Modelling Deformations of the Earth due to Surface Loading

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The rapidly increasing accuracy of space-geodetic observation techniques allow to measure displacements of the Earth surface resulting from surface loads on different spatial and temporal scales. On one hand, these observations offer the opportunity to validate geophysical models, which have been developed during the past decades to predict surface deformations due to various surface loads, such a ocean tidal loading, atmospheric loading, and hydrological loading. Comparison of, e.g., model predictions for atmospheric loading and observations show good agreement in some geographical areas but near-total failure in others. Partly, this is due to deficiencies of the theory and models used and partly to unmodelled effects in the observations masking the loading signal in the observations. On the other hand, in order to improve the results of space geodetic analyses, increasingly complex geophysical models of station motion are required (as emphasised, e.g., in the IERS Conventions).

The geophysical models require both an appropriate theory to describe the visco-elastic deformations of the Earth (including a sufficiently complex Earth model) and information on surfaces loads with adequate spatial and temporal resolution. The status and potential improvements of theory, Earth model and data sets describing the surface loads will be discussed.

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

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

Basic assumption concerning the load: thin mass distribution.

$$\boldsymbol{u}(\boldsymbol{x},t) = \int_0^\infty \int_S \boldsymbol{G}_{\boldsymbol{u}}(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau)\,\mathrm{d}^2\boldsymbol{x}'\,\mathrm{d}\tau \tag{1}$$

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

Widely used Earth model:

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

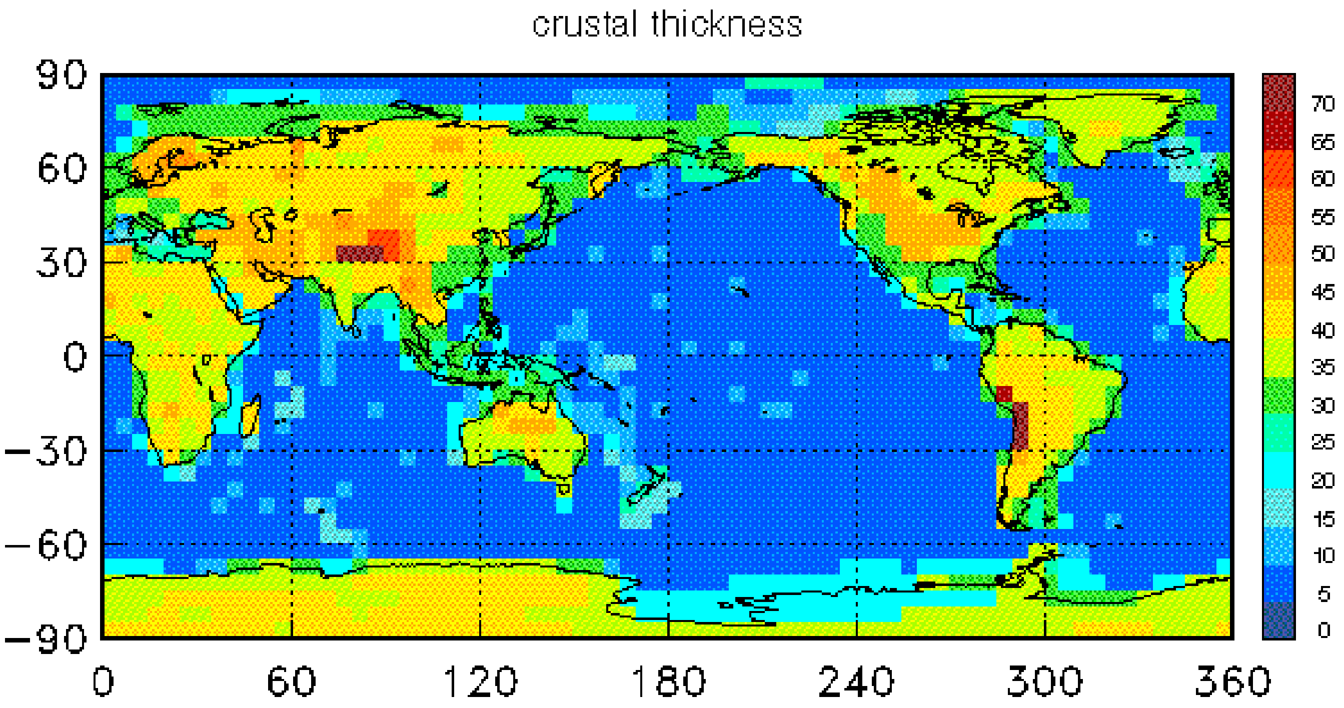
Advantage:
Green’s Function depends on angular distance between load and observer, only.

Problems:

- boundary undulations (e.g. surface topography)
- lateral heterogeneities (density, bulk modulus, shear modulus)
- global ocean
- elastic (?)

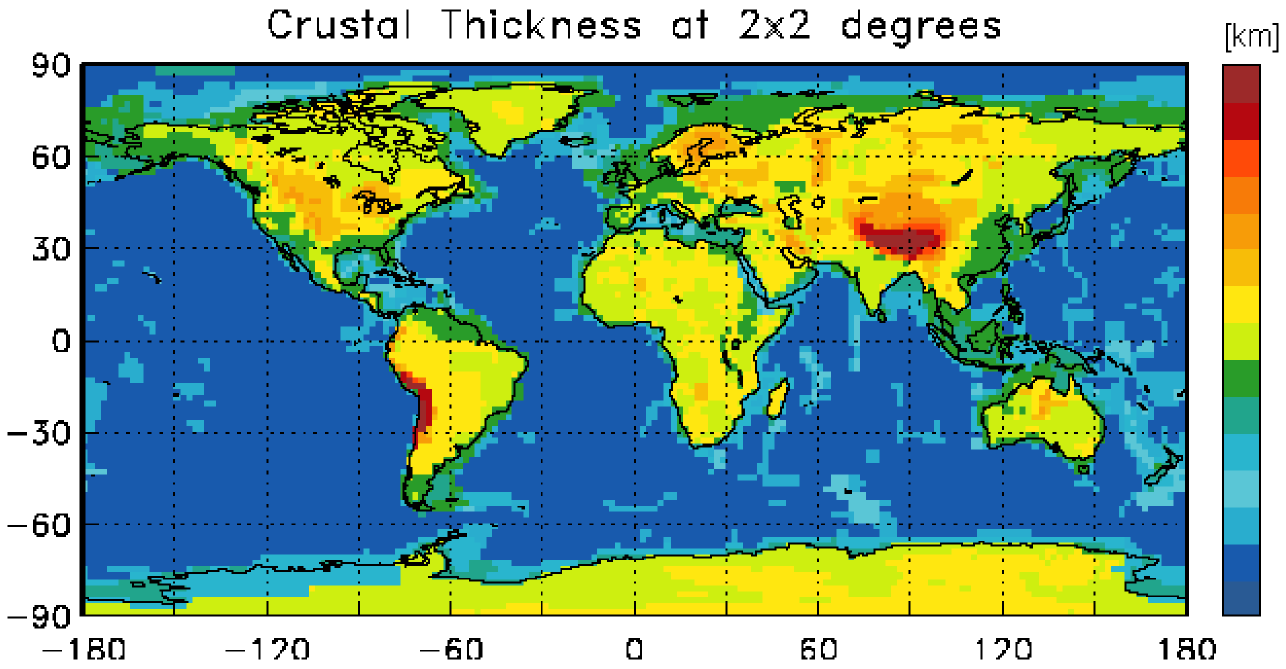
Depending on the Earth model, we get the following classes of Green's functions:

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



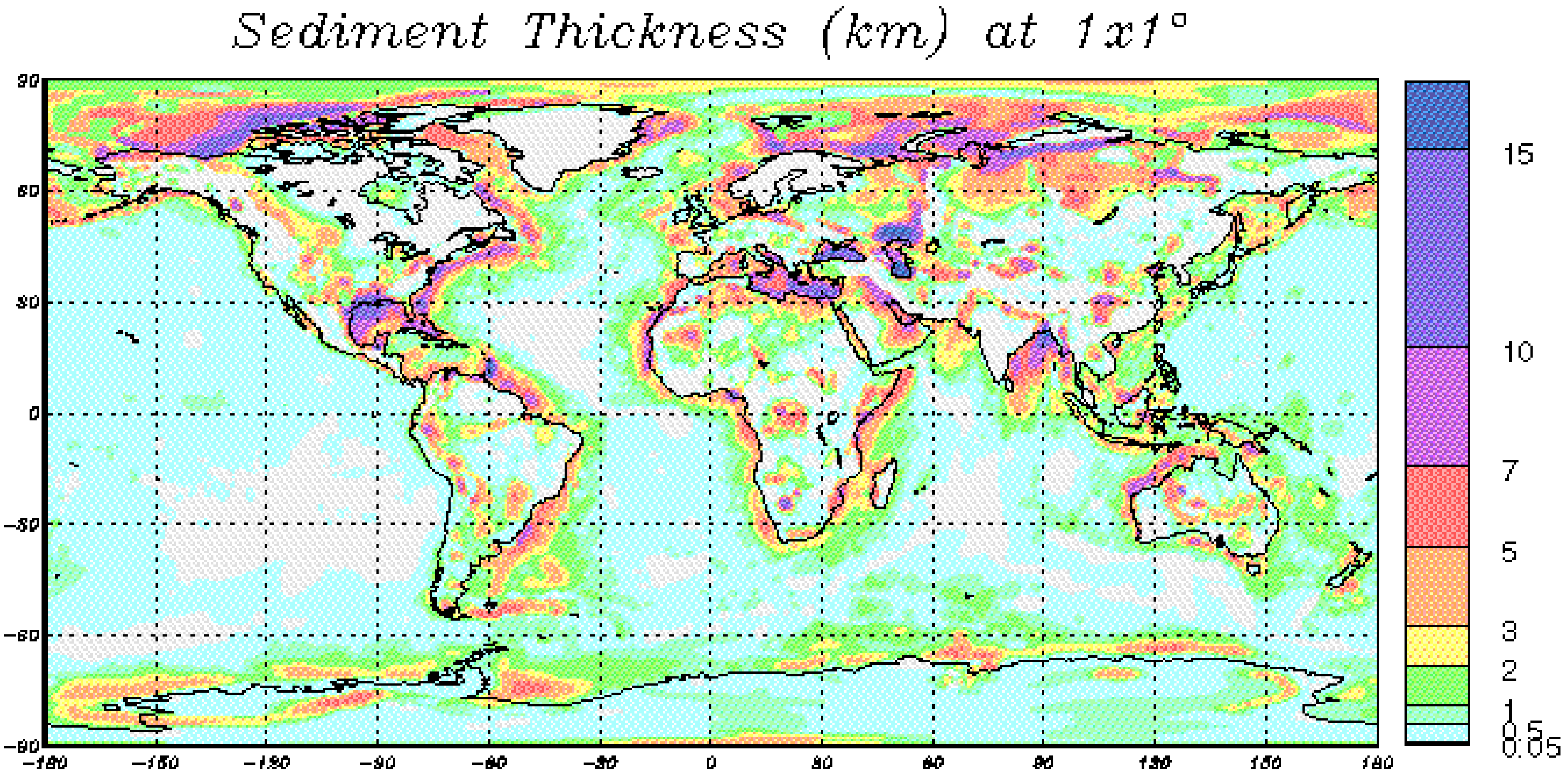
W.D. Mooney, G. Laske and G. Masters, CRUST 5.1: A global crustal model at 5° × 5°. J. Geophys. Res., ***103****,*

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.*



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

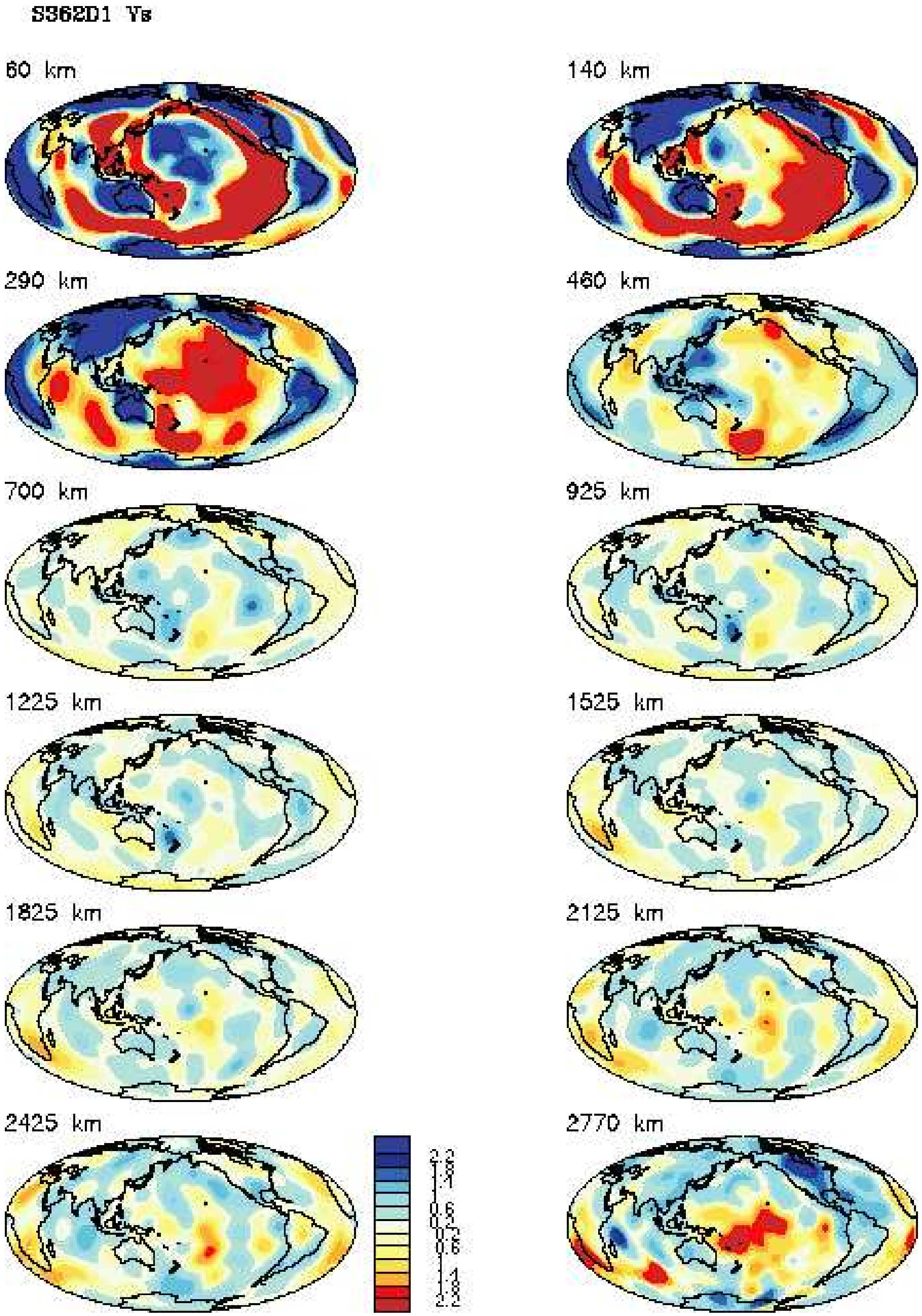
Title of http://mahi.ucsd.edu/Gabi/rem2.dir/shear-models.html:

Towards a 3D Reference Earth Model

Five high-resolution models available:

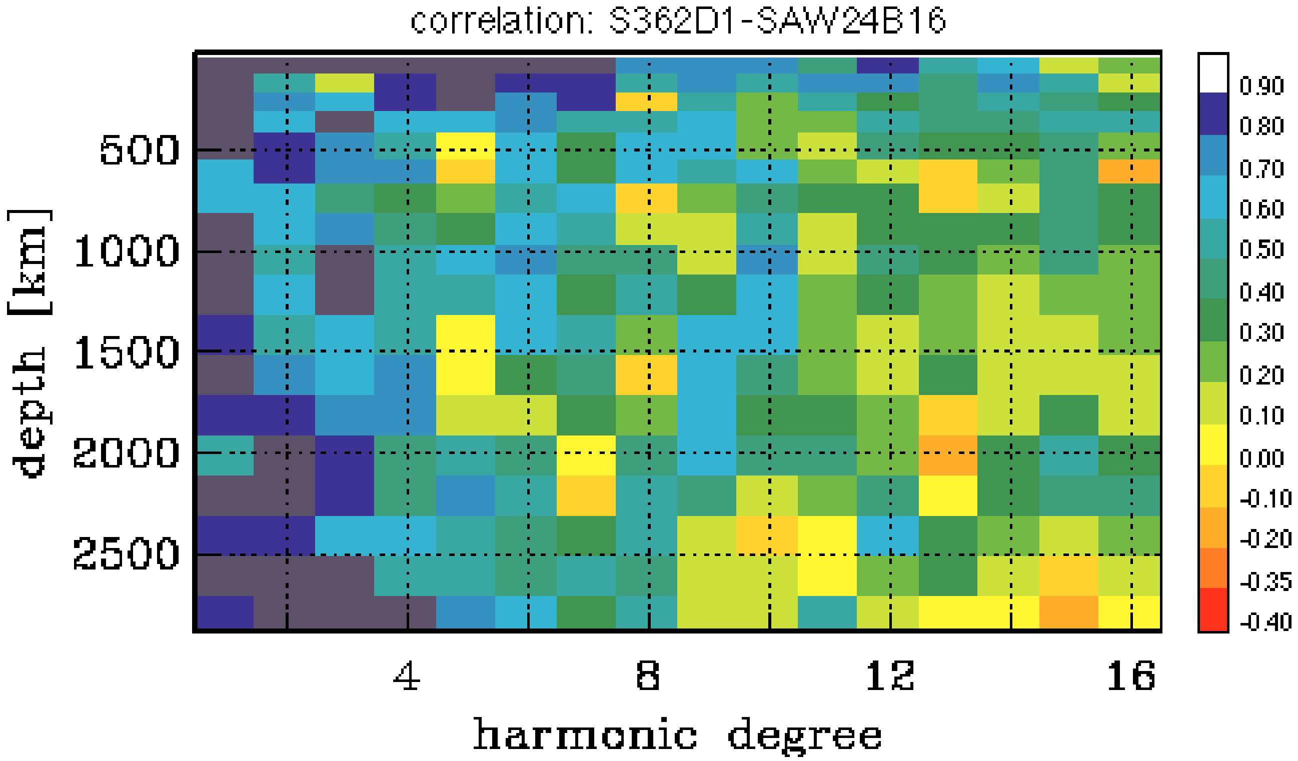
- Masters et al. (SIO),
- Dziewonski et al. (HRV),
- Romanowicz et al. (Berkeley),
- Grand (UT Austin),
- Ritsema et al. (Caltech)

Dziewonski et al. (HRV):

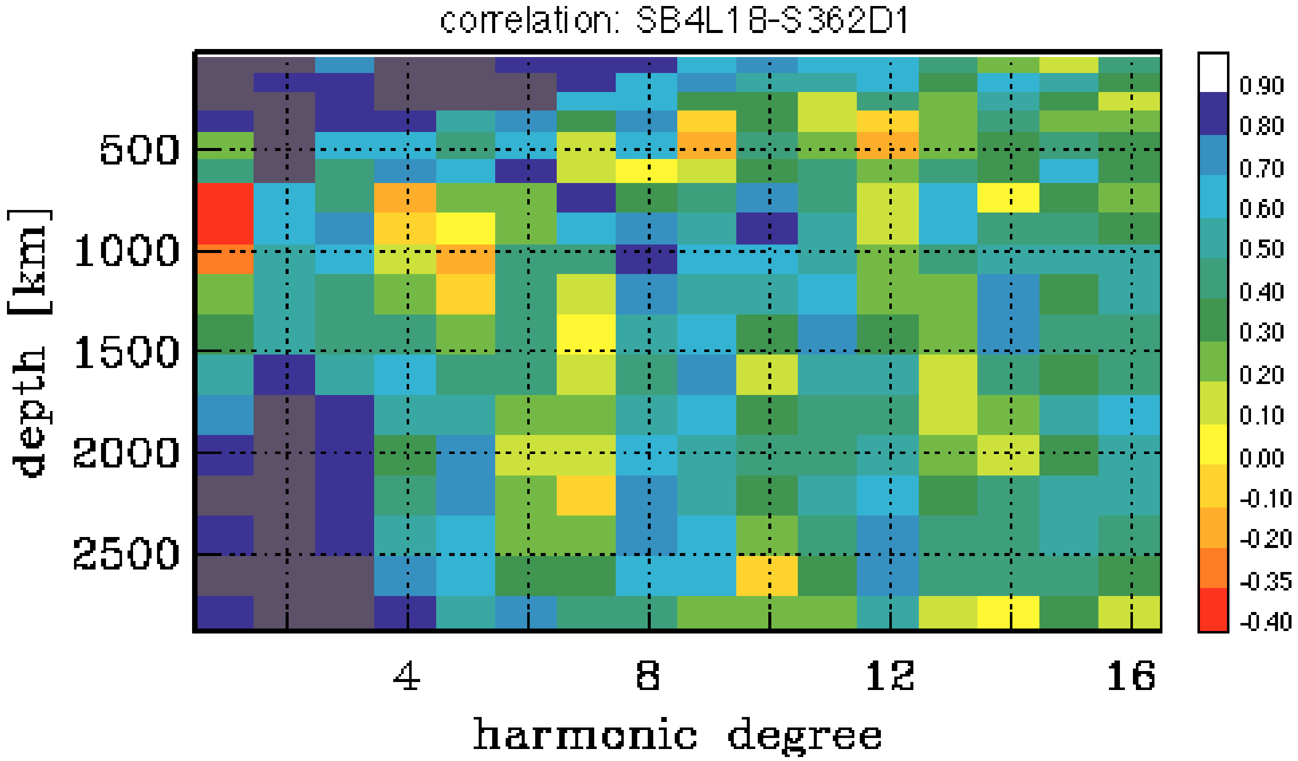


Correlations:

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



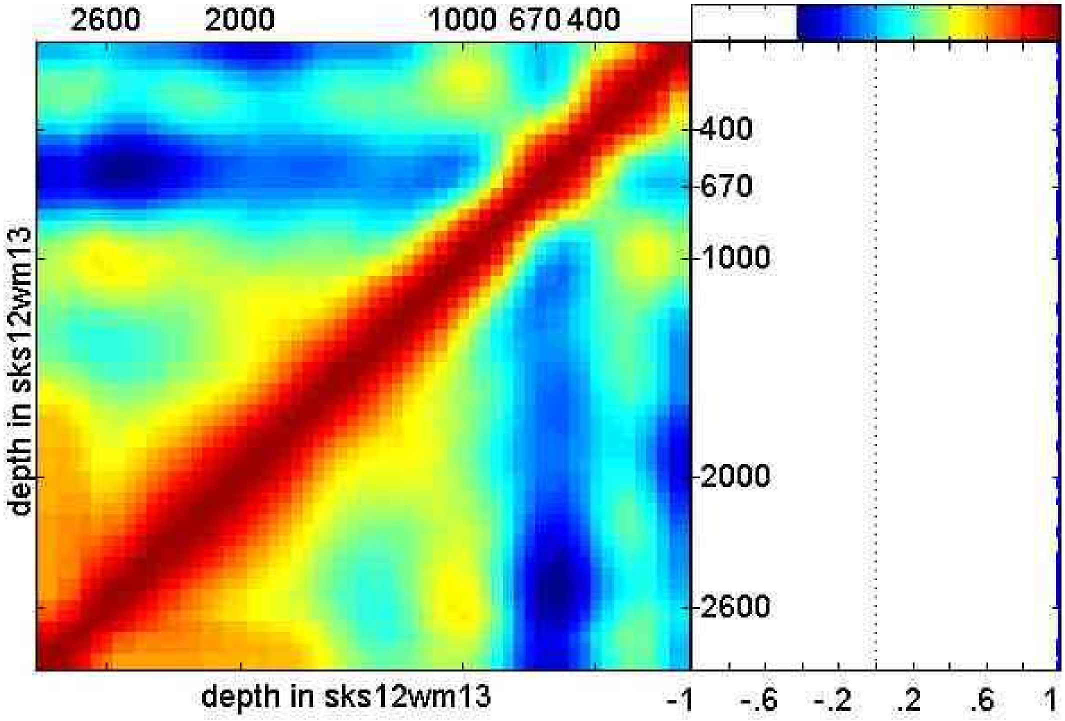
Masters et al. (SIO) versus Dziewonski et al. (HRV)



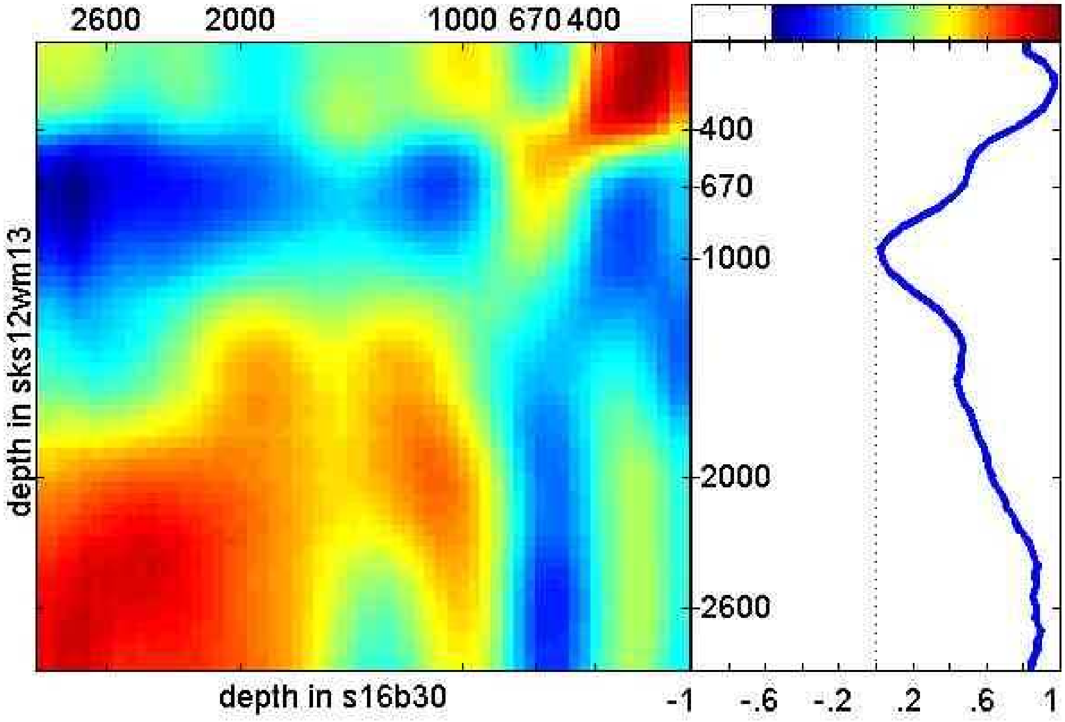
From: http://mahi.ucsd.edu/Gabi/rem2.dir/shear-models.html

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

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

Surface Loads

Relevant surface loads:

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

Data sets:

- atmosphere: global surface pressure, 6 hours;
- non-tidal ocean: circulation models (e.g. 6 hours), satellite altimetry (e.g. 10 days);
- continental water storage: observations and models.

Eventually needed:

Gobal pressure field on the surface of the solid Earth:
$p = p(\lambda, \theta, t; h_s)$
where h_s height of Earth's surface.

Density variation above the surface of the solid Earth:
$\delta\rho = \delta\rho(\lambda, \theta, h, t)$

Previous studies of

- atmospheric loading (e.g.van Dam and Herring, 1994a (VLBI baselines), Mac Millan and Gipson, 1994 (VLBI baselines), van Dam et al., 1994b (GPS));
- non-tidal ocean loading (e.g. van Dam et al., 1997);
- continental water storage: (e.g. Van Dam et al., 2001a/b (GPS))

General conclusion:
some improvement of the rms at some sites, but also considerable disagreement between model predictions and observations.

Potential sources of disagreement (van Dam et al., 1994: atmospheric loading):

- lateral heterogeneities not included in the modelling;
- errors in GPS estimates of tropospheric delay, i.e. loading signal partly included in delay;
- errors in surface (air) pressure, in particular ocean response to atmospheric loading/forcing
- annual signals in time series of loading and station heights, unmodelled effects.

	Height		Latitude		Longitude		WZTD		Air pres.	
	A	ϕ	A	ϕ	A	ϕ	A	ϕ	A	ϕ
NYAL	4.79	1.66	0.49	1.50	1.03	0.60	4.14	4.30	4.66	4.98
NYA1	2.93	1.59	1.10	2.30	0.84	0.44	3.98	4.30	4.66	4.08
VARD	1.14	3.17	1.16	2.40	1.13	2.07	5.33	4.23	6.62	4.55
TRO1	3.38	2.13	0.22	2.83	0.96	1.19	5.20	4.26	6.88	4.49
TRON	3.44	1.90	0.71	1.28	0.65	4.01	4.92	4.25	5.79	4.58
ALES	2.52	2.42	0.65	1.75	1.30	6.13	4.74	4.28	5.50	4.73
BERG	1.69	2.14	0.79	6.07	0.54	0.05	4.32	4.17	5.50	4.73
STAV	0.57	1.49	0.70	0.27	0.31	0.51	4.20	4.21	4.50	4.74
KRIS	1.76	0.08	0.78	3.06	0.74	0.60	4.21	4.14	4.17	4.59
OSLO	3.57	2.22	0.46	1.07	0.92	1.01	4.68	4.19	3.76	4.47