Generating velocity solutions with `globk`

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Material from R. W. King, T. A. Herring, M. A. Floyd (MIT) and S. C. McClusky (now at ANU)

Overview

- Basics of "velocity" solutions
  - Invoked with "apr_neu all xx xx xx <NEU velocity sigmas>"
- Strategies for setting up solutions (they can take a long time to run)
- Strategies for speeding up solutions
- Methods for "cleaning up" potential problems
- Different reference frame realizations
- Some examples
- *These solutions involve making decisions about how to treat data and the type of solution to be created – lots of decisions*

GLOBK velocity solutions

- The aim of these solutions is to combine many years of data to generate position, velocity, offset and postseismic parameter estimates
  - Increasingly common to have 10,000 parameters in these solutions if large networks over many years
- Input requirements for these solutions:
  - a priori coordinate and velocity file
    - Used as a check on positions in daily solutions (for editing of bad solutions) and adjustments are a priori values (a priori sigmas are for these values)
  - Earthquake file which specifies when earthquakes, discontinuities, and misnamed stations affect solution
    - Critical that this file correctly describe data.
  - Process noise parameters for each station
    - Critical for generating realistic standard deviations for the velocity estimates (e.g. `sh_gen_stats`).

GLOBK long-term velocities

- Combine daily (continuous) or short-term combined h-files (e.g. surveys; see last slide)
- Plot long-term time series from short-term combination ".org"-file(s) (`sh_plot_pos`)
- Inspect time series to identify (and remove) outliers
- Run `globk` to form final solution file for all data (another ".org"-file) *with velocity estimation*, e.g. in `globk` command file
  ```
  apr_site all 10 10 10 1 1 1
  ```
  or
  ```
  apr_neu all 10 10 10 1 1 1
  ```

- `sh_glred` capable of running all these individual commands to produce time series, short-term combinations and long-term velocity solutions

Velocity solution strategies

- In general careful setup (i.e. correct a priori coordinates, earthquake file and process noise files) is needed since each run that corrects a problem can take several days. Incorrect solutions may not complete correctly and results may be subtly wrong.
- General strategy for iteratively generating velocity solution:
  - Define a core-set of sites (usually 20-200 sites) where the solution runs quickly. Test files on this solutions and use the coordinate/velocity estimates to form the reference frame for time series generation.
  - Time series using these reference frame sites and then test (RMS scatter, discontinuity tests) to form a more complete earthquake and apriori coordinate/velocity files.
  - Steps above are repeated, usually increasing number of stations until solution is complete. As new stations are added missed discontinuities and bad process noise models can cause problems.
- Aim here is make sure that when a large solution is run (maybe several days of CPU time) that the run completes successfully.

Before velocity runs

- Surveys may be combined into one solution per survey
- No need to re-run `glred` again to see long-term time series
- Multiple ".org"-files may be read by `tssum` or `sh_plot_pos`

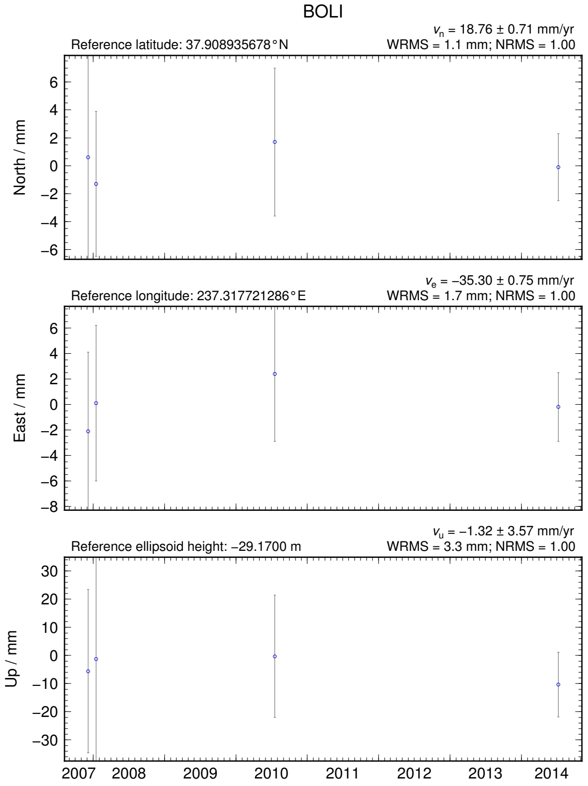
  `tssum ts_pos mit.final_igb14 -R survey1_comb.org survey2_comb.org` …

    - ts_pos is the name of a directory for the .pos files. (“.” can be used)

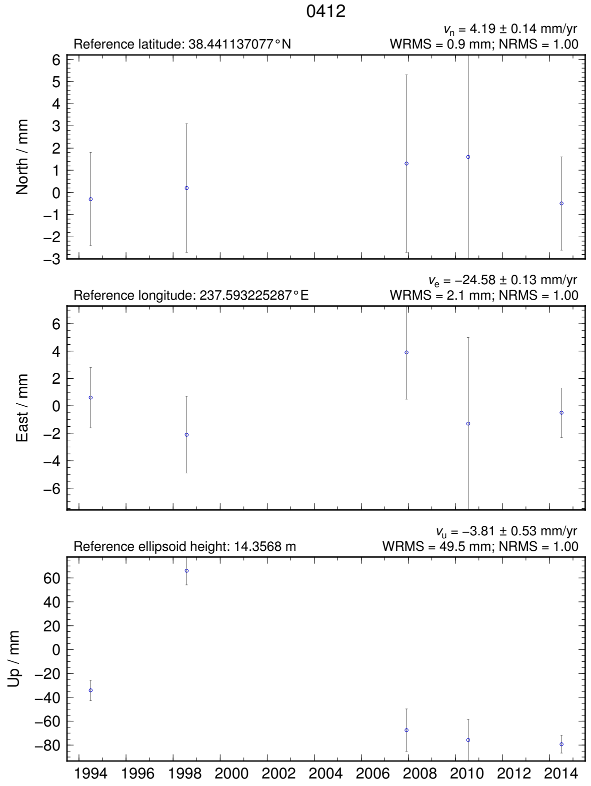
  `sh_plot_pos -f survey1_comb.org survey2_comb.org -k` …

Example: Long-term time series for survey sites

Reasonable repeatability



Outlier in vertical



Excluding outliers or segments of data

- Create "rename" file records and add to GLOBK command file's "eq_file" option, e.g.

```
rename PTRB     PTRB_XPS h1407080610_nb4a
rename PTRB     PTRB_XPS 2014 07 07 18 00 2014 07 08 18 30
rename ABCD     ABCD_XCL 2013 07 08 00 00
```

- "XPS" will not exclude data from `glred` (so still visible in time series) but will exclude data from `globk` (combination or velocity solution)
- "XCL" will exclude data from all `glred` or `globk` runs

Run `globk`

- Create new ".gdl"-file with *combined* binary h-files, e.g. from vsoln/, assuming standard directory hierarchy

```
ls ../*/gsoln/*.GLX > vsoln.glx.gdl
```

- Optionally run `glist` to see size of solution
  - Recommended to prevent problems during long `globk` run
  - `glist` can read earthquake file and `globk` use site type commands (useful if a globk solution seems to be missing or has extra sites)
- Run `globk`
  - This may take many hours for very large/long velocity solutions
  - Use `tsfit` with earthquake file to generate a priori site coordinates. Be careful if ~/gg/tables/igb14_*.apr files also used because some site names permutations may have inconsistent coordinates (use `unify_apr` to be safe)

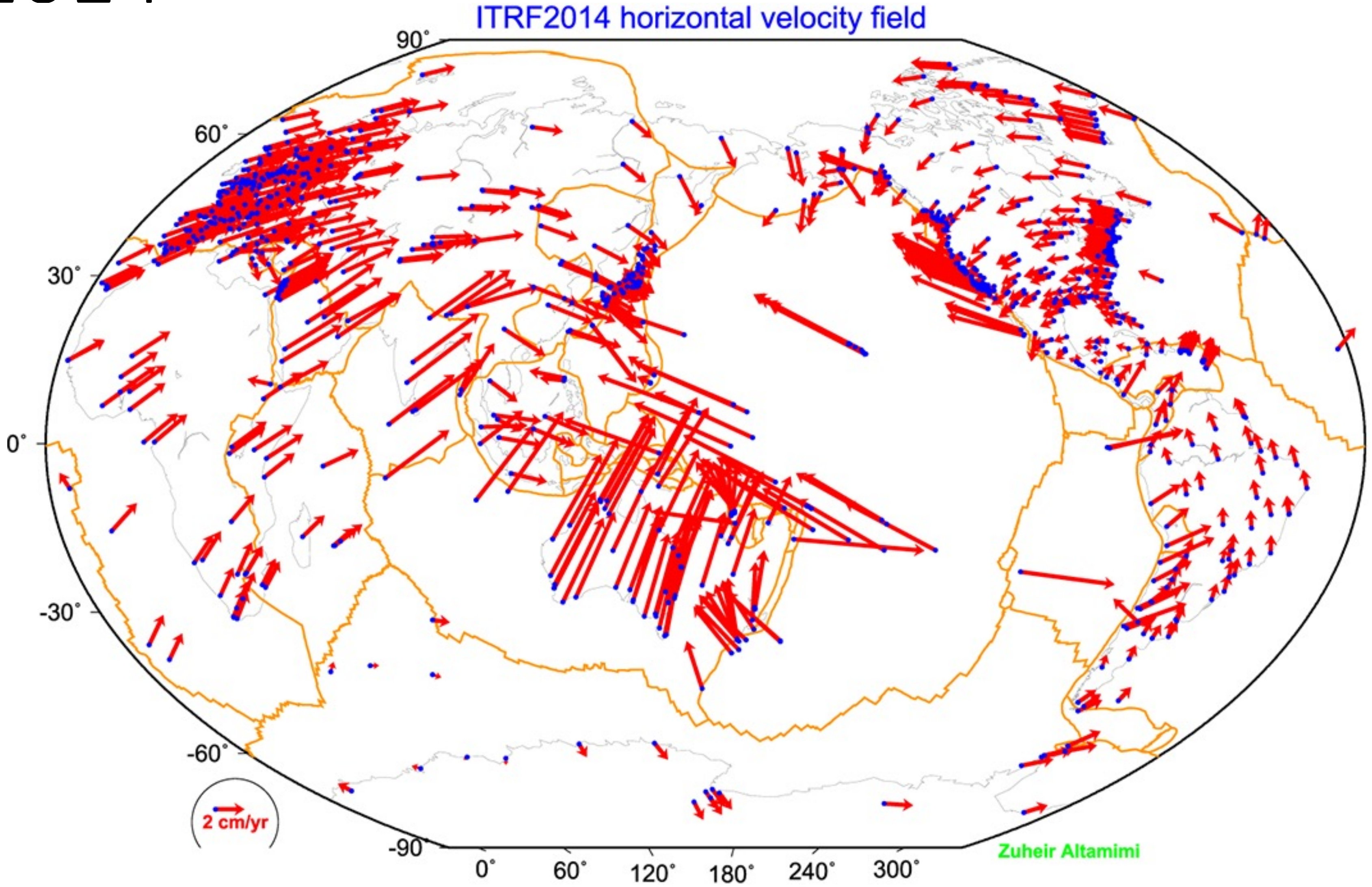
glorg for different reference frames

- No need to re-run globk every time you want
- glorg is usually called from globk command file ("org_cmd" option) but glorg may be run separately

```
globk 6 globk_vel.prt globk_vel.log globk_vel.gdl globk_vel.cmd
glorg globk_vel_noam.org ERAS:… glorg_vel.cmd vel.com
```

- Must have saved the ".com"-file!
  - e.g. "com_file @.com"
  - Do not use "del_scra yes" in globk command file
  - "apr_neu" must be loosely constrained ("apr_rot" and "apr_tran" will also need to be used for sestbl. "BASELINE" experiment solutions)

ITRF2014


ITRF2014 horizontal velocity field
90°
60°
30°
0°
-30°
-60°
-90°
0°
60°
120°
180°
240°
300°
2 cm/yr
Zuheir Altamimi

ITRF2014

What are some general features of plate motion that you can see?

- North America rotates around a point in the Pacific off South America
- Eurasia and Africa appear to have very similar motions
- Antarctica is moving very little

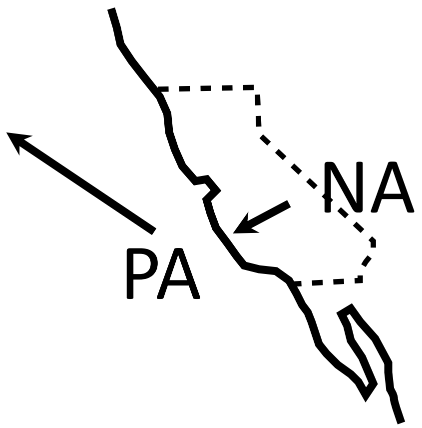
- ITRF2014 is a not-net-rotation frame which is a mathematical construction. For some geophysical problems other frames may make more sense (e.g., mantle fixed, hot spot frame, specific plate).
- Frames for different plates (based on Euler pole fits) are in ~/gg/tables.

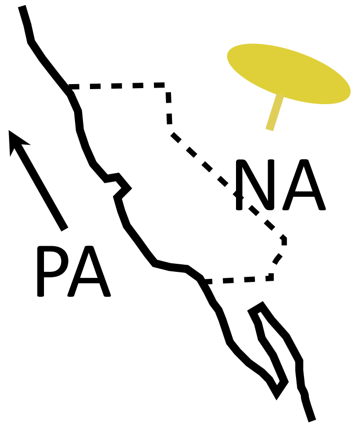
Choices of reference frame

- Choose your reference frame based on your geophysical objectives
  - Velocities in ITRF are difficult to interpret visually from a geophysical perspective
    - Local surroundings of a volcano
    - One side of a fault
    - Upper plate of a subduction zone
- Major plate reference frame
  - Major plates are often chosen to conform with conventional perspectives of velocity solutions
  - Relative to Eurasia, Nubia, North America, South America, etc.
  - But don’t feel restricted by this. Sometimes your geophysical discussion is best visualized relative to any stable boundary of a deforming region
- Regional reference frame
  - Central Valley of California, non-deforming part of Anatolia, smaller coherent regions, etc.
- Local reference frame
  - Sites near but outside the influence of a volcano, geothermal field, etc.

Examples

- Expressing velocities in ITRF is not very meaningful or useful when we want to look at the deformation at a plate boundary, e.g. the San Andreas Fault system
- Better to look at velocities with one side "fixed" so we can see what the other side is doing relative to it





Basic issues in reference frame realization

- Concept is to align the estimated site positions and possibly velocity to a set of well defined locations that have physical significance for the analysis being performed (e.g., GAGE aligns to a realization of the North America plate based on ITRF2014)
- `glorg` is the module which does this and computes the covariance matrix of the aligned solution in the reference frame chosen.
- Transformation is often called an *N*-parameter Helmert transformation
  - *N* = 3: translation only (could also be just rotation)
  - *N* = 6: translation and rotation
  - *N* = 7: translation, rotation and scale
- In GLOBK analyses, you need to decide
  - How many parameters (3/6/7)
  - Sites to use to determine the parameters (`sh_gen_stats`)
  - Values of the positions/velocities of the reference frame sites
  - Weight to be given to heights in computing the transformation parameters ("cnd_hgtv" command; first two arguments for position and velocity, other arguments are sigma limits)

Rules for stabilization of time series

- Small-extent network: translation-only in `glorg`, must constrain EOP in `globk`
- Large-extent network: translation and rotation, must keep EOP loose in `globk`
- If scale estimated in `glorg`, must estimate scale in `globk`
- First pass for editing:
  - Adequate “stab_site” list of stations with accurate a priori coordinates and velocities and available most days
  - Keep in mind deficiencies in the list
- Final pass for presentation, assessment and statistics
  - Robust “stab_site” list of all/most stations in network, with coordinates and velocities determined from the final velocity solution
- System is often iterated (velocity field solution, generate time series, editing and statistics of time series; re-generate velocity field)
- If you have time series, you can test options using `tscon`

Use of equates

- With earthquakes and discontinuities, there can be many site names for the same physically location:
  - Equate commands in `glorg` allow the velocity adjustments at these sites to be made the same (or constrained to be the same within a specified sigma)
  - "eq_dist" allows site separate by distance to equated (and constrained in latest `glorg`)
  - "eq_4char" equates sites with same 4-character name (useful to stop equates at sites that share antennas)
  - chi-squared increments of equates allows assessment of equates (use "unequate" for large chi-squared values)
  - Use "FIXA" option to make a priori the same for equated sites (better to use consistent a priori file)

Uses of `sh_gen_stats`

- Velocity solutions are often iterative:
  - Generate time series using some reference frame sites (IGb14 sites initially for example)
  - Fit to the time series (`tsfit`) to:
    - Find outliers, nature of earthquakes (log needed?), discontinuities
    - Self consistent a priori file.
    - Used FOGMEx model (realistic sigma) to get process noise model and list of low-correlated noise reference frame sites). Use “stabrad” option for dense networks
  - Run `globk` velocity solution to refine reference frame site coordinates and velocities
  - Re-generate time series and repeat

Some comparisons: Approach

- Use `sh_exglk -f <soln.org> -vel <soln.vel> -rmdup` to extract velocity estimates (rmdup removes equated sites with the same estimates)
- Program `velrot` allows fields to be compared (change frames and merge fields as well), for example:
  `velrot solna.vel nam14 solnb.vel IGb14 '' '' '' '' N`
  compares to solutions directly (use "RT" instead of "N" to allow rotation and translation rates)
  - Use "`grep '^S '`" to get statistics

Comparisons: Decimation

- Decimation: Different days of week (1996-2015 solution, small subset of sites):

```
Un-aligned fields
compare 1 NMT_vel_150418_day1.vel NMT_vel_150418_day3.vel
S Component North    #    75 WMean  -0.00 WRMS   0.04 mm/yr, NRMS   0.198
S Component East     #    75 WMean  -0.02 WRMS   0.04 mm/yr, NRMS   0.203
S Component Up       #    75 WMean   0.03 WRMS   0.16 mm/yr, NRMS   0.180
S Component Horz     #    75 WMean  -0.01 WRMS   0.04 mm/yr, NRMS   0.200
compare 2 NMT_vel_150418_day1.vel NMT_vel_150418_day5.vel
S Component North    #    74 WMean  -0.01 WRMS   0.04 mm/yr, NRMS   0.207
S Component East     #    74 WMean  -0.02 WRMS   0.05 mm/yr, NRMS   0.225
S Component Up       #    74 WMean   0.04 WRMS   0.19 mm/yr, NRMS   0.212
S Component Horz     #    74 WMean  -0.01 WRMS   0.04 mm/yr, NRMS   0.217
compare 3 NMT_vel_150418_day3.vel NMT_vel_150418_day5.vel
S Component North    #    76 WMean  -0.01 WRMS   0.03 mm/yr, NRMS   0.177
S Component East     #    76 WMean  -0.01 WRMS   0.03 mm/yr, NRMS   0.161
S Component Up       #    76 WMean   0.01 WRMS   0.13 mm/yr, NRMS   0.142
S Component Horz     #    76 WMean  -0.01 WRMS   0.03 mm/yr, NRMS   0.169
```

Comparison: Time series vs GLOBK

- PBO Combined analyses:

```
Un-aligned fields (no rotation and translation).
compare 1 PBO_vel_150425.vel PBO_vel_150425KF.vel
S Component North    #  2105 WMean  -0.01 WRMS   0.12 mm/yr, NRMS   0.925
S Component East     #  2105 WMean  -0.00 WRMS   0.13 mm/yr, NRMS   0.934
S Component Up       #  2105 WMean   0.02 WRMS   0.31 mm/yr, NRMS   0.871
S Component Horz     #  2105 WMean  -0.01 WRMS   0.12 mm/yr, NRMS   0.929
compare 4 PBO_vel_150425.vel PBO_vel_150425_NAM08.vel
S Component North    #  1972 WMean   0.03 WRMS   0.13 mm/yr, NRMS   0.965
S Component East     #  1972 WMean   0.02 WRMS   0.15 mm/yr, NRMS   1.049
S Component Up       #  1972 WMean  -0.07 WRMS   0.41 mm/yr, NRMS   0.943
S Component Horz     #  1972 WMean   0.02 WRMS   0.14 mm/yr, NRMS   1.008
compare 7 PBO_vel_150425KF.vel PBO_vel_150425_NAM08.vel
S Component North    #  1969 WMean   0.04 WRMS   0.16 mm/yr, NRMS   0.952
S Component East     #  1969 WMean   0.02 WRMS   0.17 mm/yr, NRMS   0.967
S Component Up       #  1969 WMean  -0.08 WRMS   0.44 mm/yr, NRMS   0.935
S Component Horz     #  1969 WMean   0.03 WRMS   0.16 mm/yr, NRMS   0.959
```

PBO_vel_150425.vel: tsfit solution to time series
PBO_vel_150425KF.vel: tsfit Kalman filter solution to timeseries
PBO_vel_150425_NAM08.vel: GLOBK combined velocity solution (NMT+CWU), decimated 7 days, 28-subnet combination.
Reference frame realization to NAM08 frame sites (~600)

- See Herring et al., Reviews of Geophysics, 2016 for more detailed comparisons

Final comments

- Practice large solutions with decimated data sets and small networks (run time increased cubically with number of stations)
- Make sure your a priori coordinates files are consistent (especially with equates)
  - Use the out_aprf command in `tsfit` to generate an a priori which is consistent with your timeseries estimates