Radio observations of long period oscillations in sunspots

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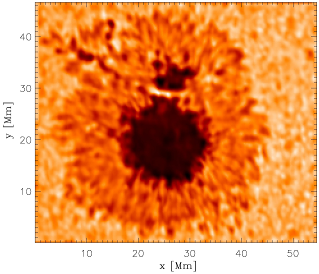
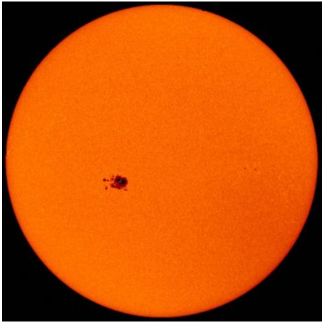
Introduction - Sunspots

- Structures associated with solar magnetic field.
- Formed by emerging magnetic flux.
- Field strength (photosphere) $\approx 10^3$ G (10^{-1} T)
- Lognormal distribution of sizes.





Introduction - Oscillations in sunspots

- Sunspots are dynamic features.
- 3 minute oscillations (Beckers & Tallant 1969).
- Running penumbral waves (Zirin & Stein 1972).
- 5 minute oscillations (Thomas, Cram & Nye 1984).
- Solar p-modes absorbed by sunspots.
- Helioseismology also mentions g-modes: waves where restoring force is buoyancy.
- Typical period for g modes: $\sim$ 1-3 hours.
- Longer period oscillations - two kinds: compressible and incompressible (possibly torsional oscillations).

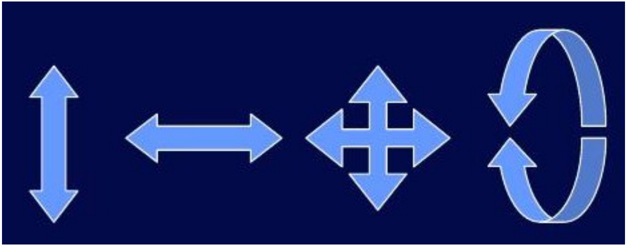
Introduction - Longer period oscillations

- Demchenko et al. 1985: 70 min oscillations of sunspot areas.
- Berton & Rayrole 1985: 40-50 min vertical velocity oscillations coupled with magnetic field torsional oscillations.
- Nagovitsyn & Vyal'shin 1990: 45-120 min torsional oscillations.
- Druzhinin et al. 1993: 20-60 min penumbral vertical oscillations.

- Wiehr et al.: 50, 60, 64 min Hα emission oscillations from prominences.
- Foullon et al. 2004: Ultra-long-period oscillations in filaments (8-27 hours).

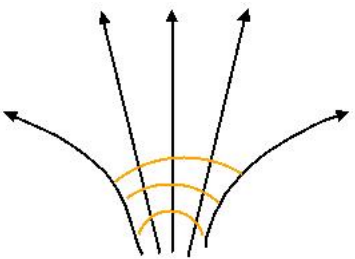
Motivation - Longer period oscillations

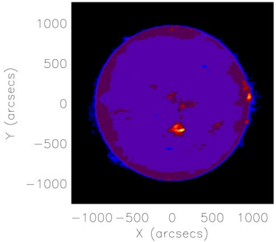
- $P > 60$ minutes.
- What is their nature?
- Can we learn about the solar interior and dynamo?
- Shallow sunspot model. $v_A = \frac{B}{\sqrt{\mu_0 \rho}} \approx 16$ km s^{-1}.
- Distance travelled in ≈ 60 mins ≈ 57 Mm. "Typical" sunspot diameter ≈ 6000 km.
- Coronal origin? Excitation by other processes in the corona, e.g. prominence oscillations.



Data generation

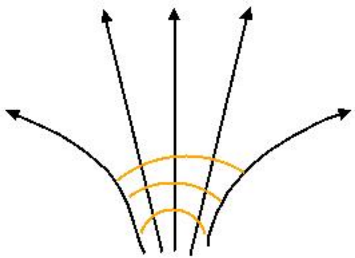
- Physical mechanism for radio emission: electron gyroresonance.
- Images from Nobeyama Radioheliograph @ 17 GHz.
- Emission generated at the second or third harmonic of electron cyclotron frequency.
- Spatial resolution: 10" per pixel.
- Temporal resolution: 1 sec.





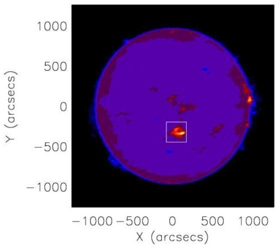
Data generation 2

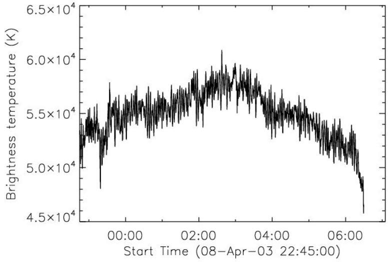
- Modulation of emission in two ways:
  - Fast mode-like: field “breathes” and emitting layer oscillates vertically.
  - Slow mode-like: density in emitting layer varies.



Data pre-processing

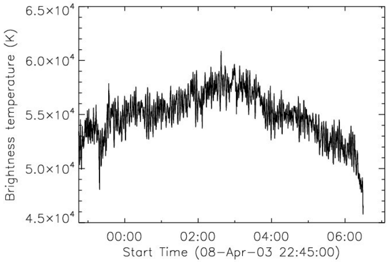
- Small field of view taken and microwave intensity signal integrated over this.
- Images derotated before integation.

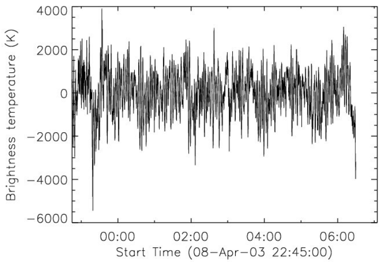




Methods - Trend removal

- Source of trend: projection effect.
- Polynomial fit.
- Filtering to remove longest periods (connected with daily trend).
- Oscillations with 3 periods or fewer are filtered out.

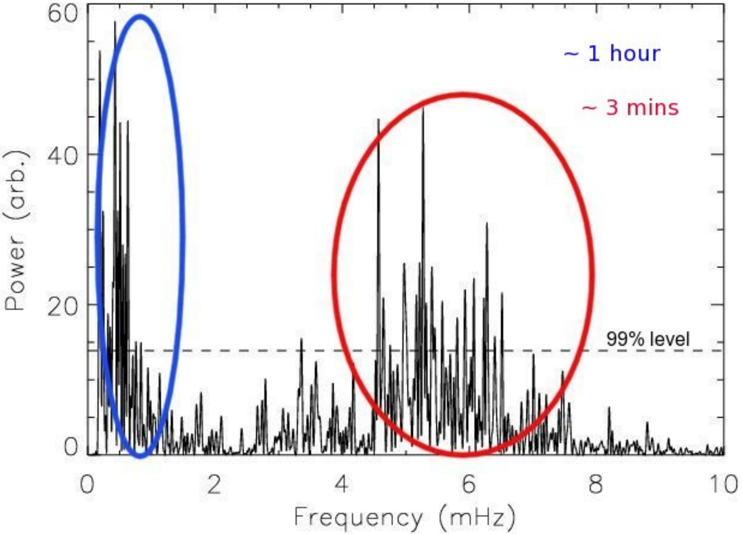




Methods - Scargle periodogram

- Classical periodogram: $P(\omega) = \frac{1}{N} \left| \sum_{j=1}^{N} x\left(t_j\right) \exp(-i\omega t_j) \right|^2$
- Scargle periodogram:
  $P(\omega) = \frac{1}{2} \left\{ \frac{\left[\sum_i x_i \cos\omega(t_i - \tau)\right]^2}{\sum_i x_i \cos^2 \omega(t_i - \tau)} + \frac{\left[\sum_i x_i \sin\omega(t_i - \tau)\right]^2}{\sum_i x_i \sin^2 \omega(t_i - \tau)} \right\}$
- Advantages: estimate of $P(\omega)$ close to that of classical periodogram, allows simple estimation of significance level.

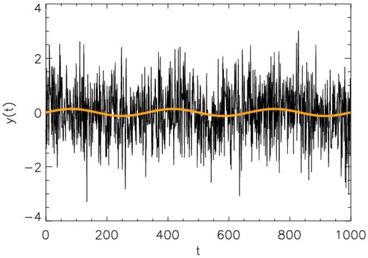
Methods - Scargle periodogram example

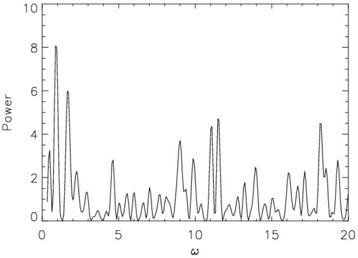


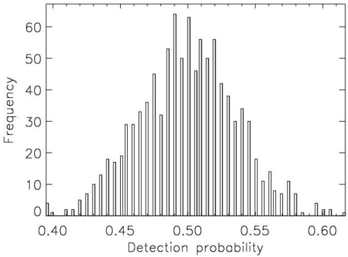
Methods - Fisher randomisation

- Significance test - are detected periods real?
- No periodicity implies observations independent of time.
- $n!$ possible orderings of data.
- Test statistic: amplitude of highest peak in spectrum of randomised signal, compared with original signal.
- Problem: n usually large, so choose $m \ll n$, $n \sim 3000$, $m \sim 200$.
- False alarm probability estimate, $p = \frac{m_p}{m}$.
- m_p = number of times amplitude of highest peak in spectrum of randomised signal is greater than or equal to highest peak in original spectrum.

Methods - Fisher randomisation example





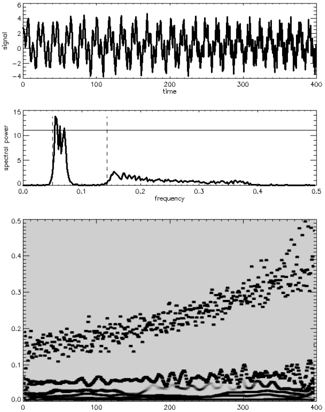


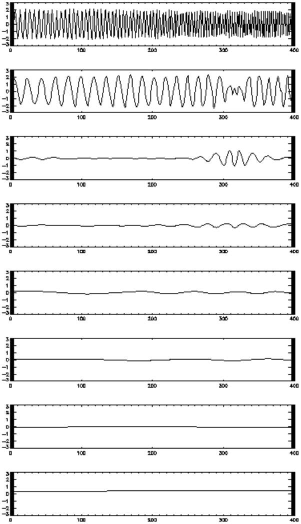
- Detection probability quite high, in view of noise level.

Methods - Empirical Mode Decomposition (EMD)

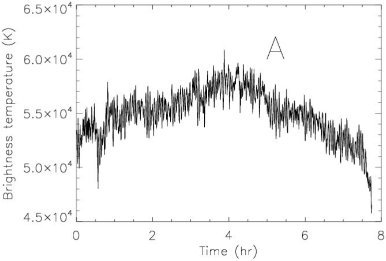
- Assumption: data is sum of intrinsic modes of oscillations.
- Intrinsic mode functions (IMFs) must satisfy two conditions:
    - 1. The number of extrema and the number of zero crossings must differ by at most one.
    - 2. Mean value of envelope defined by local maxima and the local minima must be zero at all times.
- Upper and lower envelopes are found by connecting local maxima and minima by cubic splines.
- Mean of the envelope, $m(t)$ is found and subtracted from the data.
- Process repeated until all possible IMFs are found.
- No need for trend removal!
- Visualised with Hilbert transform or wavelets.
- See also poster by J. M. Harris (EMD applied to flares) and papers by Terradas et al. 2004 and Komm et al. 2001.

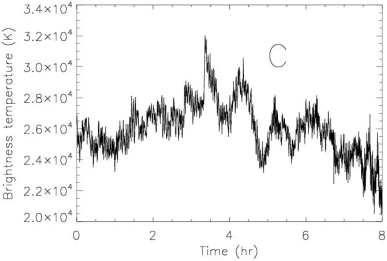
Methods - EMD example for a synthetic signal

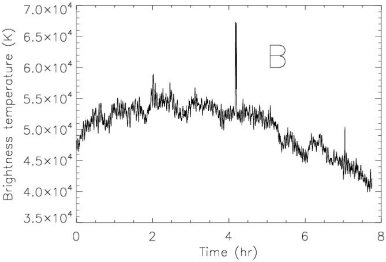




Application - Sunspot time series from NoRH

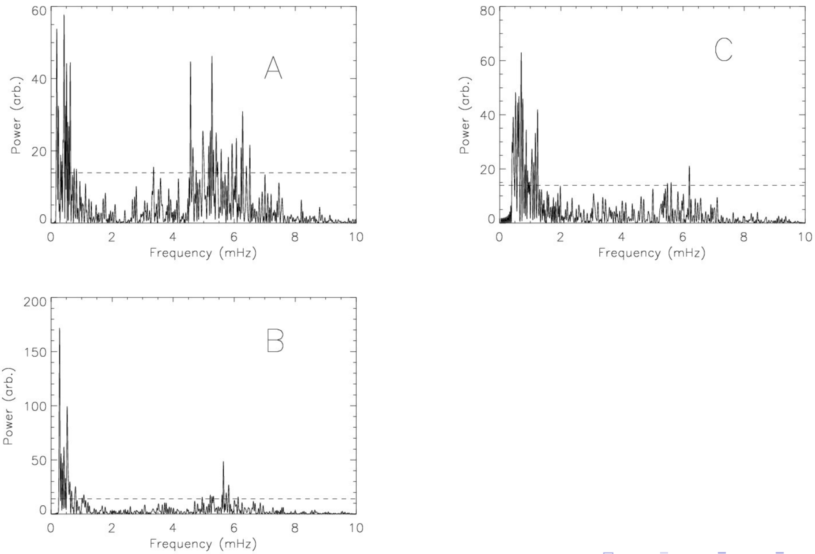




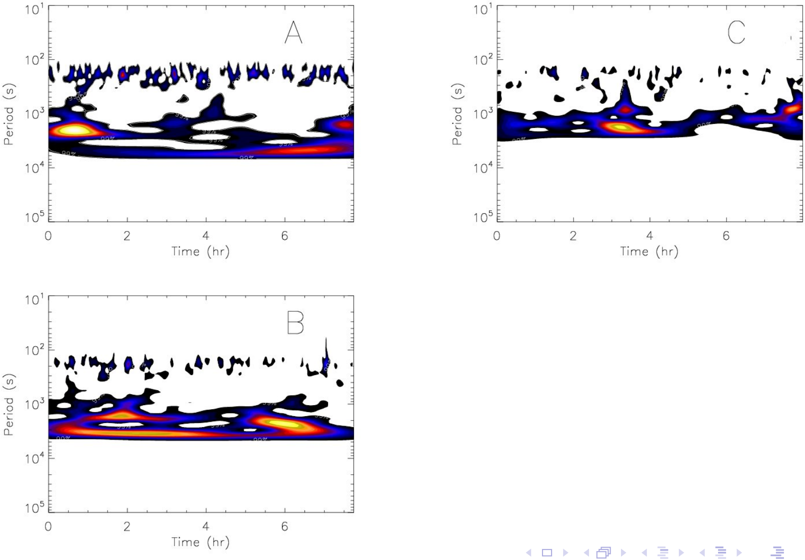


- A: AR0330, 08-Apr-2003 22:45 - 09-Apr-2003 06:29.
- B: AR108: 10-Sep-2002 22:45 - 11-Sep-2002 06:29.
- C: AR673: 21-Sep-2004 22:45 - 22-Sep-2004 06:45.

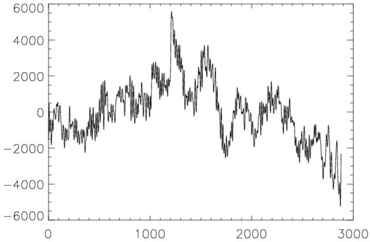
Results 1 - Scargle periodograms

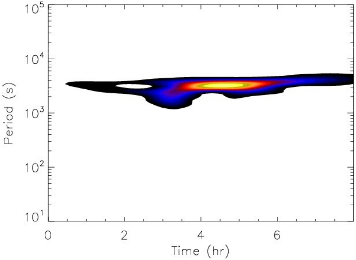


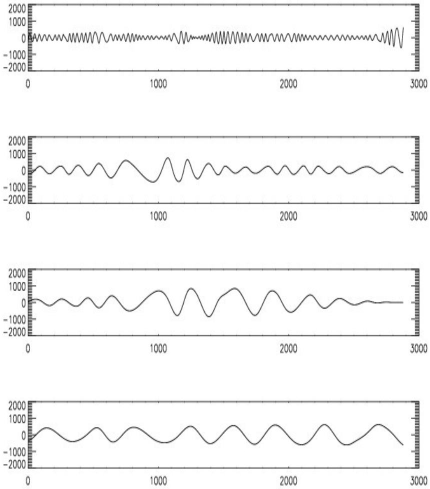
Results 2 - Wavelet power spectra (Morlet)



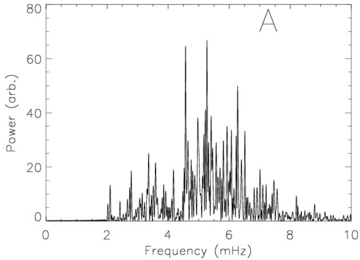
Results 3 - EMD + wavelets

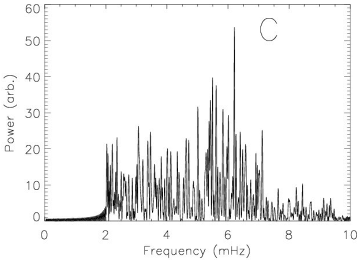


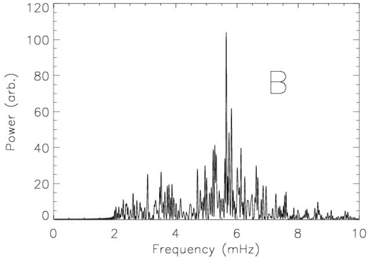




Results 4 - Fine structure of 3 minute oscillations

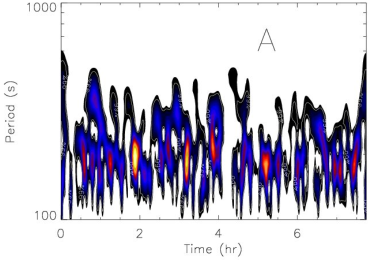


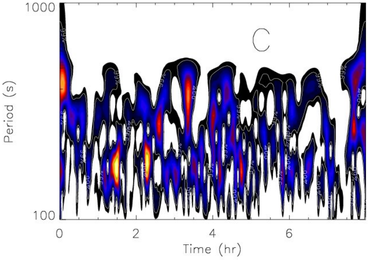


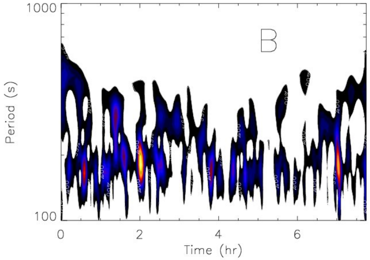


- Modulation by longer periods: $\omega = [\omega - \Omega, \omega + \Omega]$.
- ω = 3 min oscillations, Ω = longer period oscillations.

Results 5 - 3 minute oscillations (wavelets)







- No wave train structure seen.

Conclusions

- Long periods (several tens of minutes) persist throughout observation periods and remain stable.
- Fine structure of 3 minute oscillations varies between sunspots and a link between these and the long period oscillations has not yet been found.
- Could these be g modes? Is there a connection to prominence oscillations?
- This is a work in progress.