Workshop di consultazione della comunità scientifico/applicativa sulla missione ESA NGGM/MAGIC

Hazard reduction potential of an innovative gravity mission

C. Braitenberg, A. Pastorutti, T. Pivetta,
F. Brandolin, M. T. Javed,
Università di Trieste

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Descrizione del team coinvolto nell'attività

- Team:
- Carla Braitenberg: Prof. Associato Universita' di Trieste. Ricerche e insegnamento in ambito Campi Potenziali Gravita' e Magnetico. Monitoraggio Geodetico, Telerilevamento. Ampia esperienza nel processing e modellazione del campo di gravita' statico e dinamico. Scala da locale a globale.
- Tommaso Pivetta: Assegnista di Ricerca in progetto MOCAST+. Gia' assegnista di ricerca in progetto MOCASS. Ampia esperienze in modellazione campo gravita', modellazione idrosfera e glaciosfera. Campo di gravita' variabile nel tempo e modellazione idrologica.
- Alberto Pastorutti: Assegnista di ricerca in progetto MOCAST+. Analisi spettrale localizzata sulla sfera. Periodo di 1 anno presso TUMunich presso gruppo Prof. R. Pail.
- Tahir Javed: PhD Student. InSAR, earthquakes, crustal deformation, gravity field.
- Francesco Brandolin: Sea mount modeling. Inversion with Deep neural networks. Master Geosciences student.

Heritage sulla tematica della referente insieme al gruppo

- EO ESA GOCE.
- Progetto ASI GOCE-Italy (2009-2012)
- Progetto ESA GOCE User toolbox (2013-2015)
- Progetto ASI MOCASS (2017-2018)
- Progetto ASI MOCAST+ (2020-2022)
- Progetto con ENI per inversione basamento crostale e spessore della crosta da campo di gravita’ (2015-2017).
- 2013-2015 Int. Working group under IUGG, IAG: Define Science User needs for a future satellite gravity observing system. C. Braitenberg e I. Panet responsabili per tematiche Terra Solida. (Pail et al., 2015).

Heritage continued..

- 2019 Mass variation observing system by high low inter-satellite links (MOBILE). Core Mission proposal ESA call Earth Explorer 10 (Pail et al., 2019).
- H2020 Proposal DIGGER (Data Integration for Global Geophysical-studies and Earth-interior Research). Keywords: *Satellite observations, gravity and magnetic data, Earth observation from space, Lithosphere, Solid Earth, Geodynamics, Bayesian approach, Joint interpretation.*
  - *P*roject was above the threshold (it has been evaluated 13.5 out of 15, and the threshold was fixed at 10), the score was not sufficient to obtain the funding. The evaluators recognize the excellence of the proposal (score 5/5), its impact (score 4.5/5) and the its quality and efficiency of the implementation (score 4/5).

Present and proposed activities related to NGGM-
SRL1 Initial Scientific Idea (si preferisce formulare le segenti schede in lingua inglese)

- Objective: improve resolution of gravity field compared to GRACE and GOCE. A number of geophysical phenomena definitely generate observable gravity changes.
- Hypothesis: a larger impact can be achieved by observing a larger percentage of the overall existing phenomena and a higher completeness level.
- Example Earthquakes: very rare events (mega events) can be presently observed, but they are a small percentage of the damaging earthquakes. The observation does not compete with seismologic and geodetic observations, except for special cases.
- Example Hydrologic basins: Large scale hydrologic basins drawdown is observed by GRACE/FO. Limited number of applications and coverage, small percentage of total hydrologic volume. A more complete identification including smaller basins is needed. Deep hydrologic reservoirs may not be accessible by terrestrial observations.
- Example identification geologic structures: large scale structures identified by GOCE. Smaller scale is necessary for practical applications as for geologic services. Applications are manifold, as improvement of structure needed for regional geothermal estimation potential.
- Documented by publications: IUGG user group Pail et al. 2015; Publications on gravity effect of geophysical phenomena (hydrosphere, glaciosphere, solid earth, geology, tectonics, volcanism, climate change).

Present and proposed activities related to NGGM-
SRL2 Consolidation of Scientific Idea

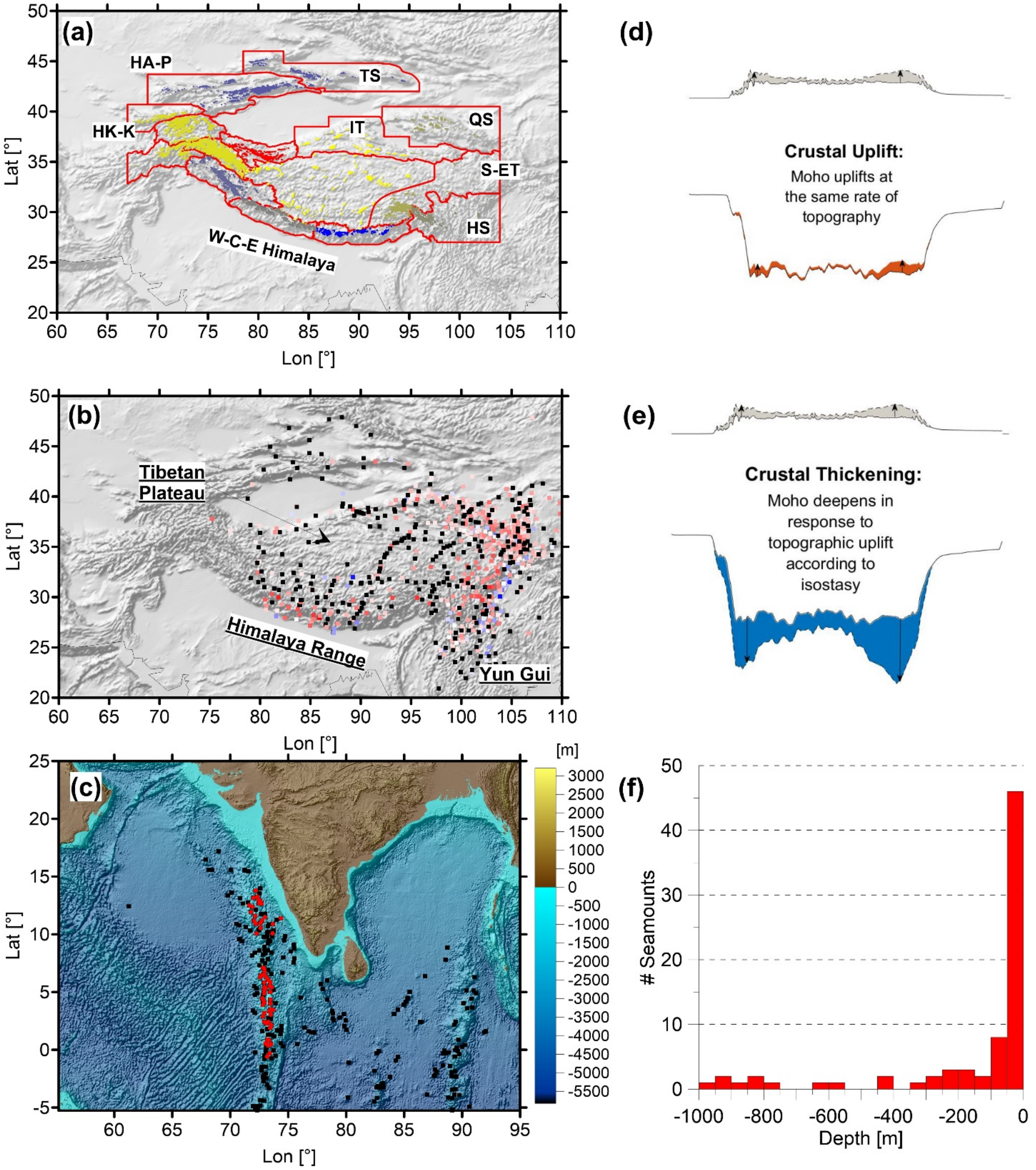
- Scientific evidence: it has been established that there are phenomena not observable by GRACE and GOCE that generate gravity fields, and that are of broad interest to be observed.
- Scientific strategy to adress scientific challenge: Geophysical simulations on hydrosphere, glaciosphere, tectonics and volcanism have shown that signals at a lower level of what is observable by GRACE, GOCE and satellite altimetry exist.
- Observation of these signals brings to an important increase of completeness level of detection.
- Documented by publications:
- IUGG user group Pail et al. 2015;
- To be completed: review of existing literature.

Present and proposed activities related to NGGM- **SRL3 Scientific and Observational requirements.**

- Product accuracy, temporal and spatial sampling mapped against user requirements:
- The scientific activities made in the frame of the MOCASS simulations were aimed to achive the goal of SRL 3.
- Geophysical modeling:
- High Mountains of Asia glaciers mass variations
- Topographic and crustal uplft of orogens to be separated from climate signal due to glaciers and lakes
- Seamounts of Indian Ocean. Volume changes based on recent and historical eruptions.
- Simulated gravity fields compared to spectral error curves of GRACE, GOCE, MOCASS, NGGM

- Result: Significative improvement can be achieved by the MOCASS-type system with the cold atom gradiometer on board a GOCE-type orbit constellation. The improved performance of the atom gradiometer at low frequencies translates into lower spectral noise at the intermediate degrees in the spherical harmonic expansion. This allows significant improvement for the studied examples.

- Documented by publications:
- Migliaccio et al. 2019; Pail et al. 2019; Pivetta et al., 2021; Reguzzoni et al.,2021.



a) *outlines of the glaciers in the HMA region according to RGI catalogue* (Pfeffer et al., 2014)*, colorized proportionally to the (de)glaciation rate in m/yr.*

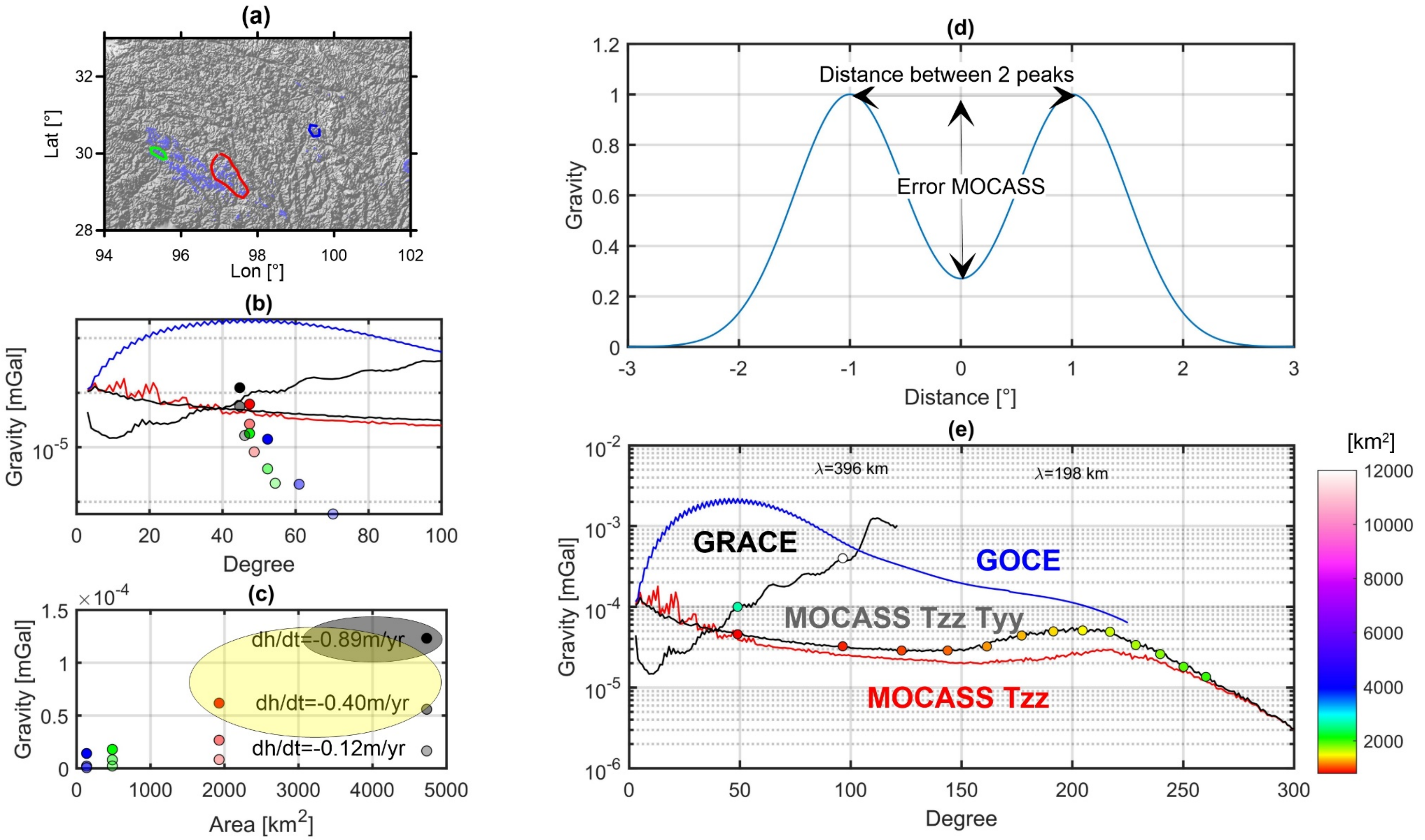
b) *GNSS observations in the study; color scale proportional to the vertical rates.*

c) *topo/bathymetry of the area from ETOPO1 with the seamounts location according to* (2010) *catalogue (black squares) and the seamounts with top within 200m from the surface (red points).*

d) *sketch illustrating the crustal uplift model.*

e) *model of crustal thickening.*

f) *statistical distribution of the seamounts based on their top's depth from sea surface.*



a) Four classes of glacier areas of increasing areal extent in which glaciers have been aggregated. Outlines mark classes: blue: 100 km^2, green: 500 km^2, red: 1900 km^2, and the total area of the glaciers in the window is 4750 km^2 b) Spectral comparison of the simulated gravity change for single glaciers or groups of glaciers in HMA. The error curves correspond to one year of gravity observation. c) area of glaciers and the gravity change in one year due to height loss of the glaciers.. d) Minimum distance between two gravity peaks to be distinctly detected. e) Resolving power of MOCASS for distinguishing two adjacent glaciers from their gravity change rate. The dots are colored according to their areal extent. Glacial height loss is assumed to be 0.4 m/yr.

Present and proposed activities related to NGGM-
SRL4 Proof of concept, Measurement concept validation

- Trade-off analysis based on the spectral error curves of different satellite and instrumental options.
- Present studies in the frame of MOCAST+ project
- Stage: implementing geophysical simulations of hydro-, glacio-, tectonic-, volcanic sphere
- Optimization of methodology to evaluate instrument performance against simulated fields. Improved methodology uses localized spherical spectrum analysis of phenomenon. This is required because the geophysical transients are temporally and spatially localized.
- Spectral error curves are based on globally evaluated spectra and this point requires attention for realistic sensitivity assessment.
- We will use portfolio of noise curves of NGGM in function of time resolution -> lower time resolution, corresponds to lower noise level of instrumental noise curve
- We will give feedback on the preferred error curves required for the geophysical needs.
- The assessment will include an analysis of the impact, based on the completeness level of the simulated geophysical phenomenon.

- Supportive publications:
- Migliaccio et al. 2019; Pail et al. 2019; Pivetta et al., 2021; Reguzzoni et al.,2021.

Proposed activities in relation the NGGM-
SRL5 (End to End Performance Simulations)

- The present activities are proposed to be expanded to develop the geophysical segment of the E2E simulation software for the user comunity, flexible for different instrument and constellation performances of the NGGM.
- Partner work unit: responsible of spectral error curves and spatial noise simulations
- Backward testing of methodology using the spectral noise curves or alternatively an observed noise patch over the simulated area from GOCE,GRACE/FO. Useful also for NGGM performance comparison.
- The software would include a database of a series of globally distributed geophysical phenomena, supported by the completeness analysis in relation to instrument performance.
- Include opportunity for the user to load own simulated fields, whereas further spectral evaluation is made by the software. The E2E software could also be used in the higher SRLs to validate predictions with the real observations
- The theoretical and experimental background for the E2E software is present, but a user friendly and comprehensive SW application would require some work to be implemented. This would lead the activities from SRL 4 to SRL 5, once the NGGM characteristics have been defined.

- Supportive publications:
- Migliaccio et al. 2019; Pivetta et al., 2021; Reguzzoni et al.,2021.

Scientific Readiness Assessment at SRL 5. Q/A from the SRL Manual 1/2

Is an E2E simulator in place and are the most important processes and input parameters (including uncertainty estimates) properly represented?

E2E instrument performance simulator: support for quantitative evaluation of new instrument and satellite concept in terms of:

- Performance simulations,
- Design optimisation
- Trade-off analysis

Answer: The methodology and software for the geophysical simulation is available and is being used in the frame of the MOCAST+ simulations.

• Is an error propagation model in place allowing the rigorous computation of uncertainties (e.g. accounting for co-variant error effects) for measurements and observations?

Answer: handled by project partners.

Gap: for the geophysical recovery assessment: geophysical noise level targeted to the specific geophysical phenomenon to be evaluated. Different from the comparison to instrument sensitivity. Can progress in time, when background geophysical noise is improved. Background noise is colored, so affects in different ways the portfolio of phenomena.

• Has a set of realistic test scenarios been established and are they scientifically justified?

Answer: a) observational noise handled by project partners

b) Geophysical test scenarios: yes, different geophysical scenarios have been considered.

Gap: to be expanded to cover more geophysical phenomena.

Scientific Readiness Assessment at SRL 5. Q/A from the SRL Manual 2/2

- Is the simulator tested and validated and applied for the predefined set of scenarios?

Answer: a user friendly E2E for geophysical assessment could be developed.

- Are all assumptions of the performance simulator documented and critically

discussed?

Answer/Gap: documentation and critical discussion of geophysical part of simulator should be developped. Presently documentation of methods existing in project reports and scientific publications. Gap: if E2E simulator should be accessible to wide spectrum of users, a targeted work should be made to develop software and interface, including documentation of the E2E simulator.

- Has the robustness of the simulator been demonstrated against independent

observations (e.g. campaign data)?

Answer: yes, for the geophysical part the simulations are based on documented mass variations, based on observables as seismic records, volcanic islands appearance on surface and observed by multispectral satellite, terrestrial observations of hydrology and glaciers.

- Is a draft instrument calibration strategy available and properly described?

Answer: handled by project partners of POLIMI

- Is there a demonstrated interest of users?

Answer: yes, see IUGG working group and documentation in Pail et al., 2015

- Is there a first evaluation of (simulated or measured data) in applications?

Answer: this can be done as soon as the definitive error curves of NGGM are available. In our geophysical analysis we include applications in which the NGGM fileds are evaluated in terms of significant improvement in applications with respect to existing satellite derived observations.

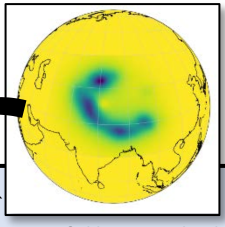
Example on detectability assessment strategy. Localized spectra.

Simulation of geophysical phenomena

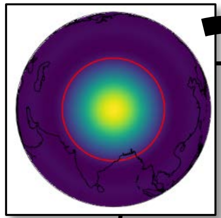
input mass distribution (grid)

- model and grid resolution
- computation height

spatial-domain gravity forward modelling on local grid

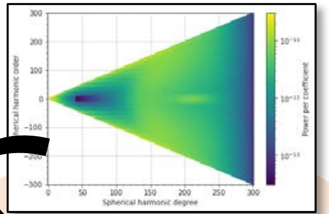


zero-fill to global grid, transform to SH expansion



localization windows

- spherical cap radius
- number of tapers



Simulated from GOCO06s coefficients formal errors

- *Upward-continued to computation height*
- *Average of localized random Monte Carlo realizations of perturbed GGM*

spatial error estimate (local grid) *

Detectability assessment of geophysical phenomena

localize in cap, compute power spectra

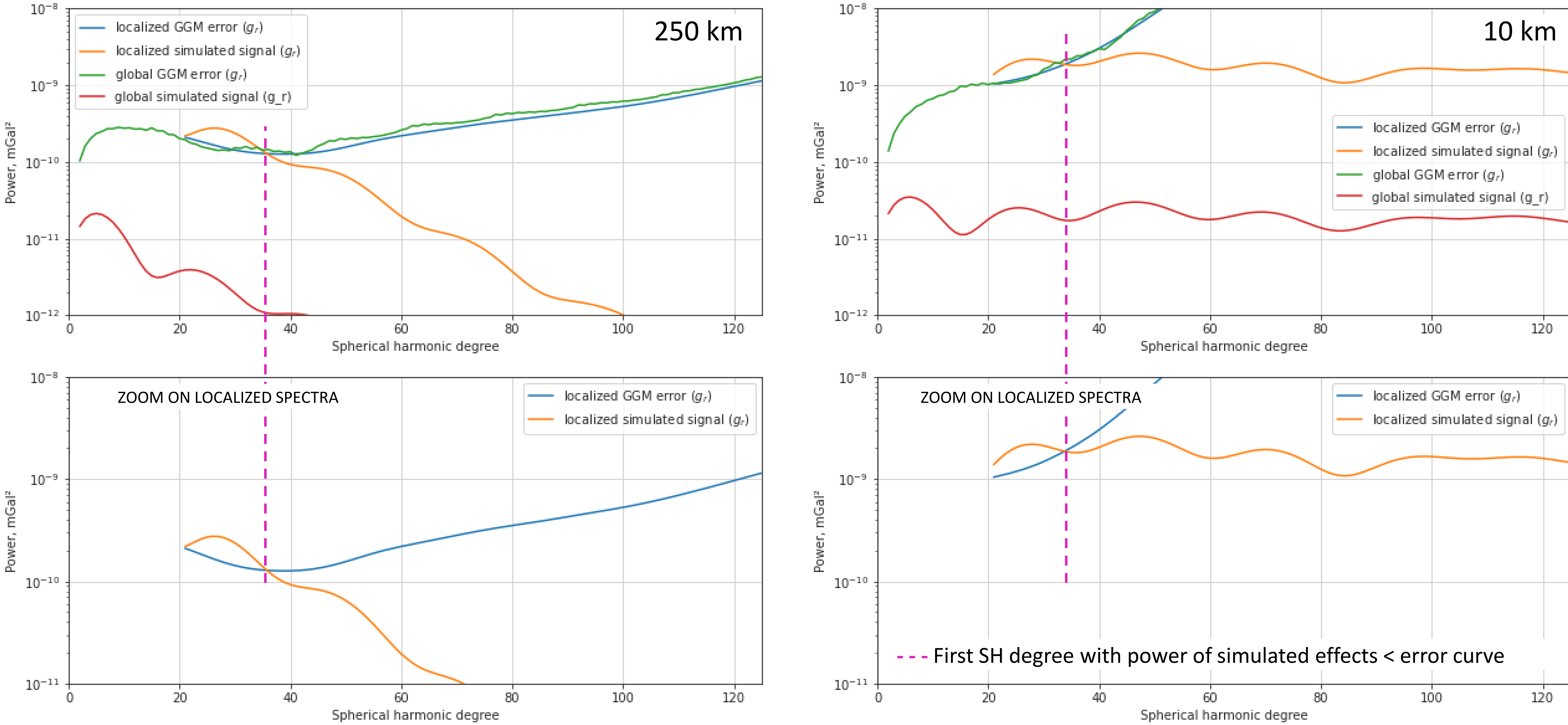
localize in cap, compute power spectra

localized power spectrum of <u>simulated phenomena</u>

DETECTABLE?

localized power spectrum of <u>error estimate</u>

Application example



Summary: Proposed activities in relation to NGGM

- Identify all applications of the NGGM in the estimation of natural hazards.
- Estimate required instrumental error curves for a breakthrough improvement in the estimation of natural hazards, climate hazards.
- Formulate requirements to the NGGM, based on the geophysical simulations and NGGM performance, that allow ponderated choices between orbit constellations to maximize societal impact of the mission.
- Develop E2E simulation SW that is necessary to a wide user comunity that can take advantage of the products of the NGGM.
- Plan and develop Level 2 and 3 products that shall be used by user working in the frame of hazard estimations and climatic monitoring. Also products to be integrated in existing databases, as IRENA: geophysical products useful for alternative energies.
- The gravity field remains far from the direct applicability realm of many professions, althouth it is possible to formulate outputs for which the gravity field is required, and which have several applications. These should be identified and higher level user-friendly products could be planned and developped

Relevant references SRL1-SRL2

- Pail R., Bingham R., Braitenberg C., Eicker A., Horwath M., Ivins E., Longuevergne L., Panet I., Wouters B. and IUGG group (2015). Observing Mass Transport to Understand Global Change and and to benefit Society : Science and User Needs. Deutsche geodatische Kommission der Bayerischen Akademie der Wissenschaften, Reihe B, Angewandte Geodesie, Heft Nr. 320, 1-124, ISSN 0065-5317, ISBN: 978-3-7696-8599-2.
- Pail R., Bingham R., Braitenberg C., Dobslaw H., Eicker A., Guntner A., Horwath M., Ivins E., Longuevergne L., Panet I., Wouters B., IUGG Expert Panel (2015). Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society. Surveys in Geophysics, 36(6), 743-772, dOI:10.1007/s10712-015-9348-9.
- Migliaccio. F., M. Reguzzoni, K. Batsukh, G. M. Tino, G. Rosi, F. Sorrentino, C. Braitenberg, T. Pivetta, D. F. Barbolla, S. Zoffoli (2019) MOCASS: a satellite mission concept using Cold Atom Interferometry for measuring the Earth gravity Field, Surveys in Geophysics, 40(5), 1029-1053.
- Pivetta T., Braitenberg C., Barbolla D.F. (2021) Geophysical challenges for future satellite gravity missions: assessing the impact of MOCASS mission, PAGEOPH under Review.

Supporting scientific evidences for gravity field from satellite and geophysical phenomena (supportive to SRL 1 and SRL2)

- Shin Y. H., Shum C. K., Braitenberg C., Lee S. M., Na S.-H., Choi K. S., Hsu H., Park Y.-S., Lim M. (2015). Moho topography, ranges and folds of Tibet by analysis of global gravity models and GOCE data. SCIENTIFIC REPORTS, 5, 11681; doi: 10.1038/srep11681, 1-7.
- Pivetta T., Braitenberg C. (2020). Sensitivity of gravity and topography regressions to earth and planetary structures. Tectonophysics, 774, 228299, doi:10.1016/j.tecto.2019.228299,
- Alvarez O., Gimenez M., Folguera A., Chaves C. A. M., Braitenberg C. (2019). Reviewing megathrust slip behavior for recent Mw>8.0 earthquakes along the Peru-Chilean margin from satellite GOCE gravity field derivatives. Tectonophysics, Volume 769, 20 October 2019, 228188, https://doi.org/10.1016/j.tecto.2019.228188 ,
- Pastorutti A., Braitenberg C. (2019) A geothermal application for GOCE satellite gravity data: modelling the crustal heat production and lithospheric temperature field in Central Europe, Geophysical Journal International, 219, 1008–1031, https://doi.org/10.1093/gji/ggz344.
- Motta J. G., de Souza Filho C. R., Carranza E. J. M., Braitenberg C. (2019). Archean crust and metallogenic zones in the Amazonian Craton sensed by satellite gravity data. Scientific Reports, 9:2565, 1-10, doi:10.1038/s41598-019-39171-9.
- Chen W., Braitenberg C., Serpelloni E. (2018). Interference of tectonic signals in subsurface hydrologic monitoring through gravity and GPS due to mountain building. Global and Planetary Change, 167, 148-159, doi:10.1016/j.gloplacha.2018.05.003.
- Alvarez O., Nacif S., Spagnotto S., Folguera A., Gimenez M., Chlieh M., Braitenberg C. (2015). Gradients from GOCE reveal gravity changes before Pisagua Mw = 8.2 and Iquique Mw = 7.7 large megathrust earthquakes, Journal of South American Earth Sciences, 64, 273-287, doi: 10.1016/j.jsames.2015.09.014.

Relevant References SRL3-SRL4

- Pail, R., Bamber, J., Biancale, R., Bingham, R., Braitenberg, C., Eicker, A., Flechtner, F., Gruber, T., Güntner, A., Heinzel, G., Horwath, M., Longuevergne, L., Müller, J., Panet, I., Savenije, H., Seneviratne, S., Sneeuw, N., Dam, T. van and Wouters, B. (2019). Mass variation observing system by high low inter-satellite links (MOBILE) – a new concept for sustained observation of mass transport from space, Journal of Geodetic Science, 9(1), 48–58, doi:10.1515/jogs-2019-0006.
- Migliaccio. F., M. Reguzzoni, K. Batsukh, G. M. Tino, G. Rosi, F. Sorrentino, C. Braitenberg, T. Pivetta, D. F. Barbolla, S. Zoffoli (2019) MOCASS: a satellite mission concept using Cold Atom Interferometry for measuring the Earth gravity Field, Surveys in Geophysics, 40(5), 1029-1053.
- Reguzzoni, M., Migliaccio. F., Batsukh K. (2021) Gravity field recovery and error analysis for the MOCASS mission proposal based on cold atom interferometry, PAGEOPH, under Review.
- Pivetta T., Braitenberg C., Barbolla D.F. (2021) Geophysical challenges for future satellite gravity missions: assessing the impact of MOCASS mission, PAGEOPH under Review.

References in e2e simulations

- Uieda L., Barbosa V. C., F. Braitenberg C. (2016). Tesseroids: forward modeling gravitational fields in spherical coordinates, Geophysics, 81, 5, F41-F48, doi:10.1190/GEO2015-0204.1.