Height Reference Systems

by

Dag Solheim

Norwegian Mapping Authority

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Main items

- Geoid
- Traditional height determination (leveling)
- Satellite altimetry
- Tide gauges
  - Harmonic analysis
  - Lowest Astronomical Tide, LAT
- Practical implementation
- Summary

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Definition of the geoid

An equipotential surface of the earth's gravity potential W, W=const.

W=U+T where U is the known normal gravity potential and T is the disturbing or anomalous potential

One of physical geodesy's main tasks is the determination of T

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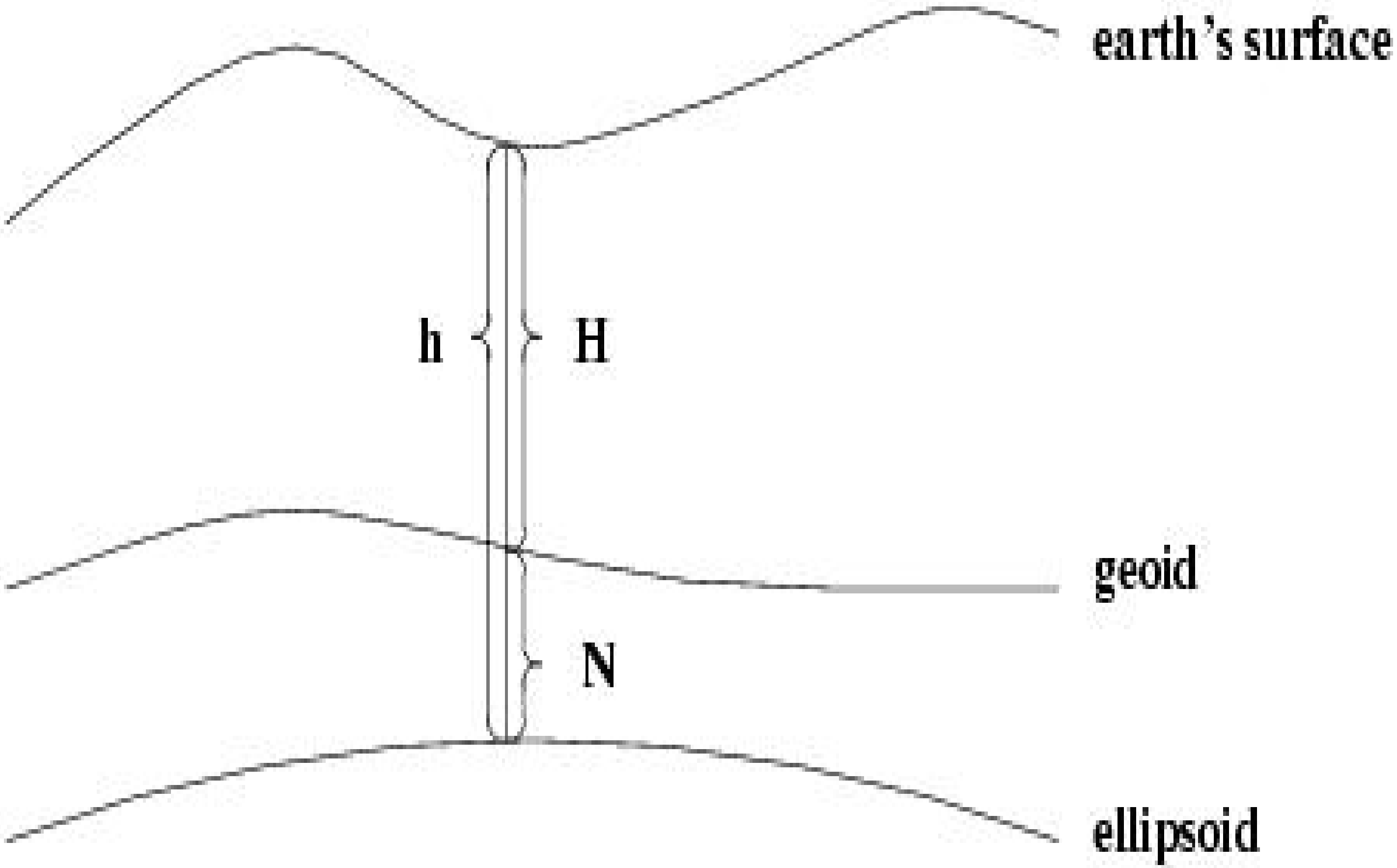
The importance of the geoid

- Classical reference surface
- Physical meaningful
- Water flows in the right direction
- Satellite techniques
  - Height determination with GPS
  - Optimal use of satellite altimetry in oceanography



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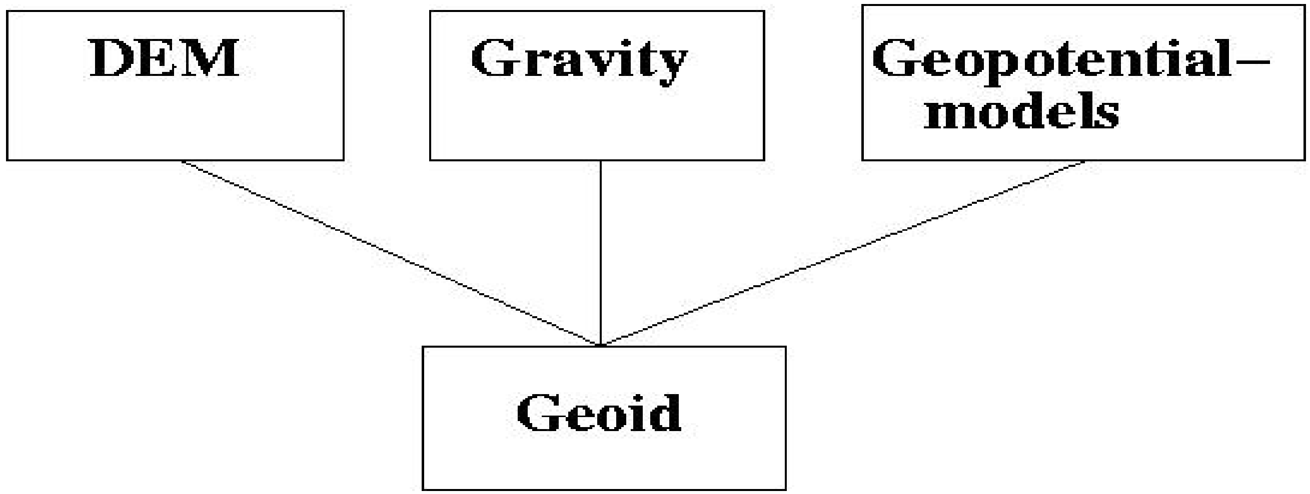
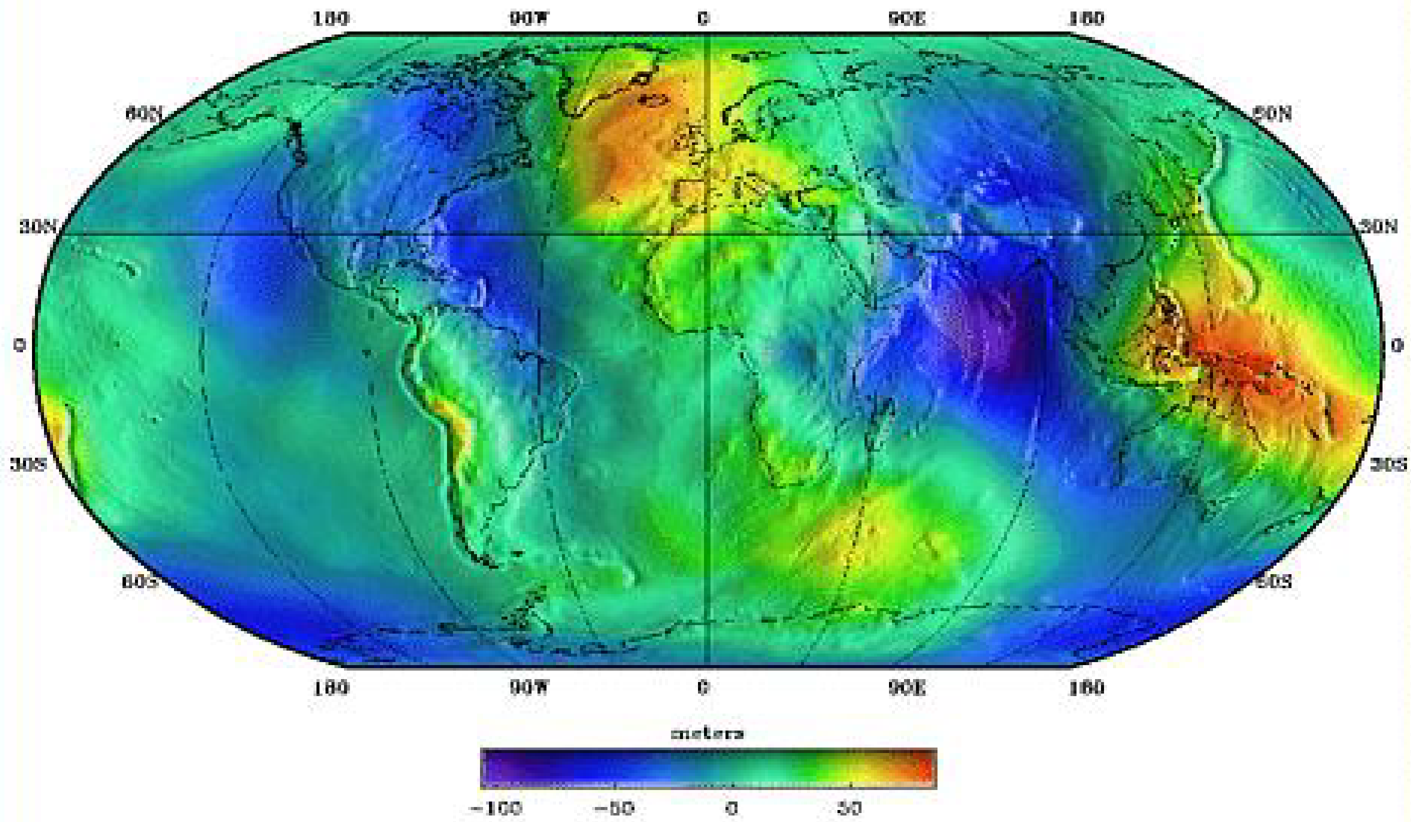
Determination of the geoid



The geoid is determined by using a remove/restore technique and by solving either integral (FFT) or differential equations (collocation)

EGM96 Geoid



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Future enhancements

- Improved data coverage and quality
- Improved geopotential models from the new satellite missions
  - CHAMP
  - GRACE
  - GOCE
- Theoretical improvements and refinements
- Digital density models
- Bathymetry

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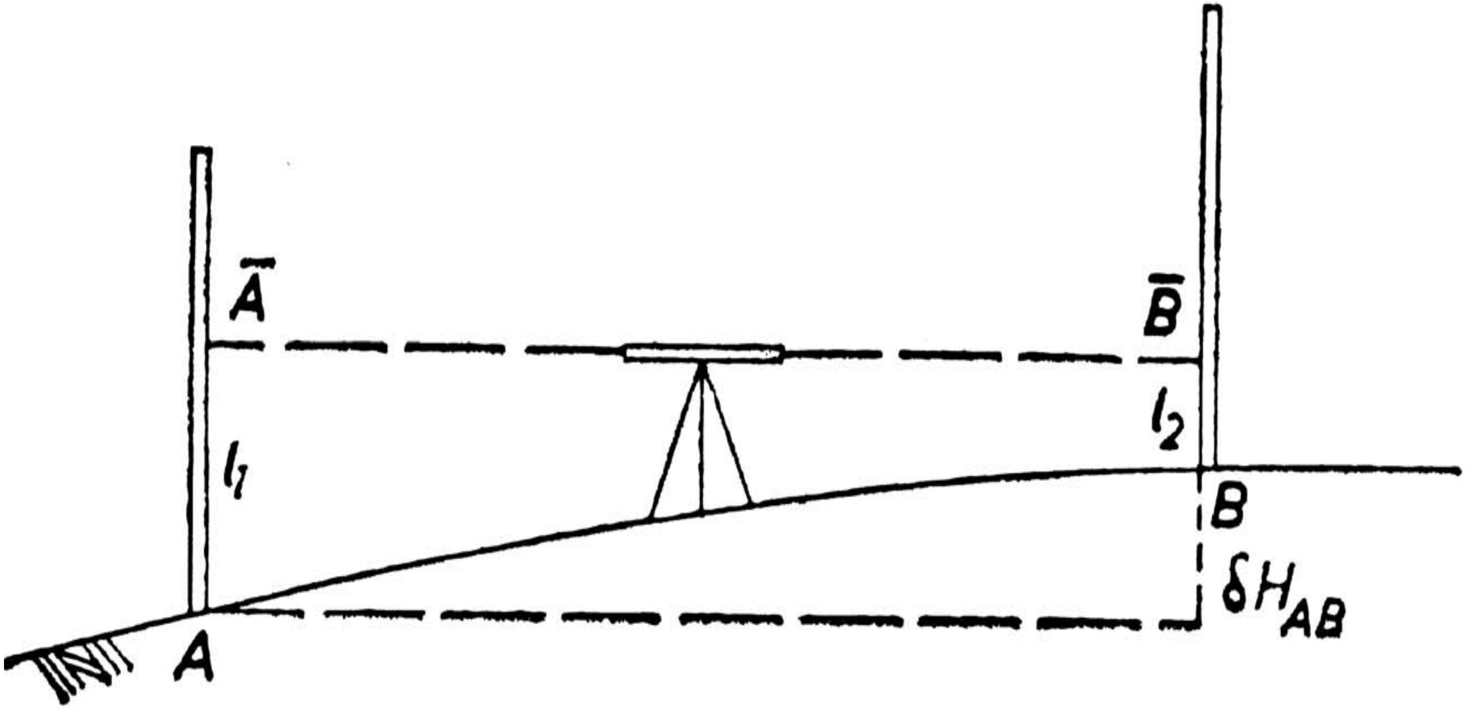
Leveling

The height difference between two neighboring points are measured



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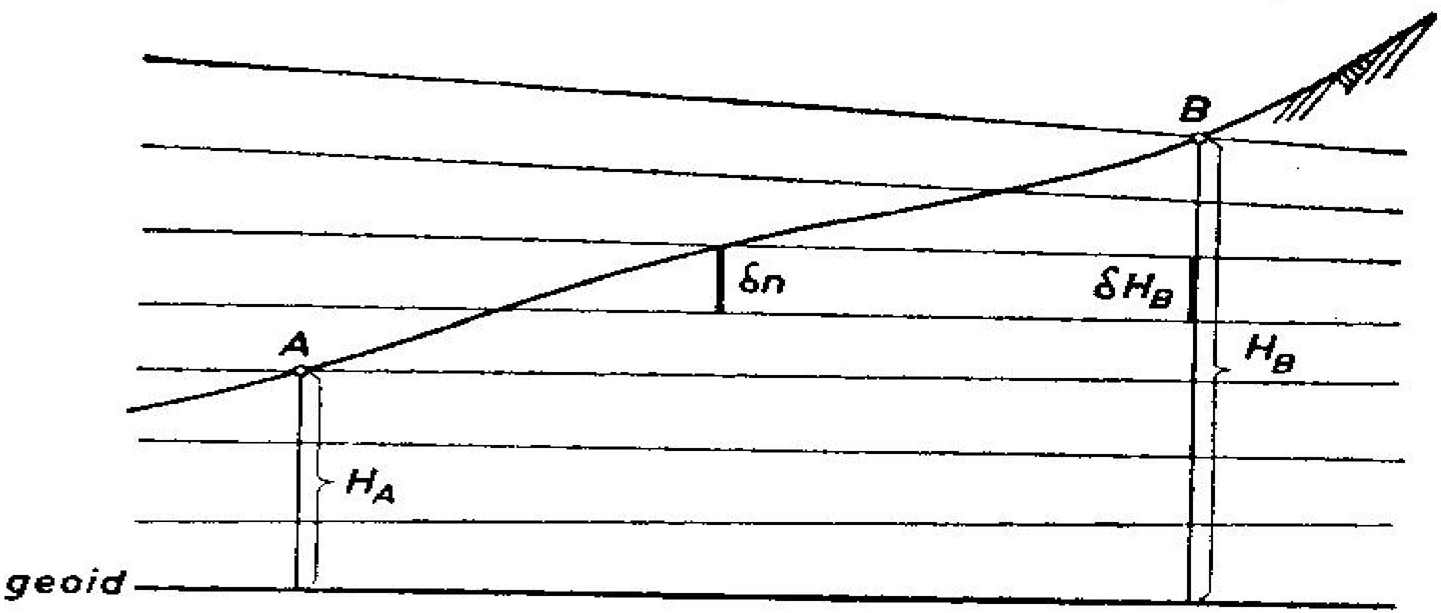
The height difference between the points A and B consists of a sum of leveling measurements



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As can be seen from the last figure the sum of dn's is not equal to the sum of dH's!

Leveling must be combined with gravity measurements, g, to produce potential differences. If O is a point on the geoid then the geopotential at A is defined by

$$C = \int_O^A g \, dn$$

The geopotential C is independent of the particular leveling line used

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Different height systems

Given geopotential C then the heights can be defined as follows:

Height=C/G

where we have

Orthometric height: G= mean of the gravity g along the plumb line from the point down to the geoid

Normal height: G=mean of the normal gravity along the plumb line

Dynamic height: G=mean normal gravity for some standard latitude (like 45)

Some inconveniences

Mean gravity is not known

Each leveling observation is very accurate, but be aware of small systematic errors that may sum up

Leveling instruments do sometimes not function as intended

Time dependency, land uplift

Very time consuming technique and thus expensive

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Satellite Altimetry

Radar signals emitted from satellites in low earth orbits are being reflected from the earths surface. Combined with accurate tracking of the satellites this determines the instantaneous surface of the earth. So far the technique has primarily been used to map the ocean surface.

See also:

http://www.aviso.oceanobs.com/html/alti/welcome_uk.html

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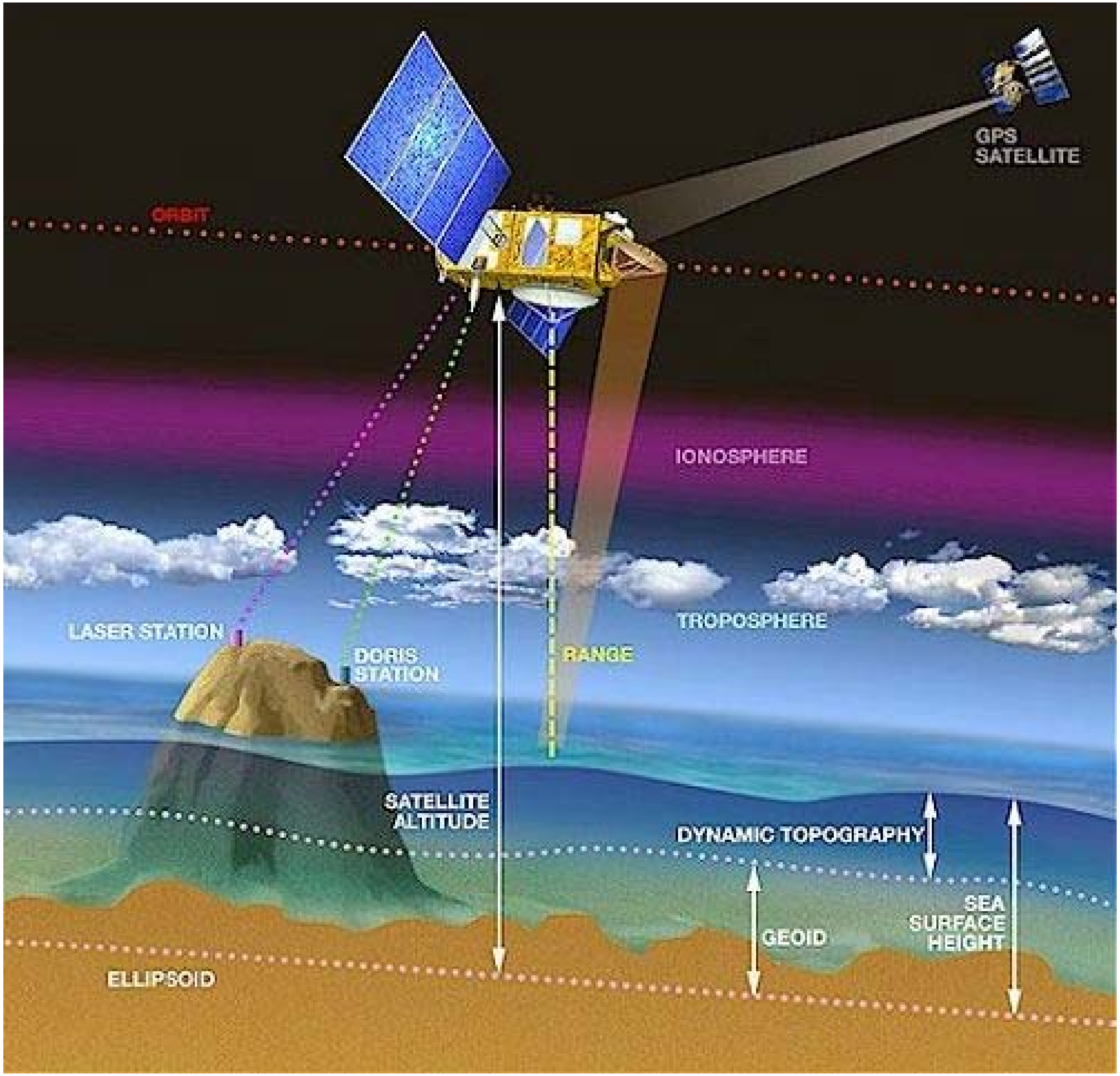

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Altimetry satellites

Satellite	Launch date	Orbital height (km)
Seasat	June 26, 1978	800
Geosat	March 12, 1985	800
ERS-1	July 17, 1991	800
Topex/Poseidon	August 10, 1992	1300
ERS-2	April 21, 1995	800
GFO	February 10, 1998	880
Jason-1	December 7, 2001	1300
Envisat	March 1, 2002	800

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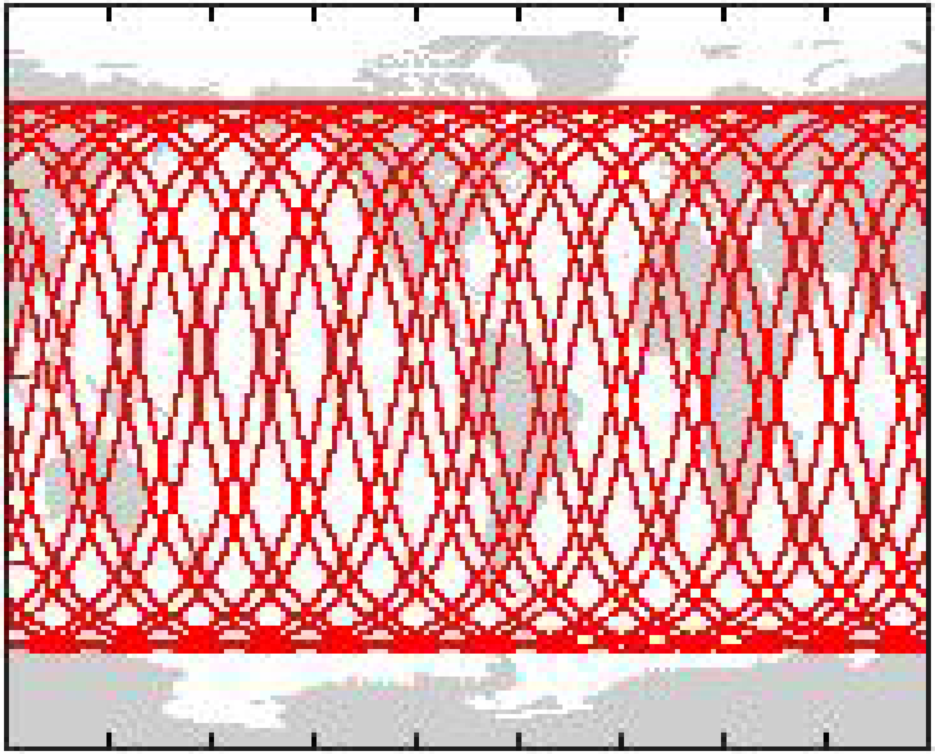
Altimetry tracks



TOPEX/POSEIDON altimeter tracks

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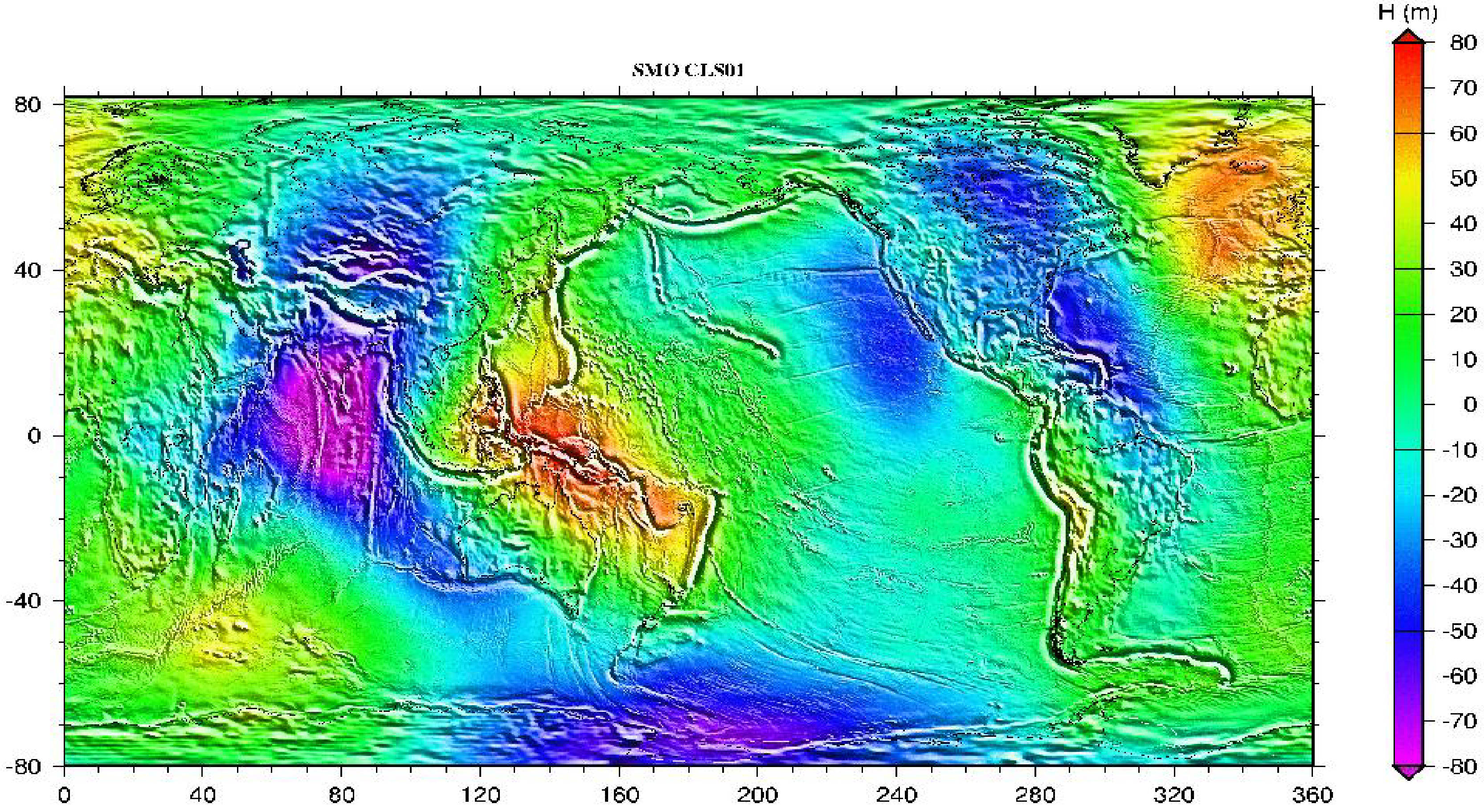
CLS 01 Mean Sea Surface



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Challenges

- Problematic areas
  - Shallow water
  - Islands and close to the shore
  - Areas with sea ice
- Retracking may solve some of these problems

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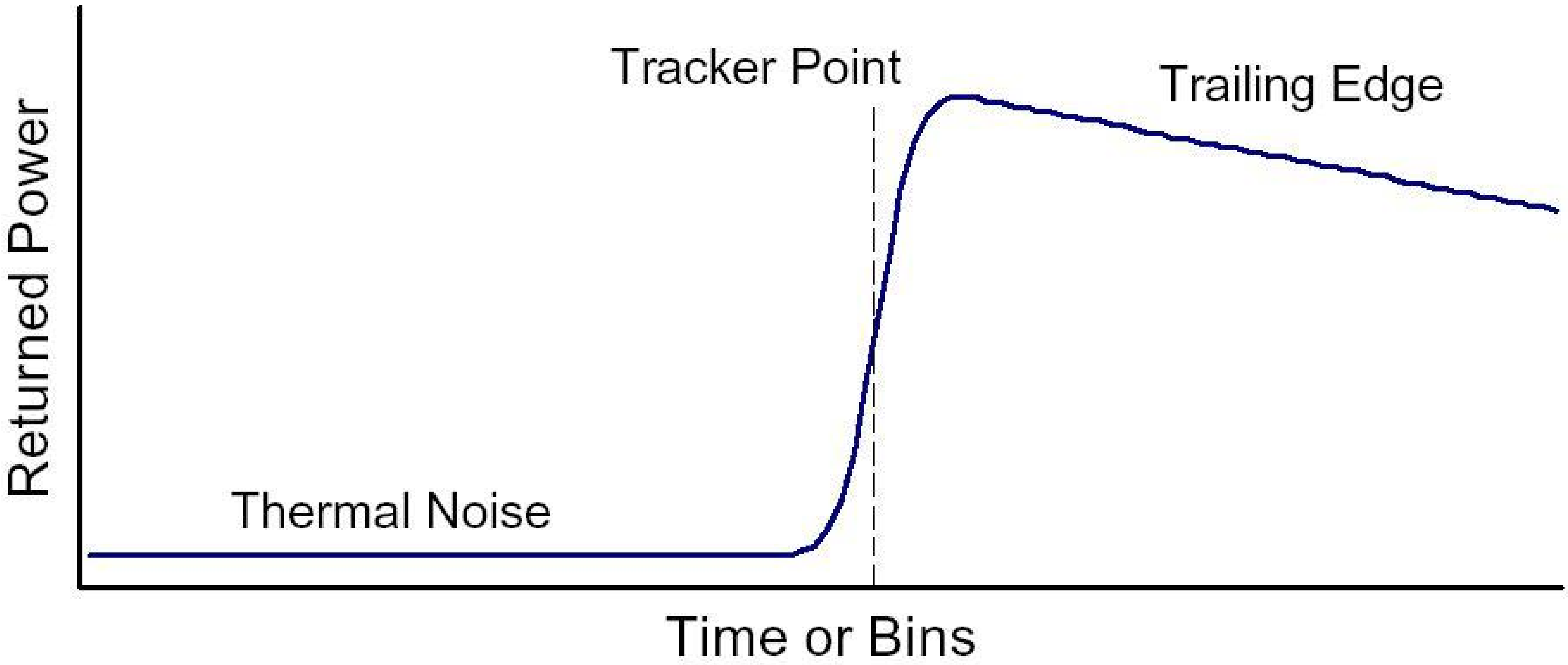
Retracking



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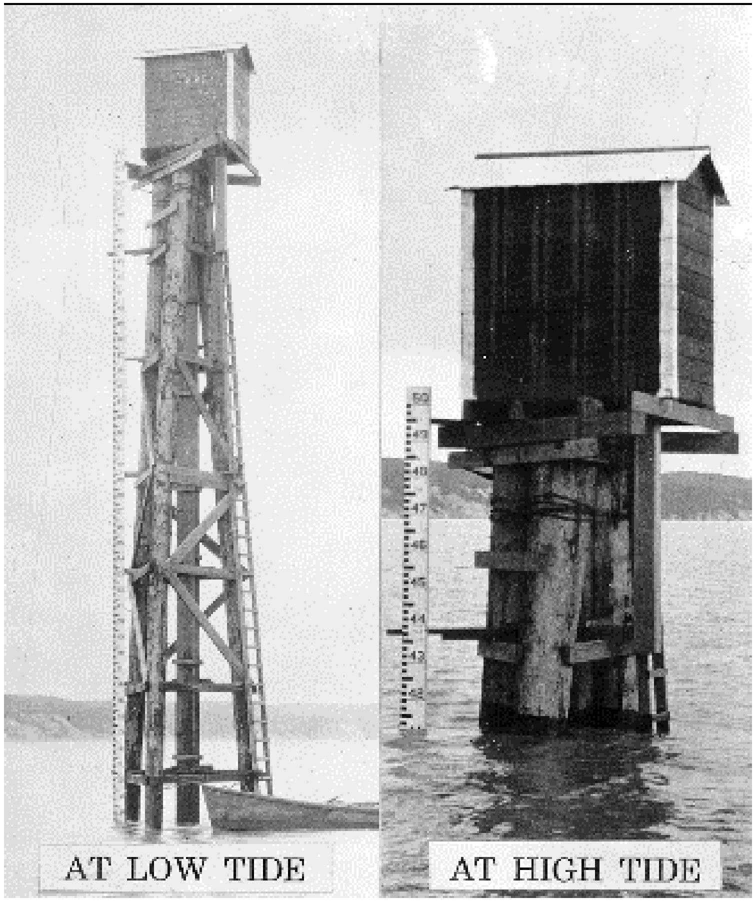
Orbits

Conflict of interests

Long repeat period, geodesy, good geographical/ spatial coverage

Short repeat period, oceanography, the same marine areas are surveyed repeatedly with short repeat periods, advantageous for study of time dependent features

Tide gauges



- Tide gauges measure the sea level relative to a nearby geodetic ***benchmark***

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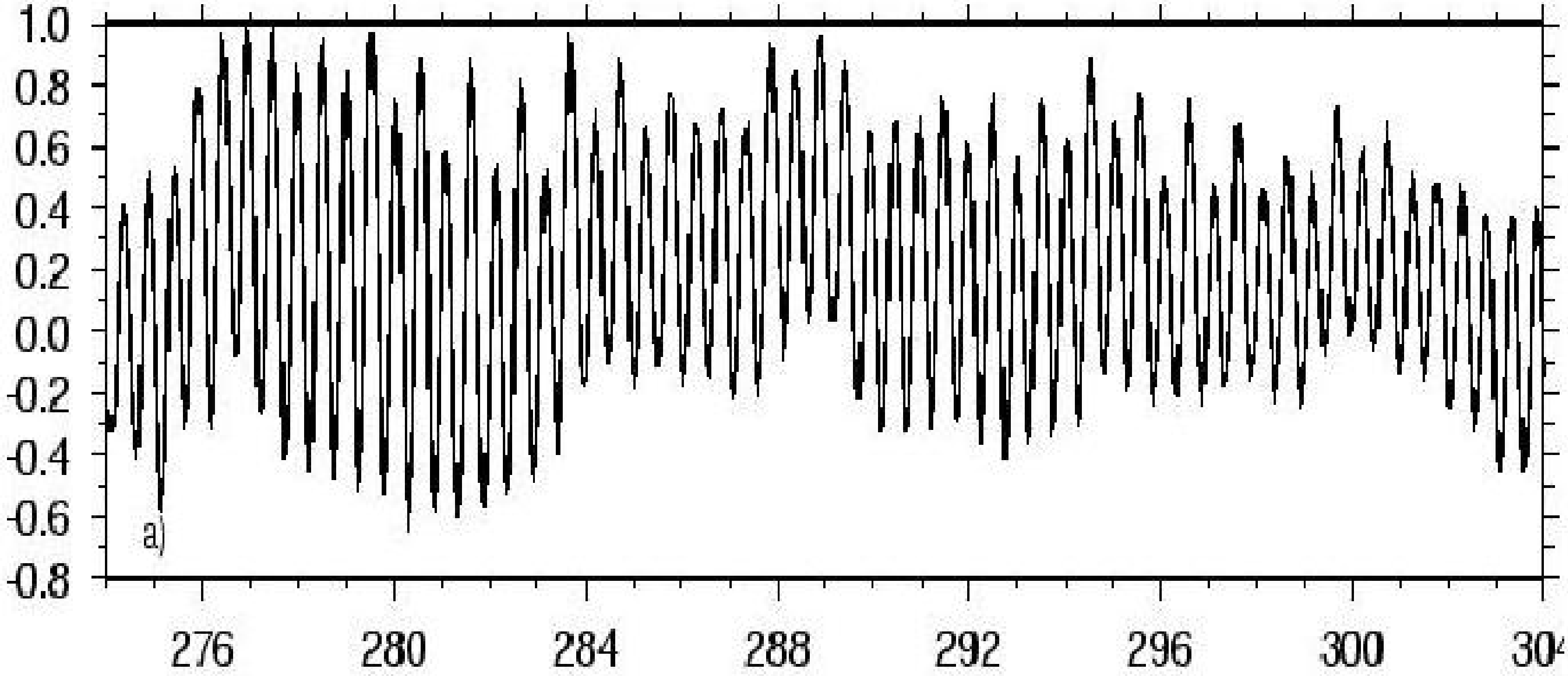
Observed tide gauge



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Harmonic constituents

Determined by the sun and the moon.

Most important constituents have been given names. Examples are:

M2: 2 cycles per lunar day

M1: 1 cycle per lunar day

S2: 2 cycles per solar day

Combination of frequencies: K1, O1, L2, N2 etc.

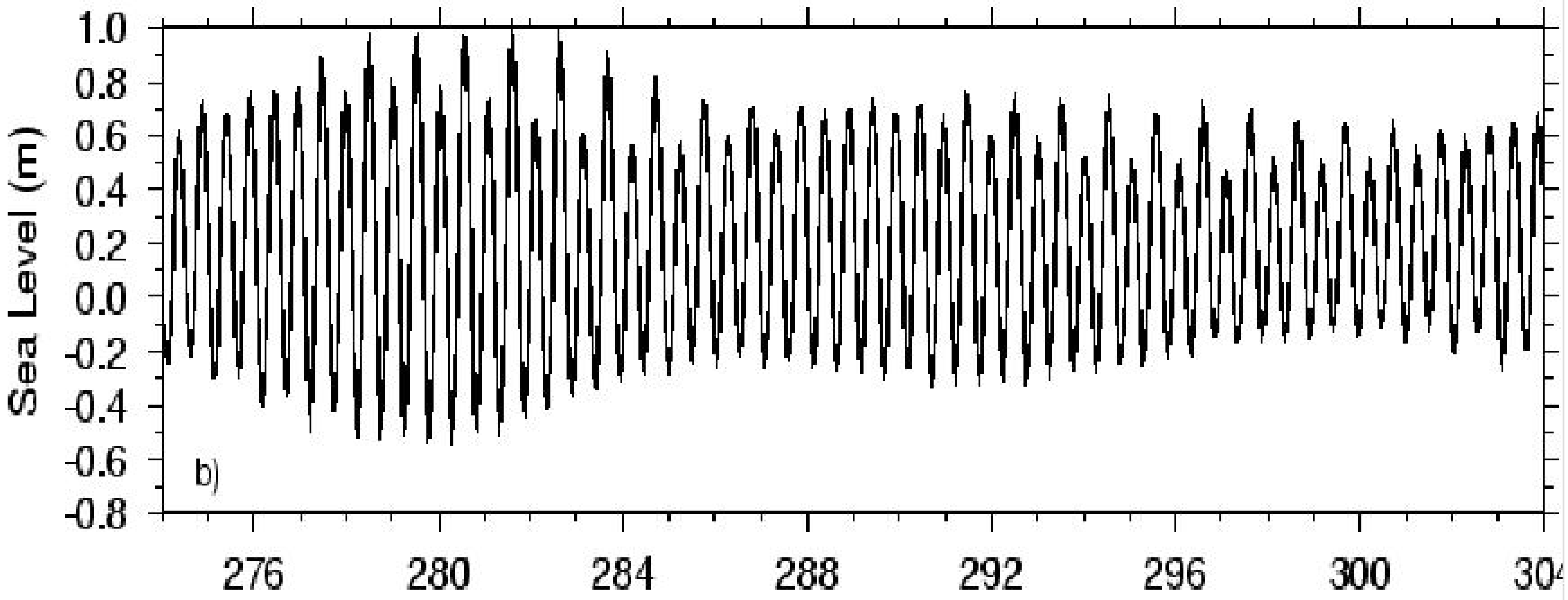
Harmonic analysis

Tide, approximated with a Fourier series

Known frequencies and time

Solve for amplitude and phase by least squares

Predicted tide gauge



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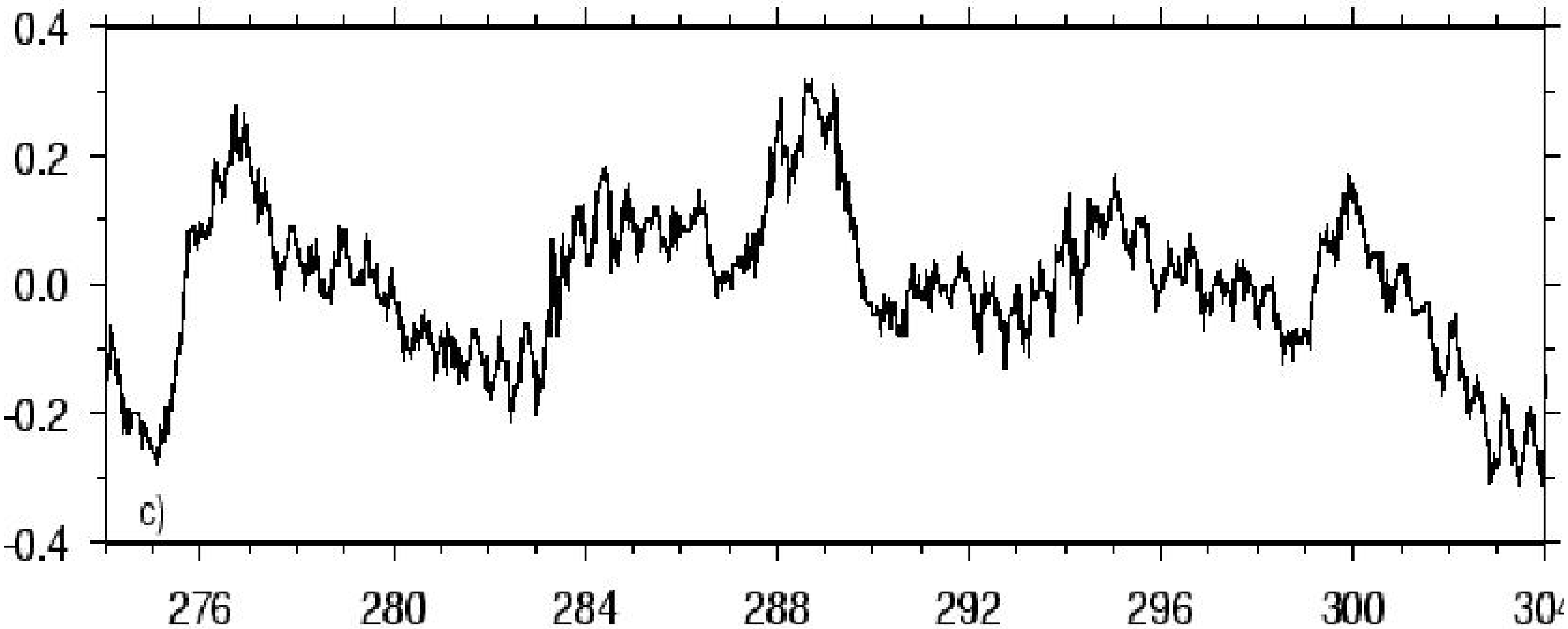
Residual tide gauge



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Lowest Astronomical Tide, LAT

- *Tide gauge observations*
- *Harmonic analysis*
- *Harmonic constituents*
- *These harmonic constituents defines LAT, Lowest Astronomical Tide*
  - *This is the lowest tide that can be expected to occur under average meteorological conditions*

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Variation with time

Changes relative to geodetic benchmark

Changes in sea level?

Land uplift?

Combination of both?

GPS needed to determine the cause of the change

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Practical implementation of height reference systems

Land areas

Geoid/quasigeoid

Fit model to GPS/leveling

Example of the method used in Norway

- *Iterative procedure*
- *Example of adjustments*
- *Limitations and future work*

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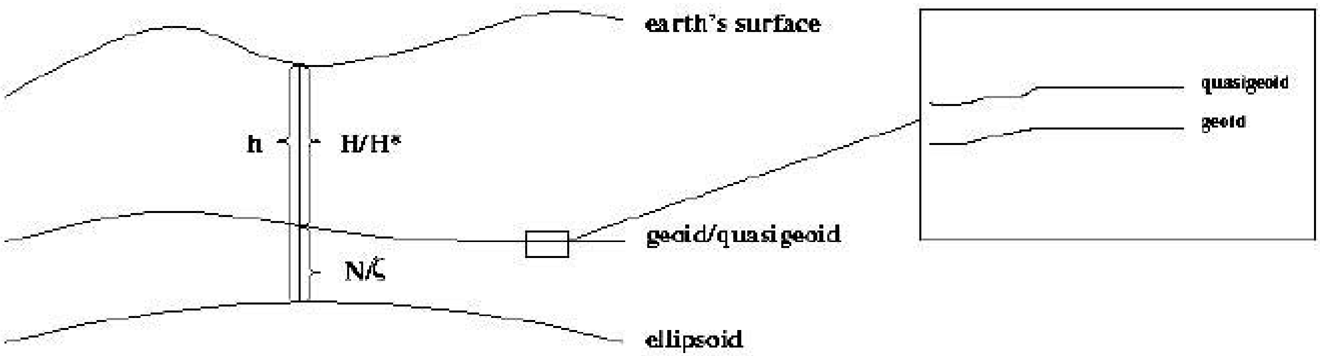
Geoid, quasigeoid, heightreferencesurface

- Geoid:
  - Equipotential surface, W=const. Requires knowledge about the earth's density. GPS + geoid => Orthometric heights.
- Quasigeoid:
  - Geoid-like surface but no equipotential surface. No knowledge about the earth's density required. GPS+quasigeoid => Normal heights.
- Height-reference surface:
  - Surface adjusted to a vertical datum by GPS/leveling data. GPS + height-reference surface => Heights in desired datum.

Geoid/quasigeoid



$$h = H + N = H^* + \zeta$$

H: Orthometric height
N: Geoidal undulation
H^*: Normal height
ζ : Height anomaly

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Iterative procedure

Given a model N

Given a set of GPS/leveling data

Adjusting this data set to model N gives us a new model N+1

The adjustment is typically performed by adjusting the existing model in a limited geographical area where there are discrepancies between the old model and the GPS/leveling dataset. As more GPS measurements in leveling points are made available new local adjustments can be performed.

List of models

HREF + GPS => Normal–heights
VREF + GPS => Orthometric heights

All models are derived from the NKG96 quasigeoid

NKG96	--->	NKG96n
↓		↓
HREF1996		VREF1996
1998		1998
1999a,b		1999a,b
2000a,b,c		2000a,b,c
2001a,b,c		2001a,b,c
2002a,b,c,d,e		2002a,b,c,d,e
2003a,b,c,d		2003a,b,c,d

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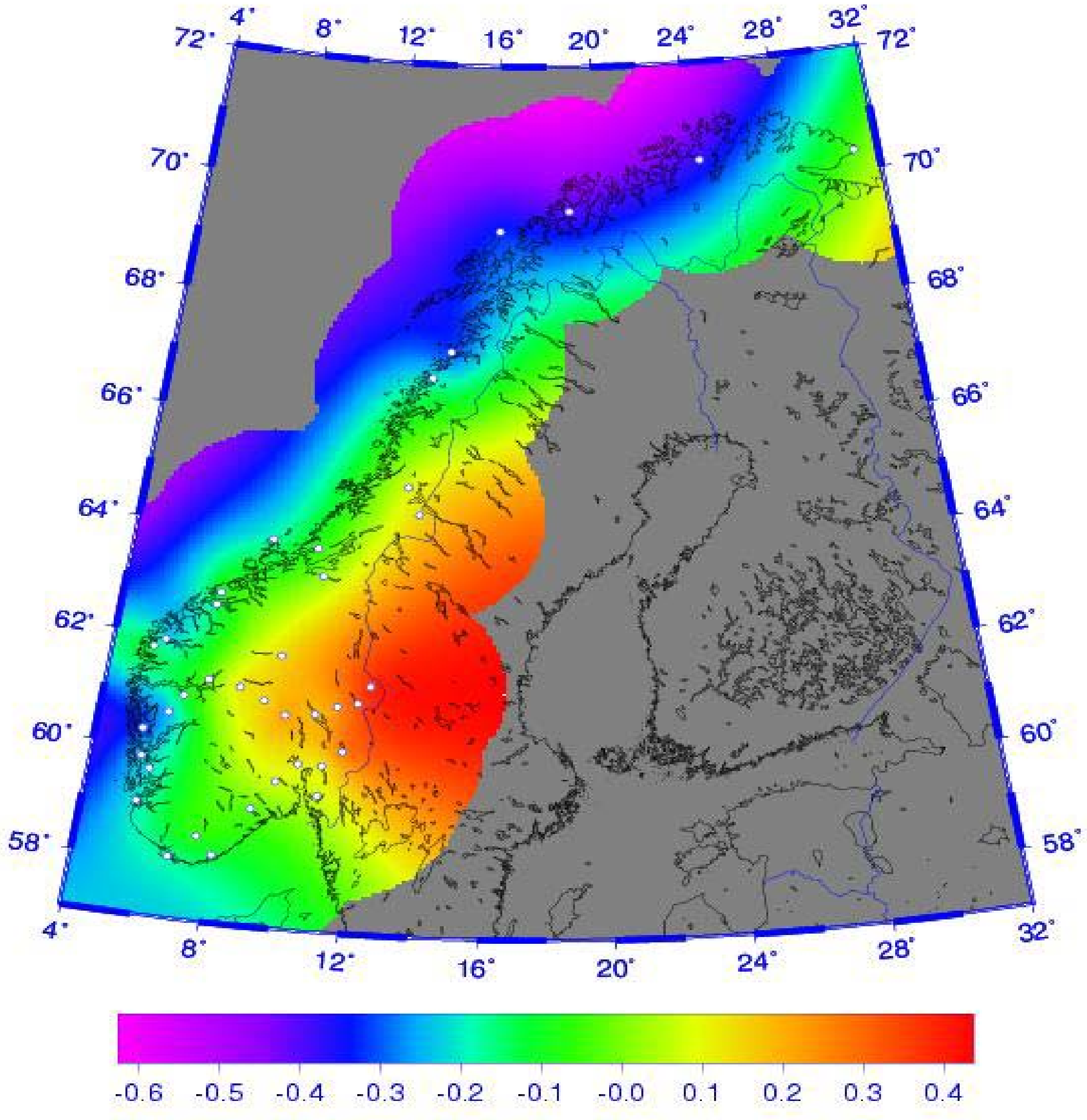
HREF1996- NKG96 (m)



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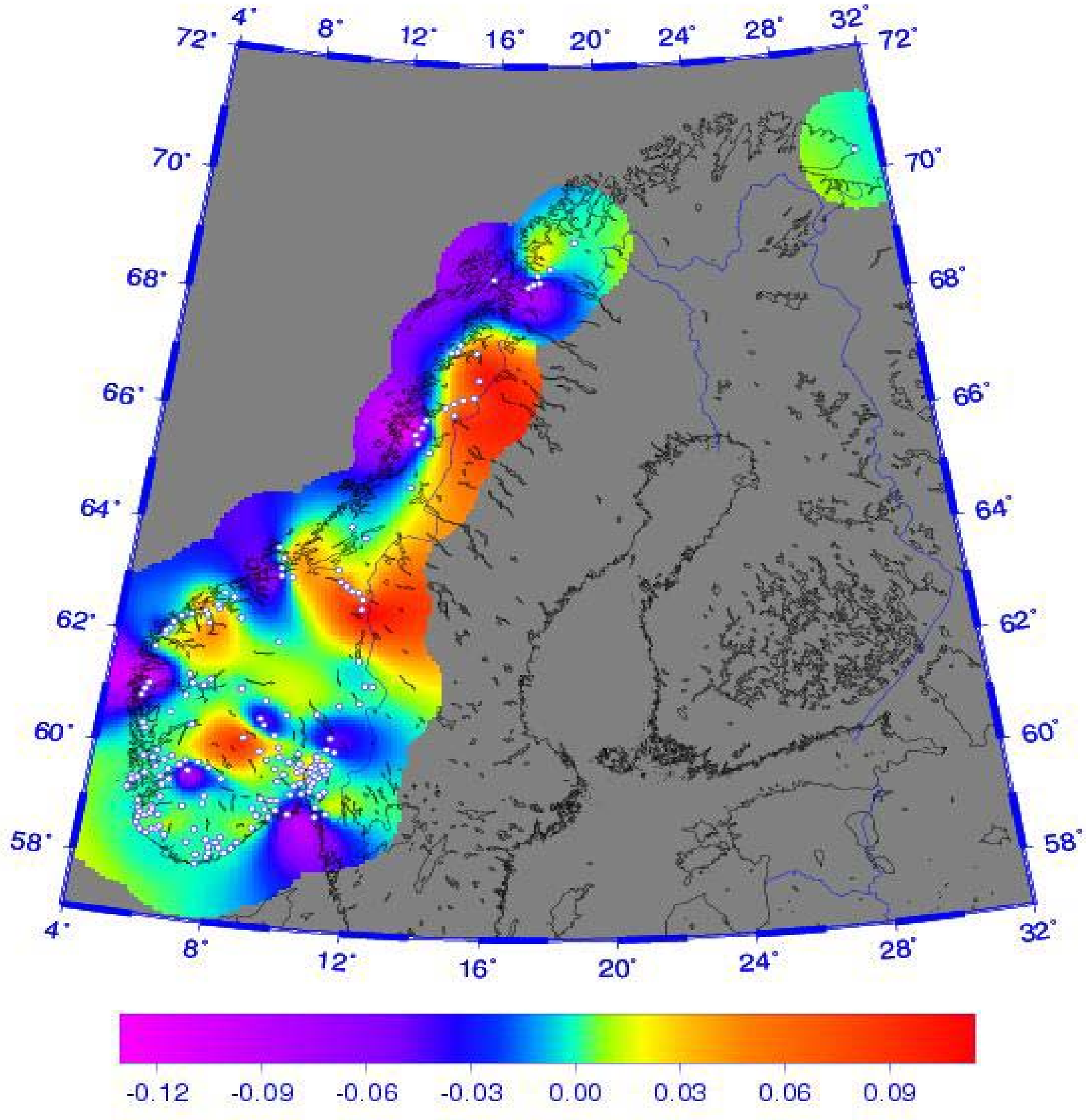
HREF1998- HREF1996 (m)



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Quality control of the models

Compare the models with GPS/leveling data that has not been used in the adjustment procedure.

The next table shows this comparison for a few Norwegian models (m).

Model	N	mean	min	max	rms	stdv
NKG96	915	-.029	-.467	.378	.161	.158
HREF1996	877	.002	-.165	.150	.047	.047
HREF1998	787	-.001	-.164	.126	.043	.043
HREF2000b	718	-.004	-.156	.110	.028	.028

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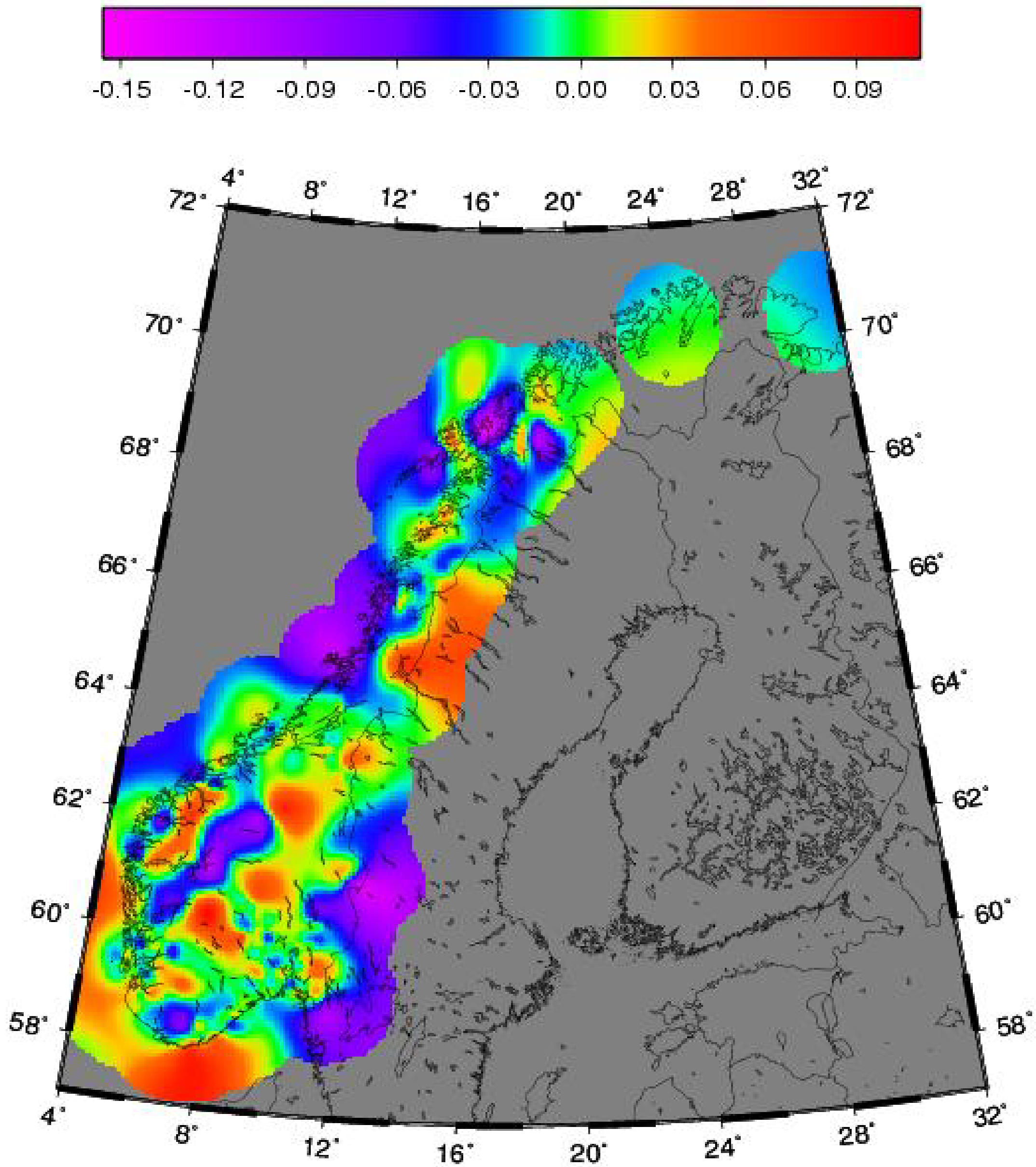
$N_{GPS/LEV} - N_{HREF2000b}$ (m)



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Challenges

- Improve the uneven distribution of GPS measurements in leveling points
- Improve the methods (theory, data coverage and data quality)
- Investigate alternative methods
- Land uplift
- Time dependency
- Point positioning (relative or absolute)
- Impact of new height datum
- Impact of improved geoid models

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Marine reference surfaces

- *Mean Sea Surface, MSS*
- *Geoid*
- *Surface given by LAT, the Lowest Astronomical Tide*

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Mean Sea Surface

Determined by satellite altimetry

Desired by the offshore industry

Not well determined in shallow areas, near land and islands or areas with sea ice

Mean for a given period which may or may not be representative for the ¨real¨ mss

Marin Geoid

Needed by oceanography for an optimal use of satellite altimetry in determining the Mean Dynamic topography, ocean currents etc

The marine geoid may also be used as an interpolation surface between satellite altimetry ground tracks or to bridge the altimetric mss with mss from tide gauges

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GOCINA and OCTAS

Two closely related research projects, GOCINA, Geoid and Ocean Circulation In the North Atlantic funded by EU and OCTAS,Ocean Circulation and Transport Between North Atlantic and the Arctic Sea, funded by the Norwegian research Council.

Main goal: Determine the mean dynamic topography, MDT

See http://www.gocina.dk and

http://www.octas.statkart.no

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Determination of MDT

To obtain this goal a dedicated airborne gravity campaign was performed in 2003, creating a gravity reference field for adjustment of marine gravity data. This improved gravity dataset will be used to compute a state of the art geoid for the study area. Combined with the best MSS from Satellite Altimetry the MDT can be determined. A combined simultaneous determination of all the 3 fields, Geoid, MSS and MDT, is also a part of the two projects.

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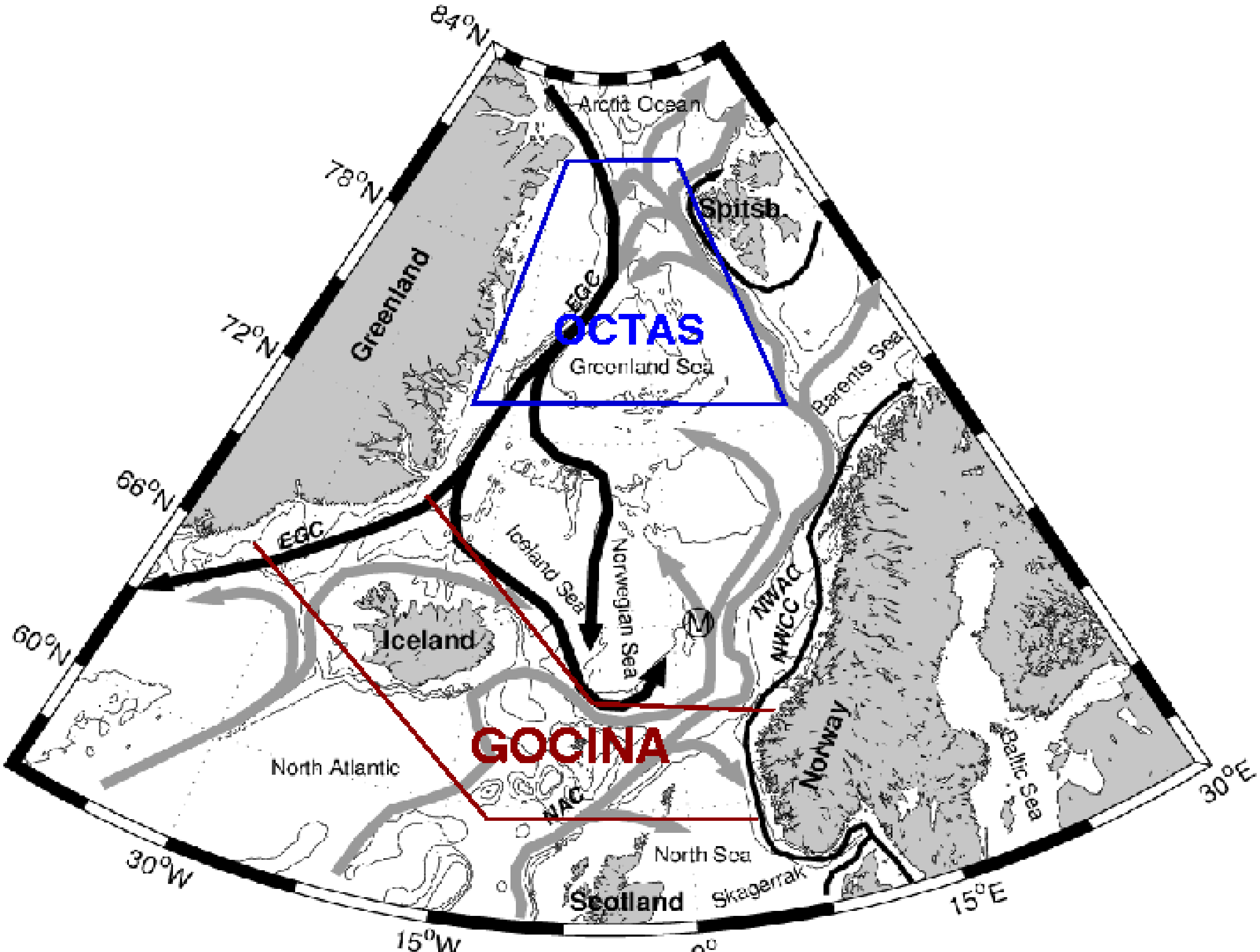
Study area



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Lowest Astronomical Tide, LAT

Tide gauges, harmonic analysis

Limited number of tide gauges along the coast where LAT is determined

MSS and tides from Satellite Altimetry determines a LAT surface for marine offshore areas

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Suggestion on how to compute a LAT model

Use a discrete number of tide gauges either alone or in combination with a LAT model from altimetry to compute a LAT model in a similar way as when adjusting geoid models to GPS/leveling This will establish a LAT model.

Having established this model then GPS in combination with a geoid model will determine LAT relatively to this GPS point.

It remains to be seen if this method is feasible or not!

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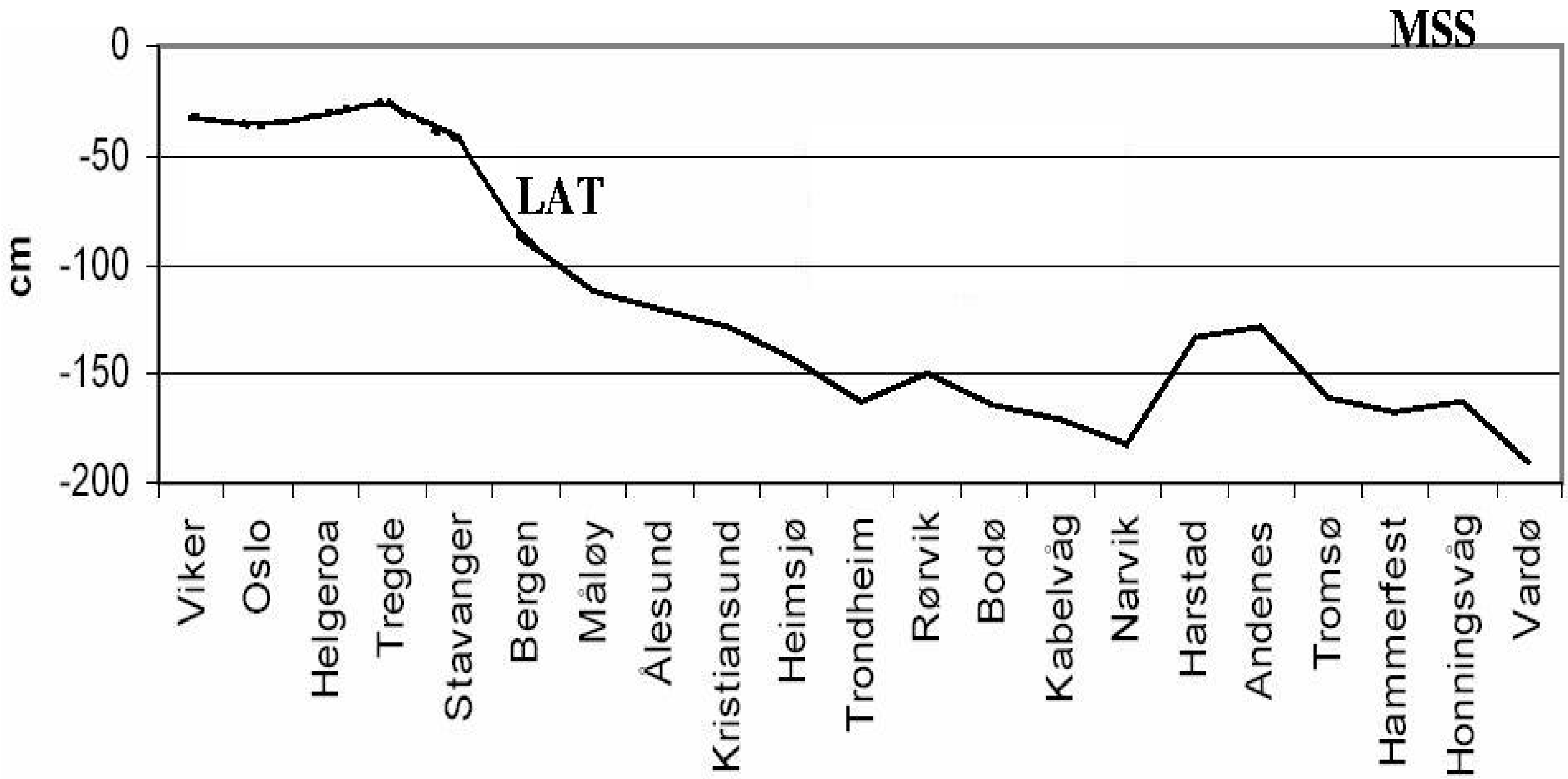
LAT and MSS at Norwegian Tide Gauges



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Other marine reference systems

- HAT, Highest Astronomical Tide
  - Navigation
- 0-level for heights
  - Norway, NN1954, do not coincide with MSS
- 0-level for depths
  - May deviate from LAT in areas with a very small tidal signal
- Local systems

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Future improvements

Satellite missions like CHAMP, GRACE, GOCE and their follow ons will improve our knowledge of the gravity field both spatially and time wise

Combined with local data (gravity etc.) new improved geoid models will be derived.

This may lead to a unified global height system.

Summary

- Geoid
- Leveling
- Satellite altimetry
- Marine and land reference surfaces
  - Adjustment to national height datums
  - Adjustment to tide gauge data
- Future improvements

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