Geodetic Reference Frame Theory

and the practical benefits of data sharing

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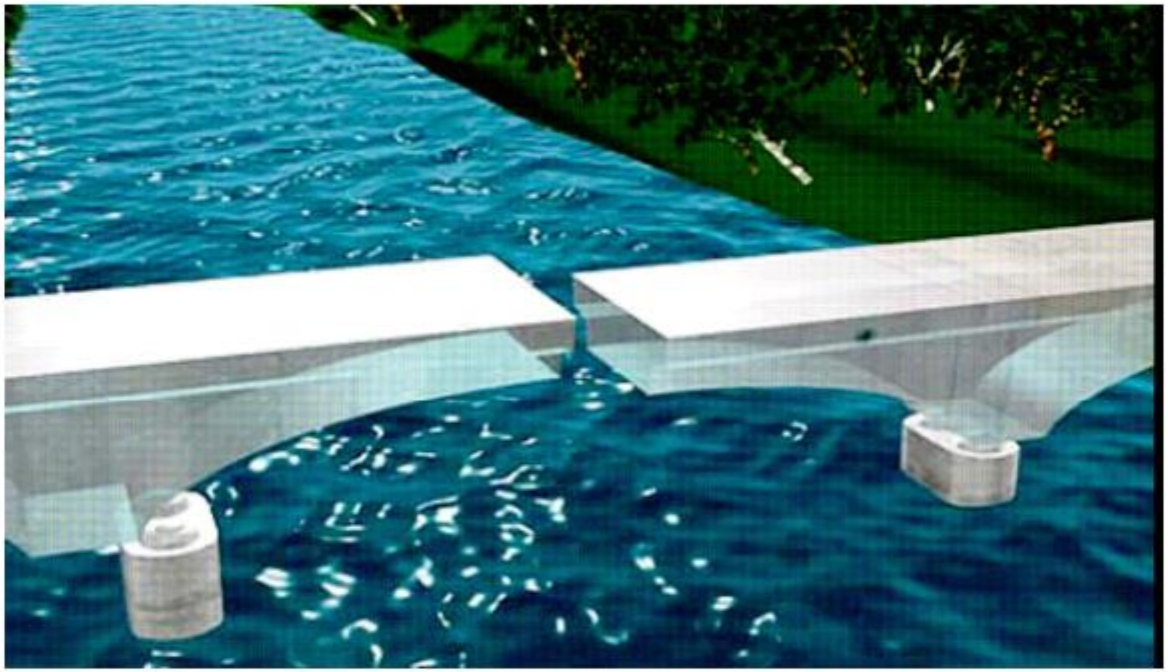
Practical Motivation

When National Reference Frames are not integrated!

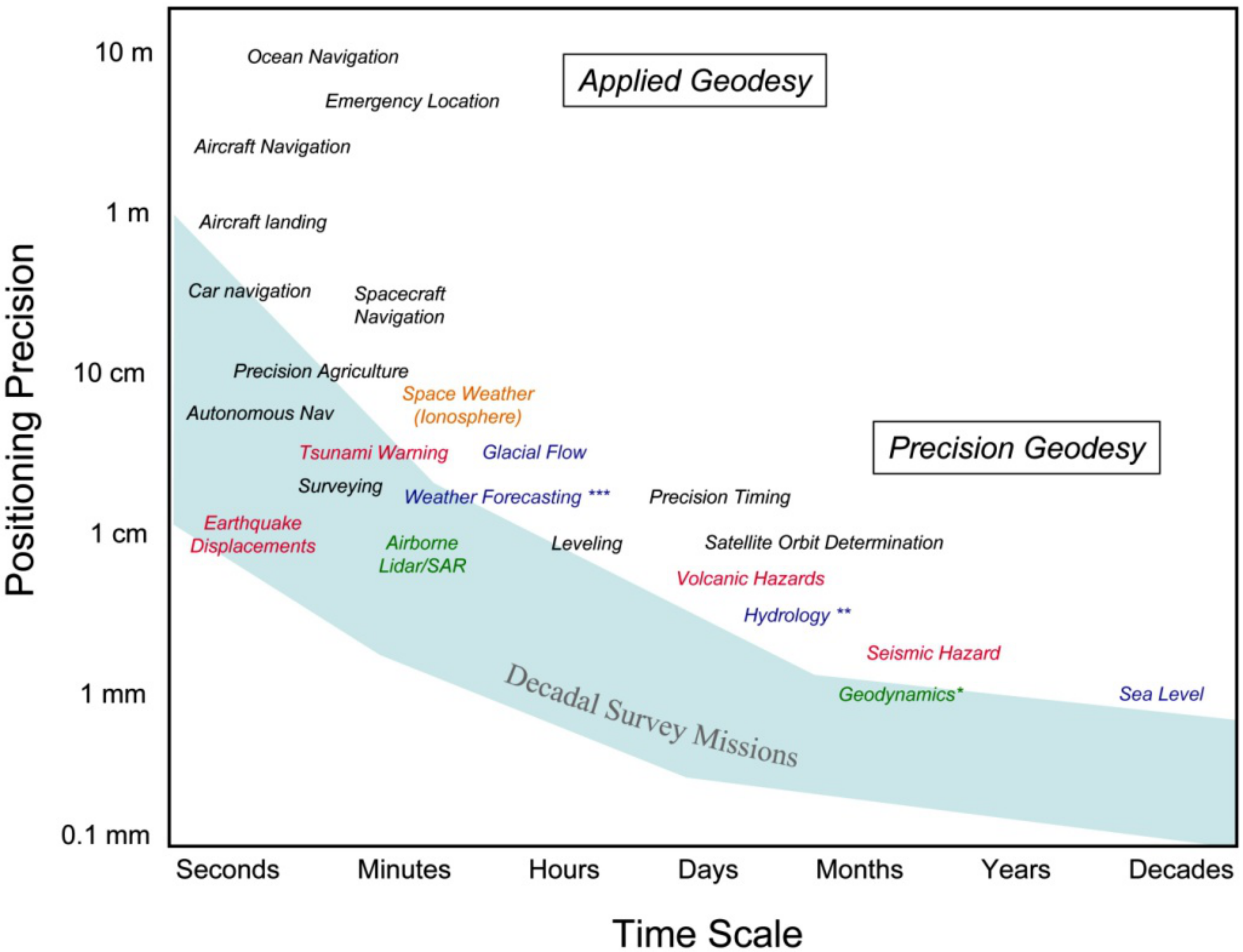


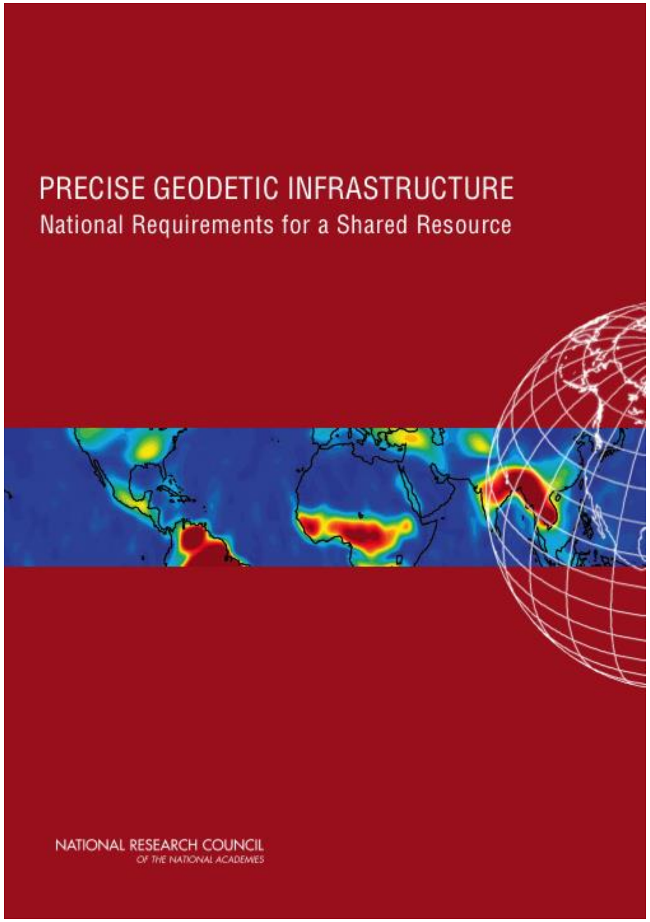
Design error at bridge construction in Laufenburg (2003): During the construction of the bridge across the Rhine river in Laufenburg, a control showed that a height difference of 54 centimeters exists between the bridge built from the Swiss side and the roadway of the German side. Reason of the error is the fact that the horizons of the German and Swiss side are based on different reference frames. Germany refers to the sea level of the North Sea, Switzerland to the Mediterranean.

Courtesy of Hermann Drewes/DGFI

Scientific Motivation

- Terrestrial reference frame requirements (*NRC, 2010*)





Reference Frame Basics

- Frames have a well-defined origin, orientation, scale
  - Scale ideally defined by speed of light together with atomic time
  - Origin ideally defined by center of mass of entire Earth system
  - Frame is "realized" by adopting a set of coordinates and velocities of frame objects that are consistent with geodetic observations
- Types of frame
  - Celestial (CRF)
    - Cartesian axes are "fixed to the sky"
    - Frame objects are distant quasars
  - Terrestrial (TRF)
    - Cartesian axes are "fixed to the rotating Earth"
    - Frame objects are stable stations, ideally with constant velocities
  - Plate-Fixed (TRF)
    - Cartesian axes are "fixed to a rotating tectonic plate"
  - Relationships
    - Terrestrial – Celestial = Earth rotation
    - Plate-fixed TRF – Global TRF = Plate rotation

Example of TRF: WGS-84

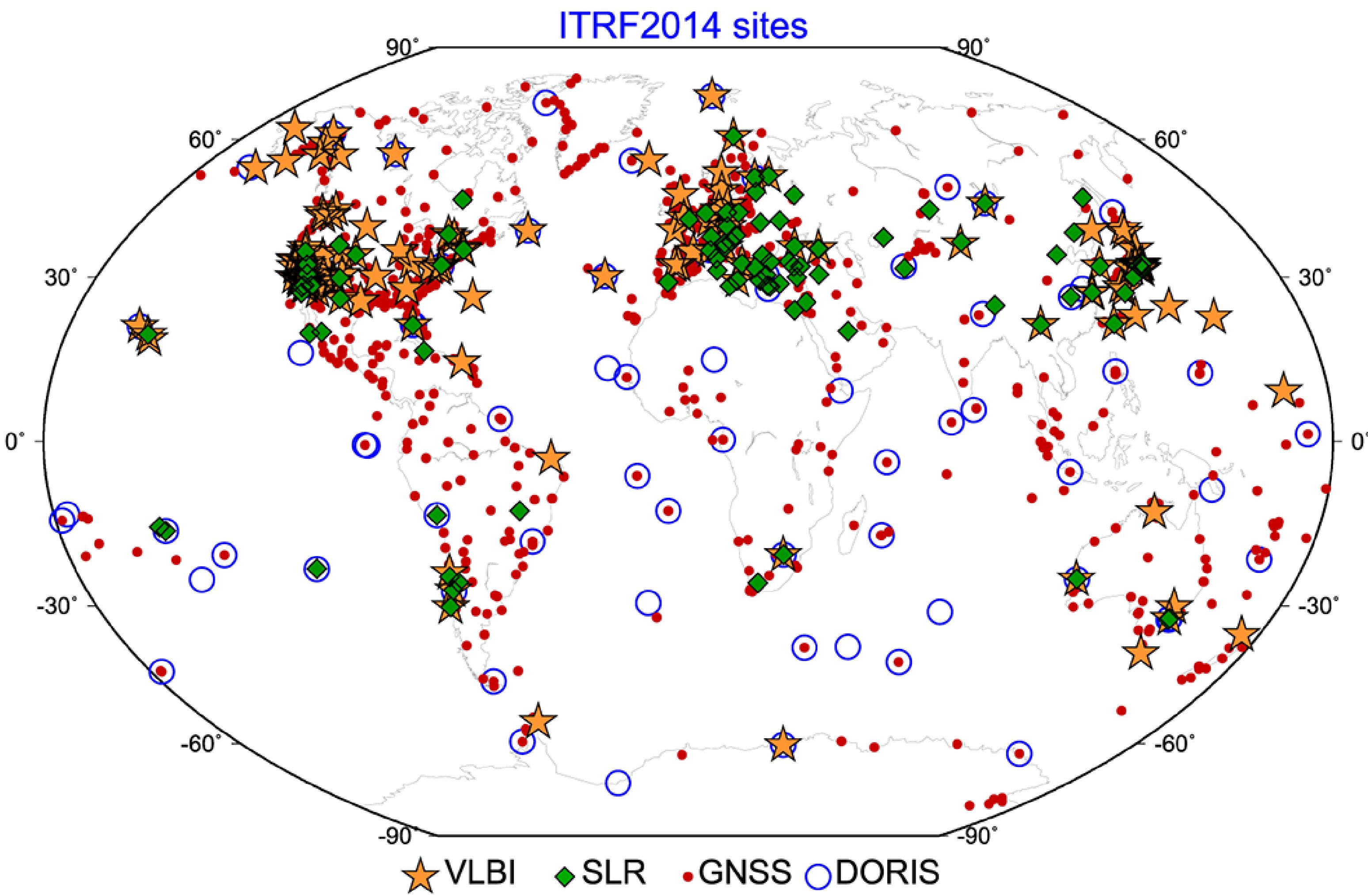
- TRF is simply a table of numbers!
  - Cartesian coordinates (position, velocity) of frame stations

Table 1. WGS 84 (G1150) Cartesian coordinates* and velocities for epoch 2001.0

Station Location	NIMA Station Number	X (km)	Y (km)	Z (km)	$\dot{X}$ (cm/yr)	$\dot{Y}$ (cm/yr)	$\dot{Z}$ (cm/yr)
Air Force Stations							
Colorado Springs	85128	-1248.597295	-4819.433239	3976.500175	-1.8	0.1	-0.4
Ascension	85129	6118.524122	-1572.350853	-876.463990	-0.3	-0.5	1.0
Diego Garcia	85130	1916.197142	6029.999007	-801.737366	-4.2	2.0	3.1
Kwajalein	85131	-6160.884370	1339.851965	960.843071	2.1	6.7	2.7
Hawaii	85132	-5511.980484	-2200.247093	2329.480952	-1.0	6.3	3.0
Cape Canaveral	85143	918.988120	-5534.552966	3023.721377	-1.0	-0.2	0.2
NGA Stations							
Australia	85402	-3939.182131	3467.075376	-3613.220824	-4.08	0.36	4.73
Argentina	85403	2745.499065	-4483.636591	-3599.054582	0.21	-1.00	0.70
England	85404	3981.776642	-89.239095	4965.284650	-1.38	1.65	0.77
Bahrain	85405	3633.910757	4425.277729	2799.862795	-2.97	0.91	2.53
Ecuador	85406	1272.867310	-6252.772219	-23.801818	0.30	0.04	0.99
US Naval Observatory	85407	1112.168358	-4842.861664	3985.487174	-1.48	-0.01	0.10
Alaska	85410	-2296.298410	-1484.804985	5743.080107	-2.22	-0.36	-0.92
Alaska**	85410	-2296.298460	-1484.805050	5743.080090	-2.22	-0.36	-0.92
New Zealand	85411	-4780.787068	436.877203	-4185.258942	-2.35	1.92	2.20
South Africa	85412	5066.232133	2719.226969	-2754.392735	0.01	2.09	1.40
South Korea	85413	-3067.861732	4067.639179	3824.294063	-2.90	-0.76	-1.02
Tahiti	85414	-5246.403866	-3077.285554	-1913.839459	-4.25	4.68	2.91

* Coordinates are for the electrical phase centers of the antennas.
** Post 3 November 2002 earthquake. Steady-state velocity is assumed to be unchanged.

Example: ITRF2014 Techniques



1499 stations at 975 sites. Each technique has its strengths and weaknesses.

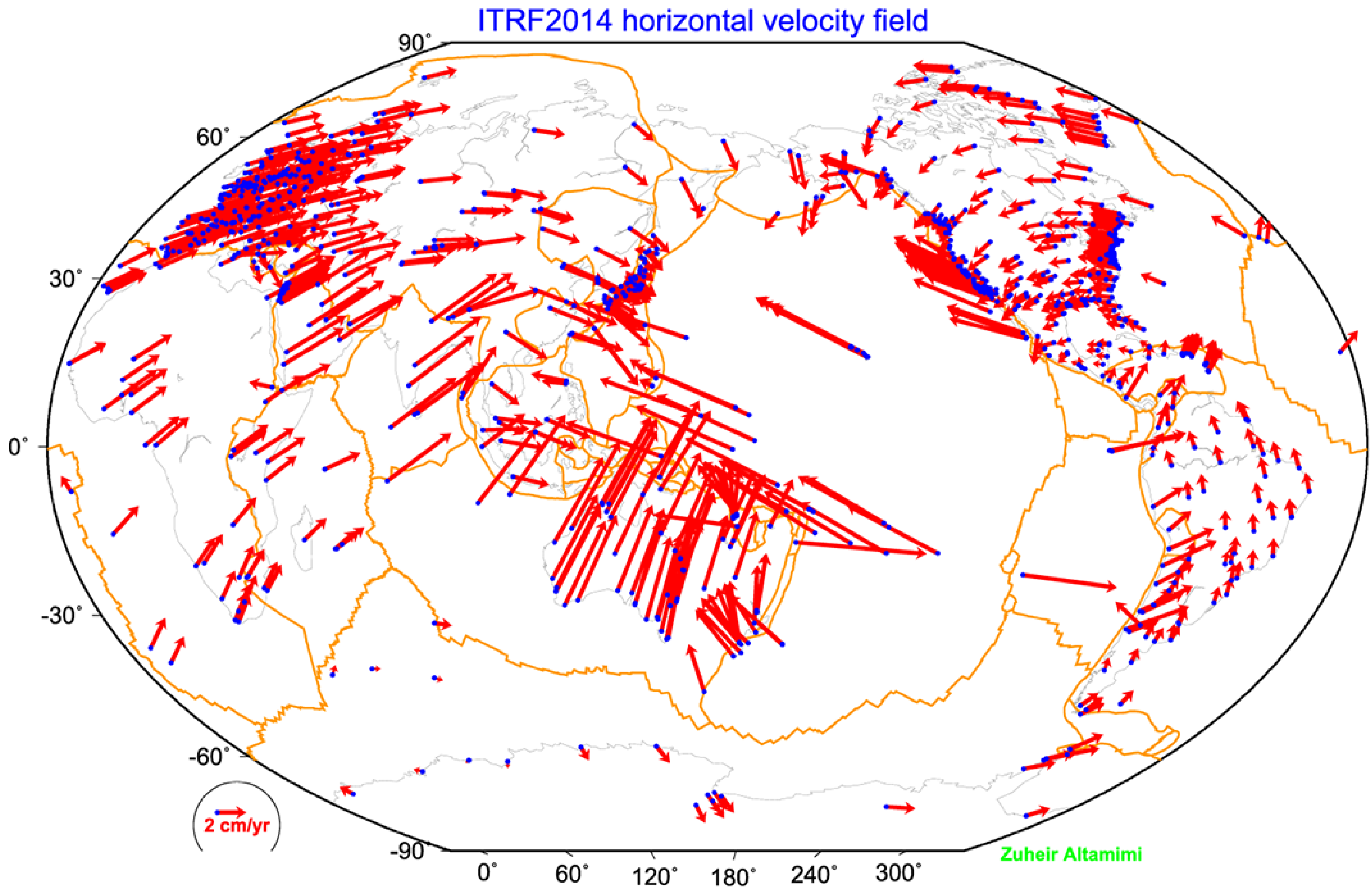
Reference: Altamimi Z., et al., http://onlinelibrary.wiley.com/doi/10.1002/2016JB013098/full

Technique Contributions

Technique - **Signal** - **Source** - **Observation type**	**VLBI** - **Microwave** - **Quasars** - **Time difference**	**SLR** - **Optical** - **Satellites** - **2-way range**	**GPS/DORIS** - **Microwave** - **Satellites** - **Biased range**
Celestial Frame and UT1 (rotation)	Yes	No	No
Polar Motion	Yes	Yes	Yes (strong)
Scale	Yes	Yes	No
Geocenter	No	Yes (strong)	Yes
Internal Geometry	Yes	Yes	Yes
Spatial coverage	Sparse & Global	Sparse & Global	Dense & Global
Temporal coverage	Daily, since 1980	Weekly, since 1983	Daily*, since 1992

*GPS high-rate solutions also available

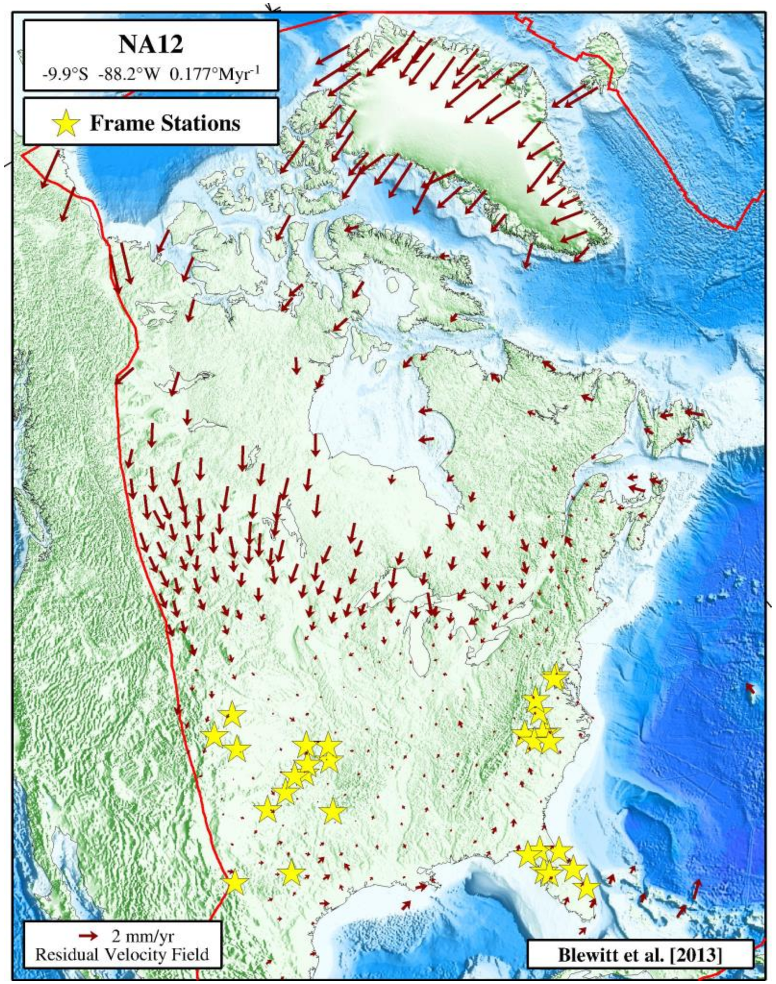
Example: ITRF2014 Velocities

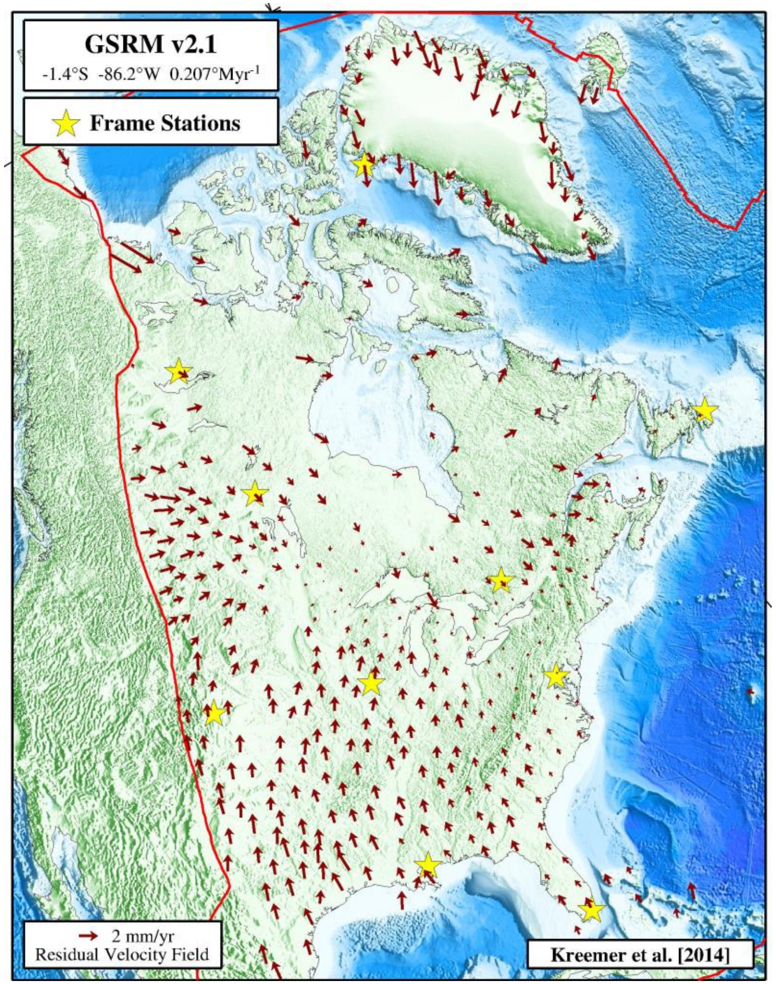


Largely reflects rotation of the tectonic plates

Examples of TRF: Plate-fixed

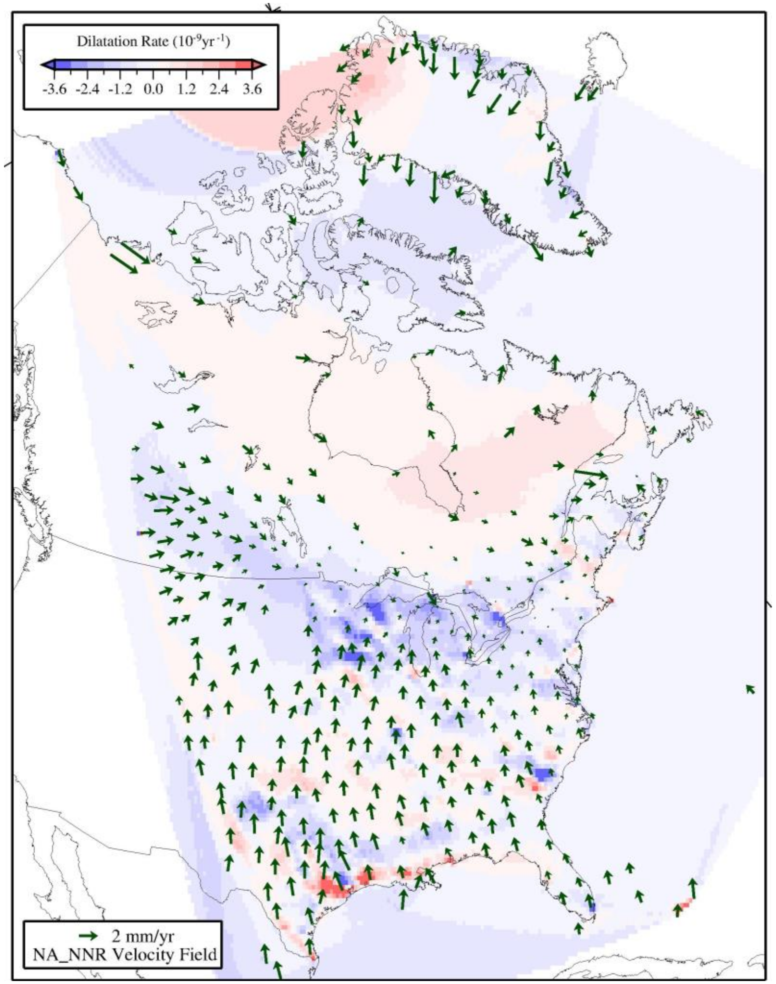
- North America: same velocity field, different frame



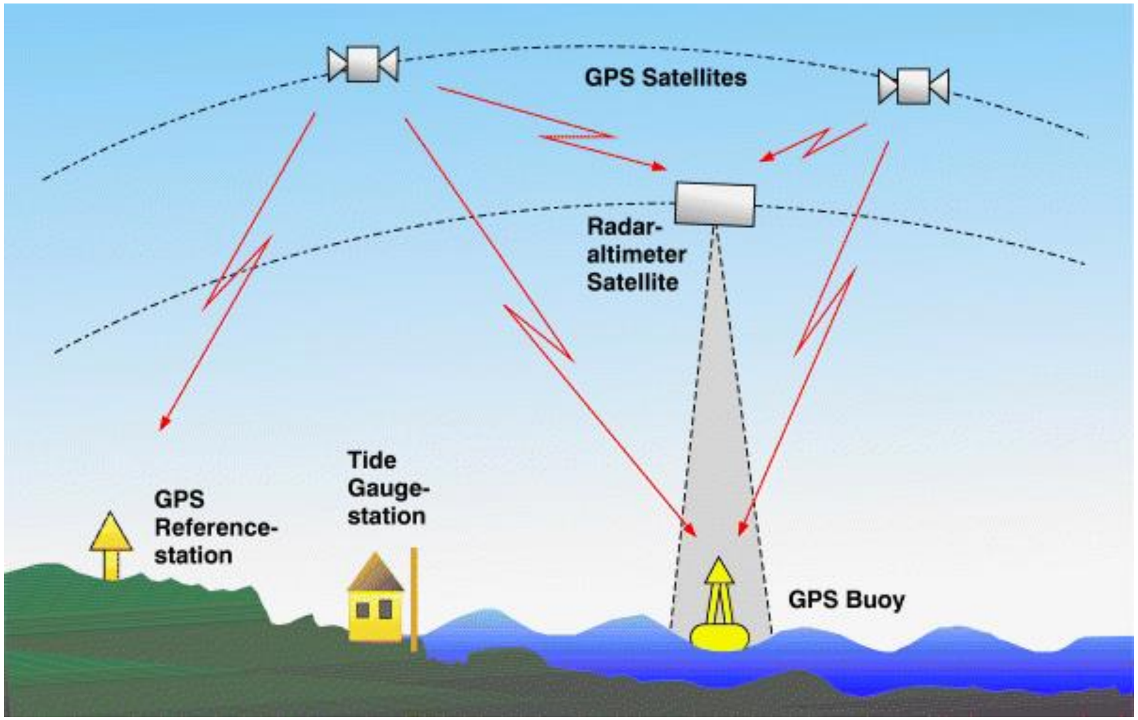


Frames and Strain Rate

- Strain = deformation (shear) + area change (dilitation)
- Strain rate = velocity gradient
- Strain rates look the same in different rotational frames
- Scientific interpretation of strain is not frame dependent



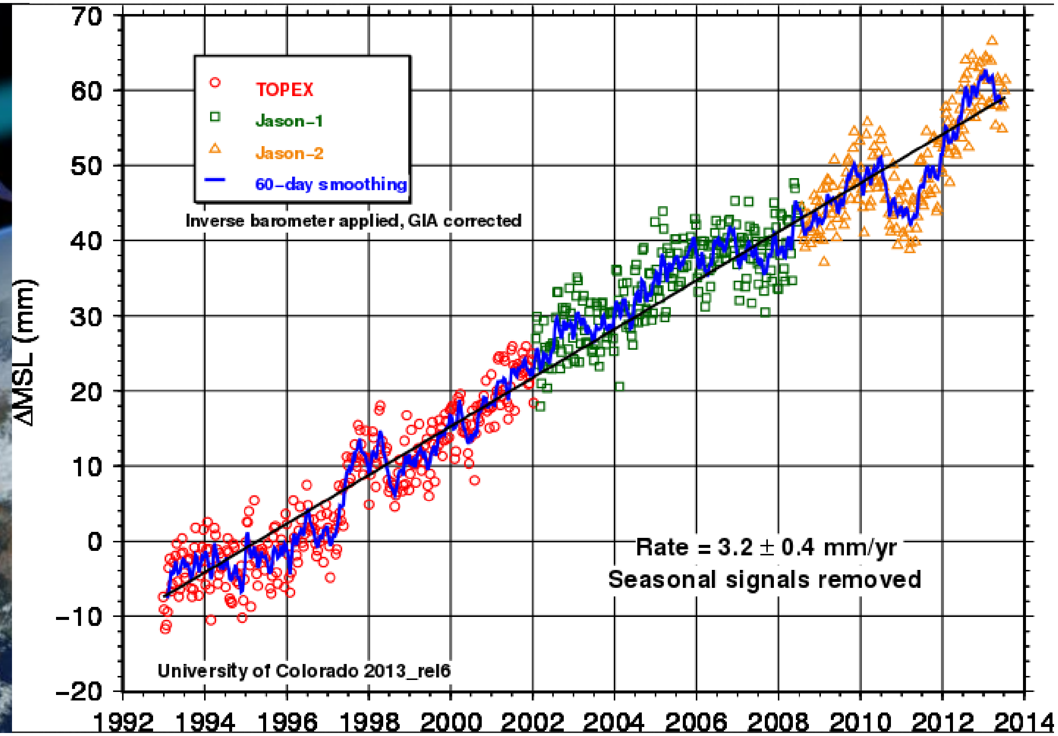
Inter-Technique Consistency



- Sea Level System
  - Reference stations used to position GPS satellites in TRF
  - GPS satellites used to position the radar altimeter satellite
  - Radar measures range to sea surface below satellite
  - Radar bias is calibrated by using GPS buoys
  - GPS buoys positioned in TRF
  - Hence <u>geocentric sea level</u> (relative to Earth's center)
  - GPS at tide gauges measures vertical land motion (VLM)
  - Hence <u>relative sea level</u>, important for local impacts

Temporal Consistency/Stability

- Connecting satellite missions



- All missions need orbits in the same TRF, consistent in time
  - Requires that frame station coordinates be accurately “predictable”
  - Requires that frame stations be physically stable and calibrated (antennas)

TRF Characteristics

- What is the "Primary Mission" of a TRF?
  1. Predictability
     - Ability to predict accurately the coordinates of a network of stations required by the user at any time needed – past, current, and future
     - Requires temporal consistency and stable stations
  2. Consistency
     - TRF can put everyone "on the same page"
  3. TRF must meet users' needs
     - Relevant characteristics to consider...
       1. The Associated Reference System
       2. Datum Definition and Inheritance
       3. Realization
       4. Spatial Coverage
       5. Temporal Coverage
       6. Quality
       7. Life Cycle
       8. Access

TRF Characteristics

(1) The Associated Reference System

- constants, conventions and models
- physical aspects
  - station motion model at the observation level
  - origin aligned to Earth system center of mass (CM)
  - scale is specified in a relativistic framework
    - speed of light, reference gravitational potential
    - models affecting scale: GM, atmosphere, satellite reflectors/transmitters,...
  - orientation
    - no net rotation and how that is realized

TRF Characteristics

(2) Datum Definition and Inheritance

- Method chosen to realize origin, scale, and orientation
  - Example: Origin: Use SLR, setting degree-1 gravity terms to zero
  - Example: Scale: Use VLBI, insensitive to GM
    Use SLR, less sensitive to tropospheric model
    - ITRF 2014 uses average of VLBI and SLR scale
  - Inheritance often used for continuity and consistency
    - Example: maintain same orientation as existing ITRF so as to ensure continuity of polar motion time series
    - Example: ITRF2014 origin and orientation is aligned with ITRF2008
    - Example: IGS08 is aligned with ITRF2008 to ensure datum consistency while improving precision for daily GPS alignment
    - Example: North America frame NA12 was realized using IGS08 time series to ensure datum consistency while allowing for a different no-net rotation condition to meet scientific needs

TRF Characteristics

(3) Realization

- specific aspects of design intended to meet user needs
- selected space-geodetic techniques to supply input data
- selected frame stations and time-window of data
- site collocation and ties
- relative data weights
- estimation of empirical station motion model parameters
  - example: reference epoch, coordinates, velocities, possible steps
  - estimated parameters define the realized frame
  - parameters implicitly define the frame origin, orientation, and scale and their evolution in time
- quality control “QC” (input) & quality assurance “QA” (output)

TRF Characteristics

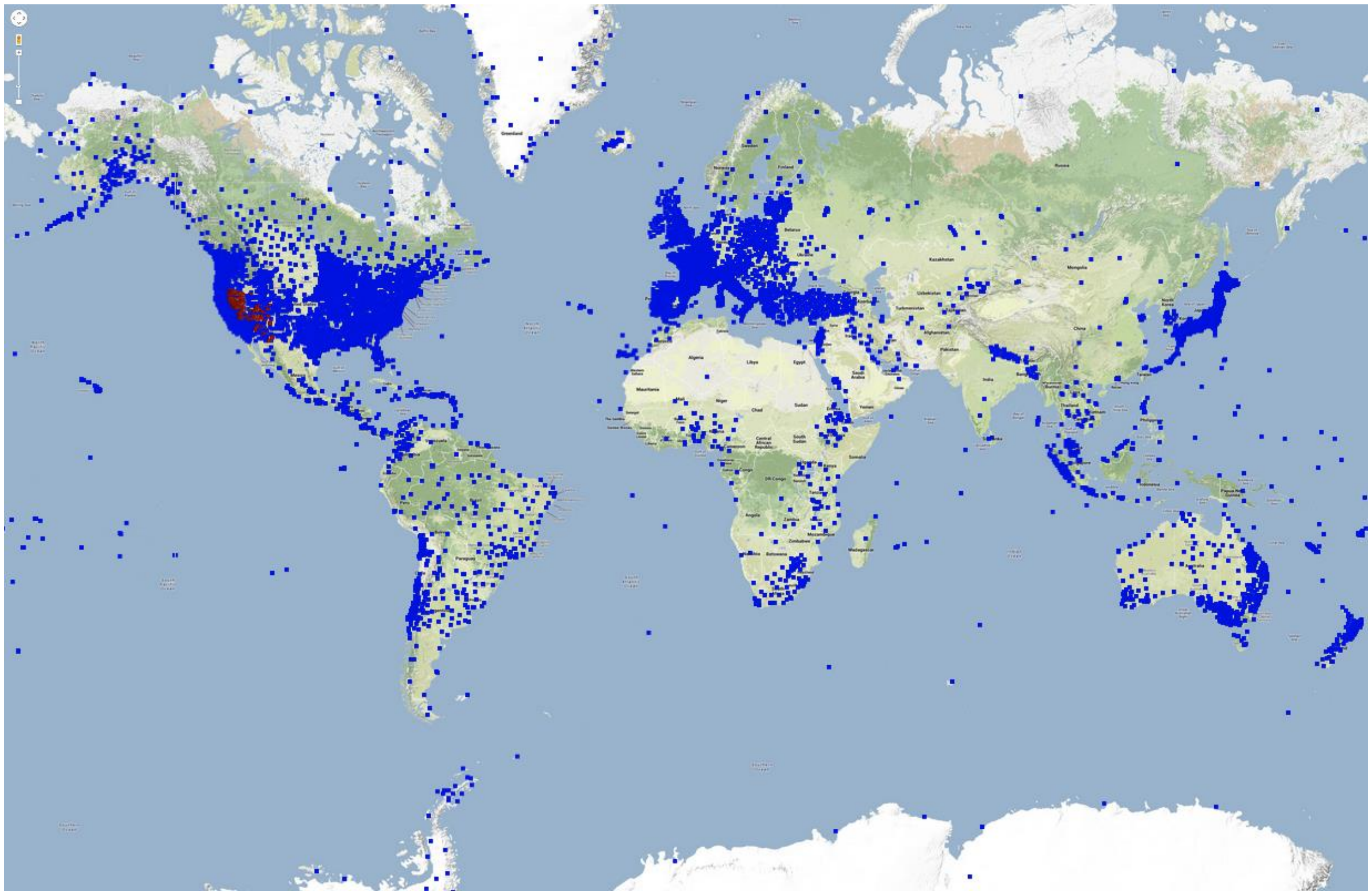
(4) Spatial Coverage

- Global, continental, regional, or local
- Spatial domain of applicability
  - Example: NA12 should only be used in or near North America
- Spatial sampling
  - may be a hemispheric asymmetry
  - may be biased to certain continents with more stations

TRF Characteristics

GPS station distribution (>16,000)

- Time series updated weekly at UNR



TRF Characteristics

(5) Temporal Coverage

- Start date and end date of contributing data
  - reference frames degrade outside this time window
- Time window of applicability per station
  - forced retirement due to earthquake
- Temporal sampling
  - number of contributing frame stations versus time

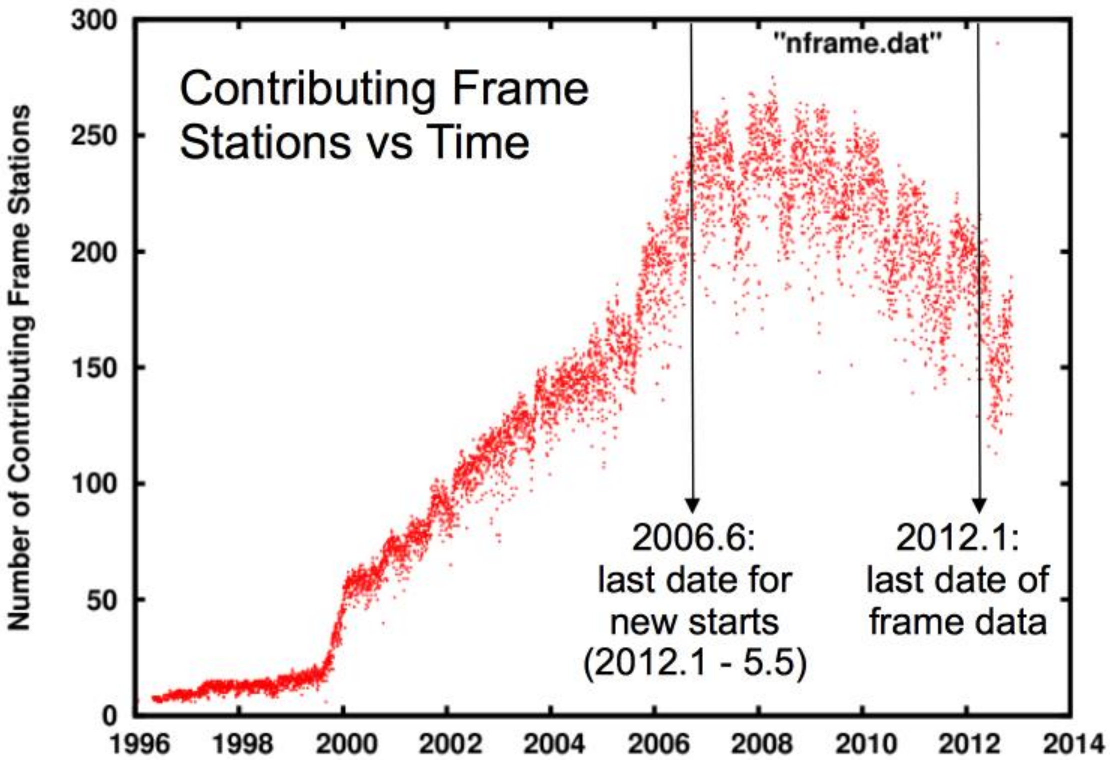
TRF Characteristics

(6) Quality (*NRC, 2010*)

- accuracy of internal geometry (angles between baselines)
- accuracy of external geometry (Earth CM, scale)
- stability (extrapolated positions)
- drift (between frames)
- spatial heterogeneity of errors
- temporal heterogeneity of errors (“heteroscedasticity”)
- connectivity and continuity (“secular frame rigidity”)
  - Collocation
  - site ties
  - steps in time series
  - simultaneous common-view observations
  - carrier phase ambiguity resolution

TRF Characteristics

- TRF improvement and inevitable degradation with time
  - Example: NA12 North America plate-fixed frame



  - Therefore, frames need to be upgraded from time to time

TRF Characteristics

(7) Life Cycle: Step by Step

- user requirements demand new frame
- reference system is upgraded
- reference frame is designed to best meet requirements
- reprocessing over specified time span produces input data
- reference frame is realized and published
- reference frame is used
- reference frame may be inherited by new frames
- reference frame degrades with time after end-date of input data
- *repeat cycle*...

Importance of Data Sharing

- Consistency
  - Clearly a globally consistent TRF requires global coverage
  - Many stations required for best quality and future stability
  - Requires global, public sharing of data
- Quality
  - Sharing leads to multiple users checking the same data
  - Leads to shared QC (input), QA (output), and lessons learned
  - Leads to better decision making and outcomes
    - products, applications, science, ...
- Economic/Societal Perspectives
  - High-quality TRF is assured for any region sharing its data
  - Benefits all commercial enterprises using GNSS
  - Robust monitoring/assessment/warning of natural hazards
    - Earthquakes, tsunamis, volcanoes, landslides, coastal inundation,...

NASA Plug and Play Concept

1. User
   - installs GPS station
   - registers metadata on-line at UNAVCO
   - makes receiver data available (data files or streaming)
2. UNAVCO
   - UNAVCO picks up data and makes RINEX files
   - RINEX files publicly available on UNAVCO archive
3. Nevada Geodetic Lab (University of Nevada, Reno)
   - notified by UNAVCO
   - picks up RINEX files and processes data
   - makes various products publicly available on NGL web page

NGL Products

- Publicly available at http://geodesy.unr.edu
  - ”Final” coordinate time series
    - 24-hour epochs, ~2 mm East/North, ~7 mm Up
    - Updated weekly; latency 1-2 weeks
  - ”Rapid” coordinate time series
    - 24-hour epochs, ~ 2 mm East/North, ~7 mm Up
    - 5-minute epochs, ~7 mm East/North, ~20 mm Up
    - Updated daily; latency 1 day
  - “Ultra-Rapid” coordinate time series (needs hourly RINEX)
    - 5-minute epochs, ~10 mm/East/North, ~30 mm Up
    - Updated hourly; latency 2-3 hours
  - Quality assurance (QA) statistics on in
    - 24-hour statistics on fits to data from individual stations
  - Time series discontinuity file
    - Earthquakes, equipment changes, empirically detected steps
  - MIDAS station velocities robust to data problems and steps

Conclusions

- Reference frames are critical to get the best out of your GNSS data
  - Quality and consistency in space and time
  - Everyone is on ”the same page”
- Sharing raw data in a better frame for everyone
- Sharing data products can motivate sharing of raw data
- Sharing of our experiences with publicly-available data (raw and products) improves outcomes for everyone
  - Scientific, commercial, and natural hazards applications
  - User community becomes better educated and aware