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# Stochastic Seismic Emission from Acoustic Glories in Solar Active Regions

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**Abstract.** Helioseismic images of active regions show enhanced seismic emission in 5 mHz oscillations in a halo surrounding the active region called the "acoustic glory". In this paper we analyse the high-frequency power excess surrounding two active regions that occurred during the "shy" ascending phase of the solar cycle 24, at the beginning of 2010. This study compares the acoustic properties of seismic emission from acoustic glories with that from the quiet Sun. The power distribution of quiet-Sun seismic emission far from solar activity is exponential, as for random Gaussian noise, and therefore not episodic. The magnitudes of the acoustic glories and their seismic structure allow us to make predictions of the seismic behaviour of active regions and compare the data with present theoretical models.

#### 1. Introduction

The wealth of data from the Michelson Doppler Imager (Scherrer et al., 1995) onboard the Solar and Heliospheric Observatory (SOHO/MDI) satellite has provided us with images of solar active regions (AR) that scatter or absorb or convert sound waves in a very efficient way. These images revealed important properties of the acoustic regions, such as 'acoustic moats' and 'acoustic glories' (Braun et al. 1998, Lindsey and Braun 1998a, Braun and Lindsey 1999). Local helioseismology techniques such as acoustic holography have been used to map the seismic powers around active regions (Braun and Lindsey 2000). The aim of acoustic holography is to identify and estimate the strength of seismic sources, absorbers or scatterers of sound waves at the solar photosphere and also in the solar interior. The computational work consists in the reconstruction of the coherent acoustic source from the observed oscillations of the photosphere, reversed back in time, to their original location in the solar convection zone.

'Acoustic moats' extend from sunspots to areas far away from these highly magnetic regions. The absorption and scattering properties of acoustic moats may be explained by the existence of a convection-type plasma cell flowing outward at high speeds just beneath the photosphere (Braun et al. 1998). 'Acoustic glories' form a seismic halo around only complex active regions, with a high power at frequencies close to 5 mHz (Donea et al. 2000). Only large multipolar magnetic regions will present complex glories; some will display conspicuous point-like seismic emitters of higher frequency seismic power. In fact, a measurable enhancement in seismic emission actually exists around single monopolar sunspots (Lindsey and Braun 1999a), approximately 2.5% above that of the seismic emission from the surrounding quiet Sun, but this is subtle and diffuse. The strong output of high-frequency energy can therefore offer new insights into the physical processes occurring in and around active regions.

We have searched for active regions in the ascending phase of the solar cycle 24. The aim is to image the high frequency acoustic glories, the halo that shows sharply *enhanced* seismic emission, largely from small, point-like elements that tend to form thin, beady strings. We used the MDI/SOHO (www.soi.standford) database. The year 2010 in the solar cycle 24 had started with a few small active regions; then, the solar cycle had again a quiet time around March – April 2010. Interestingly, during June–August 2010, the Sun produced some "perfect" monopolar sunspots, such as the 11092. Two large enough ARs have drawn our attention. They had a full development on February 07, and February 14 and were observed intensively by the MDI instrument. In this paper, we have analysed the seismic enhancements in the 5 mHz acoustic glories of the AR of the year 2010, and compared the stochastic emission signal with previous work.

#### 2. Acoustic glories in seismic power maps

We have analysed the active region, AR 8996 generated on May 18, 2000, at the maximum of the solar cycle 23. In Fig 1a we mapped the 4.5-5.5 mHz band seismic power of AR 8996 and compared this with the AR 8179 (Fig 1b). One can see features such as strings of small-scale emitter, bright individual small seismic sources. Fig 1b shows a seismic emission map of AR 8179 in the 4.5–5.5 mHz band, made from MDI Doppler observations integrated over the 24 hr period beginning at March 15, 1998. The temporal character of the acoustic glory was largely analysed in Donea et al. (2000). We will use these images as reference work when compare acoustic glories of ARs in the rise phase of the cycle 24 with other ARs. As we emphasized in the Introduction we were interested in looking at two most recent ARs with good observational coverage by MDI/SOHO.

The acoustic glories appear as bright haloes surrounding the active regions. They are largely comprised of small, discrete seismic emitters that tend to cluster in strings in low-magnetic regions. The individual small-scale emitters comprising the strings are at the acoustic diffraction limit of the 5 mHz acoustic images attainable from the medium-resolution MDI images,  $\sim 3$  Mm.

Fig 1 actually illustrates similarities in the acoustic glories of the two AR. Both ARs occurred during a solar maximum. Mostly remarkable is the conspicuous emitters in the acoustic glory surrounding the active regions and their preference for beading along the magnetic neutral line separating the two active regions (AR 8996 and 8998). The acoustic glories are generally sustained at a significantly greater level than from the quiet Sun. A further detailed analysis of AR 8996 will be presented in Donea and Newington (2011).

#### 3. Results

The two active regions of the new cycle 24 were magnetically less complex than the ARs discussed in the previous section. The active region AR11045 was located at the position N24E01, on February 07 2010. MDI/SOHO continuously observed the active region from 10:19 – 15:26 UT. The active region AR11046 was located at N23W25 (similar latitude with AR 11045) and was observed by MDI from 16:21 - 23:02 UT. We remapped the solar full disk images onto Postels projections with the scale of the map 0.002  $R_{\odot} = 1.4$  Mm per pixel over 256 pixels, so the extent of the maps are about 358.4 Mm in each direction.

Holographic images of seismic emission in the two active regions of year 2010 show highfrequency acoustic glories extending beyond the surface magnetic regions (left panel in Figures 2 and 3). However, AR 11045 and AR 11046 show only relative weak, diffuse acoustic glories that do not present intense point-like elements of enhanced seismic emission at 5 mHz, as shown for the ARs in the Figure 1. Some string-like features can be seen on the egression power map in Figure 2 (integrated over 5 h and 24 h, respectively).

Acoustic power halos at 5 mHz, are also seen in the right panels in Figures 2 and 3, as localized enhancement of the surface disturbance that registers the arrival of an underlying



Figure 1. Seismic egression-power maps (a) of AR 8998 (May 18, 2000) in a 1 mHz band centered at 5 mHz, integrated over 24-hr interval (b) of AR 8179 (March 15, 1998). Reference arrow heads indicate the locations of the beading of small-scale elements of enhanced seismic emission which comprise the 5 mHz solar acoustic glories. The maps are normalised to the quiet sun areas.



**Figure 2.** 5 mHz Egression power map (left) and the 5 mHz acoustic power map (right) of AR 11045 averaged over the full data set on February 07 2010. The coloured scales indicate egression power and acoustic power, normalized to unity for the quiet Sun. A halo of excess emission ('acoustic glory) is seen in the left map.



Figure 3. Same as Figure 2 for AR 11046 on February 14 2010.

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**Figure 4.** Histograms of 5-mHz egression power in (a) the acoustic glory (left frame) and in (b) the quiet Sun (right) for AR 11045 on February 07 2010.



**Figure 5.** Distributions of 5-mHz egression power in (a) the acoustic glory (left frame) and in (b) the quiet Sun (right) for AR 11046 on February 14 2010.

wave (Schunker and Braun 2010).

The distribution of seismic power emanating from the most intense elements that comprise the acoustic glories is likewise exponential out to approximately  $4|H|_{quiet}^2$ . However, the behaviour of the distribution at a higher seismic power (the concave down shape starting at approximately  $4|H|_{quiet}^2$ ) perhaps indicates a regime of saturation of the egression power in acoustic glories. This is still a puzzle. At this point, as Donea, Lindsey and Braun (2000) emphasized, we suggest that the sustained emission that emanates from acoustic glories involves a substantially different mechanism than that which operates in the quiet Sun.

The histograms of acoustic glories and the quiet sun are shown in the Figure 4 and 5 (we have analysed about 30 small-scale seismic elements for glories and 200 small-scale elements for the quiet sun). First, we should notice that the 5 mHz egression power glories represent the contribution from the acoustic radiation that propagates downwards from a focal point/ a source located nearby the active region, and later is refracted back into the photosphere. Secondly, the acoustic 5 mHz enhancement can also be attributed to the locally generated acoustic radiation

from the subphotosphere (in the quiet Sun only the locally generated acoustic radiation is present). Both phenomena will contribute to the final emission in acoustic glories. The high seismic emission from the small-scale seismic sources in the acoustic glories could be also a result of all the above phenomena; it is hard to know which of these two contributions dominate.

If an egression power timeseries contains a component of acoustic emission that is *substantially episodic*, this should result in a significant departure of the egression-power distribution, D, from the nominal exponential profile.

The next step was to look at the the egression power time–series representing acoustic emitters in the quiet Sun. Control measurements from the quiet Sun were taken from the 5 mHz egression power maps. The results are shown in the Figures 4 and 5 (right plots). For random Gaussian noise, the distribution,  $D(|H^2|)$  in egression power  $|H|^2$  should be simply exponential:

$$D(|H^2|) = \exp(-|H|^2/H_{quiet}^2), \tag{1}$$

with  $H_{quiet}$  representing the mean power of the quiet Sun noise.

Distributions D of egression power  $|H|^2$  from the quiet Sun far from magnetic regions show a profile that is accurately exponential. This is consistent with sustained, random Gaussian noise. In particular, for quiet sun, the histogram  $D(|H|^2)$  shows some increase at the higher values of its argument,  $|H|^2$ , by the contamination of the outlying neighbourhood of the active region by occasional glory-like emission (right plots in Figures 4 and 5).

#### 4. Conclusion

This work confirms that it is only around large-multipolar active regions that the acoustic glory is prominent, showing seismic emission averaging roughly 15% in excess of the mean quiet Sun. The glories are identified with seismic holography analysis sensitive to propagating waves.

High frequency small-scale seismic emitters are localised within acoustic glories with an episodic temporal behaviour. A small number of these small scale emitters is enough to contaminate the quiet sun region surrounding an AR and produce acoustic glories. The highest possible spatial resolution data from the Solar Dynamics Observatory (SDO) should be able to help us answering the question about "how many seismic emitters will generate a significantly seismic glory around an active region?". The new data will also improve the errors in the statistics, when dealing with 30 small-scale seismic sources, for examples.

The average spatial extension of the acoustic glories around active regions is 20 - 30 Mm. The most interesting structure of the acoustic glories, the bead alignmenet of emitters suggests that the emission sites lie preferably near low-magnetic areas, and sometimes follow the magnetic neutral line between two polarities of the host active region. This is an area with near horizontal magnetic field. This aspect will also be analysed with the new SDO data. Therefore, any theory intended to explain the acoustic glories and the beading of seismic emitters would probably refer to the interaction of acoustic waves with the magnetic field.

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