Towards a Future
Predictive Non-Linear Terrestrial Reference Frame
For Improved
Early Detection of Geohazards and
Disaster Mitigation

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Inspired by
T.A. Herring, G.Blewitt, W. Hammond, H. Drewes, Z. Altamimi, and others

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Contents

Introduction

The geohazards-related objectives:

- Facilitating assessments of geohazards;
- Supporting timely detection of specific hazardous events;
- Providing post-event assessments.

The main geodetic tools:

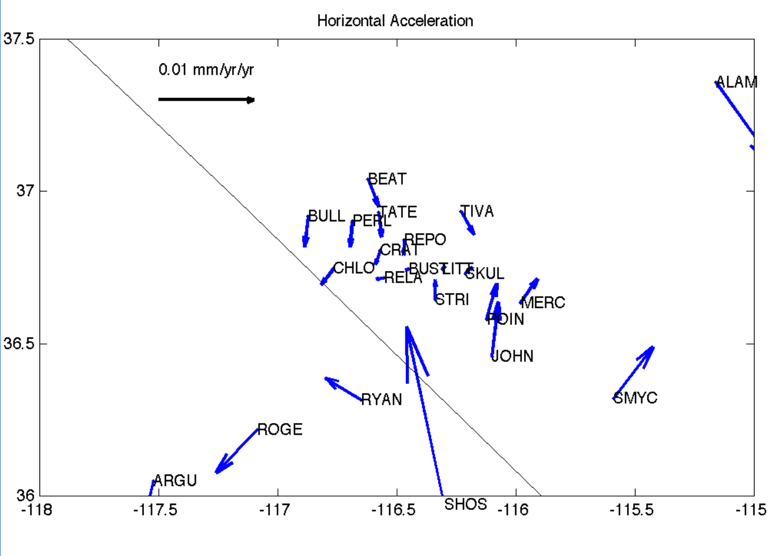
- Monitoring point motion;
- Determination of strain rates;
- Detecting of “anomalous” motion.

Hector Mine Earthquake, 1999 (M7.1, Southern California)

Goal:
Detection of post-seismic deformation

Predicted Accelerations (Example)

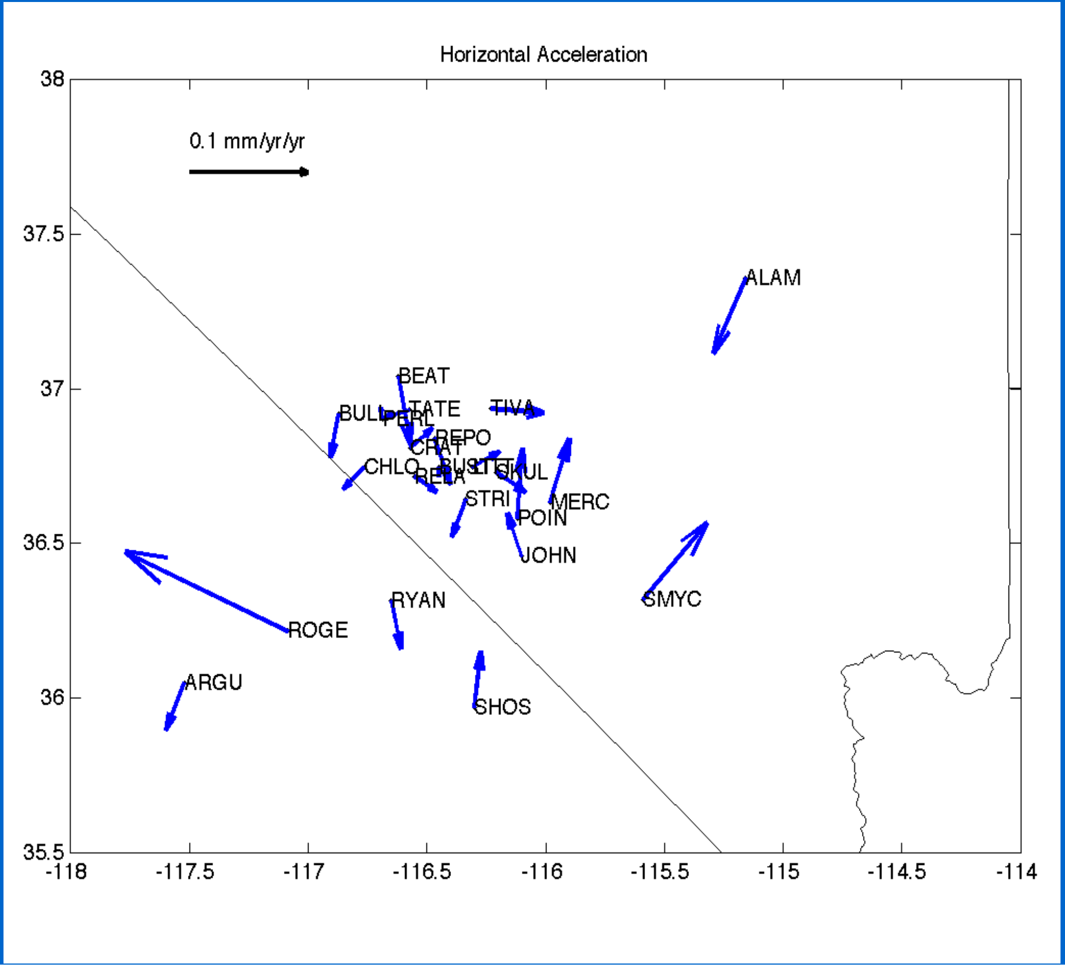
Generated using VISCO1D (Pollitz, 1997)



From Kreemer et al. (2007)

Observed Accelerations

- Time series are spatially filtered
- Magnitude of observed accelerations is 0.01 to 0.1 mm·yr^{-2}, with uncertainties ~0.01-0.02 mm·yr^{-2} per component.
- No vertical accelerations detected



Introduction

*Condensing the essential goal of a global terrestrial reference frame, we state that while the primary goal in the **past** was to allow for the determination of **point position**, the primary goal **today** is to allow for the monitoring of **point motion**.*

- In geodetic analyses, we don't really determine point motion.
- We determine time series of "displacements"
- Displacement is the difference between predicted and computed positions

Concept of "anomalous motion" *(Herring et al., 2007)***:**

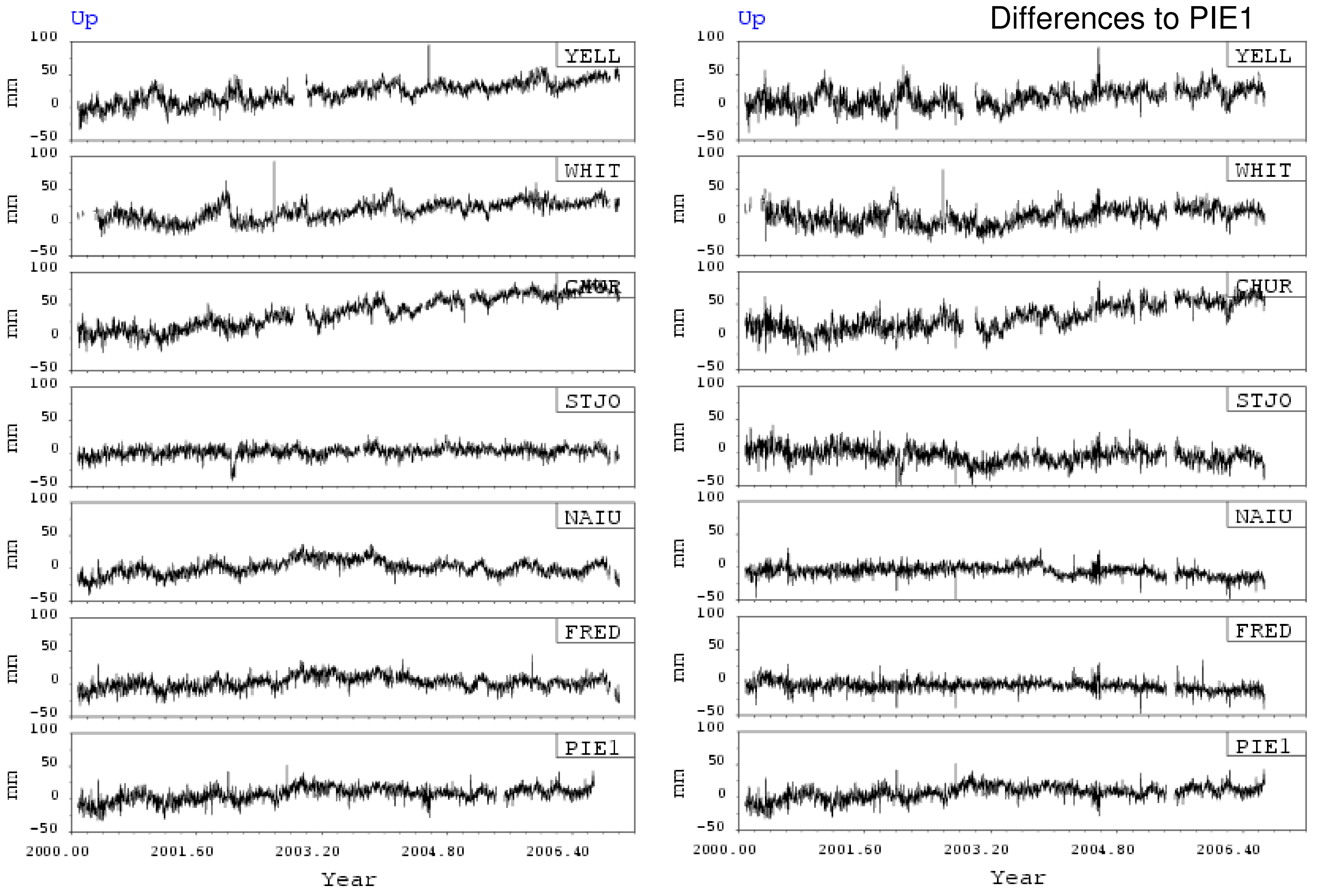
- Deviation from the predicted motion.
- High demands on quality of predicted motion:

Success in detection of anomalous motion depends on quality of reference frame

Limitation of Reference Motion

- Space-geodetic time series of Earth's surface point displacements contain unexplained variations -->;
- Sub-daily to decadal geophysical signals are significantly biased;
- Spatial and temporal resolution of the monitoring insufficient;
- Ground-based network geometry and temporal stability -->;
- Technique specific problems (antenna characteristics, satellite models, ...)
- Reference frame definition, determination, and maintenance

Time Series of Vertical Displacements – North America



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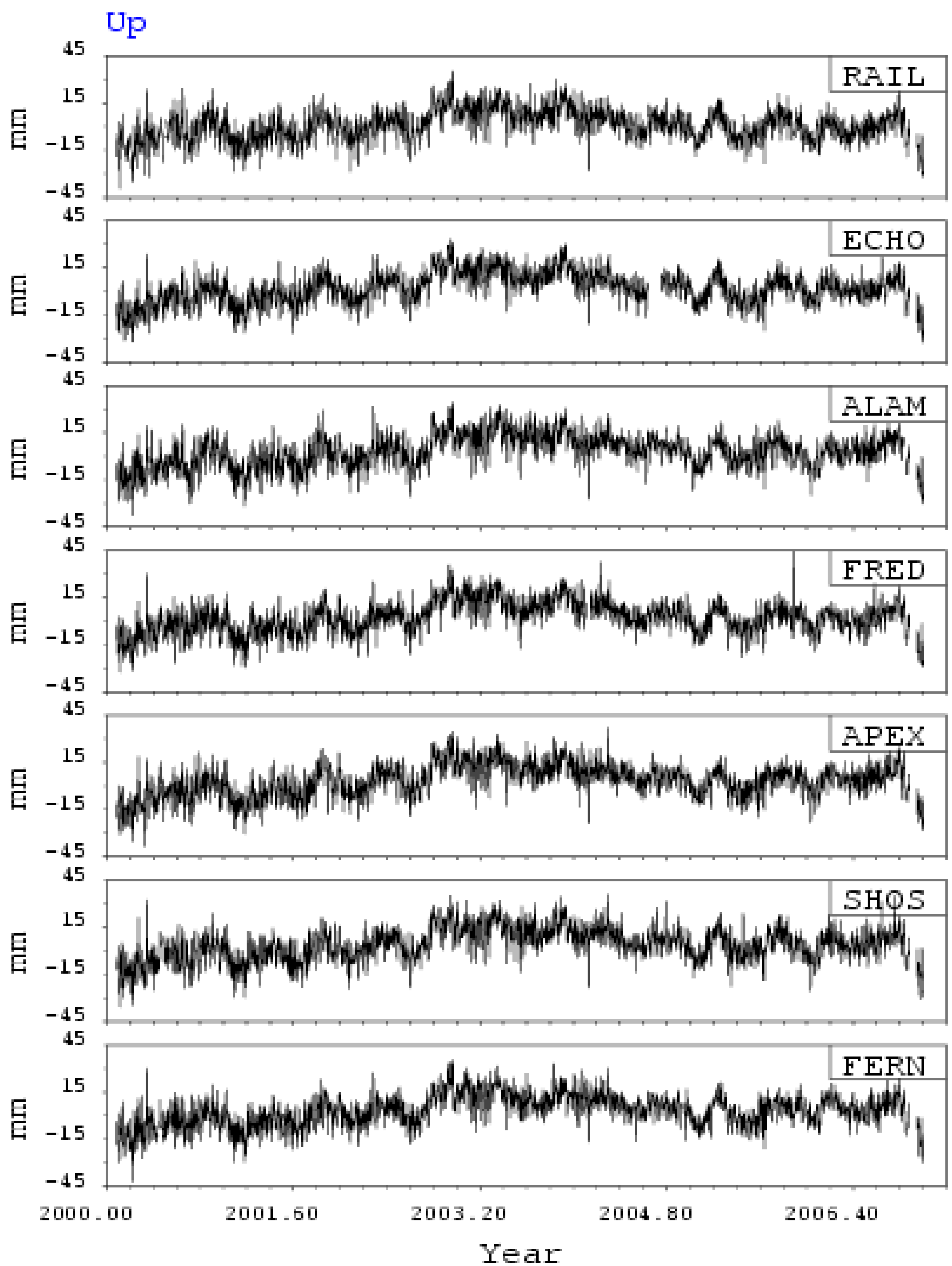
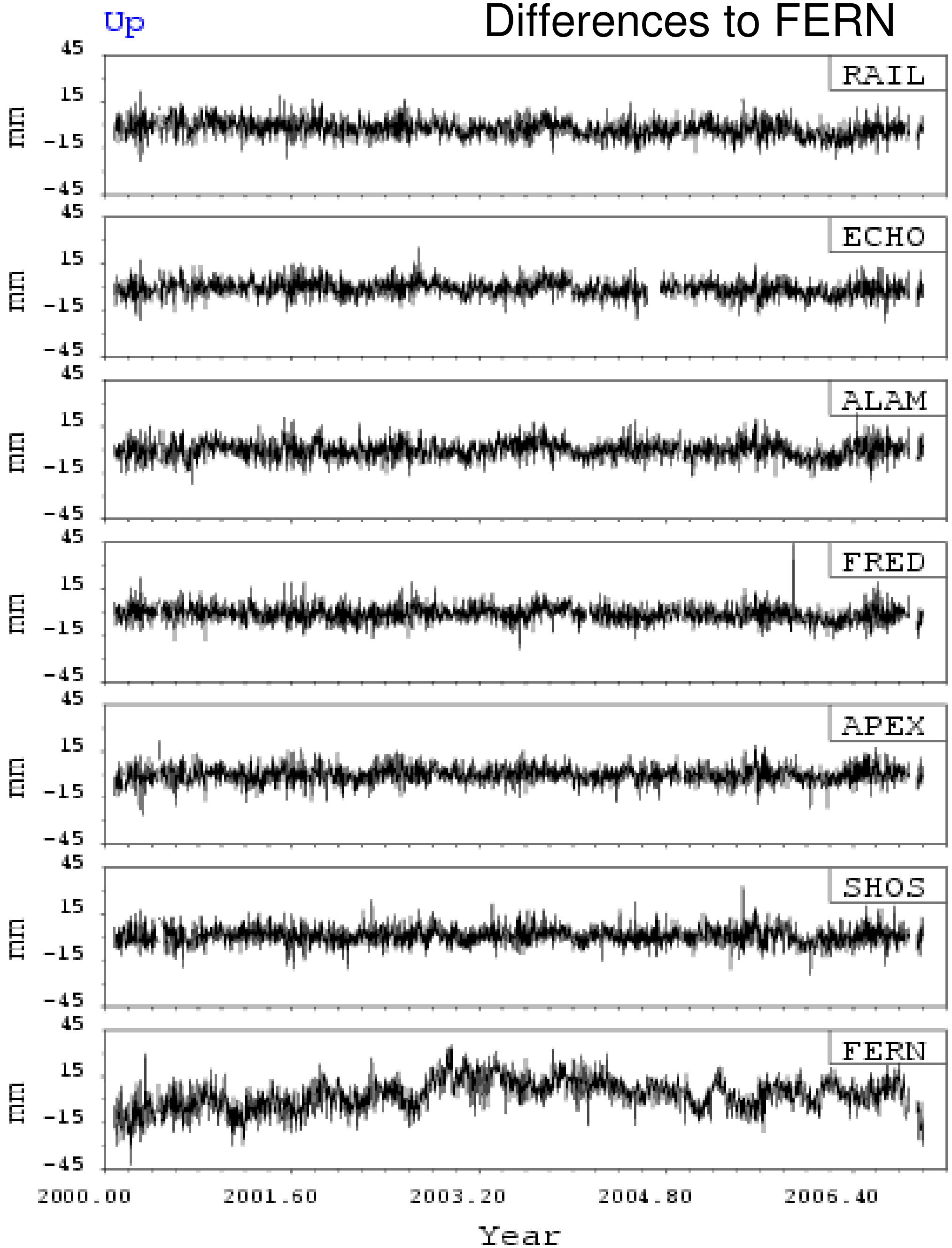


Differences to FERN



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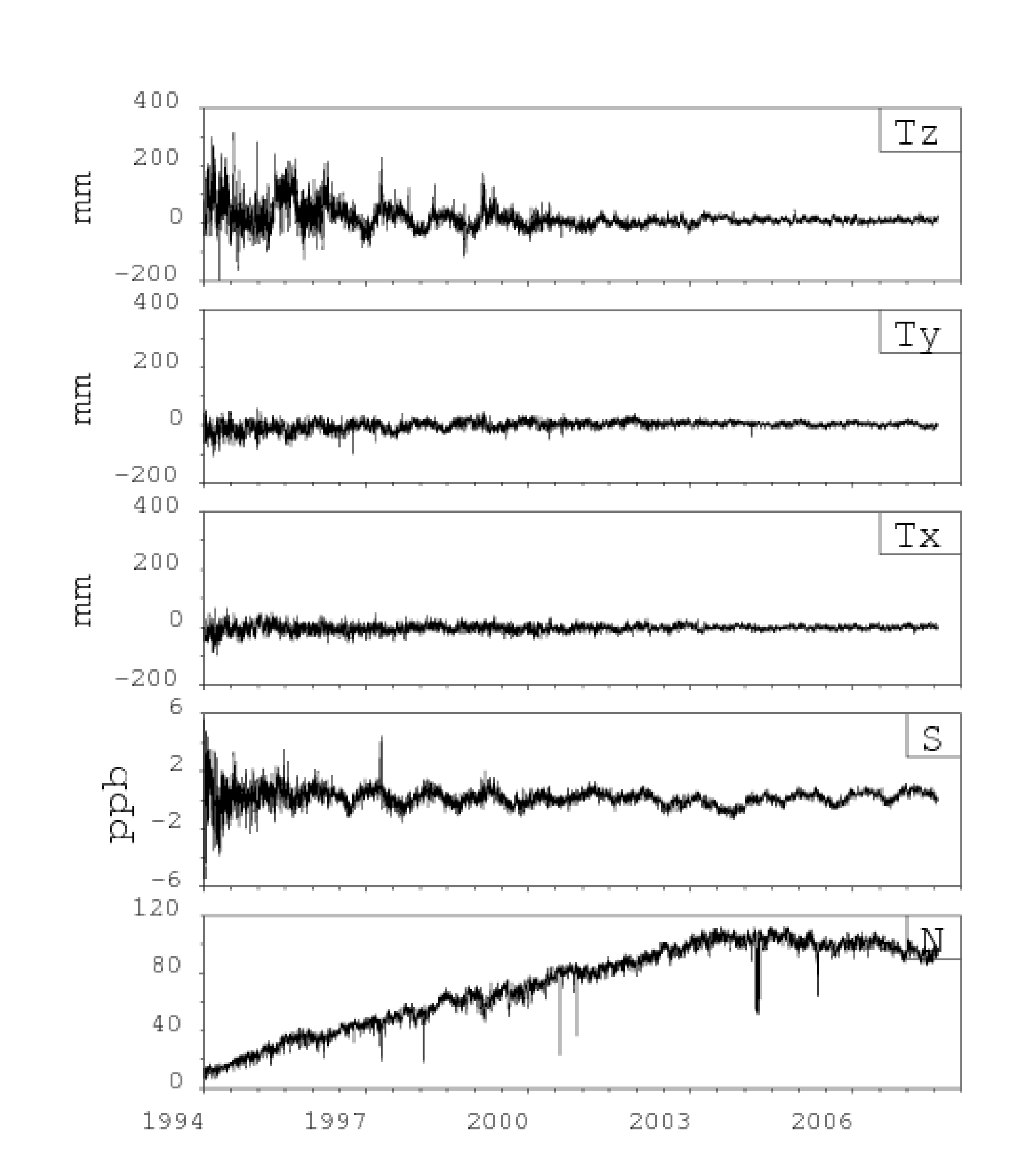
The Network

Aligning free solutions to the ITRF

- (Helmert) Transformation: Rotation, translation, scale;
- Fit to "secular ITRF polyhedron";
- Challenge: Change in network geometry;
- Leakage of unmodeled geophysical signals



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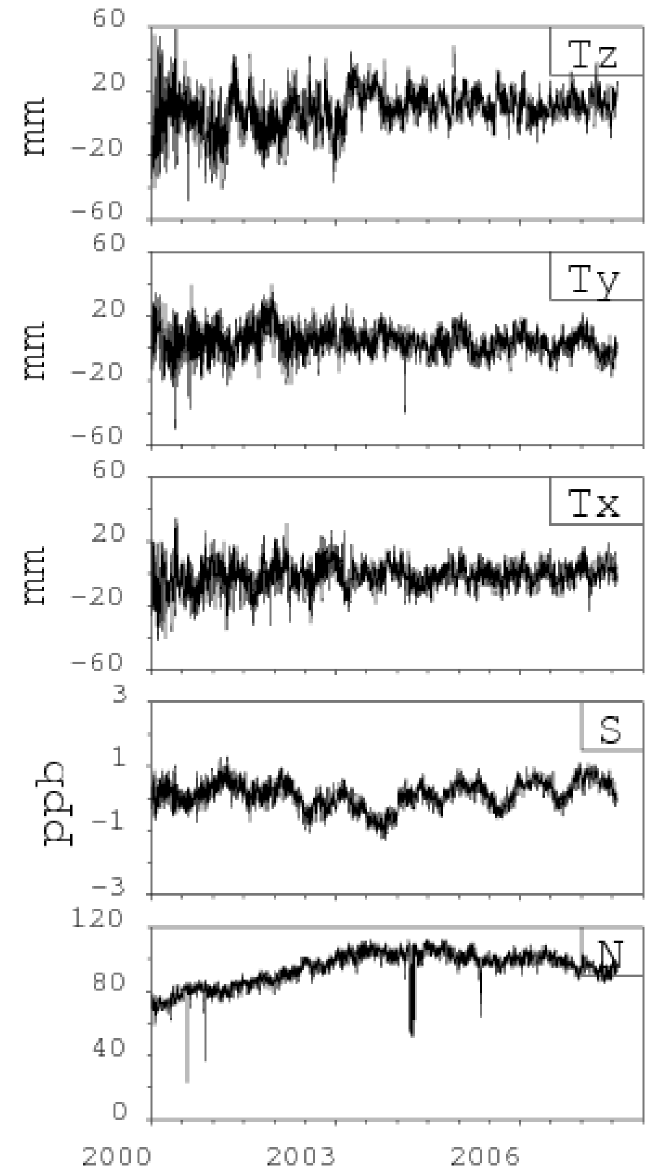

Limitation or Reference Motion

- Space-geodetic time series of Earth's surface point displacements contain unexplained variations -->;
- Sub-daily to decadal geophysical signals are significantly biased;
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- Ground-based network geometry and temporal stability -->;
- Technique specific problems (antenna characteristics, satellite models, ...)
- Reference frame definition, determination, and maintenance: Our Focus.

ITRF: Brief Review of Current Conventions

Definition of ITRF:

- Polyhedron with the motion of the vertices given as “regularized coordinates”:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0)$$

Coordinates and Velocities $\vec{X}_0^{(i)}, \vec{V}_0^{(i)}$: are:

- Determined from observations;
- Affected by “station motion model”, troposphere & ionosphere treatment, antenna model, analysis strategy, ...

Access to the ITRF:

- Through GNSS: Accurate satellite orbits and clocks and EOP.
- These global parameters are affected by station motion model, ...
- Consistency of global parameters with the ITRF determination.

ITRF: Brief Review of Current Conventions

- Station motion model (depending on length of analysis interval):

$$\vec{X}(t) = \vec{X}_0 + \sum_{k=1}^{K} g_k(t, \vec{X})$$

$$\vec{X}(t) = \vec{X}_0 + \vec{V}_0 \cdot (t - t_0) + \sum_{k=1}^{K} g_k(t, \vec{X})$$

- Conventional models:
  (1) Earth tides,
  (2) ocean tidal loading,
  (3) pole tide

Contributions not included in the reference and station motion model are globally filtered and/or biased!

Extending the Reference Frame Concept

Potential extensions of station motion model:

- Atmospheric tidal loading
- Atmospheric loading
- Ocean non-tidal loading
- Terrestrial water storage
- Earthquake displacement fields

$$\vec{X}(t) = \vec{X}_0 + \sum_{k=1}^{K} g_k(t, \vec{X})$$

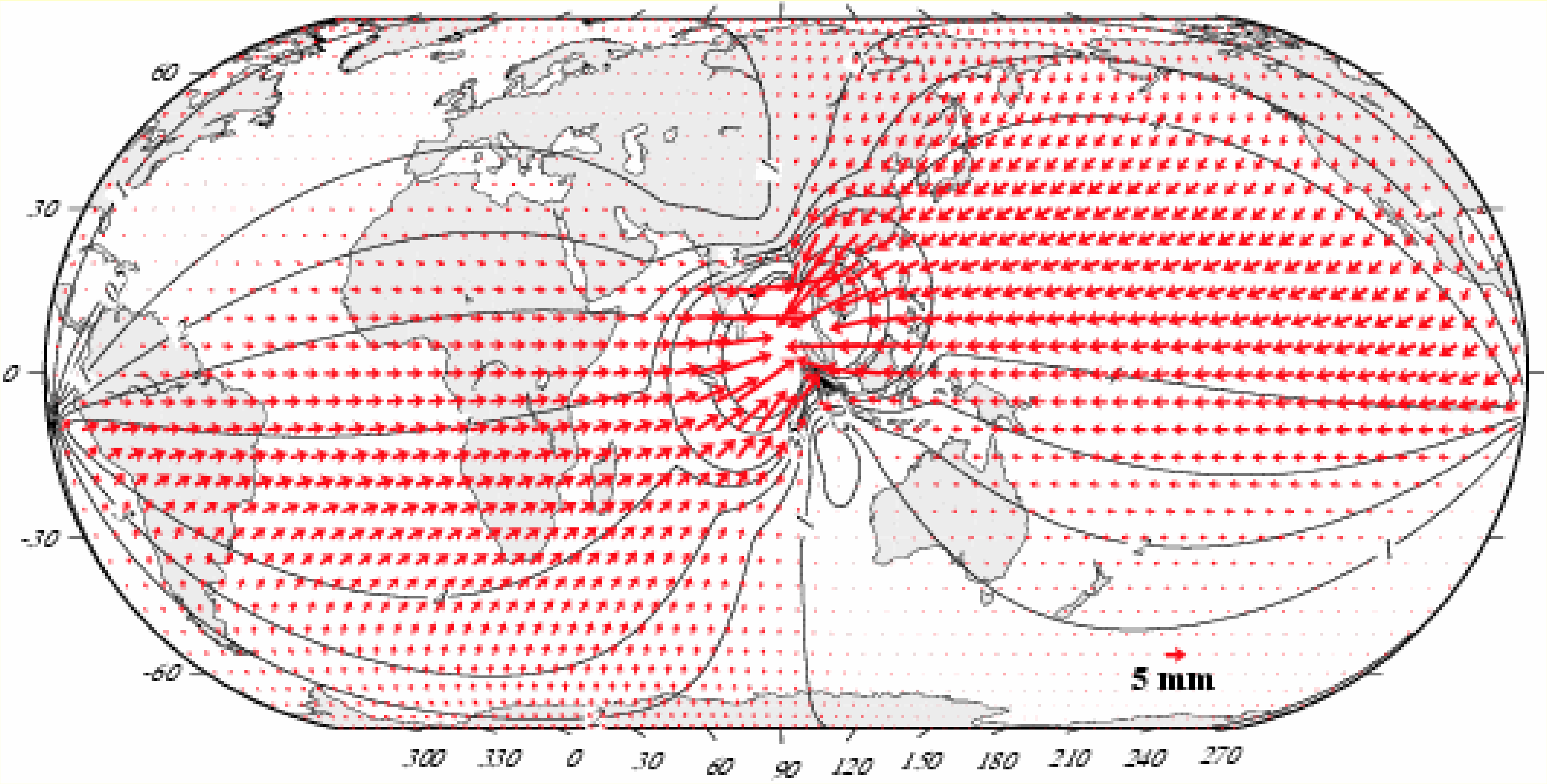
$$\vec{X}(t) = \vec{X}_0 + \vec{V}_0 \cdot (t - t_0) + \sum_{k=1}^{K} g_k(t, \vec{X})$$

Extensions either in:

- Station motion model in processing of observations
- Regularized coordinates used in the alignment of solutions to ITRF

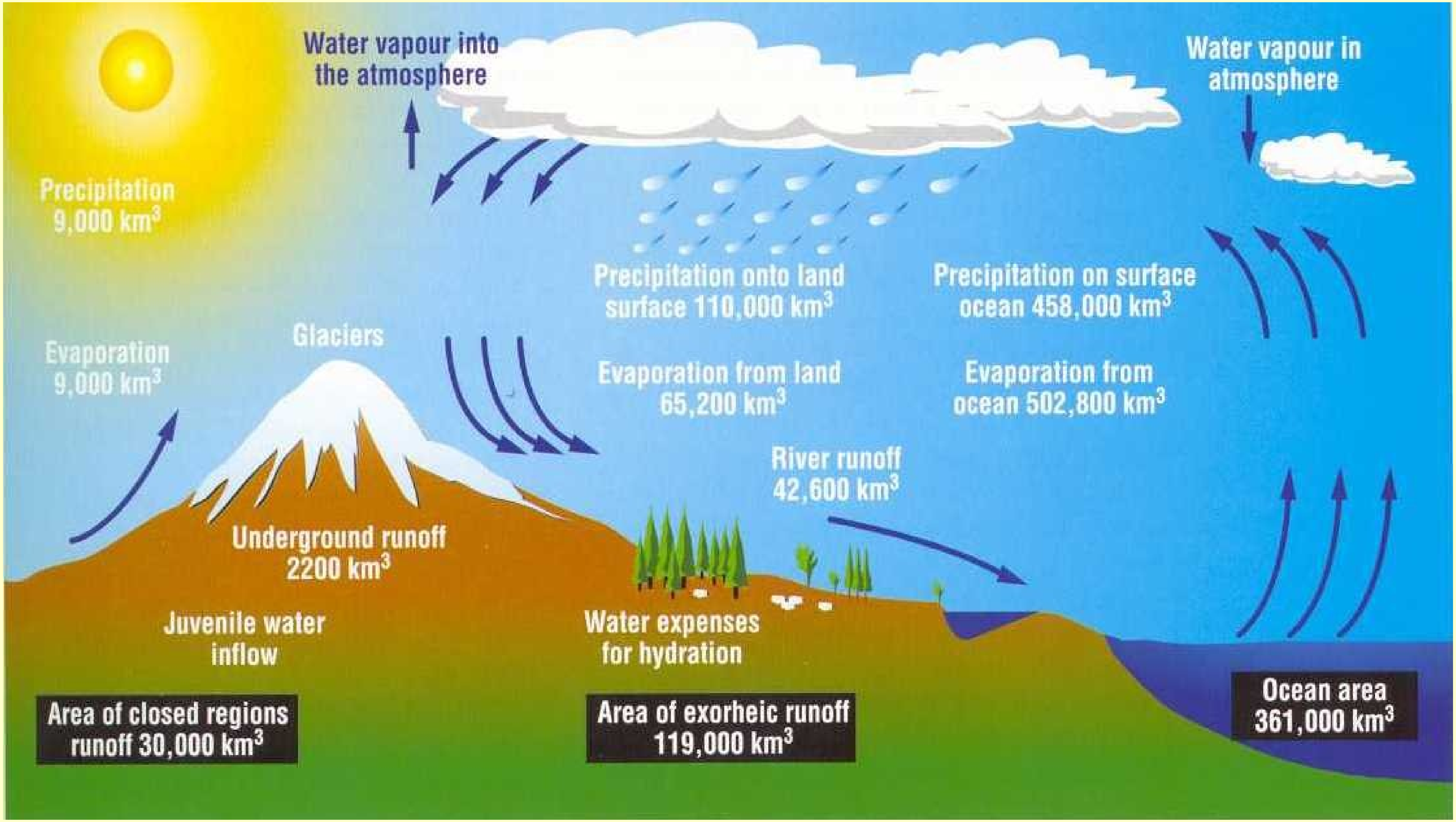
Extending the Reference Frame Concept

Global displacement field of the Sumatra Earthquake of December 26, 2004 as predicted by a global model



Plag et al., 2006

Comments on the model



At time scales from sub-daily to decades, the largest mass redistributions on the surface of the solid Earth mainly occur in the global hydrological cycle, i.e., the water stored in atmosphere, ocean, on land, in glaciers, and ice sheets.

Comments on the model

Prediction of geodetic fingerprints of mass redistribution in hydrological cycle requires gravitationally consistent modeling: *The geodetic signals of mass redistribution in the global hydrological cycle need to be modeled in a gravitationally consistent integrated model of the Earth system accounting for the linkage between reservoirs in the hydrological cycle as well as the feedback of the changes in Earth's shape, gravity field and rotation on the distribution of mass in these reservoirs (Clarke et al., 2005).*

Separate models of the main reservoirs not sufficient to meet accuracy requirements: *A conventional approach to load-induced geodetic signals based on* ***separate models*** *for the main reservoirs of the global hydrological cycle will* ***not meet*** *the accuracy and consistency goal of 1 ppb (Plag et al., 2007).*

Comments on the Model

Extending the reference frame concept:

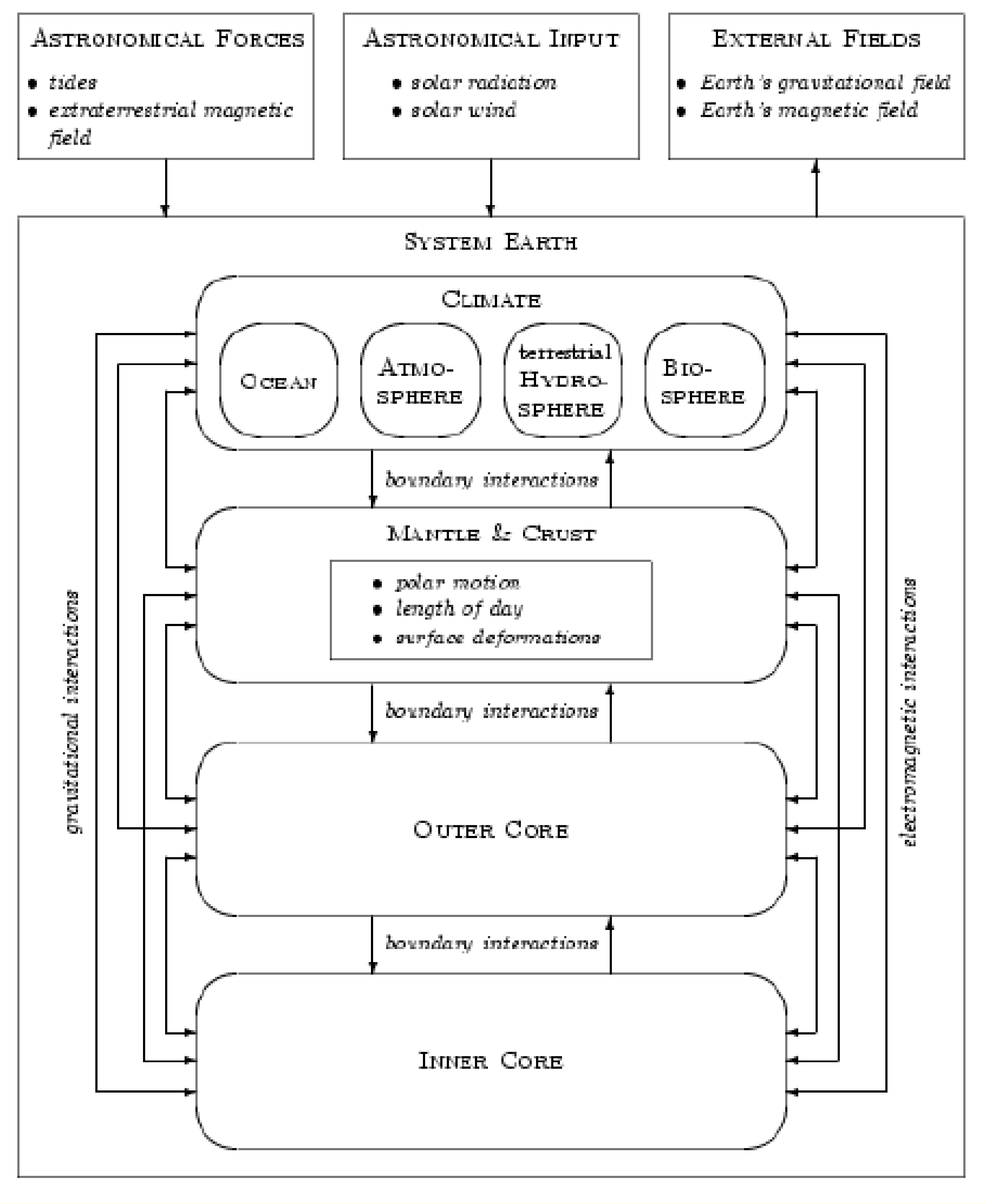
- Dynamic Reference Earth Model (DREM)
- Reference motion for any point on Earth (not just the polyhedron):

$$\vec{X}(t) = \vec{X}_0 + \vec{V}_0(\vec{X})(t - t_0) + \delta\vec{X}(\vec{X}_0, t)$$

with $\delta\vec{X}(\vec{X}_0, t)$ predicted by the DREM

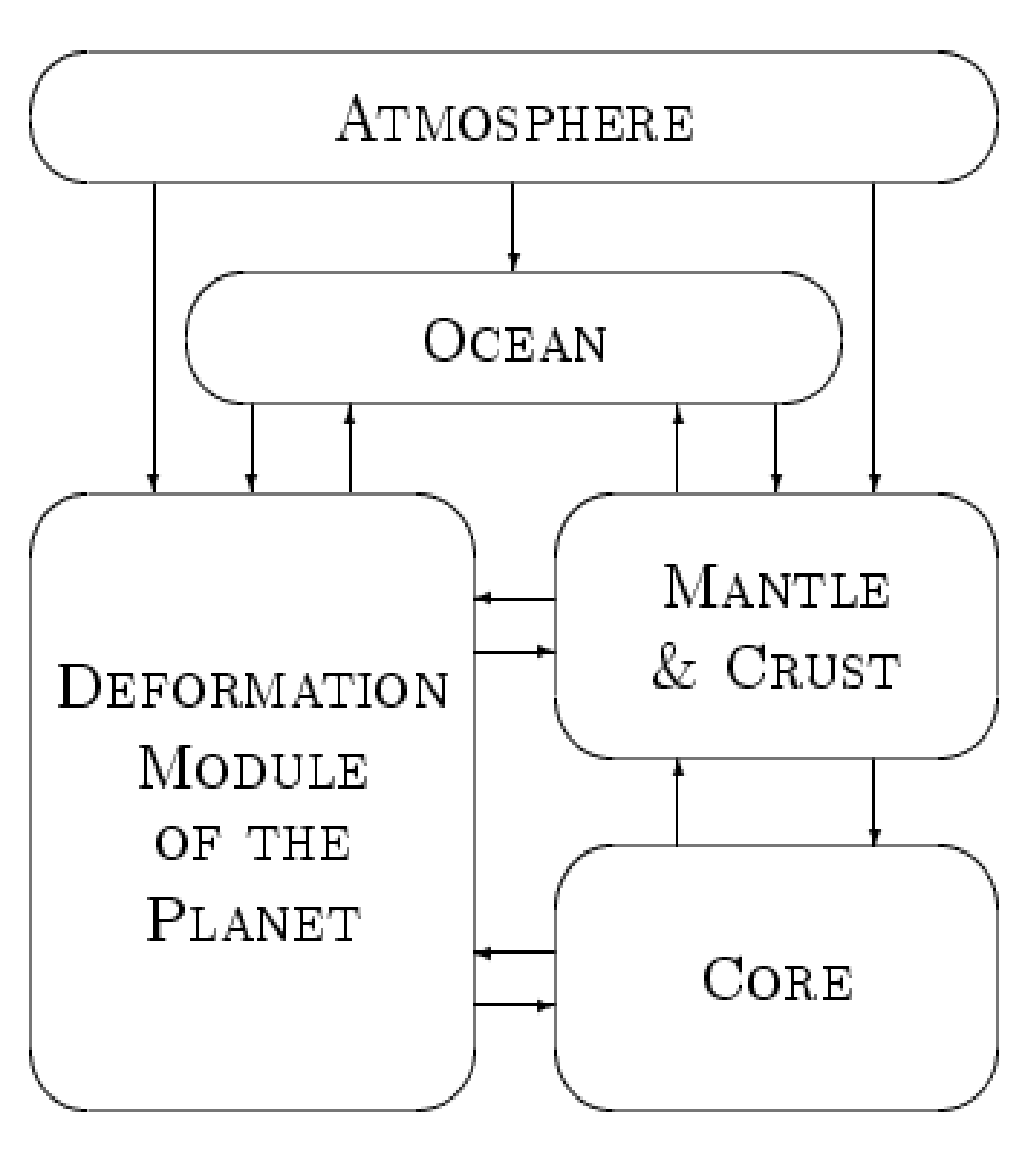
In order to capture geophysical signals unbiased and unmodified in space-geodetic time series of surface displacements, a reference frame approach based on a dynamic reference Earth model is required.

Comments on the Model



- Complex system
- Modular approach to modeling
- Comparable to climate modeling
- Independent modules interact through surface and volume forces

Comments on the Model



- Complex system
- Modular approach to modeling
- Comparable to climate modeling
- Independent modules interact through surface and volume forces
- Previously used for Earth rotation (Juettner & Plag, Thomas et al., Seitz et al.)

Steps towards DREM:

- Solid Earth coupled to ocean, atmosphere and terrestrial hydrosphere models
- Mass conservation

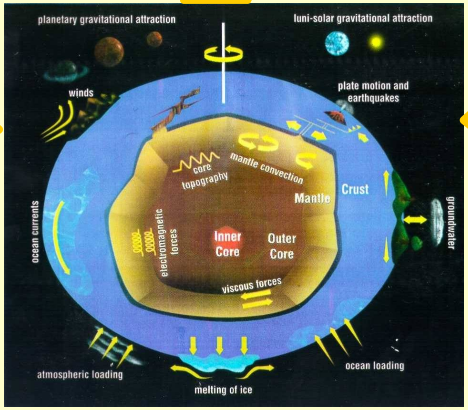
Challenges:

- Reference frames for modules
- Theory for initial value problem
- Data assimilation

Challenges

Earth system approach is required to interpret geodetic observations:

Earth rotation | **Geometry** | **Gravity/ Geoid**



- Earth Deep Interior
- Solid Earth processes
- Cryosphere
- Earth system dynamics
- Weather and Climate
- Ocean and climate
- Sea Level
- Mass Distribution and Transport
- Earth system
- Planets

Conclusion

Geodetic fingerprints of geohazards and global change processes are above the accuracy level of geodetic observations.

The accuracy of the modeled fingerprints of mass redistribution and geodynamics impacts the accuracy of geodetic products.

In order to serve Earth sciences with improved products and to extract geohazards and global change signals from geodetic observations, geodesy needs to understand and model consistently Earth system processes on a wide range of spatial and temporal scales.