Highlights of Spanish Astrophysics VII, Proceedings of the X Scientific Meeting of the Spanish Astronomical Society held on July 9 - 13, 2012, in Valencia, Spain. J. C. Guirado, L.M. Lara, V. Quilis, and J. Gorgas (eds.)

Secular measurements of the solar gravitational redshift (1976 - 2011)

P. L. Pallé [1,2], and T. Roca Cortés[1,2]

[1] Instituto de Astrofísica de Canarias (IAC), La Laguna, Tenerife, E-38200 Spain
[2] Departamento de Astrofísica. Universidad de La Laguna, La Laguna. Tenerife, E-38200 Spain

Abstract

The solar spectrophotometer "Mark-I", located at the Observatorio del Teide and continuously operated for the latest 36, provides a high precision measurement of the radial velocity of the Sun-as-a-star which has enabled the study of the small velocity fluctuations produced by normal modes solar oscillations and the characterization of its spectrum. Furthermore, because of its high sensitivity and long term instrumental stability also provides a daily accurate determination (less than 1 m s^{-1}) of the daily radial velocity offset, the so-called "solar gravitational red-shift" (GRS). In the present work, first results of the analysis of this parameter over the whole period 1976-2011 are presented.

1 Introduction

The red shift of spectral absorption lines from the solar photosphere has been empirically known since 1896 [18] and was then interpreted in terms of pressure shifts. The formulation of the principle of equivalence and later of the General Theory of Relativity [13] suggested that the phenomenon was due to the difference in gravitational potentials between the solar photosphere and the Earth's surface. This encouraged extended observational work which has certainly established that the solar red shift of spectral lines is quite a complex phenomenon with the possibility of velocity fields, collision effects, magnetic effects and others adding to the gravitational redshift (GRS) [1, 22, 8].

In contrast with astrophysical applications of the GRS an experimental test become possible only after the discovery of the Mösbauer effect [24] and is undoubtedly capable of substantial improvements in the future. It is also very likely that atomic clocks as well as laser based frequency standards will made possible substantial improvements on the accuracy of measurement of the GRS on the Earth's surface in the near future.

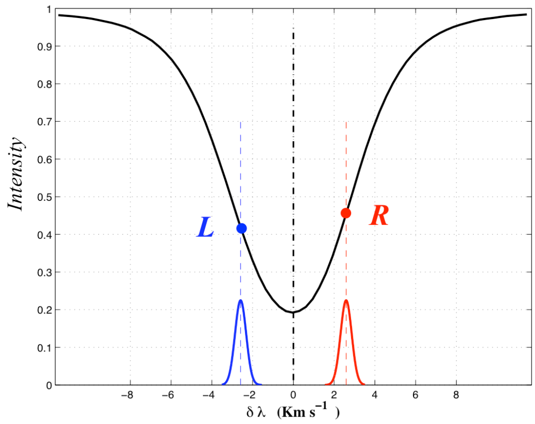


Figure 1: Principle of operation of the vapour cell resonant scattering spectrophotometry.

In recent years several measurements of the solar GRS were made [6, 27, 28, 19, 21]; the reported agreement with relativity predictions for the strong resonance absorption lines of potassium and sodium which are formed high in the photosphere are whithin observational error of some 10% including systematic effects. More recently [22, 8] there has been improvement of the knowledge of the solar effects that add to the GRS reducing systematic errors and improving the obtained results.

On the other hand, [16] and [14] have introduced the use of vapour cells in the measurement of radial velocities in the sun's photosphere when observed as a star, resulting in an improvement by more than one order of magnitude over existing techniques. These have resulted in the discovery of the solar oscillations and the birth of Helioseismology. One of such instruments, named MarkI, has been used since 1975 in the Observatorio de El Teide (Canary Islands, Spain); such instrument [7] resulted with a high long-term time stability and provided, as a byproduct, a long series of GRS measurements, from the years 1976 to 2011. In this paper, we report on a preliminary phase of such investigations which have so far been restricted to the 7699 Å resonance line of neutral potassium atom and light integrated over the entire Sun.

2 Principle of the method and apparatus

The method used by the resonant scattering spectrophotometry is best illustrated with reference to Fig. 1: circularly polarized light with an absorption line represented by the solid black curve is incident on a suitable atomic vapor cell having a resonance line overlapping the absorption line, placed in a longitudinal magnetic field of such a strength as to place the Zeeman components (curves blue and red) near the steepest parts of the absorption line. The intensity of resonantly scattered light due to left-handed circularly polarized incident light is given by L whereas that due to right-handed circularly polarized incident light is given by R. It is clear from the figure that when there is no relative displacement between the incident spectral line and the laboratory ones, L equals R. If, however, there is a relative shift between the two lines, as illustrated in the figure, the two intensities are no longer equal and the ratio defined as:

$$R = \frac{L - R}{L + R} \tag{1}$$

which gives a measure of the lineshift corrected for any intensity fluctuations, is not null. Since the narrow laboratory Zeeman components scan the steepest parts of the broader solar line this method is extremely sensitive to very small shifts. In this experiment natural potassium vapour was used to study the 7699 Å absorption line. The solar line has a full width at half depth of 6.23 km s^{-1} while the region probed by the laboratory lines is of order of 1 km s^{-1}, thus the ratio R will be linearly related to the velocity shift between the Sun and the laboratory to first order approximation. A more detailed account of modifications due to the hiperfine structure and isotopic composition are to be found in the more comprehensive paper [7].

The MarkI apparatus, was developed and build at Birmingham University (UK) during 1973 and 1974 being gradually improved over the following five years. A detailed account of its state during 1976 and 1977 in the site at Observatorio de El Teide (Izaña, Tenerife) is also to be found in [7]. A brief summary follows: a small equatorially mounted servo-controlled heliostat directs disk-integrated sunlight, appropriately filtered by a heat, a coarse and a thermostatically controlled interference filter centred at 769.9 nm and of bandwidth of 1.5 nm, through a polarizer and an electro-optical light modulator which produce the required left- or right-handed circular polarization by the application of appropriate electric potential. The light then enters a vapour cell situated in the field of a permanent magnet; the resonantly scattered light is detected by a cooled photomultiplier tube and the processed output pulses are recorded on digital magnetic tapes for subsequent computer analysis. In order to test for various optical asymmetries and to asses the overall stability of the system a light source on its own or a white light (quartz-iodine) with a vapour cell in a transverse magnetic field to provide an artificial absorption line simulating the solar K line was also used. A full description of the apparatus' performance, stability and sources of error is to be found in [7].

3 Observational procedures and strategy

From 1975 onwards, the MarkI instrument has been used exclusively to study the oscillations of the Sun as a star and the measurement of the GRS is only a byproduct which will be studied in this work. Integrated sunlight helps reduce the random shifts of the spectral line due to motions in the solar photosphere due to convective features. Moreover, it has the advantage that the rotation of the Sun is averaged to zero and possible instrumental errors due to imprecise guiding or atmospheric turbulence become minimised. Obviously, small signals due to angular non-uniformities on the photosphere such as sunspots or in sky transmission or instrumental errors will be discussed later on.

MarkI was taken to Observatorio de El Teide in 1975 and began operations by the end of the summer. Then several long summer observing campaigns were carried out there until 1984. During those years MarkI performance was being monitored and also used to develop other apparatus, based on the same principle, that helped to settle Helioseismology as an

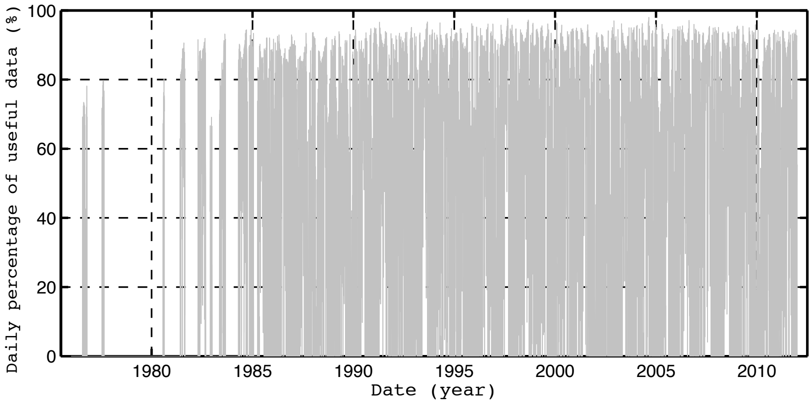


Figure 2: Census of MarkI solar observations along the years used in this work.

astrophysical discipline on its own. Moreover, from summer 1985 on the observations were taken on a daily basis in a basically undisturbed and steady regular observational procedure.

Sunlight to the spectrophotometer is being provided by an open air two flat mirrors heliostat system; the two axes servo controlled primary mirror (also moves along the north-south line throughout the year) feeds a fixed secondary mirror which provides a horizontal sunlight beam entering the spectrophotometer. This system, although symmetric around noon, has to be altered by changing the secondary mount at the equinoxes otherwise it will cast shadow onto the primary around noon. Before 1979, the heliostat system had an extra fixed flat mirror to acomodate the sunlight beam properly; also the mirrors were of lower quality.

Very minor changes in the core parts of the apparatus have been introduced and it can be said that up till 2010 MarkI has been working without interruption, weather permitting, other than some failures that have been solved quite rapidly. The main changes have come from the readout electronic system updates that evolved from fast analog electronics and seven track magnetic tapes to fast digital electronics and a computer system. Its performance has been outstandingly good and only in October 2010 the vapour cell (and PM tube) had to be changed because the darkening of the windows lowered the counting rate.

The raw data consists on a one second measurements on the lefthand side of the line followed by another second on the righthand side of the line. The counting usually spans from 0.2 to 2 MHz depending on sky transparency, thin cirrus and mirror cleanliness. Then the ratio is calculated and on the basis of blocks of 42 s finding its average and standard deviation. Therefore, a velocity measurement is taken with a velocity random error of ≈ 1 to 2 m s^{-1}. The census of the observations during these years can be seen in Fig. 2. In the period from 1976 to 2011 with a total span of 13149 days we have observed for 8300 days; however in the period from 1985 to 2011, where daily observations were started, out of a total span of 9861 days we have got 7656 days of observations for a total of 60907 of useful hours for a duty cycle of 52% of the possible daily hours.

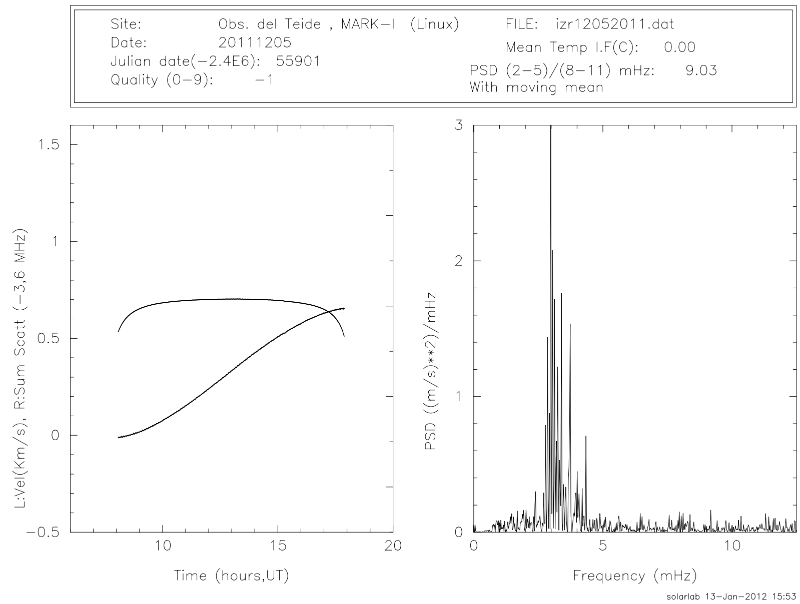


Figure 3: Results of a typical day of observation. Left panel shows the velocity and the light transmitted through the apparatus curves, while in the right graph a density power spectra of the velocity curve is shown with the 5 min solar oscillations being clearly above noise level.

4 Data analysis

The result obtained on a typical day of observation is showed in the left graph of Fig. 3 and can be understood in the following terms. If all the displacements of spectral lines of the Sun with respect to the laboratory are expressed in terms of relative velocity of the Sun with respect to the laboratory we have:

$$V_{OBS} = V_{ORB} + V_{SPIN} + V_{GRS} + V_0 + V_{OSC}(t) \tag{2}$$

where:

$$V_{ORB} = (\vec{V_\odot} - \vec{V_\oplus}) \cdot u_r \tag{3}$$

is the resolved component of the relative velocity of the Sun and Earth along the unit radius vector joining their centres, with due allowance for the planetary and lunar perturbations,

$$V_{SPIN} = \vec{V_{obs}} \cdot u_r = \omega_\oplus R_\oplus \cos\lambda_{obs} \cos\delta_\odot \sin\frac{\pi}{12}(t - t_0) \tag{4}$$

is the component due to the observatory's daily rotation, where $\omega_\oplus$ is the angular velocity of the Earth, $R_\oplus$ is the observer's distance from the center of the Earth, λ_{obs} is the latitude of the observatory, $\delta_\odot$ is the declination of the Sun and t_0 is the local noon,

$$V_{GRS} = \frac{GM_\odot}{c}\left(\frac{1}{R_\odot} - \frac{1}{AU}\right) - \frac{GM_\oplus}{R_\oplus} = 635.8 \text{ m s}^{-1} \tag{5}$$

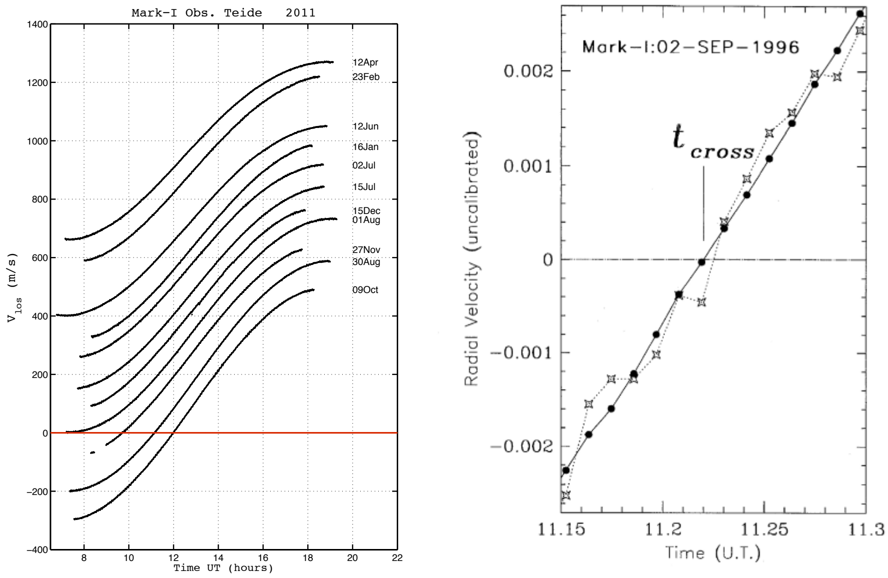


Figure 4: *Left panel:* a few days of observations spread along the year illustrating that only from August to December the daily velocity curve crosses zero. *Right panel:* zoom to show the location of the crossing time,t_c, that is the time of the day when the velocity of the sun relative to the observatory is zero.

is the GRS velocity equivalent, where G is the gravitational constant, c the velocity of light and $M_\odot, R_\odot, M_\oplus, R_\oplus$ are the Sun and Earth masses and radius respectively,

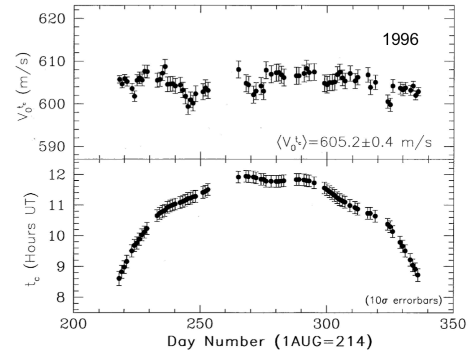
$$V_0 + V_{OSC}(t) \tag{6}$$

are unknown solar velocities; the first term represents the solar velocity fluxes that can be considered stable over a day while the second stands for the measured global oscillations with periods lower than a day [9].

The term V_{GRS} may be regarded as constant, V_{ORB} varies along the year with a maximum of ≈ 12 m s^{-1} between succesive days whereas the V_{SPIN} varies sinusoidally over a day with an amplitude that changes from 375 and 408 m s^{-1} at Observatorio de El Teide depending on the sun's declination. This terms can be best seen in Fig. 4. Notice that these Earth's movements provide an accurate (and daily) calibration of the Doppler measurements in terms of velocity units to the nearest cm s^{-1}. On the other hand, instrumental, systematic and random noises can provide spurious velocity terms that shall be dealed with further.

5 A null measurement of the GRS

In Fig. 4, the seasonal changes (due to V_{ORB}) can be also clearly seen and it can be noticed how the ratio R crosses a zero value sometime in the mornings of summer-autumn seasonal days. In fact, at Observatorio de El Teide this happens roughly from the 1$^{\text{st}}$ of August to



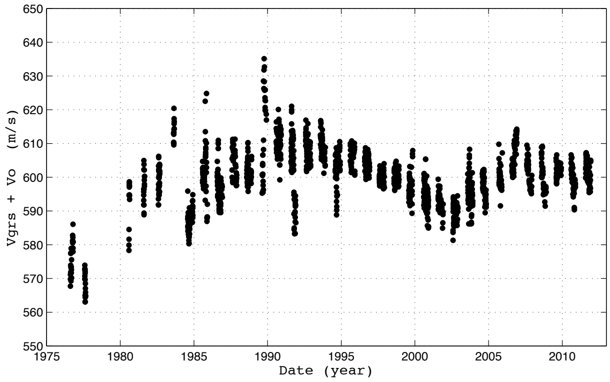


Figure 5: *Left panel:* GRS velocity obtained along year 1996 which is quite similar to anyone year observed; bottom, the crossing time obtained from the observations and, top, the corresponding calculated velocity. *Right panel:* the GRS velocity obtained along all years where observations are available.

the 4$^{\text{th}}$ of December. At that precise time the solar absorption line and the laboratory lines have a relative zero shift. It is clear that such a null observation provides a very sensitive means of determining a daily value for $V_{GRS} + V_0$ in terms of the very accurately known value of $V_{ORB} + V_{SPIN}$ (see Fig. 4, right). The term $V_{OSC}(t)$ having the information of the solar oscillations is very small in amplitude (less than 1 m s^{-1}) and period (around 5 min) and can be filtered out quite well in this work. Moreover, this measurement is independent of various background instrumental noise problems and curvature effects of the solar absorption line near the operating region making it quite independent of the calibration of the apparatus in terms of velocity. There are other methods to obtain such measurement, but they require velocity calibration and do not have the properties mentioned before.

Therefore, a way of obtaining the crossing time is to fit a straight line to a given short interval around the crossing. The interval should be short enough so that a straight line is a good approximation and long enough so that the oscillations signal can be appropriately averaged out. The interval found appropriate is of 40 min centered on the crossing time. The actual way of measuring de crossing time is shown in Fig. 4 (right). Following the passage of a moving mean filter, a straight line is fitted and the crossing time and its uncertainty calculated. The fit has been made with and without filtering, various filters were also checked, without significant changes in the result.

For anyone year of observation (1996 for instance) one obtains tipically under 90 measurements that can be seen ploted in Fig. 5. The graph on the left shows the observed $V_0^{t_c} = V_{GRS} + V_0$ daily values where we can notice that the average value, (605.2 ± 0.4) m s^{-1}, is not that expected from the frist term alone, therefore V_0 is not null. Moreover, there are daily variations well out of the errors on each measurement. Such daily variation have amplitudes of up to 10 m s^{-1} and periods around half the solar rotation period, which clearly remembers the activity features on the photosphere moving across the visible solar hemisphere. Therefore, we have to understand the result found which is similar in all observed

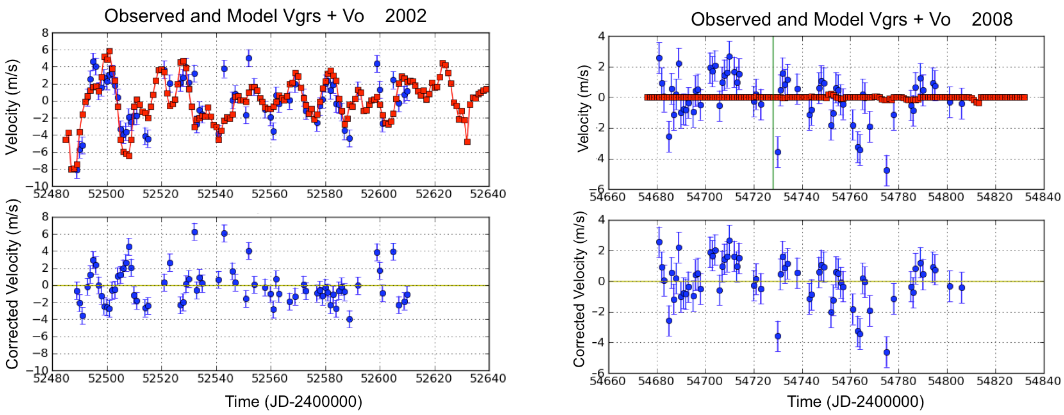


Figure 6: Variations on the GRS velocity obtained along a particular year (blue dots) and the results of the numerical simulations (red squares) in a year close to maximum (2002, left) and another one close to minimum solar activity (2008, right).

years. Moreover, the graph on the right show all raw determinations of the GRS using the available observations.

6 Corrections

Fig. 5 shows a clear daily variation with periods around half the solar rotation period, the so called 13-day period variation due to the passage of sunspots across the visible solar photosphere, already pointed out by [12], [2] and [15]. Moreover Fig. 5 also show a mean value far from the predicted GRS velocity. Therefore, the V_0 will or can have contributions from many sources, mainly solar and instrumental.

6.1 Solar effects

Obviously, the observed signal will vary in amplitude from solar maximum to solar minimum as can be seen in the same figure. Such signal can be modelled so as to understand the observed data and eventually be substracted from it. A simple model has been done using the impresive sunspot data archive in NOAA-NGDG (http://ngdc.noaa.gov/) where daily sunspots' areas and positions are recorded with very few gaps. The numerical model is fairly simple and has been done in the past (see above mentioned authors); in this paper we have followed the work of [15] which uses data for the potassium line [26, 5] and references therein.

Another effect which is also well known is the so-called limb-shift effect, which is due to the granulation velocity fiels present in the sun's photosphere whose effect result in an asymmetry on the spectral lines (the C-shapes bisectors) which change as we move from center to limb [10, 11, 20]. As we observe the sun as a star the measurements will be affected by the disk-integrated result of this effect which usually results in a net blue-shift in most of the photospheric spectral lines. This effect for the KI7699 line has been measured in the past

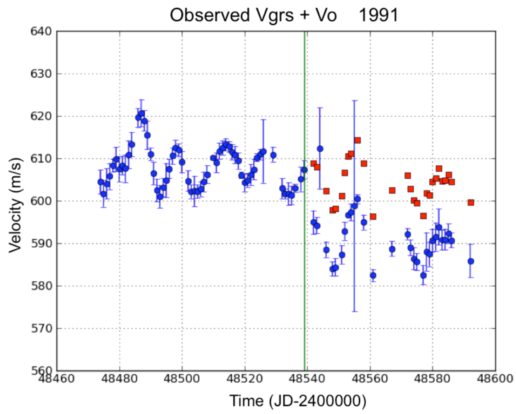


Figure 7: Instrumental effect on the GRS velocity of the summer to winter secondary mirror mount changeover (green vertical line). Notice that if a positive shift is added to the blue dot points following the mount changeover (red square points), the observed velocity matches much better the observations obtained before showing continuity.

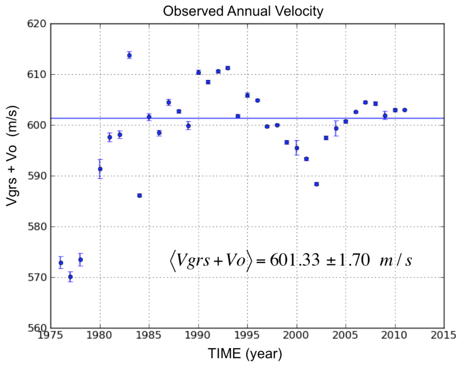
[4, 3, 22] and theoretically studied [23] resulting to be small, with some differences among the author. Once it has been included in the numerical simulation an integrated effect of 10 m s^{-1} has been obtained.

The numerically simulated results are quite interesting and can be seen for two years in Fig. 6 (red squares),one near solar maximum and the other near solar minimum. As it can be seen in the figure the match is quite impresive given the observational errors, although some minor details that do not seem to match which probably suggest that the use of a bit more realism would be interesting (inclusion of faculae contribution for instance) but difficult, due to the lack of data. The numerically obtained average GRS is of 601 m s^{-1} and its amplitude had to be multiplied by a factor of 2 to match well the observed data.

6.2 Instrumental systematic errors

A thorough analyses of the posible instrumental errors in the apparatus is to be found in [7] and in [25]. Along the observing days there have been done many tests that confirm the expected results in these analyses. Such tests were always performed by changing one item at a time and leaving at least a complete day of observation to be able to measure the actual effect of the change on the observed data. Moreover, from 1985 onwards some housekeeping data has been also recorded.

To summarise here the results, it can be said that the systematic errors (mechanical, thermal, optical and electronic) are kept well below 1 m s^{-1} level in all parts of the instrument. However, the most sensitive source of error is the misalignment of the electro-optical light modulator (EOLM) with respect to the entrance sun-beam. This can be observed and measured near the equinoxes when the secondary mirror mounting is changed. In doing this change a realignement is made and sometimes the same relative position, between the



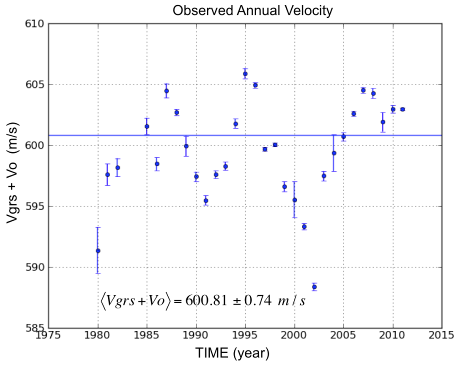


Figure 8: *Left panel:* annual averages of the GRS observed velocities. *Right panel:* the same graph once corrected some values (1990-93) for instrumental systematic errors and deleted others (1976-1978,1983) due to different heliostat set-up. See text.

entrance sunbeam and the EOLM axis, is not achieved. The resulting effect on the daily offset velocity measurement can be seen in Fig. 7, where precisely at the day of the mount changeover (green vertical line on the graph) a step in the measured velocity is clearly seen. By calculating the mean value of a few points before and after the mount changeover day we can correct for such systematic effect.

Another possible systematic effect might come from the existence of the isotope ^{41}K with a proportion of 7.4% respect to ^{39}K which may produce an isotope shift of up to -98 m s^{-1} as optical thickness of the vapor changes from thin to thick [17]. These effect can only happens if the optical thickness is different between the vapor in the cell and the one in the sun. In the cell can only change if the temperature of the oven changes; this parameter has been checked and made to vary by as as a factor of two in power found no significant changes in the results. On the other hand this parameter has no reason to change on the sun.

7 Discussion

Once the numerically calculated effect of the passage of the sunspots is corrected an annual average of the GRS velocity is obtained and plotted in Fig. 8 (left). Data from 1976 to 1978 result in some 30 m s^{-1} lower than the rest; this is probably due to the fact that in these years the heliostat system that feeds the spectrophotometer with the sunbeam was different than afterwards and included mirrors of lower quality. Later, during 1979 we had no useful data on integral sunlight as the instrument was used in another observing program. Moreover, in 1983 we had very few useful results (as much as 6) as the electronic channel analyser didn't work properly. These points have therefore been discarded. Finally, in the years 1990 to 1993 the systematic effect in the mount changeover was kept 17 m s^{-1} too high; once corrected a second definitive graph (see Fig. 8, right) has been produced.

The final average of this data is (600.81 ± 0.74) m s^{-1}. However, it also shows a ±5 m s^{-1} variation with a period of 10-12 years which coincides with the solar activity cycle.

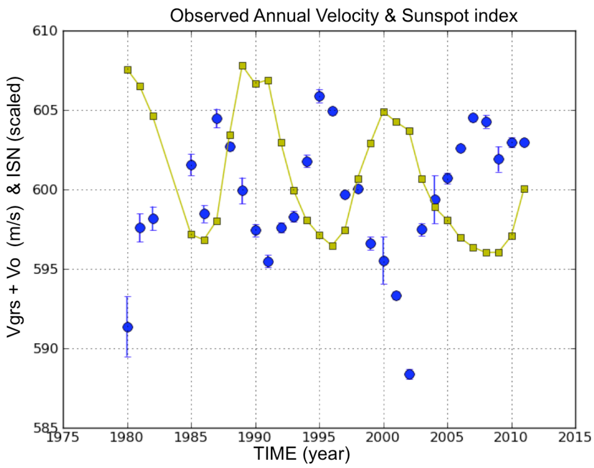


Figure 9: Annual averages of the GRS observed velocity (blue) and annual averages of the sunspot number (scaled appropriately too fit in the graph, green squares).

In order to understand this effect we have plotted, in Fig. 9, the results found together with the annual average sunspot number average (right); it can be seen a clear anti-correlation between the two graphs suggesting an explanation in terms of magnetic activity effects.

8 Conclusions

Preliminary results of the solar gravitational redshift measured in the KI7699Å line for the period 1976 to 2011 have been obtained as a by-product of the measurements of the integral sunlight oscillations. The average result over this period results in (600.81 ± 0.74) m s^{-1} with clear variation in anticorrelation with the solar cycle of roughly ± 5 m s^{1}. Correction for this effect should lower the error bar obtained. The value found for the GRS is -35.0 m s^{-1} from the theoretically value expected (5.5% of the full effect) . We believe that given the correlation found between the variations around the mean value and the solar activity cycle suggest that the discrepancy can be attributed to the overall asymmetry of the spectral line.

An obvious consequence of this work is that an accurate measure the solar GRS needs the use of non-magnetically sensitive spectral lines. A second consequence that can also be learned is when other stars are studied in radial velocity, the current reported findings would warn against interpretations as possible planets or other components in stellar systems.

Acknowledgments

The instrument, updates, and observations are also due to the latest Bob van der Raay, George Isaak and Bill Brookes whose dedication made possible the start and run for many summer campaigns. Without the work of many individuals, past and present members of the helioseismology group at the IAC, this extensive work would have never been possible. The authors acknowledge finacial support from the Spanish National Plan of R&D under projects AYA2012-17803 and AYA2010-20982-C02-02.

References

[1] Adam, M.G. 1948, MNRAS, 108, 446

[2] Andersen B.N. & Maltby, P. 1983, Nature, 302, 808

[3] Andersen, B.N., Barth, S., Hansteen, V., et al. 1985, Solar Phys., 99, 17

[4] Anguera, M., Pallé, P.L., Régulo, et al. 1987, in *The role of fine scale magnetic fields in the structure of the solar atmosphere*, E.H. Schröter, M. Vázquez, & A. Wyller (eds.), CUP, 24

[5] Bonet, J.A., Márquez, I., Vázquez, M., & Wöhl H. 1988, A&A, 198, 322

[6] Brault, T. 1962, Ph.D. Thesis, Princeton University, USA.

[7] Brookes, J.R., Isaak, G.R., & van der Raay, H.B. 1978, MNRAS, 185, 1

[8] Cacciani, A., Briguglio, R., Massa, F., & Rapex, P. 2006, in *Celestial Mechanics and Dinamical Astronomy*, 95, 426

[9] Claverie, A., Isaak, G.R., McLeod, C.P., et al. 1979, Nature, 282, 591

[10] Dravins, D., Lindegren, L., & Nordlund, Å. 1981, A&A, 96, 345

[11] Dravins, D. 1982, ARA&A, 20, 61

[12] Durrant, C.J. & Schröter, E.H. 1983, Nature, 301, 589

[13] Einstein, A. 1911, Ann. Phys. Leipzig, 35, 905

[14] Fossat, E. & Ricort, G. 1973, Solar Phys., 28, 311

[15] Herrero, A., Jiménez, R., & Roca Cortés T. 1984, Mem. Soc. Astron. Ital., 55, 331

[16] Brookes, J.R., Isaak, G.R., & van der Raay, H.B. 1976, Nature, 259, 92

[17] Jackson, D.A. & Kuhn, H. 1938, Proc. Roy. Soc, A165, 303

[18] Jewell, L.E. 1896, Ap J, 3, 89

[19] Jiménez, A., Pallé, P.L., Régulo, C., et al. 1986, Adv. Space Res., vol. 6, 8, 89

[20] LoPresto, J.C. & Pierce, A.K. 1985, Solar Phys., 102, 21

[21] LoPresto, J.C., Schrader, C., & Pierce, A.K. 1991, ApJ, 376, 757L

[22] LoPresto, J.C., Kraus, P.M., & Pierce, A.K. 1994, Solar Phys., 149, 243

[23] Marmolino, C., Roberti, G., & Severino, G. 1987, Solar Phys., 108, 21

[24] Pound, R.V. & Rebka, G.A. 1960, Phys. Rev. Lett., 4, 337

[25] Roca Cortés, T. 1979, Ph.D. Thesis, Universidad de La Laguna, Spain

[26] Roca Cortés, T., Vázquez, M., & Wöhl, H. 1983, Solar Phys., 88,1

[27] Snider, J.L. 1970, Solar Phys., 12, 352

[28] Snider, J.L. 1972, Phys. Rev. Lett., 28, 853