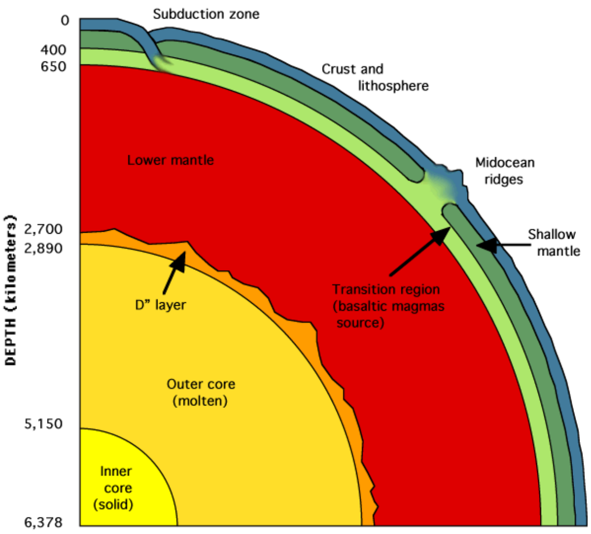
Geodynamics. Geodetic reference systems

- Geodynamics
  - Global tectonic (continental drift)
  - Postglacial land uplift
  - Sea level change,
  - Earth tide, permanent tides, direct vs indirect tides
- Celestial reference systems/frames
  - ICRS, ICRF
- Terrestrial reference systems/frames
  - ITRS, ITRF
- Existing terrestrial reference frames
  - ITRF ??, EUREF 89, WGS 84, SWEREF 99

1

Earth's interior



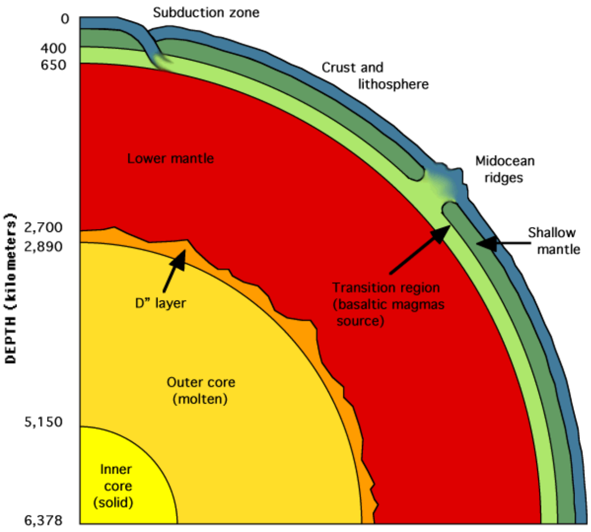
- Crust
- Upper mantle (lithosphere, astenosphere, rest of upper mantle)
- Lower mantle
- Outer core
- Inner core

The Crust

- Solid materials
- 35km/6km thick
- ρ=2.67 g/cm**3
- 15-25° C

2

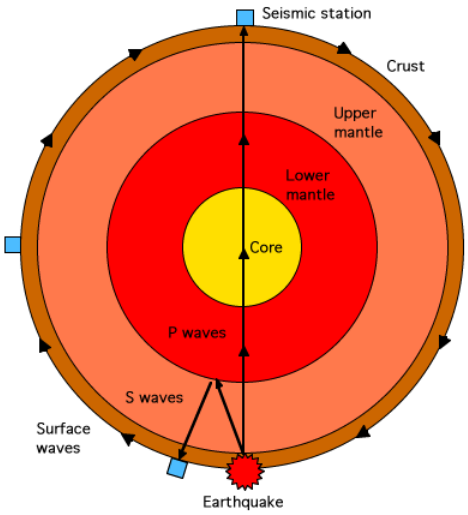
Earth's interior – Upper mantle



- viscoelastic,
- up to 700 km depth,
- ρ= 3.3-4.1 g/cm**3
- lithosphere <100 km, asthenosphere<400 km
- Seismic waves change velocity on the bounday surface (Moho surface) between the crust and mantle

3

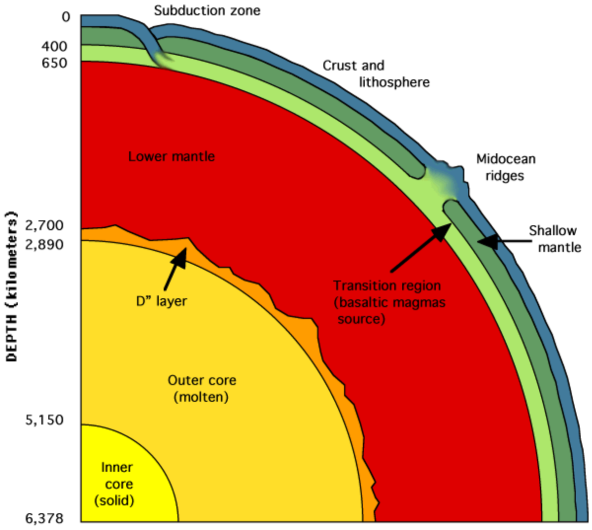
Surface waves & compression waves



- S-waves (shear waves) travel along the surface at 4-7 km/s
- P-waves (compression) travel through the earth at 6-8 km/
- P-waves change velocity at the crust-mantle boundary (Moho-surface)
- Seismic measurements are uesed to monitor earthquakes, atomic bombing tests and studies of the interior mass distribution inside the earth

4

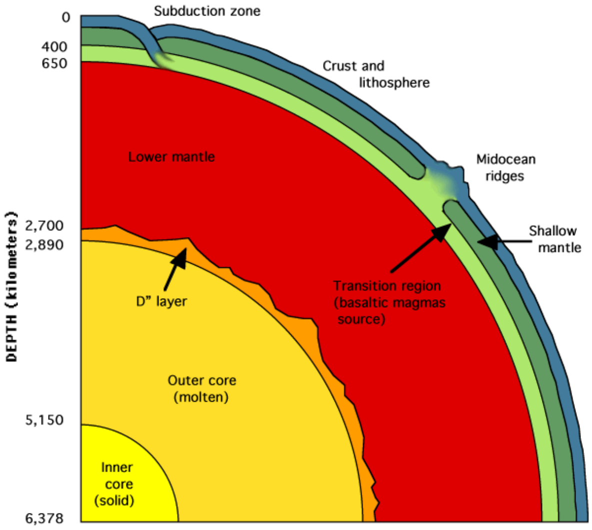
Lower mantle, outer core, inner core



- Viscoelastic
- 700-2890 km
- ρ= 4.2-5.6 g/cm**3
- Radioactivity in the lower mantle creates heating, 1200-2800° C
- Thermal convection in asthenosphere causes mantle convection
- Molten outer core
- solid inner core
- 2800-4000 ° C
- Thermal convection" inside the outer core creates geomagnetism

5

Mechanism of plate tectonics



- Radioactivity in the lower mantle warms up asthenosphere
- Cooler lithosphere floats above the warmer asthenosphere, meanwhile attracted by the earth's gravitational force
- Mantle convection: warmer mantle masses come up at *ocean ridges*, cooler litho-sphere sinks at *ocean trenchs*
- With mantle convection, the continents or different tectonic plates move in relation to each other.

6

Evidences of continental drift

- Bacon (1620): Africa’s coasts fit South America
- Wegner (1920’s): similar types/ages of vegetations, animal fossils on different continents
- Paleomagnetism (1950’): Rocks in Europa and North America show different magnetic North Poles
- Isostasy hypothesis ”needs” a viscoelastic mantle
- Postglacial land uplift supports mantle’s *viscoelastivity*
- Ocean bottoms’ age increases at ocean ridges

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Characteristics of global tectonics

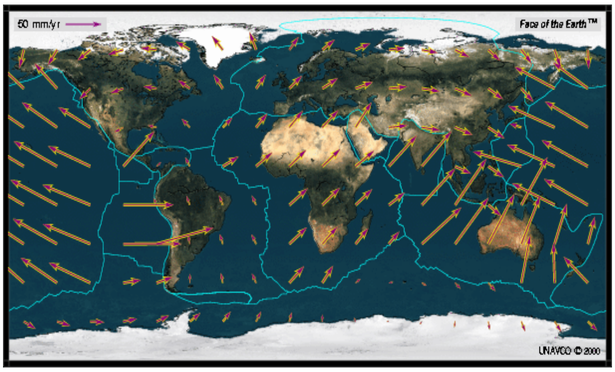

Plate motion model NUVEL-1A NNR

- The lithosphere is divided into several big plates: Euroasia, Pacific, North/South America, Africa, Indian, Antarctica
- Subduction (convergence) at ocean trenches: a heavier oceanic plate collides with and sinks below a lighter continental plate. Nazca-plate vs South America
- Sea floor spreading (divergence) at ocean ridges: mantle masses come up when two oceanic plates move away from each other. Ex: Mid-atlantic Ridge
- Earthquakes and vulcanos at plate borders. Ex: California, Japan, Southeast Asia, …

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Theory of Global Tectonics

9

Implification of Global Tectonics

- Geodetic points on the ground are moving !
- Coordinates of ground points are changing with time:
  - GRS must refer to a specific time epoch: SWEREF 99, ITRF 2000
  - Coordinates must refer to a specific time epoch
  - Velocity vectors must be computed together with position vectors
  - Helmert transformation parameters change with time
- Repeated geodetic measurements give direct determination of global tectonic movement velocity

  → Wegener’s prediction comes true !

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'' This must be left to the geodesists.

I have no doubt that in the not too distant future we will be successful in making a precise measurement of the drift of North America relative to Europe. ''

Alfred Wegener , 1929

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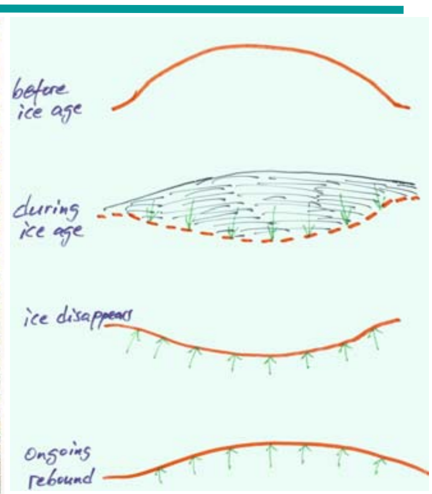
Land uplift - postglacial rebound



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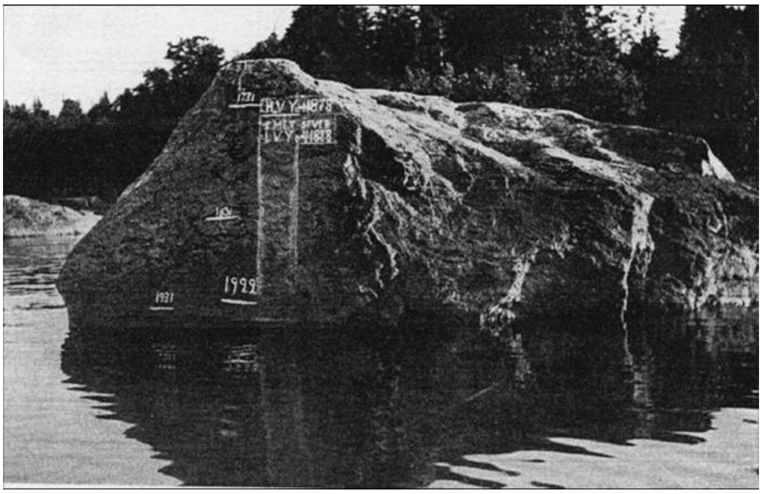
Land uplift or water sinking ???



Anders Celsius 1765

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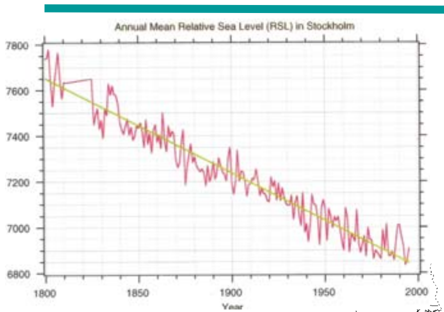
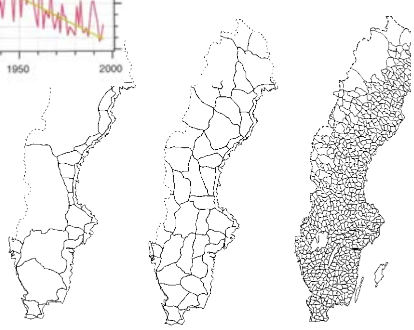
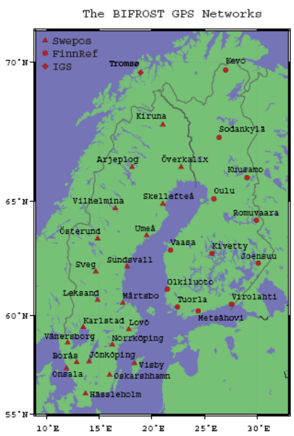
Determination of land uplift







(From Jan Johansson)

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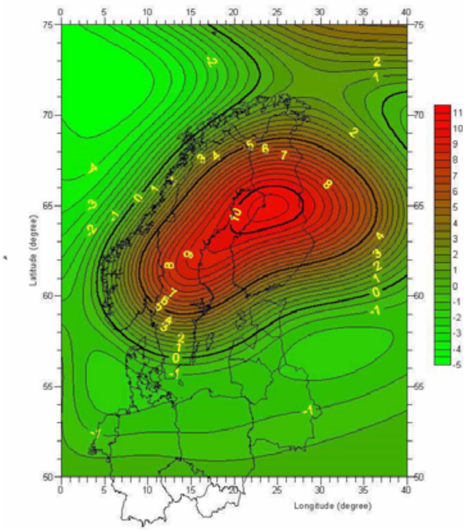
Geophysical modelling of land uplift



- Input data (ICE + PREM)
  - Ice history
  - Depth of the lithosphere
  - Viscosity of the upper mantle and the lower mantle
  - Gravity inside the earth
  - Density of the earth's interior
  - Seismic velocities
- Prediction:
  - Land uplift

(Software by J Mitrovica, Department of Physics, University of Torronto, 1996)

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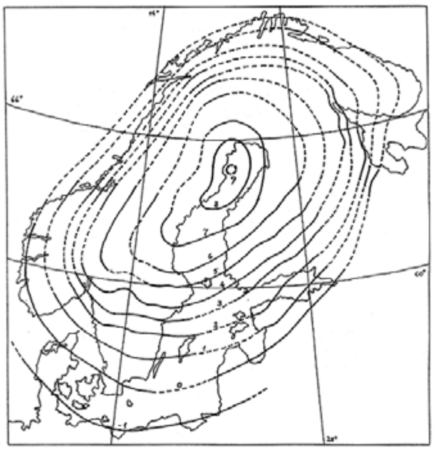
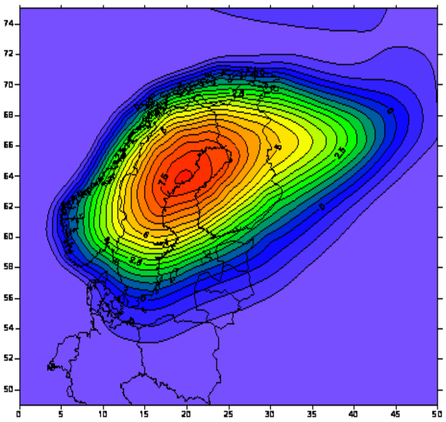
Swedish land uplift model (mm/year)



Martin Ekman (1998)



RH 2000 LU Computed by LMV and based on data from repeated levellings, mareograph, permanent GPS & geophysical model

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Implification of Land uplift for height determination

- Ground points will rise due to land upgift
- Heights of ground points will change with time
- Geodetic vertical reference systems must refer to a specific time epoch: RH 00, RH 70, RH 2000
- Geodetic heights (elliposidal or levelled) must refer to a specific time epoch
- Geoid model + land uplift: SWEN 08 LR

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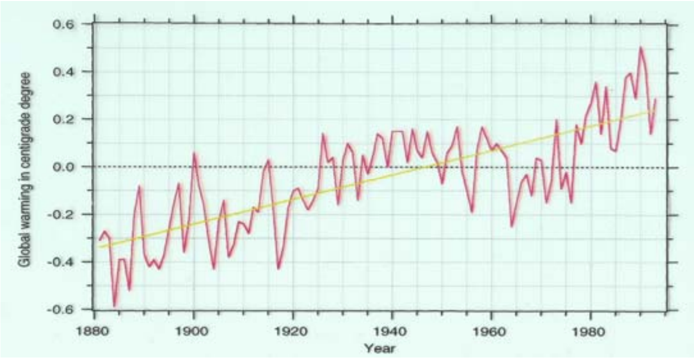
Global warming 1880-1995



- Polar ice to melt, water to expand, sea level to rise
- 1.7 mm/y (1870-2004), 2.7 mm/y (1993-2015)
- Effects of sea level rise and land uplift are mixed up

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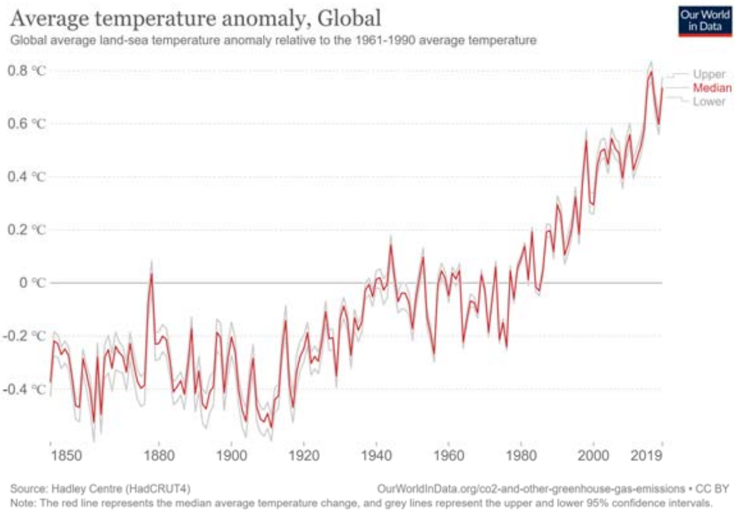
Global warming 1885-2019



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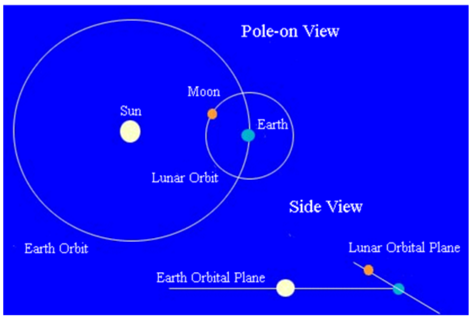
Earth Tide

- Tidal potential T
  - Earth-Moon system.
  - Tidal potential of the Moon
- Equilibrium earth tide
- Love's number, h, κ, l
- Observed earth tide
  - Observed tidal effect on
- **Permanent tidal effect**
  - Direct/indirect effects
  - 3 tidal systems



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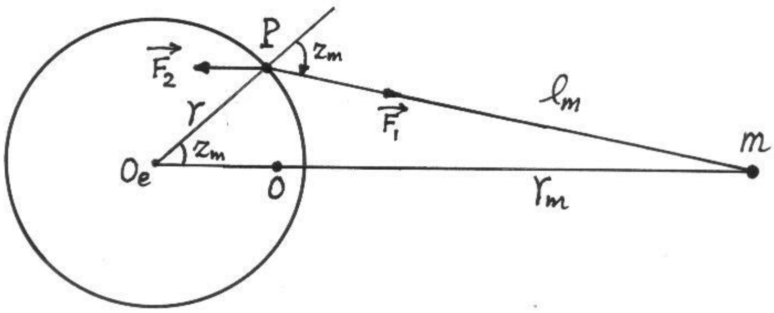
Tidal potential of the Moon



$$T^m = \frac{Gm}{\ell_m} - \left(\frac{Gm}{r_m} + Gm\frac{r}{r_m^2}\cos z_m\right)$$

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Equilibrium tides for a rigid earth

Tidal effect on the geoid height for a rigid earth:

$$\delta N_0 \approx 26.7\left(\cos 2z_m + \frac{1}{3}\right) + 12.3\left(\cos 2z_s + \frac{1}{3}\right) \qquad (cm)$$

Tidal effect on the gravity magnitude for a rigid earth:

$$\delta g_v \approx -\left(\frac{\partial\{T_2^m + T_2^s\}}{\partial r}\right)_{r=R} = -\frac{4D}{3R}\left(\frac{c}{r_m}\right)^3(3\cos^2 z_m - 1) - \frac{4D_s}{3R}\left(\frac{c_s}{r_s}\right)^3(3\cos^2 z_s - 1)$$

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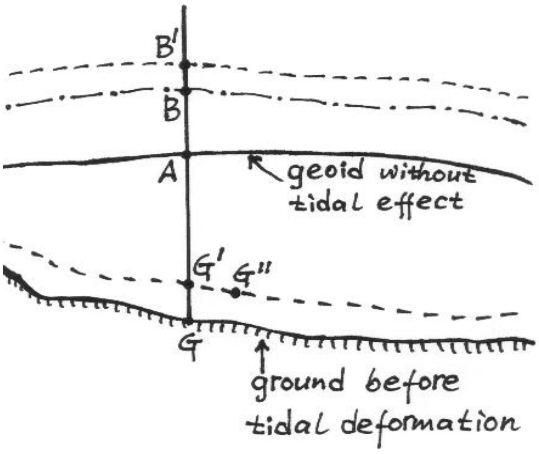
Earth deformation & Love's numbers



$$h = \frac{\overline{GG'}}{\overline{AB}}$$

$$k = \frac{\overline{BB'}}{\overline{AB}}$$

$$\ell = \frac{\overline{G'G''}}{\overline{AB}}$$

$$h \approx 0.62$$
$$k \approx 0.30$$
$$\ell \approx 0.085$$

$$\overline{AB} = \frac{T}{g}, \quad \overline{BB'} = \frac{\delta T}{g}$$

$$k = \frac{\delta T}{T}$$

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Observed tides for a deformed earth

Observed geoid tide for a deformed earth:

$$\delta N = \overline{G'B'} - \overline{GA} = \overline{AB} + \overline{BB'} - \overline{GG'} = (1 + k - h) \cdot \overline{AB} = (1 + k - h) \cdot \delta N_0$$

Observed gravity tide for a deformed earth:

$$\delta g \approx (1 - \frac{3}{2}k + h) \cdot \delta g_v$$

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Non-zero time-average

$$T_2 = D\left[\left(\frac{1}{3}-\sin^2\phi\right)+3\left(\sin^2\phi-\frac{1}{3}\right)\sin^2\delta+\cos^2\phi\cos^2\delta\cos 2t+\sin 2\phi\sin 2\delta\cos t\right]$$

$$T_2 = D\ (T_z + T_s + T_t)$$

$$\overline{T_s} = \frac{1}{2\pi}\int_0^{2\pi} D\cdot T_s\ dt = 0$$
$$\overline{T_t} = \frac{1}{2\pi}\int_0^{2\pi} D\cdot T_t\ dt = 0$$
$$\overline{T_z} = \frac{1}{2\pi}\int_0^{2\pi} D\cdot T_z\ d\ell\ = D\ \left(\tfrac{1}{2}\sin^2\varepsilon-\tfrac{1}{3}\right)\ \left(\sin^2\phi-\tfrac{1}{3}\right)$$

The time-average of the tidal potential T_2 does not vanish. This causes permanent tidal effects, including permanent deformation of the solid earth.

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Permanent tide and tidal systems

- 4 parts of tidal effects
  - Direct (extra-terrestrial masses) vs indirect effects (earth's deformation)
  - Periodic vs permanent effetcs. Periodic effects can be averaged out.
  - Treatment of the permanent tide leads to 3 tidal systems
- Non-tidal model (Tide-free) (GNSS - ITRF)
  - Permanent deformation of the earth is *eliminated* $\longrightarrow$ *earth's form changed*
  - Permanent tidal effects are *eliminated* from the measurements
- Zero tidal model (EVRS 2000)
  - Permanent deformation of the earth is *retained* $\longrightarrow$ *masses outside the geoid*
  - Permanent tidal effects are *eliminated* in the measurements
- Mean tidal model
  - Permanent deformation of the earth is *retained*
  - Permanent tidal effects are *retained* $\longrightarrow$ *included in the normal gravity filed ?)*

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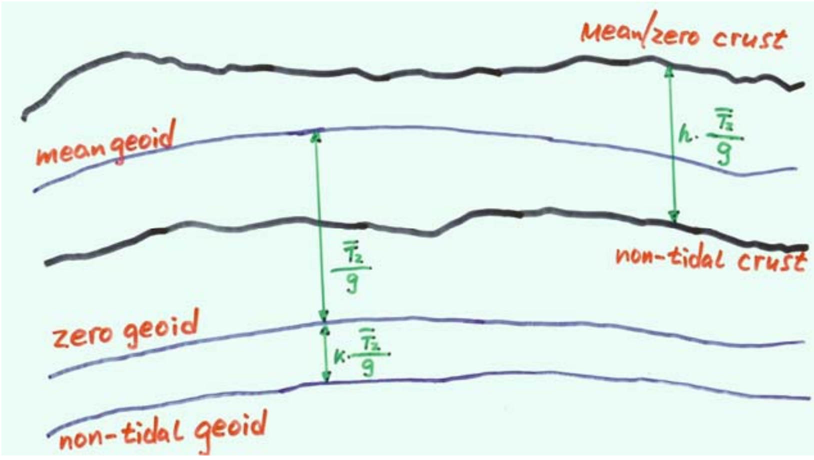
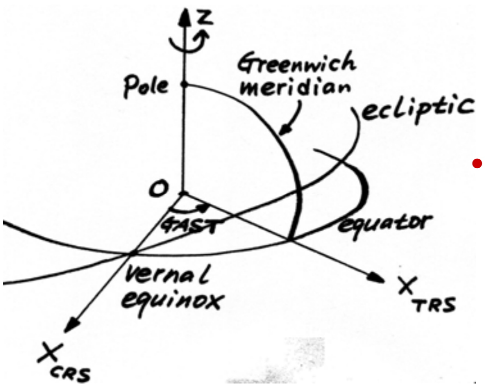
Tidal Systems: Non-Tidal, Mean vs Zero Tide



Tidal Systems: geoidal differences

Latitude FI	3 sin(FI) **2 - 1	Geoid separation, cm	Geoid separation, cm	Crust separation, cm					
(degree)		Non-tidal - Zero	Zero - Mean	Non-tidal - Mean/zero					
0	-1,000000000	6,80	2,04	4,21	PI/180	0,017453293	D =	26206	cm**2/s**2
5	-0,977211630	6,64	1,99	4,12	YPSILON, deg	23,439291	g=	980	cm/s**2
10	-0,909538931	6,18	1,85	3,83	sin (YPSILON)	0,3977772	D/g	26,741	cm
15	-0,799038106	5,43	1,63	3,37			T0	-6,79805	
20	-0,649066665	4,41	1,32	2,74					
25	-0,464181415	3,16	0,95	1,96					
30	-0,250000000	1,70	0,51	1,05					
35	-0,013030215	0,09	0,03	0,05					
40	0,239527733	-1,63	-0,49	-1,01					
45	0,500000000	-3,40	-1,02	-2,11					
50	0,760472267	-5,17	-1,55	-3,21					
55	1,013030215	-6,89	-2,07	-4,27					
60	1,250000000	-8,50	-2,55	-5,27					
65	1,464181415	-9,95	-2,99	-6,17					
70	1,649066665	-11,21	-3,36	-6,95					
75	1,799038106	-12,23	-3,67	-7,58					
80	1,909538931	-12,98	-3,89	-8,05					
85	1,977211630	-13,44	-4,03	-8,33					
90	2,000000000	-13,60	-4,08	-8,43					

Reference system vs reference frame



- Definition of the origin and the orientation of the 3 coordinate axes, together with related assumptions, is called a reference system
- A network of ground points or celestial bodies, at which the coordinates and velocities in a certain reference system have been explicitly specified, is called a reference frame which is an realization of the (theoretical) reference system

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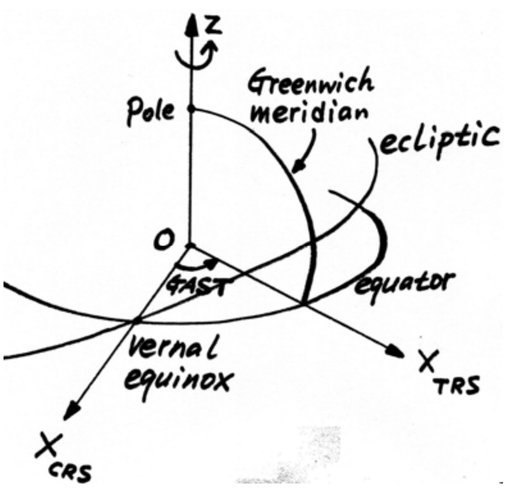
International Celestial Reference System (ICRS)



- Origin at the barycentre (practically at geocentre)
- Z-axis toward the *mean celestial North Pole* at **J2000.0**
- X-axis toward the *mean equinox* at J2000.0
- Y-axis follows to form a right-handed system

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IERS

- IERS, International Earth Rotation Service, was established in 1987 by IAU and IUGG to replace
  - International Polar Motion Service (IPMS)
  - Bureau International de l'Heure (BIH)

- Renamed in 2003 as International Earth Rotation and Reference Systems Service

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International Celestial Reference Frame (ICRF)

- First realization of ICRS, ICRF1, is made by IAU in 1997 based on VLBI measurements of 212 defining radio sources

- Two extentions of ICRF1 are made by IERS in 1999 and 2004

- Second realization of ICRS, ICRF2, is made in 2009
  - VLBI measurements of 3414 radio sources
  - 295 defining radio sources

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International Celestial Reference Frame (ICRF2)

Coordinates of 295 ICRF2 defining sources

ICRF Designation (1)	IERS Des. (2)	Right Ascension J2000.0 h m s	Declination J2000.0 o ' "	Uncertainty R.A. s	Uncertainty Dec. "
ICRF J000435.6-473619	0002-478	00 04 35.65550384	-47 36 19.6037899	0.00001359	0.0002139
ICRF J001031.0+105829	0007+106	00 10 31.00590186	10 58 29.5043827	0.00000491	0.0000930
ICRF J001101.2-261233	0008-264	00 11 01.24673846	-26 12 33.3770171	0.00000660	0.0000936
ICRF J001331.1+405137	0010+405	00 13 31.13020334	40 51 37.1441040	0.00000482	0.0000683
ICRF J001611.0-001512	0013-005	00 16 11.08855479	-00 15 12.4453413	0.00000435	0.0001005
ICRF J001945.7+732730	0016+731	00 19 45.78641940	73 27 30.0174396	0.00000989	0.0000424
ICRF J002232.4+060804	0019+058	00 22 32.44120914	06 08 04.2690807	0.00000439	0.0000956
ICRF J003824.8+413706	0035+413	00 38 24.84359231	41 37 06.0003032	0.00000499	0.0000613
ICRF J005041.3-092905	0048-097	00 50 41.31738756	-09 29 05.2102688	0.00000278	0.0000428
ICRF J005109.5-422633	0048-427	00 51 09.50182012	-42 26 33.2932480	0.00000932	0.0001177
ICRF J010245.7+582411	0059+581	01 02 45.76238248	58 24 11.1366009	0.00000523	0.0000414
ICRF J010645.1-403419	0104-408	01 06 45.10796851	-40 34 19.9602291	0.00000376	0.0000455
ICRF J010915.4-604948	0107-610	01 09 15.47520598	-60 49 48.4599686	0.00001744	0.0001750
ICRF J011205.8+224438	0109+224	01 12 05.82471754	22 44 38.7863909	0.00000379	0.0000653
ICRF J011327.0+494824	0110+495	01 13 27.00680344	49 48 24.0431742	0.00000597	0.0000727
ICRF J011857.2-214130	0116-219	01 18 57.26216666	-21 41 30.1399986	0.00000683	0.0001138
ICRF J012141.5+114950	0119+115	01 21 41.59504339	11 49 50.4131012	0.00000279	0.0000429
ICRF J013305.7-520003	0131-522	01 33 05.76255607	-52 00 03.9457209	0.00001218	0.0001605

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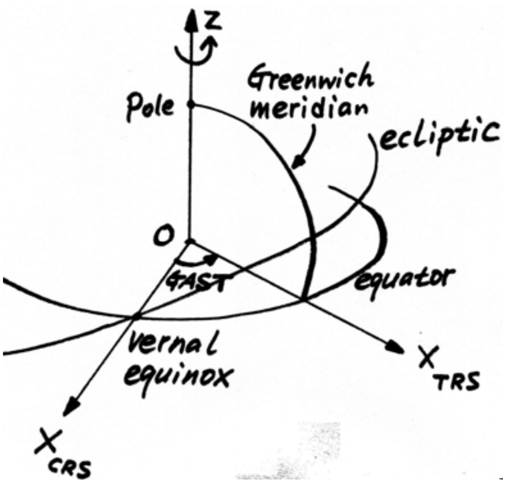
International Terrestrial Reference System (ITRS)



- Origin at the earth's centre of masses including the oceans and the atmosphere
- Z-axis toward the **CIO** (IRP - IERS Reference Pole)
- X-axis along intersection of the equator and the Greenwich Meridian
- Y-axis inside the equator to form a right-handed system

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International Tererstrial Reference Frame

- ITRF is realization of ITRS
- ITRF networks consists of stations all over the world, measured by 4 space geodetic methods
  1) Very Long Baseline Interferometry (VLBI)
  2) Satellite Laser Ranging (SLR)
  3) GNSS
  4) Doppler Orbitography Integrated by Satellites (DORIS)
- Final products include:
  - Position coordinates and velocities for a reference epoch
  - Transformation parameters and their time derivatives
  - Consistent estimates of 5 EOP

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Earth Orientation Parameters (EOP)

- 2 Polar coordinates with respect to CIO : x_p , y_p
- 2 Nutation parameters :
  - nutation in obliquity (Δε)
  - nutation in longitude (ΔΨ)
- 1 time parameter
  - UTC-UT1 (provide UT1 when UTC is known)
- EOPs are estimated and distributed by IERS
- EOPs relate (X,Y,Z) defined in ICRF to (x,y,z) defined in ITRF

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Transformation from ICRF to ITRF

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R_p(x_p, y_p) \cdot R_3(GAST) \cdot N(\varepsilon_0, \Delta\varepsilon, \Delta\psi) \cdot P(z, \vartheta, \xi) \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$P(z, \vartheta, \xi) = R_3(-z) \cdot R_2(\vartheta) \cdot R_3(-\xi)$$

$$= \begin{bmatrix} +\cos z \cos\vartheta \cos\xi - \sin z \sin\xi & -\cos z \cos\vartheta \sin\xi - \sin z \cos\xi & -\cos z \sin\vartheta \\ +\sin z \cos\vartheta \cos\xi + \cos z \sin\xi & -\sin z \cos\vartheta \sin\xi + \cos z \cos\xi & -\sin z \sin\vartheta \\ +\sin\vartheta \cos\xi & -\sin\vartheta \sin\xi & +\cos\vartheta \end{bmatrix}$$

$$\underset{3\times 3}{N}(\varepsilon_0, \Delta\varepsilon, \Delta\psi) = R_1(-\varepsilon) \cdot R_3(-\Delta\psi) \cdot R_1(\varepsilon_0) \qquad (\varepsilon = \varepsilon_0 + \Delta\varepsilon)$$

$$= \begin{bmatrix} \cos\Delta\psi & -\sin\Delta\psi \cos\varepsilon_0 & -\sin\Delta\psi \sin\varepsilon_0 \\ \sin\Delta\psi \cos\varepsilon & +\cos\Delta\psi \cos\varepsilon \cos\varepsilon_0 + \sin\varepsilon \sin\varepsilon_0 & +\cos\Delta\psi \cos\varepsilon \sin\varepsilon_0 - \sin\varepsilon \cos\varepsilon_0 \\ \sin\Delta\psi \sin\varepsilon & +\cos\Delta\psi \sin\varepsilon \cos\varepsilon_0 - \cos\varepsilon \sin\varepsilon_0 & +\cos\Delta\psi \sin\varepsilon \sin\varepsilon_0 + \cos\varepsilon \cos\varepsilon_0 \end{bmatrix}$$

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Computation of *GAST*

$$\varepsilon_0 = 23^0\ 26'\ 21.448'' - 46.8150'' \cdot T - 0.00059'' \cdot T^2 + 0.001813'' \cdot T^3$$

$$\left.\begin{aligned} \xi &= 2306.2181 \cdot T + 0.30188 \cdot T^2 + 0.017998 \cdot T^3 \\ z &= 2306.2181 \cdot T + 1.09468 \cdot T^2 + 0.018203 \cdot T^3 \\ \vartheta &= 2004.3109 \cdot T - 0.42665 \cdot T^2 - 0.041833 \cdot T^3 \end{aligned}\right\} \quad \text{(unit: arcsecond)}$$

$$T = \frac{JD(t) - J2000.0}{36525} = \frac{JD(t) - 2\,451\,545.0}{36525}$$

$$GAST = (GMST)_0 + 1.002\,737\,909\,35 \cdot UT1 + \Delta\psi \cos\varepsilon_0$$
$$(GMST)_0 = 24\,110.54841^s + 8\,640\,184.812866^s\ T_0 + 0.093\,104^s\ T_0^2 - 6.2^s \cdot 10^{-6} T_0^3$$

$$T_0 = \frac{JD_{UT=0} - 2\,451\,545.0}{36525}$$

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List of ITRF solutions

	reference epoch
ITRF88	1988.0
ITRF89	1988.0
ITRF92	1988.0
ITRF93	1988.0
ITRF94	1997.0
ITRF96	1997.0
ITRF97	1997.0
ITRF2000	1997.0
ITRF2005	2000.0
ITRF2008	2005.0
ITRF2014	2010.0

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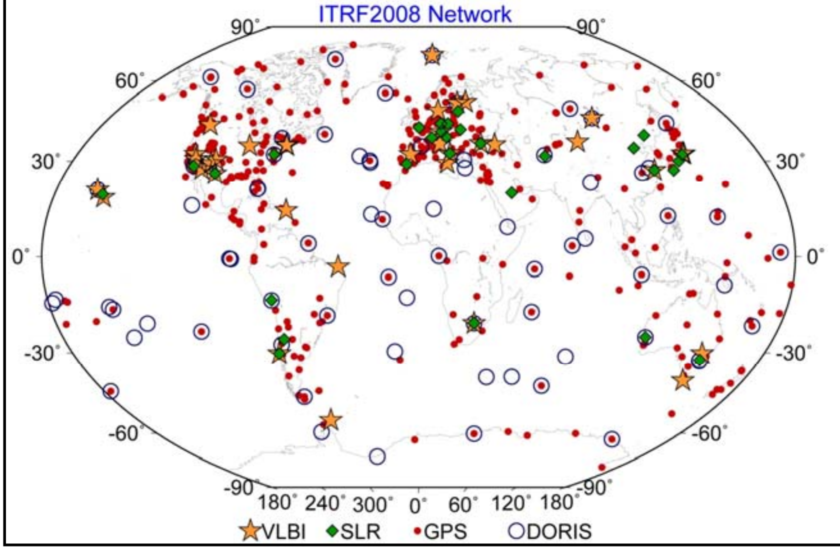
Global Network of ITRF 2008



VLBI: 138
SLR: 155
GPS: 910
DORIS: 170

Total: **934**
at 580 sites

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ITRF 2008

- Computations in 3 steps
  1) Each type (VLBI,SLR,GPS,DORIS) is processed separately to produce weekly (daily VLBI) time series of positions and EOP
  2) Above results are combined to estimate position coordinates for epoch 2005.0, velocity and daily EOP
  3) Combination with local survey at co-locating stations

- ITRF 2008 results:
  - Origin and scale are defined by SLR data
  - Orientation is defined by average of VLBI and SLR data
  - Scale accuracy: **1 ppb, 0.05 ppb / year** (VLBI-SLR agreement)
  - Origin accuracy: at the level of or better than **1 cm**

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Station coordinates/velocities of ITRF 2008

```
10 VELX    7205   A     1 05:001:00000 m/y  2 -.154701843128797E-01 0.47543E-04
11 VELY    7205   A     1 05:001:00000 m/y  2 -.121094247184766E-02 0.62981E-04
12 VELZ    7205   A     1 05:001:00000 m/y  2 0.408529863128065E-02 0.69402E-04
13 STAX    7204   A     1 05:001:00000 m    2 0.882879772507557E+06 0.13845E-02
14 STAY    7204   A     1 05:001:00000 m    2 -.492448231271830E+07 0.35634E-02
15 STAZ    7204   A     1 05:001:00000 m    2 0.394413070534473E+07 0.27791E-02
16 VELX    7204   A     1 05:001:00000 m/y  2 -.143669405946909E-01 0.81983E-04
17 VELY    7204   A     1 05:001:00000 m/y  2 -.102511002663171E-02 0.20579E-03
18 VELZ    7204   A     1 05:001:00000 m/y  2 0.274104971026836E-02 0.17380E-03
19 STAX    7216   A     1 05:001:00000 m    2 -.132421109976204E+07 0.97620E-03
20 STAY    7216   A     1 05:001:00000 m    2 -.533202313706689E+07 0.15257E-02
21 STAZ    7216   A     1 05:001:00000 m    2 0.323211831880121E+07 0.11575E-02
22 VELX    7216   A     1 05:001:00000 m/y  2 -.126619959048342E-01 0.51526E-04
23 VELY    7216   A     1 05:001:00000 m/y  2 0.339720116768070E-03 0.84921E-04
24 VELZ    7216   A     1 05:001:00000 m/y  2 -.467559096977887E-02 0.69110E-04
25 STAX    7213   A     1 05:001:00000 m    2 0.337060591485963E+07 0.65329E-03
26 STAY    7213   A     1 05:001:00000 m    2 0.711917602784800E+06 0.54467E-03
27 STAZ    7213   A     1 05:001:00000 m    2 0.534983082091565E+07 0.69138E-03
28 VELX    7213   A     1 05:001:00000 m/y  2 -.142016652825457E-01 0.54415E-04
29 VELY    7213   A     1 05:001:00000 m/y  2 0.145280633229021E-01 0.36261E-04
30 VELZ    7213   A     1 05:001:00000 m/y  2 0.103568368182873E-01 0.76909E-04
31 STAX    7203   A     1 05:001:00000 m    2 0.403394735308593E+07 0.30487E-02
32 STAY    7203   A     1 05:001:00000 m    2 0.486990645775994E+06 0.11888E-02
33 STAZ    7203   A     1 05:001:00000 m    2 0.490043088922310E+07 0.34356E-02
34 VELX    7203   A     1 05:001:00000 m/y  2 -.137947899098904E-01 0.23546E-03
```

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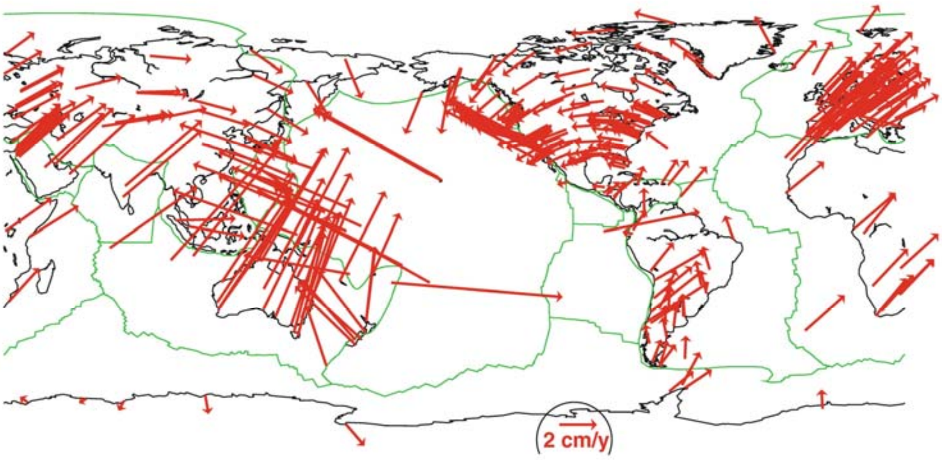
Horizontal velocity from ITRF 2008



406 stations have formal errors < 0.2mm/year

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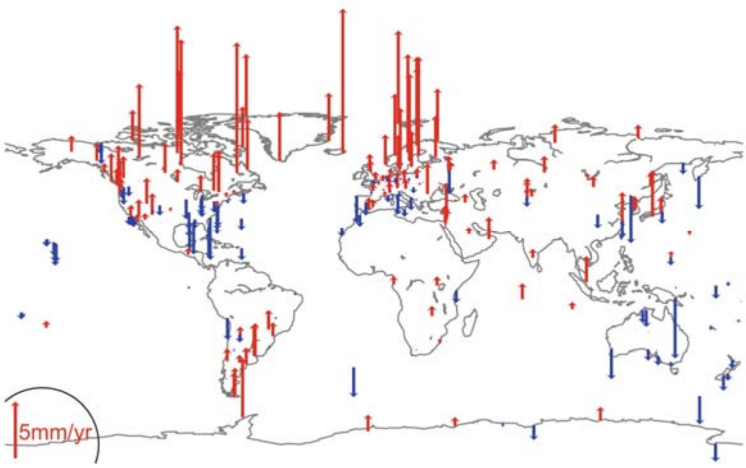
Vertical velocity from ITRF 2008



278 stations have formal errors < 0.2mm/year

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Transformation between different ITRF

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ITRFyy} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ITRF\,2000} + \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} + \begin{bmatrix} \delta & -\omega_Z & \omega_Y \\ \omega_Z & \delta & -\omega_X \\ -\omega_Y & \omega_X & \delta \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ITRF\,2000}$$

$$T_1(t) = T_1(t_0) + (\frac{dT_1}{dt}) \cdot (t - t_0)$$

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Remarks on ITRF

- With ITRF, a internationally common reference system has been established for positioning, navigation and space applications
- ITRF-related work demonstrated geodesy's contribution to basic sciences as well as current problems related to global change
- Achievable accuracy of latest ITRF: **1cm**, **1ppb**
- It is desirable for all the countries to go over to ITRF-based or ITRF-connected GRS.

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Reference systems of GNSS (=ITRS)

- GPS
  - WGS 84, defined in 1987 using TRANSIT observations. **1-2 m**
  - WGS 84 (G730) defined in 1994, WGS 84 (G873) defined in 1996, agrees with **ITRF94** at **10cm** level
  - WGS 84 (G1150), defined in 2002, agrees with **ITRF2005** up to **1cm**
- GLONASS
  - PZ-90, defined in 1990 using 26 ground stations
  - Agrees with ITRF at **meter level** (from a joint campaign in 1999)
- Galileo
  - GTRF agrees with ITRF within **1.5cm**

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Navy Navigation Satellite System (NNSS)

- Developped for US strategic nuclear submarines (Polaris) in 1960's
- 6 polar satellites at 600km
- 4 ground monitoring stations defining **World Geodetic System 1972**
- Doppler effects of satellite signals are measured by ground receivers
- 10 metres accuracy achieved with dual frequency receivers
- Also called TRANSIT or Doppler system

Swedish west coast was probably the best place for Polaris submarines to launch missile attacks toward Moscow ?

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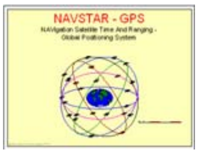
World Geodetic System 1984 (WGS 84)

- GPS = a new satellite navigation system to replace TRANSIT
  - Space segment: 24 satellites in 3 orbits, 55º inclination, 22000km altitude
  - Control segment: 6 Air Force OCS monitoring stations
  - User segment: GPS receivers



- WGS 84 ≈ Conventional TRS
  - Origin at the earth's centre of masses including atmosphere/oceans
  - Z-axis toward CIO, as defined by the IERS Reference Pole (IRP)
  - X-axis along intersections of the equator and Greenwich Meridian
- Realization of WGS 84
  - 6 OCS stations determined by NNSS (TRANSIT) in 1987
  - Parameters: a = 6378137m, GM = 3.986005*10**14, C_{20}, ω, 1/f=298.257223563
  - Estimated accuracy: ≈ 1 metre
- TRANSIT-derived WGS 84 is less precise than GPS measurements !

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Ellipsoids of *WGS 84* and *GRS 80*

Parametres	*Values of WGS 84*	*Values of GRS 80*
Defining parametres		
Semi-major axis a	6 378 137 m	6 378 137 m
Gravitational constant GM	$0.398\,600\,5 \cdot 10^{14}\ m^3 s^2$	$0.398\,600\,5 \cdot 10^{14}\ m^3 s^2$
Normalized dynamic factor $\overline{C}_{20}$	$-0.4\,84\,166\,85 \cdot 10^{-2}$	
Non-normalized factor J_2 $(= -\sqrt{5}\overline{C}_{20})$		$0.108\,263 \cdot 10^{-2}$
Angular velocity ω	$0.729\,211\,5 \cdot 10^{-5}\ rad\ s^{-1}$	$0.729\,211\,5 \cdot 10^{-5}\ rad\ s^{-1}$
Derived Parametres		
Semi-minor axis b	6 356 752.314 2 m	6 356 752.314 1 m
Flattening $(1/f)$	298.257 223 563	1/298.257 222 101
First eccentricity (e^2)	0.006 694 380 004	0.006 694 380 023

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WGS 84 (G703, G873)

- Same system definition – ITRS
- Realization of WGS 84 (G873)
  - 6 OCS, 13 NIMA, 18 IGS are surveyed by GPS in 1996
  - Coordinates of 12 IGS fidual stations in ITRF 94 are held fixed
  - Coordinates of all other stations are computed in ITRF94
  - New parametres:
    - a= 6378137 m, 1/f=298.257223563, GM=3.986004418*10**14, ω
    - orbits defined by EGM96
  - Final coordinates consistent with ITRF within 10 cm

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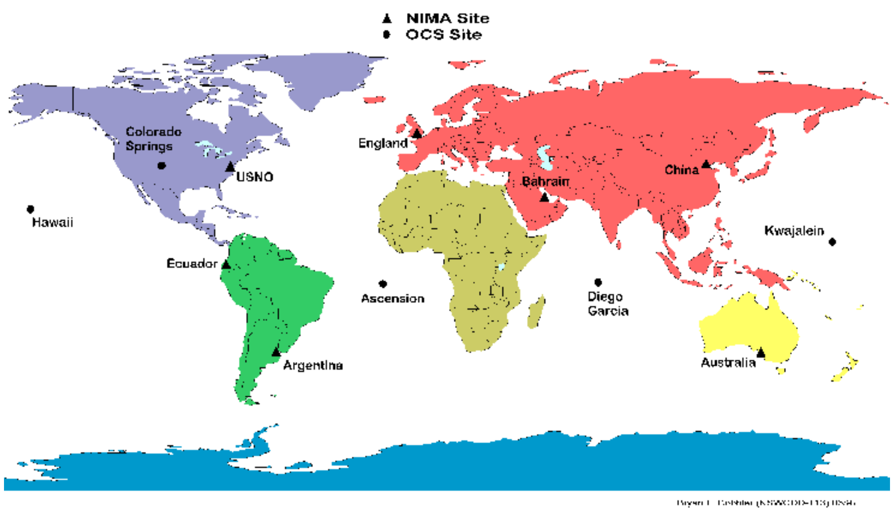
NIMA and Air Force OCS Tracking Stations



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New GPS Tracking Network

NSWCDD/TR-96/201

FIGURE 1. WORLDWIDE DISTRIBUTION OF TRACKING STATIONS

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EUropean REference Frame EUREF 89

- EUREF Permanent Network (EPN)
  - 118 Permanent GPS stations in >30 european countries
  - Part of IGS / ITRF networks.
  - 5 Swedish stations
  - OC, LDC, LAC, CB
- EUREF 89
  - Based on a 1989 EPN campaign
  - Coordinates computed in ITRF 89
  - Reference epoch: 1989.0
- Computation of coordinates in EUREF 89
  - From ITRFyy coordinates
  - From GPS field measurements

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Computation of Coordinates in EUREF 89

- From coordinates in ITRFyy
  - Compute ITRFyy coordinates at epoch 1989.0
  - Transform into EUREF 89 coordinates
  - Compute velocity in EUREF 89
- From GPS measurements made at epoch t_c
  - Carry out field measurements at epoch t_c (epoch of middle meaurements)
  - Transform ITRFyy coordinates of fiducial stations referred to epoch t_0 into coordinates referred to central measurement epoch t_c
  - Process GPS measurements to obtain ITRFyy coordinates referred to epoch t_c
  - Convert into EUREF 89 coordinates at epoch t_c
  - Convert into EUREF 89 coordinates at epoch 89.0

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Swedish 3D reference systems

- SWEPOS - 21 permanent GPS stations (25 since March 2000)
- Realization of Swedish 3D reference systems
- Monitoring GNSS system integrity
- Support network-RTK – VRS(Virtual Reference Station) (70km, 1-2cm (H), 2-3cm (V))
- SWEREF 93
  - 4 Swedish GPS stations in EUREF 89 campaign
  - 23 GPS stations in DOSE campaign, computed in ITRF 91 at epoch 1993.6
  - 11 DOSE points (5 Swedish) are fitted to EUREF coordinates
  - The final set of coordinates is named **SWEREF 93**

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3D reference system SWEREF 99

- Based on a Nordic GPS campaign in 1999, with 49 stations incl. 25 SWEPOS stations
- Coordinates computed in ITRF97 for 1999.5
- Transformed to EUREF89 for 1989.0
- Adopted in 2000 as a realisation of ETRS 89
- Introduced in 2001 as Swedish national reference frame **SWEREF 99**
- Tectonic epoch: 1989.0
- Height epoch: 1999.5 (GPS campaign)
- Ellipsoid: GRS 1980

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Transform SWEREF 99 to RT 90/RH 2000

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{RT\ 90} = \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} + (1+\delta s)\cdot R(\alpha_1,\alpha_2,\alpha_3)\cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{SWEREF\ 99}$$

$$\delta x = -414.0979 \text{ metres}$$

$$\delta y = -41.3381 \text{ metres}$$

$$\delta z = -603.0627 \text{ metres}$$

$$\delta s = +0.000\,000\,000\,0 \cdot 10^{-6}$$

$$\alpha_1 = -0.855\,043\,431\,4''$$

$$\alpha_2 = +2.141\,346\,518\,5''$$

$$\alpha_3 = -7.022\,720\,951\,6''$$

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