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Cold Atom Gravimetry for Planetary Missions

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Abstract

Cold Atom Interferometry (CAI) – is a promising new technology for gravity missions [1], enabling measurements with a potential error improvement of several magnitudes compared to classical electro-static accelerometers. Whereas the latter typically suffer from high noise at low frequencies, cold atom interferometers are highly accurate over the entire frequency range. Especially for interplanetary missions, drift-free cold atom interferometry can be highly beneficial, because there are fewer possibilities for calibration. In this work, simulations of a CAI instrument in Earth orbit are scaled to Venus and Mars and the spherical harmonic degree strength of the gravitational field retrieval is estimated. In the future, cold atom sensors can help to improve the gravity models of planets such as Mars and Venus and to test the fundamental theories of physics.

1. Introduction

1.1 Gravimetry: Earth & Beyond

In Earth Observation, measuring the gravitational field from space – or its first and second order derivatives: gravitational acceleration and gravity gradient – can help us understand geoscience questions about e.g. geological processes, ocean circulation and climate change. There are several past and on-going gravity missions around Earth. GRACE and the currently flying GRACE-FO mission consist of two spacecraft with low-low satellite-to-satellite tracking (SST) using microwave or laser ranging. To distinguish non-gravitational effects, the satellites contain on-board accelerometers. With those combined measurements, gravity field parameters are retrieved.

In contrast to low-low SST, the GOCE mission comprised a gravity gradiometer (GG) instrument. A set of six 3-axis electro-static accelerometers was used to retrieve the full gravity gradient tensor.

Cold Atom Interferometry can be used in two ways for gravity field measurements. The first way is a gravity gradiometer GOCE-like concept: A CAI GG suppresses the common vibration effects on the instrument as the inertial reference of the two clouds of atoms is the same. Currently, the mass of a CAI GG is 260kg but it is expected to be reduced to 50kg in ongoing studies. The second is a hybrid CAI accelerometer concept (targeted mass: <10kg) of correcting drift errors of electrostatic accelerometers that are used in a satellite-to-satellite ranging concept for measuring non-gravitational accelerations.

For other objects than Earth, there was only one dedicated gravitational mission: NASA’s lunar GRAIL mission [2]. Two spacecraft in a GRACE-like formation, including SST and radio ranging from earth, where used for gravitational field mapping of the moon. A gravity mission utilising CAI technology could potentially improve current gravitational models, which are mainly retrieved from radio science experiments, by orders of magnitude.

1.2 Cold Atom Interferometry

To enable atom interferometry, atoms (e.g. 87-Rb isotope) need to be cooled down nearly to absolute zero. Only for very low temperatures, the quantum nature of matter becomes visible and is not eclipsed by thermal noise. Atoms are confined in a Magneto-Optical-Trap and several laser-cooling mechanisms are then used to achieve temperatures in the range of μK down to nK.

With the cooled atoms, matter-wave interferometry is conducted. Matter-wave interferometers coherently split and recombine the atoms quantum-mechanical de-Broglie-matter-waves. A common scheme is to use three so-called “Raman” laser pulses to construct a Mach-Zehnder type interferometer. A Raman laser pulse places the atoms into a superposition of two momentum states. The atom clouds in different momentum states accumulate a quantum-mechanical phase and when being spatially overlapped at the end, the phase difference between the two interferometer arms leads to an interference pattern. The measured phase difference at the end of the interferometer sequence is proportional to the gravitational acceleration g acting on the atoms (T: interferometry time, k_{eff}: effective wavevector) [3]:

$$\mathit{\Delta}\phi = k_{eff} g T^2 \qquad (1)$$

CAI Gradiometer sensitivities are shown in Table 1.

Table 1: CAI GG sensitivities for two scenarios, Eötvös: unit of gravity gradient, 1E=1e-9 s^-2

Case	T	Sensitivity	Cooling Tech.
Optimal	5s	3.5mE	BEC [4] (~nK)
Relaxed	0.3s	200mE	MOT [5] (~µK)

2. Model

The model utilizes simulations conducted within ESA's EOP-SME section of spherical harmonic coefficients for a CAI Gravity Gradiometer at different altitudes (*250km, 300km, 350km*) around Earth. The signal degree RMS error is derived from the simulated coefficients. Signal degree amplitudes (square root of signal degree variance) are derived from the GOCO03s [6] combined gravitational model of earth. For an additional, flexible altitude the RMS error curves are modelised and extrapolated.

In order to estimate the performance of a CAI GG instrument for other terrestrial planets, a scaling ratio for the gradiometer *error* is derived. Assuming the same gradiometer sensitivity for earth and the other planet (R_P: mean radius, g_P: surface grav. acceleration) leads to the factor: $(R_P/R_E)^2 g_E/g_P$

In Konopliv et al. [7] the following ratio is used to scale the gravitational *signal*: $(g_E/g_P)^2$

Both of the above scaling factors are used to scale the gravity gradiometer *error* and an uncertainty is derived from the difference of the results. *Signal* degree amplitude and *error* degree amplitude are scaled with the factors above. For Venus, the scaled signal degree amplitude is compared to an empirical "Kaula rule of thumb [8]" for Venus [9] (degree n):

$$\sigma_n = \frac{1.2 \cdot 10^{-5}}{n^2} \sqrt{2n+1} \qquad (2)$$

3. Results

The degree, at which signal and error are equal (*SNR=1*), yields the degree strength (Figure 1). The intersections of the error curve with the two signal amplitudes (Scaled Earth and Kaula Venus) are well matched. For a variation of satellite altitudes, the estimated degree strength (or gravity field resolution) is shown in Figure 2 for two different CAI sensitivities and it is compared to the performance of the radio science Doppler-tracking technique, intended to be used for the ESA candidate mission EnVision.

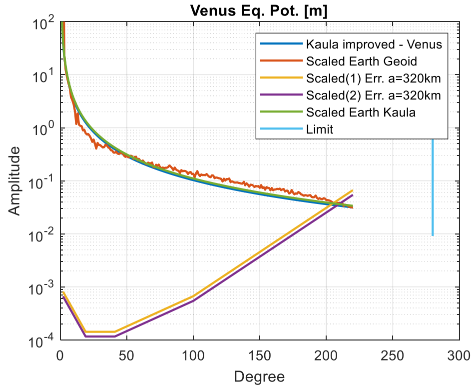

Figure 1: Venus equipotential signal vs. error; for a CAI GG S=3.5mE, Mission duration: 12 months.

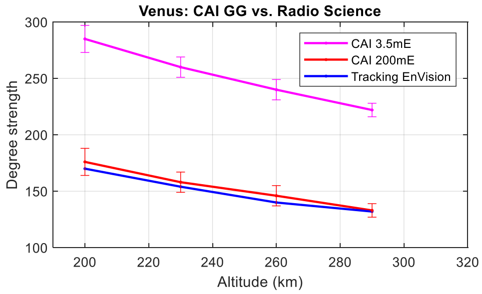

Figure 2: Estimated gravity field resolution with CAI GG compared to the estimated performance for EnVision radio science tracking for different satellite altitudes.

4. Summary and Outlook

These simulations are just first order approximations, but they show that a CAI GG would help to significantly improve the gravity models of planets such as Mars and Venus. Parameters such as orbital and attitude knowledge have to be considered in a refined model.

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