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A PROPOSAL FOR SOLAR GRAVITATIONAL REDSHIFT MEASUREMENT

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Abstract. The Gravitational Red Shift (**GRS**) is the loss of energy of a photon ascending a gravitational potential. Even if it can be interpreted in terms of classical mechanics, deviations from its theoretical value imply considerations about General Relativity. Hence, a precise determination of its value will be an independent test of the theory. Because of its large mass, compared to Earth, the Sun is a preferred source to be considered to study this effect; nevertheless, up to now, the best precision of the solar GRS is quoted not better than 1%, as from the historical measurement of Lo Presto. A new acquisition hardware has been developed at the Solar Laboratory of the University of Rome. It takes advantage of a Magneto Optical Filter (**MOF**), a very narrow bandpass filter, tuned on Na or K lines, that allows to acquire Doppler images of the sun. The starting point of this technique is that sun shows a very large Doppler signal due to its rotation: the only points displaying zero values are those close to the rotation axis. Their separation is indeed a measure of the solar GRS. With our instrumentation, the GRS can be measured with high precision as some preliminary analysis on previous data demonstrate. This presentation at SPSE meeting is for large part taken from a paper of the same authors accepted by the journal Celestial Mechanics and Dynamical Astronomy.

Key words: solar physics, GRS, MOF, solar lines, Doppler signal, general relativity

1. Introduction

The gravitational potential of a celestial body affects the physical time, slowing down any periodic phenomenon assumed as the physical clock. In order to verify this statement, the behavior of different types of clocks, located in different gravitational potentials, must be compared. During the last decades, four main experiment attempted to provide a measurement of gravitational redshift. The first is the famous Pound-Rebka-Snider experiment (Pound *et al.*, 1960) using the Mossbauer effect and measuring the frequency shift of γ-rays ascending a 22.6 m. tower at Harvard. The accuracy was of the order of 10%. In 1980 Vessot compared the frequency standard of two Hydrogen Masers, one on the ground and the other at 10000 Km on a spacecraft, was able to verify the theoretical prediction at the level of about $2 \cdot 10^{-4}$. In 1993 a similar experiment was conducted on board Galileo spacecraft by Krisher, using radio signals, and achieving a precision of 1%.

A different kind of possible experiments is provided by the solar spectral lines. The solar gravitational potential shifts their wavelengths relative to laboratory lines on Earth by the amount of $\approx 2.1 \cdot 10^{-6}$ towards the red. In terms of velocity, this is equivalent to a Doppler shift of 636 m/s outside the Earths gravitational field and 633 m/s at the Earths surface. Lo Presto ((LoPresto *et al.*, 1991)) used chromospheric Oxygen lines in emission, that are formed well above the main convective velocity field, reaching the precision of about 2%. The solar spectrum is attractive in this context because the Sun is a massive body monitoring the GRS to values far larger than what is possible on Earth (dynamic range).

2. Solar measurement

A number of problems arise when attempting to measure the GRS using the solar spectrum. One has to consider that, while helioseismology deals with differential signals (so that the need for accurate bias or systematic errors removal is not so strong) in the GRS case the wanted signal is itself a constant offset. Hence, one has to take into account a number of bias contributions, partly instrumental, partly arising from the solar lines themselves. As an example, the entire visible solar surface seems to move towards the observer as a consequence of convective motions; the result is a global, non uniform (turbulent, convective) blueshift. Helioseismology, on the other hand, brings by itself another source of noise: oscillating Doppler signals are superimposed on the GRS signature.
Let's consider the resulting equation from all the sources of Doppler shifts:

$$V_{Obs} = V_{GRS} + V_{BS} + V_{LE} + V_{dR} + V_{EOS} + V_{IB} + V_{He} \tag{1}$$

where V_{Obs} is the overall observed Doppler signal from a point on the Earth's surface (the observatory),V_{GRS} is the amount of the solar gravitational redshift relative to the same point, V_{BS} is the convective blue-shift, V_{LE} is the limb effect, V_{dR} is the contribution of solar differential rotation, V_{EOS} accounts for terrestrial rotation and sun-earth motion, V_{IB} takes into account instrumental biases and V_{He} is the helioseismic signal.

Among all these sources of noise, only V_{EOS} can be easily removed (from the ephemeris); for the other effects one can only rely on suitable models. As an example, convective blue shift exhibits a cosine dependence from the disk center (minimum at the solar limb, maximum on its center). Viceversa the limb effect is maximum at limb, minimum at disk center. Similar considerations (see also section 4) lead to the conclusion that an imaging Doppler acquisition is a necessary and efficient method to deal with this kind of noises. The instrument we use to acquire solar Doppler images has been developed during last decades in Rome by Cacciani ((Cacciani *et al.*, 1990),(Cacciani *et al.*, 2001)) and is called the Magneto Optical Filter (MOF).

3. The Magneto Optical Filter

The MOF is the core of the system that makes this experiment unique. Here let be enough to say that it is a very stable and narrow double band filter. The two bands

could be as narrow as $50m\AA$, achieving unsurpassed performances as far as its central wavelength reference stability and symmetrical tuning in the wings of the solar lines (Red and Blue sides). Each band can be selected separately at will so that a computer comparison (difference) between the transmitted images can produce the wanted Doppler image, while their sum gives an intensity image. As a filter, the MOF will be located between the telescope and the image sensor. In this manner we are able to reject all the other wavelengths of the solar spectrum, but the wanted line, so that we can definitely say that the MOF produces an artificial night, which is the necessary condition to detect faint signals. As an example, in Figure 1 (which is an image tuned in the core of the Sodium D lines) an intensity reversal (faint emission) is visible in the narrow MOF band-pass wherever magnetic field emerges from below at photospheric levels. Indeed, the magnetic field excites the emitting atoms and modifies the line profiles: the consequent slight increase of its central luminosity appears well visible in our MOF image. This effect should be taken in due consideration to obtain a precise determination of the line shift because it creates macroscopic distortions of the velocity measurement: magnetic regions should therefore be avoided, excluding them from the analysis. In Figure 1 the predominant rotation signal (from the East limb to the West limb) amounts to about 4 Km/sec. The signal originated by the GRS amounts to 633 m/sec (Doppler equivalent). We have been able to measure Doppler signals as low as 1 mm/sec by integration over the whole solar disk. Figure 2 shows a plot of the oscillatory signal due to solar p-modes in the 5 minute band (peak-to peak amplitudes 1 m/sec , integration time=30 seconds, telescope aperture 2 cm; JPL facility, Pasadena, California); therefore, our instrument has the potential capability to improve considerably the accuracy beyond the few percent so far achieved. Our final goal is to reach the precision of at least one part per mil.
The MOF's weight (about 1 Kg) and dimensions (10x10x30 cm^3) are very attractive for space applications. In this context, we could imagine a space project aimed to test the second order gravitational time dilation (a real test of the General Relativity metrics) going close to the Sun. A comparison between the solar signals from two satellites, one near the Earth and the other close to the Sun, will cancel all the unwanted effects listed above, but the GRS alone. In fact GRS depends on distance Sun-telescope, while the sources of noise are common in the two cases. The second order effect is proportional to ΔU^2 (where U is the gravitational potential and δU is its difference between the source and the detector) and is in the range of a mm/s (Doppler equivalent), well within the capability of our MOF. A space mission is also desirable to avoid spurious effects from the Earth's atmosphere; however, due to the high costs and other difficulties of space projects (as, for example, the spacecraft motions), it is preferable to perform our first measurements from the ground, taking advantage of the absolute wavelength reference of the MOF and the well known Sun-Earth relative Doppler shifts at any time.

4. First results

For a full and complete description of preliminary analysis and results, please refer to (Cacciani *et al.*, 2006). Now, just few comments about the advantages of using

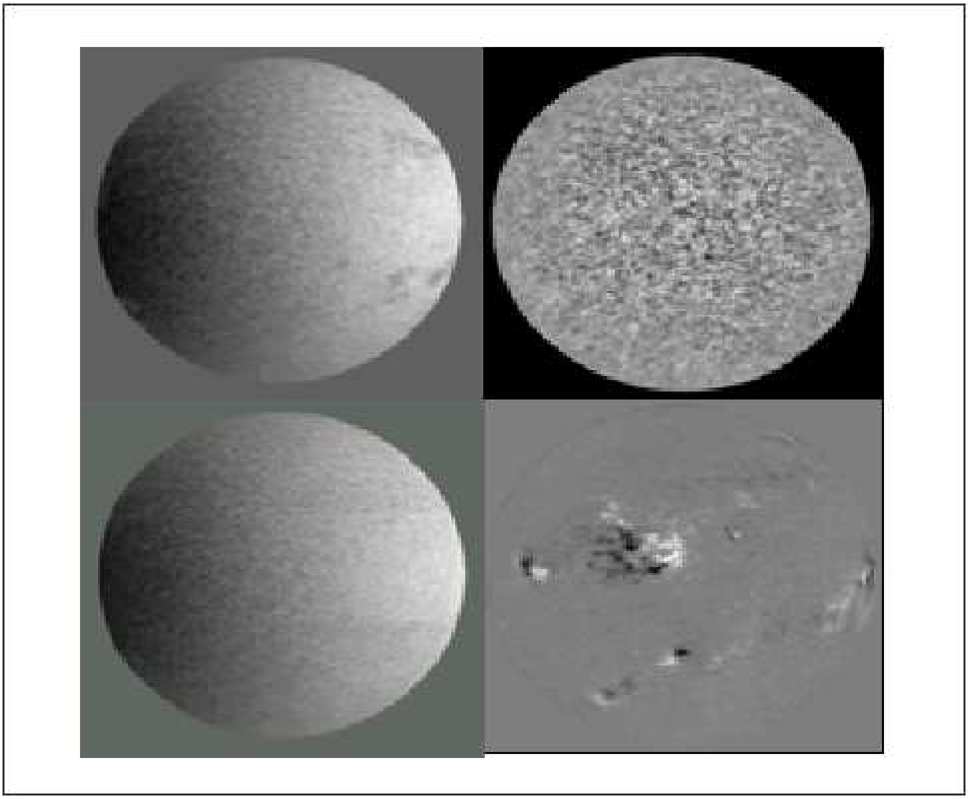

Fig. 1. Image of sun disk acquired with MOF. The left panel show the Doppler effect due to sun rotation. The right panel shows the Doppler signal when rotation is removed (upper) and the magnetogram of sun disk (lower)

full-disk Doppler images:

- It is possible to identify and avoid the magnetic regions during the analysis (see the dark patches in Figure 1.
- Each pixel can be normalized to the local intensity (that is not homogeneous over the solar disk). This could prevent any crosstalk between Doppler and Intensity in the case we have very high image resolution, practically unachievable. Indeed, included in each resolution element coexist microscopic rising and falling elements, the first being hotter and brighter than the descending ones, so that a net blue shift results when the image resolution is poor.
- It is possible, pixel by pixel, to account for the fact that the above blue shift, V_{BS} is maximum at the solar centre and vanishes at the limb as $\cos\phi$.
- The solar rotation signal, V_{dR}, although differential in latitude, appears always null at the axis where it is perpendicular to the line of sight.
- Finally, although the effect of V_{LE} (the centre to limb variation of the solar line profile) is more difficult to be accounted for, it is possible to evaluate its contribution assuming a linear behaviour with the distance from the disk centre,

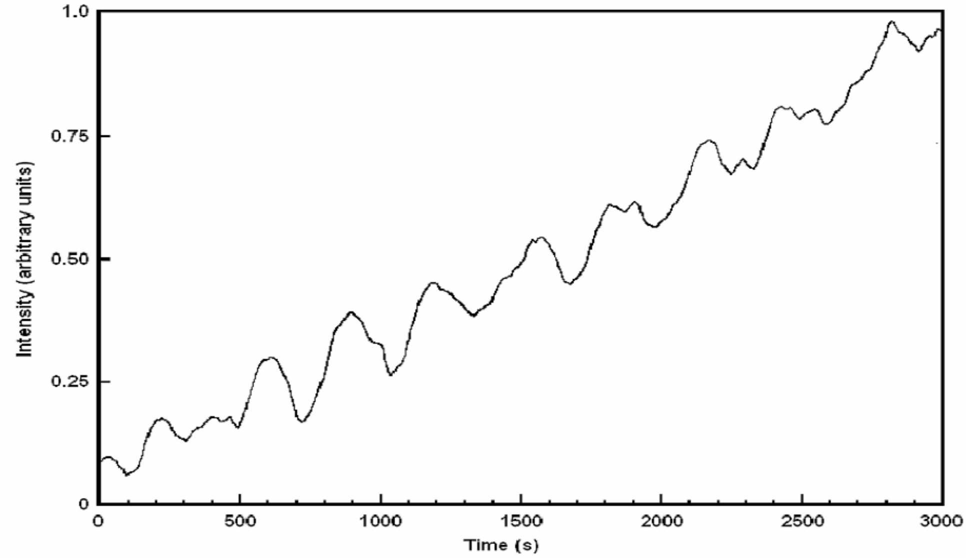

Fig. 2. A plot of helioseismology signal with MOF: peak to peak amplitude is of the order of 1 m/s, superimposed to the Earth rotation effect.

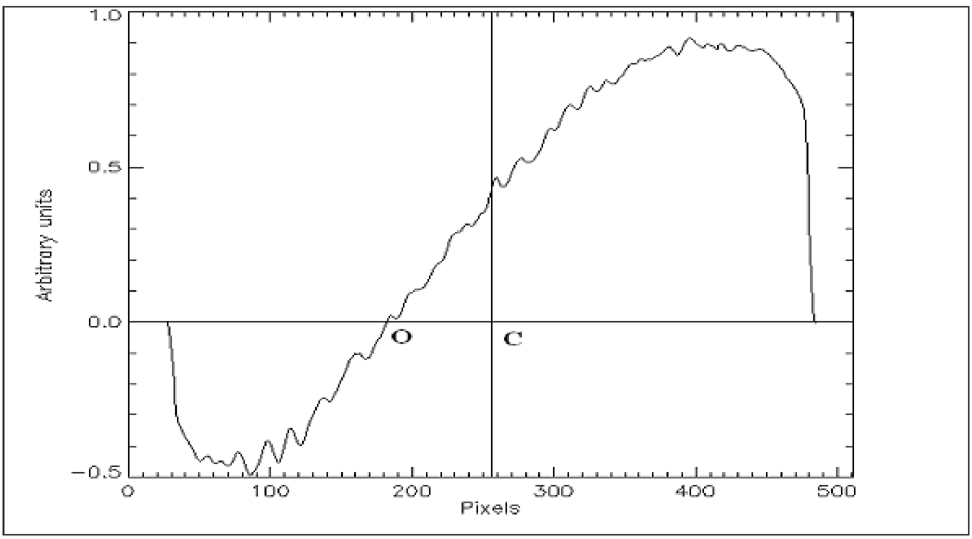

Fig. 3. Plot of Doppler effect signal on sun equator: the zero-crossing point displacement from rotation axis is the indicator of solar GRS.

within a limited region (inside the larger circle in Figure 1.

Each Doppler image will thus offer many points where the full signal can be computed (redundant system of equations). The Ephemeris data will help determining the values for V_{dR} and V_{EOS} to a very high degree of accuracy, while the two quantities

V_{BS} and V_{LS} will be obtained measuring distances in pixels (as both are assumed to be linear functions of distance, inside the limited central region). With a large time series of Doppler images we are confident to achieve our result with an error within the 10^{-3} limit. Indeed, our software procedure to identify image centres and diameters has shown that the time series of those quantities is normally distributed, allowing controlling the degree of accuracy as a function of length of the time series.

4.1. Data analysis

The full project is quite expensive and several funding proposals have been submitted. While waiting for the necessary financial support, we have analyzed a few MOF Doppler images, including some taken previously during our 1999 expedition at the Antarctic Italian site of Baia Terranova. It is remarkable the fact that just looking at the Figure 1, the zero velocity line appears crossing the equator at about one quarter radius eastward which corresponds to about 500 m/s taking into account the line of sight component of the solar rotation only.

We shall limit the analysis within a given circle around the centre, such as that the two signals V_{BS} (which is maximum at the centre) and V_{LE} (which is null at the centre and maximum at the limb) vary linearly with the distance r from C:

$$V_{BS} = (1 - r)V_{BS}(C)$$

$$V_{LE} = r \cdot V_{LEmax}.$$

For the centre C and all the points L_i along the rotation axis, $V_{dR} = 0$ and the equation 1 becomes

$$V_{Obs} = V_{GRS} + V_{BS}(C) + (V_{LEmax} - V_{BS}(C)) \cdot r + V_{EOS} + V_{IB} + V_{He} =$$

$$V_{GRS} + V_{BS}(C) + \gamma \cdot r + V_{EOS} + V_{IB} + V_{He}$$

where $\gamma = (V_{LEmax} - V_{BS}(C))$. Using this equation for the centre C and another point L_i , we can determine the value of γ:

$$V_{Obs}(Li) = -\gamma \cdot r_{Li} + \Delta V_{He}$$

$$\gamma = V_{Obs}(Li) - V_{Obs}(C))/r_{Li} + \Delta V_{He}.$$

The term ΔV_{He} can be made negligible just smoothing the signal along the rotation axis and taking its average from a long time series of images. For a rough signal calibration, we can use eqn a) for a point L_i on the axis and a point P off axis, but at the same distance from C. We get

$$V_{Obs}(P) - V_{Obs}(Li) = V_{dR}(P),$$

which is well known. The final results of such calibration leads $V_{GRS} = 625m/s$. The above result is already at the level of 1% internal error; however, it is only indicative being affected by errors, unknown biases and long term instabilities that our project will be able to characterize very precisely.

A better calibration will come from the orbital motion of the Earth during a full year of data.

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