Synthesis Assignment: Estimating interseismic strain accumulation along the San Andreas fault system

Aims:

To estimate the interseismic strain rate from GNSS timeseries along a chosen segment of the San Andreas fault system. This overall aim has three sub aims:

1. Estimate a linear rate from GNSS time series and test what model best describes the local site motion in time.
2.
   a) Either estimate a spatially continuous linear horizontal velocity field for the chosen fault segment.
   b) or pre-process the velocities to obtain more robust point velocities.
3. Calculate strain rates for the area and compare this to independent geological or seismological data.

Present findings in a precise and organized way, both numerically as well as graphically.

Tools: To be developed by the students or use existing tools*
PyGMT for making figures.

*Existing tools that can handle the core steps of the assignment (i.e. the above aims) can only be used after discussion with the responsible lecturers.

Datasets:

- Daily GPS solutions from University of Nevada at RENO:
  - http://geodesy.unr.edu (Map browse GPS stations)
  - Use tenv3 format, (see Readme File for the format http://geodesy.unr.edu/gps_timeseries/README_tenv3.txt)

optional data sets:

- Atmospheric pressure changes from NOAA (NCEP-NCAR Reanalysis 1):
  - https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html
    - Choose Sea Level pressure – Mean – Surface – Monthly

- Surface mass changes from GRACE/GRACE-FO, mascon solutions by GSFC:
  - https://earth.gsfc.nasa.gov/index.php/geo/data/grace-mascons

Introduction San Andreas fault system and its geodetic expression

The San Andreas fault system forms the boundary between the North American plate and the Pacific Plate. The relative motion between the two plates is accommodated by the transform faults that make up the San Andreas fault system. The fault system comprises of parallel fault branches that together take up the relative motion of about 45 mm/yr (e.g. Tong et al., 2013). In the creeping section (e.g. stably sliding) of the San Andreas fault system the relative motion between the two plates is a nearly discrete velocity discontinuity (e.g. Tong et al., 2013). For the largest portion of the San Andreas fault, friction on the faults does however not permit continuous sliding. This leads to a gradual interseismic velocity change over the fault, which is typically interpreted as a locked fault in the shallow portion of the crust, overlying a weak shear zone at deeper depths. Depending on the location the velocity gradient is taken up by a single fault, or multiple fault branches (Tong et al., 2013). This means that the strain rate field is either narrow (single fault) or broad (multiple parallel fault branches). A dense network of GNSS sites allows the estimation of the strain rate field caused by the fault system (Kreemer & Young, 2022).

Estimating Linear rates

For geodetic and geophysical applications, it is typically assumed that fault deformation in the interseismic period leads to a linear velocity component. This linear velocity is the component that needs to be estimated to construct a strain rate field. However, as discussed in the 3rd week lecture (on GNSS), other mechanisms can affect the surface position, such as coseismic displacements, postseismic transients (Klein et al., 2018), atmospheric loading, surface (hydrological) loading, offsets due to antenna changes, seasonal changes due to local environmental changes, network errors, etc. These mentioned effects can be different for different sites. You are expected to test what model best describes the local site horizontal position time series. Use spectral analysis to determine what harmonic components are needed to include in the model. Discuss the testing of models that you use to estimate linear rates.

For inclusion of coseismic displacements and postseismic transients, check https://earthquake.usgs.gov/earthquakes/search/ for nearby large earthquakes in the observational period.

Estimating a spatially continuous interseismic velocity field

For the next step, calculating strain rates, the classical approach is to triangulate the GNSS network and estimate strain rates (Hammond et al., 2014). However, this approach is very sensitive to errors in velocities of individual sites (or local effects, i.e. deformation mechanisms that only play a role at a single observation site), leading to erratic spatial strain rate patterns. To calculate a more robust strain rate field, it is better to pre-process the velocity field. Here you have multiple options:

Options including pre-processing of site velocities and triangulation

First aim to replace site velocities by a more robust velocity, before estimating strain rates.

- (option 1) Pre-process sites with a median filter (Hammond et al., 2016), and apply triangulation to the median filtered interseismic velocities. Note: It is not recommended to apply the median filter for interpolation, as it leads to discontinuous interpolated fields.

Options including interpolation and spatial smoothing

Apply first an interpolation that:

either applies geometrical smoothing of the point velocities:

- (option 2a) Inverse distance weighting and interpolation. This option allows to use not only the most nearby stations for interpolation, but also sites located farther away, which reduces the effect of errors (or local velocity effects) of single sites (Allmendinger et al, 2007, Piña-Valdés et al., 2022). The interpolation is based on weights dependent on distance of the interpolation point and the observation point.

- (option 2b) Spline interpolation. This option aims at the same goal as option 2a, but does so by fitting a smooth function to the point velocities (Hackl et al., 2009). *Pygmt* has existing routines to perform spline smoothing (in the function *surface*).

or that stochastically interpolates the site velocities:

- (option 2c) Ordinary kriging interpolation, a form of linear least squares applied to interpolation (Tiberius et al). This option has the same aim as inverse distance weighting: reducing the effect of velocities that do not agree with the general sense of motion of a region (Porkolab et al., 2023). It is more advanced and requires more effort to use, but it is more powerful. The advantage of kriging is that it does not apply more smoothing than needed (driven by similarities in the observation data) and that it can well handle uneven distribution of observation points. Kriging interpolation involves two steps: i) the estimation of a spatial covariance structure that fits to the covariance of observations, and ii) using this covariance structure to interpolate.

What to choose?

It is up to the students to choose one of the options. All options can provide satisfactory results. Options 2a and 2b require less implementation work. Option 2c is more advanced and thus requires more work to implement and test, but may potentially lead to better results. Option 1 is expected to be intermediate in terms of required effort. It is also allowed to find another solution from literature and use that.

Calculating strain rates

Depending on the option chosen in the previous step: pre-processing site velocities vs. interpolation and smoothing calculating strain rates will be different.

For a triangulation of pre-processed velocities, the velocities can be estimated using linear least squares (e.g. Cai and Grafarend, 2006). This results in an estimated horizontal strain rate tensor for each triangle.

For interpolated and smoothed velocity fields estimating strain rates is more straight forward (Porkolab et al., 2023), strain rate tensors at each spatial location can simply be calculated from gridded (interpolated) velocities.

For both options, strain rates are typically inspected in terms of their principal components and orientation (Cai and Grafarend, 2006), as this provides a description that is not dependent on the orientation of the reference frame. Furthermore, from the principal components, quantities such as dilatation rate and the square root of the J_2 invariant can be calculated to show results as a scalar field.

Independent observations

The previous steps provide a geodetically based estimate for strain rates. Strain rates are typically used as an indicator for interseismic stress accumulation that may eventually lead to seismic release of interseismic stress in the form of earthquakes (Tong et al., 2013, 2014). If we have good observations of the location of earthquakes (e.g. seismicity) we can compare whether the location of geodetically derived strain rates agree with the spatial distribution of seismicity (Kreemer and Young, 2022). Interpret your results and discuss your results in relation to existing literature on strain accumulation on the San Andreas fault.

Literature:

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