HELIOSEISMOLOGY OF PRE-EMERGING ACTIVE REGIONS. I. OVERVIEW, DATA, AND TARGET SELECTION CRITERIA

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ABSTRACT

This first paper in a series describes the design of a study testing whether pre-appearance signatures of solar magnetic active regions were detectable using various tools of local helioseismology. The ultimate goal is to understand flux-emergence mechanisms by setting observational constraints on pre-appearance subsurface changes, for comparison with results from simulation efforts. This first paper provides details of the data selection and preparation of the samples, each containing over 100 members, of two populations: regions on the Sun that produced a numbered NOAA active region, and a “control” sample of areas that did not. The seismology is performed on data from the GONG network; accompanying magnetic data from SOHO/MDI are used for co-temporal analysis of the surface magnetic field. Samples are drawn from 2001–2007, and each target is analyzed for 27.7 hr prior to an objectively determined time of emergence. The results of two analysis approaches are published separately: one based on averages of the seismology- and magnetic-derived signals over the samples, another based on Discriminant Analysis of these signals, for a statistical test of detectable differences between the two populations. We include here descriptions of a new potential-field calculation approach and the algorithm for matching sample distributions over multiple variables. We describe known sources of bias and the approaches used to mitigate them. We also describe unexpected bias sources uncovered during the course of the study and include a discussion of refinements that should be included in future work on this topic.

Key words: methods: data analysis – Sun: helioseismology – Sun: interior – Sun: oscillations – Sun: surface magnetism – Sunspots

1. INTRODUCTION

We refer to the appearance of new solar active regions as “emergence,” implying a rise from below the visible photosphere. Yet the appearance and evolution of an active region from the surface through the corona is the symptom, the result—filtered through the \( \tau = 1 \) boundary and the transitions from high- to low-\( \beta \) plasmas—of some (yet unknown) process happening below the visible surface.

One general class of theories suggests that active regions form as the result of magnetic flux concentrations rising buoyantly from the base of the convection zone (for a review see Fan 2009). Another possibility is that sunspots are formed via coagulation of magnetic fields generated closer to the solar surface (Brandenburg 2005 and references therein). The pre-emergence (PE) seismic signatures expected from these two approaches differ substantially. From the former scenario, one should expect signals generally taking the form of a bulk and quickly moving disturbance whose internal plasma flow should result in a signal detectable with today’s tools (Birch et al. 2010). In the latter case, the expectation would likely be a slower change in the subsurface temperature, flow, and magnetic field environment over a less localized area. Simulations which focus on the dynamics of flux systems rising through the upper layers imply that slowly rising flux systems may impact the convection only minimally (Stein et al. 2011), depending on the field strengths involved. Still, simulations provide clues but are limited; observations must continue to provide guidance.

Being able to peer below the visible surface at the subsurface structure and dynamics could provide the guidance regarding the formation mechanism for solar active regions (“AR”). Helioseismology seems to promise the ability to detect changes in the flow patterns and temperature beneath the visible surface. From the pure physics perspective, the tools of local helioseismology (Gizon & Birch 2005; Gizon et al. 2010) should help determine the subsurface dynamics associated with active-region formation, and thus could provide evidence for or against the basic model types. Some preliminary work (described below) applying sensitive tools of this type to data sets well suited for these techniques suggests that the capability may now be available.

Most recent efforts have been case studies, focusing on the emergence of one or a few active regions (e.g., Jensen et al. 2001; Zharkov & Thompson 2008; Komm et al. 2008; Ilonidis et al. 2011; Braun 2012). The results have been inconclusive when taken as an ensemble, possibly due to the physics of active-region emergence, possibly due to the differences between the studies themselves. Inverting time–distance data from the Michelson Doppler Imager (MDI) using three-dimensional kernels, Jensen et al. (2001) found perturbations indicating wave-speed increases 20 Mm below two active regions in the hours after their appearance. Zharkov & Thompson (2008), using a very similar method for two active regions, found a similar increase when surface flux was visible, but also a “loop-like structure” with decreased sound speed, days prior to the appearance of surface flux. Ilonidis et al. (2011) also employ time–distance analysis of MDI data, and present very large negative travel-time shifts (increases in the sound speed) located between 42 and 75 Mm up to two days prior to surface flux appearance of four active regions. They associate these disturbances with magnetic structures emerging at speeds of 0.3–0.6 km s\(^{-1}\), and do see a high rate of flux emergence following the perturbations. Yet Braun (2012), using acoustic holography on the same data for the same four active regions, detect no such unique signals at the specified times and depths.
Employing ring-diagram analysis of GONG data for 13 new or growing active regions (and contrasting with control areas), Komm et al. (2008) found evidence for upflows prior to the appearance of emerging flux at the surface, followed by a transition to predominantly downflows once the active region was established.

Ring-diagram analysis was also used in statistical studies of seismic signatures associated with emerging magnetic flux, comparing average signals for hundreds of regions with increasing flux to either “quiet” areas or to those with decreasing flux (Komm et al. 2009, 2011). While the analysis had fairly low temporal and spatial resolution, upflows were associated with emerging flux at depths below 10 Mm whereas at shallower layers, upflows changed to downflows as surface field became stronger. These studies examined the broad spectrum of surface-field behavior: growing flux, consistent flux, and decreasing flux. However, the “emerging flux” category did not differentiate between “new” active regions and emerging flux within already-established regions.

The conflicting results in case studies could indicate that there is no unique signature, or that results are sensitive to subtle methodology differences. The few published statistical studies have been based on a single method, and now need to be refined to focus solely on the pre-emergence context, and employ higher resolution analysis.

In the present investigation, we employ a combination of local helioseismology, surface magnetic field diagnostics, and statistical tests to examine what can be learned with regards to subsurface magnetic flux systems, their structure, and their evolution. The basic premise of this series of papers (this paper along with Birch et al. 2012; Barnes et al. 2012) is to determine if there are detectable changes in the solar interior that indicate an emerging active region prior to the appearance at the solar surface of a magnetic field concentration.

We have designed and completed a study to examine the possibility of pre-emergence detection of active regions, with the goal of characterizing the subsurface changes in the context of emerging-flux models. The approach pays attention to sources of bias, statistical and systematic error, and includes statistical validation of the results. The organization of this paper is as follows: In Section 2, we outline the physical parameters within which the overall study must work and the statistical motivation for the overall design of our study. We describe the data used and its treatment in Section 3, and in Section 3.1 describe the target selection criteria, justification, and implementation. We discuss sources of statistical contamination in Section 4. The most salient points are synthesized in Section 5 as groundwork for the other were obtained from west of central meridian, then all samples for the other were obtained from east of central meridian while all samples could be differentiated simply due to a bias in the Doppler signal from solar rotation, not a true detection of emergence. We refer to this bias as statistical contamination.

It is fortunate now that there are sufficient data available to perform such a study, including a statistical analysis of the results. The statistical method we use in Barnes et al. (2012) is discriminant analysis (e.g., Kendall et al. 1983), a technique that tests for any difference between the two samples. As such, any systematic bias that is present in the sampling from one population but absent in the other may appear as a false discriminant. For example, if all samples for one population were obtained from east of central meridian while all samples for the other were obtained from west of central meridian, then the samples could be differentiated simply due to a bias in the Doppler signal from solar rotation, not a true detection of emergence. We refer to this bias as statistical contamination.

The basic data comprise time series of Doppler velocity obtained at the solar surface, from which shifts in subsurface travel times are derived using helioseismic holography (Lindsey & Braun 2000; Braun et al. 2007). Obtaining a reliable seismic signature requires a temporal sequence of data, the length of which will govern the signal-to-noise ratios of the inferred subsurface patterns; yet the data quality may degrade with proximity to the solar limb. These realities create limits on the observable solar disk available for drawing the samples.

In the case of analysis using helioseismology, bias may take many forms. Due to the global frequency shifts with solar cycle (Woodard & Noyes 1985; Christensen-Dalsgaard 2002; Chaplin et al. 2007), the Doppler velocity signals may have a component distinctly linked directly to the date. Systematic effects (Braun & Birch 2008; Zhao et al. 2012; Baldner & Schou 2012) may create a dependence of the helioseismology results on apparent disk position. Active regions emerge within a fairly narrow latitude range, which itself shifts with the phase of the activity cycle, leading to another potential source of bias.

To allow an unambiguous detection of subsurface signals, the emergence episodes should be isolated in time and space from other strong magnetic sources and nearby emergence episodes. Yet active regions often emerge in close proximity to already-established active regions or remnant fields (Petrovay & Abuzeid 1991; Harvey & Zwaan 1993; Pojoga & Cudnik 2002). The controls must ideally also have no magnetic emergence occurring, and minimal strong-field regions within the immediate field of view, but they must also match the magnetic context of the population of emerging targets, as the solar disk gets crowded with active regions and their remnants during the solar maximum years.

Thus, it is key to couple observations of the solar surface magnetic field and its evolution to the selection and characterization of the seismology data. Pairing the magnetic data to the seismic data provides guidance for interpreting any seismic signature observed, both in the control and event groups.

The study is designed based on the following steps.

1. Locate and identify a statistically significant sample of the population of new active region appearances, according to constraints imposed to minimize bias and noise.
2. Locate and identify a sample of the emergence-free population, matched in time and position to the pre-emergence sample, to serve as a control.
3. Apply helioseismic data analysis “blindly” to the two samples.
4. Parameterize the results from the helioseismic analysis and magnetic field data.
5. Apply Discriminant Analysis to the seismic and magnetic parameters to quantify the differences between the two samples.
3. DATA

A study such as this requires a statistically significant sample drawn from the populations in question. Limitations posed due to observational and statistical constraints, described in detail below, thus pointed to using data from the Global Oscillations Network Group (GONG), from the era after the camera upgrades (beginning in 2001, Harvey et al. 1998; Hill et al. 2003). The GONG system records wavelength-modulated full-disk images sampled at 2.5 for 5° optical resolution from which Doppler signals are retrieved on a 1 minute cadence.

Key to interpreting any detected seismic signature is knowing the “landscape” of the surface magnetic field. As we are specifically interested in pre-emergence signatures, the surface magnetic fields and the signature of magnetic flux emergence define the timing for the entire project. At the time of design and implementation of this study, the line-of-sight field from the GONG data was not readily available. We thus rely upon the full-disk line-of-sight component magnetic field data from the MDI aboard the Solar and Heliospheric Observatory (SOHO/MDI; Scherrer et al. 1995). Specifically, we used the level 1.8.2 synoptic data acquired with a 96 minute cadence and 1°98 pixel size to qualitatively and quantitatively evaluate the magnetic landscape of the samples.

Helioseismic data from MDI were not used in this study for two reasons. First, the high-rate full-disk data (“dynamics campaigns”) are only available for a few months per year, limiting the data available for a statistical study. Second, the medium-ℓ (“structure”) data are not optimal for studying wave propagation at distances less than approximately ten heliocentric degrees (Giles 2000) whereas the present work examines depths ≲ 25 Mm which requires small distances. For these reasons, we have used the GONG data for the helioseismic analysis performed in this study.

3.1. Target Selection Criteria: The “PEs”:
Pre-emergence Regions

The initial target list for emerging active regions was derived from the “Sunspot Group Reports” produced by USAF/NOAA and available through the National Geophysical Data Center. The date range used was chosen according to requirements for the helioseismology data, and covered 2001 July–2007 November. Regions listed as first appearing within θ ≤ 30° of disk center and which achieved an area > 10 × 10⁻⁶ hemispheres (μH) during their disk passage determined the initial target list and the initial emergence times and locations that were subsequently refined.

MDI three-day time-series were constructed centered on this initial emergence date and time, using a fixed 128 × 100 pixel box centered on the initial emergence location (see Figure 1 for a schematic), and tracked with the synodic rotation rate (Figure 2). As a check against extreme viewing angles at the beginning or end of the time series, additional limits on the edges of the box were placed at E41 and W67 heliographic longitude (east longitudes are <0) and ±60° heliographic latitude. The Blos data were initially summed to a pseudo-“flux,” \( \Phi_{\text{los}} = \sum |B_{\text{los}}|/\mu \Delta A \), where \( \mu = \cos \theta \) and \( \theta \) is the observing angle, and \( \Delta A \) is the physical area of a pixel. A refined emergence time, \( t_0 \), was defined as the time of the first MDI observation after \( \Phi_{\text{los}} \) reached 10% of the maximum achieved (minus any flux present at the beginning of the time series) over the time series. That is, the “10% rule” refers to 10% of the maximum increase detected. The kurtosis (fourth moment) of the distribution of \( B_{\text{los}} \) in the frame generally increases dramatically at the time of emergence, signifying a distinct change in the spatial distribution of \( B_{\text{los}} \); a sudden change in the kurtosis was used to confirm the “10% rule” but was not relied upon in isolation. Thus, the emergence time is only defined within the 96 minute MDI cadence. For the analysis methods later applied, which require many hours of data, there is little to be gained by refining this definition further. The NOAA reports of active region coordinates were generally accurate, although our definition of \( t_0 \) was generally earlier than the NOAA reports by anywhere from a few hours up to a day.

Emergence of surface field is rarely a smoothly monotonic process (Zwaan 1985; Leka et al. 1994; Kubo et al. 2003). An example of that reality is shown in Figure 3 (and discussed further in Section 4.3). As such, the flux history and thresholds here constitute a selection rule to be used for a statistical approach, rather than a profound statement of solar physics. And as such, there will be regions for which the definition blatantly misses the mark of rising flux presence. The goal here is a well-defined “good option,” which is objective and repeatable for a statistically significant sample of data. Regions were rejected for a number of reasons, primarily data gaps (in either MDI at or near the emergence time, or GONG data for final analysis) or immediate proximity (within the 128 × 100 pixel box) of another active region. No further tests were made concerning the eventual size of the active region

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4 Emergence times were initially determined using earlier level 1.8.1 data, but we do not expect any systematic differences as the emergence times were based on the change of the signal, not a pre-determined threshold.

5 http://www.ngdc.noaa.gov/stp/solar/sunspotregionsdata.html
Figure 2. Example of a pre-emergence target, NOAA AR 10559, which had an assigned emergence time $t_0$ of 2004-02-13T11:15:02.677Z (see the text for details) at N07 W22.4. The images (a–e) are the $128 \times 100$ pixel images from the MDI full-disk line-of-sight magnetic data used for initial evaluation of the emergence episode, all scaled to $\pm 500$ G. The image (c) shows the assigned "emergence time" $t_0$. The temporal evolution of the pseudo-flux $\Phi_{\text{los}} = \sum |B_{\text{los}}|/\mu \Delta A$ for this test field of view is shown in (f), as a function of time relative to the inferred time of emergence, determined as the first MDI magnetogram when 10% of the eventual maximum change in flux, $\Phi_{\text{los}}$, has appeared (c). Data points for the images shown are filled in and labeled; a mix of 30 s and 300 s MDI data are both used and shown here, evident by the different apparent noise levels.

Figure 3. Example of a pre-emergence target with a less-clear emergence time, NOAA AR 9564, which had an assigned emergence time $t_0$ of 2001-08-01T06:27:01.250Z (see the text for details) at N14 W21.2. The images (a–e) are in the same format as in Figure 2. The temporal evolution of $\Phi_{\text{los}}$ is shown in (f), except that the maximum flux observed is truncated to better show the early evolution. Data points for the images shown are filled in and labeled. In this case, the "background" $\Phi_{\text{los}} = 0.96 \times 10^{21}$ Mx is larger than the previous example. The region eventually reached $9.5 \times 10^{21}$ Mx, or a maximum increase of $8.6 \times 10^{21}$ Mx, hence point (d) at $1.8 \times 10^{21}$ Mx was the identified emergence time by the objective algorithm. However, it is clear that a small episode of flux emergence apparently occurred between (b) and (c) as well. While in this case we can argue a 6 hr uncertainty in the emergence times, there was very little if any surface signal of the emergence for many hours prior to (c).

or speed of emergence; a later subjective evaluation rejected regions if $t_0$ appeared incorrect by more than a few MDI-derived data points. The fixed box used at this stage was fairly restrictive.

The refined location and time of emergence, defined as above, were used to generate the Doppler-velocity data (see Section 3.4). The final result is 107 pre-emergence (“PE”) target regions between 2001 and 2007. In Table 1, we list the identifying features of these regions: the NOAA active region number, the $t_0$ as defined above, and the latitude and longitude of the center of the $128 \times 100$ pixel box at that time. Note that the longitude was generally refined from the NOAA reports, while the latitude generally was not, and as such is effectively an integer. In Figure 4, we show the final distribution of the (eventual) maximum size achieved (as reported in the NOAA compilations) for the active regions in the PE list.
### Table 1
Identifying Coordinates for Pre-emergence Targets (Continued)

| Region | ID   | Date “t” | Location (°) | Max Size | Date “t” | ID   | Date “t” | Location (°) | Max Size |
|--------|------|----------|--------------|----------|----------|------|----------|--------------|----------|
|        |      |          | Latitude     | Longitude | (μH)     |      |          | Latitude     | Longitude |
| 9759   | 2003 Nov 8 20:47 | -8.0 | 1.3 | 40 |
| 9503   | 2003 Nov 15 09:35 | 18.0 | -21.7 | 20 |
| 10522  | 2003 Dec 11 11:11 | 15.0 | 8.9 | 50 |
| 10529  | 2003 Dec 18 22:23 | 9.0 | -17.2 | 20 |
| 10532  | 2003 Dec 23 22:15 | -11.0 | -36.2 | 70 |
| 10543  | 2004 Jan 19 08:03 | -18.0 | -19.6 | 110 |
| 10550  | 2004 Jan 31 20:47 | -8.0 | -21.2 | 40 |
| 10553  | 2004 Feb 3 14:23 | -6.0 | -36.5 | 40 |
| 10559a | 2004 Feb 13 11:15 | 7.0 | 15.7 | 80 |
| 10568  | 2004 Feb 26 20:47 | -17.0 | -13.5 | 30 |
| 10591  | 2004 Apr 11 14:27 | -15.0 | -25.7 | 100 |
| 10602  | 2004 Apr 28 22:23 | -14.0 | 19.7 | 60 |
| 10601a | 2004 Apr 29 14:23 | -9.0 | 5.3 | 310 |
| 10605  | 2004 May 3 12:47 | -12.0 | -24.7 | 130 |
| 10619  | 2004 May 23 01:36 | -9.0 | 18.5 | 30 |
| 10623  | 2004 Jun 1 00:03 | 7.0 | 3.9 | 70 |
| 10626  | 2004 Jun 4 19:12 | 5.0 | -16.2 | 20 |
| 10643  | 2004 Jul 8 15:59 | -8.0 | -16.4 | 30 |
| 10645  | 2004 Jul 9 03:11 | 12.0 | -26.2 | 20 |
| 10671a | 2004 Sep 6 08:03 | -10.0 | 13.6 | 540 |
| 10688  | 2004 Oct 19 06:27 | -7.0 | 16.6 | 170 |
| 10737  | 2005 Feb 23 03:15 | -9.0 | 12.5 | 50 |
| 10753  | 2005 Apr 12 14:27 | 12.0 | -18.2 | 20 |
| 10757  | 2005 Apr 27 15:59 | -5.0 | -27.2 | 110 |
| 10770a | 2005 May 28 23:59 | 12.0 | -17.1 | 70 |
| 10771  | 2005 May 29 12:47 | 24.0 | 8.0 | 50 |
| 10829  | 2005 Dec 2 04:48 | 11.0 | -18.7 | 40 |
| 10839  | 2005 Dec 20 11:15 | 18.0 | -30.0 | 40 |
| 10846  | 2006 Jan 14 06:27 | 4.0 | 1.1 | 140 |
| 10850  | 2006 Jan 22 11:12 | 6.0 | -21.6 | 30 |
| 10852  | 2006 Feb 6 22:24 | -10.0 | -28.7 | 20 |
| 10868  | 2006 Apr 4 07:59 | -7.0 | -21.9 | 40 |
| 10889  | 2006 May 27 09:39 | -3.0 | -21.4 | 60 |
| 10890  | 2006 May 27 22:24 | -14.0 | 7.6 | 50 |
| 10902  | 2006 Jul 30 01:36 | -9.0 | 12.5 | 50 |
| 10916  | 2006 Oct 9 06:24 | -13.0 | -22.2 | 30 |
| 10919  | 2006 Oct 27 09:11 | -16.0 | -17.7 | 20 |
| 10937  | 2007 Jan 7 11:11 | -13.0 | -33.2 | 50 |
| 10939a | 2007 Jan 19 22:27 | -3.0 | 4.2 | 180 |
| 10964a | 2007 Jul 12 09:35 | 4.0 | 0.4 | 90 |
| 10971  | 2007 Sep 27 09:35 | 6.0 | -35.4 | 70 |
| 10972a | 2007 Oct 5 12:51 | -6.0 | -20.7 | 70 |
| 10974  | 2007 Nov 15 20:51 | 12.0 | -15.9 | 40 |

Note. a Member of the “Ultra-Clean” subset.

A subset of 11 regions is singled out as being particularly “clean,” and these regions are indicated with a superindex “a” in Table 1. The criteria for this list are completely subjective: no neighboring active region in the extracted areas, a very flat pre-emergence flux history, and an emergence characterized by a very uniform and steep slope of $d\Phi_{\text{ne}}/dt$. The example shown in Figure 2 is one such member of the “Ultra-Clean subset.”

### 3.2. Target Selection Criteria: The “NE”s:

No-emergence Control Regions

The active-region emergence targets required an accompanying set of “control data.” As our final analysis is a statistical analysis based on the results of both helioseismology-derived and magnetic-derived parameters, the control data needed to be constructed so as to not introduce statistical bias into the final distributions. We outline the construction of this data set here.
Starting every two MDI days during the same 2001–2007 interval, using the same-sized $128 \times 100$ pixel tracked boxes, areas were identified where the underlying signal stayed consistently $<1000 \mu H$. This was accomplished by “stacking” three days’ worth of MDI data and extending the target box to effectively cover the tracked area, as shown in Figure 5. Random locations for these low-field areas were chosen on the disk for each stack, subject to the same general constraints as the PE targets with regards to limits on latitude and longitude. A time close to the center of the 3 day interval, falling on an MDI observed time, is designated $t_0$ for the no-emergence (NE) data. While there was the possibility of overlapping areas being chosen, any randomly selected NE patch which did overlap was “weedied out” as described below. An example of a “no-emergence” region is shown in Figure 6.

This selection algorithm initially provided thousands of possible NE targets over the 7 years. A subset of approximately 500, selected to generally follow the distribution in latitude, longitude, and time as the initial set of PE targets, were used to acquire GONG data (see Section 3.4).

From these, a subjective evaluation was made, removing approximately 20 targets from consideration primarily due to the existence of small (obviously, un-numbered) emerging flux regions at the center of the field-of-view which were not previously detected. While no specific criteria were used regarding increasing or changing total flux over the time interval, the single criterion specified above effectively performed to constrain selection to regions with impressively consistent magnetic flux levels, on the whole.

Candidate NE regions were further evaluated and removed if the central $16^\circ \times 16^\circ$ (used for the majority of the helioseismology analysis, see Section 3.4) overlapped with the central $16^\circ \times 16^\circ$ portion of a PE or another NE at any time. The final number of NE controls available for distribution control (see Section 3.3, below) was 308.

### 3.3. Distribution Control

An algorithm was developed for post-facto selection from a larger sample of controls (NE) to match the distribution of the targets (PE) simultaneously in latitude, longitude, and time. A non-parametric density estimate (NPDE; e.g., Silverman 1986), using the Epanechnikov kernel and the optimal smoothing parameter for a normal distribution, was used to estimate the probability density function for the three variables on a regular grid in longitude, latitude, and ln(time) (see Figure 7). The non-parametric approach was used to avoid misrepresenting non-Gaussian distributions such as the latitude of emergence (which is decidedly and expectedly double peaked); similarly, the logarithm of the time variable was used to compensate for its extremely skewed distribution. A simulated annealing algorithm (e.g., Press et al. 1992; Metropolis et al. 1953; Kirkpatrick et al. 1983) was employed to select the subset of NE of a specified size (equal to the number of PE) that minimizes the integrated absolute value of the difference between the two NPDEs (NE and PE). Using the integral preserves the general shapes of the distribution rather than (for example) employing a peak or maximum difference as a Kolmogorov–Smirnov test would do.

The results of this matching exercise are shown for the three variables in Figure 7. A table listing coordinates for the final NE targets is provided in Table 2, where we list the MDI orbits generally containing the NE region, the mid-point of the GONG day used for analysis (see Section 3.4, below), and the coordinates of that mid-point (note we do not list $t_0$ precisely, but it is fairly inconsequential).

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6 Gauss are used as units, with the understanding it is a pixel-averaged quantity.

7 Specifically, the logarithm of the number of Julian days since 2001 July 25, two days before the first data set.
The equal sample sizes of PE targets and NE controls impose a specific requirement on the statistical tests: the prior probabilities, of which type of event (PE or NE) is more or less frequent, is set to be equal. This statistical requirement is maintained even after a further restriction is placed on the data for acceptable GONG duty cycle (see Section 3.4 and Table 3) which in fact creates small inequities in the sample sizes. With equal prior probabilities, the goal of determining whether these populations differ is emphasized. Were this a test of prediction, the sample sizes (hence prior probabilities) should reflect the chances of any random place on the Sun being a location and time of emergence; clearly this is a ratio of many thousands to one.

3.4. Preparing the Doppler-velocity Cubes

After the appropriate target selection, there is no difference in the treatment of the PE and NE data cubes produced from the GONG Doppler-velocity data. Cubes 32° × 32° in extent were tracked at the Carrington rate and extracted from the GONG 1 minute velocity data (Corbard et al. 2003). As indicated in Figures 1 and 8, this extracted area is larger than the original 128 × 100 MDI-pixel area used for initial evaluation.

The final cubes used for this analysis are one “GONG-day” long (1664 minutes); for the PE data, the cubes end 16 minutes after the emergence time $t_0$ due to a small communication error; given the temporal sampling of the magnetic field data, we do not assign significance to the 16 minutes aside from assuming there will be early emergence magnetic flux appearing near the end of the GONG day.

The extracted Doppler-velocity data are re-projected using a Postel projection (Pearson 1990). The 1664 minute time series are then broken into five time intervals, each 384 minutes long but starting every 320 minutes (thus an overlap of 64 minutes between each interval). A schematic of the data and the temporal relationship between time intervals is shown in Figure 9.

The GONG facility includes different observing sites whose data are combined to create full temporal coverage. While the average duty cycle for GONG data is very high, at times the coverage falters for a variety of reasons. Intervals that fall below a duty cycle of 80% are not included in the analysis. This restriction removes data randomly; there is no reason for duty cycle to be tied to PEs preferentially over NEs, especially after the matching was performed for location and date. In addition, what are removed from consideration are individual intervals rather than an entire PE or NE target. Table 3 presents the resulting sample sizes for PE and NE populations by interval, after removing data with insufficient duty cycle.

3.5. The Accompanying Magnetic Data for Analysis

In addition to the considering each event (or lack thereof) as viewed by helioseismology, to confirm that the results are a result of subsurface processes, we produced a complementary data set of the surface field. For analysis we attempt to mitigate projection effects present due to the fact that the MDI data detect only the line-of-sight component of the flux density (explained in detail below). We also want to match the measure of the surface magnetic field to the area and projection used with the GONG Doppler-velocity data cubes. To achieve this, first the location and 32° × 32° spatial extent of the GONG cubes were identified in MDI data covering the same time interval.

To minimize projection effects and, more adroitly, use the most physically meaningful magnetic measure available from the MDI data, we use a potential-field calculation to retrieve an estimate of the radial component of the field. Specifically, the potential field was calculated to directly match the observed line-of-sight boundary (Sakurai 1982; Bogdan 1986; Rudenko 2001), rather than assuming the boundary was equivalent to the radial component of the field.

In general, the radial component of a potential field (without a source surface) in the volume above the solar surface can be expressed in a spherical harmonic expansion as

$$B_\phi(r, \mu, \phi) = \sum_{l=1}^{\infty} \sum_{m=0}^{l} \left( \frac{R_\odot}{r} \right)^{l+2} \times \left[ g_l^m \cos m\phi + h_l^m \sin m\phi \right] P_l^m(\mu),$$

(1)
where the $P^m_l$ are the associated Legendre functions, $R_\odot$ is the solar radius, $r$ is distance from the center of the sun, $\theta$ is colatitude, and $\phi$ is longitude (measured for any choice of the polar axis). Following the approach of Rudenko (2001) by taking the polar axis of the coordinate system to lie along the line of sight, and using relationships among the associated Legendre functions as done by Bogdan (1986), the coefficients can be written as

$$g_l^m = \frac{(2l + 3)(l - m)!}{4\pi(l + m + 1)!} \int_0^1 d\mu \times \int_0^{2\pi} d\phi \cos m\phi P^m_{l+1}(\mu) B_l(R_\odot, \mu, \phi)$$

(2)

and

$$h_l^m = \frac{(2l + 3)(l - m)!}{4\pi(l + m + 1)!} \int_0^1 d\mu \times \int_0^{2\pi} d\phi \sin m\phi P^m_{l+1}(\mu) B_l(R_\odot, \mu, \phi),$$

(3)

where $B_l(R_\odot, \mu, \phi)$ is the line-of-sight component of the field at the solar surface. To ensure that the monopole term vanishes in the sum, we further assumed that the field on the far side of the Sun was given by $B_l(R_\odot, \pi - \theta, \phi) = B_l(R_\odot, \theta, \phi)$, where the front side of the Sun is assumed to lie in the range $0 < \theta < \pi/2$. This can produce some unphysical results very close to the limb, but does not greatly affect the field at the surface in the restricted area of the disk considered in this investigation. The integrals were evaluated using a simple trapezoid method, and the spherical harmonics were computed using the freely available software archive SHTOOLS,\(^8\) which have a relative error of less than $10^{-5}$ up to degrees of at least 2600. However, only terms up to degrees of 1000 were included, as this is sufficient to reconstruct spatial scales on the order of the resolution of MDI. Note also that the acoustic modes in the GONG data are seen up to about $l = 1000$ (see Figure 1 from Birch et al. 2012).

The above calculations were performed on an extracted cube slightly larger than $32^\circ \times 32^\circ$, then the potential field radial component was subjected to Postel projection and trimmed to

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\(^8\) Available at http://www.ipgp.fr/~wieczor/SHTOOLS/SHTOOLS.html.
### Table 2
Identifying Coordinates for No-emergence Targets

| Region ID | GONG-Day | Reference Date | Latitude | Longitude |
|-----------|----------|----------------|----------|-----------|
| (MDI Orbits) | | | | |
| 3137-3140 | 2001 Aug 5 07:11 | 4.5 | -26.9 |
| 3148-3151 | 2001 Aug 16 08:48 | 13.3 | -11.4 |
| 3154-3157 | 2001 Aug 22 10:23 | 26.5 | -19.4 |
| 3175-3178 | 2001 Sep 12 00:51 | 27.6 | -29.5 |
| 3177-3180 | 2001 Sep 13 19:59 | 15.6 | -26.4 |
| 3216-3219 | 2001 Oct 23 08:47 | 16.0 | -14.1 |
| 3225-3228 | 2001 Nov 1 07:15 | 15.8 | -32.9 |
| 3226-3229 | 2001 Nov 2 00:51 | 20.6 | 12.2 |
| 3232-3235 | 2001 Nov 8 02:27 | 6.7 | 13.6 |
| 3234-3237 | 2001 Nov 10 07:11 | 0.2 | -3.0 |
| 3249-3252 | 2001 Nov 25 00:51 | 0.7 | 23.5 |
| 3257-3260 | 2001 Dec 2 13:39 | 18.5 | 16.7 |
| 3277-3280 | 2001 Dec 3 00:47 | 23.9 | -9.7 |
| 3283-3286 | 2001 Dec 10 29:12 | 25.2 | -21.1 |
| 3304-3307 | 2002 Jan 19 04:00 | 26.7 | -28.0 |
| 3355-3358 | 2002 Mar 10 15:15 | 14.9 | -18.2 |
| 3369-3372 | 2002 Mar 25 04:00 | 18.7 | -9.0 |
| 3372-3375 | 2002 Mar 27 16:48 | 4.4 | -35.0 |
| 3405-3408 | 2002 Apr 19 12:23 | 24.1 | -25.2 |
| 3415-3418 | 2002 May 10 00:47 | 5.6 | 11.1 |
| 3418-3421 | 2002 May 13 02:22 | 15.6 | -19.2 |
| 3420-3423 | 2002 May 25 02:24 | 2.3 | -6.0 |
| 3455-3458 | 2002 Jun 16 16:51 | 8.9 | -17.2 |
| 3456-3459 | 2002 Jun 20 08:48 | 21.1 | -13.0 |
| 3471-3474 | 2002 Jul 5 02:27 | 14.5 | -2.6 |
| 3472-3475 | 2002 Jul 5 13:35 | 12.0 | -23.1 |
| 3479-3482 | 2002 Jul 13 08:47 | -1.4 | 3.0 |
| 3484-3487 | 2002 Jul 18 02:23 | -29.0 | 2.8 |
| 3502-3505 | 2002 Aug 1 04:03 | 21.9 | -10.7 |
| 3508-3511 | 2002 Aug 11 00:47 | -11.4 | -21.4 |
| 3519-3522 | 2002 Aug 22 02:27 | 3.7 | 0.4 |
| 3553-3558 | 2002 Sep 7 05:35 | 8.8 | -36.2 |
| 3547-3550 | 2002 Sep 19 02:23 | 12.9 | -29.0 |
| 3555-3558 | 2002 Sep 27 00:48 | 13.7 | -33.2 |
| 3555-3558 | 2002 Sep 27 02:24 | 15.3 | 7.9 |
| 3564-3567 | 2002 Oct 5 11:59 | -6.0 | -0.1 |
| 3565-3568 | 2002 Oct 7 00:51 | -18.7 | -22.9 |
| 3597-3600 | 2002 Nov 8 17:29 | -29.1 | -32.7 |
| 3600-3603 | 2002 Nov 1 10:24 | -24.5 | 12.8 |
| 3607-3610 | 2002 Nov 17 16:51 | 11.0 | -17.7 |
| 3607-3610 | 2002 Nov 18 07:15 | 6.2 | 7.3 |
| 3611-3614 | 2002 Nov 25 03:16 | 10.4 | 8.5 |
| 3615-3618 | 2002 Nov 26 02:27 | -13.2 | -2.0 |
| 3636-3639 | 2002 Dec 17 04:03 | 2.8 | -35.9 |
| 3646-3649 | 2002 Dec 27 08:48 | -12.5 | -2.7 |
| 3683-3686 | 2003 Feb 1 11:59 | 17.1 | -27.6 |
| 3694-3697 | 2003 Feb 13 05:35 | 11.2 | -6.7 |
| 3703-3706 | 2003 Feb 21 18:26 | -7.7 | 5.9 |
| 3703-3706 | 2003 Feb 21 20:02 | -10.1 | -11.2 |
| 3753-3756 | 2003 Apr 12 18:23 | -6.6 | -8.5 |
| 3758-3761 | 2003 Apr 18 08:47 | -5.9 | -25.4 |
| 3780-3783 | 2003 May 10 07:11 | -15.8 | 9.0 |
| 3782-3785 | 2003 May 11 18:22 | -13.1 | -27.2 |
| 3789-3792 | 2003 May 19 05:35 | -5.4 | -7.5 |
| 3795-3798 | 2003 May 24 19:59 | 24.6 | -3.6 |
| 3802-3805 | 2003 May 31 11:59 | -20.7 | -33.0 |
| 3810-3813 | 2003 Jun 9 08:47 | -27.6 | 12.6 |
| 3855-3858 | 2003 Jul 24 02:22 | 23.2 | -27.7 |
| 3863-3866 | 2003 Jul 31 13:35 | 7.6 | 17.9 |
| 3874-3877 | 2003 Aug 1 12:27 | 7.9 | 1.0 |
| 3893-3896 | 2003 Aug 30 15:15 | 10.3 | -32.5 |
| 3910-3913 | 2003 Sep 16 21:36 | 15.7 | -4.5 |
| 3969-3972 | 2004 Nov 14 23:11 | 18.4 | 11.1 |
| 3983-3986 | 2004 Nov 28 21:39 | 0.3 | -31.1 |
| 3997-4000 | 2004 Dec 12 15:15 | -12.9 | 1.5 |

### Table 3
Duty Cycle for NE and PE Targets

| Time Interval | NE Samples | PE Samples | Ultra-Clean PE Samples |
|---------------|------------|------------|------------------------|
| TI-0          | 81         | 89         | 7                      |
| TI-1          | 85         | 88         | 10                     |
| TI-2          | 85         | 89         | 11                     |
| TI-3          | 82         | 87         | 9                      |
| TI-4          | 83         | 86         | 9                      |

Exactly match the GONG data cubes. Hence, we have for each PE and NE data set, a time series of the radial component of the field matched in area, and matched in projection, to subsurface observations made by helioseismology, albeit the latter by a different instrument.

From these maps, an appropriate time series of the history of the field at the target and its immediate surroundings is computed, for comparison with the results of helioseismology. Sample pairs of average radial field density and average...
corresponding Doppler data are shown in Figure 8 for the PE and NE examples of Figures 2 and 6.

For these accompanying magnetic data, we show in Figure 10 the unsigned radial field averaged over all samples, for each of the time intervals used for the seismology analysis. To provide context, we extend this slightly in time and show the averages for two additional post-emergence time intervals. Of note is the distinct lack of variation in the NE data, but also the noticeable bands of stronger signal at the top and bottom of the NE data cubes compared to the central portion. The PE data show a distinct early signature of surface field 24 hr prior to the emergence time, and a clear bipolar signature after emergence is underway. The bipolar structure is less clear but arguably present in the subset of PE data, the early signature is arguably completely absent when only the cleanest, “most virgin” examples were chosen. At the same time, averaging over a smaller number for the “ultra-clean” data set allows a single sample to influence the average: the strong persistent signal on the right-hand portion of the “ultra-clean” mean in Figure 10 is primarily due to a strong plage area near NOAA AR 9645.

### 3.6. Further Corrections

The latitude reported by NOAA was generally unchanged for extracting the GONG data cubes; the longitude was obviously updated according to $t_0$. For the later analysis, especially the averages over all samples used in Birch et al. (2012), the coordinates were refined in the following manner. The time series of the radial magnetic field were used to construct bitmaps of new flux using the difference ($\delta B$) between the field roughly 12 hr after $t_0$ and the first time interval (roughly 24 hr before $t_0$), and only including in the bitmap areas where $|\delta B| > 0.3 \times \max(|\delta B|)$. A centroid was created from the resulting bitmap, and the coordinates were then assigned to be the location of this centroid.

In this manner, the analysis that is performed on averages taken over space, time, or sample will provide results that are not...
dilated by subtle differences in emergence location within the field of view. Accordingly, no similar refinement was performed for the NE samples, as there are no events by which to define such a refinement.

4. STATISTICAL CONTAMINATION ISSUES

This is a study trying to detect a small difference between two populations. How these populations are defined and the samples obtained, then, will directly affect the reliability of the results. The goal is that the PE regions be clear, distinct, isolated, and fairly near disk-center emergence episodes, and the NE regions be emergence-free episodes matched to the PE distributions in location and time (effectively, solar-cycle activity level) as described above.

Statistical contamination, the existence of a bias that will inadvertently identify the two populations without being directly related to the emergence process, may take a variety of forms. As alluded to in Section 2, we describe below our understanding of various contributions to possible contamination, and our efforts to mitigate them.

4.1. Nearby Field

Ideally, the background, nearby, or pre-existing field in the NE targets (their distribution in space, flux density, total flux, etc.) is indistinguishable from that of the PE targets prior to emergence. The emergence episodes and NE regions were initially characterized by 128 × 100 pixel tracked boxes in the MDI image-plane coordinate frame. The data cubes used for analysis were, as described above, 32° × 32° on a heliographic grid. The difference between these two can be seen in Figure 8, and is not insignificant. The most noticeable effect is that the NE cubes in fact often contain stronger field at the periphery than the cutoff used to select the smaller areas (Figure 10). The PE cubes were isolated from nearby active regions in the original 128 × 100 pixel evaluation, but strong field (active regions) can be found in the larger 32° × 32° field of view.

By comparing the signals averaged as shown in Figure 11, it is clear that there is a bias: the median signal of magnetic field is larger in the PE samples as compared to the NE samples. Note that by showing the median, rather than the mean, the results are not influenced by outliers and the distributions display a real difference. For the full 32° × 32° field of view, the difference is significant but not large: when considering only the smaller central 16° × 16°, the PE sample result does not change noticeably (until emergence begins in the last time interval), whereas the NE sample median signal is quite reduced. This confirms that the initial 128 × 100 pixel evaluation area for the NE sample is “too quiet” compared to the enhanced signal in the NE sample peripheries and to the PE sample, even though the selection threshold was a generous 1 kG (Section 3.2).

The source of this bias may be introduced or it may be a real effect. The emergence really could start more than a day before $t_0$, in which case there is no error, just a real physical effect only visible in the ensemble. However, by imposing a field strength limit on the NEs but not PEs, we may have introduced an artificial bias into the samples. Due to the matching in latitude and longitude, there should be no gross preferential prevalence of “background” field as there would be had all of the NE regions, for example, been selected outside the active latitudes or all in the same hemisphere. However, there was also no de-selection of PE candidates based on “active longitudes” (Petrovay & Abuzeid 1991; Gaizauskas et al. 1994; Pojoga & Cudnik 2002), and active longitude lifetimes are likely too short to be captured simultaneously in the time matching and longitude matching. If the bias is the effect of active longitudes, this is a real (solar) bias toward having pre-existing field for the PEs. The fact that the NEs are “too quiet” implies that the inconsistent use of a threshold contributes to the bias, but may not be the only effect. The significance of this
systematic difference between the samples is discussed in detail in Paper III.

4.2. Nearby or Short-lived Emergence

It is conceivable that nearby or ongoing short-lived flux emergence may contaminate the seismology signal we search for.

No screening or diagnostics was performed to specifically rule out nearby emergence episodes for either PE or NE samples. Both may have emerging flux regions in the periphery, and these data sets were not removed from consideration (as long as there were no emerging flux regions within the central $16^\circ \times 16^\circ$, or $\approx 100 \text{ Mm} \times 100 \text{ Mm}$). A variety of seismic analyses will be performed with varying pupil sizes (Birch et al. 2012), thus the influence of field in the sample peripheries can in fact be studied.

Very small-scale short-lived emergence episodes, “ephemeral regions” are ubiquitous and bring substantial flux to the solar surface (Harvey & Zwaan 1993; Hagenaar et al. 2003). The presence of ephemeral regions is not selected for or against, as their peak field strengths generally fall below the NE-selection threshold of 1 kG in MDI data, except one or two cases of removing an NE candidate due to a long-lived or especially large ephemeral region occurring at the center of the target. We make the assumption that the rate and distribution of ephemeral regions is the same between the samples of the NE and PE populations, and propose that no statistical bias is introduced due to the presence of ephemeral regions.

4.3. Misdetermination of Emergence Time

Numerous sources of error could lead to a misdetermination of $t_0$, with effects presenting as bias or as random error.

The coarse temporal resolution MDI data used here could lead to a significant amount of “new” surface flux being present for an hour or so before the “emergence time” $t_0$. “Significant” is used here qualitatively, because it is the lack of data that is the primary source of the uncertainty itself. Lack of adequate sampling should add an element of random noise to comparisons between segments. The reliance on line-of-sight data, however, may present a systematic late determination of $t_0$ with respect to observing angle, since early flux emergence is signaled by horizontal field (Zwaan 1985; Zhang & Song 1992; Leka et al. 1996; Bernasconi et al. 2002; Kubo et al. 2003). In and of itself, the instrumental limitations should not present a statistical contamination between the NE and PE samples. Since the presence of surface field when none is expected (as due to the misdetermination of $t_0$) may impact the Doppler signal and hence the inferred helioseismic parameters, the results for the time interval comprising the last hours prior to $t_0$ will be interpreted with this uncertainty taken into account (Birch et al. 2012; Barnes et al. 2012).

Of a more subtle nature, in terms of this study, is the nature of flux emergence itself, the early evolution of active regions, and whether or how a very young active region is distinguishable from the general evolving magnetic background. While we employed an objective and quantitative method to determine $t_0$, as needed for a statistical study, upon examination of any individual case, $t_0$ could be argued with. An example is shown in Figure 3. An area of unchanging plage is co-spatial with the eventual emergence of NOAA AR 9564, and episodes of small bipoles appearing are evident prior to $t_0$ upon detailed inspection. These bipoles would not gain attention beyond the numerous ephemeral regions continuously appearing on the surface (see Section 4.2) and indeed they did not gain NOAA’s attention, except that they were located where NOAA AR 9564 eventually appeared.

We hypothesize without further investigation that the pre-emergence surface-field signature in the all-PE averages (Figure 10) is an indication of this very common characteristic: pre-emergence field can be present, whether as remnant plage or very early emergence episodes that are unnotable in any individual PE time series. As commented on earlier, when only examples are selected for which—by visual inspection—there is no pre-emergence surface field, the PE field signature is reduced if not absent. A third option is that very early emerging flux is distributed and weak, and detectable only on average (Figure 10) with the MDI data due to the significantly reduced noise; in this case the pre-emergent surface-field signature is absent for the clean subset not due to their “ultra-clean” nature, but due to the smaller number of data sets being averaged, and hence the increased noise (compared to averages for all regions).

The impact of a varied flux-emergence rate on later analysis should be a source of noise but not statistical contamination. The rate of emergence of flux was cited in Ilonidis et al. (2011) as a key parameter relating to the strength and timing of the PE signal. However, it does not bias the NE versus PE samples.

The final evaluation is that $t_0$ may be misdetermined by an amount comparable to the MDI 96 minutes sampling, hence the final time interval used for helioseismology analysis will be assumed contaminated by early emergence. Smaller episodes of new flux appearance are indistinguishable from that which routinely occurs over the solar disk without the subsequent formation of an active region, and can simply be considered a source of noise for the present analysis.
5. DISCUSSION

The tools of local helioseismology rightfully hold hope of sensitive and powerful diagnostics of the solar subsurface structure, evolution, and behavior. To interpret the helioseismic signals with physical insight, they must be isolated to those relevant to the events in question. To fruitfully make use of the signals, the full extent of bias and contamination must be understood. We have designed a study to examine what signatures prior to the appearance of solar active regions may be detected by local helioseismology tools and data at this time, and outlined the data selection criteria and preparation herein.

This study focuses on determining whether or not a seismology signal is evident prior to emergence and what its character might be. The goal is, as discussed in Section 1, inferring changes in the subsurface associated with active-region formation. Based on the preparation described here, in Birch et al. (2012) we report on average subsurface properties of the two samples (PE and NE) as derived using helioseismic holography, and find statistically significant signatures in average subsurface flows and wave speeds, but do not detect evidence of strong spatially extended flows in the top 20 Mm during the day preceding visible emergence. In Barnes et al. (2012), parameters are derived from the seismology and magnetic field to characterize each of the PE and NE regions, and discriminant analysis is used to measure differences between the sample sets. While statistically significant differences are found from this analysis, it is found that no single parameter can clearly distinguish a PE from an NE for any single region.

To mitigate sources of bias, the distributions of the samples are matched in location and time (epoch within the solar cycle). This approach is novel; however, PE areas are targeted here exactly because they did form an active region significant enough to be noticed by NOAA. The PE targets can thus be studied with respect to the known location and time of emergence, and the magnetic- and seismology-based analysis performed with respect to the target’s known coordinates. There is a random component in the selection of the NE regions, but they, too, are selected with knowledge that no emergence occurred within a specific time interval. Hence, there is a bias in that we are pre-selecting targets for study according to what is known to have happened.

There is an intrinsic difference between this study design and any attempt at “forecasting” the emergence of an active region. A forecasting study would instead be required to sample all possible emergence sites and compare the signals to all other possible sites, without a priori knowledge aiding the analysis methods. At the very least, a study designed for forecasting must employ samples and statistics which reflect the prior probability of an active region emerging at a randomly selected place and time over the observable disk, which is extremely small. While the results presented in Birch et al. (2012) and Barnes et al. (2012), and the available “blind” data sets (see Section 5.2, below) may serve to guide later studies of the true forecasting ability of seismology for active-region appearance, we caution that study design and attention to prior probabilities are crucial to answering specific questions posed.

The present study uses a fairly large sample, and hence comparisons may be made to, e.g., Komm et al. (2009, 2011), even though the definition of “emerging” differs: here we focus on the period prior to any surface field while the Komm et al. studies included both new and growing active regions (with surface flux present). As such, the present study may be seen as an extension of case studies which also focused on pre-emergence periods (e.g., Jensen et al. 2001; Ilonidis et al. 2011; Braun 2012) to statistically significant sample sizes, however, the methods and interpretive tools (depths, cadence, control samples if any) differ between these studies and the present one. We describe here the steps taken to acquire both the statistically significant sample size with a clear focus on pre-emergence phenomena (although see Section 5.1, below). With better tools and analysis approaches, the sometimes conflicting results in the literature should give way; then, only those effects which are truly specific to the emergence process will be the focus of discussion.

Any seismic changes detected prior to surface changes will be evaluated in the context of the predictions made by different theories covering the source and formation mechanisms of solar active regions. But the seismology is influenced by the early surface behavior; the interpretation of the surface behavior is influenced by our understanding of the emerging-flux scenarios, which is what we are trying to learn about using seismology. The analysis has a circularity to it which implies one thing most strongly: interpretation must be done with utmost care. Only then can model predictions be validated.

Emergence scenarios differ between active regions with respect to rate of flux increase, the existence of distinct emergence episodes, location with respect to remnant field, etc. As mentioned above, the early evolution of active regions is an active research area and distinctly tied to the subsurface behavior which is the focus of this study.

There are efforts underway (Martens et al. 2012) to perform automatic feature recognition on data from, for example, the instruments of Solar Dynamics Observatory. Combining emergence indications from HMI and AIA may be advantageous. Using such database of emergence times defined by an independent algorithm may lend objectivity to the results and ease of acquiring the larger samples we suggest, but it must be accompanied by research on the early evolution of active regions.

5.1. For Future Studies

Hindsight enables future improvement. The flaws of a study design become distinctly clear as the study progresses and “issues” arise; in the best situations the flaws can be remedied, but in many cases due to resource limitations, corrections or accommodations must be made mid-course. Specific effects that the flaws in the present study’s design had on the results will be discussed in Birch et al. (2012) and Barnes et al. (2012) as appropriate. Whereas this paper discusses the details of the design, the results also comprise the lessons learned over the duration of this study.

1. Characterizing early active-region appearance and evolution is very much a research topic. The (objective, independent) determination of emergence time and location should be performed using, ideally, vector magnetic field data to detect the earliest horizontal field (Section 4.3); vector data may thus alleviate any systematic bias in $t_0$ as a function of observing angle. Resolution issues aside, the early evolution of active regions may form a spectrum of behavior such that assigning a single location and time is in fact inappropriate. However, for a statistical study, the determination of emergence time must be performed, as we did here, in an objective and repeatable manner—recognizing that the answer is very sensitive to data resolution, sensitivity, and cadence.
2. Data selection rules must be applied to areas used in the final analysis with minimal discrepancies. As described in Section 3, the initial evaluation of the PE and NE regions was performed on a much smaller field of view than was eventually extracted from the GONG data (and than was also eventually extracted from the MDI data for magnetic-field comparisons). As such, there was more, and more varied, peripheral activity than was expected in both the NE and PE samples. The contamination is inevitable given the large number of active regions during solar maximum activity; still, the bands of significant field in the periphery of the NE average magnetograms (Figure 10) were unexpected.

3. The distribution of background field must also be matched between populations in a manner analogous to matching the distributions of location and time (epoch within a solar cycle). That is, there is in fact a bias in the data sets used here, since the NE regions are overall quieter, with less background field, than the PEs (see Figure 11). Rather than just select for “no field above a certain threshold” for the NE regions, areas should be selected which match the pre-emergence background field distribution characteristics of the PEs. This task is not trivial.

4. Related, the spatial distribution of the field may be important, since the seismology signatures are derived from Doppler signals both at the focal point and in an annulus, whose size relates to the depth sampled. Regions emerging into an existing plage area will have a different surrounding flux distribution than very quiet non-emergence areas. Contrariwise, if stable plage areas are chosen preferentially as the NE targets, then a bias is clearly introduced.

5. Utilize helioseismic data and magnetic data from the same source, if at all possible. It was unfortunate that magnetic field data were not readily available for this study from the GONG system. HMI is the logical data source for any follow-on statistical study to what is presented here.

6. Examine 48 hr or more prior to emergence rather than only 24 hr (and, of course, match this for the control data). This will decrease the number of regions available within suitable observing angles, however, will allow additional evolution to be detected.

7. For studies that employ statistical analysis, initial target sample sizes should be 5–10 times larger than assumed sufficient for the final analysis. The robustness of results depends on noise in the data and the many sources of bias. But it also involves an interplay between sample sizes versus the number of variables tested. The larger the sample size, and the larger that size is relative to the number of variables under consideration, the smaller the chance of statistical flukes in outcome. The initial “PE” target list for this study numbered almost 500 regions; after removing targets due to data problems, significant spatial/temporal overlap, matching for latitude/longitude/epoch, and accounting for duty-cycle limitations, each time interval used had \(~\approx 85–90\) samples.

5.2. Data Availability

Despite the shortcomings identified above, the present study provides a rich data set for investigating questions of pre-emergence signatures of solar active regions, the sensitivity of results to methodology, etc.

To that end, we make the data sets used in this study available through \(\text{http://www.cora.nwra.com/LWS\textunderscore Predict\textunderscore Emergence/}

Site/Data\_Sets.html (following the link that cites this paper). They have been prepared for double-blind tests, in that the data from both PE and NE samples are available but have been randomized with all identifying information removed from filenames and file headers. Also included at that Web site will be an uploadable form by which to submit “answers” to the same Discriminant Analysis code used in Barnes et al. (2012), so that groups interested in direct method comparisons can quantitatively compare performance against our published results.

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