Response to Comment on "Detection of Emerging Sunspot Regions in the Solar Interior"

Stathis Ilonidis,* Junwei Zhao, Alexander Kosovichev

Braun claims that his analysis using helioseismic holography does not confirm the detection of emerging sunspot regions. We examine his measurement procedure and explain why his method has different sensitivity than our method. We also discuss possible physical processes that may cause the detected phase travel-time shifts.

Ilonidis *et al.* (*1*) report that large sunspot regions can be detected before their appearance on the solar disc and as deep as 65,000 km below the solar surface. The detection method, based on time-distance helioseismology technique (*2*), employs a newly designed phase-speed filter and a measurement scheme with a high signal-to-noise (S/N) ratio. Braun claims that an independent analysis (*3*) with the helioseismic holography technique (*4*) is not able to detect the phase shifts associated with the emerging sunspot regions and considers our results controversial. In fact, Braun follows a completely different procedure that only shows that this particular method is not able to detect emerging sunspot regions. We mention below several important differences between our method and his and demonstrate with measurements that his method is not expected to provide a sufficiently high S/N ratio needed for a positive detection.

In our study, we used a specially designed non-Gaussian phase-speed filter [details of the filter can be found in (*5*)] because our tests with emerging-flux and quiet-Sun regions showed that it provides a higher S/N ratio than other Gaussian phase-speed filters at the same depth range (*5*). We also computed the exact pixel-to-pixel distances in spherical coordinates to avoid errors on the selection of annuli caused by the Cartesian approximation. Braun instead employed Cartesian coordinates in his analysis, although the radius of the largest pupil annulus is about 24.1° and the travel-time maps cover a region of about 22° by 22°. He also used four Gaussian phase-speed filters to compute travel-time maps at four target depths and then added these travel-time maps together.

Below, we followed our measurement method (*1*) but used the Cartesian approximation and four Gaussian phase-speed filters to construct travel-time maps at about the same target depths with (*3*) and then adding these travel-time maps together as in (*3*). The parameters of the phase-speed filtering are given in table S1. The final map (Fig. 1D) does not show, at the location of the emergence, signatures that can be determined as a positive detection. The reasons are (i) the Cartesian approximation mixes up the phases of the waves and smears out real signals (Fig. 1B), (ii) the Gaussian phase-speed filters do not provide as high a S/N ratio as the filter that we used (Fig. 1C), and (iii) focusing at four separate target depths, instead of combining the measurements from different depths as we did, further reduces the signal relative to the noise (Fig. 1D). This analysis confirms our initial finding that a successful detection is possible only if a procedure with a sufficiently high S/N ratio is used. Following the procedure that was used in (*3*), we also fail to detect significant signals.

Figure 2 shows that the measurement scheme used in (*3*) is significantly different from ours. We used acoustic waves with 1-skip horizontal distance of 111 to 198 Mm, whereas the corresponding range in (*3*) is 119 to 334 Mm.

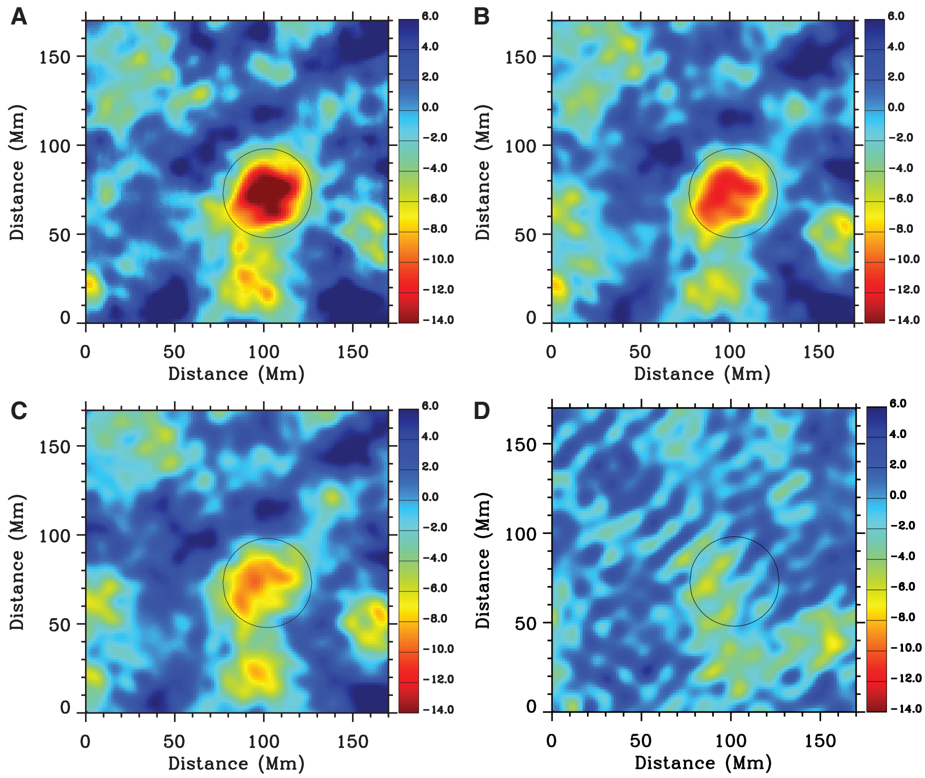

Fig. 1. (**A**) Mean phase travel-time perturbation map of AR 10488 obtained from an 8-hour data set centered at 03:30 UT, 26 October 2003. The cross-covariances were computed using our method (*1*), with arcs with a size of 45° and four different orientations. The phase shifts inside the circle, which are caused by the emerging sunspot region, have the maximum amplitude of 16.2 s. (**B**) Same as (A) except that the cross-covariances, following Braun's approach, were computed assuming Cartesian geometry (instead of the correct spherical geometry). The maximum amplitude of the phase shifts inside the circle is reduced to 12 s. (**C**) Same as (B) except that the cross-covariances were computed using a Gaussian phase-speed filter (instead of our specially designed filter). The signal inside the circle was further reduced to 9.7 s. (**D**) Mean phase travel-time perturbation map made with Braun's methodology: same as (C) except that the cross-covariances were computed using four Gaussian phase-speed filters at four target depths. The final phase travel-time map shown here is the average of the four individual maps. The strongest signal inside the circle is only 5.9 s, which is not sufficiently high to allow the detection of an emerging sunspot region. The strongest signal in this map, with amplitude of about 7.0 s as in Braun's comment, is more than 60 Mm away from the location of the emergence. These panels illustrate that only these three differences in Braun's analysis method can fully explain his negative result. Other factors, discussed in the text, may also be important.

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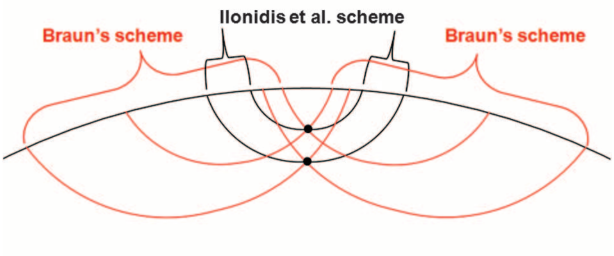

Fig. 2. Schematic representation of the largest ray paths for the smallest and largest focus depths used in our and Braun's measurement schemes. The largest 1-skip distance in our analysis is about 198 Mm, whereas in Braun's analysis it is about 334 Mm. The oscillation signals in Braun's scheme are selected from a much larger region of the solar disc, have much larger horizontal wavelengths and different wave vector orientations at the lower turning point, and they travel much deeper in the solar interior. These waves have also different acoustic power distribution over the frequency. All these factors can significantly affect the phase travel-time shifts.

These waves have very different physical properties. The horizontal wavelength at 3.5 mHz, for example, is 24 to 38 Mm in our case and 28 to 56 Mm in (*3*). It has been shown (*6*) that phase travel-time shifts can be caused by absorption of acoustic waves, and it is well known (*7*, *8*) that the absorption coefficient monotonically decreases with the horizontal wavelength. The use of much larger wavelengths (56 Mm instead of 38 Mm) may lead to a reduction of the measured phase shifts. The orientation of the wave vector at the focus point (which determines the angle with the magnetic field) is also different: It is horizontal in our case, and varies between 0° and 45° in (*3*) (Fig. 2). Further studies are required to determine how the measured phase shifts vary with this orientation angle. Last, acoustic waves suffer a 90° phase jump at the lower turning point (*9*), which, in our case, coincides with the focus point and is always located inside the magnetic region. Therefore, our method may be more sensitive to perturbations that cause phase shifts at this point.

The definition of the phase travel time in (*3*) is also different from ours. The phase shifts in our study are obtained by fitting the computed cross-covariances with a Gabor wavelet (*10*), and the phase travel time corresponds to the location of just one of the highest peaks of the cross-covariance function. The phase travel time in (*3*) represents the argument angle of the cross-covariance function (for a selected window) in the Fourier domain and most likely represents averaged phase shifts of all peaks in the selected window. These two definitions are not equivalent and may produce different values.

Regarding the physical origin of the perturbation, the observed phase shifts can be caused not only by sound-speed and magnetic-field perturbations or plasma flows but also by more complex effects such as absorption and scattering. There has been also evidence, both from observations and numerical simulations (*11*), that submerged magnetic regions can modify the acoustic power above them. This effect may also cause phase travel-time shifts in measurements. The estimates of acoustic travel times from a numerical model of emerging flux (*12*) mentioned in (*3*) are based on a simple assumption that the travel-time shifts are caused by sound-speed perturbations or flows. These theoretical estimates do not include other effects of acoustic waves and thus cannot justify Braun's claim that our results lack physical basis.

Overall, Braun (*3*) employs an analysis procedure that is different in many aspects from our analysis and does not provide a sufficiently high S/N ratio for the detection of emerging sunspot regions. We have demonstrated with measurements that the selection of filters, geometry, and measurement scheme can fully explain this negative result.

References and Notes

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Supplementary Materials
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Table S1

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