UNITED NATIONS GLOBAL GEODETIC CENTRE OF EXCELLENCE

MODERNISING GEOSPATIAL REFERENCE SYSTEM CAPACITY DEVELOPMENT WORKSHOP

Height datums and geoid models

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HOW

Day 3, Session 2 [3_2_1]

Acknowledgements: Kevin Ahlgren (USA); David Avalos (MEX); Jack McCubbine (AUS); Nikolaos Pavlis (USA); Anna Riddell (AUS); Laura Sanchez (GER); Michael Sideris (CAN).

Summary

- Traditionally, people want to know the height of something with respect to sea level.
  - These are known as “physical heights”.
- Satellite positioning systems (GNSS and remote sensing) determine heights relative to the ellipsoid.
  - These are known as “geometric heights”.
- Geoid models provide the offset between the ellipsoid and the geoid and provide an efficient way to transform between geometric height and physical heights.
- To create a geoid model which is accurate at the 2-3 centimetre level for a country, a combination of space, airborne and terrestrial gravity is required.

Height is hard … but important

- Which way does water flow?
- What is at risk during a flood?
- How do we build a sewerage system in the city?
- How to develop an efficient irrigation system for agriculture?
- How to ensure the correct inclination of railways and roads?
- How to know the under keel clearance of a ship?
- How to monitor the sea level change?
- What is the height of the top of the mountain?

https://www.welt.de/vermischtes/weltgeschehen/gallery9348988/Das-Jahrzehnt-der-Wetterkatastrophen.html

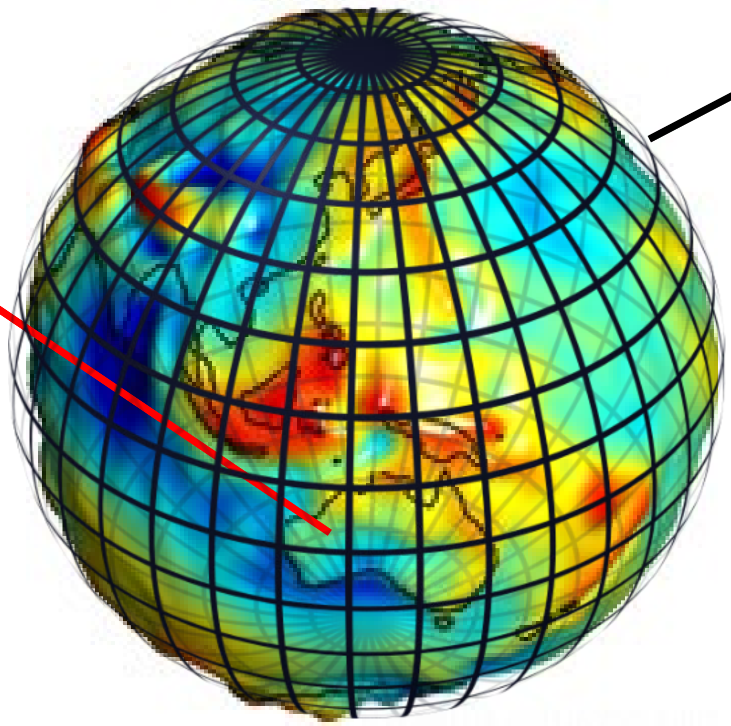
Introduction to height

- Traditionally, people want to know the height of something with respect to sea level.
  - These are known as "physical heights"
- Satellite positioning systems (GNSS and remote sensing) determine heights relative to the ellipsoid.
  - These are known as "geometric heights"
- It is important to understand how these systems are different and how data from these systems can be used together.

Physical vs Geometric heights

Equal Gravitational Potential

- Complex
- Physically meaningful
- Precise
- Need a model to use with GNSS
- Water always flow downhill

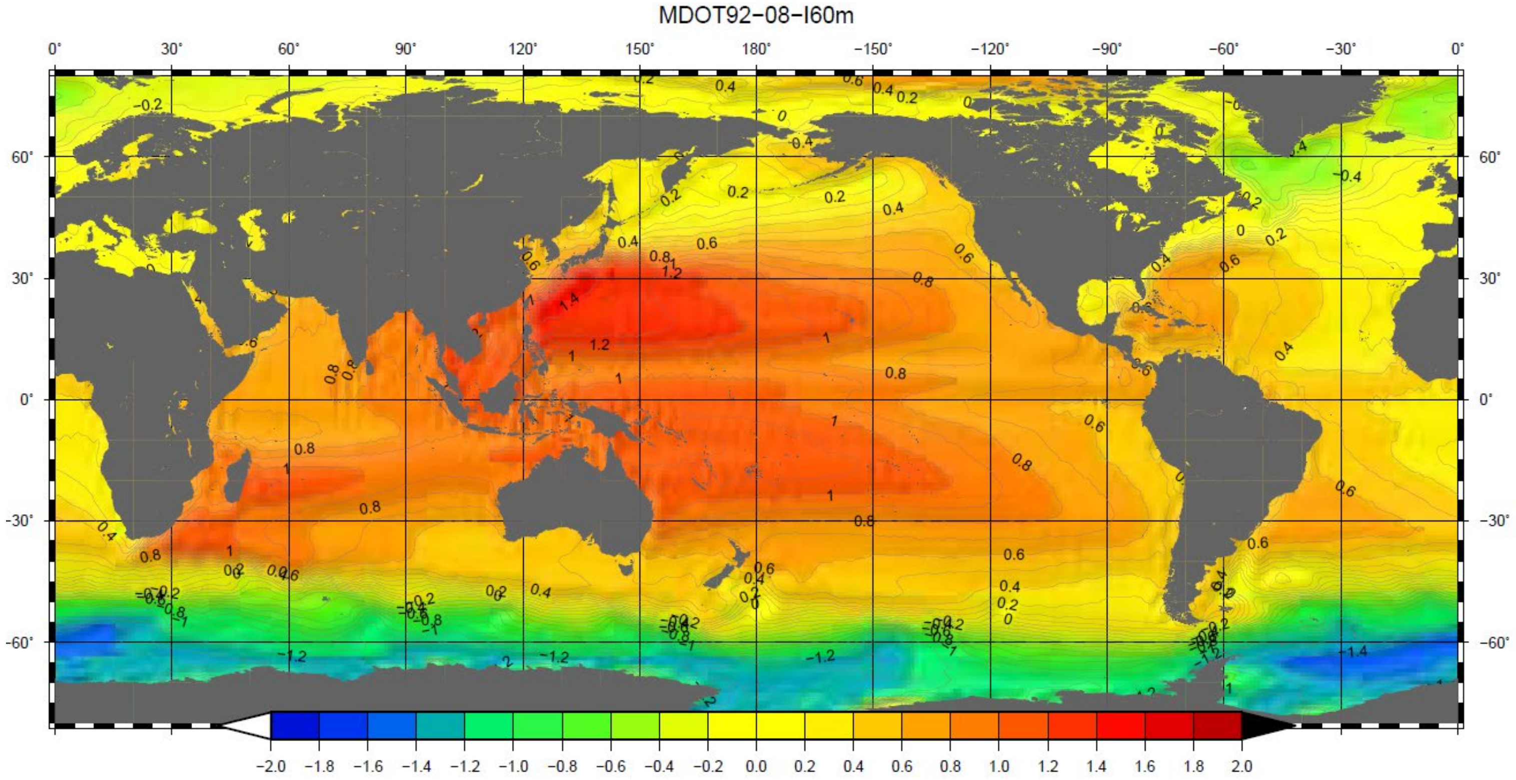


Geometric

- Simple
- Not physically meaningful
- Precise
- Used by GNSS
- Water doesn't always flow downhill

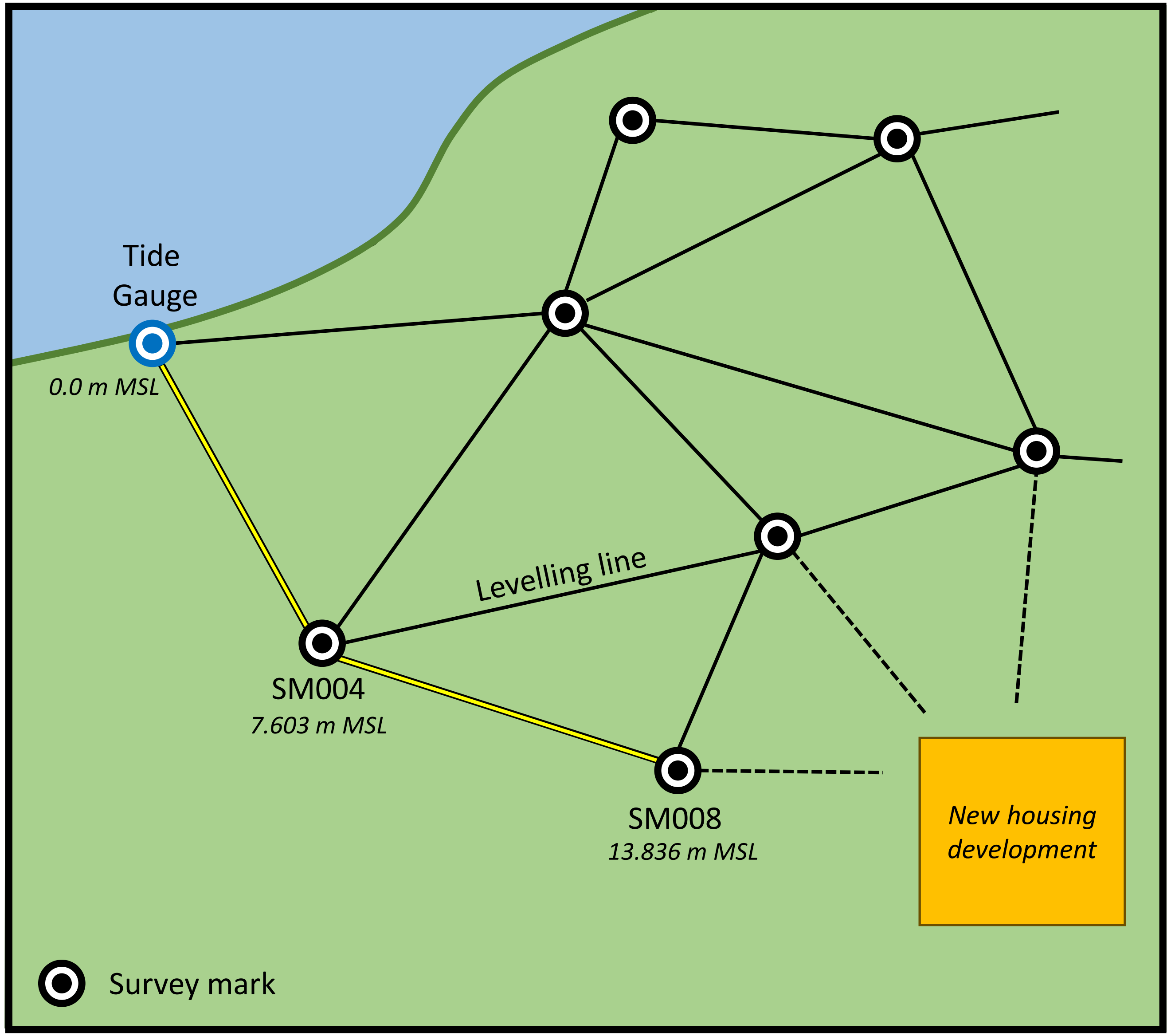
Heights referring to mean sea level

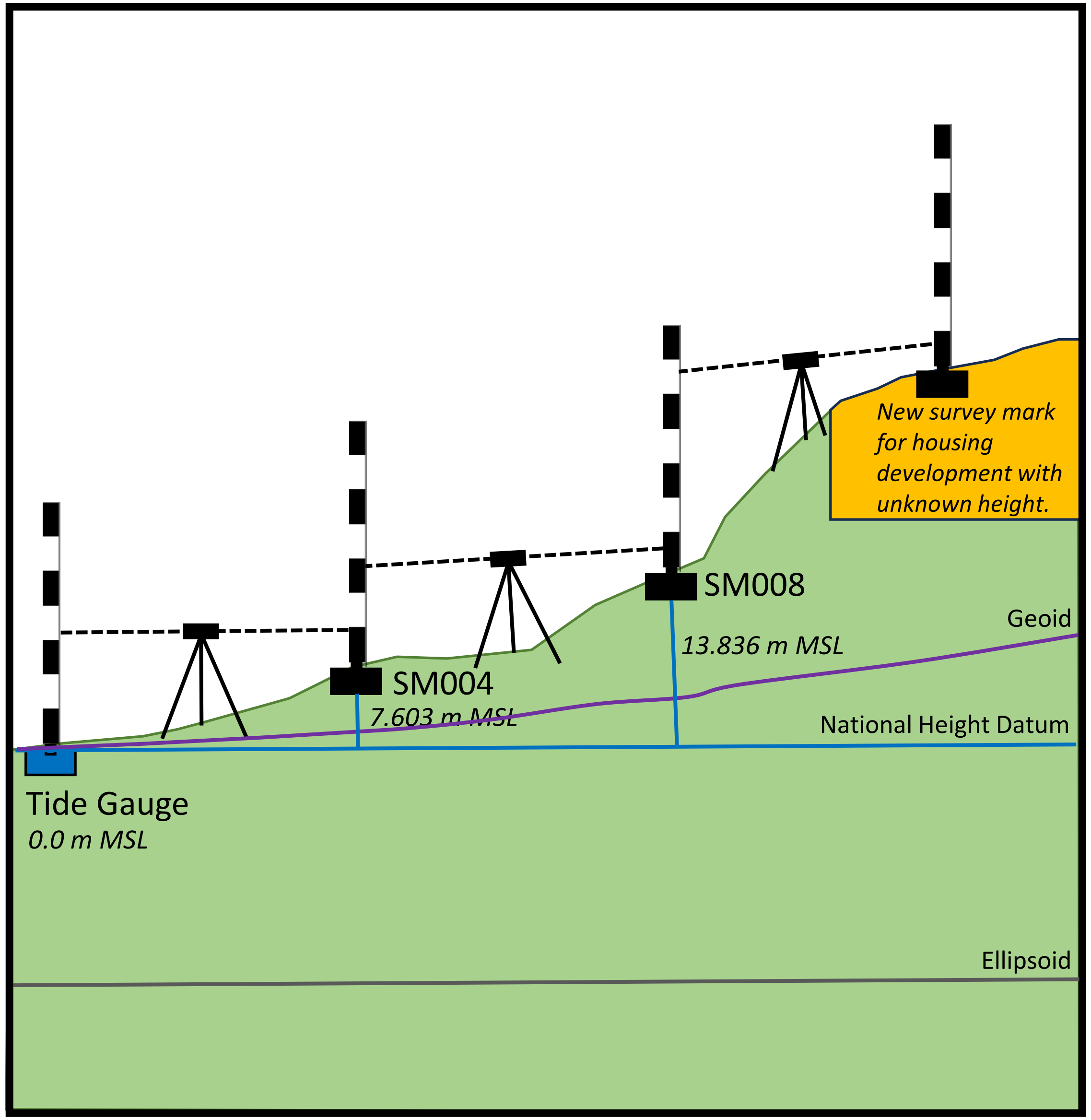
- Levelled heights (often) refer to the mean sea level determined at selected tide gauges.
- The sea surface is not always the same height above the geoid, it varies due to ocean currents, water temperature and salinity.
- The mean sea level may be closer to or farther from the equilibrium figure of the Earth (geoid) depending on the geographical location.
- Thus, the zero elevation as defined by one country (or region) differs up to ±2 metres from the zero elevation as defined by other countries.



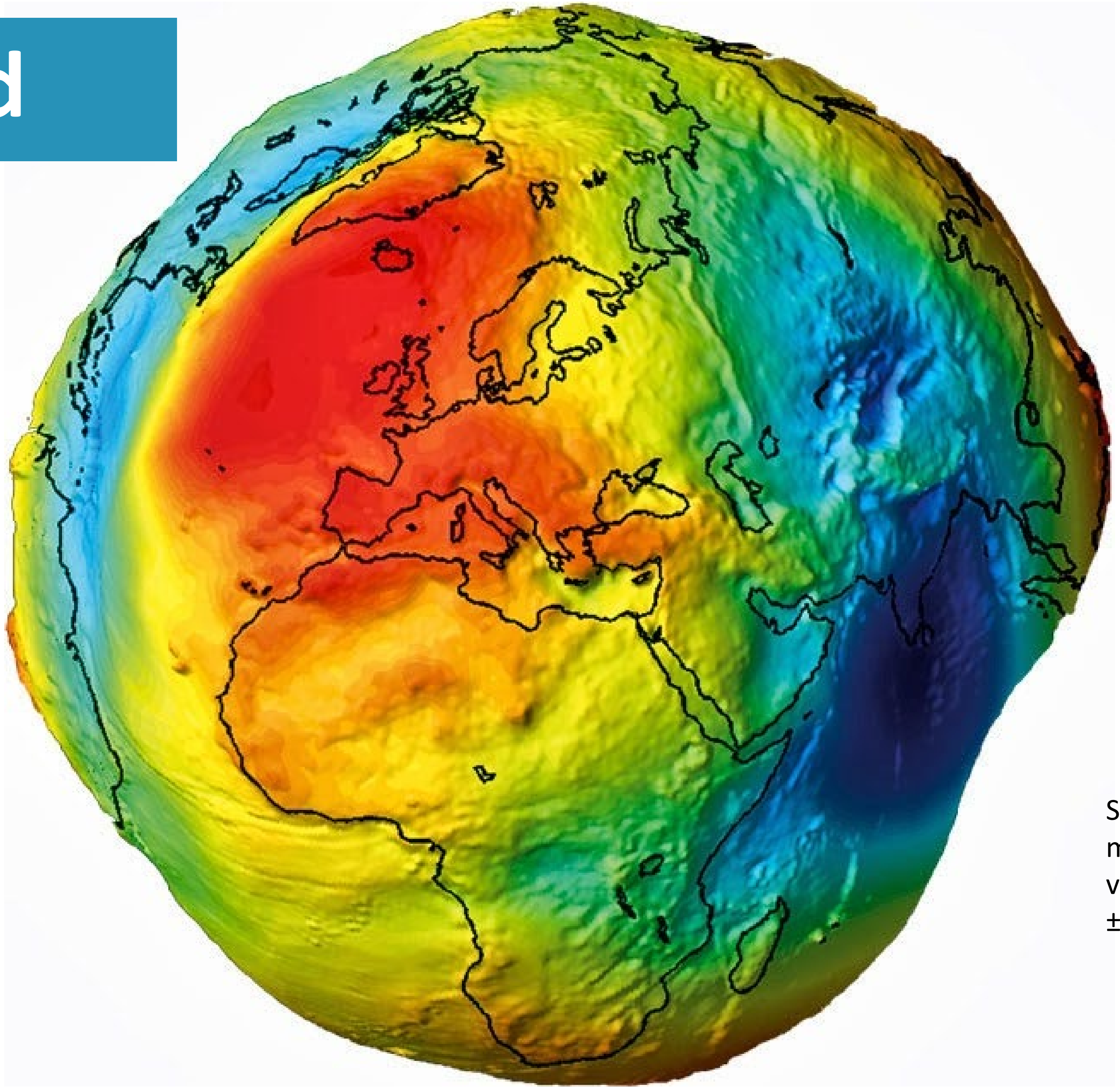
Topography of the mean sea surface in metres (©DGFI-TUM)

Height datum referenced to tide gauge

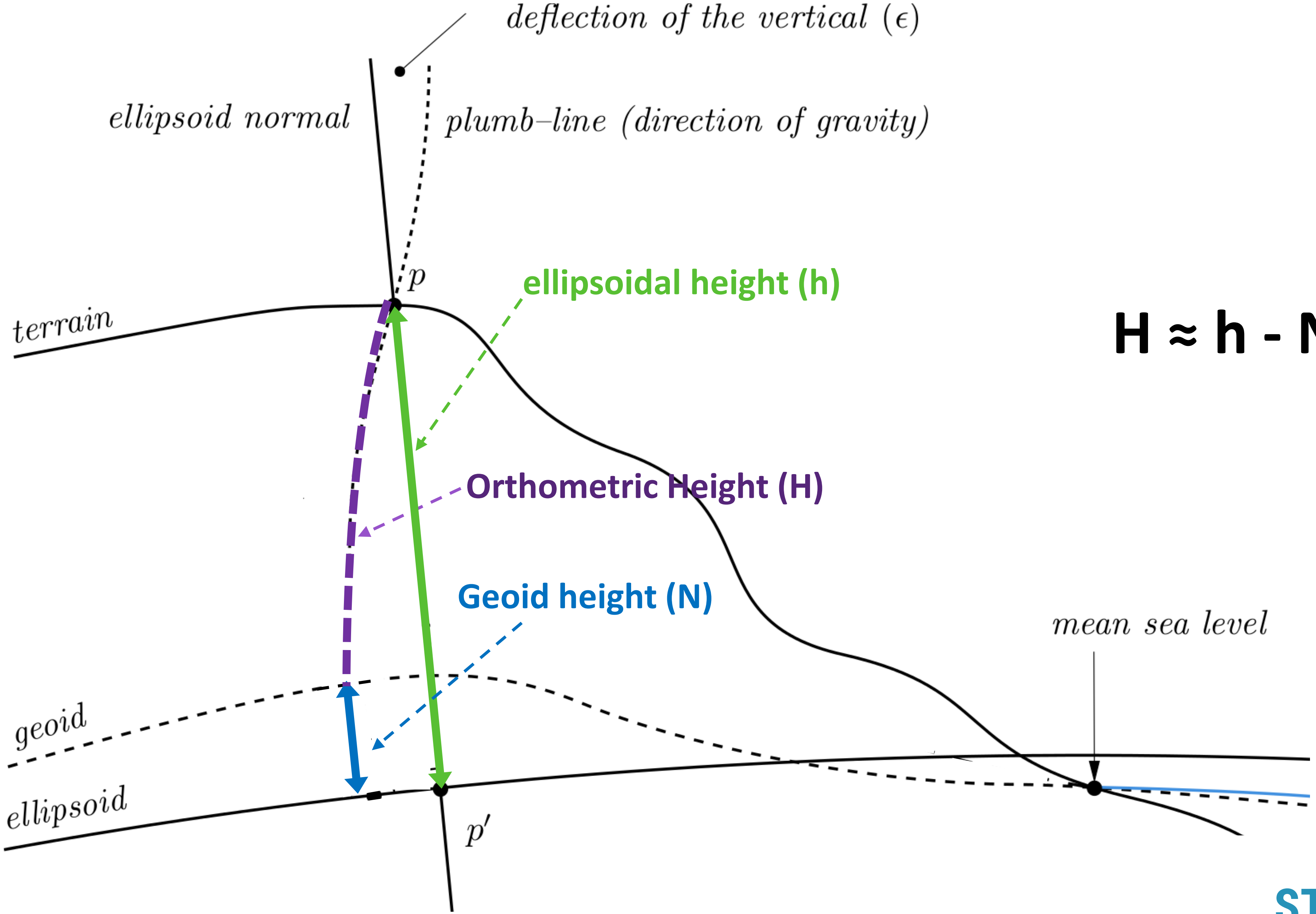




The Geoid



Scale exaggerated to make the difference visible. In reality ±150 m.



H ≈ h - N

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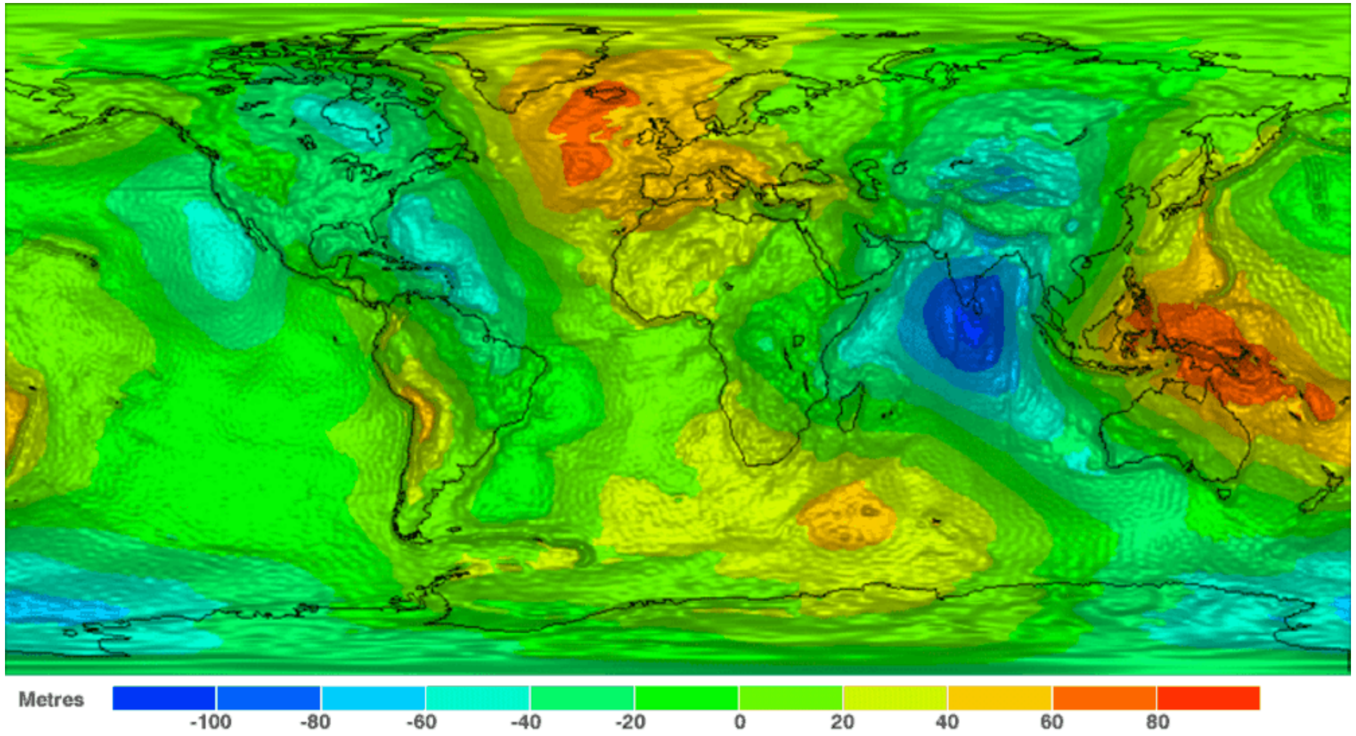
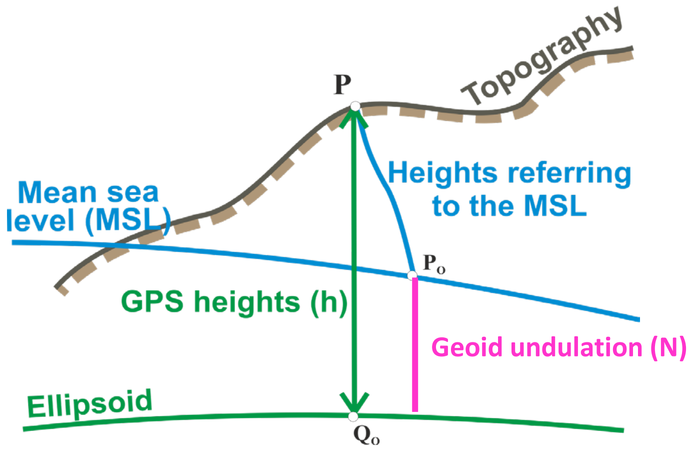
Geometric vs Physical height

- Different techniques are used to determine heights.
- However, there is no guarantee that each technique will produce the same height.
- Heights determined with GNSS do not refer to the mean sea surface, but to the ellipsoid (a geometry model of the Earth).
- Differences between GNSS heights and those referring to the mean sea surface may reach up to ±100 m.



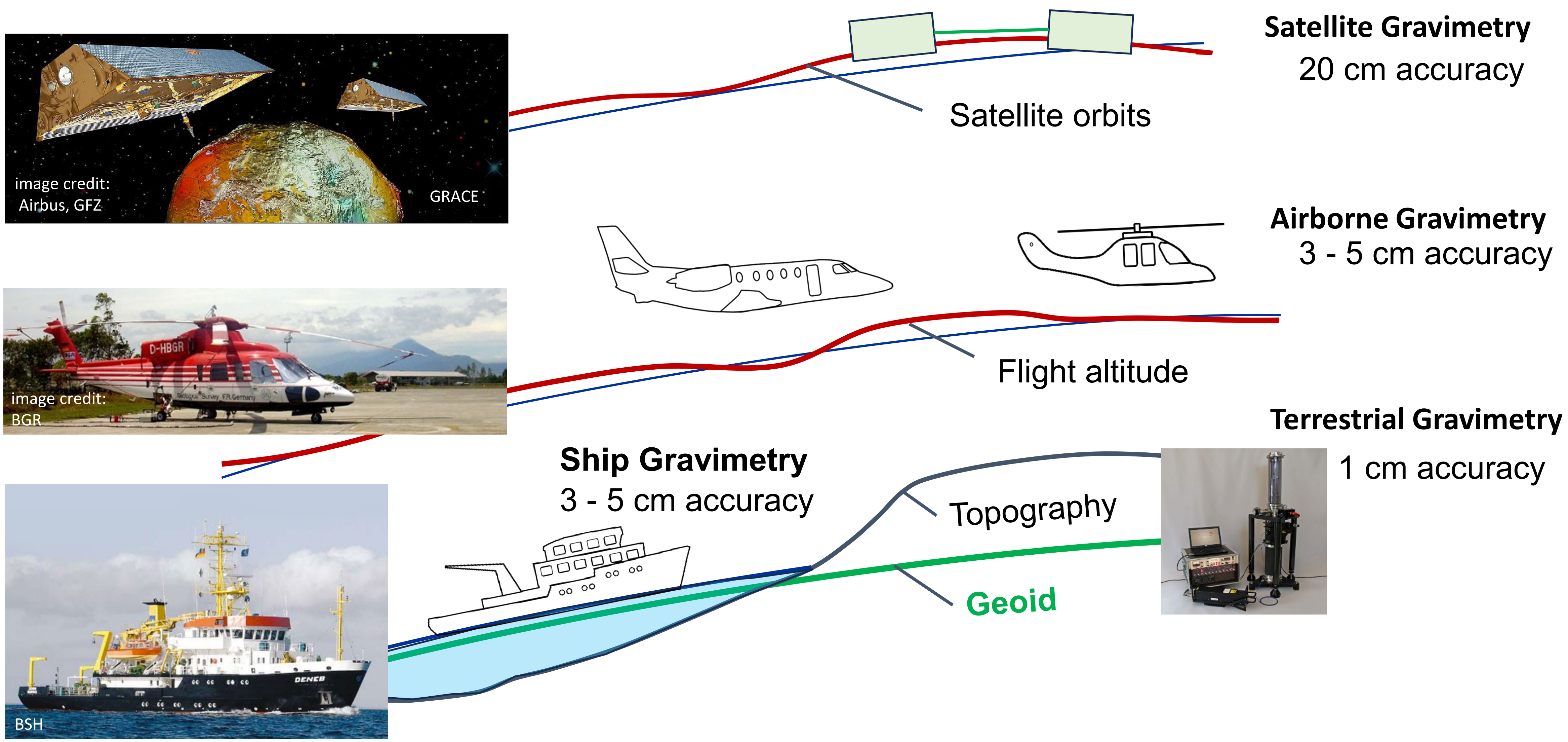
Differences in metres between GNSS heights and heights referring to mean sea level (©ESA)



$$H = h - N$$

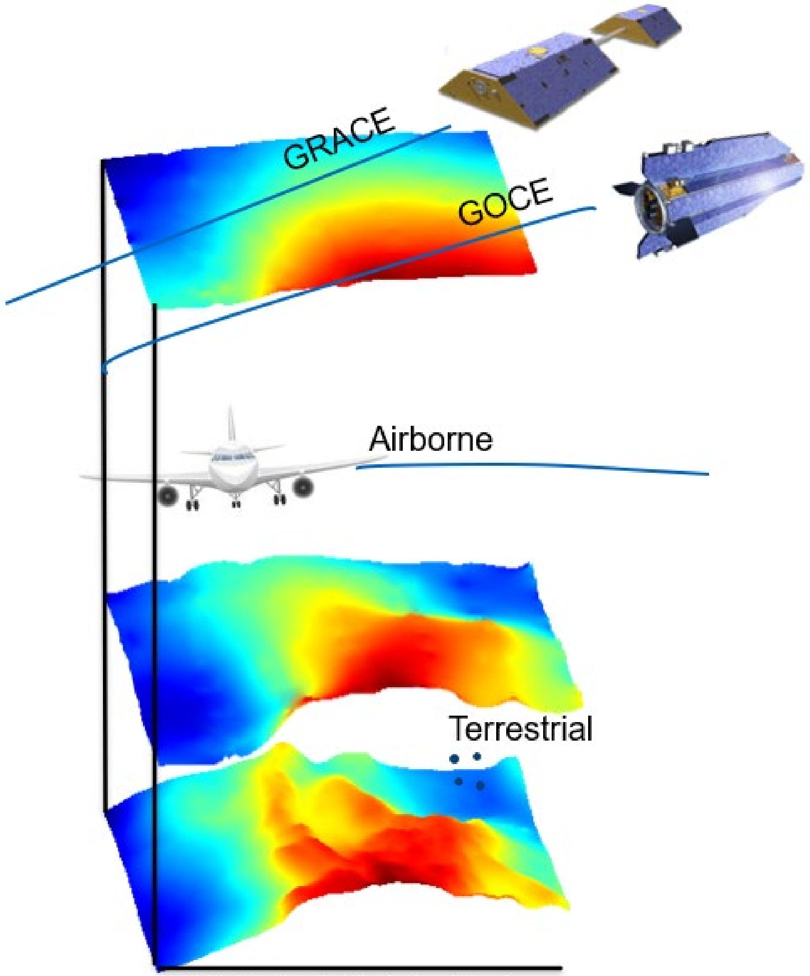
Creating a geoid model

Gravity measurements



Physical datums

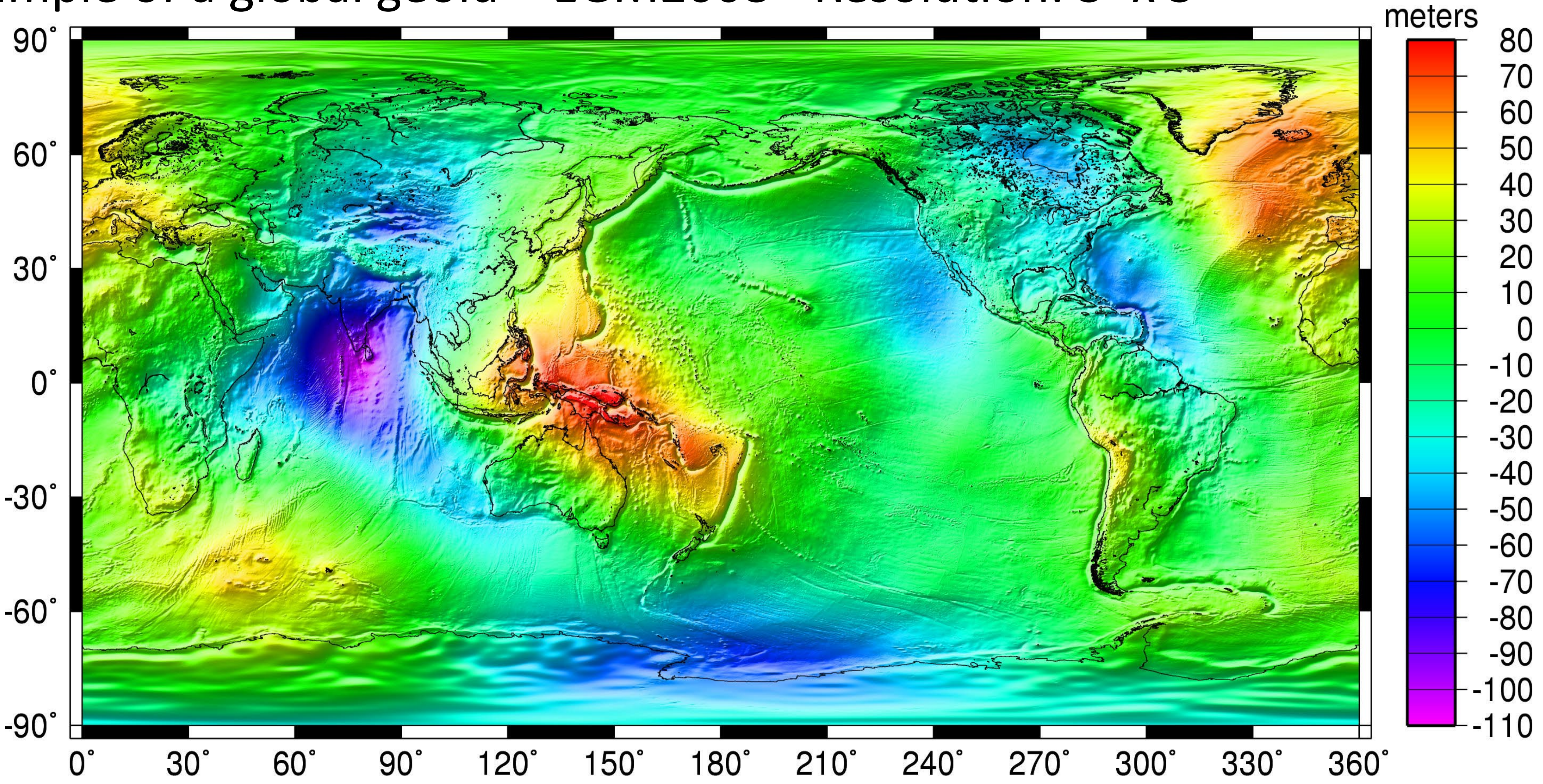
- The determination of the gravitational potential at any point requires gravity anomalies all over the Earth.
  - The long wavelength contribution N_G is provided by a set of spherical harmonic coefficients (geopotential or global gravity model);
  - The middle wavelength contribution N_L is estimated from the local anomalies (terrestrial, marine or airborne gravity in the area of study)
  - The short wavelength contribution N_T is computed by using a digital terrain model (topographic heights)
  - The geoid undulation (or height anomaly) is given by $N = N_G + N_L + N_T$



GRACE satellite: http://geoid.colorado.edu/grace/
GOCE satellite: https://gisgeography.com/earth-satellite-list/

Global geoid model (EGM2008)

Example of a global geoid – EGM2008 - Resolution: 5’ x 5’



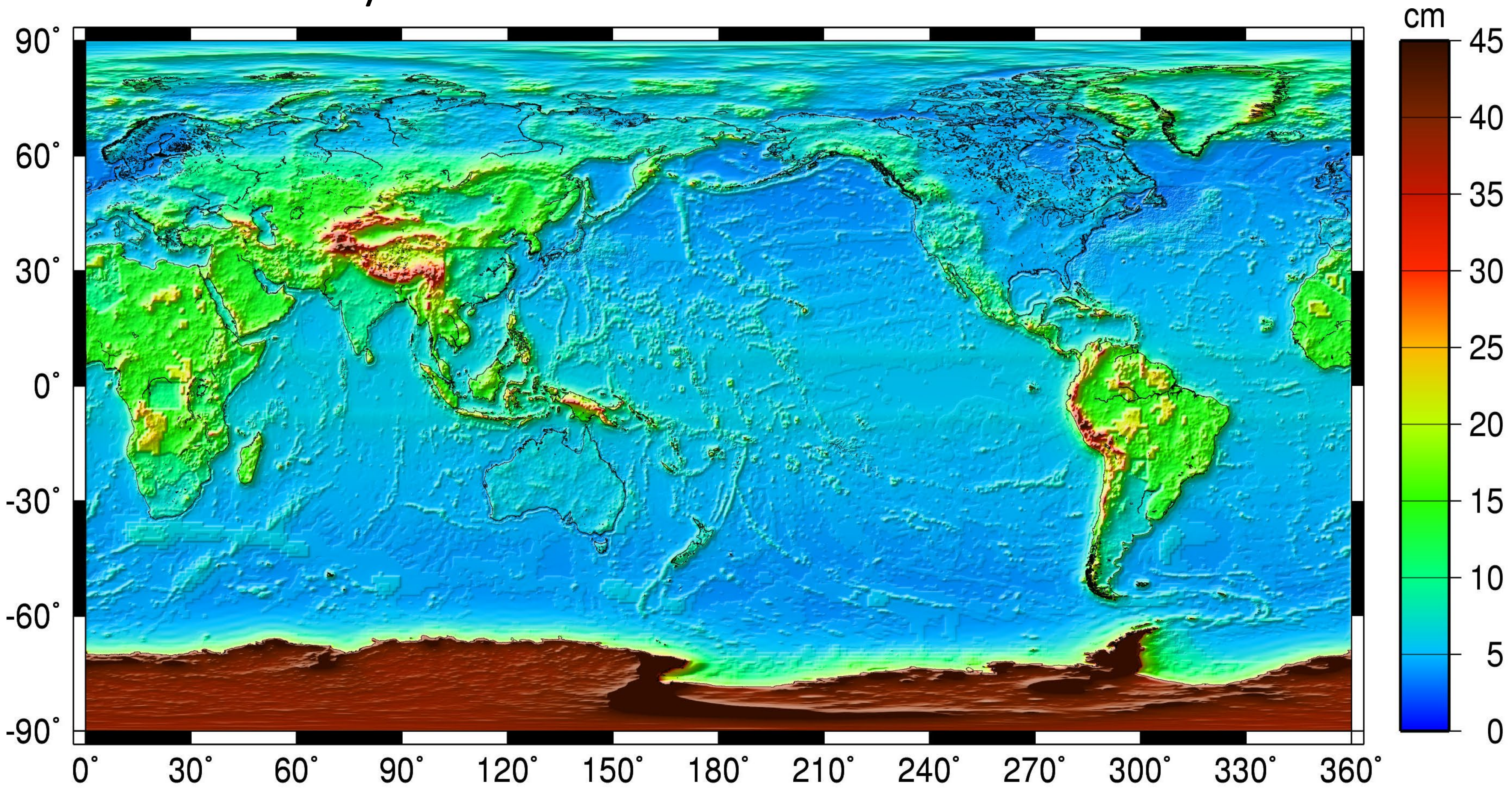
Credit: N.Pavlis

Global geoid model (EGM2008)

- Models like the Earth Geopotential Model 2008 are a combination of space, air, ship and terrestrial gravity and can form the basis of a country height datum.
- The amount of data from different regions in EGM2008 is not the same.
- In some cases, countries have added to EGM2008 models with extra gravity data to improve the accuracy of the model.

Global geoid model (EGM2008)

EGM2008 uncertainty



Credit: N.Pavlis

Other global gravity models

https://icgem.gfz-potsdam.de/tom_longtime

ICGEM

Global Gravity Field Models

We kindly ask the authors of the models to check the links to the original websites of the models from time to time.
Please let us know if something has changed.

The table can be interactively re-sorted by clicking on the column header fields (Nr, Model, Year, Degree, Data, Reference).
In the data column, the datasets used in the development of the models are summarized, where **A** is for altimetry, **S** is for satellite (e.g., GRACE, GOCE, LAGEOS), **G** for ground data (e.g., terrestrial, shipborne and airborne measurements) and **T** is

The links **calculate** and **show** in the last columns of the table directly invoke the *Calculation Service* and *Visualization page* for the selected model.
For models with a registered **doi** ("digital object identifier") the last column contains the symbol ✓, which directly opens the page on "http://dx.doi.org/".
If you click on the reference, the complete list of references can be seen.

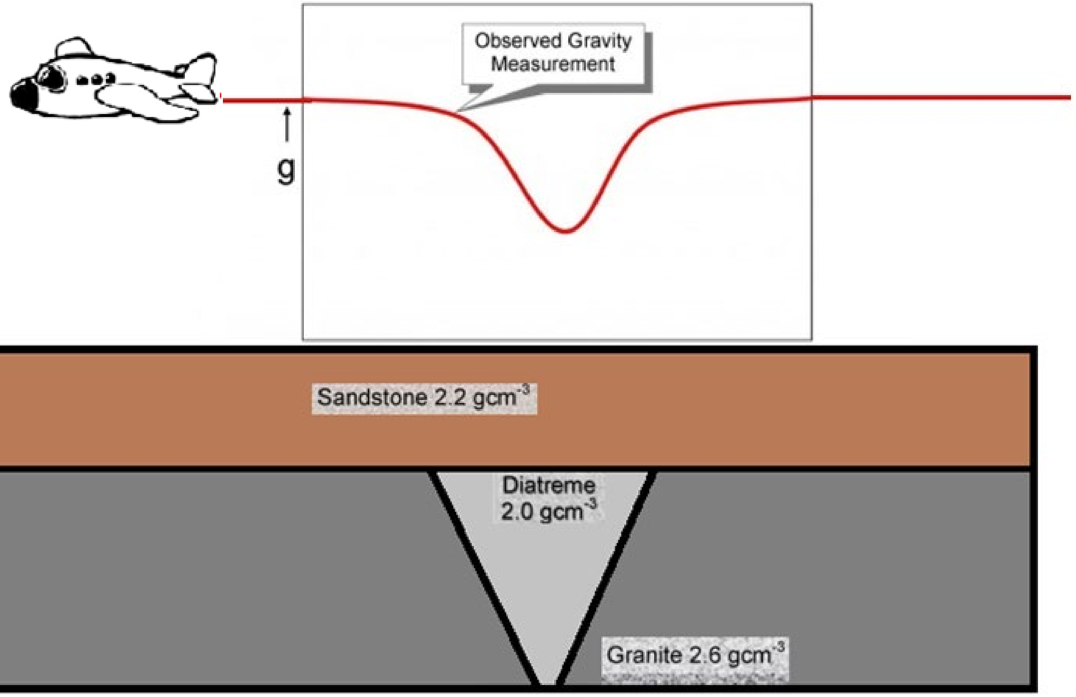
Nr	Model	Year	Degree	Data	References
180	WHU-SWPU-GOGR2022S	2023	300	S (Goce), S (Grace)	Zhao, Yongqi et al 2023
179	GOSG02S	2023	300	S (Goce)	Xu, Xinyu et al 2023
178	Tongji-GMMG2021S	2022	300	S (Goce), S (Grace)	Chen, J. et al, 2022
177	SGG-UGM-2	2020	2190	A, EGM2008, S(Goce), S(Grace)	Liang, W. et al, 2020
176	XGM2019e_2159	2019	**2190** 5540 760	A, G, S(GOCO06s), T	Zingerle, P. et al, 2019
175	GO_CONS_GCF_2_TIM_R6e	2019	300	G (Polar), S(Goce)	Zingerle, P. et al, 2019
174	ITSG-Grace2018s	2019	200	S(Grace)	Mayer-Gürr, T. et al, 2018
173	EIGEN-GRGS.RL04.MEAN-FIELD	2019	300	S	Lemoine, J.M. et al, 2019
172	GOCO06s	2019	300	S	Kvas, A. et al, 2021
171	GO_CONS_GCF_2_TIM_R6	2019	300	S(Goce)	Brockmann, J. M. et al, 2021
170	GO_CONS_GCF_2_DIR_R6	2019	300	S	Bruinsma, S. L. et al, 2014
169	IGGT_R1C	2018	240	G, S(Goce), S(Grace)	Lu, B. et al., 2019
168	Tongji-Grace02k	2018	180	S(Grace)	Chen, Q. et al, 2018
167	SGG-UGM-1	2018	2159	EGM2008, S(Goce)	Liang, W. et al., 2018 & Xu, X. et al. (2017)
166	GOSG01S	2018	220	S(Goce)	Xu, X. et al., 2018
165	IGGT_R1	2017	240	S(Goce)	Lu, B. et al, 2017
164	IfE_GOCE05s	2017	250	S	Wu, H. et al, 2017
163	GO_CONS_GCF_2_SPW_R5	2017	330	S(Goce)	Gatti, A. et al, 2016
162	GAO2012	2012	360	A, G, S(Goce), S(Grace)	Demianov, G. et al, 2012
161	XGM2016	2017	719	A, G, S(GOCO05s)	Pail, R. et al, 2017
160	Tongji-Grace02s	2017	180	S(Grace)	Chen, Q. et al, 2016
159	NULP-02s	2017	250	S(Goce)	A.N. Marchenko et al, 2016
158	HUST-Grace2016s	2016	160	S(Grace)	Zhou, H. et al, 2016
157	ITU_GRACE16	2016	180	S(Grace)	Akyilmaz, O. et al, 2016

Airborne gravity

Measures the total vertical acceleration. Need highly accurate GPS data and IMU to remove of the effect of the aircraft motion to recover a gravity signal.

Benefits of airborne gravity observations

- ✓ Easy to obtain consistent coverage over otherwise inaccessible areas (mountains, shallow coastal regions)
- ✓ Covers large areas quickly and cheaply compared to terrestrial methods.
- ✓ Can cover the littoral zone easily where there are large errors in satellite altimetry and terrestrial/Shipborne methods aren't practical.



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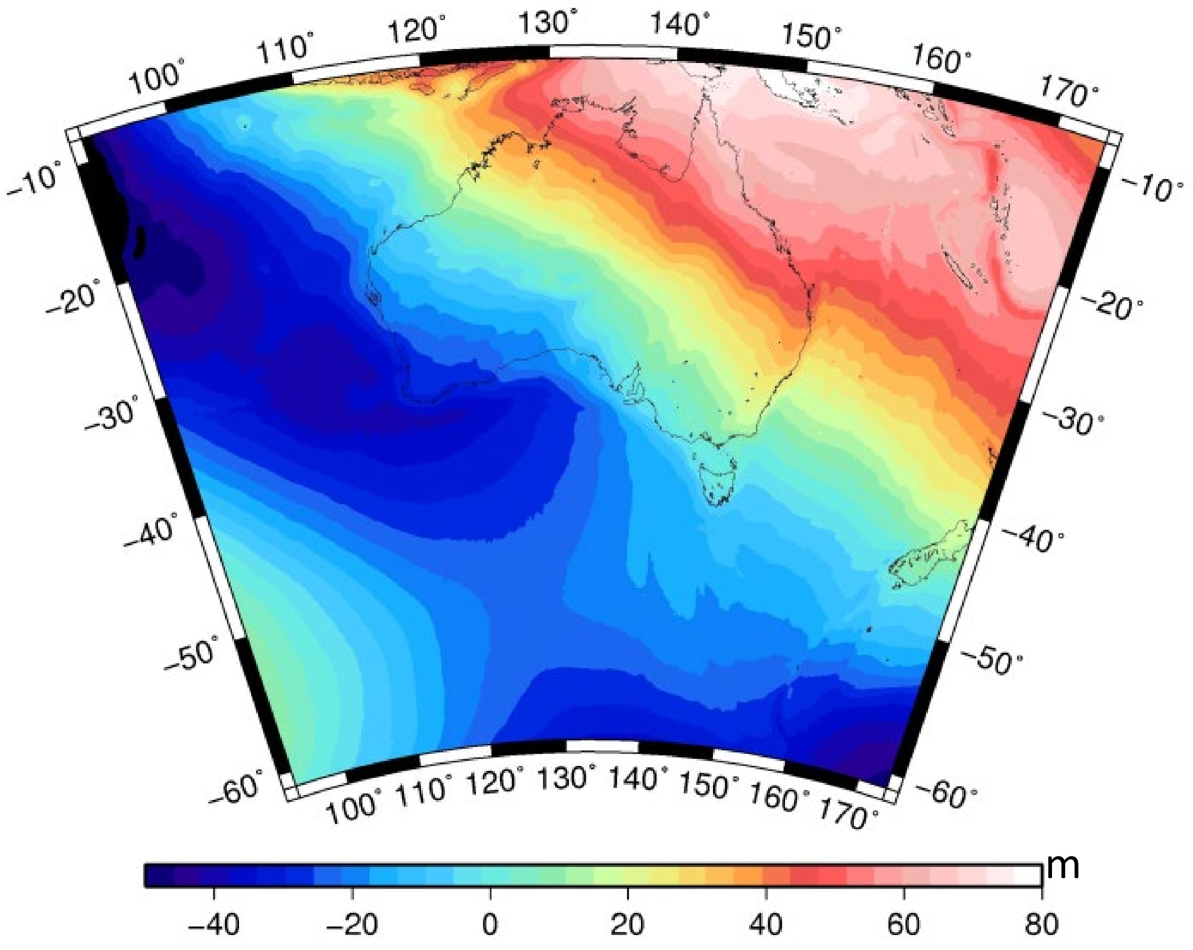
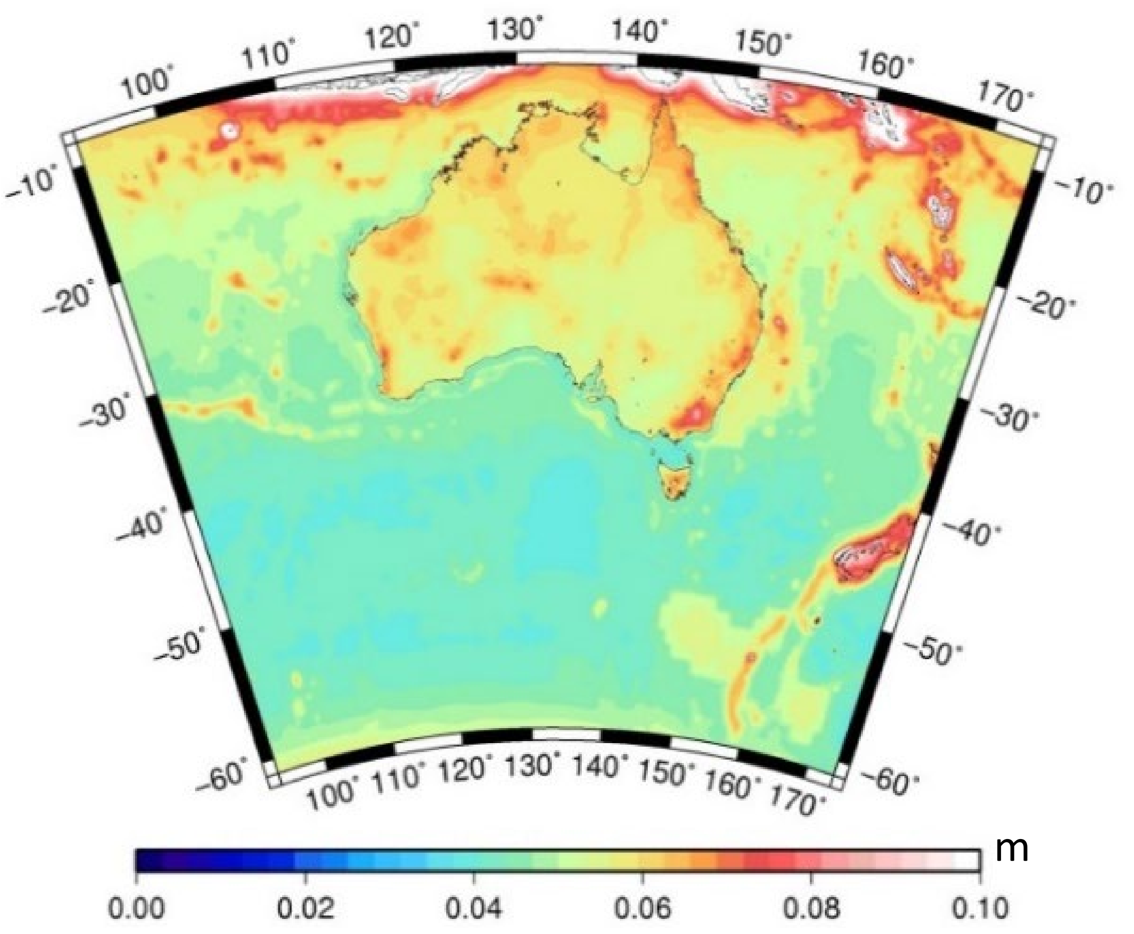
Example of geoid model EGM2008+airborne(partial)+terrestrial

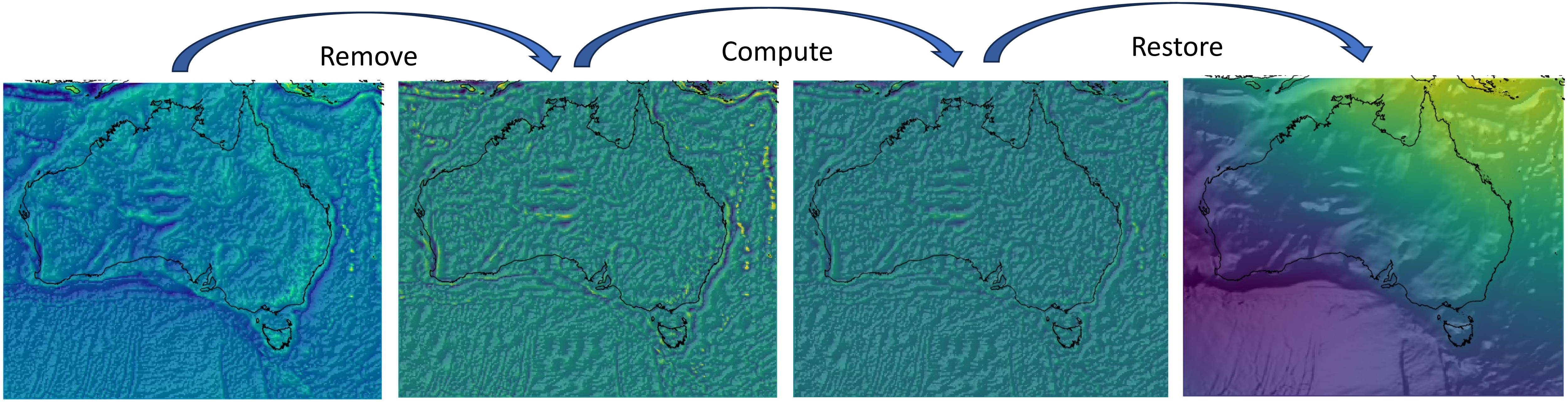
Australian Gravimetric Quasigeoid 2017 (AGQG2017)



AGQG2017 - Uncertainty



Regional scale geoid modelling



Regional gravity anomalies $(\pm 150\ mGal)$

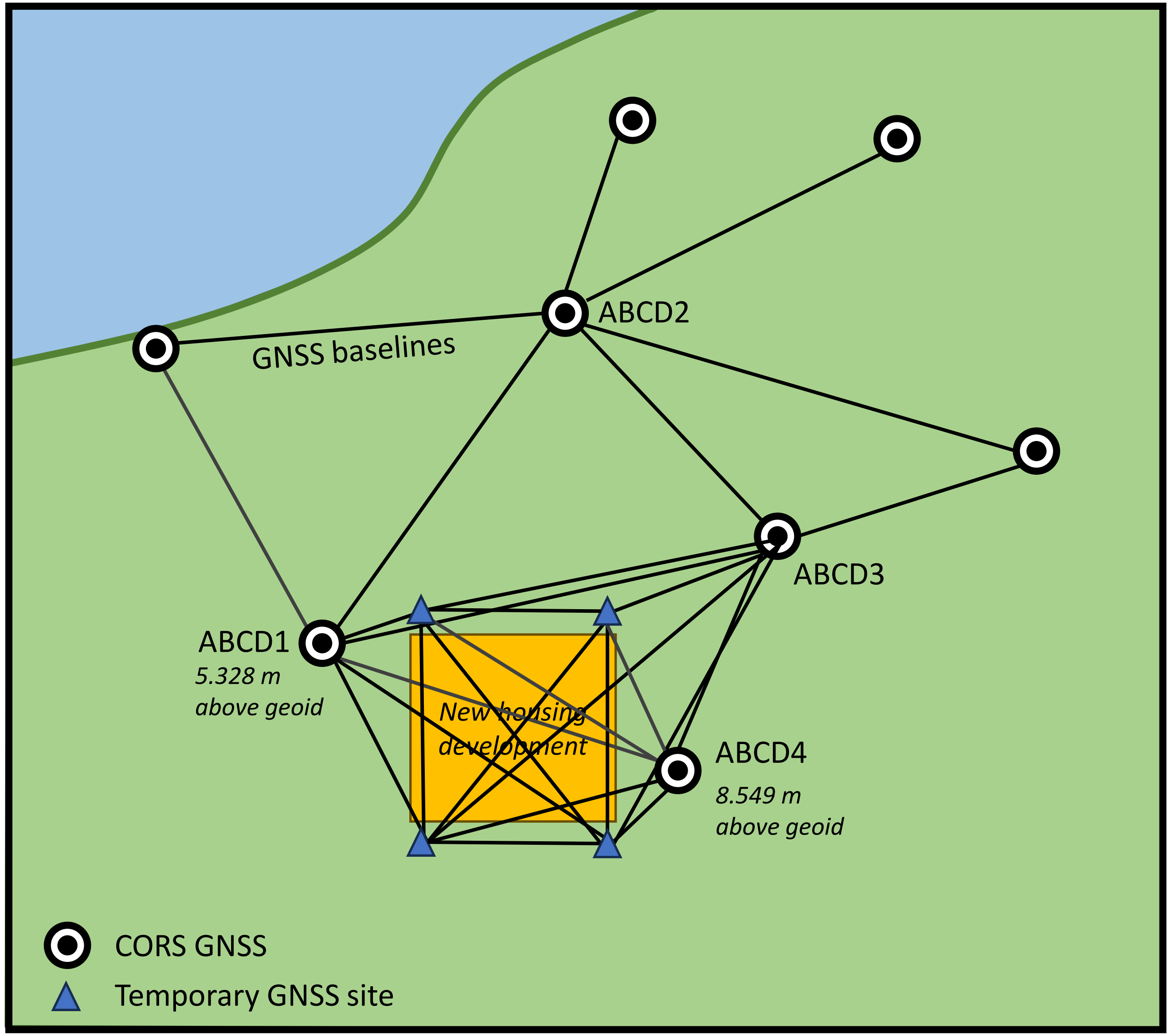
Residual gravity anomalies $(\pm 50\ mGal)$

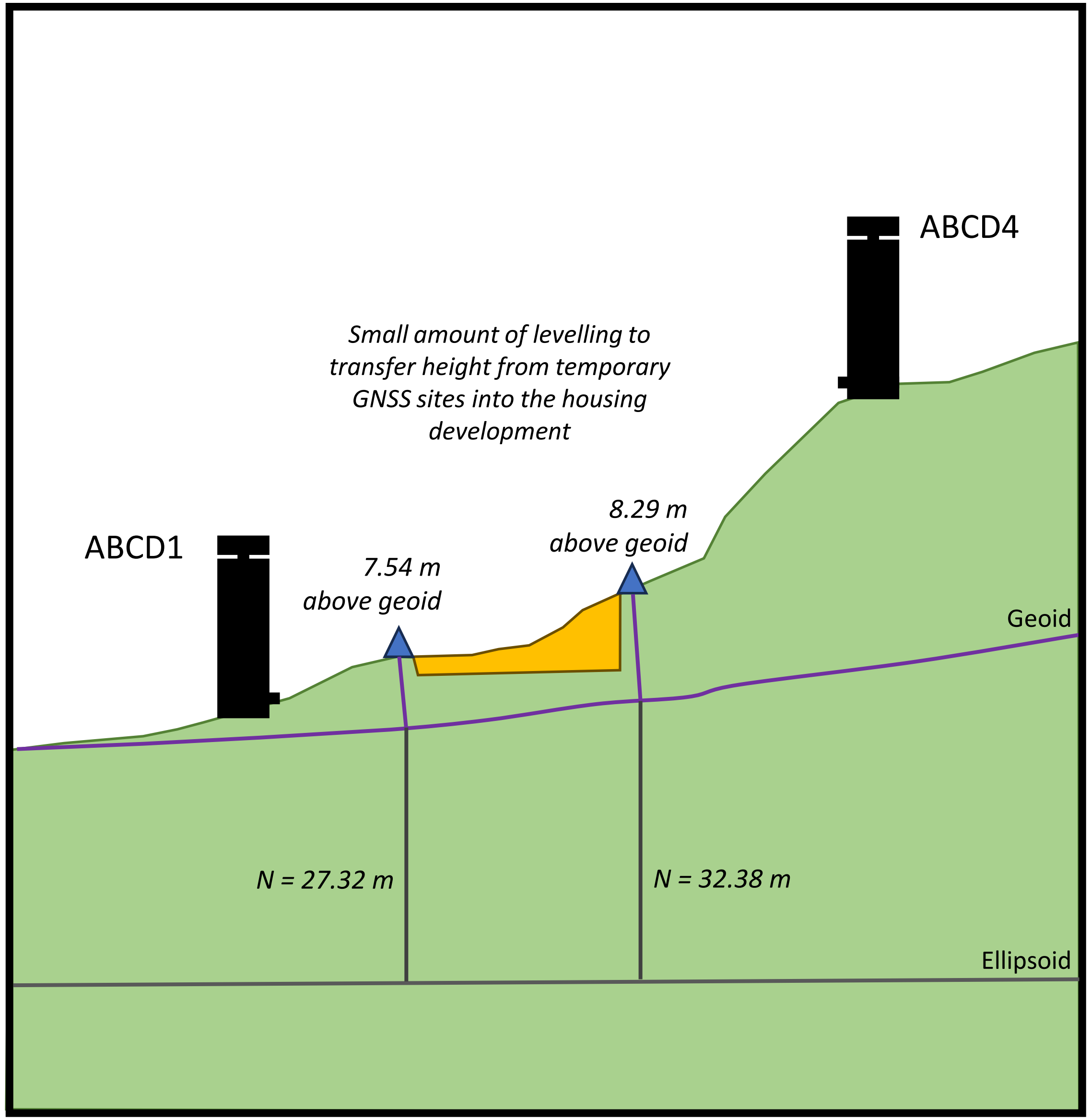
Residual Geoid variations $(\pm 5\ m)$

Regional Geoid Variations (±50m)

- **Data augmentation procedure** – Regional gravity anomaly data are augmented with global gravity models to incorporate finer scale features (< 100 km and often up to $\pm 1\ m$ variations) using the so-called "Remove-Compute-Restore" technique.
  - **Remove:** Long wavelength Global Gravity Model derived gravity anomalies are subtracted from the regional Gravity anomaly data to produce a residual – ideally composed of only only high frequency signals.
  - **Compute:** The residual gravity anomalies are then transformed into residual geoid variations. This process can be undertaken in several ways (e.g. gridding the data and using FFT/Numerical Stokes integration or via statistical techniques such as Least Squares Collocation) and often includes low & high pass filtering (e.g. using modified Stokes kernels) to optimise the features determined from the regional scale residual gravity data.
  - **Restore:** The long wavelength global gravity models is then "restored" (added back) to the residual geoid model from the compute step to produce the final – full spectrum – model (generally gridded at 1 arc minute).

Height datum referenced to geoid model





Considerations for a geoid model based vertical datum

- Requires permanent operation of a CORS network with ample distribution of stations throughout your country.

- For much of the world, the datasets available to assess the quality of precise geoid models is scarce (high quality GNSS and levelling networks). Many countries also lack the gravity data required.

- The most popular technique to create the input gravity model is combination of satellite airborne and terrestrial data.

- The transition from any vertical datum to another should be accompanied by a transformation surface to allow traceability to the old standard.

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Considerations for a geoid model based vertical datum

- You need a reliable GNSS CORS network
- You need a geoid model which is more accurate than your current levelling network
- Users need to be proficient in the use of GNSS to determine a local height network
- It may permit reassignment of ongoing maintenance costs of ground marks to be directed to gravity observations and geoid model
- Particularly relevant for big countries and / or countries with surface heave (e.g. colder)

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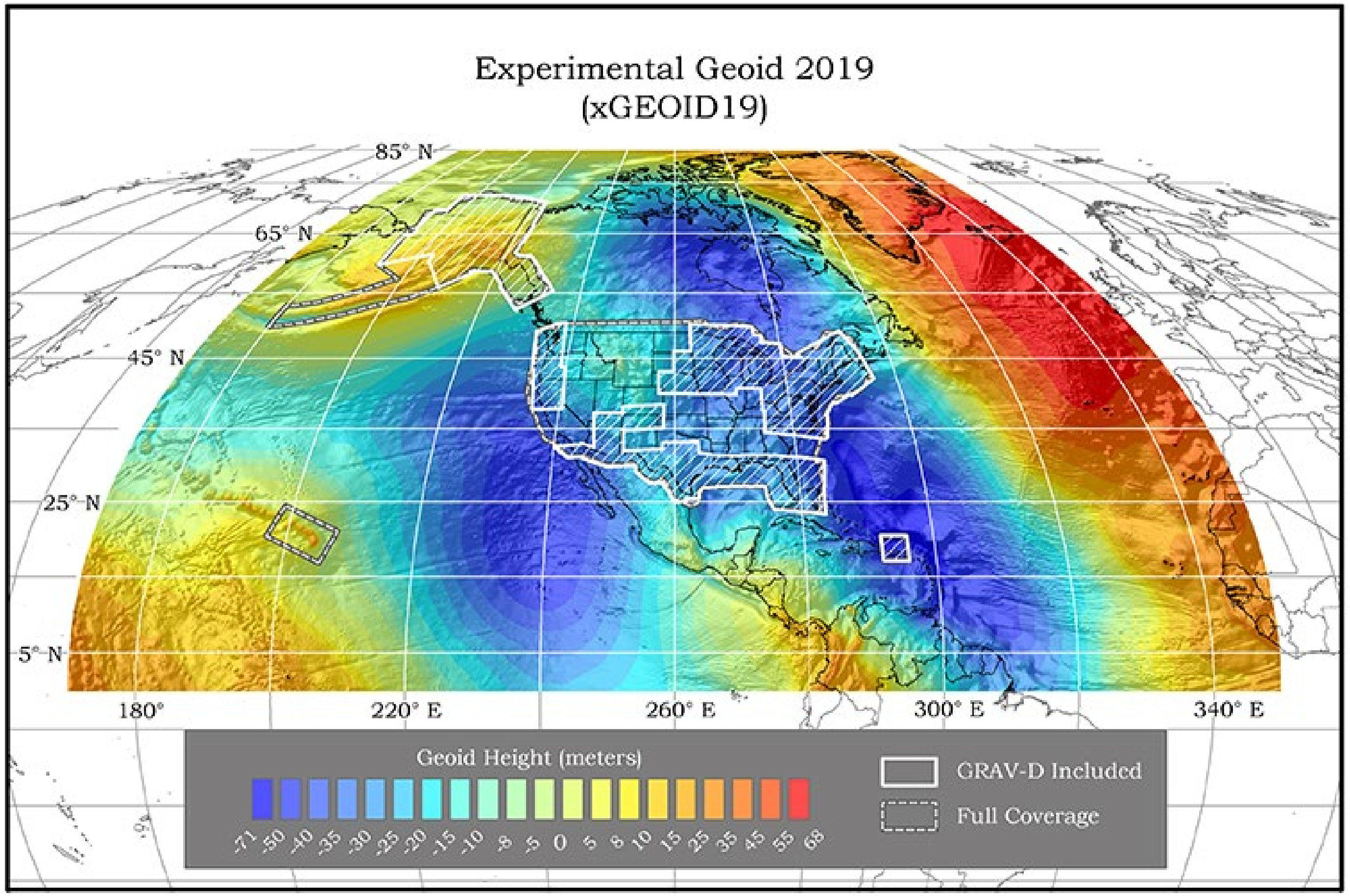
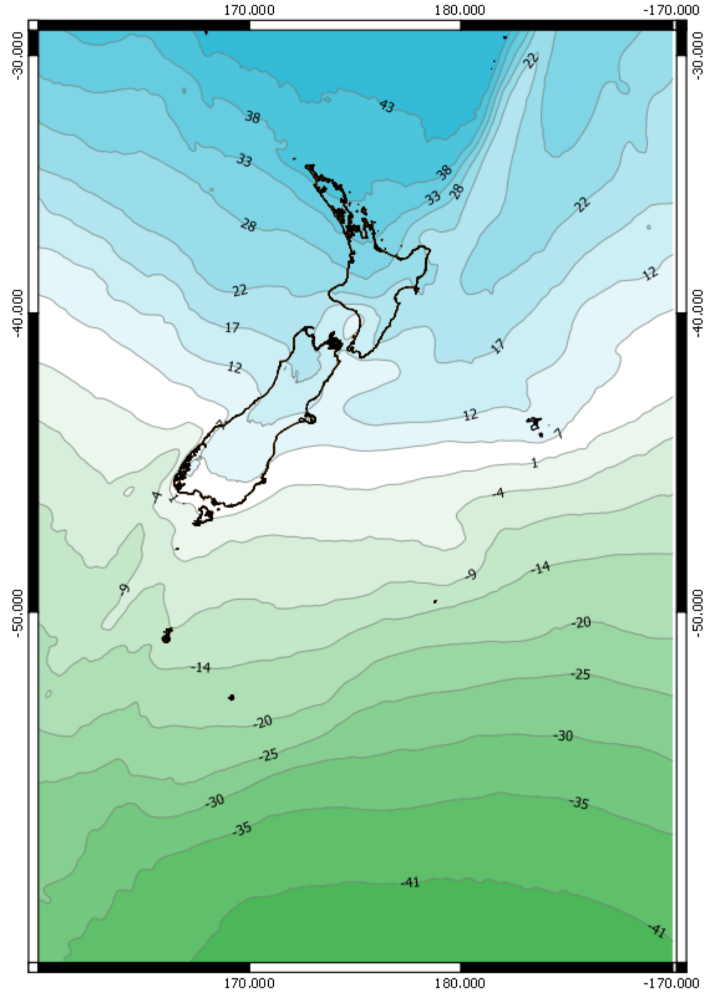
USA and NZ geoid models



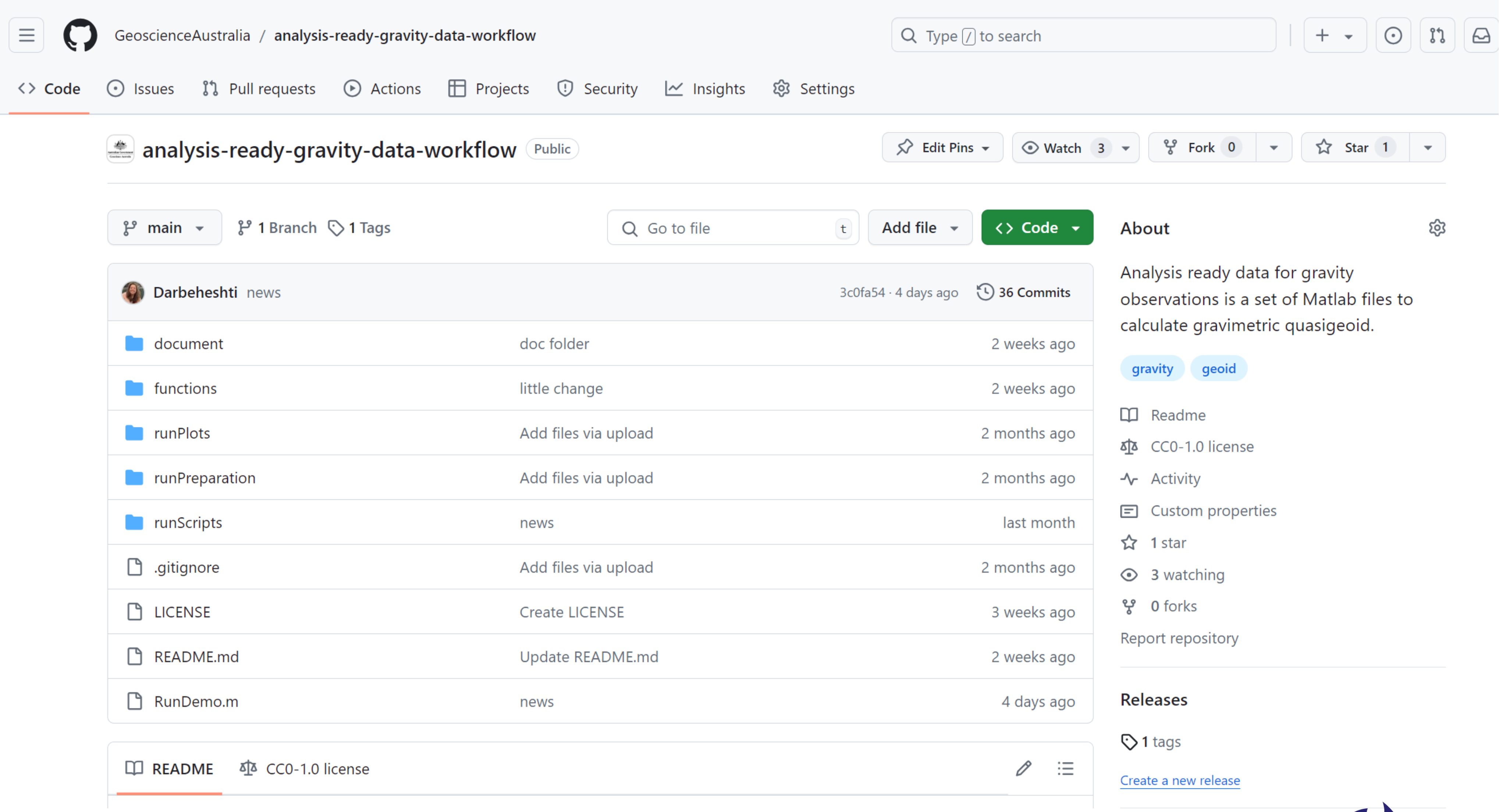
Sauce: https://beta.ngs.noaa.gov/GEOID/xGEOID19/

NZGeoid2016



Sauce: https://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/vertical-datums/new-zealand-quasigeoid-2016-nzgeoid2016

LSC workflow in GitHub



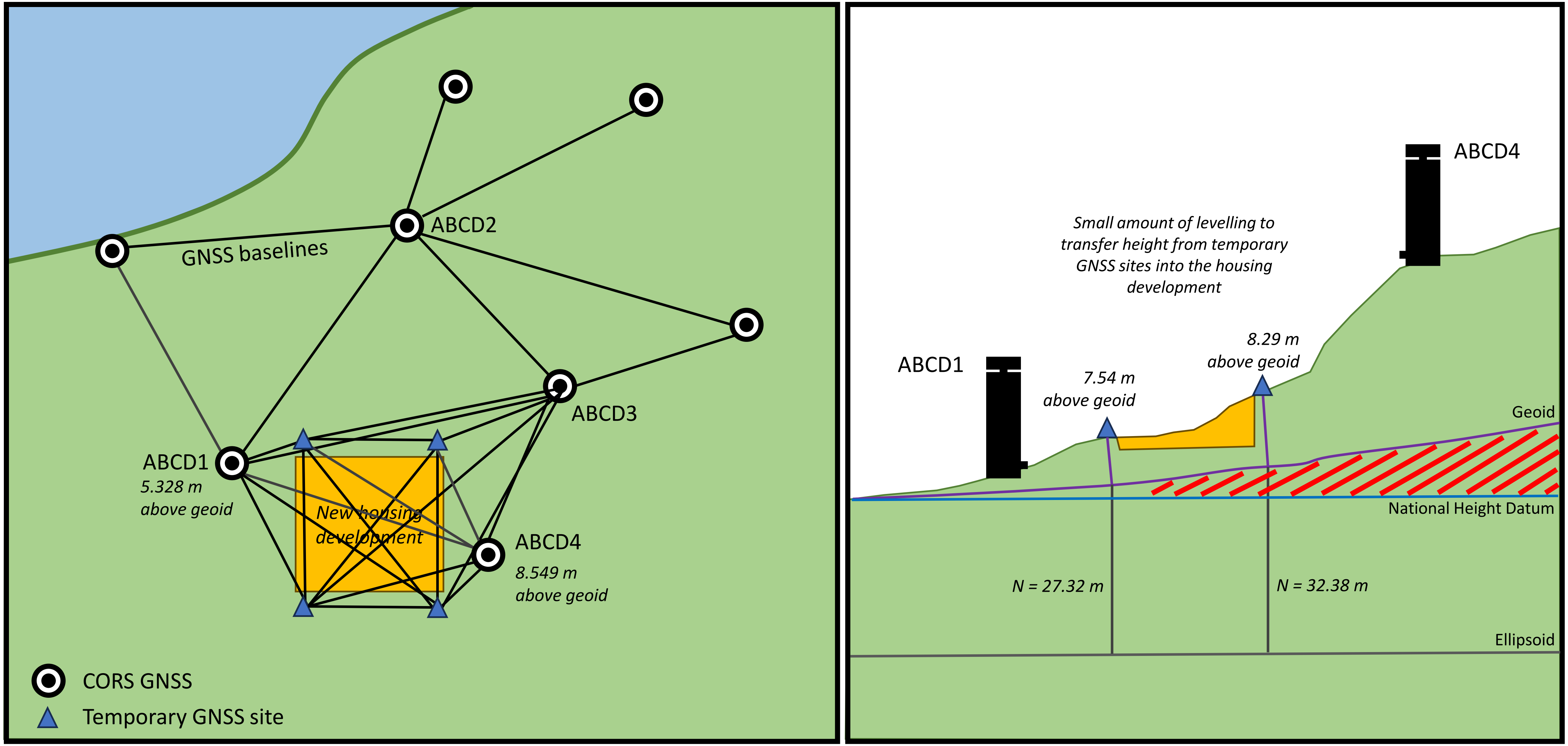
https://github.com/GeoscienceAustralia/analysis-ready-gravity-data-workflow

AuScope | NCRIS National Research Infrastructure for Australia An Australian Government Initiative

Corrector surface (h,H,N)

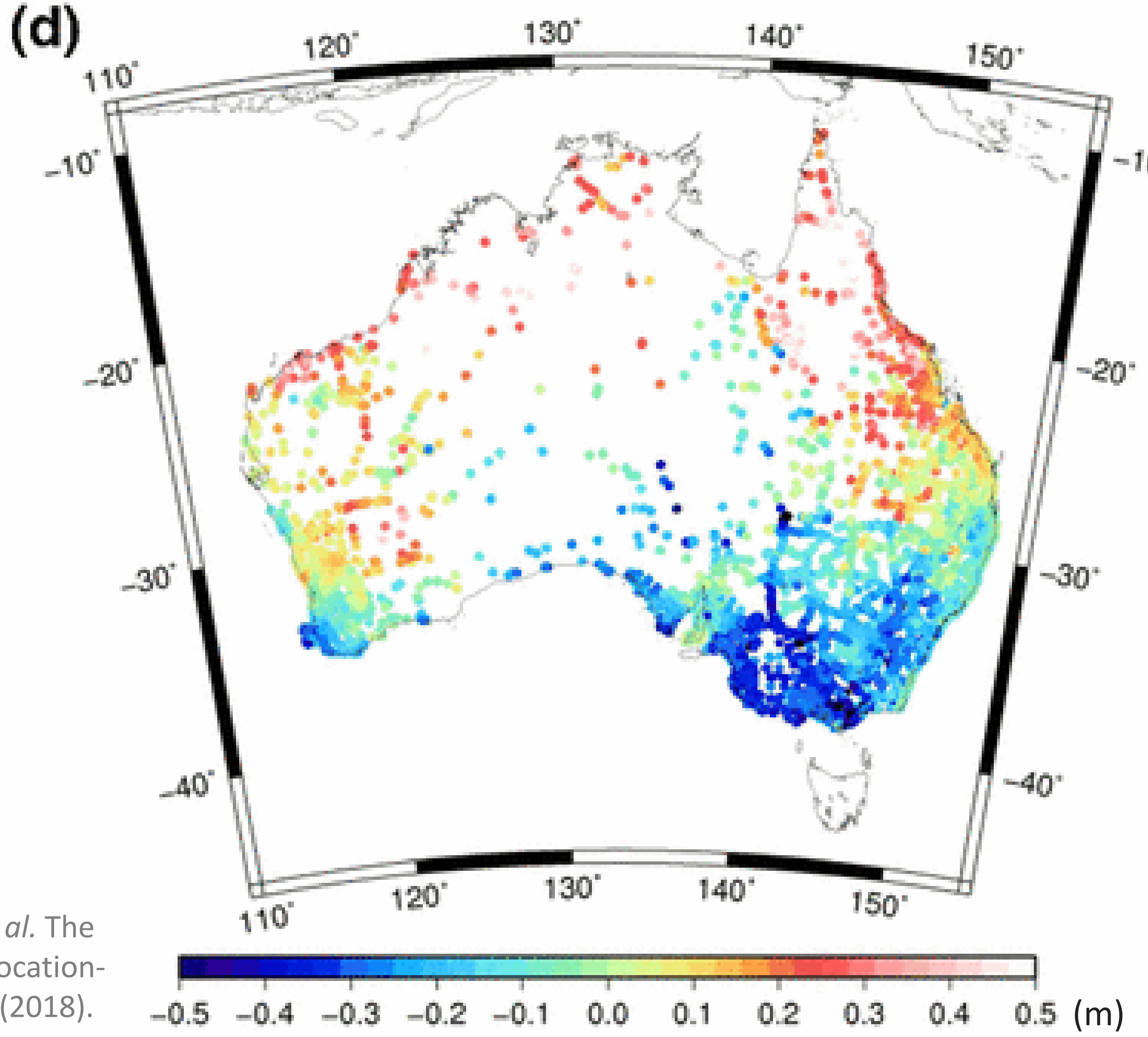
- Correction between a geoid model and a height datum implemented in a country.
- Model of bias, discrepancies and systematic effects in a height datum when it was realised or since it's realisation.
  - The residual errors $\varepsilon = h - H - N$ are modelled using a parametric model (corrector surface), which may be based on a simple bias, a bias and a tilt, higher order polynomials with different base functions, finite element models, Fourier series, or least squares collocation-based approaches.
  - The unknown parameters for the selected corrector surface are obtained via a common least-squares adjustment of ellipsoidal, orthometric and geoid height data over a network of co-located GNSS-levelling benchmarks.

Height datum referenced to geoid model + corrector surface



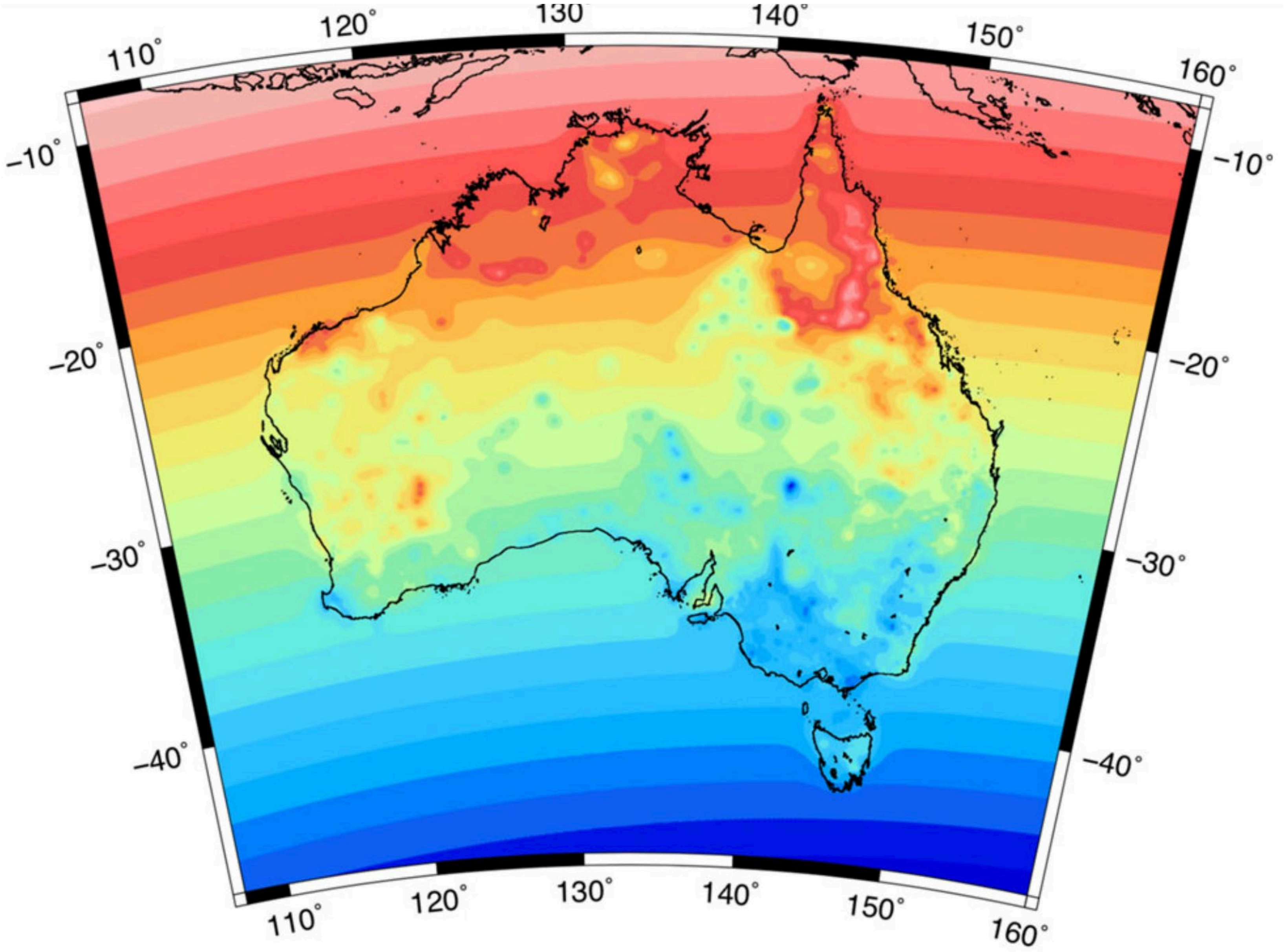
Differences between gravimetric and geometric quasigeoid at the 7224 GNSS-AHD stations on the mainland

- North-south tilt
- Regional biases
- Levelling errors



Featherstone, W.E., McCubbine, J.C., Brown, N.J. *et al.* The first Australian gravimetric quasigeoid model with location-specific uncertainty estimates. *J Geod* **92**, 149–168 (2018). https://doi.org/10.1007/s00190-017-1053-7

Corrector surface (h,H,N)



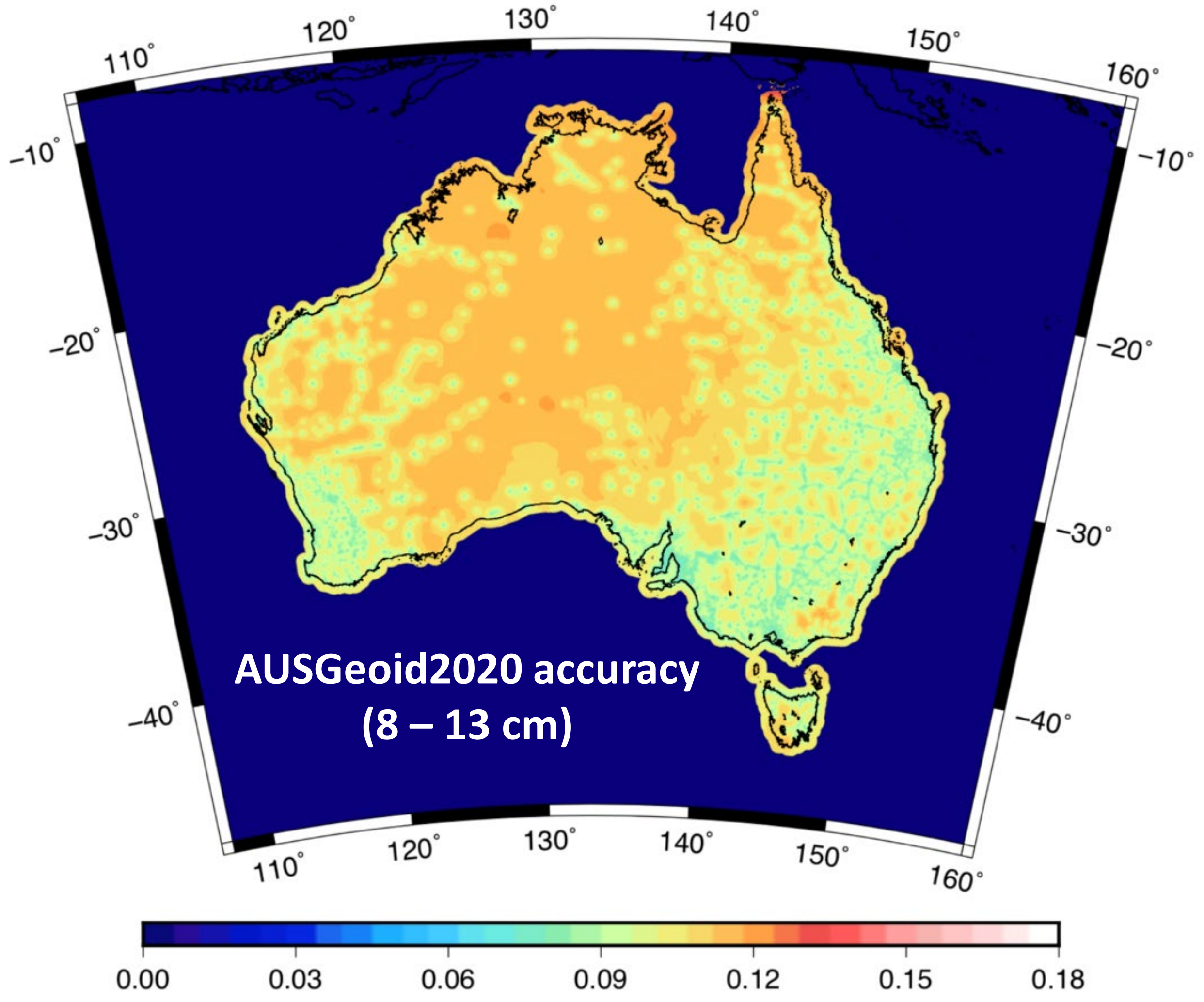
Corrector surface (h,H,N)

Remarks:

- A well-distributed set of levelling points co-located with GNSS positioning is desired;
- The applicability of the corrector surface depends on the number and quality of the included points with co-located data (h, H, N);
- The more points the better the corrector surface;
- The better the geographic distribution of co-located data the better the corrector surface;
- GNSS points and levelling points of low order should not be included;
- The predicted data are the height uncertainties; the original data are not improved.

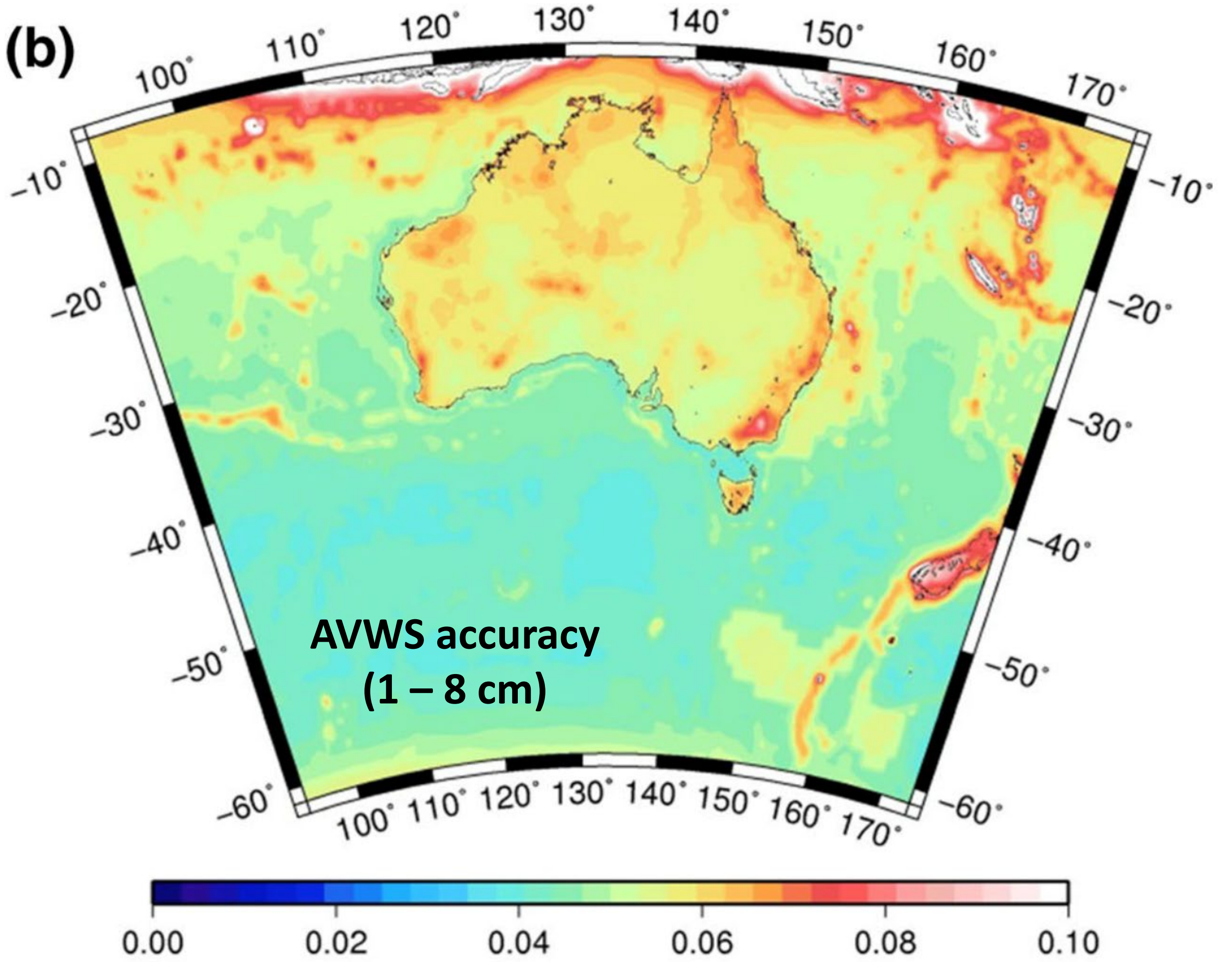
Two frame solution

Gravimetric + Geometric



Brown et al. (2018), Journal of Geodesy

Gravimetric



Featherstone et al. (2017), Journal of Geodesy