FINAL REPORT

Acoustic Holography of the Solar Convection Zone with SOHO-MDI Observations

GRANT NUMBER:	NAG5-12901
SPONSOR:	National Aeronautics and Space Administration
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Background

The original grant with the title stated above was NAG5-10984, awarded to the Solar Physics Research Corporation (SPRC) in July, 2001, and was to be a three-year project. The basic theme of the project was the development and application of computational seismic holography for imaging, diagnostics, and monitoring of magnetic anomalies beneath active regions, in the deep solar interior, and on the Sun's far surface. The project was roughly separated into the following five tasks:

(1) A holographic survey of active regions.

(2) p-Mode absorption diagnostics of magnetic regions.

(3) Acoustic modeling of the shallow subphotospheres of active regions and the quiet-Sun supergranulation based on phase-correlation seismic holography.

(4) Seismic holography of the deep convection zone.

(5) Improvements in holographic imaging of the far surface of the Sun.

Following the death of Karen Harvey, President of SPRC, during the first year, the grant was transferred to NorthWest Research Associates as NAG5-12901. Substantial but progress had been made on most of the above tasks in the first year under NAG5-10984, but none were completed. This work was continued under NAG5-12901.

Statement of Work Accomplished under NAG5-12901

Under the circumstances, a clean separation between the incomplete work done under NAG5-10984 and its continuation under NAG5-12901 would be awkward and probably impractical. In this report I will simply review what has been accomplished in all five tasks by the completion of NAG5-12901 with no effort to discriminate substantial technical work that was actually accomplished in the first year under NAG5-10984. All of the publications listed in this report can be regarded as inclusive of substantial work done under the two-year term of NAG5-12901.

(1) *Holographic survey of active regions.* The original proposal called for a survey of holographic signatures, including "egression power" and a range of phase-correlation

diagnostics applied to approximately 25 active regions over various time periods. Greatly expanded computing power and the involvement of collaborators in Australia resulted in a considerably expanded survey. The original survey was focused on quasi-static phase-correlation signatures of magnetic regions integrated over 24 hours. In the second year the survey was expanded to include a search for "sun quakes," instances of transient acoustic emission from flares. * At the outset of this project, acoustic emission from a single solar flare had been discovered (see Kosovichev & Zharkova 1998; Donea, Braun & Lindsey 1999). The flare survey led to the discovery of a large number of sun quakes, not anticipated in the original proposal. In a survey of 113 active regions more than a dozen acoustically active flares were been discovered. A table of the survey results is available at the website `http://www.maths.monash.edu.au/~adonea`.

Holographic phase-correlation diagnostics of active regions in the survey have led to the recognition of systematic signatures that are diagnostic of important aspects of the interaction of acoustic waves with photospheric magnetic fields. These are particularly pertinent to our understanding of how p-modes absorb acoustic waves. They are also important to modeling of thermal anomalies and flows in the shallow subphotosphere helioseismic data. Both of these topics are reviewed directly below.

(2) *p-Mode Absorption Diagnostics.* The absorption of p-modes by magnetic regions is only one aspect of the general problem of how magneto-acoustic gravity waves interact with photospheric and shallow subphotospheric magnetic fields. These dynamics appear to explain important phenomena discovered under NAG5-12901. The major discoveries that came out of our investigation of p-mode absorption are those of (1) the "penumbral acoustic anomaly," and (2) a phenomonon we will refer to here simply as the "Schunker effect." What we presently know about the penumbral acoustic anomaly at least tentatively supports a general theory of wave-magnetic field interactions that grew out of work by Cally and Bogdan (1997). This theory explains p-mode absorption by conversion of p-modes to slow Alfv́en modes, particularly in regions of inclined photospheric magnetic fields. Theoretical work on the physics of p-mode absorption under NAG5-12901 is described by Cally, Crouch and Braun 2003. This is now the subject of the PhD thesis research of graduate student Hanah Schunker, at Monash University, under the direct supervision of collaborator Paul Cally. The Schunker effect has to do with the behavior of acoustic motion waves emerging from beneath the solar surface into a photosphere with an inclined magnetic field. Using holographic diagnostics applied to MDI Doppler observations from different aspect angles with respect to inclined penumbral magnetic fields, Ms. Schunker established the strong dependence of the phase of acoustic motion on the horizontal azimuth between the line of sight and the inclined magnetic

* This effort was organized by A.-C. Donea as part of our collaboration with Monash University. It included Diana Besliu, an undergraduate at the Astrophysical Institute of the Romanian Academy, in Bucharest, and Hamed Moradi, a graduate student at Monash. The original collaboration with Monash included only Prof. Paul Cally. Dr. Donea joined Prof. Cally's group at Monash during the term of NAG5-12901.

field, as predicted based on elementary MHD considerations related to p-mode absorption. These results, which are published in Schunker et al. (2004), are fundamental to our understanding of p-mode absorption by magnetic regions, and more broadly to our understanding of the the interaction of p-modes with magnetic fields. They are also fundamental to realistic seismic diagnostics of thermal anomalies and flows that lie substantially beneath the magnetic photospheres, for reasons described directly below.

(3) *Acoustic modeling of the shallow subphotosphere based on phase-correlation seismic holography.* Acoustic modeling exercises were developed under NAG5-12901 for both the quiet Sun and for active regions. For the quiet Sun, the object was the supergranulation, for which modeling under the first Born approximation appears to be practical. Holographic phase correlation maps of the supergranulation fashioned to be responsive to flows show clear signatures consistent with supergranular flows directly observed at the solar surface. The major question is to what depth these flows penetrate beneath the photosphere. Tentative models based on the holographic signatures suggested shallow flows, mostly within 3 Mm of the surface, once certain artifacts were accounted for. However, further modeling work at NWRA, shared by another NASA contract, NNHY05CC76C, has indicated that the holographic signatures could also be consistent with deeper flows suggested by other seismic diagnostics. Work to resolve this question is being continued under NNHY05CC76C.

Phase correlation diagnostics of active regions in our survey have invariably shown signatures that appear to be consistent with seismic anomalies mostly confined to within 3 Mm (and possibly much less) of the photosphere. These anomalies are now described by the term "acoustic showerglass." Phase perturbations introduced by the acoustic showerglass are sufficient to impair the coherence of waves emerging from the underlying solar interior. This complicates seismic diagnostics of the subphotospheres of strong magnetic regions.

Efforts to model the subphotospheres of active regions under NAG5-12901 have centered on modeling and understanding the acoustic showerglass, a careful account for which is needed to see substantially beneath it. A particularly useful utility to be developed is a magnetic proxy of phase perturbations the showerglass introduces to acoustic signatures in terms of the photospheric magnetic fields observed. Such a proxy, combined with appropriate cospatial magnetic observations, can be used to correct the effects of the acoustic showerglass to a significant degree. This undertaking is analogous to techniques in adaptive optics that have been so successful in astronomical imaging through the turbulent terrestrial atmosphere. The development and application of a rough magnetic proxy to correct showerglass phase errors has been published (Lindsey & Braun 2005a,b). Preliminary models based on holographic signatures corrected for the acoustic showerglass show tentative evidence for outflows from sunspots in the top 3–5 Mm, but no evidence for thermal anomalies or flows beneath 5 Mm. This is somewhat in conflict with some models based on other time-distance diagnostics. Holographic diagnostics of active regions under NAG5-12901 are not entirely conclusive at this point, but have led to a general consensus that a careful account for acoustic showerglass is necessary for credible modeling of thermal anomalies and flows in the 1–10 Mm subphotospheres of active regions. Proposals have been submitted to NASA for work on improved magnetic proxies of the acoustic showerglass.

(4) *Deep interior seismic holography.* Work on this project was begun under NAG5-12901 but is incomplete due to a somewhat greater level of technical difficulty than was initially anticipated. NASA has granted us a $40,000 1-year extension, to do further work on deep interior seismic holography and on solar flares. This will be described in our reports on NNG05GF50G.

(5) *Improvements in holographic imaging of the far surface of the Sun.* Stanford's farside synoptic imaging program (see `http://soi.stanford.edu/data/farside`) has been extremely popular. Its users include the airline industry, electrical power suppliers, commercial satellite operators, communications companies, amateur radio operators, and NASA itself. Also included are clients of the Space Environment Center (NOAA/Department of Commerce) and other space-weather specialists. Considerable work was done to improve imaging of active regions on the Sun's far surface under NAG5-12901 and under another NASA grant, W-10230, with collaborators Irene Hernandez-Gonzalez and summer students Anna Malanushenko (GONG) and Kenny Oslund (Stanford/MDI). (Work at NWRA on W-10230 was done under subcontract with the GONG project at the National Solar Observatory.) The original farside imaging computations operating under Stanford's farside synoptic imaging program (`http://soi.stanford.edu/data/farside`) are sensitive only to active regions within approximately 45° of the antipode of disk center. Coverage of the full far hemisphere has been under heavy demand. Under NAG5-12901 and W-10230 farside imaging techniques have been extended to cover the entire far hemisphere of the Sun and have been adapted for application to GONG observations. The GONG project has now recently begun its own farside synoptic program (see `http://www.gong.nso.edu/data/farside`).

Beyond NAG5-12901

A major part of research under NAG5-12901 has been modeling of the acoustic showerglass in order see beneath it into the 1–10 Mm subphotospheres of active regions. In fact, this is only one aspect of the study of the showerglass. The whole subject of what causes the acoustic showerglass turns out to be a very interesting physics problem, and is now the subject of major theoretical and observational attention identified by the title "magnetohelioseismology." Research under NAG5-12901 has been an important impetus for the early development of magnetohelioseismology. We have already mentioned the discovery of the penumbral acoustic anomaly and the Schunker effect. More examples are certain to be forthcoming. NASA has provided us with a $40,000 1-year extension of NAG5-12901, identified as NNG05GF50G. A new and major prospect of research opened by NAG5-12901 has been the possibility of discriminating thermal anomalies within the upper few hundred km of magnetic subphotospheres, particular those of sunspot umbrae and penumbrae. This is a major thrust of research under NNG05GF50G and proposals we have recently submitted to NASA.

In accord with 14 CFR Part 1260.28 there are no inventions to be reported under NAG5-12901.

Publications under NAG5-12901

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Other References

Cally, P. S. & Bogdan, T. J. 1997, "Simulated f- and p-Mode Interactions with a Stratified Magnetic Field Concentration," *Ap. J.* **486**, L67.

Donea, A.-C., Braun, D. C & Lindsey, C. 1999, "Seismic Images of a Solar Flare," *Ap. J.* **513**, L143.

Kosovichev A. G. & Zharkova V. V. 1998, "X-Ray Flare Sparks Quake inside the Sun," *Nature* **393**, 317.