Gravity from Space by Cold Atom Interferometry: the MOCASS Study and Preliminary Results

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The MOCASS Study

MOCASS (Mass Observation with Cold Atom Sensors in Space) is an on-going study project funded by the Italian Space Agency in the framework of preparatory activities for future missions and payloads of Earth Observation. The object of the proposal is **an innovative satellite gravity mission based on advanced cold atom interferometry (CAI) accelerometers.**

Goals:
- ✓ modelling the static and time-variable Earth gravity field with high accuracy and resolution,
- ✓ monitoring mass variations that occur on and below the Earth surface.

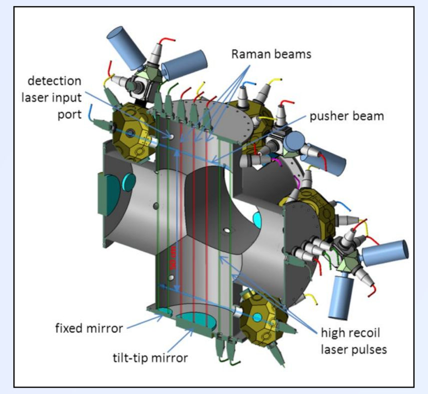
The MOCASS team

- **AtomSensors srl – AS** (Spin-off of University of Florence): study of the technological characteristics of an atom interferometer that delivers the gravity and gradient field at satellite altitude
- **Polytechnic University of Milan – POLIMI** (Department of Civil and Environmental Engineering): estimation of the global signal characteristics as a result of the geodetic data analysis
- **University of Trieste – UNITS** (Department of Mathematics and Geosciences): study of the signal requirements from the geophysical point of view.

Proposed mission concept

The idea is based on a GOCE follow-on, which is much less investigated by the geodetic community with respect to the idea of a GRACE follow-on.
The proposed gradiometer is to be based on technology exploiting **Cold Atom Interferometry (CAI).**

Main advantages:
- ✓ possibility to "spatialize" observations acquired by the on board gradiometer and not derived by differentiating observations acquired from two different (and far) satellites;
- ✓ the CAI technology can give the possibility to strongly improve the performances of GOCE in the static gravity field in terms of accuracy and resolution and to extend the application to the estimation of the time-variable gravity field.



Cutaway drawing of the vacuum chamber of the 3D CAI gradiometer

Scientific challenges

- Investigating the **Earth structure** (Solid Earth), e.g. for:
  - ✓ megathrust earthquake modeling,
  - ✓ study of mass distribution and transport inside a volcano,
  - ✓ mass transport in general at an increased spatial and temporal resolution,
  - ✓ Earth crust,
  - ✓ Moho discontinuity and upper mantle.
- Studies on **oceanography, hydrology and cryosphere**:
  - ✓ dynamic topography (GOCE has significantly contributed at global scale, but resolution is still insufficient for smaller close or semi-closed basins like the Mediterranean Sea);
  - ✓ ice-sheet mass variations and their impact on climate.

→ **CLIMATE AND CLIMATE CHANGE STUDIES**

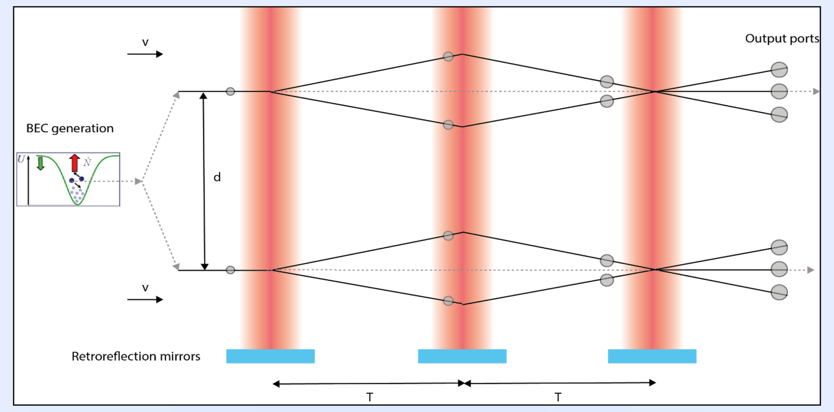
The CAI instrument

The CAI gradiometer concept

The light-pulse atom interferometry utilized in the acceleration measurement and the CAI gradiometer considered in this study were proposed by Carraz et al., 2014.

An atom interferometer exploits interference of matter waves which are coherently manipulated by light fields. At each atom-light interaction, a phase is imprinted onto the atoms which depends on the relative position between the light field and the atoms. The light field, consisting of two frequencies, is retro reflected at a mirror and drives two-photon transitions during each interaction. Effectively, the mirror serves as a reference plane for the position of the atoms during the interactions.

Atom interferometry scheme for gradiometric measurements



The phase shift φ due to an acceleration a is equal to $\varphi = k\,a\,T^2$
where k denotes the effective wave vector corresponding to four photon momenta.
The gradient information is recovered from the differential signal divided by the baseline ***d***.
In this case, the QPN limited sensitivity is given by:

$$\sigma_\Gamma = \frac{\sqrt{2}}{\sqrt{N}\,k\,T^2 d}\sqrt{\frac{t_c}{\tau}}$$

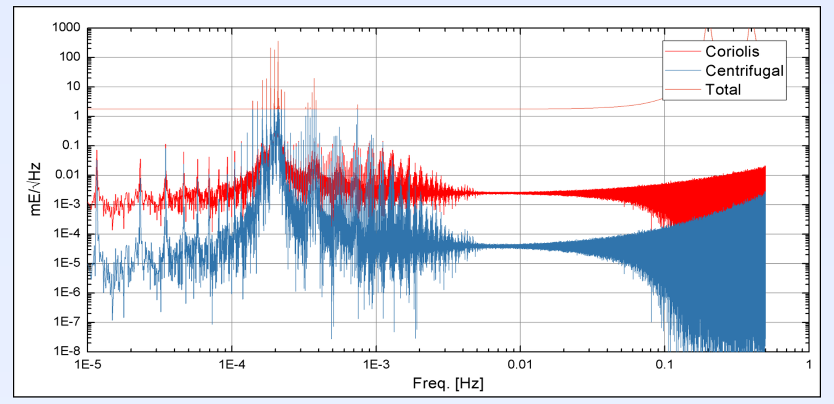
where N is the atom number, t_c is the cycle time and τ is the integration time.

Instrument Power Spectral Density (PSD)

The expected PSD of the instrument has been evaluated.
Two possible modes of operation have been considered: the **nadir-pointing** mode, which corresponds to the usual Earth-pointing satellite attitude, and the **inertial mode**.
For each one, the effect of the satellite angular velocity has been computed considering the time series of the GOCE orbit coordinates at two different altitudes.

- Coriolis noise term $\quad 2\,k\,T^2\,\Omega\,v$
- Centrifugal noise term $\quad k\,T^2\,\Omega^2\,d$

CAI PSD in nadir mode along the radial orbital direction



The so obtained PSDs are then employed as input elements for numerical simulations of the measurement and processing work flow.

The geodetic data analysis

The MOCASS simulation scenario

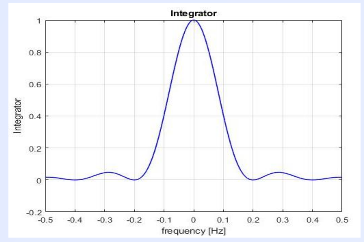
- Reference model: EIGEN_6C4 up to degree and order 360
- Reference orbit: GOCE orbit from November 2009 to January 2010 (≈ 2 months)
  - ✓ Nadir-pointing configuration
  - ✓ Inertial configuration
- Observations: T_{xx} T_{yy} T_{zz} → Predicted grids: T $T_{\lambda\lambda}$ T_{rr}

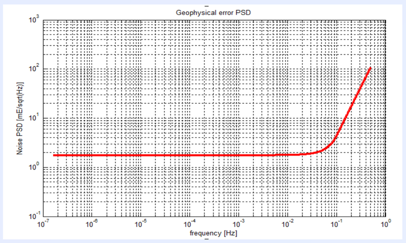
Space-wise solver

along-orbit data → Wiener deconvolution → Local gridding by collocation → Spherical harmonic analysis → spherical harmonic coefficients

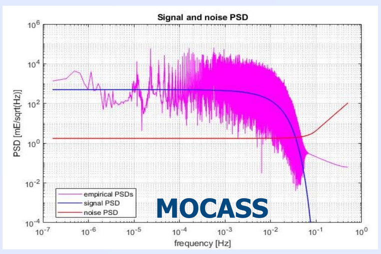
CAI instrument: measurement error spectrum and its parameters

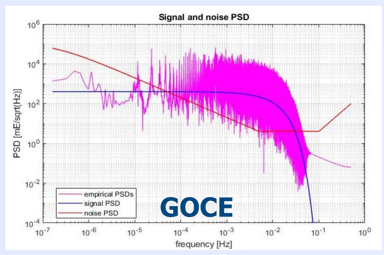
Number of atoms: $N = 10^6$
Interferometer time: $T = 5$ sec
Distance: $d = 0.5$ m
Cycle period: $t_c = 1$ sec





Empirical and modelled analytic spectra – comparison with GOCE



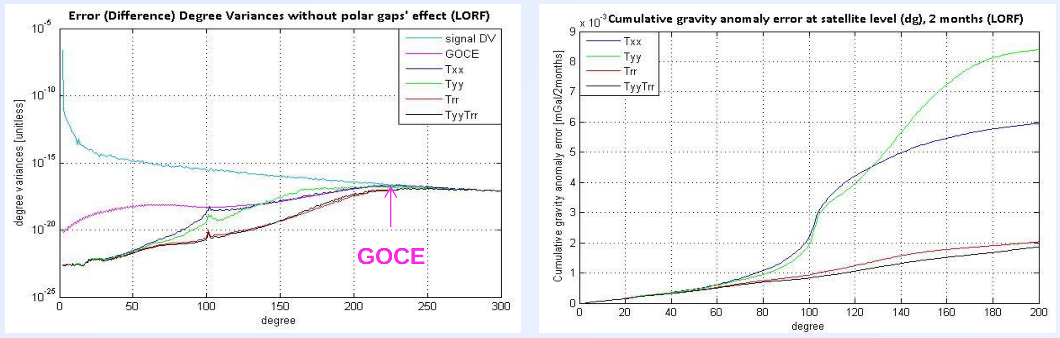


The power spectral density of the measurement error of CAI instrument shows high values only at high frequencies, while the measurement error of the GOCE gradiometer shows high values both at low and high frequencies.

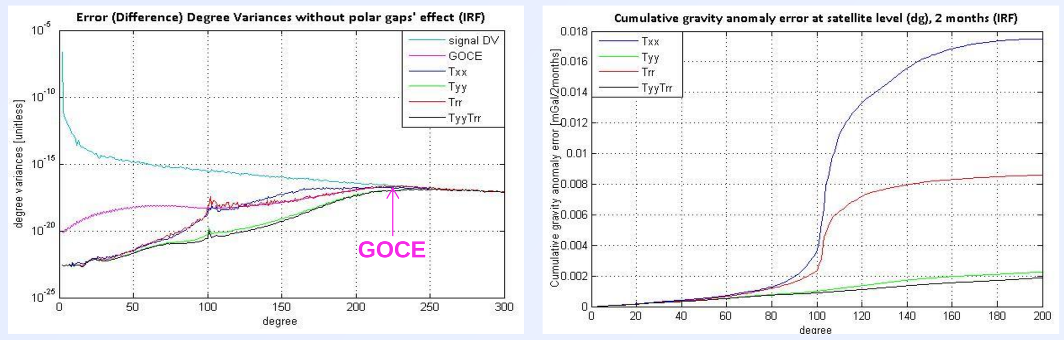
Results: static gravity field

- Local collocation procedure was applied to the Wiener filtered data, implementing an additional filter by grouping data, which are «close in space», but «far in time».
- Data were partitioned into 8325 «clouds» around grid nodes.
- An improvement with respect to GOCE can be seen in the results.

Nadir-pointing configuration

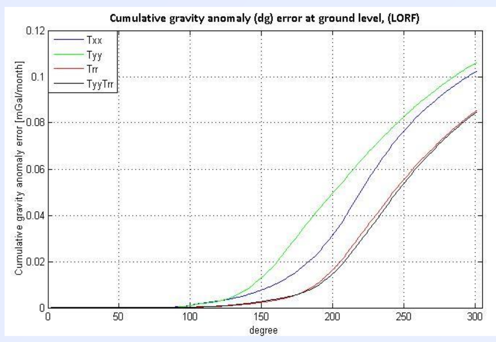


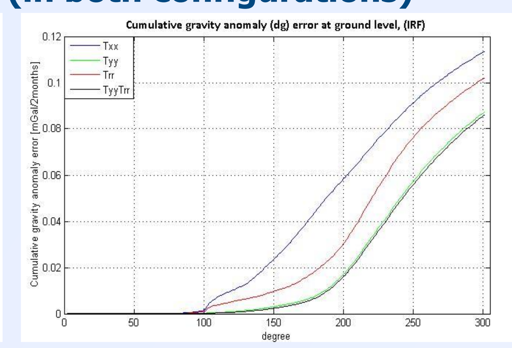
Inertial configuration



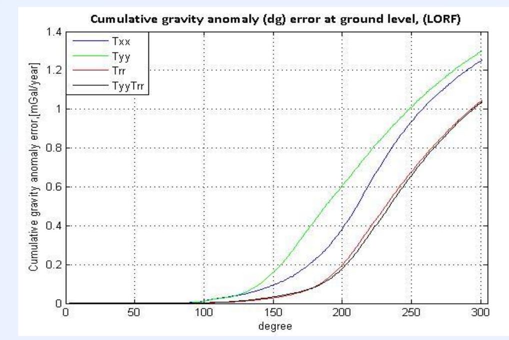
Results: time-variable gravity field (five-year-mission)

Two-month-solution (in both configurations)





One-year-solution (nadir mode)



Conclusion

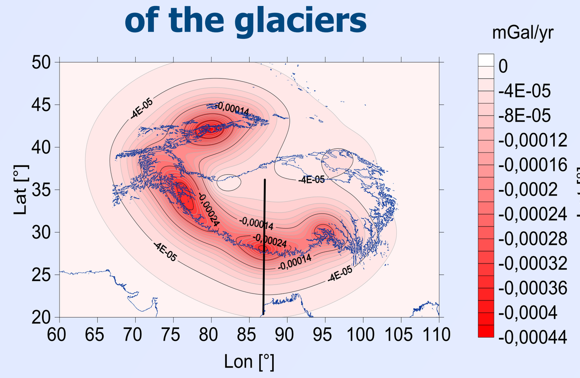
The radial direction (T_{rr} component) in nadir pointing configuration and the T_{yy} component in the inertial one (radial at the equator only) have similar performances.

The geophysical challenges

The focus was on the **India-Tibet area**, which involves important and different **movements of mass through time** and comprises several **different crustal structures**. The area is continuously studied and presents challenges for a satellite mission.
The gravity effects of four geophysical phenomena of interest were simulated at an height of 250 km and the estimated signals were compared with the error curves simulated for the MOCASS mission.

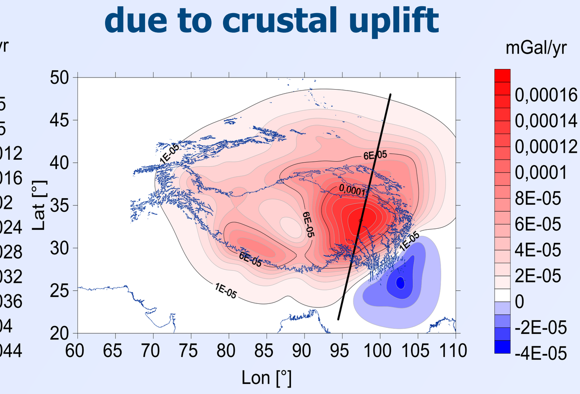
Time varying phenomena in the Tibet-Himalaya region

Yearly gravity change due to mass variations of the glaciers



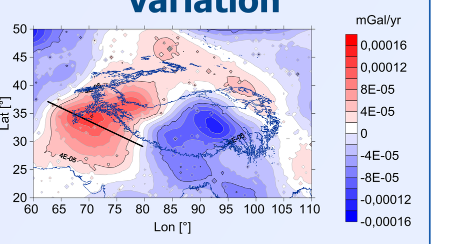
The glaciers mass variations have been calculated by extracting the outlines of the glaciers of the area from the RGI catalog and assigning the yearly mass variations (Gardner et al., 2013) estimated for different subareas of the region.

Yearly gravity change due to crustal uplift

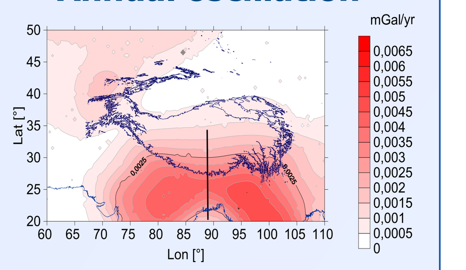


Himalaya and Tibet are experiencing uplift in the whole plateau as testified by GNSS data (Liang et al., 2013). The gravity effect of a pure crustal uplift model was calculated in a similar way as proposed by Braitenberg and Shum (2017) and Yi et al. (2016).

Hydrology long term variation

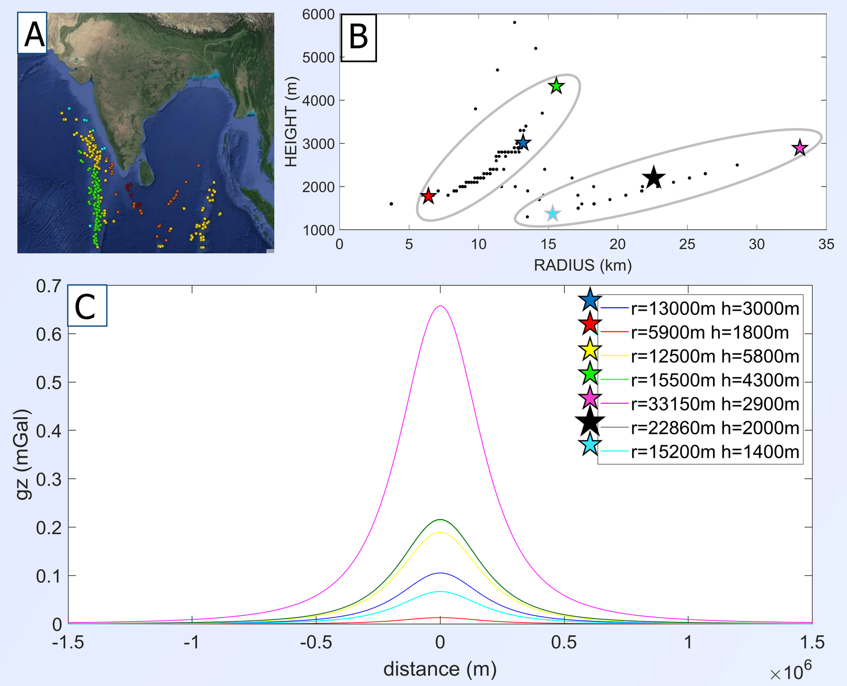


Annual oscillation



The gravity effects due to hydrology have been calculated from GLDAS model for the period 2002-2016. From the 4D data a long term linear trend and the annual variation have been extracted.

Static phenomenon: seamount distribution



- The study of **seamounts distribution in the India area** (A) based on radius and height (Wessel et al., 2001) allowed the identification of two trends (B) of which some points were chosen (stars).
- For each dimension the expected **gravimetric effect (gz)** was calculated at 250 km above sea level (C) through the Comsol Multiphysics software.
- The seamounts have been modeled as truncated cones with a density contrast of 1800 kg/m³.

Comparison of the simulated signals with the error curves of MOCASS

From each phenomenon a profile was extracted (as shown in the above figures) and fitted with a gaussian curve.
From the gaussian curve, the wavelength content and the amplitude of the signal was estimated.
The signals of the phenomena are reported with dots.