Solid Earth deformation and gravity changes due to surface loading and

Presented by

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- **Brief Introduction**
- **Scientific and Operational Agenda**
- **Loading Predictions: The Ingredients**
- **Work, Tasks and Products of the SBL**
- **Action Items**

Loading enters at two points into space-geodetic analyses:

- through the ”station motion model”:

$$\vec{X}(t) = \vec{X}_0 + \vec{V} \cdot (t - t_0) + \sum_i \Delta\vec{X}_i(t) \quad (1)$$

- through the geopotential

IERS Conventions specify how to treat:

- solid Earth tides,
- ocean loading,
- atmospheric loading;

but not

- non-tidal ocean loading,
- terrestrial hydrological loading,
- other loading.

Conventions are not consistent.

Call for Proposals October 31, 2001:

Objectives

... IERS conventions currently do not give comprehensive recommendations for treating the loading signals due to the full range of possible effects. ...

... timely to set up the tools that provide a basis for a future conventional treatment of loading effects in all IERS analyses ...

future requirements calls for considerable theoretical work, algorithm developments, model compilations and studies of relevant observations ...

SBL service operations ... computing and releasing the loading deformation and relevant geodynamic products, ...

... both vertical and horizontal components on both land surface and ocean bottom, with as high temporal- and spatial-resolution as feasible, and released in a fashion of as near-real time as feasible. ...

... atmosphere, oceans, land hydrology, cryosphere, and tides.

Tonie van Dam	European Center for Geodynamics and Seismology, Luxembourg, (chair)
Hans-Peter Plag	Norwegian Mapping Authority, Norway (co-chair)
Geoffrey Blewitt	University of Nevada, Reno, U.S.A.
Jean-Paul Boy	Goddard Space Flight Center, U.S.A.
Pascal Gegout	Ecole et Observatoire des Sciences de la Terre, Strasbourg, France
Halfdan Pascal Kierulf	Norwegian Mapping Authority, Norway
Tadahiro Sato,	National Astronomical Observatory, Mizusawa, Japan
Hans-Georg Scherneck	Onsala Space Observatory, Sweden
John Wahr	University of Colorado, Boulder, U.S.A.

Members ex-officio: Chairs of the existing SBs

Ben Chao	SB Mantle
Veronique Dehant	SB Core
Richard Gross	SB Oceans
Richard Ray	SB Tides
David Salstein	SB Atmospheres
Michael Watkins	SB Geocenter
Clark Wilson	SB Hydrology

Agenda

Two separate agendas:

operational: provide in near real-time a consistent global solution data set describing at least the surface deformation, gravity signal and geo-centre variations due to the various surface loading process in reference frames relevant for direct comparison with existing geodetic observing techniques.

scientific: major scientific advances with respect to the Earth model, the theory and algorithms used to model deformations of the Earth and the observational data of surface loading.

Precision of observations
versus
Precision of model predictions.

Observations:

for example:

- 3-D surface movements or deformations from space-geodetic measurements;
- gravity changes from superconducting and absolute gravimeters;
- gravity variations from satellite missions.

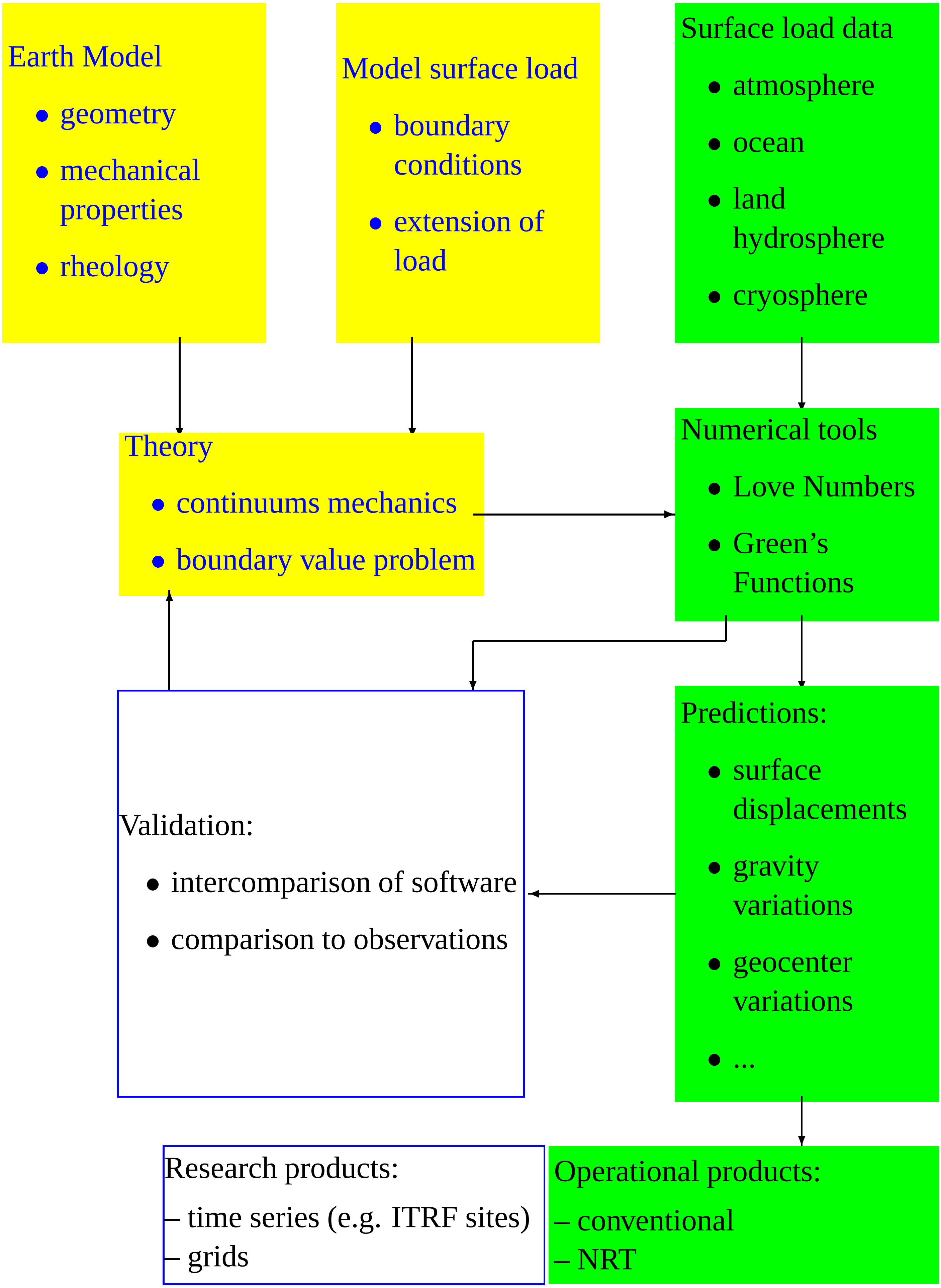
Time scales from less than 1 hour up to several years.

model predictions:

Based on:

- theory (continuum mechanics)
- Earth model
- surface loads

Loading Predictions



Mostly used: Green's functions (boundary value problem)

Basic assumption concerning the load: thin mass distribution.

$$\boldsymbol{u}(\boldsymbol{x},t) = \int_0^\infty \int_S \boldsymbol{G_u}(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau) \mathrm{d}^2\boldsymbol{x}' \mathrm{d}\tau \qquad (2)$$

$$\delta g(\boldsymbol{x},t) = \int_0^\infty \int_S G_g(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau) \mathrm{d}^2\boldsymbol{x}' \mathrm{d}\tau \qquad (3)$$

Earth Model

Widely used Earth model:

- Spherically symmetric, Non-Rotating, Elastic, Isotrop
- Preliminary Reference Earth Model (PREM)

Advantage:
Green's Function depends on angular distance between load and observer, only.

Problems for SNREI:

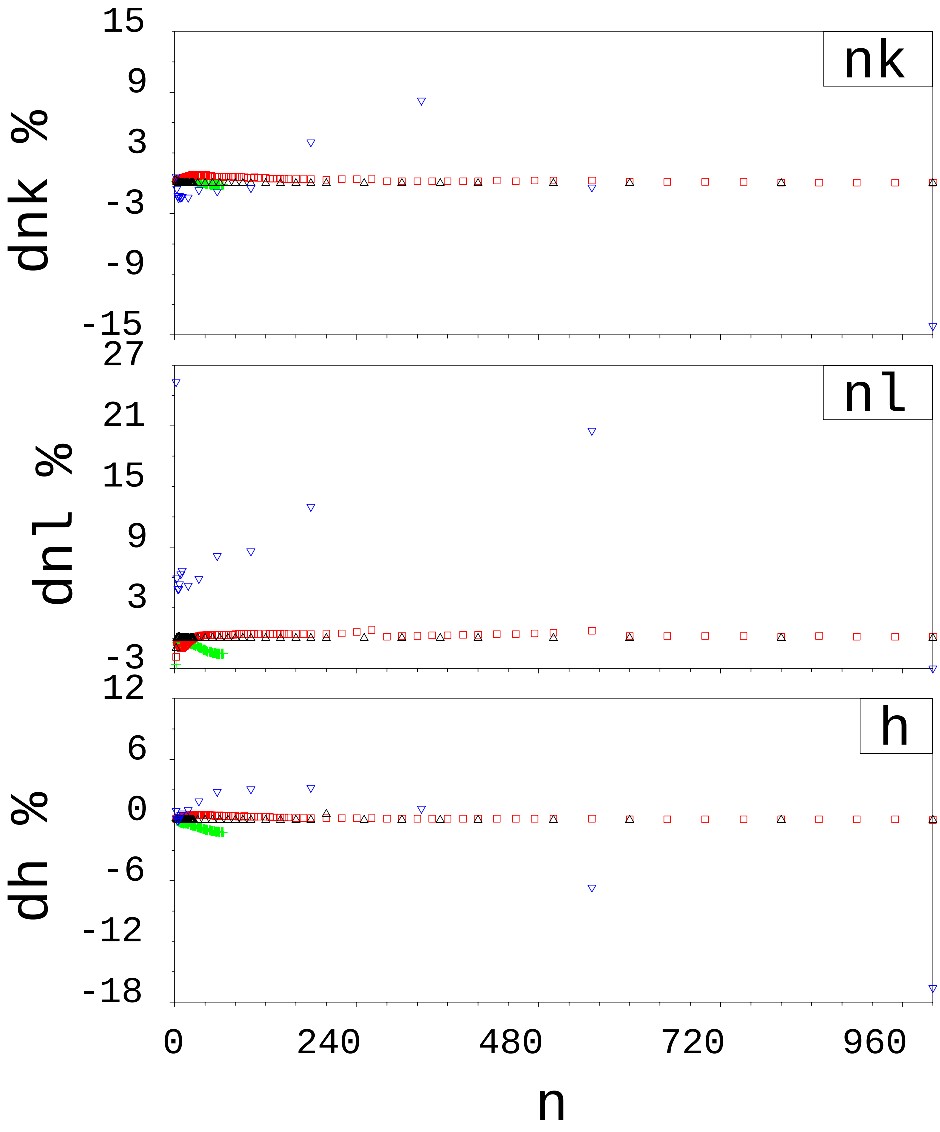
- PREM or ?
- PREM: surface layer: 3 km ocean
- PREM: frequency-dependent shear modulus: elastic module?
- PREM: parameterisation of depth-dependency

Action Item SBL-M1-2: Carry out an intercomparison of Load Love Number computed by different programs/groups for the PREM model.

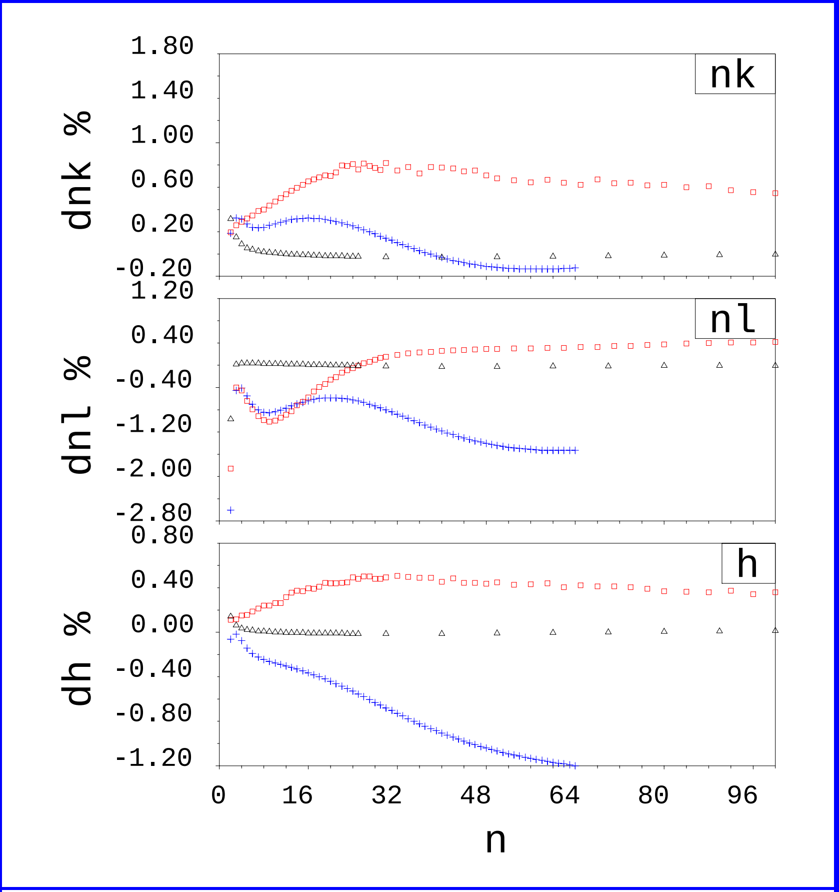
Moreover, can we assume SNREI?

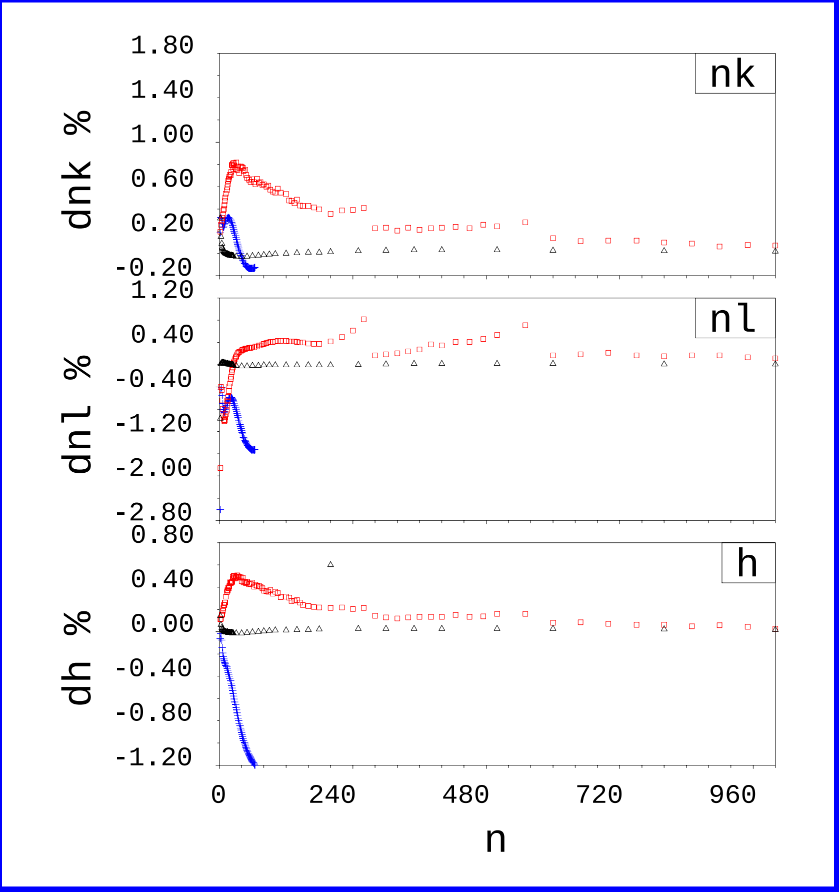
- elastic or viscoelastic
- non-hydrostatic pre-stress
- lateral heterogeneities (density, bulk modulus, shear modulus)
- boundary undulations (e.g. surface topography)

Earth Model: Load Love Numbers



PREM Love Numbers

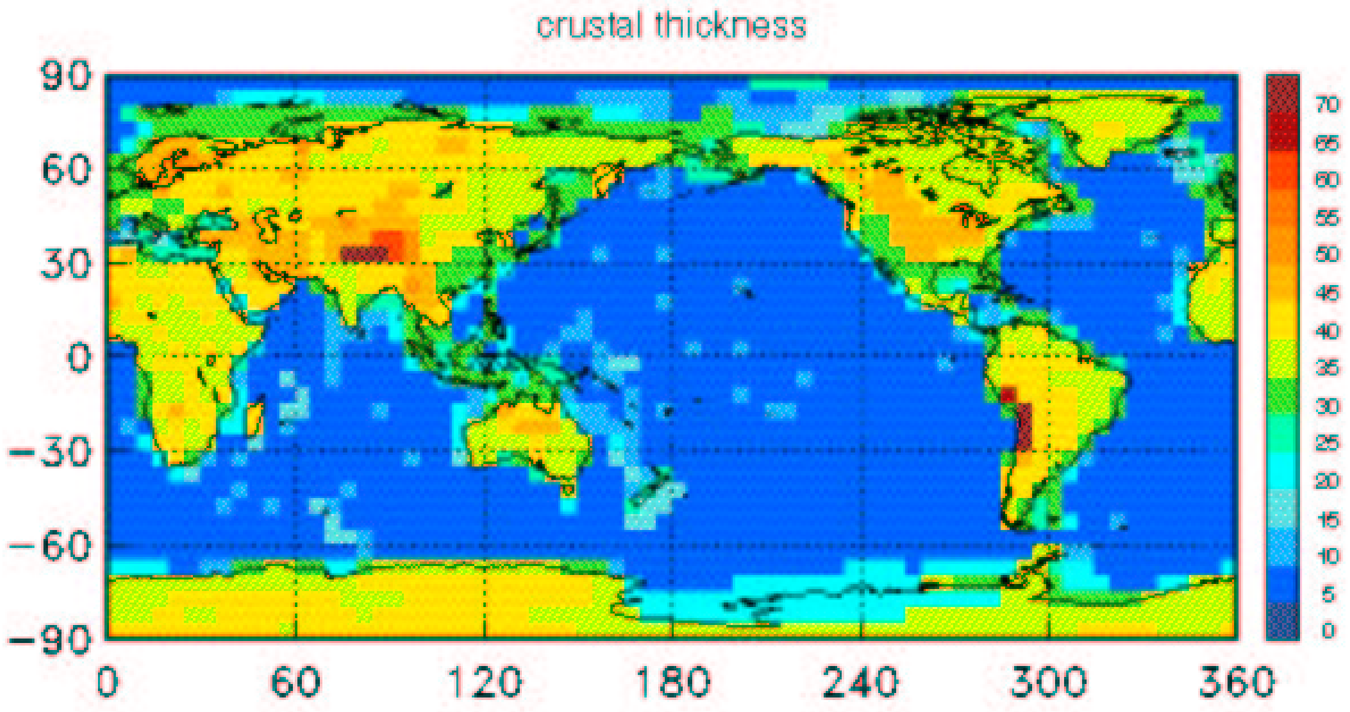




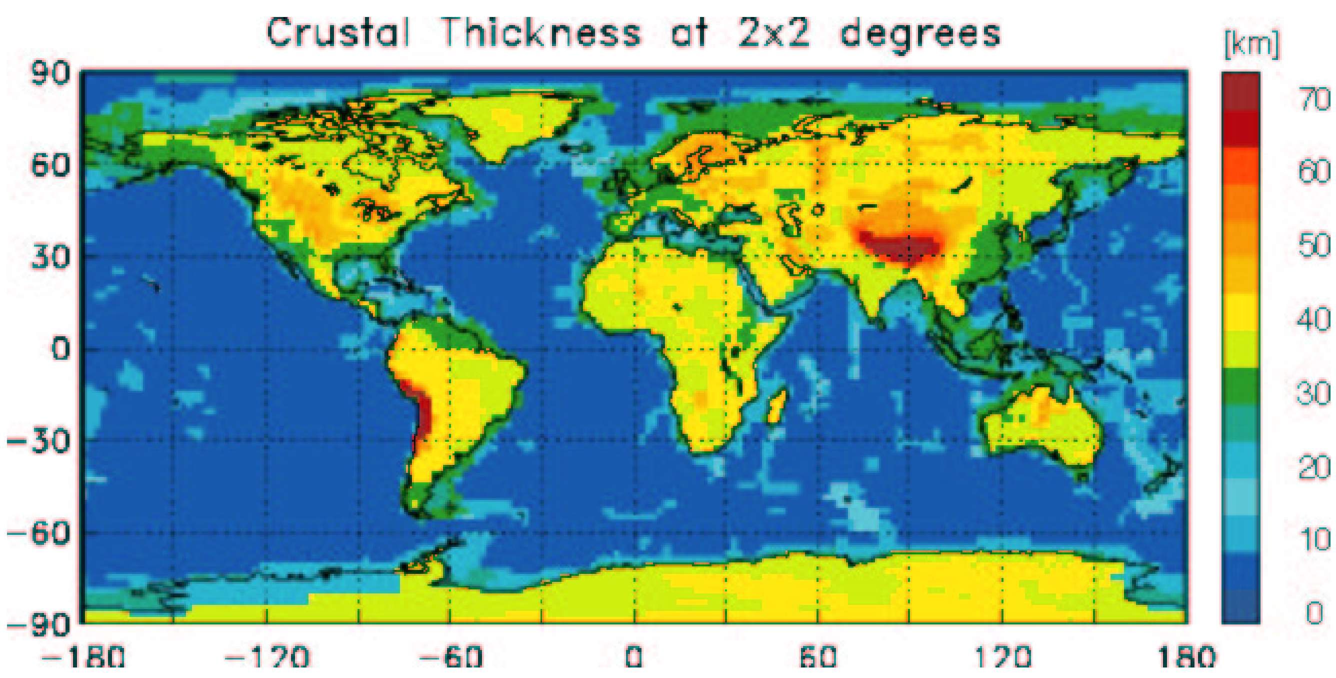
Depending on the Earth model, we get the following classes of Green's functions:

SNREI:	Spherically symmetric, Non-Rotating, Elastic, Isotrop $\boldsymbol{G_u} = \boldsymbol{G_u}(\vartheta(\boldsymbol{x}, \boldsymbol{x}'))$ $G_g = G(\vartheta(\boldsymbol{x}, \boldsymbol{x}'))$
EREI	Rotating, elliptically symmetric, elastic, isotrop
LHREI	Laterally heterogeneous, (rotating), elastic, isotrop $\boldsymbol{G_u} = \boldsymbol{G_u}(\boldsymbol{x}, \boldsymbol{x}')$ $G_g = G(\boldsymbol{x}, \boldsymbol{x}')$
SNRVI	Spherically symmetric, Non-Rotating, Visco-elastic, Isotrop $\boldsymbol{G_u} = \boldsymbol{G_u}(\vartheta(\boldsymbol{x}, \boldsymbol{x}'), \tau)$ $G_g = G(\vartheta(\boldsymbol{x}, \boldsymbol{x}'), \tau)$
LHRVI	Laterally heterogeneous, rotating, viscoelastic, isotrop $\boldsymbol{G_u} = \boldsymbol{G_u}(\boldsymbol{x}, \boldsymbol{x}', \tau)$ $G_g = G(\boldsymbol{x}, \boldsymbol{x}', \tau)$

Laterally Heterogeneous Earth Crust Models

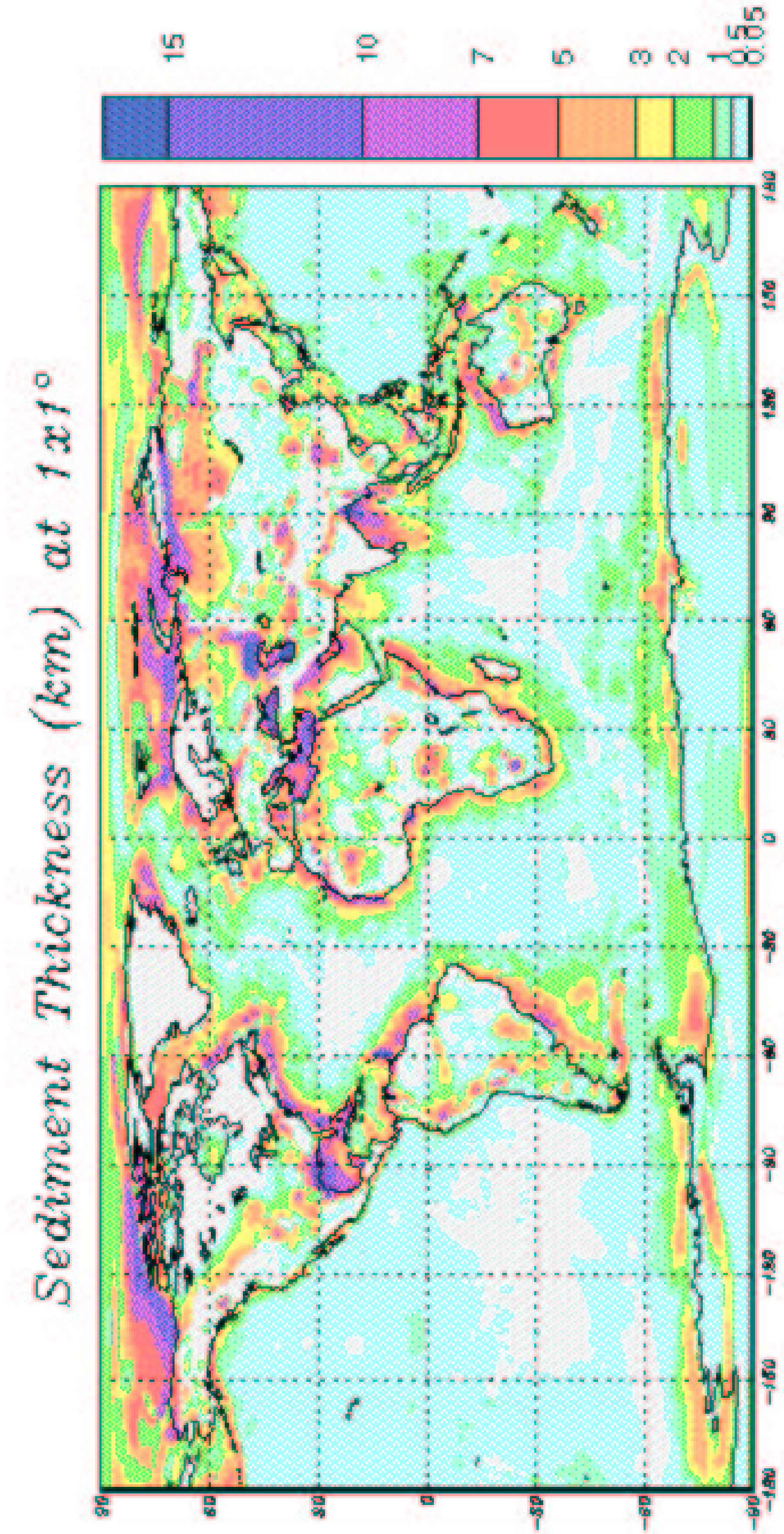


W.D. Mooney, G. Laske and G. Masters, CRUST 5.1: A global crustal model at 5° × 5°. J. Geophys. Res., ***103****, 727-747, 1998.*



http://mahi.ucsd.edu/Gabi/rem.html or Bassin, C., Laske, G. and Masters, G., The Current Limits of Resolution for Surface Wave Tomography in North America, EOS Trans AGU, ***81****, F897, 2000.*

Laterally Heterogeneous Earth Crust Models



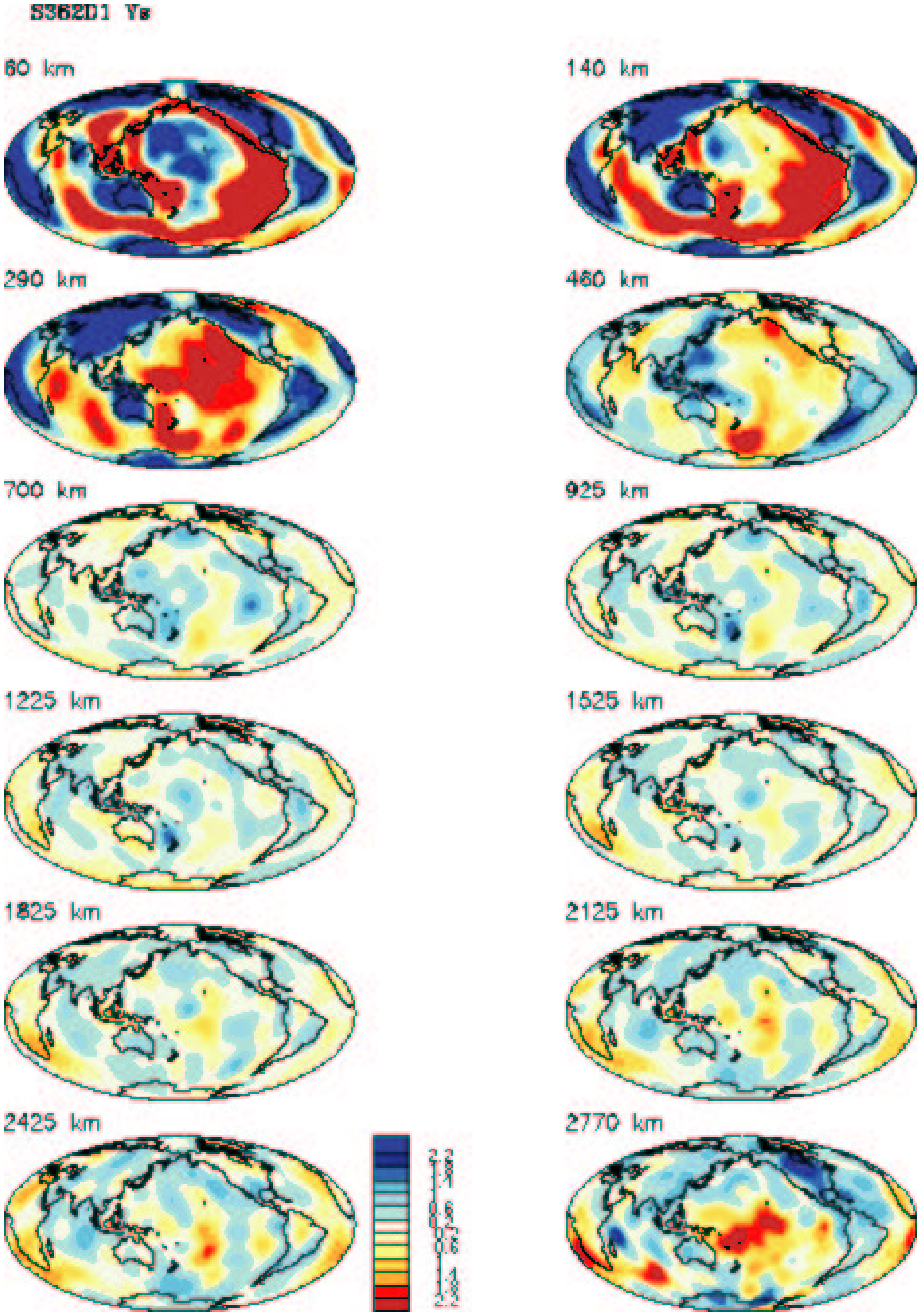
http://mahi.ucsd.edu/Gabi/rem.html

Title of http://mahi.ucsd.edu/Gabi/rem2.dir/shear-models.html:
Towards a 3D Reference Earth Model

Five high-resolution models available:

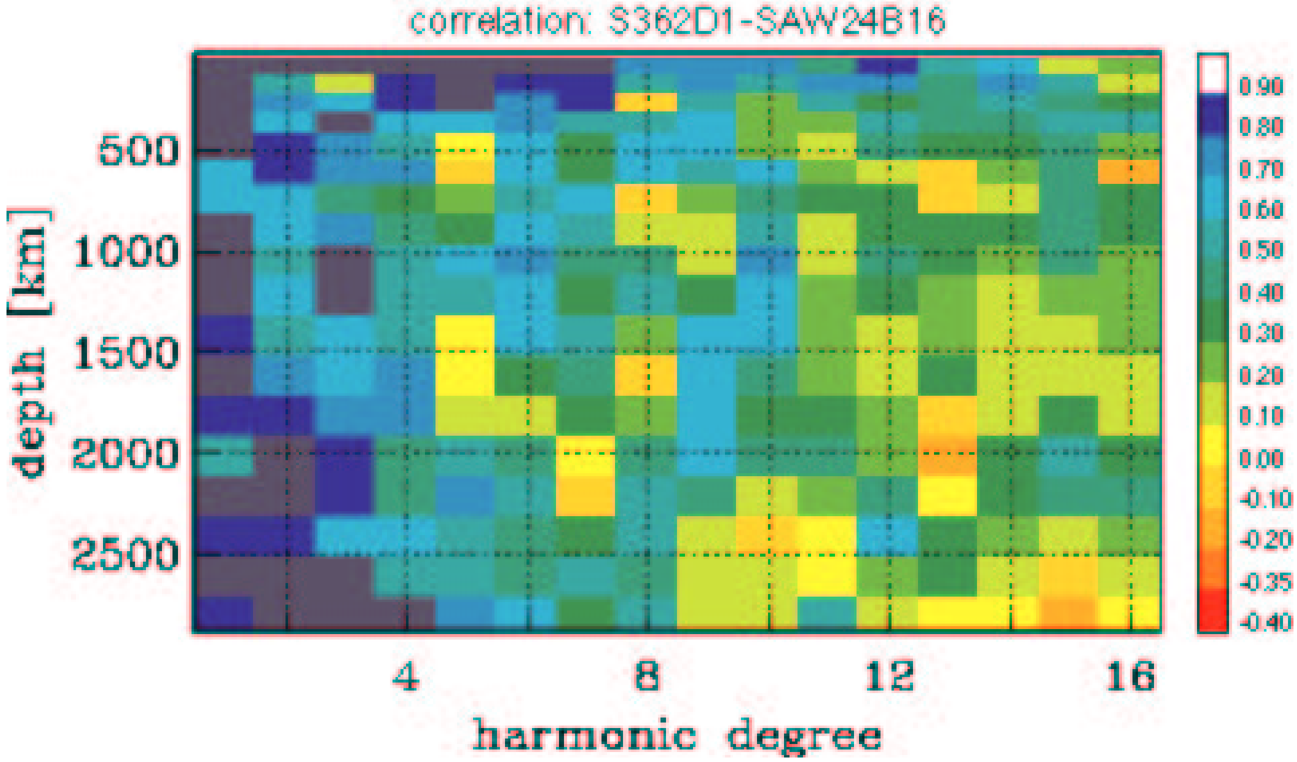
- Masters et al. (SIO),
- Dziewonski et al. (HRV),
- Romanowicz et al. (Berkeley),
- Grand (UT Austin),
- Ritsema et al. (Caltech)

Dziewonski et al. (HRV):

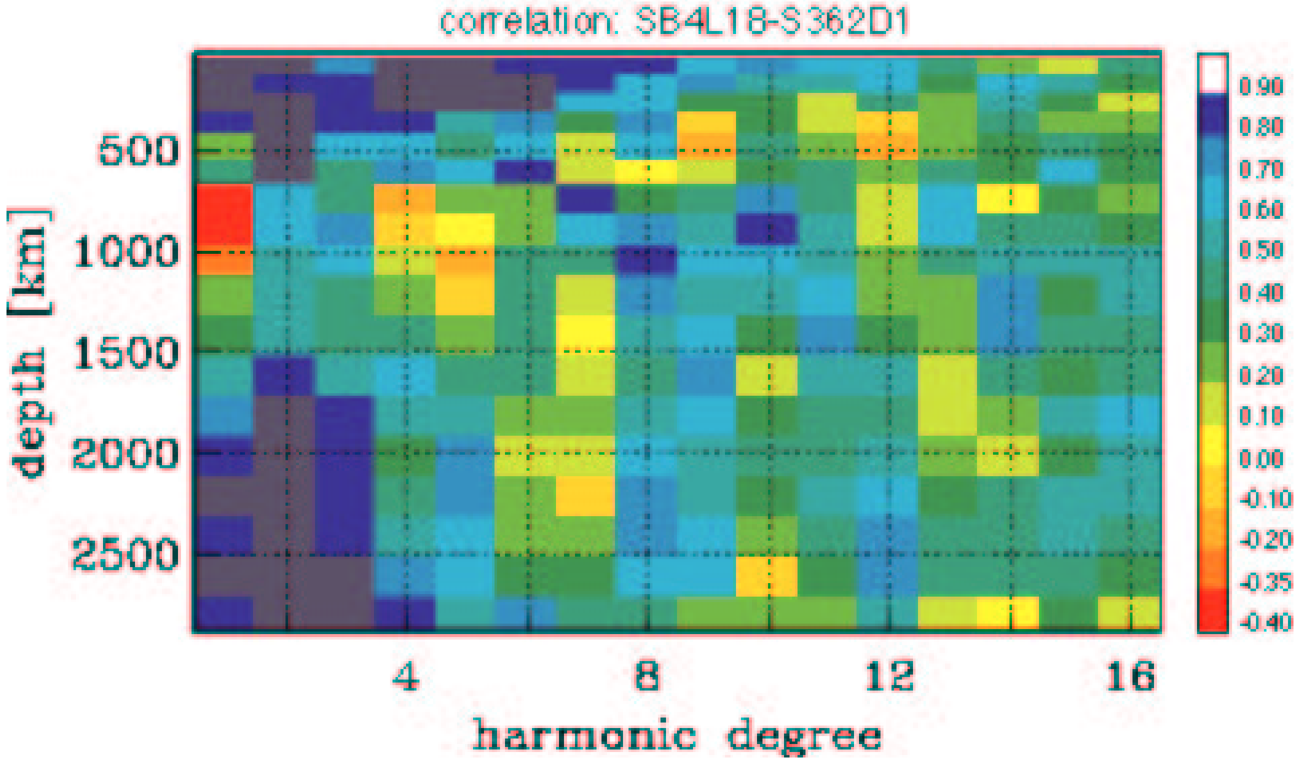


Correlations:

Romanowicz et al. (Berkeley) versus Dziewonski et al. (HRV)



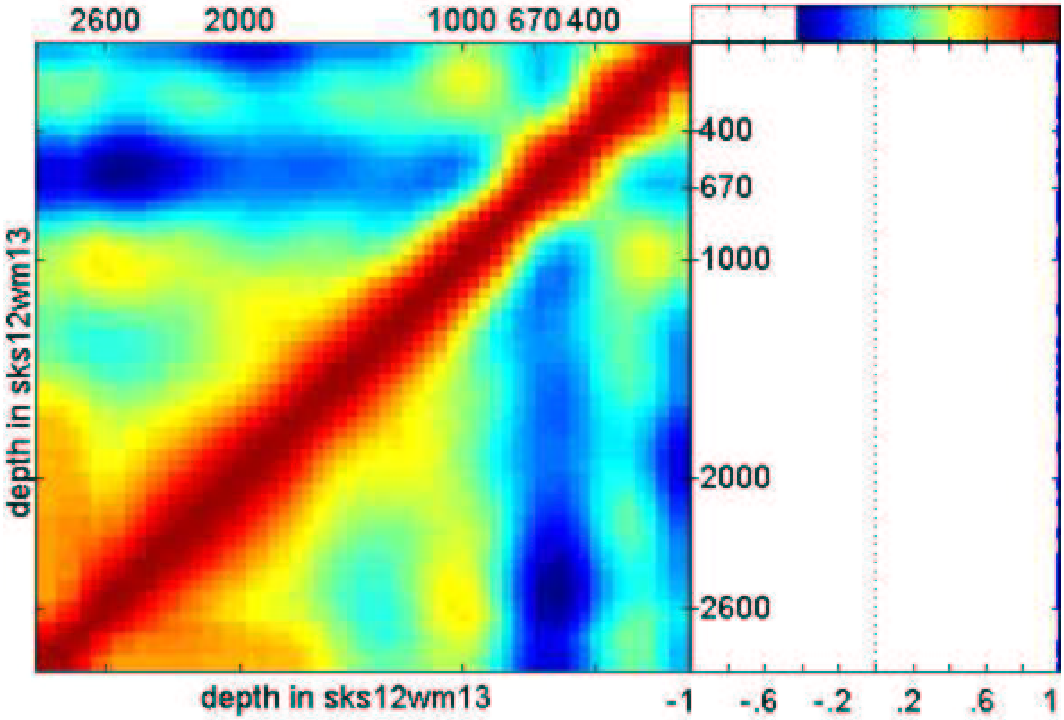
Masters et al. (SIO) versus Dziewonski et al. (HRV)



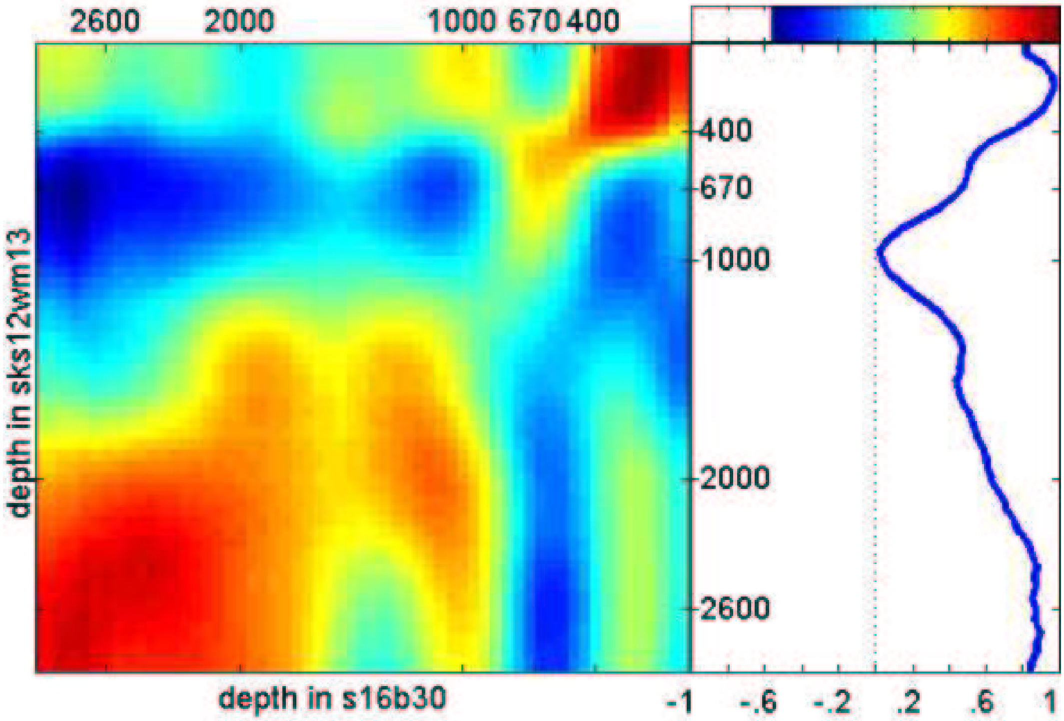
From: http://mahi.ucsd.edu/Gabi/rem2.dir/shear-models.html

Correlations:

Dziewonski et al. (HRV) versus Dziewonski et al. (HRV)



Dziewonski et al. (HRV) versus Masters et al. (SIO)



From: http://cfauvcs5.harvard.edu/lana/rem/correlation.htm

Summary Earth Model and Theory

Status:

- SNREI most likely not sufficient
- 3-D Earth models are developing,
  transition from PREM to REM seems feasible
- But: considerable differences between existing 3-D models

Not discussed:

- anisotrophy
- non-hydrostatic prestress
- thin load assumption

Relevant surface loads:

- atmospheric loading
- ocean loading (tidal and non-tidal)
- continental water storage

Eventually needed:

Gobal pressure field on the surface of the solid Earth (including the ocean bottom):

$p = p(\lambda, \theta, t; h_s)$

where h_s height of Earth's surface.

Density variation above the surface of the solid Earth:

$\delta\rho = \delta\rho(\lambda, \theta, h, t)$

Surface Loads: Atmosphere

Atmosphere:

- National Center for Environmental predictions, USA (NCEP): Analyses and forecasts for 5 days;
- Japan Meteorological Agency (JMA): Analyses and forecasts to 8 days;
- European Centre for Medium-Range Weather Forcasts (ECMWF): Analyses and forecasts to 10 days.

Action Item SBL-M1-3: Carry out a sensitivity study which shows the effect of different Earth models and surface pressure fields on computed surface displacements.

Surface Loads: Ocean

Ocean (non-tidal):

- two models with regular update:
  - Mercator
  - ECCO
- Forcing: surface wind stress, heat and salinity fluxes

Problems:

- no air pressure forcing;
- spin-up very long;
- mass conservation.

Action item SBL-M1-4: Investigate the space-time spectrum for the ocean-bottom pressure field.

Surface Loads: Hydrosphere

Continental hydrology:

- models using meteorological observations as input:
  - Huang et al. (1996): monthly results 1979 - 1993;
  - Shmakin & Milly (1999): 1978 - 1998, ground water, soil moisture and snow.

Problem: large uncertainties.

Action Item SBL-M1-5: Study mass conservation of ocean and continental hydrosphere models.

Surface Loads: General Problems

General problems:

- Which reference surface to use?
- How to treat trends in the surface loads?
- How to ensure no changes of ITRF coordinates?

Action Item SBL-M1-6: Investigate the spatial distribution of trend in air pressure.

New Action Items:

Action Item SBL-M2-1: Determine space-dependent reference surfaces and study their temporal stability.

Action Item SBL-M2-2: Study the effect of loading corrections on mean station coordinates

Reference Frame

CE: Center of mass of the solid Earth
(Farrell, 1972)

CM: Center of Mass of the Earth System
(SLR)

CM: Center of Figure
(GPS)

Basic difference:
degree-one Load Love Numbers

Conventional Operational Products:

- Goal:
  - to allow for a conventional treatment of loading
- Requirements:
  - available for all locations on the Earth's surface
  - well documented in the IERS Conventions
    - Earth model to be used
    - surface loads to be used
    - reference surfaces to be used
    - reference frame to be used
    - ....
    - ....

Some issues to clarify:

- Should a ”regression model” be used for air pressure?
- ...
- ...

Research Products:

- Should be available for all ITRF sites as far back as ....? YES/NO
- Should be available as grids to allow for re-processing of non ITRF sites (e.g. CGPS at tide gauges) as far back as ....?: YES/NO
- ...
- ...