

## CALIBRATING 15 YEARS OF GOLF DATA

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**Abstract.** The GOLF resonant scattering spectrophotometer aboard SoHO has now provided 15 years of continuous high precision Sun-as-a-star radial-velocity measurements. This length of time series provides very high resolution in the frequency domain and is combined with very good long-term instrumental stability. These are the requirements for measuring the low-l low-frequency global oscillations of the Sun that will unlock the secrets of the solar core. However, before the scientifically interesting gravity and mixed modes of oscillation fully reveal themselves, a correction and calibration of the whole data set is required. Here we present work towards producing a 15 year GOLF data set corrected for instrumental ageing and thermal variation.

Keywords: Sun, helioseismology, instrumentation

### 1 Introduction

The Global Oscillations at Low Frequency (GOLF) instrument measures the Sun-as-a-star radial velocity field (Gabriel et al. 1995, 1997). Raw measurements are made in intensity and then corrected and calibrated to produce final residual velocities (García et al. 2005). The ability of this calibration process to produce high quality and very long time series (15 years) is important as GOLF is forced to operate in a single wing mode (Pallé et al. 1999). The scientific motivation for an improved calibration comes from the need for a stable 15 year time series. This will allow detailed analysis of the impact of the solar cycle on helioseismic parameters (Broomhall et al. 2009b; Salabert et al. 2009) and the detection of new low-frequency oscillations. Low-frequency oscillations have low signal-to-noise ratios making their detection a significant challenge. Recent reports on the signature of g modes (Turck-Chièze et al. 2004) and their fingertips (García et al. 2007, 2008) sparked much debate. An improvement in GOLF performance at low frequency could reveal the secrets of the solar core.

### 2 GOLF observations

GOLF makes measurements of intensity,  $I$ , integrated over narrow bands in wavelength,  $\lambda$ , and integrated over the visible surface of the solar disk,  $S$ . We can state this as a simple model,

$$I = \int_{\lambda} \int_S I_{\odot}(\lambda, S, v_{\text{los}}) W(\lambda, S, v_{\text{los}}) d\lambda dS, \quad (2.1)$$

where  $I_{\odot}$  is the solar D1 and D2 absorption line spectrum,  $W$  is the instrumental weighting, and  $v_{\text{los}}$  is the line-of-sight velocity between GOLF and the Solar surface. Given the measured intensity, the solar line function, and the instrumental weighting it would be possible to determine  $v_{\text{los}}$ . However, all three components contain some level of uncertainty and/or cannot be sufficiently modeled (Ulrich et al. 2000). So we make simplifications and propose a method that relies on the following statement: a well corrected instrument will give intensity measurements that are only a function of  $v_{\text{los}}$ . This gives us the definition of a parameter for good - the correspondence of intensity and line-of-sight velocity.

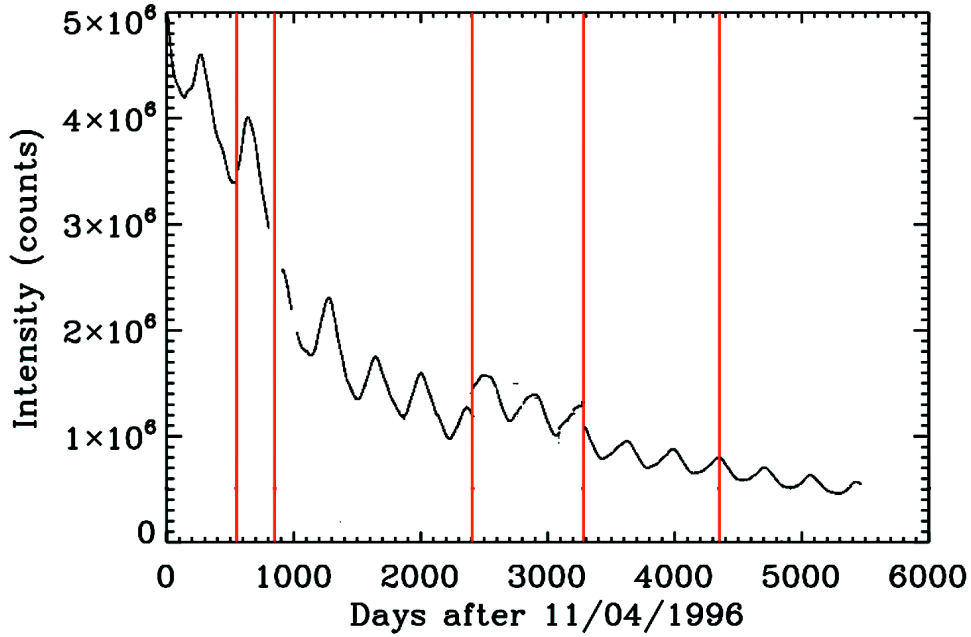
To achieve the best possible GOLF signal-to-noise ratio, it is necessary to correct for long term instrumental effects and to provide a stable calibration that minimizes non-solar variation in mode amplitude. Previous work

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has tackled these two aspects one after another. However, the gain of the instrument (photons detected divided by photons collected) and the instrument sensitivity ( $dI/dv_{\text{los}}$ ) are coupled. The two processes must be treated concurrently to give an optimum calibration. Figure 1 shows GOLF raw-intensity measurements as a function of time. There are two processes that are clearly visible: the yearly variation in the Sun-instrument line-of-sight velocity; and the ageing of the instrument. Further to this there is a less obvious variation of instrumental gain which is a function of the temperature of the instrument.

To account for all effects present in Fig. 1 we modify equation 1. We add the ageing of the instrument



**Fig. 1.** GOLF raw-intensity measurements as a function of time. Red lines mark breaks in continuity due to instrumental adjustments. The obvious effects displayed are the ageing of the photomultiplier tubes (PMT near exponential decay), the Sun-instrument line-of-sight velocity (one year period), and the discontinuities due switching between the “red” and “blue” wings and PMT high voltage adjustment.

(probably dominated by the ageing of the photomultiplier tubes)  $P(t)$ , the variation in flux as a function of the spacecraft-Sun distance  $F(d)$ , and the variation in gain due to the changes in instrument temperature  $K(T)$ . This gives

$$I = P(t)F(d)K(T) \int_{\lambda} \int_S I_{\odot}(\lambda, S, v_{\text{los}})W(\lambda, S, v_{\text{los}}) d\lambda dS. \quad (2.2)$$

Given the simple model of the the underlying system and a goodness-of-fit parameter, we can use the 15 years of GOLF observation to determine instrumental parameters. First we must define the parameters and functions describing the instrument.

The ageing of the instrument is expected to be dominated by the exponential loss of efficiency in GOLF’s photomultiplier tubes. From GOLF’s measurements we find that the rate of ageing varies as a function of time. To describe this in the simplest possible manner we use the following function,

$$P(t) = p_0 \exp -(t(p_1 + p_2t)). \quad (2.3)$$

The change in flux due to the variation in the spacecraft-Sun distance is determined by the solid angle presented by the GOLF aperture. It is trivial to how that

$$F(d) = f_0^2/d^2, \quad (2.4)$$

where  $f_0$  is a reference distance.

For the gain of the instrument due to temperature we use the form of García et al. (2005),

$$K(t) = 1 - k_1(T - k_0) - k_2(T - k_0)^2, \quad (2.5)$$

where  $k_0$  is a reference temperature. Variations in instrumental gain due to temperature have a number of possible sources: variation in the vapour cell stem temperature; variation in the detector temperature (PMT and counting electronics); and other sources including the temperature of the interference filters. Rather than considering a function for each temperature we note that each of the measured temperatures (particularly the cell stem and detectors) are well correlated. Using this we apply a single correction using only the stem temperature, which is the measured temperature with the greatest precision.

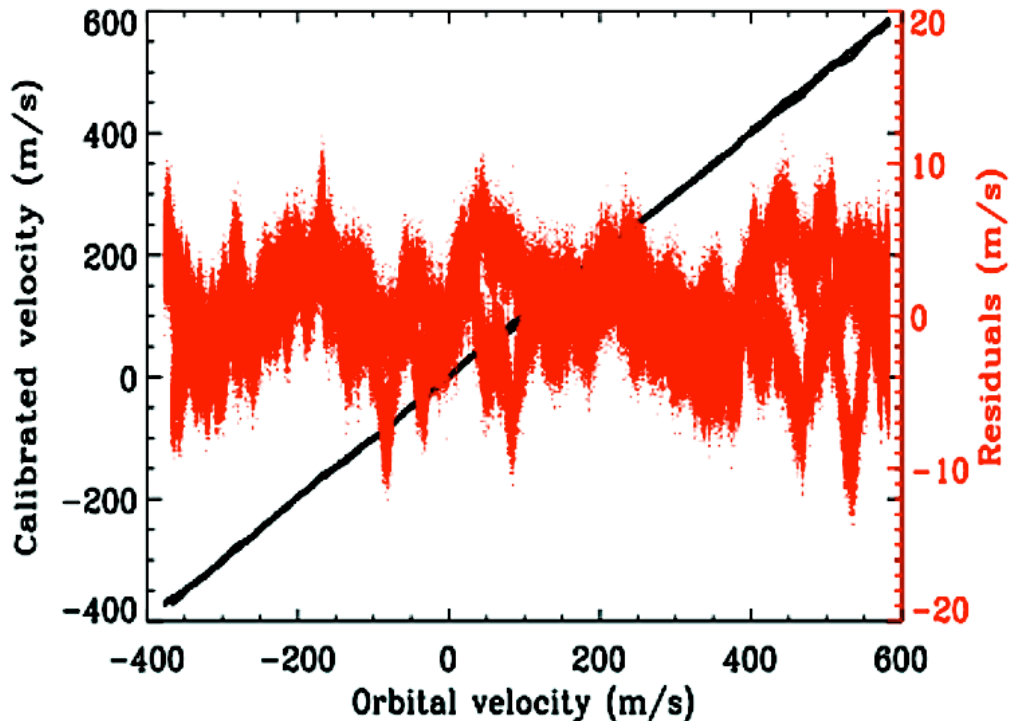
We must also describe the sensitivity of the instrument ( $dI/dv_{\text{los}}$ ). In this work we use the derivative of a fourth order polynomial as we know this has been successfully applied to similar but ground based instruments (Elsworth et al. 1995; Broomhall et al. 2009a),

$$\frac{dI}{dv_{\text{los}}} = \sum_{i=1}^4 a_i i v_{\text{los}}^{i-1}. \quad (2.6)$$

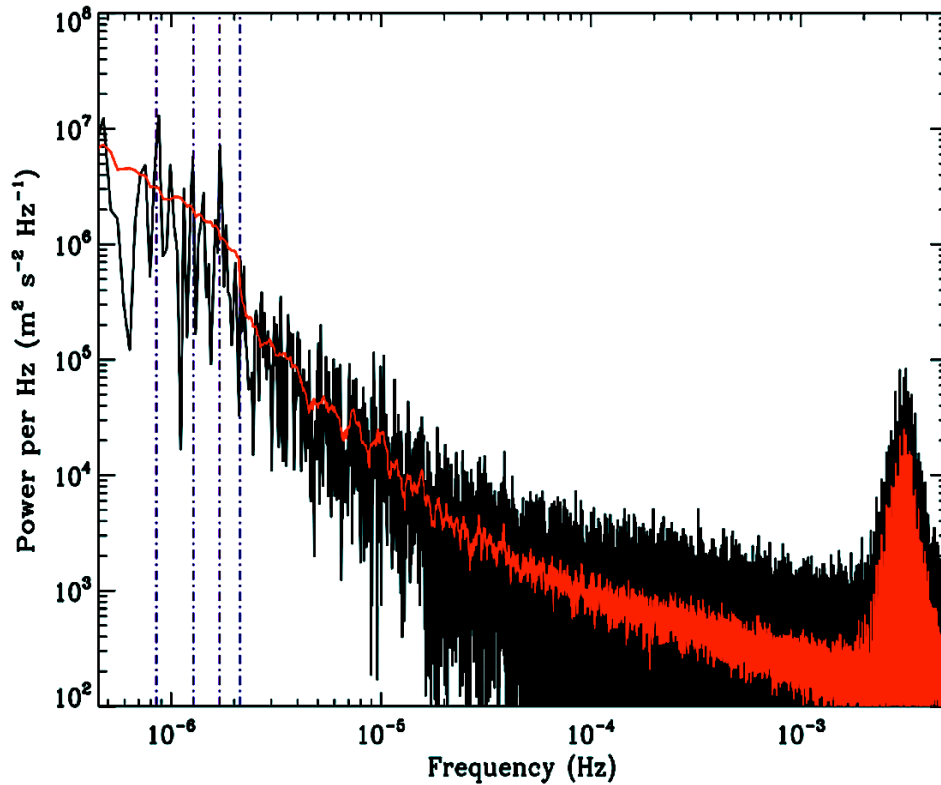
We have developed more sophisticated models of the instrumental sensitivity that require more space for description than is available here. The full description will be presented in Davies et al. (in prep.).

### 3 Results

We show an example of the new correction and calibration technique applied to 387 days of GOLF data. Figure 2 shows the strong correspondence between the Sun-instrument line-of-sight velocity and the calibrated velocities returned by the new method. In addition, Fig. 2 shows the residual velocities (measured velocity less  $v_{\text{los}}$ ) which show both the impact of solar surface activity (period around 13 days) and solar oscillations (period of about 5 minutes and amplitude of a few  $\text{m s}^{-1}$ ). Figure 3 shows the power spectrum of the residual velocities. The frequency domain again shows the presence of solar surface activity and solar oscillations.



**Fig. 2.** Calibrated velocity as a function of Sun-instrument line-of-sight velocity. Residual velocities shown in red with scale on the right ordinate. The impact of solar surface activity in the residuals can be clearly seen as a near 13 day period fluctuation. The magnitude of the solar oscillation signal is a few  $\text{m s}^{-1}$ .



**Fig. 3.** Power spectrum of the 387 day residuals using the new correction and calibration method. Black: power spectrum. Red: 20 point boxcar smoothed power spectrum. Vertical lines: overtones of the Carrington rotation rate (highlighting peaks in the power spectrum due to solar surface activity). The “five minute” modes are clearly visible at high frequency ( $\approx 3$  mHz).

#### 4 Conclusions

Here we present work focusing on achieving a stable correction and calibration of GOLF data that could be applied to 15 years of observations. We demonstrate that we can achieve a good correspondence between the Sun-instrument line-of-sight velocity and the calibrated velocity. The calibrated velocities show the signatures of both solar surface activity and solar oscillations.

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