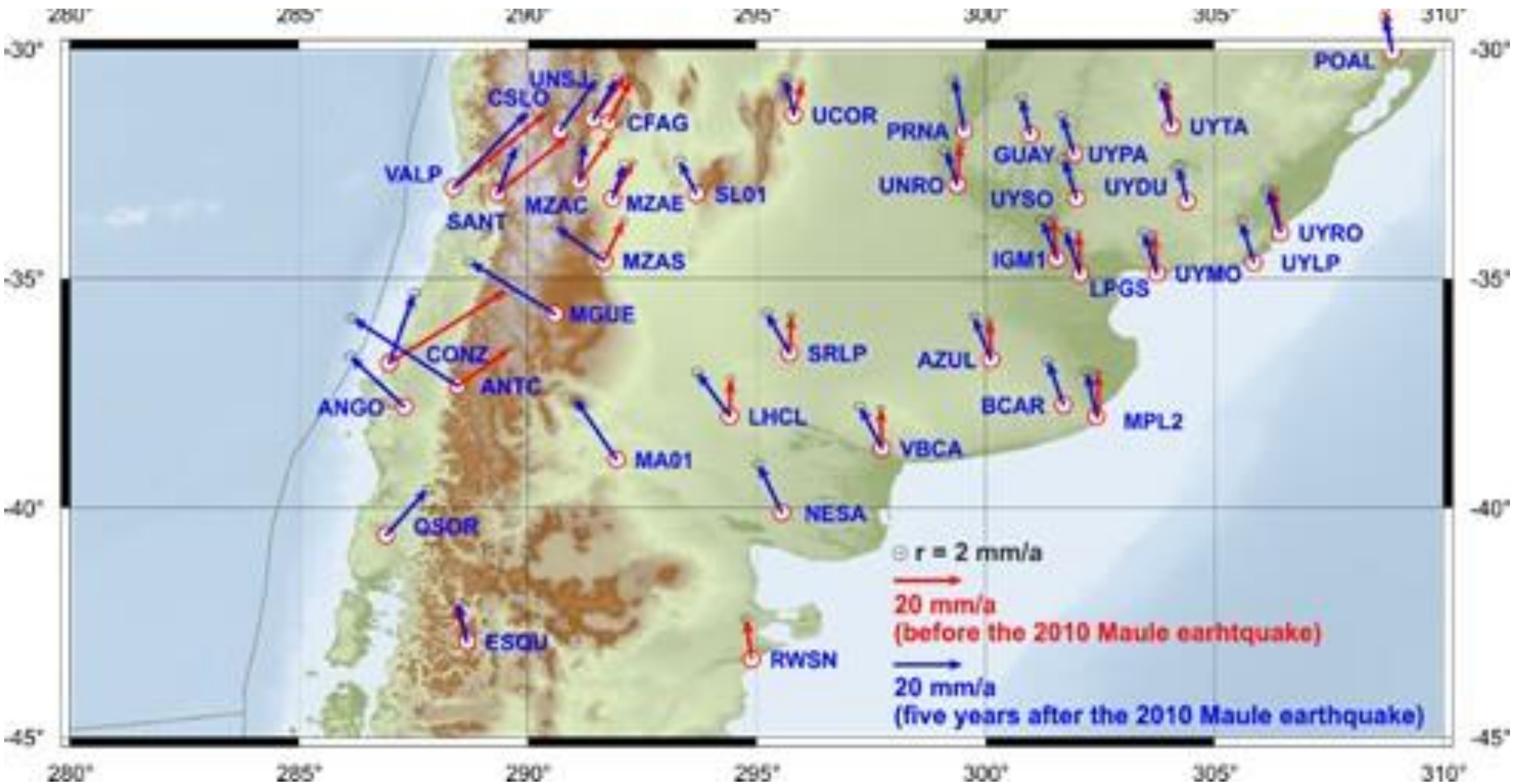




https://sideshow.jpl.nasa.gov_post_series.html

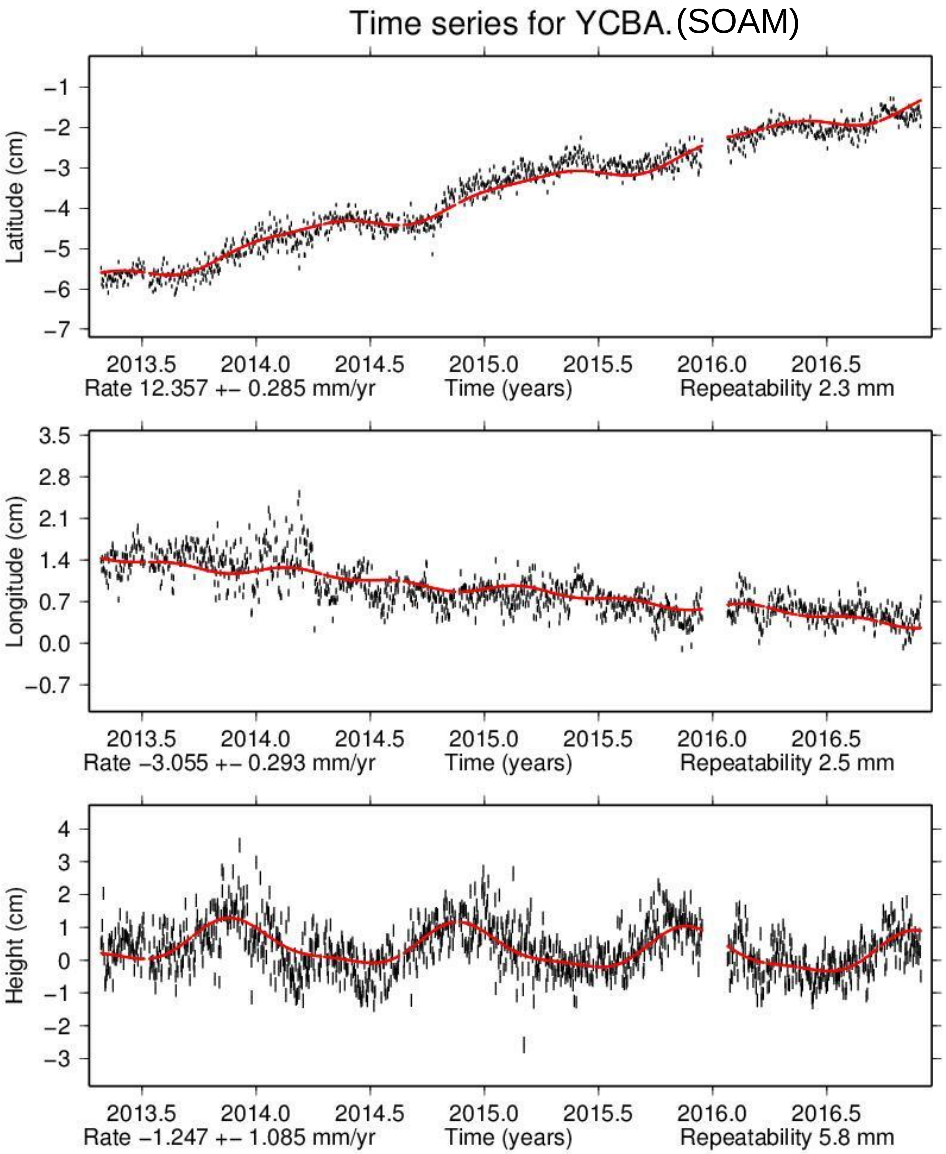
Velocity changes after the Maule (Chile) earthquake 2010

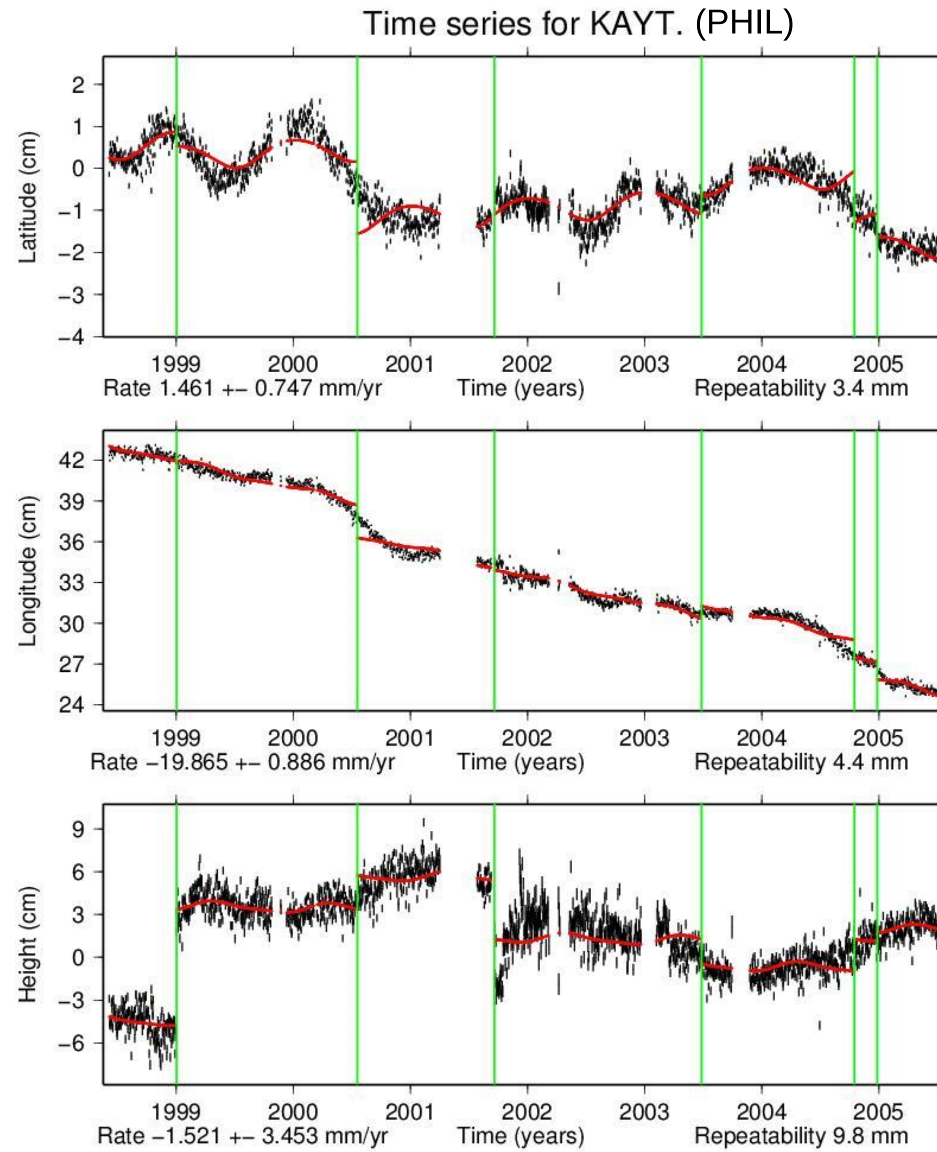
The velocity change extends between latitude -30° and -40° over the entire continent from the Pacific to the Atlantic coast (Sánchez and Drewes 2016)



Environmental effects on position time series

3. Seasonal, long-periodic or irregular coordinate variations





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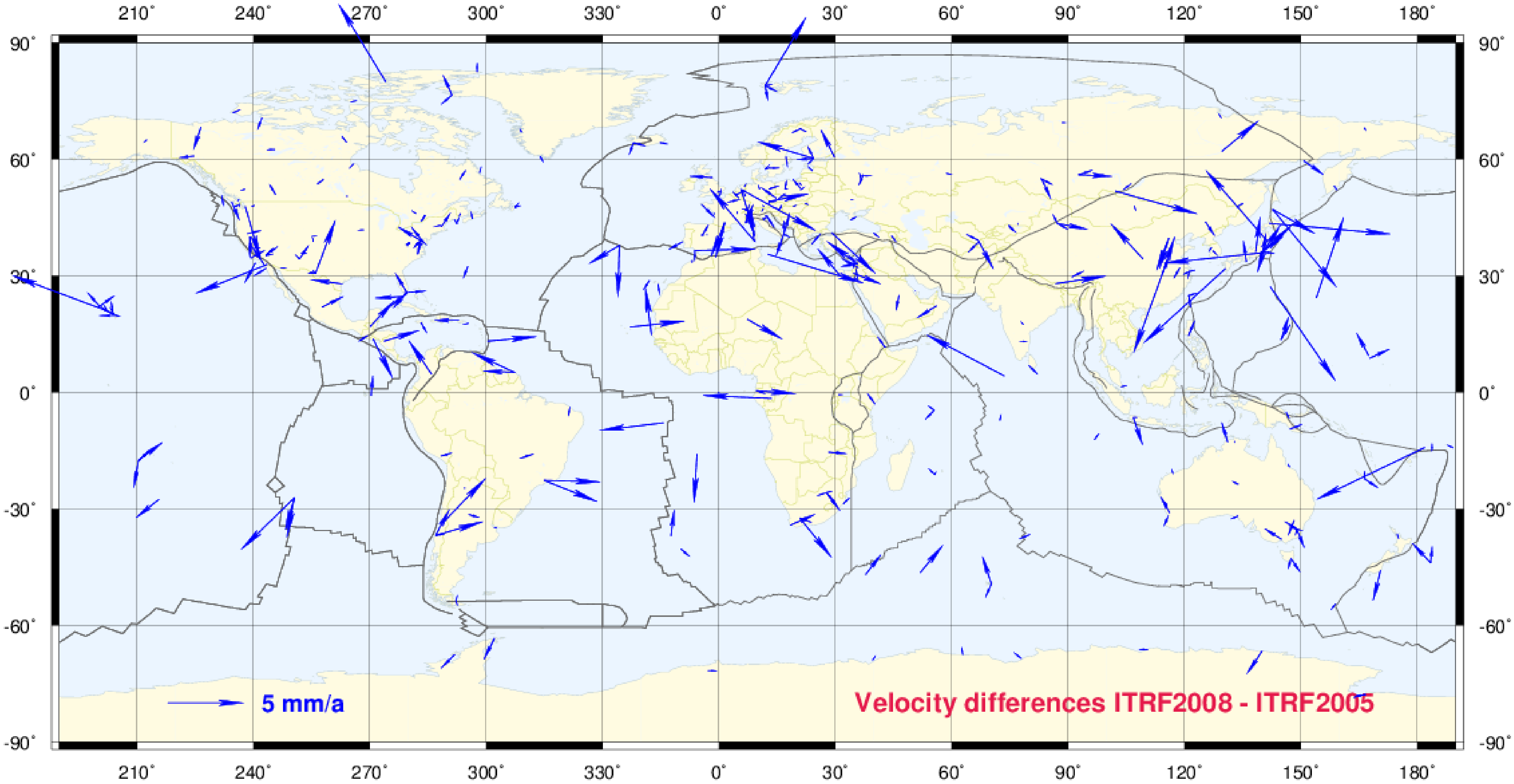
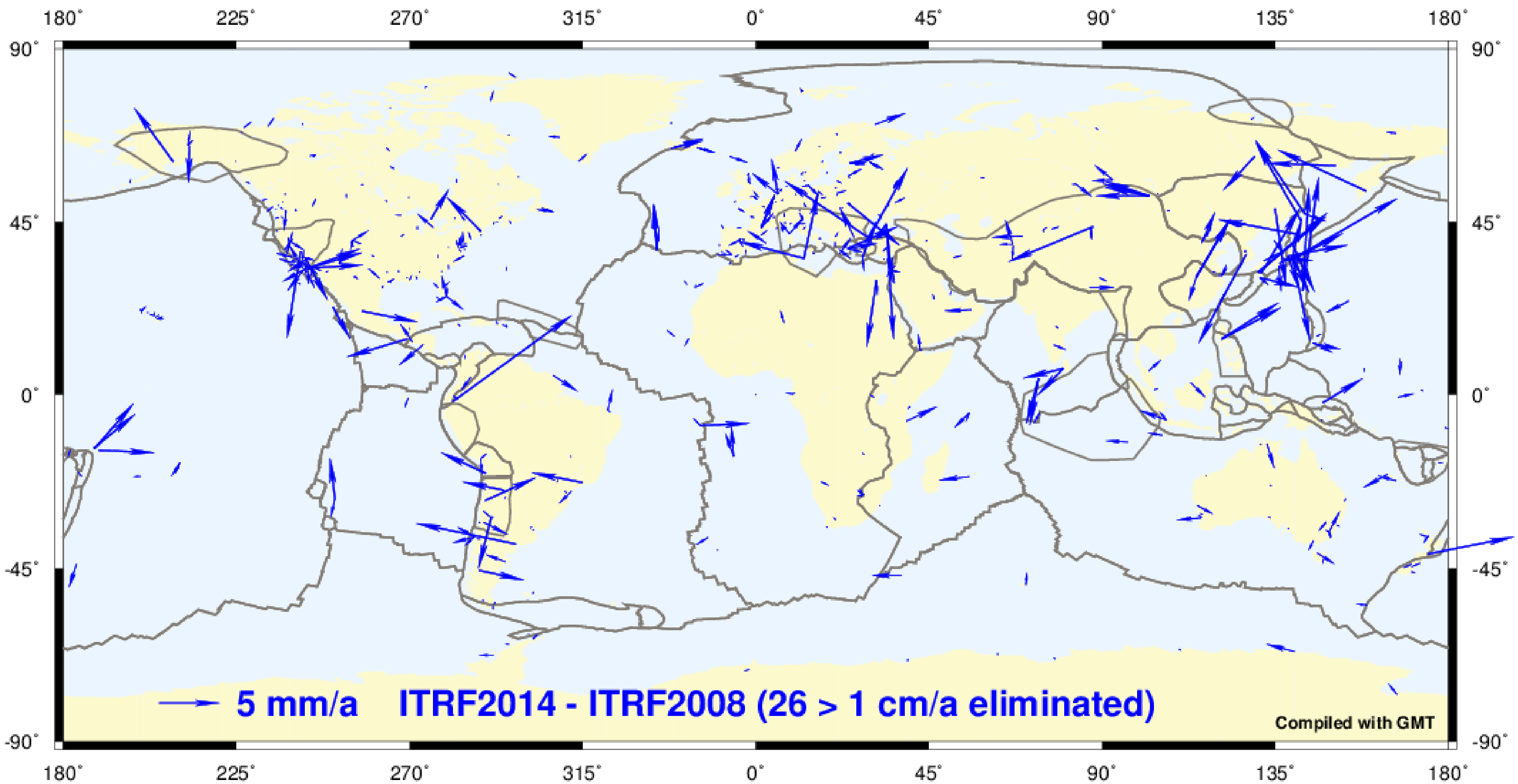
Effect of variable station velocities on the ITRF

Velocity differences ITRF2008 - ITRF 2005 (outliers > 1 cm/a not included)



Effect of variable station velocities on the ITRF

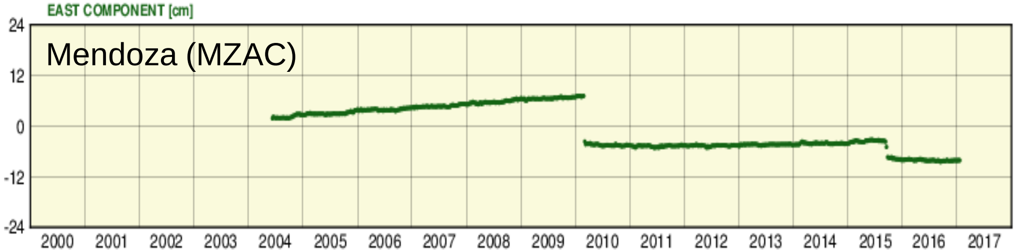
Velocity differences ITRF2014 – ITRF 2008 (outliers > 1 cm/a not included)



Variable station velocities in SIRGAS (→ Sánchez 2017)

Different velocities in SIRGAS multi-year solutions

2000.0 … 2010.1 | 2010.2 (2012.2) … 2015.2 | 2014.0 … 2017.1



The need of time-dependent coordinates

Where are time-dependent coordinates needed?

- Satellite orbit determination:
  - satellite orbit is independent of crustal movements, tracking stations not;
  - tracking station coordinates must refer to the actual (real) position;

  –> e.g., missing seasonal effects falsify sea level estimates of satellite altimetry.

- Geodynamics and global change studies:
  - studies are based on time-dependent station coordinates (deformation);

  –> seismic precursors and effects of climate change (e.g. sea-level rise) are at the mm-level.

- Precise point positioning, e.g. cadastre, engineering (tubes, power lines), precise navigation:
  - actual station coordinates are required to relocate the positions ;

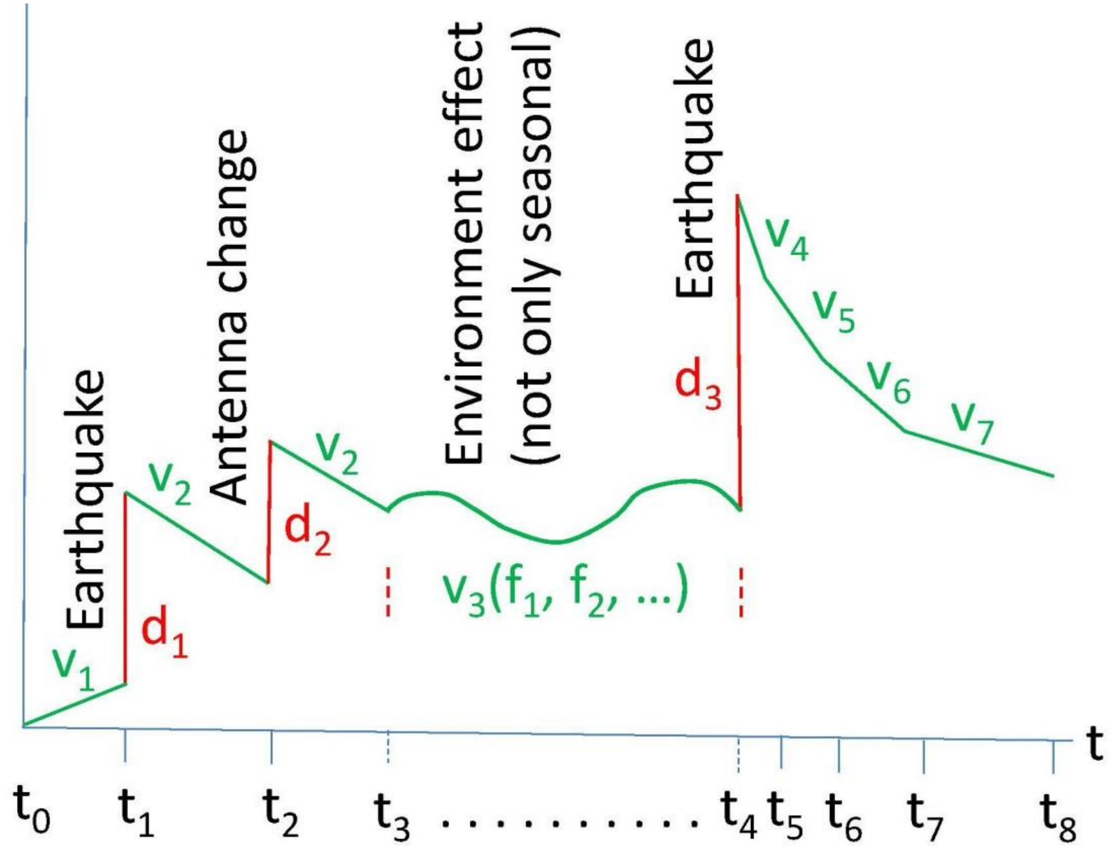
  –> e.g., Japan and Chile could not use the ITRF after the 2010 earthquakes.

➢ Geographical and temporal inter- / extrapolation is required.

Compute ITRF coordinates of an arbitrary point at an arbitrary epoch (geographic and time extrapolation)

In principle, a consecutive extrapolation with different dislocations and velocities is required.

- The ITRF provides the coordinates and velocities at different epochs via the corresponding "**solutions**".
- There are new solutions (coordinates, velocities) after each discontinuity.
- For non-ITRF stations we have to perform a geographic and consecutive time extrapolation.



➢ Instead of irregular "new solutions" at discontinuities we can introduce frequent regular epochs (every week, month, …) and quit the velocities.

Requirements of regular ITRF epoch reference frames

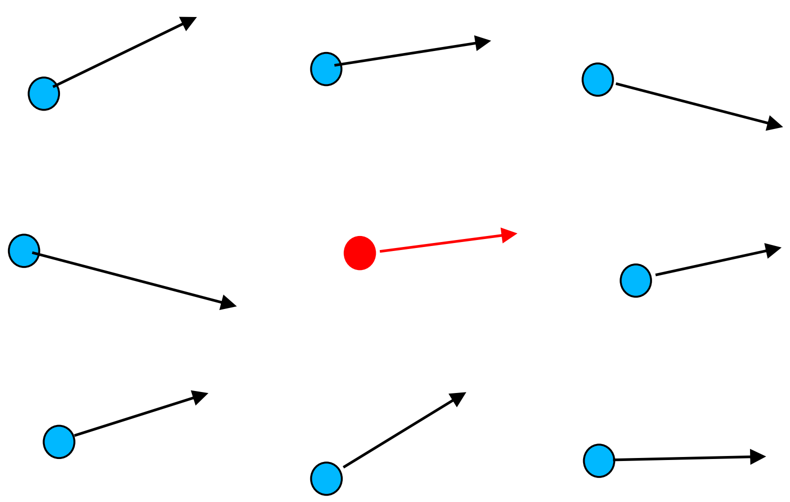
Epoch reference frames must fulfil the IERS conventions, in particular:

- They must be **geocentric** at any time (without “geocentre motion”); (“geocentre motion” is its motion relative to the varying ITRF positions)
  - it is realised by SLR if we don’t add any constraint (e.g. NNR, NNT).
- There must be **no global rotation** of stations (over the entire Earth’s crust); (present ITRFs rotate ~0.06 mas/a (max. 1.8 mm/a) due to rotating NUVEL-1A);
  - it can be realised by integrating an epoch grid over all the Earth surface.
- They must be **consistent with the ICRF** (EOP determined by VLBI);
  - the present time resolution might not be sufficient;
  - sub-daily EOP are already in discussion.
- The **time resolution** of epoch reference frames should be 1 month;
  - this is necessary for precise geocentric realisation (SLR);
  - it is sufficient because maximum velocities are ~ 10 cm/a.
- For **global accessibility** they should include continental reference frames;
  - AFREF, APREF, EUREF, NAREF, SIRGAS refer to the ITRF;
  - It can be done by decentralised data processing.

Transforming epoch coordinates to a conventional frame

Most reference frames refer to a conventional reference date (epoch) [$\mathbf{X}(t_0)$] (e.g. ITRF2014 to 2010.0, national SIRGAS frames to different t_0)

- Coordinates determined in an epoch reference frame [$\mathbf{X}(t_E)$] must be transferred to the conventional date [$\mathbf{X}(t_0)$].
- For reference frame stations, the differences $\Delta\mathbf{X} = \mathbf{X}(t_E) - \mathbf{X}(t_0)$ are known.
- For (new) stations not included in the reference frame, the differences must be interpolated. This can be done equivalently to the interpolation of station velocities using $\Delta\mathbf{X}$ instead of $\Delta\mathbf{v}$.



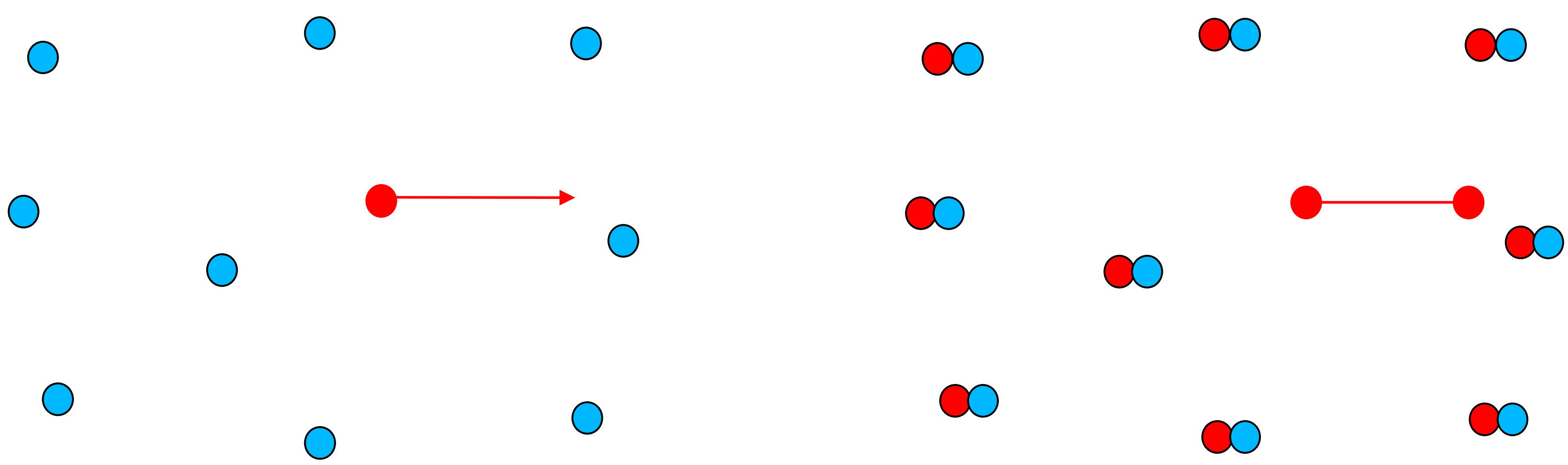
For interpolation one may use any vector technique (e.g. bilinear, least squares collocation, kriging, splines). This includes the method of VEMOS.

The advantage of interpolating directly $\Delta\mathbf{X}$ instead of extrapolating $\Delta\mathbf{X} = \mathbf{v} \cdot \Delta t$ is that the propagation of errors is less.

Transforming epoch coordinates to a conventional frame

A frequently made mistake is to apply a similarity (Helmert) transformation.

- Similarity means that two networks are identical in the order of coordinate precision (e.g. ± 1 mm) and differ only in datum (origin, rotation, scale).
- Network deformation (of the Earth crust) exceeds the precision by far.
- When applying similarity transformation, the network deformation is split among translation, rotation, scale **and** transformed coordinates.
- Example: Coordinates of only one station (out of 10) are changed by 1 cm.



The transformation **changes the datum** by 1 cm : 10 = 1 mm. 9 coordinates change by 1 mm, and coordinates of the displaced station change by 9 mm.

Conclusions

- There are many SIRGAS/ITRF stations with abrupt co-seismic dislocations.
- There are many SIRGAS/ITRF stations with abnormal velocities after seism.
- There are many SIRGAS/ITRF stations with non-linear environment effects.
- There are many SIRGAS/ITRF stations with antenna changes creating jumps.

➢ All these effects make the determination of velocities difficult.

➢ The proposal is to replace velocities by frequent epoch reference frames!

Thank you very much for your attention!