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A new method to estimate the time-position coordinates of a free falling test-mass in absolute gravimetry

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In the framework of the research activity carried on at the Institute of Metrology G. Colonnetti CNR-Turin and concerning the development of the IMGC02 absolute gravimeter, a new method to estimate time occurrences of interference fringes was developed, tested and finally adopted.

The measurement of the acceleration due to gravity is based on the reconstruction of the trajectory of a test mass subjected to a free falling motion in vacuo. Optical interference methods are widely used. In particular the IMGC02 gravimeter adopts an optical layout derived from a Michelson interferometer. Two corner-cube retroreflectors replace the mirrors to avoid loss of contrast in case of rotation during the flight. The inertial mass of a long-period seismometer holds one retroreflector while the other one is directly subjected to the vertical free-motion. An iodine-stabilized laser, which is a standard of length, is used to generate the light beam and a detector acquires the interference signal during the flight. An interference fringe occurs each half wavelength of the laser beam crossed by the falling object. The position-time pairs of the test-mass during the flight are measured by timing the interference fringes by a rubidium clock, which is the standard of time. Afterwards these position-time pairs are fitted by a suitable motion-model in a least-squares algorithm and the gravity value together with the uncertainty are obtained. The measurement accuracy concerning the time of occurrence of fringes becomes very important.

There are several fringe signal processing techniques which extract these time-position coordinates from the interference fringes. Among them, the mostly used by modern absolute gravimeters, included the IMGC02 up to few months ago, makes use of some electronic devices. The interference signal is recorded by a detector and sent to a zero-crossing discriminator ZCD after removing the DC component. The ZCD produces a TTL pulse each time the input voltage crosses the zero level in the positive going direction. The TTL pulses are scaled by a pre-defined factor N and a time interval analyser TIA, synchronized with a standard reference clock, measures times of occurrence of scaled pulses as to a starting reference time. The trajectory is consequently reconstructed for equally spaced data.

The main advantage of this technique is that the data processing is very fast. On the other hand there are some disadvantages. The zero-crossing discriminator introduces a time delay, dependent on the signal slew-rate, between the actual voltage zero-crossing and the TTL edge. Also the lower corner frequency of the RC network used for ac-coupling introduces frequency-dependent time delays. These frequency-dependent time delays can be critical sources of error in absolute gravimetry. Moreover this technique doesn't allow any real time evaluation of uncertainty in timing measurement because the information concerning the interference fringes shape is lost.

By taking advantage of new generation waveform digitisers and computing power of present processor we developed a new method to estimate the time of occurrence of fringes. It requires only a detector, a waveform digitiser synchronized to a rubidium clock and a computer. This method applies equally well either to a simple fall or a symmetric rise and fall system. The interference signal is recorded by the detector and buffered by the waveform digitiser in an indexed array. This array is processed and the indexes relevant to the crossing of a threshold (the average value of the signal) in a positive going direction are computed and buffered in a new array. Such indexes are scaled by a factor N and, for each crossing index, a number of following samples correspondent to one single period of the interference signal is extracted from the first buffered array and form a kind of window on to the interference signal. The interference fringe inside the window has a time shift as to the time correspondent to the crossing index which is known by the clock frequency. The time shift together with the uncertainty are measured by fitting an interference signal model to the intensity-time data concerning the window by a total least squares algorithm. The test-mass trajectory is easily obtained by adding this time shift to the relevant time correspondent to the index for each widows. Along the trajectory, it is possible to estimate the residuals concerning the interference signal and other interesting parameters such as the amplitude and offset level of interference fringes, which are lost in the traditional method.

This fringe signal processing technique gives several advantages. Expensive and bulky electronic devices such as the zero crossing discriminator and the time interval analyser are avoided and the RC network used for ac-coupling is unnecessary. The associated frequency-dependent time delays, potential source of error in absolute gravimetry, are completely removed.

The real time evaluation of the variation in the amplitude and offset level of the fringe signal, the timing uncertainty and fitted data residuals yield diagnostic information of the instrument performance and give to users new powerful tools for checking the experimental conditions. All this information is lost in the traditional technique. Once the data processing software code is tested and certificated it gives an higher level of robustness and reliability than the previously electronic devices which were subjected to aging.

Concerning the disadvantages, at present the program processes about seven hundred and fifty windows of the interference signal in about thirty-five seconds on the adopted 1.8 GHz Pentium® IV processor. There is the possibility to decrease this time by further optimisation of the software code but currently it is not the limiting timing factor for the IMGC02 absolute gravimeter.

Experimental and simulated tests were done to assess accuracy and uncertainty of this new data processing technique. Several measurements were performed with the IMGC02 by processing simultaneously the same fringe signal both by the new method and by the traditional one. The best agreement between the two methods was found in case of constant fringe visibility during the test mass trajectory, with a discrepancy < 1 μGal.

To complete the assessment of the uncertainty introduced by the new method, the fitting algorithm has been also tested on simulated data. A Monte Carlo simulation, consisting of 180 launches, was done by generating interference fringes according to equations concerning the motion of the test-mass and the interference signal.

It has to be underlined that the simulation is performed under the hypothesis of an ideal time and length reference, it doesn't take into account the short-term instability of a real rubidium clock and a real He-Ne laser.

The limiting factor to the timing measurement accuracy was found to be the resolution of the waveform digitiser which samples the interference signal (8 bit in our case), nevertheless the expected systematic bias in *g* is within 0,05 μGal with a standard deviation of 0,2 μGal which is negligible if compared to the total combined uncertainty.