# Improving observations and interpretation of changes in Earth's shape: Present and future Contributions of the GGFC

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### **Goal: Answer the question: What can the GGFC do?**

In order to reach to an answer, I will consider three questions related to positioning and displacements\*:

- **Q1:** What are the operational geodetic products and what is needed to make them satisfy users' needs?
- **Q2:** What do we know (and thus can model) and what do we want to research?
- **Q3:** Improvement: Where are key problems?

**Conclusions**: Potential GGFC products.

\*) Displacement: difference between expected and computed position

Main operational products: reference frames ITRF & ICRF and the EOP.

# I will focus on ITRF:

- increasingly important to have access to the ITRF anywhere, anytime with high accuracy and reliability;
- many application require 'fixed' coordinates: ability to relate coordinates measured at time t to reference epoch t<sub>o</sub>;
- global approach to reference frame: contribution to sustainable development by providing equal access to resources;
- displacements with respect to ITRF are the difference between the expected ITRF position and the computed position.

## **Determination of ITRF:**

• Currently described as polyhedron with regularized coordinates:

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

•  $\vec{X}_0^{(i)}, \vec{V}_0^{(i)}$ : affected by station motion model, troposphere & ionosphere treatment, antenna model, analysis strategy, ...

# Access to the ITRF:

- Through satellite orbits and clocks and EOP.
- These global parameters are affected by station motion model, ...
- Should be the same as used for the determination of the  $\vec{X}_0^{(i)}, \vec{V}_0^{(i)}$

# Main task of the Services with respect to access to ITRF:

• Monitoring of ITRF (also EOP)

**Experience shows:** On the level of approximately 1 cm, the current ITRF definition (regularized coordinates) and determination not sufficient (i.e., displacements can be much larger than 1 cm).

# **Possible sources for uncertainties:**

- A: linear model (regularized coordinates) inadequate
- B: station motion model inaccurate
- C: other sources (troposphere, ionosphere, gravity field treatment, ...)

# A: linear model (regularized coordinates) inadequate

improvement: extension to non-linear models or time series;
requirement: knowledge of non-linear velocity field;

• potential contribution of GGFC: models, time series analysis, velocity field.

# **B:** station motion model inaccurate

 improve the station motion model (see Q2) both for determination of ITRF and for access to it;

• consider high-frequency and low-frequency part separately.

# **C:** other sources (troposphere, ionosphere, gravity field treatment, ...)

• hopefully addressed by others, I will only address troposphere.

Models for describing reference point motion:

(0) Regularized coordinates:

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

required:  $\vec{V}_0^{(i)} = f(\vec{X})$ (1) Piecewise linear:

$$\vec{X}^{(i)}(t) = \vec{X}_{0}^{(i)} + \vec{V}_{0}^{(i)} \cdot (t - t_{0}) + \sum_{i=1}^{N^{(i)}} A_{j}^{(i)} H(t - t_{j})$$

required:  $A_j = g_j(\vec{X})$ : earthquake displacement fields (GGFC?) (2) Piecewise linear and harmonic:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0) + \sum_{i=1}^N A_j^{(i)} H(t - t_j) + \sum_{k=1}^K (\alpha_k^{(i)} \sin(\omega_k t) + \beta_k^{(i)} \cos(\omega_k t))$$

required:  $\alpha_k$ ,  $\beta_k = h(\vec{X})$ : determined from observations and/or models (GGFC?) (3) Geophysical models:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0) + \sum_{i=1}^M g_i(t, \vec{X}^{(i)})$$

required:  $g_i$ ; i = 1, M: determined from observations and/or models (GGFC?) (4) Observed polyhedron:

$$\vec{X}^{(i)}(t) = \vec{O}^{(i)}(t)$$

required:

(a) model for interpolation of  $\vec{O}^{(i)}$  (GGFC?)

(b) approximation of  $\vec{O}^{(i)}$  to improve station motion model for analysis (GGFC?)

#### **B:** station motion model inaccurate

- improve the station motion model (see Q2) both for determination of ITRF and for access to it;
- consider high-frequency and low-frequency part separately.

# **High-frequency part:**

- "significant"\*) variation during the analysis interval (for GNSS typically 1 day);
- needs to be taken into account during the analyses;
- necessary high-frequency station motion model from GGFC?

# Low-frequency part:

- "nearly constant"\*) during analysis interval;
- should be considered in aligning solution to ITRF;
- could be considered by using an extended non-linear model for the reference coordinates;
- necessary low-frequency station motion model from GGFC?

\*) depends on target accuracy.

C: other sources (troposphere, ionosphere, gravity field treatment, ...)hopefully addressed by others, I will only address troposphere.

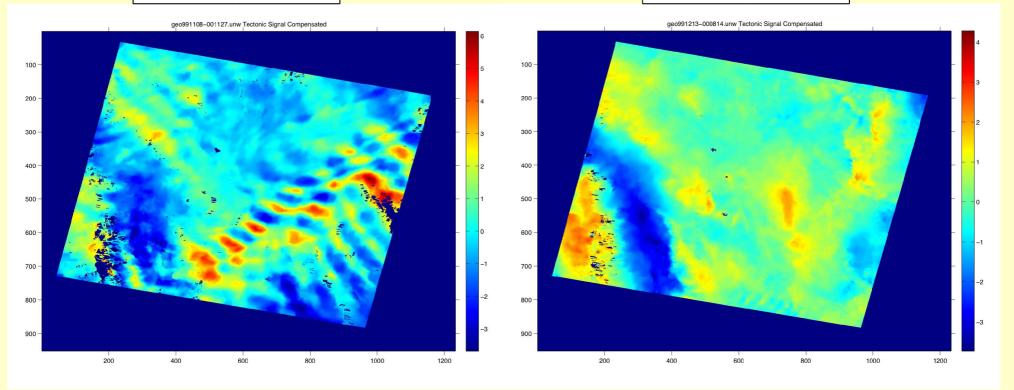
Just one example: Determination of displacements with InSAR ...

#### Frame 2871: Yucca Mountain

#### Two example interferograms

### 991108-001127

#### 991213-000814



Hammond et al., 2006

'Observed' displacements are the difference between expected and computed positions: How well do we know displacements?

Modeled/derived phenomena include:

- static offsets (earthquakes)
- strong motion
- Earth tides
- ocean tidal loading
- surface loading
  - \* atmosphere
  - \* terrestrial hydrosphere
  - \* non-tidal ocean
  - \* grounded ice
- postglacial rebound
- tectonic secular motion

All phenomena affect Earth's shape, gravity field and rotation.

Some phenomena are quantitatively well known, others still in research state.

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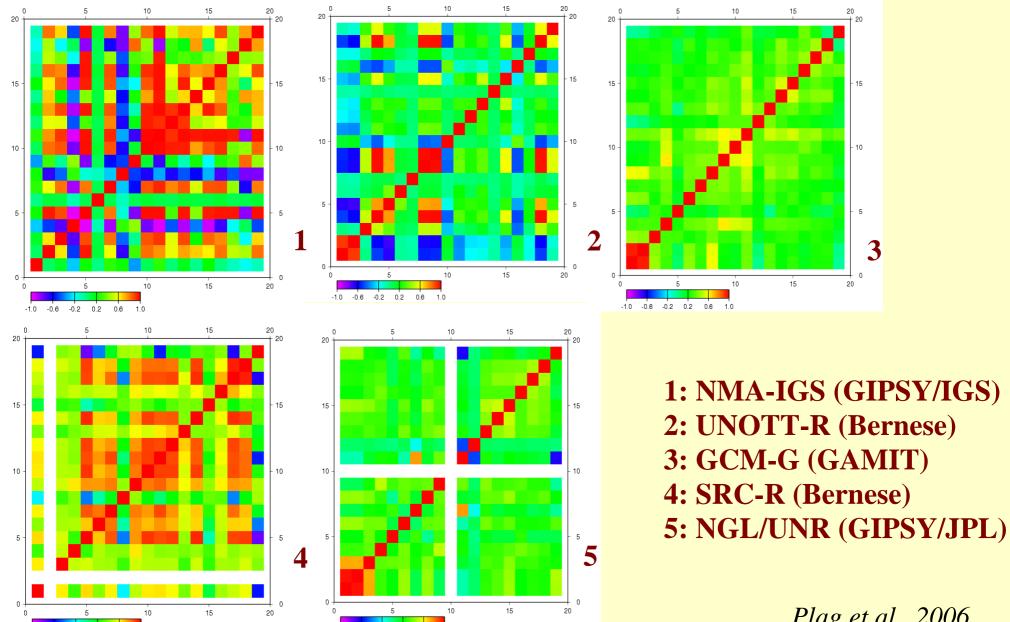
#### **Computed displacements**

**Example:** ESEAS GPS Analysis Comparison

#### **Analysis statistics:**

- 7 groups
- 3 program packages
- 3 analysis strategies
- 2 orbits/clocks
- 5 alignments to ITRF2000

Plag et al., 2006



-1.0 -0.6

-0.2 0.2 0.6 1.0 -0.2 0.2 0.6

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#### Spatial correlation of computed displacements

Plag et al., 2006

5 mm

270

240

90 120 1.50 180 210

Derived Phenomena:static offsets (earthquakes)

300

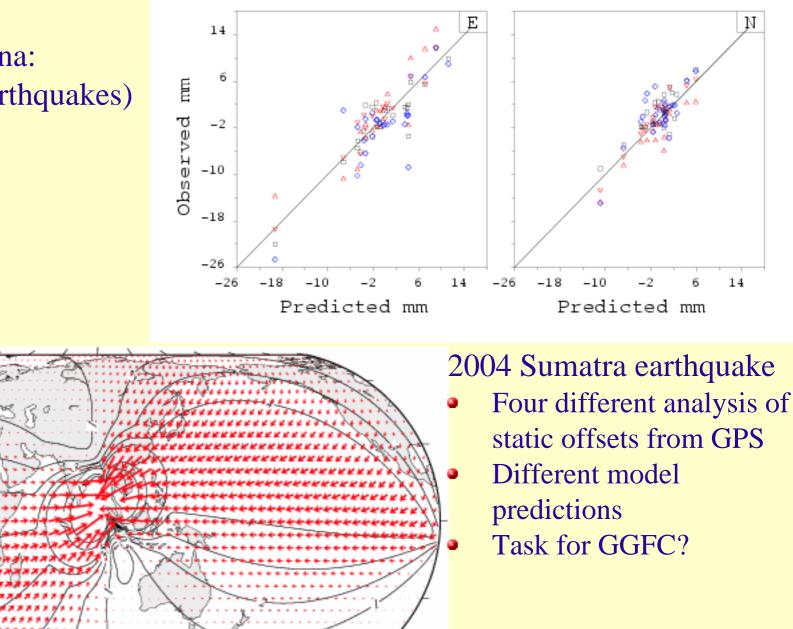
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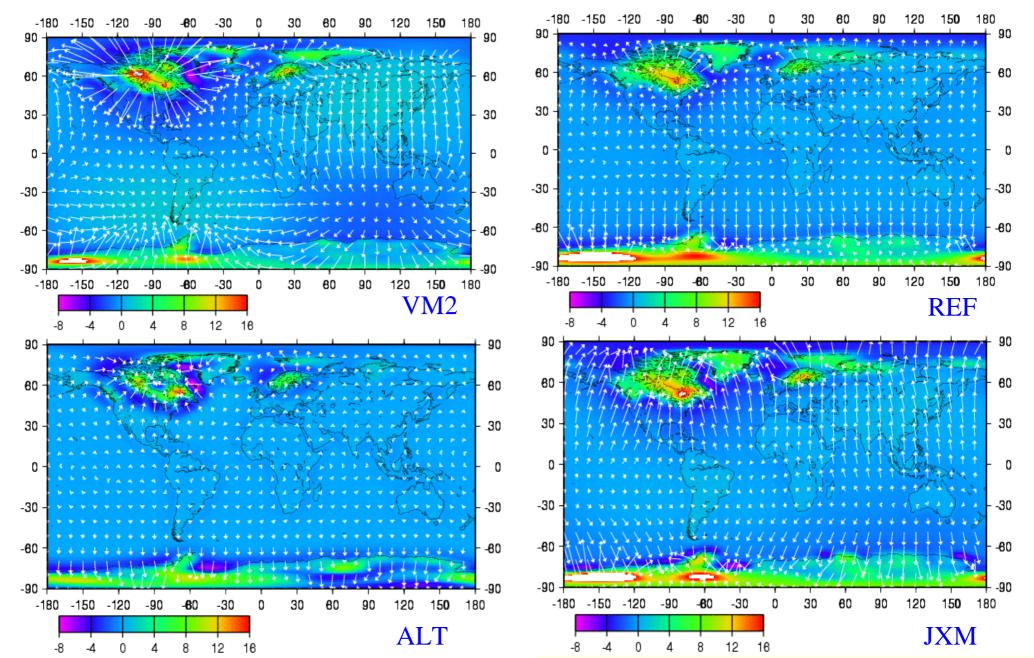
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Plag et al., 2006

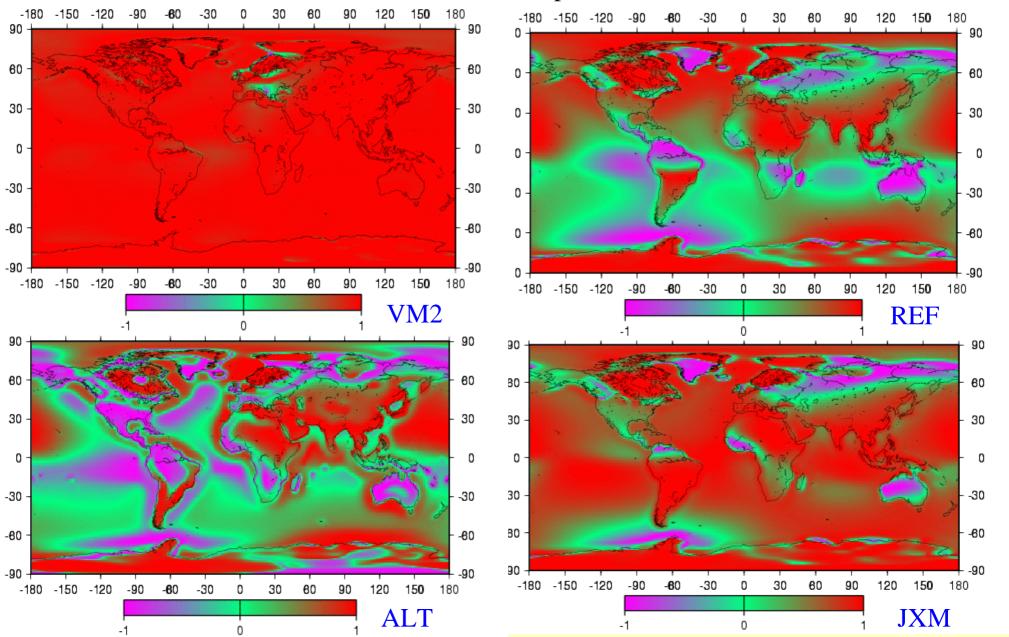
# **Q2: What do we know and what do we want to research?** Modeled phenomena:

#### postglacial rebound



# **Q2:** What do we know and what do we want to research? Modeled phenomena:

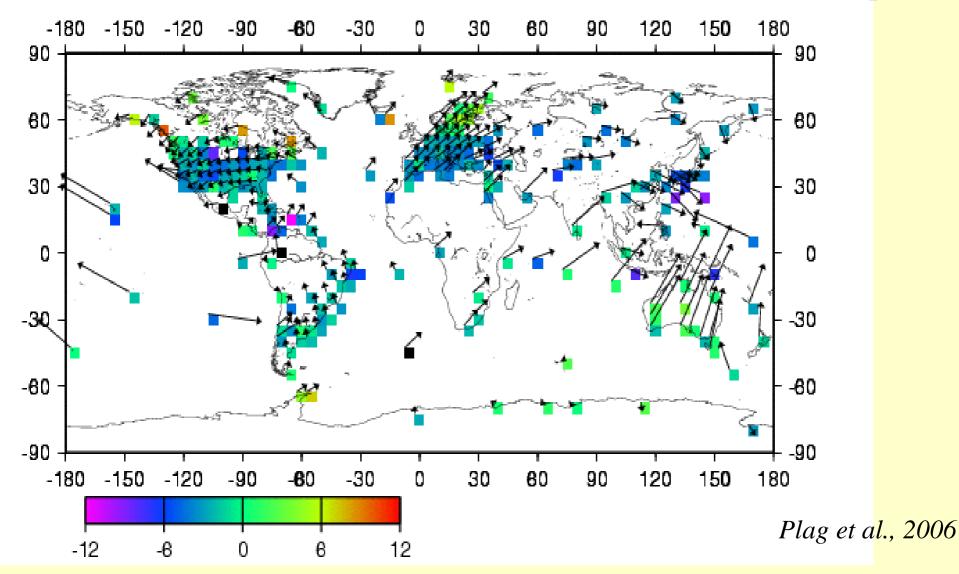
postglacial rebound Normalized Scalar Product of 3-D Displacements for VM4 and the Other Models



**Q2: What do we know and what do we want to research?** Derived phenomena:

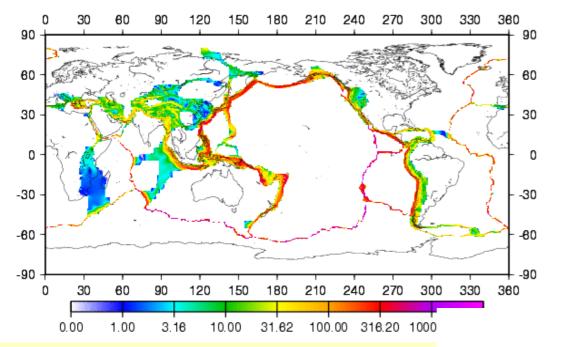
tectonic secular motion

- 5 X 5 degrees
- Total of 222 grids elements
- 78 elements with multiple values

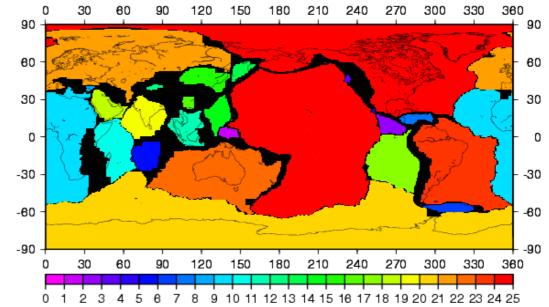


# **Q2: What do we know and what do we want to research?** Derived phenomena:

#### tectonic secular motion



- Strain model: Kreemer et al., 2003
- Plate model: 25 Plates
- Deformation zone not allocated



# **Summary:**

- Computed displacements (*difference between expectation and results*):
  - Considerable inter-analysis differences at daily resolution.
  - Considerable inter-analysis differences at seasonal and secular time scales
- Modeled/derived phenomena:
  - static offsets (earthquakes): observations constrain models
  - strong motion, free oscillation, tsunami loading: short temporal scales
  - Earth tides: can be modeled with high accuracy
  - ocean tidal loading: ocean tide model is main uncertainty
  - polar motion: can be modeled
  - surface loading
    - \* atmosphere: pressure anomaly at Earth's surface main uncertainty
    - \* terrestrial hydrosphere: hydrological anomaly main uncertainty
    - \* non-tidal ocean: ocean bottom pressure anomaly main uncertainty
    - \* grounded ice: mass balance of ice sheets and glaciers uncertain
    - \* postglacial rebound: model predictions show large discrepancies
  - tectonic secular motion: insufficient spatial coverage with observations
- All phenomena affect shape, gravity field and rotation

# **Q3: Improvements: Where are key problems?**

# **Ocean tidal loading**:

- no standard ocean tide model for operational applications;
- no 'easy' access (fully automated) to loading coefficients; grid-based routines;

# **Atmosphere/Pressure field** (more during the SBL presentation):

- what pressure field to use?
- what spatial and temporal resolution is necessary?
- sea surface pressure field has low quality;
- model topography pressure field has low resolution;
- inverted barometer is an insufficient approximation.

# **Terrestrial hydosphere**:

Iack of operational model with low latency.

# Non-tidal ocean loading:

lack of operational model with low latency (including response to air pressure and wind).
 Ice loads:

- no operational model;
- no model at inter-annual to sub-seasonal times scales.

# Surface loads:

• no comprehensive, modular model; common problem: reference surfaces.

# **Potential GGFC Products**

### **Station motion model:**

- Offsets: earthquake-induced displacement fields
- High-frequency part:
  - ocean tidal loading:
    - \* improved access through grid-based routines
    - \* one standard ocean model for operational applications
  - surface loads:
    - \* atmospheric pressure loading (also for gravity)
    - \* non-tidal ocean loading (only in special cases?)
- Low-frequency part:
  - surface velocity field:
    - \* geophysical models for loading-induced displacements (including PGR)
    - \* empirical surface velocity field

# **Forcing:**

- ocean tidal model (standard for operational applications)
- comprehensive, modular surface mass transport model (agile, see SBL presentation)
   Others:
- Tropospheric water content (for InSAR), high temporal and spatial res.
- All predictions also for gravity field and PM/LOD