4D DEEP DYNAMIC EARTH (4D3 EARTH)

A new ESA initiative

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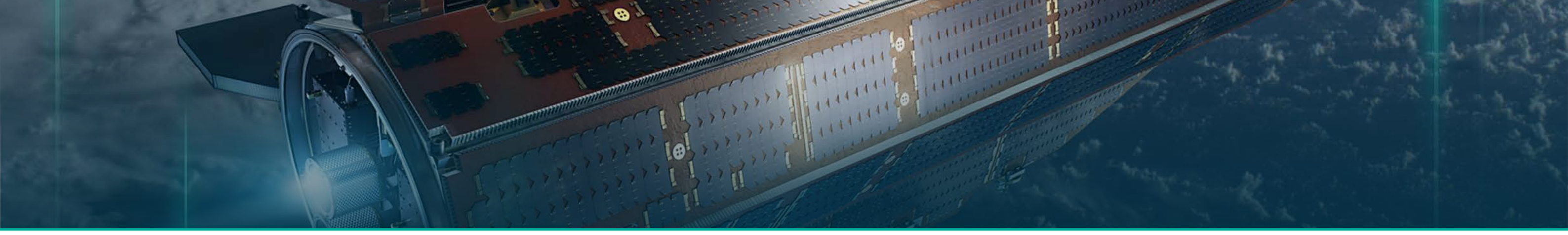
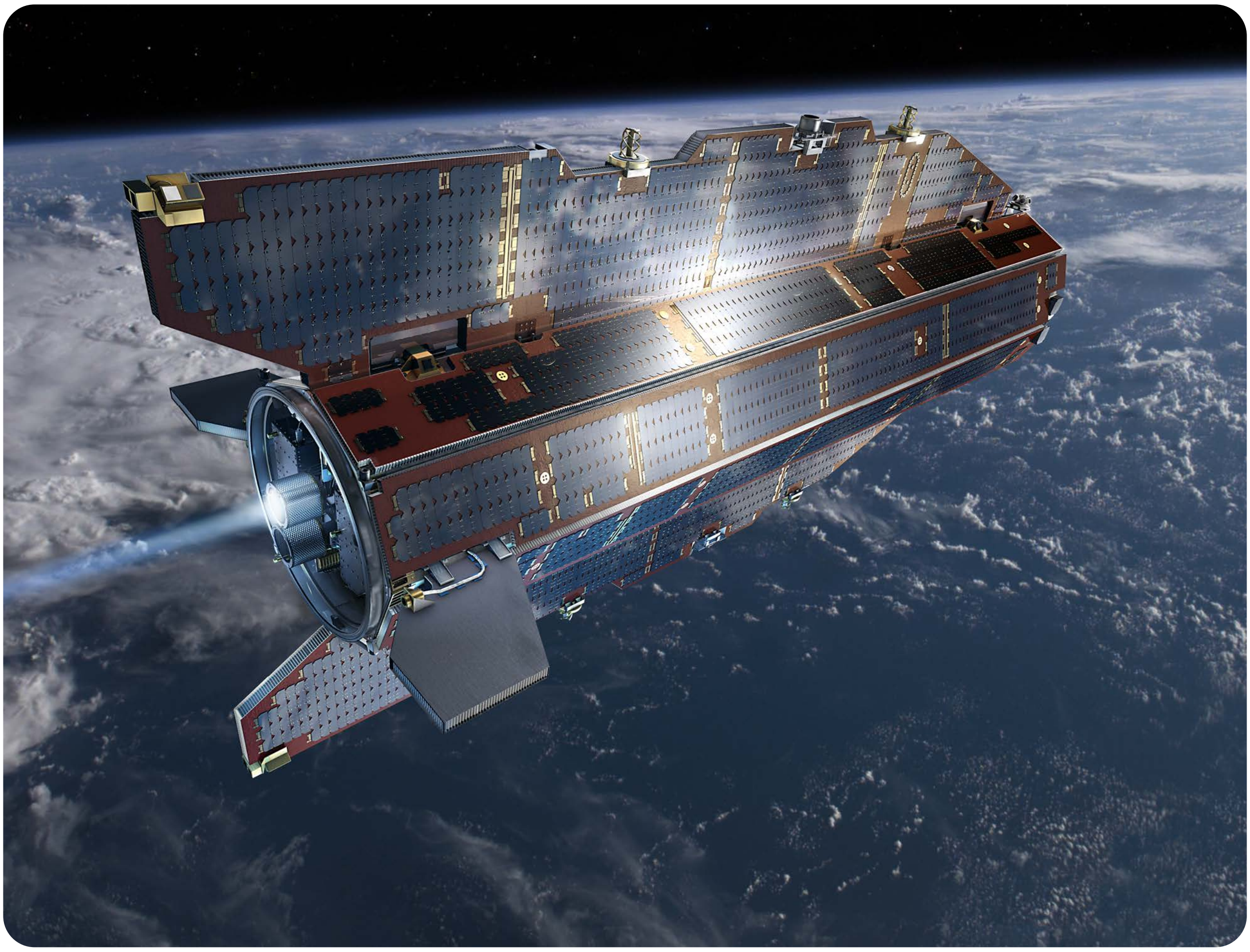


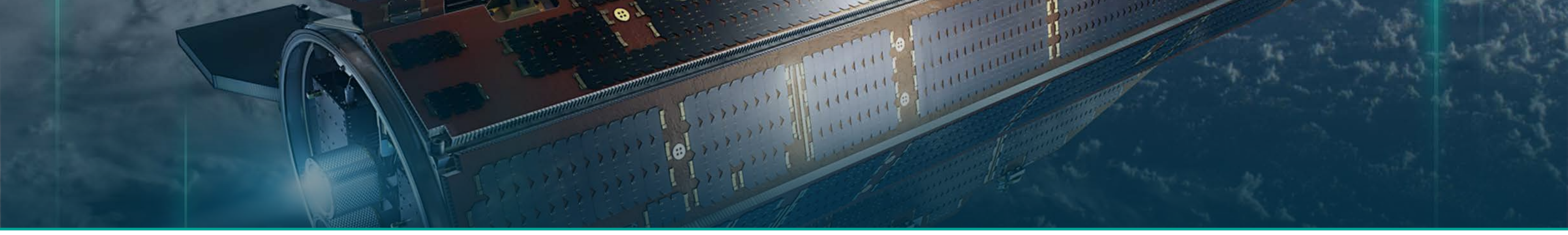
1. INTRODUCTION

This document summarizes part of the content and discussion of the 4D Deep Dynamic Science Meeting, which took place virtually on the 28th and 29th of September 2022 and focused on the structure and dynamics of the deep Earth, from the core-mantle boundary to the surface. Furthermore, it proposes a new project description that is envisioned from the lessons learned and discussions held at the meeting. The new project is based on extending the successful 3D Earth project and adding new elements to make it a whole-mantle model to support dynamical studies of the Earth.

To understand the dynamic Earth a complete picture of Earth's mantle is necessary. The 3DEarth project in ESA's Support to Science Element showed successful possibilities of a joint study across multiple disciplines toward the construction of a structural model of the upper 400 km of the Earth. For this, satellite data (GOCE and Swarm) significantly improved models from seismology. A next phase is envisioned, in which whole 4D Earth models are developed in order to understand the link between the deep Earth and processes at the surface of the Earth.
This is also of societal benefit by advancing our understanding of the underlying cause of geohazards such as volcanoes or earthquakes.



GOCE, *launched on 17 March 2009.*



2. OVERVIEW OF THE 4D3EARTH SCIENCE MEETING

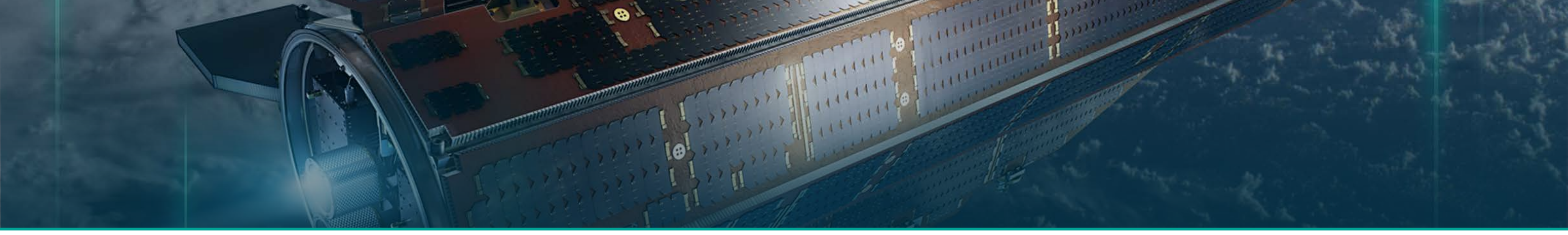
Lessons learned from the 4D Earth Meeting focus mainly on how to incorporate dynamic processes and how to include the deep mantle within whole Earth models. An improved crustal structure was also envisioned, but this was found challenging as often high-resolution data are only available to industry and have less impact on deriving large-scale structures. The suggested way forward toward such a model is to develop a joint-inversion of satellite and terrestrial data, together with a joint petrological information to better constrain this geophysical model.

3DEarth already showed the benefit of this kind of approach. The final product (WINTERC-G) is suitable for various applications. For example, the seismologically ambiguous lithosphere in eastern North America has now been mapped (Li et al. 2021). A 3DEarth study advanced our understanding of the plume structure underneath Iceland and North Atlantic lithospheric structure (Celli et al. 2021), which improves dynamic modelling of the plume and GIA processes in Greenland. In addition, the project resulted in improved resolution of the global lithospheric structure (Fullea et al. 2021). Multi-parameter lithospheric imaging combining seismic and satellite gravity data can contribute to the physical models of the distribution of seismicity and improve our understanding of the earthquake hazard in Europe and elsewhere around the world. It also has other applications of high societal and economic importance, including mineral and geothermal resource assessment.

Proper use of satellite gravity field data leads to major improvements in the model as compared to the use of terrestrial data only.

In particular, the crustal and upper mantle sub-lithospheric density structure can be resolved. Satellite gravity data can also be used to obtain independent density estimates for the upper mantle (Root et al. 2017), allowing us to characterize the resolution and dampening of seismic tomographic models (Root 2020). Regularisation of tomographic models needs to be taken into account for the deeper parts of the Earth and satellite gravity can assist in addressing this. Often, tomographic models are still used with simple conversion factors to estimate density and viscosity in mantle convection studies.The stresses and dynamic topography estimated based on these models tend to vary significantly (Flament et al. 2013, Root et al. 2021). However, adding these calculated stresses into the isostatic equation has improved estimates of density variations in the lithosphere and has allowed us to utilise the full spectrum of the available satellite gravity data.

GOCE, *in orbit.*



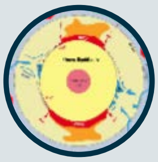
• Seed questions

Some examples:

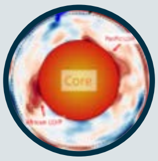
- Using seismic tomography to predict future plate motion
- Disentangling composition and temperature contribution
- Can we find a signature of BEAMS in data?

How are **observations of present-day Earth** useful for understanding 4D Deep earth **processes?**

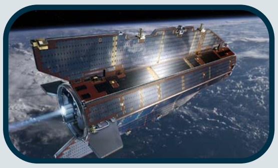
Processes create **Earth's structure,** which determines our **observables**



Dynamic modelling



inversion



PROCESSES

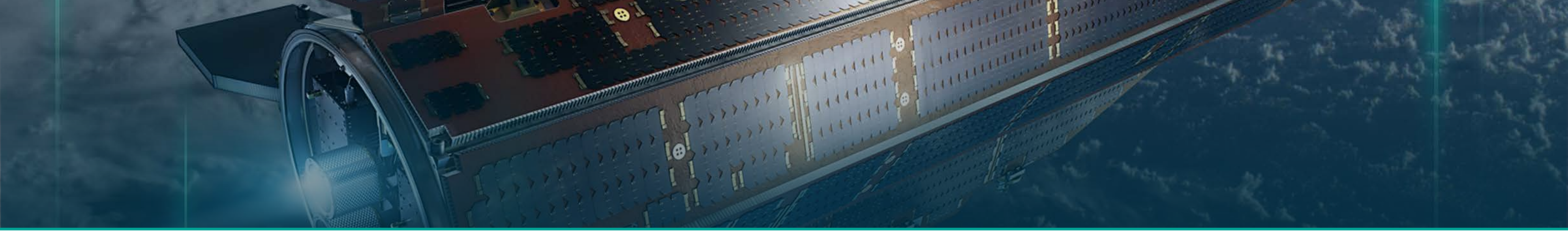
STRUCTURE (today)

OBESRVATION MEASUREMENT

When infering **processes** we have to work backwards from the **observables** and possible **processes suggests structures** to look for

To achieve this, a non-ambiguous density model of the deep mantle is needed. We expect similar challenges, as well as new ones, when applying this type of approach to constrain the density structure of the deep mantle.

Working towards a 4D Deep model requires as a starting point a global lithospheric/upper mantle thermochemical model integrating satellite gravity, waveform tomography, petrology, SHF and isostasy as available from WINTERC-G. Including the coupling between upper and lower mantle models is an essential step in extending the model. Consequently, dynamic models based on the present-day thermochemical model (density + viscosity) can predict dynamic topography, which can then be compared to residual isostatic topography as well as long-wavelength gravity and gravity gradient constraints, closing the feedback loop between dynamic and static models. Adding Swarm magnetic data into thermochemical mantle models has the potential to incorporate information on volatiles (water, melt) affecting strongly the electrical conductivity of mantle rocks therefore complementing the constraints from seismology and gravity field data. Towards the structure of the deeper mantle, a proof-of-concept for discrete trans-dimensional inversion has been shown as a complementary approach (Szwillus, ESA Fellow 2021). The discrete parametrization is useful for combining data with vastly different spatial sensitivities, such as surface wave tomography and satellite gravity, and can also be applied to bridge observations such as those that place constraints on structures at the core-mantle boundary.



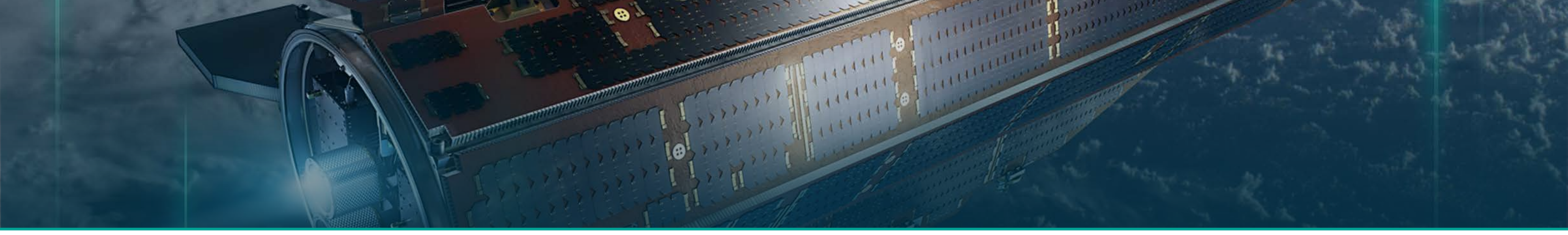
Observations of Deep Earth Dynamics

Seismology provides an (at most) 3D picture of the velocity anomalies inside the Earth. Global seismic signals recorded today yield a snapshot of the current mantle and thus lack a long time series that would allow us to detect velocity changes associated with mantle processes. To observe the dynamic mantle, we can use two indirect methods. First, mapping anisotropy helps us to understand mantle flow, and we can compare inferred mantle flow patterns with predictions from high-resolution dynamic models. Second, using different seismic methods and datasets (e.g., reflections and splitting, PKS, discrepant splitting, etc.) in combination with satellite observations can help to constrain structures in the deep Earth (velocity, density, electrical conductivity, viscosity). These can then serve as input into geodynamic models or can be used as constraints on such models. Testing the dynamical behavior of different inferred structures (with uncertainty), with a variety of methods, a combination of methods, and using different seismic waves and density constraints can help us to understand the range of dynamical behaviors that are possible. In the end, no single discipline should be pursued in isolation; because only in combination can we understand the limitations of each discipline

Discussion

Using seismic waves, it is possible to determine seismic anisotropy within the Earth, which gives us information on the flow of the rock at depth. Surface wave anisotropy, in particular, constrains the current and past deformation of the lithosphere and sub-lithospheric mantle. Normal modes constrain anisotropy of the deep mantle, as well as its other properties. The density structure of the deep mantle does not affect the attenuation of the normal modes. However, the crystal structure of post-perovskite has a lot of anisotropy. Azimuthal anisotropy is also very interesting and could be the next step in providing useful constraints on mantle flow directions—near the top and bottom of the mantle, where the flow is likely to be the most complex and anisotropy the strongest—and in the mid mantle as well, where non-zero azimuthal and radial anisotropy has also been detected. Geodynamic models predict CMB deflections near the edges of the LLSVPs – could these be detectable? What is the periodicity of plumes rising from the lowermost mantle? Sedimentary observations could provide information about the periodic rising of plumes. Knowledge of this could help constrain the mantle viscosity through which they are rising.

Bardabunga eruption, Iceland.



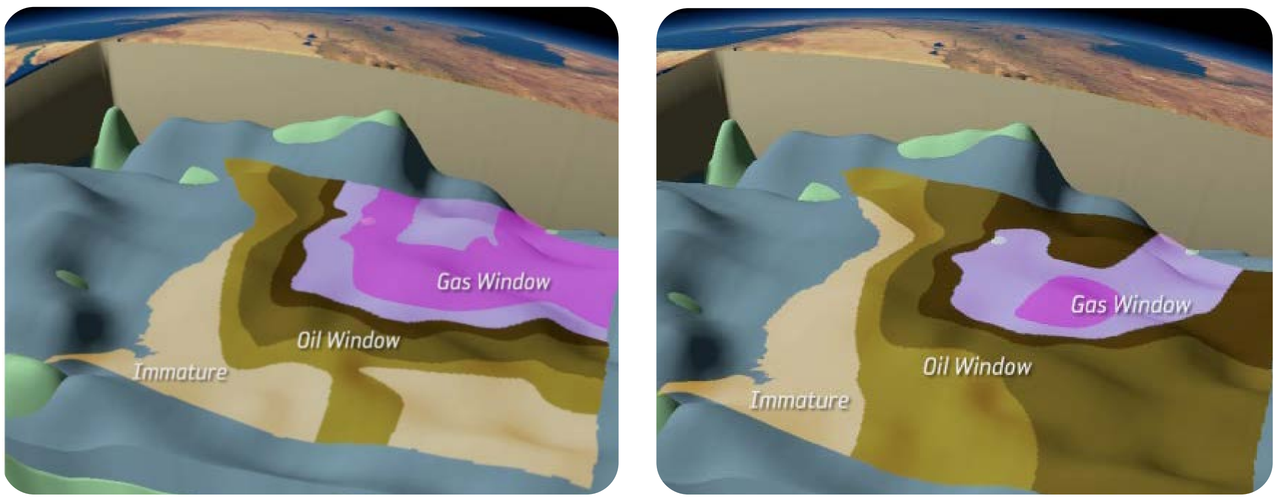
• Geophysical Constraints on Deep Mantle Structure

To observe the lower mantle, different types of seismological data need to be included. Whole Earth free oscillations provide important constraints on the density and attenuation structure of the lowermost mantle, with implications for mantle dynamics (Deuss et al. 2013). The previously derived continental-sized Large Low Seismic-Velocity Provinces (LLSVPs) have a dense central base and are weakly attenuating (Deuss et al. 2013). These structures are mapped using both the normal mode (free oscillation) data and body-wave measurements. They are interpreted as stable mantle anchors, characterized by large grain size and increased iron content. They are thought to be surrounded by strongly attenuating slab graveyards, which are more dynamic due to their smaller grain size, and easily entrained in mantle plumes at the edges of the LLSVPs. GPS and Tidal Tomography are able to constrain the deep mantle's buoyancy (Lau et al. 2017). Furthermore, tidal tomography can give constraints on frequency-dependent rheology (Lau & Faul 2019). More precise measurements of the seismic-geodetic transition can offer new insights into the Earth's deep mantle.

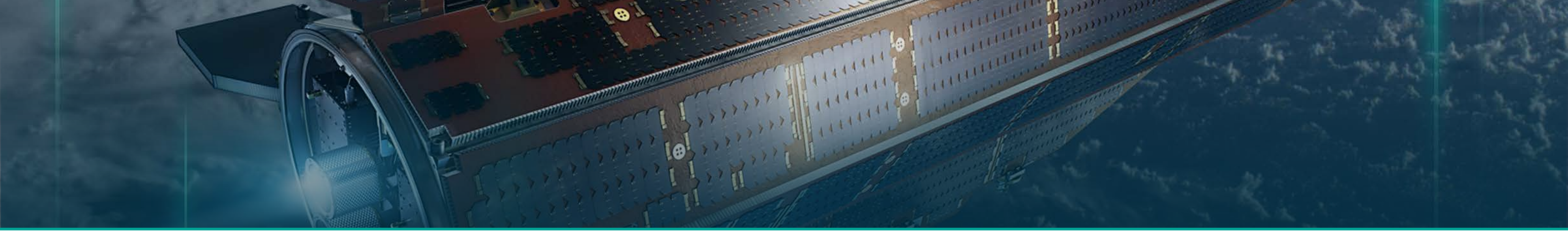
In order to image the whole mantle, a combination of different data types is required. The lithosphere-asthenosphere depth range in the upper mantle can be imaged with high, regional-scale resolution by the fundamental mode surface waves, as was achieved in the construction of WINTERC-G (Fullea et al. 2021). The mantle transition zone and the relatively shallow lower mantle down to 1000-1500 km depth are sampled by the overtones (higher modes) of surface waves. Large new overtone datasets have recently been assembled and will provide important new constraints on this depth range. These data complement the normal modes, providing information on the whole-mantle structure at relatively long wavelengths, and tele-seismic body waves, also sampling the entire mantle.

Discussion

LLSVPs could still be a collection of little plumes for the Pacific. However, normal mode modelling prefers a dense bottom structure surrounded by positively buoyant material, composing the LLSVPs. This can be explained by a combination of different compositions and temperatures, but also different grain-sizes.



Pinpointing hyrodcarbon maturity

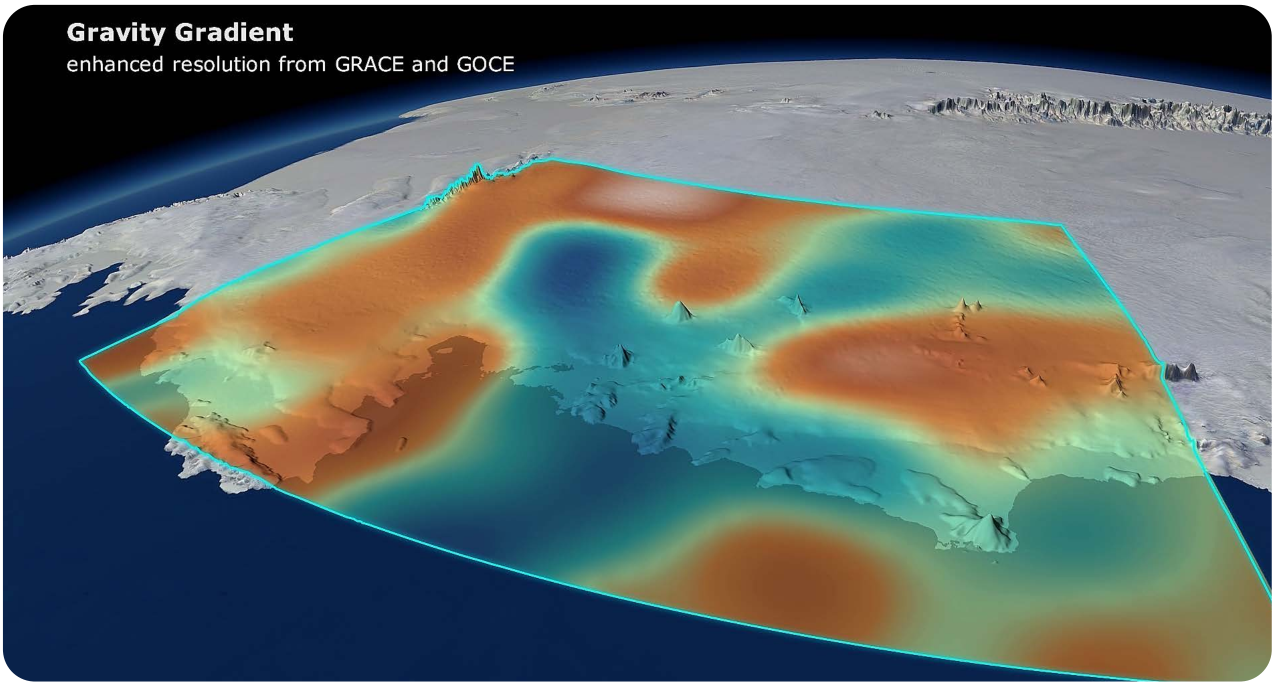


Gravity Gradients

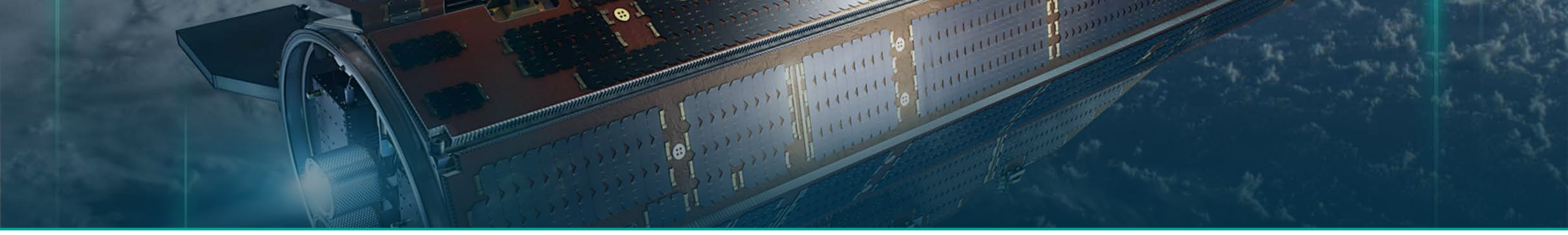
GOCE gravity gradients can detect and constrain the dynamical processes of the Earth especially for the longest wavelengths (e.g., the global mantle flow patterns inferred by Steinberger et al. 2019 and Conrad et al. 2013). Using gravity gradients, signatures of mantle dynamics at different timescales in satellite gravity data can be identified (Panet et al. 2014). New information on the evolution of the subducted slabs in the upper mantle at monthly timescales makes a connection between giant ruptures at the surface and deeper slab dynamics (Panet et al. 2018a). A description of regular patterns of convection below ocean basins likely reflects dense sources in hot upwelling areas down to the base of an extended transition zone (Panet et al, 2018b). Their possible origin relates to the formation of dense melts as the rolls cross a moderately hydrous transition zone. Furthermore, GOCE and Swarm provides an original way to study couplings between mass redistributions at the core-mantle boundary and core flows at sub-decadal timescales (Mandea et al. 2015). This shows that satellite gravity gradients provide useful constraints on mantle processes at all depths.

Discussion

How can gravity and seismic data be used in a combined approach to study the lower mantle structure? Could this be done in a similar manner as in 3DEarth or should the approach be different? Can we use adaptive regularization for this? Gravity inversion for the shape of the LLSVPs suggests that broadly speaking these regions as a whole have a positive density anomaly. Maybe there is not enough resolution (and with seismic constraints) to constrain the LLSVP characteristics more than this. Here, an opportunity is envisioned for the Swarm data, as it could examine the electrical conductivity of these large structures and better constrain the size and locations of these structures from an independent data source.



Ice loss dips gravity

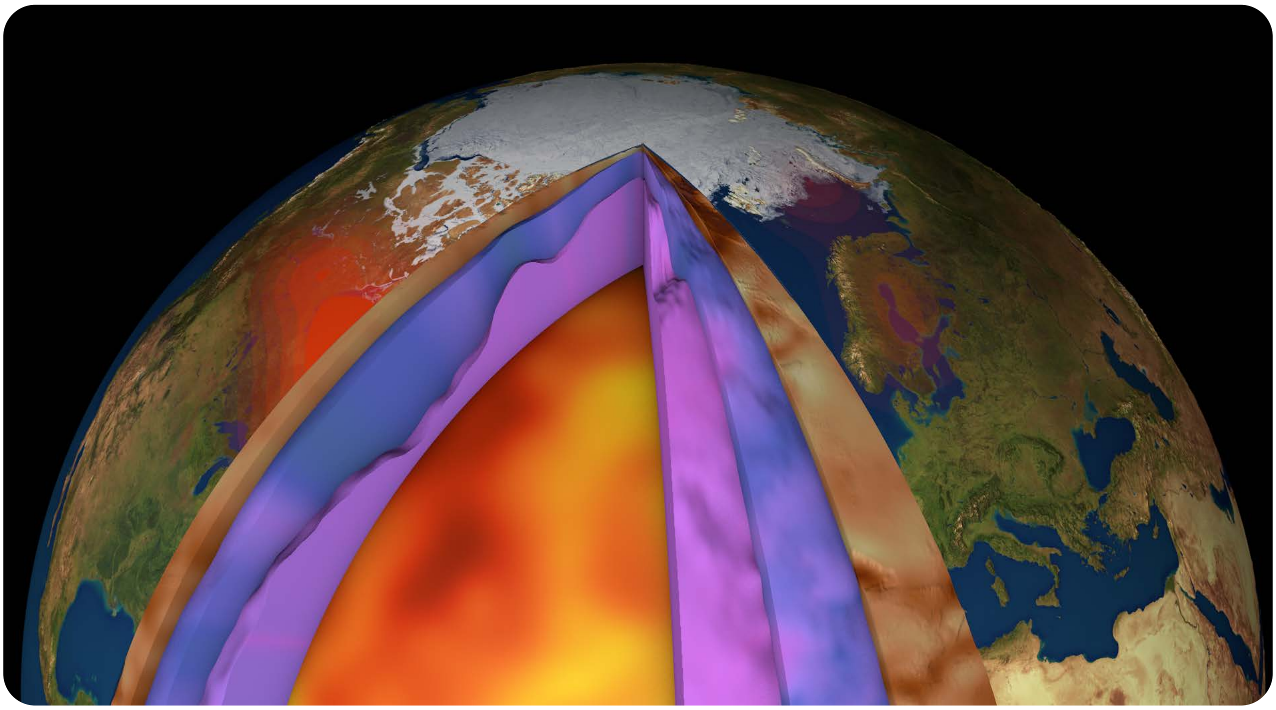


Dynamic Earth: the importance of a 3D viscosity model

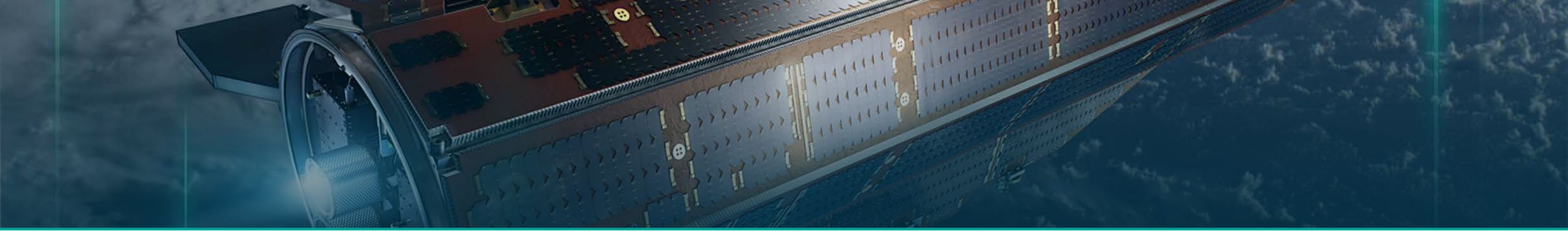
How to model the deep Earth dynamics and observe these dynamics with satellite data? If density and especially viscosity models can be constrained, then the dynamics will naturally follow. However, we anticipate resolution/meshing/interface complications, and incorporating high resolution data into a stokes solver is expensive. New methods need to be developed for whole Earth mantle convection models that incorporate similar resolution scales as the structure model. Such methods will be useful to many researchers linking interior structure to dynamics.

Discussion

A full geodynamical model to compare with seismology models is much needed to reduce the ambiguity of the interpretations, and to allow geophysical observations to be used as constraints more effectively. For example, Bull et al. 2009 proposed to run 3D geodynamical models and 'translate' their output to shear wave dVs. These predicted dVs fields can be compared to observed tomography. Overall, there exist two different types of geodynamic models: prescribed models (with imposed plate motions) and time-dependent fully dynamic models (with challenges to represent the lithosphere and its deformation). For both types, scales are the biggest problem for capturing the effects of both petrology and strain-localization in geodynamical models. Not only spatial scales but also time scales might be a problem. The multi-scale problem might be tackled for example in ASPECT, which uses adaptive mesh refinement to assign high resolution only where it is needed. Here, viscosity contrasts could be used as a condition for mesh refinement. Mantle convection models could be compared to deep mantle seismic anisotropy data, which is obtained from splitting and reflection modelling of deeply-travelling body waves, to constrain lowermost mantle flow.



GOCE, *helps create new model of crust and upper mantle.*



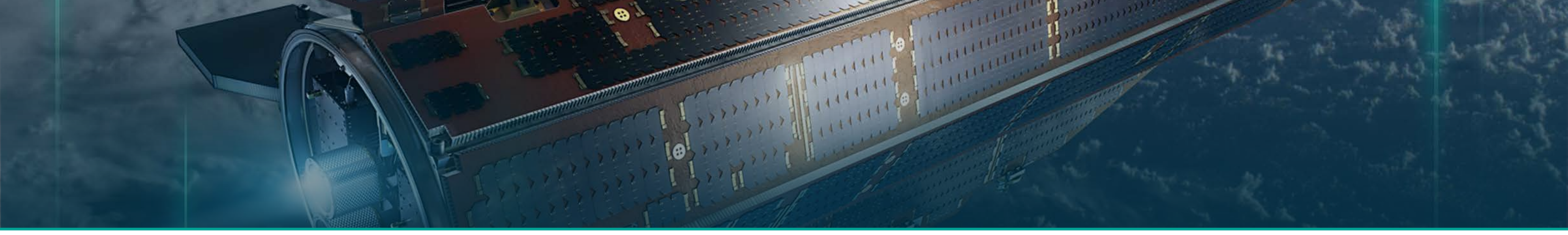
Dynamic Topography and Global Mantle Flow

Dynamic topography constrains Earth's interior dynamics but is difficult to both observe and interpret. Observations (±0.5 km) and modelling results (2-3 km) for global large-scale dynamic topography still mismatch (Steinberger et al. 2019). Other surface observations (e.g., plate tectonic motions and seismic anisotropy patterns) relate to global convection and suggest an organizing influence of Large Low Seismic-Velocity Provinces (LLSVPs) on global mantle flow patterns (Conrad et al. 2013). Deeper down, dynamic topography on the CMB should also reflect mantle flow patterns over long-wavelengths. Short-wavelength deflections of the CMB may occur beneath plumes rising from the LLSVP edges, and may help to constrain their viscosity (Heyn et al., 2020). Subduction zones must be considered as they provide a useful constraint on the global mantle flow pattern and seem to be significant in the geological past. For example, polar subduction (Shephard et al. 2016) exerts an important impact on the Earth's moment of inertia tensor, which affects true polar wander and the planet's rotational stability (e.g., Steinberger and Torsvik, 2008). A need to reconcile and address these observations with current time-dependent models of mantle convection is crucial to fully understand the Earth as a whole.

Discussion

Constraints on the rate of change of dynamic topography present a very interesting opportunity for geodetic satellite data, but such observations are very challenging. Land motion and polar motion due to mantle convection are more readily constrained in the paleorecord because small changes are sustained over long time periods. With these constraints, viscosity can be better constrained. Could lateral variations in the lower mantle viscosity structure help to explain the observed dynamic topography? Could a change in viscosity in space and time can help to resolve some of the discrepancy between dynamic topography observations, or would such uncertainty create more problems? For the upper mantle we are used to thinking of significantly lower viscosity in hotter regions, and temporarily low viscosity in areas of high stress. Do we think that such changes are significant in the lower mantle as well? Can studying intrinsic dissipation help us to link the different time scales to each other?

GOCE, *in orbit.*



Gravity Rate of Change

Temporal changes in gravity, which can be measured using satellite gravity, may provide a new observation of mantle convection. The planned ESA/NASA joint MAGIC gravity mission is designed to be able to measure such small gravity changes. Detection of a small global secular gravity signal could place constraints on the viscosity structure of the complete Earth. Furthermore, these models would be able to predict actual dynamic topography and its time-dependence, which could be used to correct GIA, sea level, and climate models.

Discussion

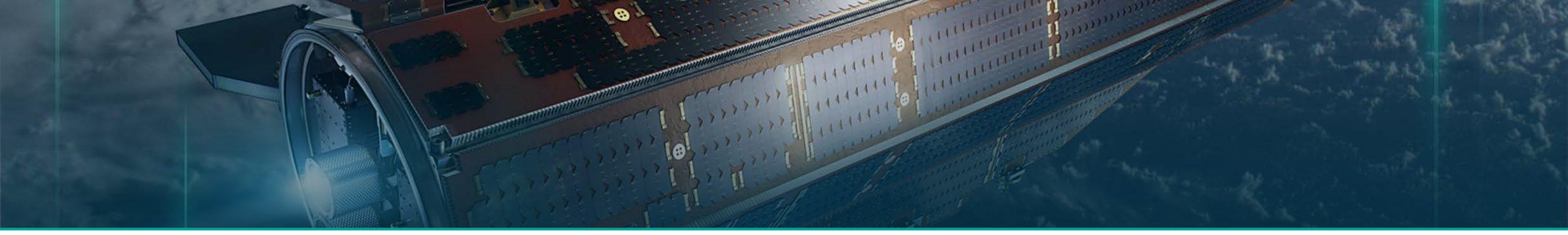
What is the uncertainty in the predictions of time-dependent changes in the geoid? If you could observe long-wavelength sustained changes in the geoid with GRACE/GRACE-FO or a future mission, which parameters would you be able to constrain? Mantle flow is predicted to produce only small (how small?) changes in gravity, dynamic topography, and the geoid, but observation such changes is made easier because these changes occur coherently across long wavelengths and should be sustained over time, unlike other contributions to the satellite gravity signal. The biggest challenge here, which needs sufficient sensitivity analysis, is to disentangle the gravity-rate signal due to mantle flow from other mass transport processes.

Petrological Models

Different petrological models will have significant consequences for stratification and dynamics. For example, at elevated temperatures, the growth of garnet may lead to negative thermal expansion in the Mantle Transition Zone (MTZ) and enhanced thermal expansion in the uppermost Lower Mantle especially for garnet-rich compositions. Phase changes are associated with non-linear density differences that would correspond to very large temperature differences in non-petrological or linearized models. The MTZ negative thermal expansion for high temperatures is associated with the growth of garnet. The observed Upper Lower Mantle (ULM) boundary thermal expansion is also associated with the growth of garnet. Furthermore, the ULM shows a reversed density relationship between depleted and enriched compositions as more garnet reduces the density. The ULM could be a trap for both depleted and enriched compositions, which accumulate at the bottom and top of the garnet-stability window, respectively. Not taking these mineral phase changes into account could result in erroneous dynamical modelling.

Discussion

The observed amplitude of (degree 2) dynamic topography is significantly smaller (factor of 2) compared to model predictions. Could this be a petrological issue? How good are the petrological models for the deeper mantle? Overall, there is much uncertainty in the petrological databases of the lower mantle, and trade-offs between composition, temperature, and other factors can complicate interpretations of the seismological constraints.

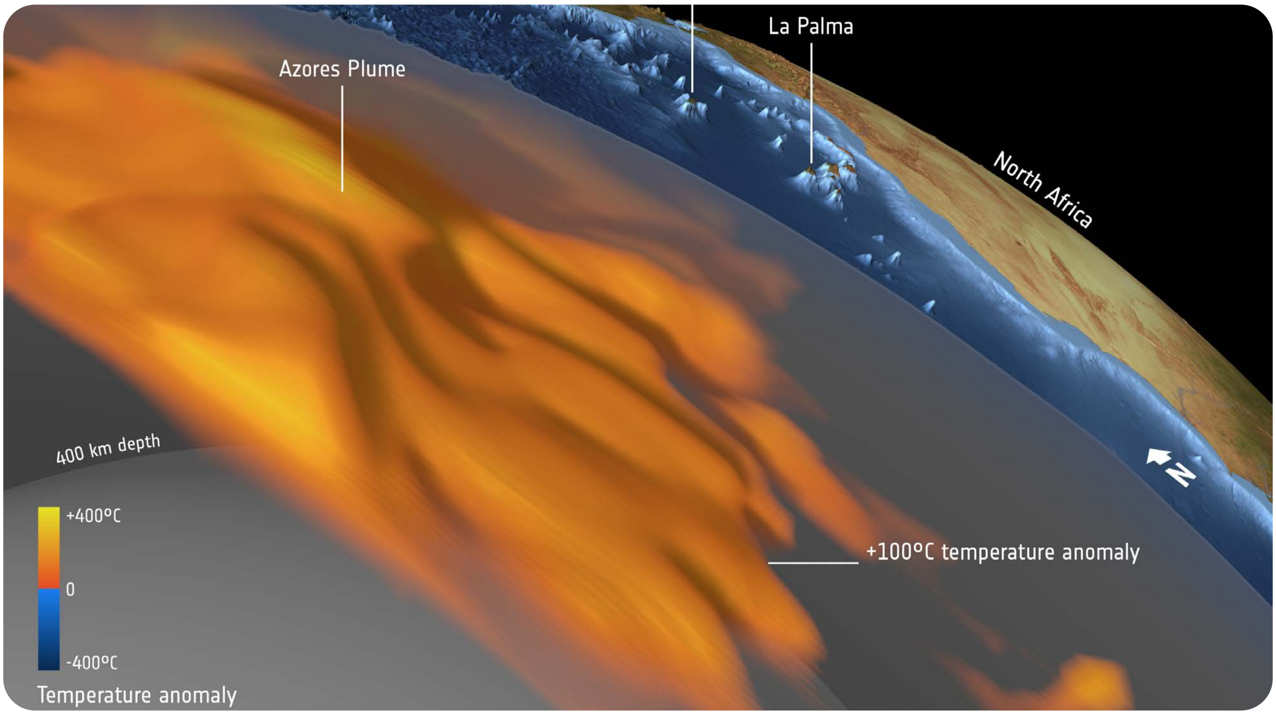


Discussed applications of a 4D3 Earth model: GIA

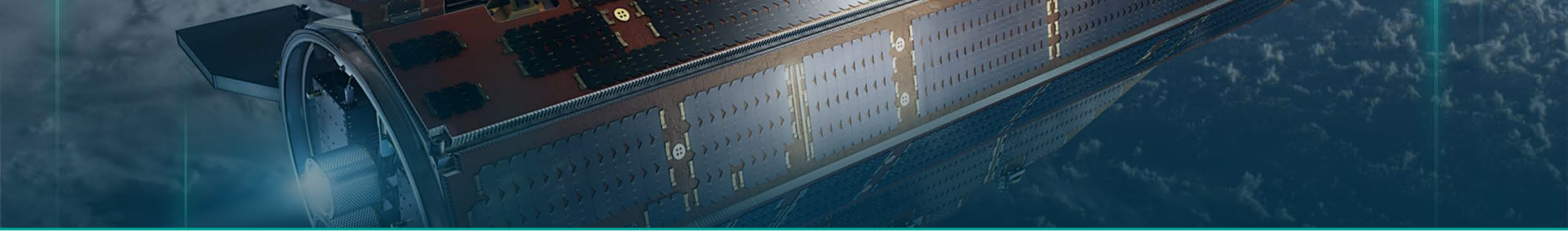
The key component in GIA-related studies is the mantle's viscosity structure. Most current studies use a simple layered viscosity structure, or apply a single conversion factor to translate seismic velocity models into viscosity. A fully consistent whole Earth model would improve our estimates of viscosity, and thus would help to constrain GIA and sea-level change, as well as climate studies. Through GIA, the solid Earth contributes significantly to the total signal for estimates of sea-level change, ice melt, and geoid change. Thus, the GIA community needs independent estimates of 3D mantle viscosity that would facilitate improvements to GIA models. Such improvements would also allow us to use geological observations to improve reconstructions of past ice sheet evolution. Furthermore, better models of time-dependent dynamic topography would help use to understand past sea level better. Such models would also help us to use earth rotation to improve estimates of lower mantle viscosity, which is poorly constrained and also important for research on GIA, sea-level, and climate (Coulson et al. 2021).

Discussion

Tomography is usually converted to viscosity in a very simple way. Thus, GIA studies will benefit tremendously from whole Earth models that place better constraints on viscosity. Improved constraints on spatially-varying viscosity are made possible by more fully constraining the structural heterogeneity in the mantle but also improving the conversion into viscosity heterogeneity. These improved viscosity constraints will improve estimates of the GIA contributions to the sea level change, and there are important links to climate research. Improved viscosity constraints can already be achieved with WINTERC-G and should be assessed in future phase1 studies.



Hot and cold beneath Tonga volcano.



Discussed applications of a 4D3 Earth model: Surface Deformation

Satellite observations (GNSS and InSAR) of surface deformation can map ground movement from space over very large areas. The resulting strain rate maps correlate with seismic hazard maps and could potentially map new hazardous terrain.
A better knowledge of deep earth dynamics will help us to better understand these strain rate maps because surface deformations ultimately result from the dynamics of the deep earth.

Thus, large scale surface deformation fields can also be a useful data set for linking the surface and deep earth (Zheng et al. 2017). For example, stress changes from very large earthquakes place an important constraint on upper mantle rheology (Weiss et al. 2020).

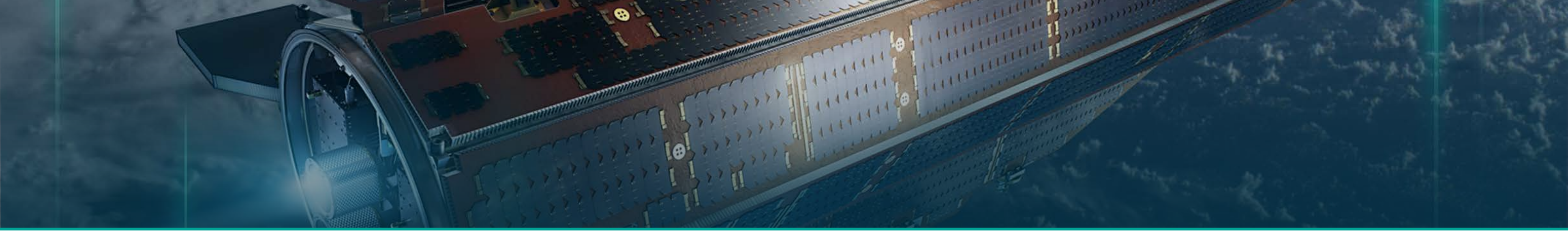
Discussion

One of the big questions is what can be done concerning geohazards with this model. For example, the Canary Islands seem to be located on top of a huge high temperature mantle structure that could explain the current volcanic activity in La Palma. Better characterisation of such structures could help to assess the geohazard risk maps. Deformation studies of the tectonic plates can benefit from improved geodynamic models because they facilitate a better understanding of the underlying forces that control (volcanic and seismic) surface processes.
This could help to constrain the risk assessment in certain areas, but such models also can also help to determine certain viscosity constraints.
This is important because we have few other constraints on viscosity, and yet it controls many important mantle processes.

Core and Magnetic Field

We can improve our understanding of the Earth's mantle by observing its interactions with, and its effect on, the magnetic field. From Deep Core studies we have learned that interannual field changes associated with one interannual QG MC mode, of period ≈ 7 years (Gillet et al, PNAS, in revision), can be modeled. This paves the way to a deterministic interpretation of magnetic changes and towards prediction of the shorter-term field evolution.

Torsional waves are sensitive to the deep mantle electrical conductivity. Relationships exist between the velocity flow and magnetic fields in the core interior and at the core surface, as dictated by the mantle electrical conductivity and as measured by the dimensionless number Q. Core surface velocities and magnetic fields are consistent with a scenario where most of the lowermost mantle is poorly conducting (1-10 S/m). The assumption of a weakly conducting mantle is commonly used to model of the core magnetic field. However, such low conductivity values are difficult to reconcile with Earth rotation changes (electromagnetic coupling core-mantle): we need to explore the alternative hypothesis. Furthermore, magnetospheric field modelling suggests a thin high conductivity at the CMB; this could be related to mineralogical changes and chemical composition. The thickness and lateral extent of such a conducting layer, and its possible relationship to the seismologically-determined Ultra Low Velocity Zones (ULVZs), remains unconstrained.



Feedback between core magnetic and lower mantle magnetic and seismic modelling plus mineral physics is needed. Lateral variations of the electrical conductivity of the lowermost mantle, based on properties of the magneto-Coriolis modes that have just been detected, limit the study to small azimuthal numbers as a result of the dispersion relation for these modes. Upward continuation of the magnetic secular variations from the CMB to the surface, and testing 3D lower and upper mantle conductivities, should provide useful comparisons with surface/satellite observations.

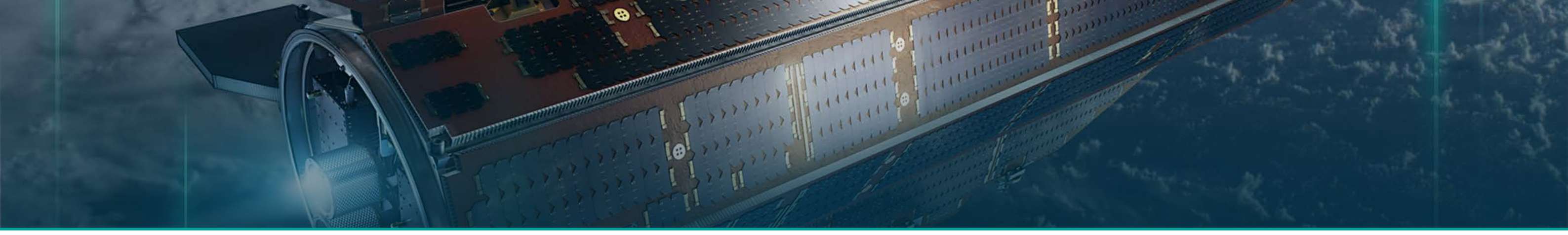
WINTERC-e is an upper mantle electrical conductivity model based on WINTERC-G (surface wave tomography + satellite gravity + SHF and isostasy) and laboratory studies on the conductivity of upper mantle minerals. In spite of being totally independent from magnetic data, WINTERC-e matches well with the first order tidal magnetic field M2 as measured by Swarm. Upper mantle electrical conductivity is related to the presence of water and melt. Therefore, it is in principle possible to add magnetic information constraining melt and water content into seismic and gravity data derived from upper mantle models such as WINTERC-G. To improve these studies, errors for the Swarm tidal magnetic fields need to be estimated.

Modelling the effects of the magnetic field of field aligned currents (FACs) and polar electrojets (PEs) could help increase sensitivity when estimating tidal magnetic fields from Swarm observations. The next step after the 3DEARTH project is to include results of the invertion of Swarm tidal magnetic field observations for the 3D upper mantle conductivity distribution including volatiles. We can thus extend the WINTERC-e electrical conductivity model deeper into the lower mantle (below 400 km) using the estimated magnetic fields of Sq magnetic variations and magnetic storms.

Synthetic tests of these inversions demonstrate that the general methodology is sound (Martinec et al. 2021). Currently, there is a discrepancy between different models of tidal signatures that are of the same order as the effect of 3-D conductivity variations. New ways of utilizing satellite data processing (cleaning of external fields, virtual observatories) and tidal model error bars including N2 and O1 tides (some preliminary results obtained) will help the inversion. A full joint inversion is currently out of computational reach, but a back-propagation to WINTERC-G with an iterative scheme by means of a-priori models and local modifications of water/partial melt content maybe possible in the future.

Discussion

3D conductivity inversion from satellite signals is still too difficult, especially for the deep mantle and 3D conductivity is also very small. A better approach would be to perform forward modelling studies to assess the sensitivity of the signal. For the 4D Earth: Core study shows that the magnetic signal is most sensitive at the equator, which could help to characterize LLSVPs. It is still unclear what the sensitivity to latitudinal-propagation is. How does the magnetic field change when the boundary conditions change, such as the conductivity or geometry of the CMB? Asymmetry of the magnetic field can be interpreted in many different ways, and boundary conditions could be one of them. Impacts of lateral variation in heat flux on the dynamo and the magnetic field have been found, and could be important for understanding dynamo history over time, and its link to the time-dependence of mantle dynamics (e.g., placement of slabs and LLSVPs on the CMB). The boundary layer just below the CMB smoothens the signals. This is debated, but we have to follow this statement also with electrical conductivity, resulting in less sensitivity for lateral structures.



3. IDENTIFICATION OF THE OPEN ISSUES FOR THE DEEP MANTLE

From the summary of the Science meeting the following points were identified for the direction of a new ESA project. These are cross-disciplinary and will require a consolidated effort across different disciplines to be addressed.

1. Most of Earth's upper mantle structure has already been well characterized by the 3D Earth project. However, both the lower mantle and upper mantle contribute to the gravity field at longer wavelengths, and separating the contributions of each requires a better understanding of lower mantle structure and dynamics and consequently a possible iteration of the upper mantle model.

2. Can we use fundamental and higher mode surface waves to constrain the large-scale and fine-scale structure of the lithosphere, asthenosphere, mantle transition zone and shallow lower mantle.

3. Integrated petrological forward and inverse modelling can be an effective means of quantitatively combining the satellite data with the different types of seismic data.

4. Can we characterize Earth's mantle structures, based on satellite gravity and seismology data, consistently with Earth's energy/heat budget?

5. Can we improve the characterization of the LLSVP and CMB structures, noting the placement of paleo-slabs in the lowermost mantle, using different datasets (gravity and various seismic constraints)?
   - Normal modes (and perhaps body wave sampling of the CMB) can give us the large-scale structure of the deep lower mantle and the core.
   - Large static field observation with new techniques: Splitting/reflection techniques can provide constraints on anisotropy (important for understanding mantle flow patterns).
   - Are the African/Pacific LLSVPs the same in terms of their composition and dynamics, and can differences be observed by seismology and/or gravity?

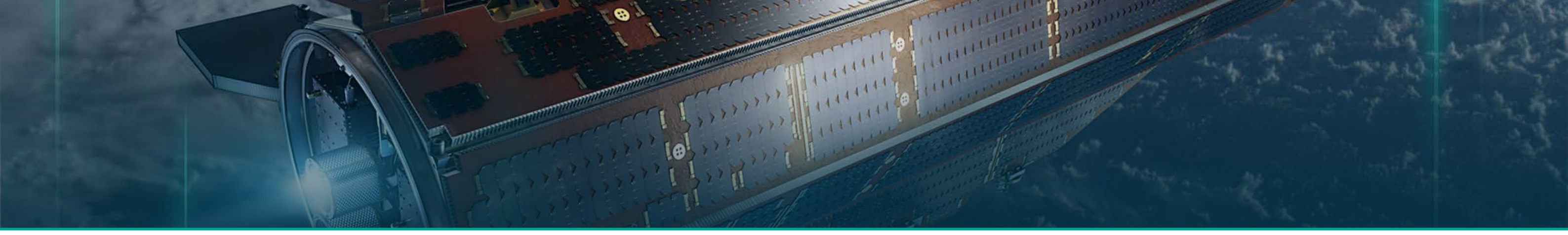
6. How are observations of the present-day Earth useful for understanding 4D Deep Earth processes? How are 4D Deep Earth processes manifested at Earth's surface?

7. Can we consistently link dynamic topography models (which include whole mantle density and viscosity) with residual topography estimates (inferred from lithospheric structure based on satellite and terrestrial data, e.g. 3D EARTH)?

8. Subduction-driven flow: Subduction must be included in the Earth's reference frame in 4D.

9. Can we constrain the lower mantle electrical conductivity distribution by combining satellite magnetic and gravity data with global seismology plus mineral/high pressure physics? (feedback to/from core studies).

10. 3D Viscosity characterization, which would be a major output of a 4D dynamic Earth study, is critically important for global GIA studies. Viscosity is difficult to constrain, and yet it is critical for a 3D geodynamic model. Thus, improving viscosity constraints is one of the major key issues to address.



4. FUTURE DIRECTION: MODELLING THE 4D DEEP DYNAMIC EARTH

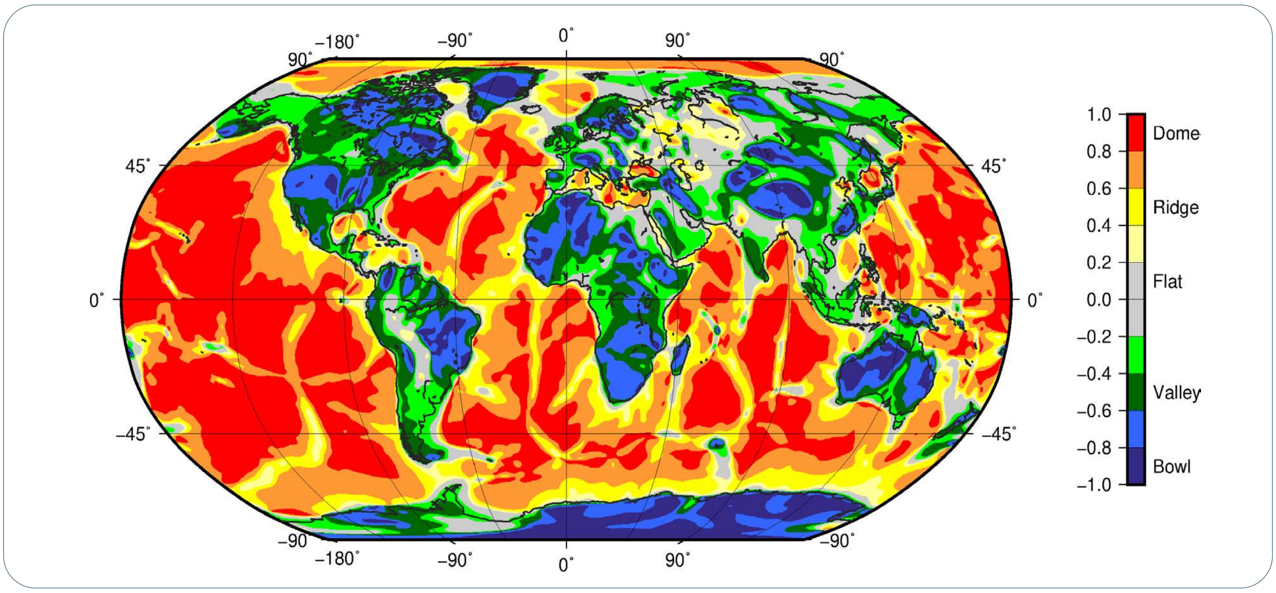
A new initiative should be split into two phases. I) A first explorative phase focused on the assessment of the sensitivity of the different datasets: surface wave seismology, normal modes, satellite gravity, and satellite magnetic field observations for probing the solid Earth; ii) A second phase focused on generating a complete and consistent mantle model, in parallel with the geodynamic model, CMB bottom-up probing, and surface processes studies. A feedback loop is advised between the three application studies and the overall structure study. These studies can run in parallel but need to have close cooperation and timely interactions similar to 3DEarth project.

• First phase: Sensitivity studies and development of joint approaches

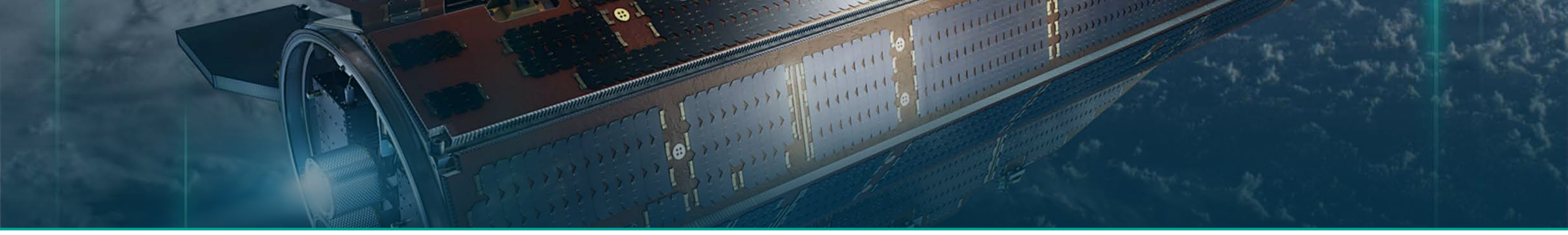
The first phase needs to contain sensitivity analyses of the different datasets and modelling approaches. With the new WINTERC-G model, uncertainty from the upper mantle is greatly reduced and could help with the interpretation of signals originating from the deeper mantle. From the 4D Science meeting it was clear that a substantial multi-disciplinary project is preferable with several preliminary sensitivity studies needed.

Proposed sensitivity studies:

1. Seismic data sensitivity for transition zone and lower mantle structures (data sensitivity)
2. Gravity rate-of-change observations from satellites to observe mantle flow (Viscosity sensitivity). State-of-the-art (e.g. GRACE/GRACE-FO) missions for real data analysis and performance estimates for future missions (e.g. MAGIC) should be included in the sensitivity analysis.
3. Electrical conductivity of large bodies on the CMB (magnetic data sensitivity)
4. Impact of the improved upper mantle constraints by WINTERC-G in deep mantle flow models (See sensitivity studies done in 3DEarth on geometry changes of slabs).



GOCE'*s global tectonic map.*



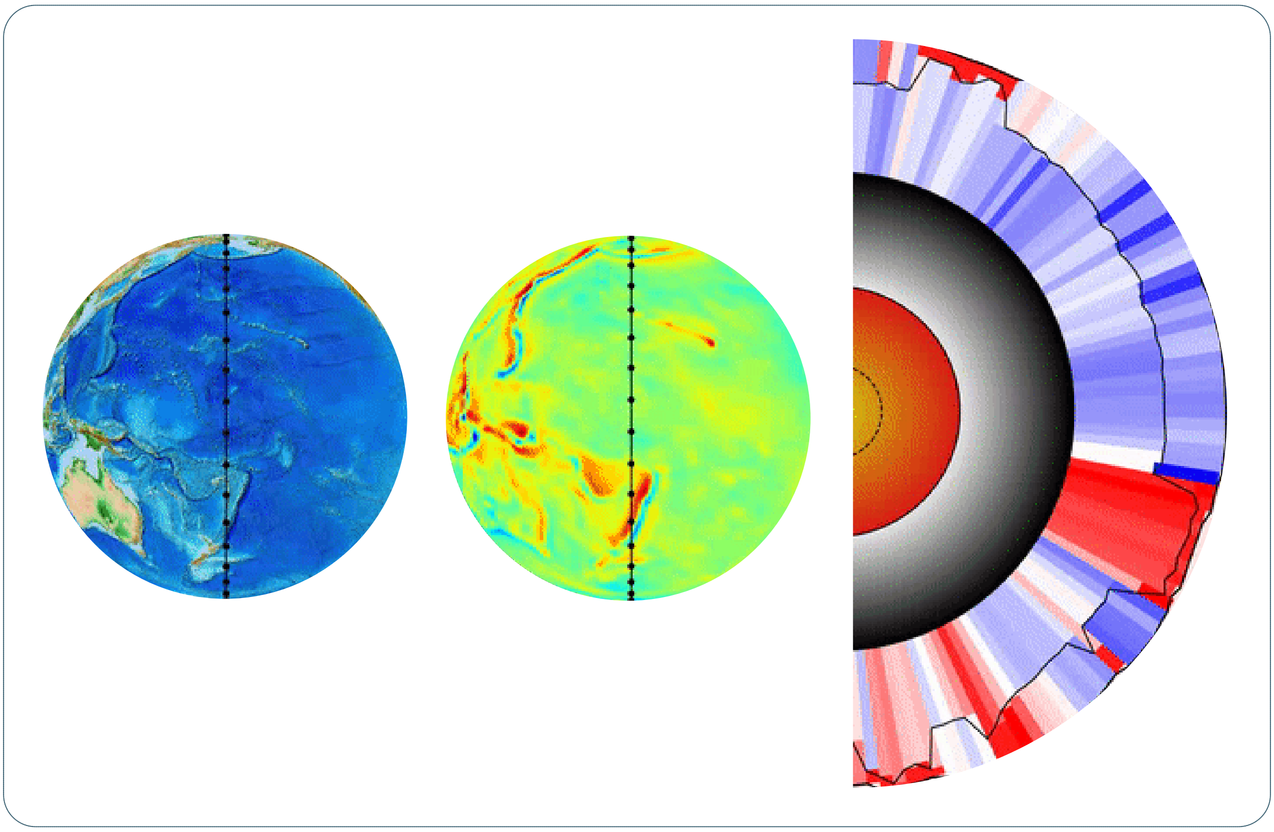
In particular:

1. A full sensitivity study needs to be performed to assess the best seismic data for the sub-WINTERC-G mantle (transition zone and lower mantle). What data is available and how sensitive is it for different regions of the mantle? Also, a large demand for uncertainty and accuracy of seismic models was noticed. This phase 1 study should clarify with data analysis and synthetic modelling the quality of the overall model and should specify how satellite data could be beneficial.

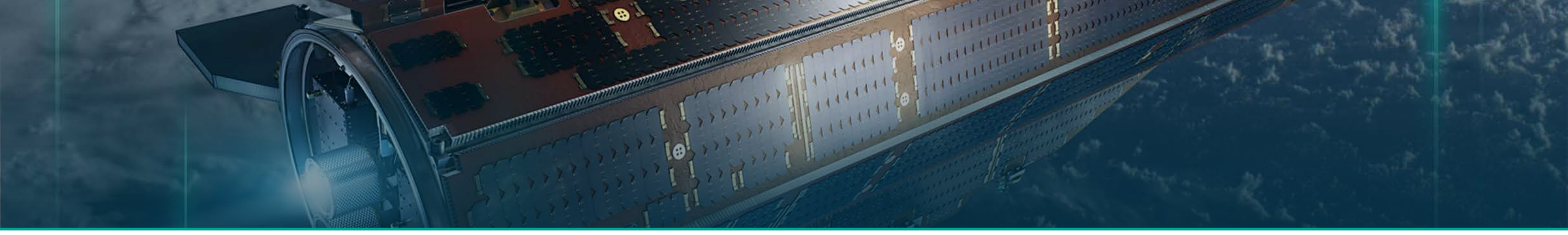
2. 3D viscosity is essential for a dynamical model of the Earth, but is still very difficult to model. Some indications were shown that the long timeseries of GRACE/GRACE-FO/MAGIC and next generation gravity missions could be able to detect the gravity change due to mantle flow. Global dynamic modelling should determine the sensitivities of viscosity and other characteristics in mantle convection modelling. Furthermore, it should assess data processing techniques to disentangle the mantle flow signal from any other mass transport determined from synthetic testing.

3. CMB structures could be conductive bodies that would have influences on the magnetic observations by Swarm. This would give extra constraints on the geometry and composition of these bodies. Sensitivity tests are needed to assess if this would be visible in long term magnetic observations.

4. WINTERC-G is currently constructed with an isostatic assumption that decouples it from the deep mantle. However, mantle convection stresses have been shown to have significant effect on the density structure of the lithosphere. Can these flow models improve the global density structure of WINTERC-G? A more refined proposal that specifies individual studies would be provided in future documents.



Density variations in the crust and upper mantle.



• Second phase: building a consistent 4D Earth model and study processes.

The second phase will need a more elaborate project group to construct the structural model and in parallel with several case studies, to show a pplicability, and to provide feedback to the structural model. The **structure** group consist of three groups:

1 One group focusses on the **LLSVP structure** and **composition** using:

- Novel body wave techniques
- Normal modes
- Gravity field
- Tidal tomography

2 Another group should concentrate on **extending** the 3D Earth model in a joint-inversion (similar to **WINTERC-G**) to larger depths using:

- Surface/body wave tomography (fundamental mode and overtones)
- Gravity field
- Magnetic field (tidal and magnetospheric currents)

3 A final group should develop fully consistent geodynamical models, focused on uncovering the viscosityanddynamicsignaturesofawholeEarthmodel. Will the modelled gravity changes be detectable with future-generation gravity missions? Furthermore, this group should compare the geodynamical model to global seismic anisotropy patterns in order to constrain mantle flow structures.

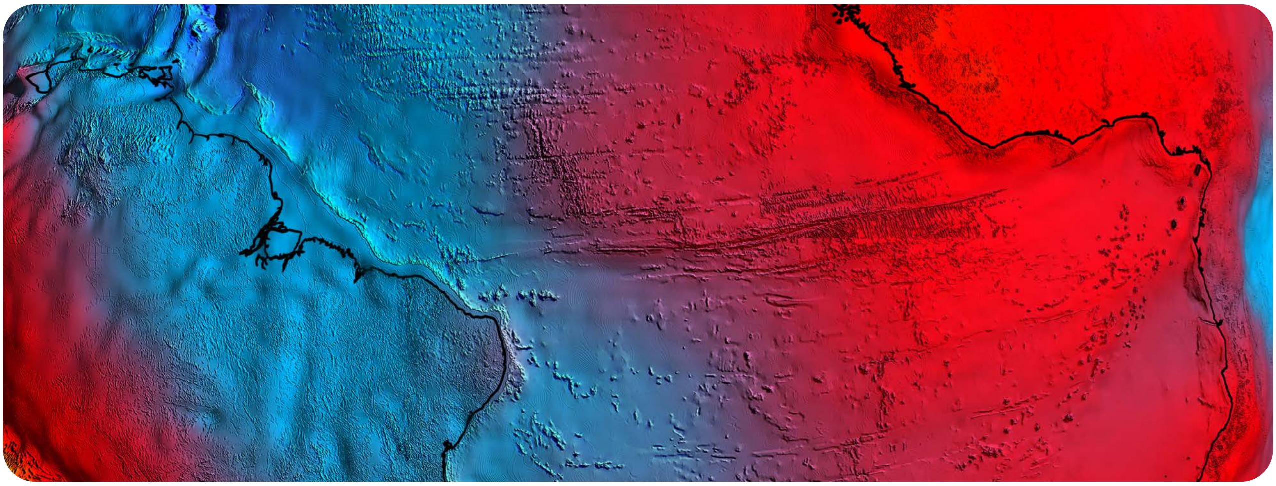
- Geoid, gravity field and (dynamic) topography
- Secular long wavelength gravity-change data
- Seismic tomography (extended WINTERC-G)
- Seismic anisotropy

In addition, **parallel** activities would be:

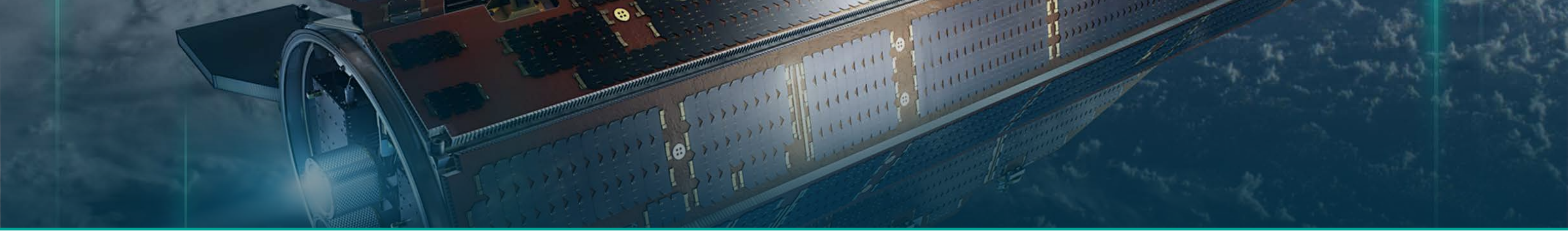
4 Magnetic **conductivity** probing from the bottom-up, and using structural data from the LLSVP group. Which magnetic signals could be related to LLSVPs or ULVZs? Are they detectable?

5 Improved understanding of **surface** processes, particularly relating to risk assessment (deformation, GIA, sea-level, relationship of seismicity to lithospheric structure)

The parallel studies will provide feedback on the applicability and accuracy of the intermediate and final structural model of 4D3 Earth.



Goce, *particular geod.*



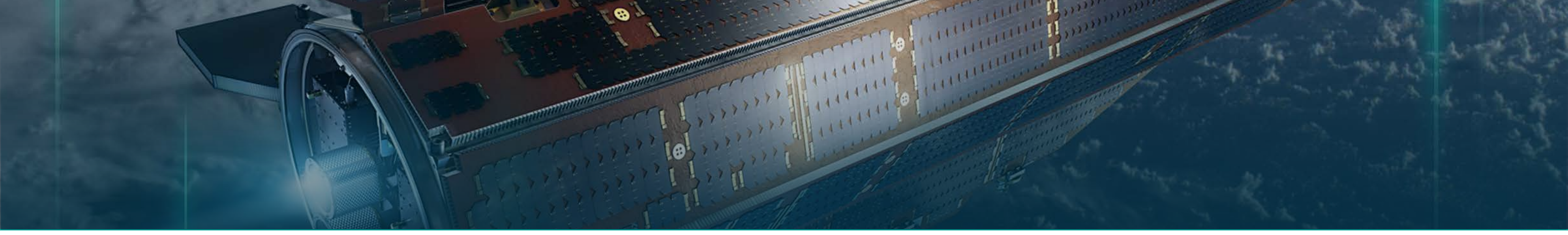
Outline of work

The project should focus on combining seismological data with satellite potential field data and polar motion, to reduce the uncertain parameter space among physical parameters.

- **Phase 1:** Setup a fully consistent data analyses and sensitivity study for the characterisation of LLSVPs.
- **Phase 1:** Test a range of fully-consistent petrological models to link seismic velocity anomalies and density/temperature/viscosity anomalies for Earth's present-day structure and within mantle convection models.
- **Phase 1:** Test whether lateral heterogeneity of electrical transmission properties within the lower mantle may affect observations of the geomagnetic field.
- **Phase 1&2:** Construct a whole-Earth multi-parameter model that simultaneously fits the satellite gravity data and seismic data (normal modes, surface waves, overtones, body waves). This model could be used as a starting point for regional case studies.
- **Phase 1&2:** Setup a mantle convection model that predicts mantle flow that is constrained by density models developed for the 3D Earth project and later will updated in the 4D3 Earth project. The predicted flow patterns can be examined in comparison to observations of anisotropy and CMB topography, and will help to probe for the influence of viscosity and its (lateral and potentially temporal) variations.
- **Phase 2:** Construct a CMB conductivity model to further study the LLSVP structures and their effect on the magnetic field, and possibly to use as an extra constraint on their size and compositional nature.
- **Phase 2:** Study the application of the 4D3 Earth model for surface processes.

Link to satellite missions

- **GOCE:** gravity potential field is used as a global constraint on mantle convection and present-day thermochemical imaging studies. The improved spectral resolution complements seismic tomography and mantle convection modelling.
- **Swarm:** magnetic field for core study. With forward modelling from the mantle and core communities, new sensitivity studies can be performed to study the effect of the CMB on the magnetic field and to gain knowledge on the sensitivity of the SWARM observations. Tidal magnetic field estimates help to constrain the upper mantle electrical conductivity structure.
- **GRACE/GRACE-FO/MAGIC:** Temporal gravity datasets becoming more substantial is beneficial for constraining secular change and improving its accuracy. These datasets can be used to measure ongoing mantle flow, which will help to constrain Earth's the 3D viscosity structure.
- **GNSS:** The GNSS network could be used to measure deformation associated with mantle convection. Plate motions should be used to force or constrain the 4D Earth model. In addition, a tidal deformation study can be used for benchmarking or deep probing.
- **SAR/inSAR:** InSAR data derived from radar satellites, including current and future ESA missions Sentinel-1, ROSE-L, Harmony, Sentinel-1NG, can be combined with results from GNSS to map surface deformation over large areas at high spatial resolution. This data type has opportunities for verification and validation studies.



Potential Outcomes

Improved understanding of the Deep Earth will help provide better understanding of different processes both linked to the core, and also to the mantle. From this project, the following outcomes are expected, in terms of products, applications, and areas that will benefit from this project.

Products:

- Fully consistent global 3D model of the entire Earth, linked to observed dynamic processes.
- 3D viscosity model of the Earth, supporting GIA and other deformation studies.
- First order model of CMB characteristics that fit seismology, gravity, and core flow studies.

Applications:

- Quantify the impact of satellite data to studies of the Earth evolution in space and time.
- Improved climate models due to better characterization of the solid Earth and improved risk assessment maps (earthquake hazard, flooding, ice sheet collapse) due to better characterization of Earth's viscosity structure and dynamics.
- Improved understanding of patterns of volcano/plume eruptions due to better structural models of Earth's deep interior, and associated constraints on patterns of mantle flow.
- Deformation associated with plate motions and subduction zones arises from the 4D dynamic Earth. Understanding the dynamics of the deep Earth will help us to characterize these dynamics.
- Sea level change includes a component of solid earth dynamics, linked to tectonics and also to GIA.
  To separate these tectonic effects from those associated with climate, we need a better solid earth characterization.

Areas of benefit

- Improved knowledge of the interaction of a more realistic 3D lithosphere with mantle convection, or in other words the link between mantle dynamics and plate tectonics.
- Range of compositional candidates for the thermochemical piles (LLSVPs) on the CMB.
- Uncertainty estimates for CMB topography would be reduced.
- A full earth model can be used to discuss the stability of the LLSVPs, a critical element in understanding the onset of plate tectonics and hotspot volcanism.
- Possible constraints on the interaction of the LLSVPs with the CMB, which could have impacts on reversals of the magnetic field.

These points benefit our knowledge about the processes and structures of the global Earth in its current state and its past forms. The project is well linked to the Solid Earth Challenges defined by ESA:

Challenge G1: Physical processes associated with volcanoes, earthquakes, tsunamis and landslides in order to better assess the natural hazards.

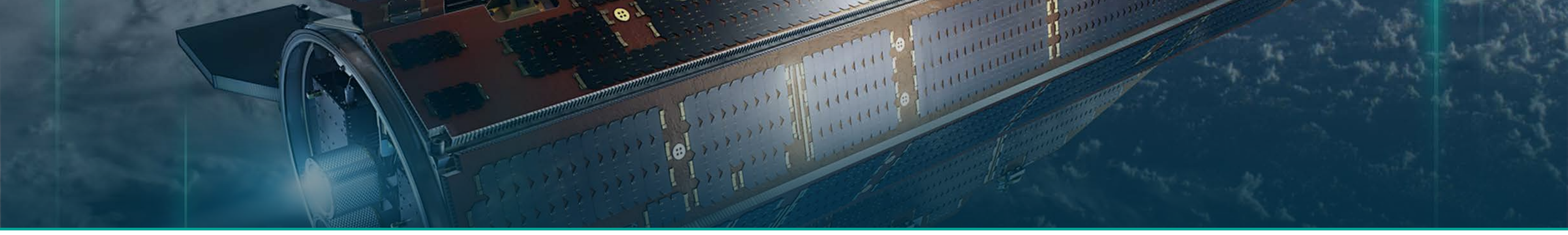
Challenge G2: Individual sources of mass transport in the Earth system at various spatiotemporal scales.

Challenge G3: Physical properties of the Earth crust and its relation to natural resources.

Challenge G4: Physical properties of the deep interior, and their relationship with natural resources.

Challenge G5: Different components of the Earth magnetic field and their relation to the dynamics of charged particles in the outer atmosphere and ionosphere for Space Weather research.

The proposed project 4D3 Earth contributes directly to G1, G2, and G5. In the applications we also see that the project is useful for understanding deep interior and surface processes related to climate (sea-level, ice sheet change, flooding) and hazard detection (hot spot volcanism, earthquakes, surface deformation), which are related to G3 and G4.



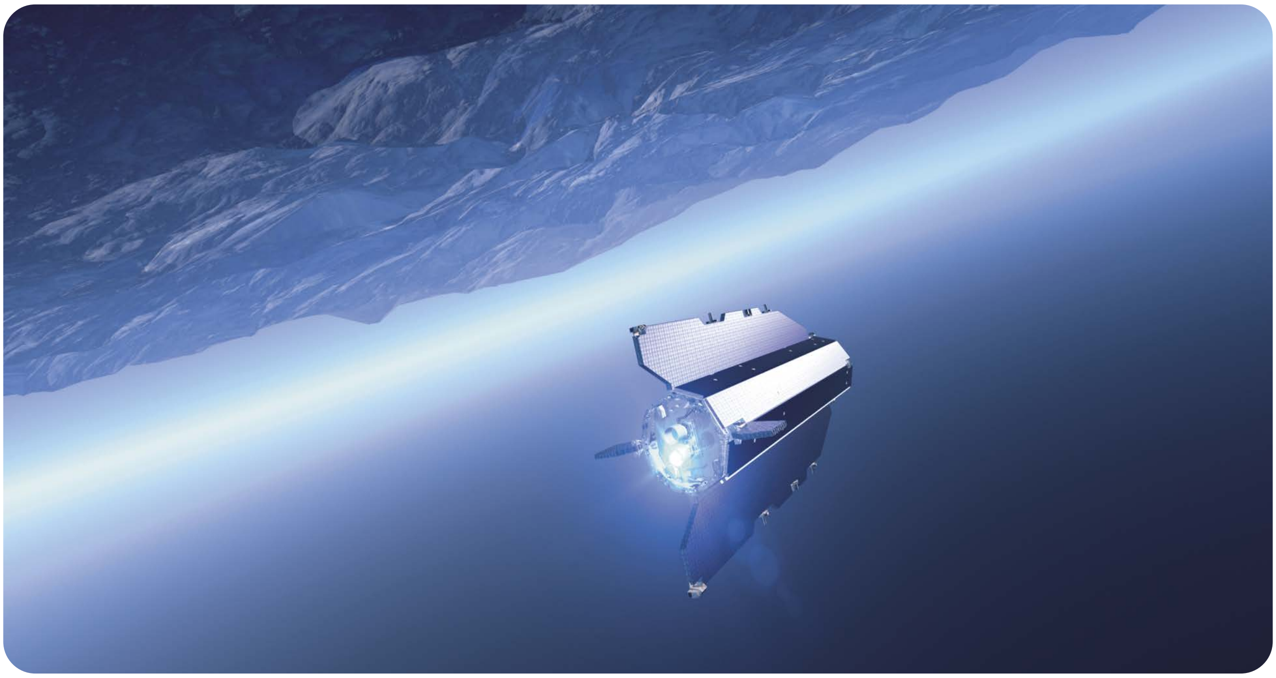
Outreach perspective

A dedicated "4D Deep Earth – Interactions of core and mantle" study needs to be linked with other activities organized by ESA, such as STSE 3D Earth and activities within the Polar Cluster. The links to 3D Earth are clear, as a 4D deep Earth initiative would extend the 3D Earth activities deeper into the mantle, and farther backward in time. Projects such as 4D Antarctica are important because they utilize some of the same satellite-data sources (e.g., gravity gradients), and therefore some of the same data (long wavelength gravity anomalies) and data-processing techniques.

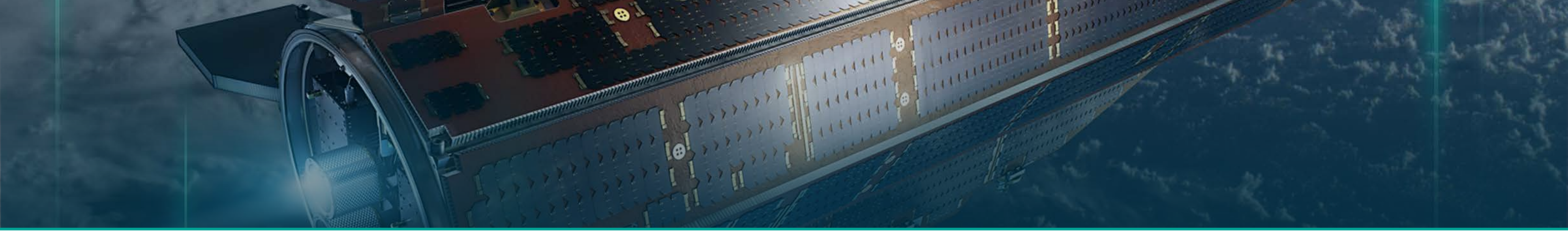
ESA must ensure the exchange of results between planned and ongoing projects, and all results must be validated and evaluated by such related processes. Additionally, sharing and benchmarking of codes for processing and modelling (e.g., gravity calculation tool to test parameters as planned in 3DEarth) should be facilitated. Also, workshops that foster collaborative interactions between and within the mantle geodynamics and core dynamics communities should be arranged, as well as possible dedicated summer schools and MOOCs designed to help educate the next generation of scientists.

State of Readiness

Theory and models on deep mantle structure and dynamics are in a high state of maturity. Both global mantle convection and seismic tomography modelling are capable of handling a huge amount of data. 3D global synthesis and analysis modelling techniques are available for gravity field and magnetic field modelling. The 4D3 Earth project is constructing a next generation global model of the whole mantle that can be used as starting point for regional studies.



GOCE, *in orbit.*



5. REFERENCES

- Bull, A. L., A. K. McNamara, and J. Ritsema (2009), *Synthetic tomography of plume clusters and thermochemical piles, Earth and Planetary Science Letters*, 278(3), 152-162, doi:https://doi.org/10.1016/j.epsl.2008.11.018.
- Celli, N.L., S. Lebedev, A.J. Schaeffer, and C. Gaina (2021), *The tilted Iceland Plume and its effect on the North Atlantic evolution and magmatism, Earth and Planetary Science Letters*, 569, 117048
- Conrad, C. P., B. Steinberger, and T. H. Torsvik (2013), *Stability of active mantle upwelling revealed by net characteristics of plate tectonics, Nature*, 498(7455), 479-482, doi:10.1038/nature 12203
- Coulson, S., Lubeck, M., Mitrovica, J. X., Powell, E., Davis, J. L., & Hoggard, M. J. (2021). *The Global Fingerprint of Modern Ice-Mass Loss on 3-D Crustal Motion. Geophysical Research Letters*, 48(16), e2021GL095477.
- Deuss, A., Ritsema, J., and H. J. van Heijst (2013). *A new catalogue of normal-mode splitting function measurements up to 10 mHz, Geophysical Journal International*, 193 (2), p.920-937
- Flament, N., M. Gurnis, and R. D. Müller (2013), *A review of observations and models of dynamic topography, Lithosphere*, 5(2), 189-210, doi:10.1130/l245.1.
- Fullea J., Lebedev S., Martinec Z., Celli N.L., 2021. *WINTERC-G: mapping the upper mantle thermochemical heterogeneity from coupled geophysical-petrological inversion of seismic waveforms, heat flow, surface elevation and gravity satellite data, Geophys.* J. Int., 226, 146–191., doi:10.1093/gji/ggab094.
- Heyn, B. H., C. P. Conrad, and R. G. Trønnes (2020), *Core-mantle boundary topography and its relation to the viscosity structure of the lowermost mantle, Earth and Planetary Science Letters*, 543, 116358, https://doi.org/10.1016/j.epsl.2020.116358.
- Lau, H.C.P. & Faul, U., 2019, *"Anelasticity from Seismic to Tidal Timescales: Theory and Observations", Earth and Planetary Science Letters*, 508: 18-29.
- Lau, H., Mitrovica, J., Davis, J. et al. *Tidal tomography constrains Earth's deep-mantle buoyancy.* Nature551, 321–326 (2017). https://doi.org/10.1038/nature24452
- Xueqing Li, Xiaohui Yuan, Rainer Kind, *The lithosphere-asthenosphere boundary beneath the western United States, Geophysical Journal International, Volume 170*, Issue 2, August 2007, Pages 700–710.
- MANDEA, M., C. Narteau, I. Panet, and J.-L. Le Mouël, *Gravimetric and magnetic anomalies produced by dissolution-crystallization at the core-mantle boundary, J. Geophys. Res. Solid Earth*, 120, doi:10.1002/2015JB012048, 2015.
- Martinec, Zdeněk, Javier Fullea, Jakub Velímský, Libor Šachl, *A new integrated geophysical-petrological global 3-D model of upper-mantle electrical conductivity validated by the Swarm M2 tidal magnetic field, Geophysical Journal International, Volume 226, Issue 2*, August 2021, Pages 742–763,
- Panet, I., Bonvalot, S., Narteau, C. et al. *Migrating pattern of deformation prior to the Tohoku-Oki earthquake revealed by GRACE data.* Nature Geosci 11, 367–373 (2018a).
- Panet, I. (2018b). *An analysis of gravitational gradients in rotated frames and their relation to oriented mass sources. Journal of Geophysical Research: Solid Earth*, 123, 11,062–11,090.
- Panet, I. (2018). *An analysis of gravitational gradients in rotated frames and their relation to oriented mass sources. Journal of Geophysical Research*: Solid Earth, 123, 11,062–11,090.
- Panet, I., Pajot-Métivier, G., Greff-Lefftz, M. et al. *Mapping the mass distribution of Earth's mantle using satellite-derived gravity gradients.* Nature Geosci 7, 131–135 (2014).
- Root, B.C., Javier Fullea, and Zdenek Martinec (in prep.) Global lithosphere modelling and the deep mantle interaction, Technical report, ESA's Support to Science 3D Earth project.
- Root, B.C. (2020), *Comparing global tomography-derived and gravity-based upper mantle density models, Geophysical Journal International*, 221, 1542-1554.
- Root, B.C., Ebbing, J., van der Wal, W., England, R., and Vermeersen, L.L.A. (2017), *Comparing gravity-based to seismic-derived lithosphere densities: a case study of the British Isles and surrounding areas, Geophysical Journal International*, 208, 1796-1810.
- Shephard, G. E., R. G. Trønnes, W. Spakman, I. Panet, and C. Gaina (2016), *Evidence for slab material under Greenland and links to Cretaceous High Arctic magmatism, Geophysical Research Letters*, 43(8), 3717-3726, doi:doi:10.1002/2016GL068424.
- Steinberger, B., C. P. Conrad, A. Osei Tutu, and M. J. Hoggard (2019), *On the amplitude of dynamic topography at spherical harmonic degree two, Tectonophysics*, 760, 221-228.
- Steinberger, B., and T. H. Torsvik (2008), *Absolute plate motions and true polar wander in the absence of hotspot tracks, Nature*, 452(7187), 620-623, doi:10.1038/nature06824.
- Weiss, J. R., Walters, R. J., Morishita, Y., Wright, T. J., Lazecky, M., & Wang, H., et al. (2020). *High-resolution surface velocities and strain for Anatolia from Sentinel-1 InSAR and GNSS data. Geophysical Research Letters*, 47, e2020GL087376.
- Zheng, G., Wang, H., Wright, T. J., Lou, Y., Zhang, R., Zhang, W., ... Wei, N. (2017). *Crustal deformation in the India-Eurasia collision zone from 25 years of GPS measurements. Journal of Geophysical Research*: Solid Earth, 122, 9290– 9312.