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The gravimeter "B-grav" for in-situ gravity measurements at the surface of an asteroid

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Abstract: We investigate a miniaturized 3D compact gravimeter as part of geophysical instrument package dedicated to small bodies of solar system like Asteroids. The described prototype will be setup on a CubeSats assemblage which lands on the secondary object of the Didymos system. Specificities of selected solutions meet problematic to measure very tinny 50μm/sec² gravimetric field corresponding to 5 ppm of Earth gravity. The system will operate in a hash thermal environment without leveling, with strictly limited power, mass and signal treatment facilities. A system with three components mounted in an orthogonal geometry allows obtaining the gravity field in amplitude and in all angular positions without any requirement of levelling. We set-up the gravimeter in a vertical position to reject the Earth gravity field. We induce by tilt of the system μchanges of forces like the Asteroid one. B-Grav will use a in-situ calibration process to control the laboratory transfer function determination.

Keywords: asteroid, gravity field, capacitive bridge, EDAS concept, EDAS

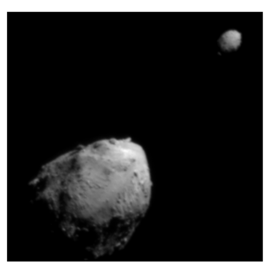
Recent impact of the DARD NASA probe achievement justifies for R.O.B. to address the gravity monitoring of small astronomical bodies

Royal Observatory of Belgium

R.O.B. expertise in geodynamics constitutes the anchor of this metrological approach

NEO-MAPP

These researches were supported by the NEO-MAPP project



(Fig1) : Image of the Didymoon system produced by the DRACO imager

(Fig2) : Type of material in the landing site which excludes simple leveling of instruments

Scientific objectives

ROB proposed to design a miniaturized 3D compact instrument (Fig3) dedicated to evaluate the gravity field in amplitude and position of small bodies of solar system like Asteroids. The described prototype is adapted to CubeSats assemblage to land on the secondary object in the 65803 Didymos binary system.

Choise of methodology

Operating mode:

- -1. Absolute Z(g) = S g + Z(0)
  g constant >>> no access to Z(0)
- -2. Modulated g variable
  Z(g1)= S g1 +Z(0) & Z(g2)= S g2 +Z(0)

Z (g1)-Z(g2) = S (g1-g2) (+ Z(0) – Z(0))

Two problems must be considered:

First, how to register the gravity field and second, how to reject its common mode

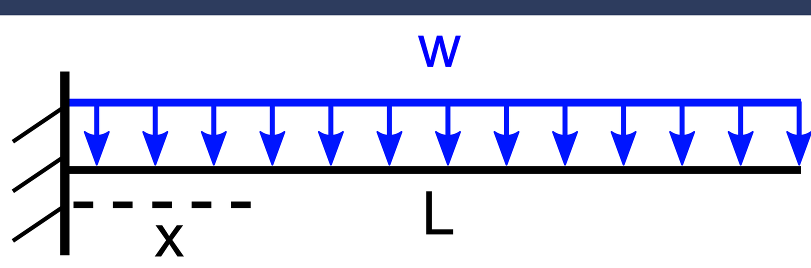
Question 1: How to measure the gravity field in one direction ? Our proposal : B-Grav sensor

Basically, we use like proof mass sensing the gravitational field w, a clamped beam constitued of a flat sping rigidly anchored at one of its extremities. This cantilever shows deformation in function of gravity following the equation reported at (Fig 4).

Displacement $f=\frac{wL^4}{8EI}$

Équation de la déformée $y=\frac{-wx^2}{24EI}\left(x^2-4Lx+6L^2\right)$

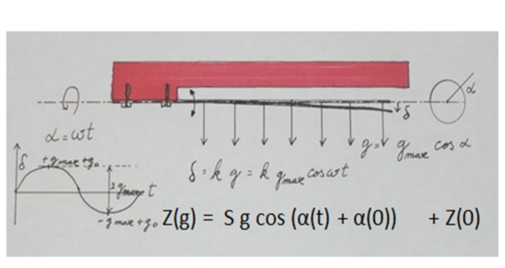
E : module de Young I : moment d'inertie



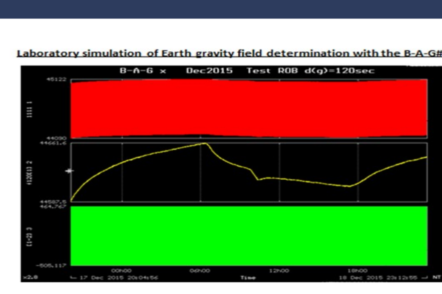
(Fig4) : Equation of the cantilever with a length L sensing a force density w

Question 2: How to modulate the effect induced by gravity? Our proposal : Rotating the B-Gravalong its axis

The torque acting on a rotating cantilever (Fig 5) is a figure of the gravity vector projected on the plan perpendicular to the axis of rotation. With three gravimeters orthogonaly set-up, we have full access to the three components and the position of the gravity field referenced to the satellite reference. This method rejecting efficiently the common mode of the signal, give signature without aging and minimum of thermal effects. Applying averaging of signals by sliding windows with the same period than the rotation, the resulting curve keeps only spurions effects which could be subtracted to correct the raw signal (Fig6).



(Fig5) : Deflexion of the cantilever turning in a gravity field g



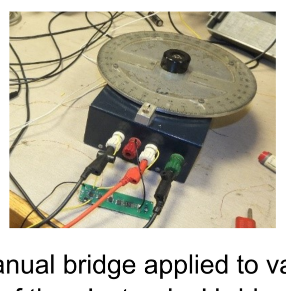
(Fig6) : (top) raw signal (center) sliding averaged signal (bottom) residual raw minus filtered signals.

Electronic interface EDAS adapted to the B-Grav probe

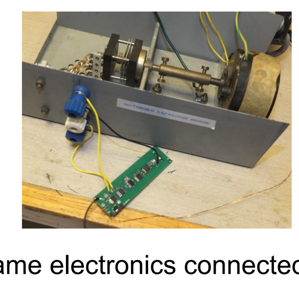
The interface (Fig 8) is supplying the capacitive bridge external électrodes with two opposed squared signals to meet linearly the very high dynamics we need for the B-Grav. The position of the flat spring influes the output signal of the bridge. Connecting it to the negative input of an operational amplifier referenced to a constant voltage applied to the positive input, we feed-back the spring potential through a capacitor in paralel with a resistor. It results a constant voltage for the spring potential. The feed-back voltage is amplified and filtered by a phase detector loop before to go to a Voltage-to-Frequency converter. The F.M. signature of the spring position is digitized by simple counting which acts like a low-pass filter. For bridge 2 x 5 pF capacitances, we obtain a Signal/Noise ration better than 100,000 x ! If the gap of the bridge is 1mm, the precision on the displacements of the spring position should be 10 nm (1/100th of μm)

(Fig8) : Proposal for the B-Grav electronics

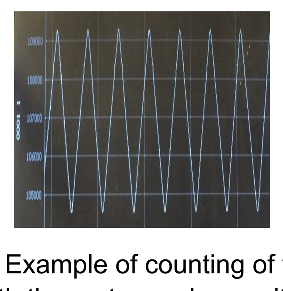
To check the patterns of the electronics, we use capacitive bridges with capacitors changing linearly by rotation. For a 1pF excursion, we need an angle of 18 degrees. Transfer function of circuit is obtained by a step-by-step series of rotations applied manualy (Fig9). or with motorized rotation (Fig10). So, we can evaluate the performance of the electronical interfaces with capacitance bridges. The output signal is a frequency modulation which is digitized just by counting (Fig11). It is very linear in more than 90% of its excursion.



(Fig9) : Manual bridge applied to validate the prototype of the electronical bridge interface.



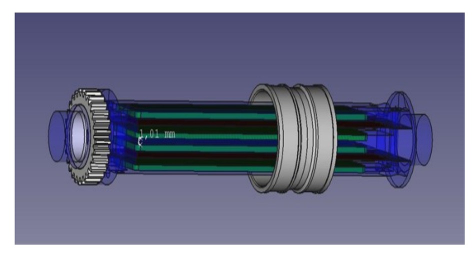
(Fig10) : Same electronics connected to a motorized capacitor bridge turning in fifteen minutes.



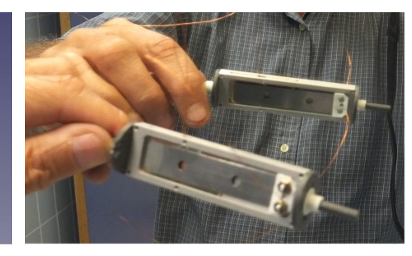
(Fig11) : Example of counting of the F.M. signals with the motorysed capacitive bridge

Proposal for the B-Grav design

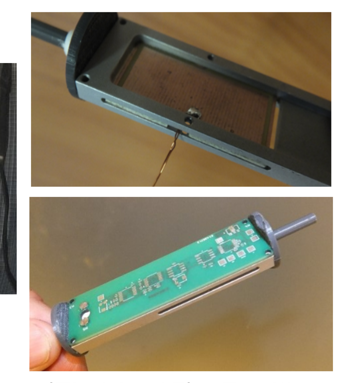
Following a temptative to design a system meeting our selected criteria (Fig12), we prepare a quite real size prototype. The body of this Bgrav is constitued by an Aluminium bloc with two cavities located at both sides, which welcome electrodes and flat springs (Fig13). Flat spings are anchored at one extremity of the gaps, keeping free the motion of their extremities. This body is ended by the two axis of rotation) allowing to turn the gravimeter without vibrations. Electrods are made directly with a printed circuit set-up at the central part of the body (Fig14) and with the back of the printed circuit of the interface (Fig15). Results we introduce provide of testsmade with a stainless steel spring having a rigidity strong enough to support the full earth gravity field deformations (Fig16).



(Fig12) : Original schema of B-Grav design with two capacitive rings coupling and tangential gear wheel.



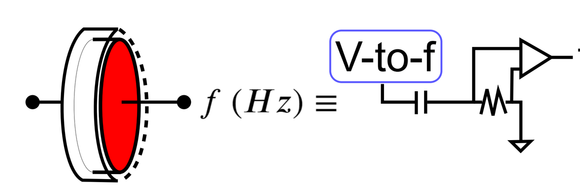
(Fig13) : BGrav body with the two springs into excentric position of the rotation axis

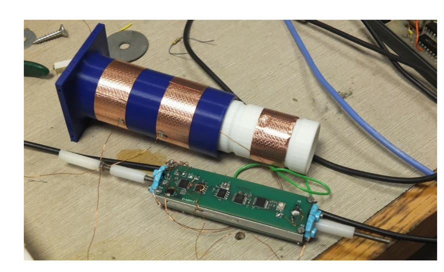


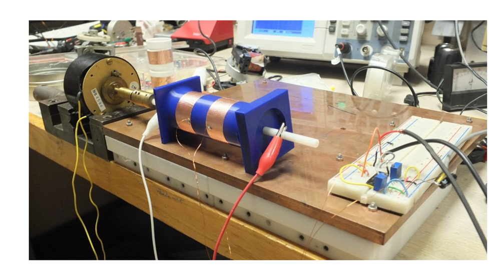
(Fig14 - 15) : Position of the electrods.

(Fig16) : Stainless steel spring anchored at its extremity inside isolated material

Interfacing of frequency modulated signals by capacitive coupler



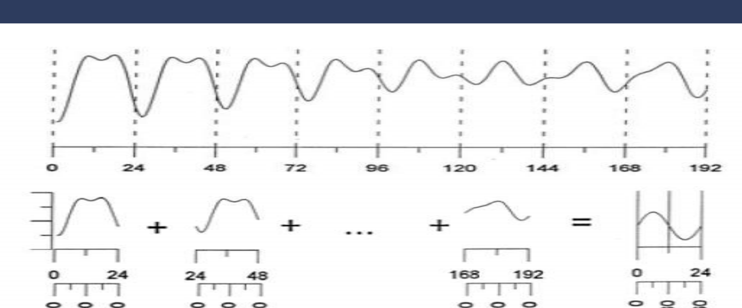




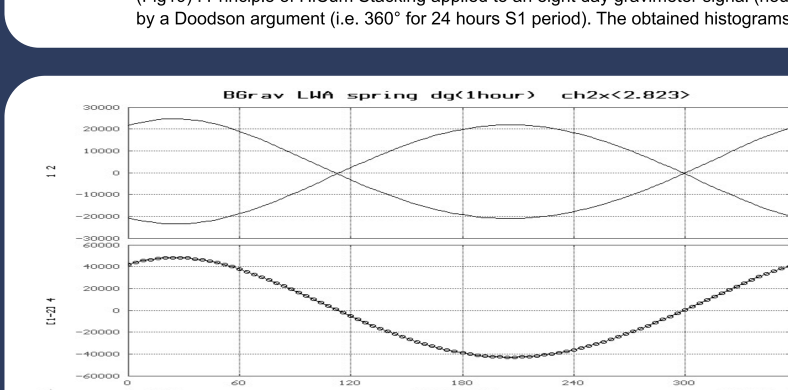
(Fig17 - 18) : The high frequencies of the electronics output allows to do a transfer through a capacitive coupler. Its first electrodes (in white) are rigid with gravimeter body, turning in front of seconds one (in blue) fixed to the external support. Two additional couplers are used to supply the rotating gravimeters.

Stacking Method (HiCum) applied to Bgrav data

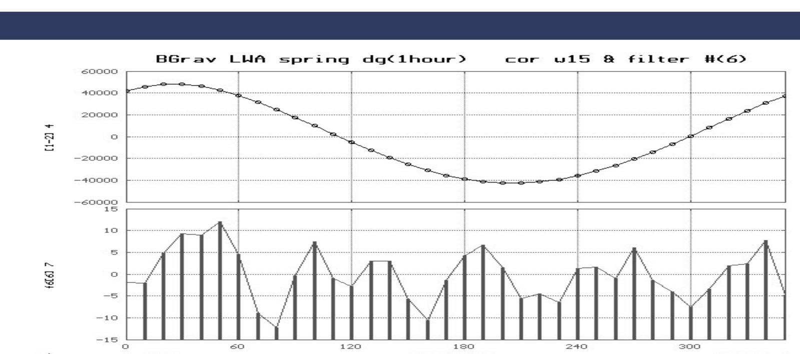
The HiCum (Histograms Cumulation) is an alternative method of signal analysis (Fig19) , which has been developed to work with the EDAS system by van Ruymbeke et al. (2001). HiCum, like Spectrum Analysis, analyses signal signatures based on Fourier Analysis. Whereas Spectrum Analysis is necessary when the frequency of the signal is not known, in situations where the time period is clearly defined, such as diurnal fluctuations, then the HiCum method is more accurate and is capable of extracting information that would be lost with Spectrum Analysis. It becomes suitable in the case of rotating gravimeters for which the period is perfectly known!



(Fig19) : Principle of HiCum Stacking applied to an eight day gravimeter signal (hourly scale). The series is cut in constant length time intervals corresponding to the period selected by a Doodson argument (i.e. 360° for 24 hours S1 period). The obtained histograms are simply added to obtain an average signal of the concerned component.



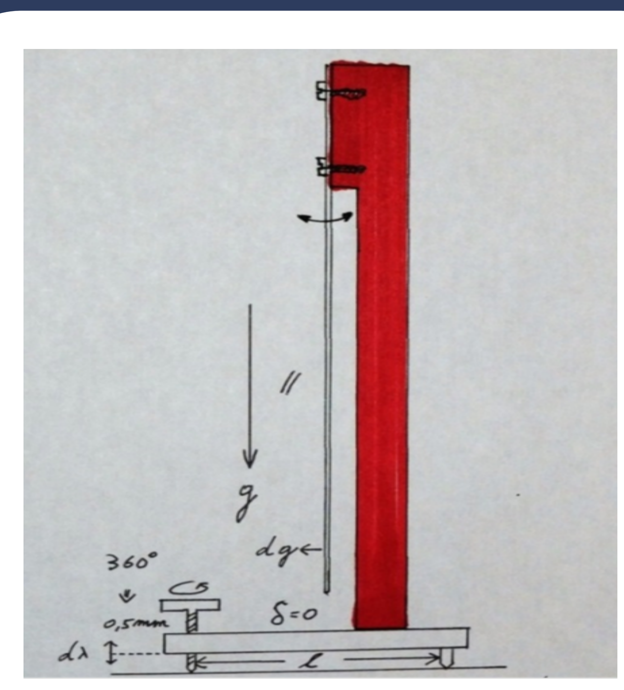
(Fig20) : Examples of the HiCum applied to the raw records of the two components of the Bgrav (Channels 1&2). This stacking is made with the one hour period of rotation of the gravimeter. After normalization of the two signals to obtain a same amplitude (Coef.2.823x), we obtain by subtraction, a signal with an amplitude of ~100000 Hz of excursion



((Fig21) : (top) HiCum applied to the signal of figure 20 combining the two the normalized gravimeters ones. (bottom) Residuals of the curves after corrections of the HiCum for fundamental and harmonics 2,3 & 4 components. The uncertainties on the average is about 10 Hz

Question 3: How to reject the effect of the Earth-gravity field?

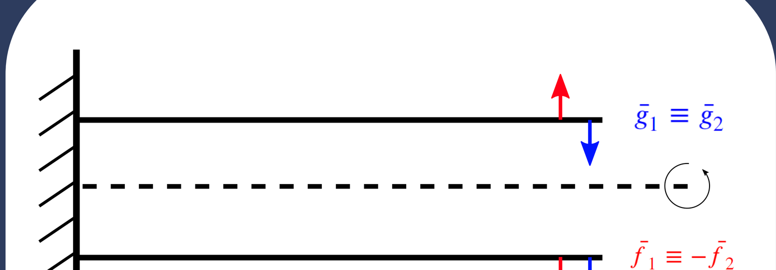
A gravimeter set-up verticaly feels only a very small part of the Earth gravity field.



(Fig22) : example of tiltmeter with option to support verticaly the Bgrav. It opens possibilities to simulate very small gravity changes like asteroid cases.

Gravity of the Earth : g(E) = 9,81 m/s²= 981gal
1 micrometer turn = 50 units = 500μm For L=50cm >>> 1 turn = 500μm/50cm= 1/1000
>>> 9.81m/sec² / 1000= ~1gal = 200x DDm gravity field >>> 1 micrometer unit = 20mgal =
4 x didimoon gravity field Arcsin (0.001)=0.0573°

Question 4: How to calibrate the gravimeter?



(Fig23) : Centrifugal and gravity torques acting for rotating BGrav

The calibration is obtained applying rotation of the Bgrav to produce centrifugal forces. No procedure to achieve a leveling of instrument oblige to develop such method which is independent of the orientation. It is suitable for on site check of transfer function determined before the launching.
Interest of the twin symmetrical gravimeters geometry is that they are submitted at the same torque in opposite direction. Inversely, for the gravity field, torques are in the same direction. So it is possible to simply separate gravity of centrifugal components by addition and subtraction signals. Calibration made with various periodicities allows to control coherency of the transfer function.

Additionnaly, it is possible to connect electronics to electrodes through large capacitors with high impedance resistors allowing to biais their with signal. Small voltage is sufficient to simulate Didymoon gravity field.
Active damping by electrostatic torque could be set-up if necessary.

In addition, notice that it is possible to survey sismic activity by a circuit which gives a FM signal equal to the difference between the two gravimeters, followed with F-to-V converter.

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