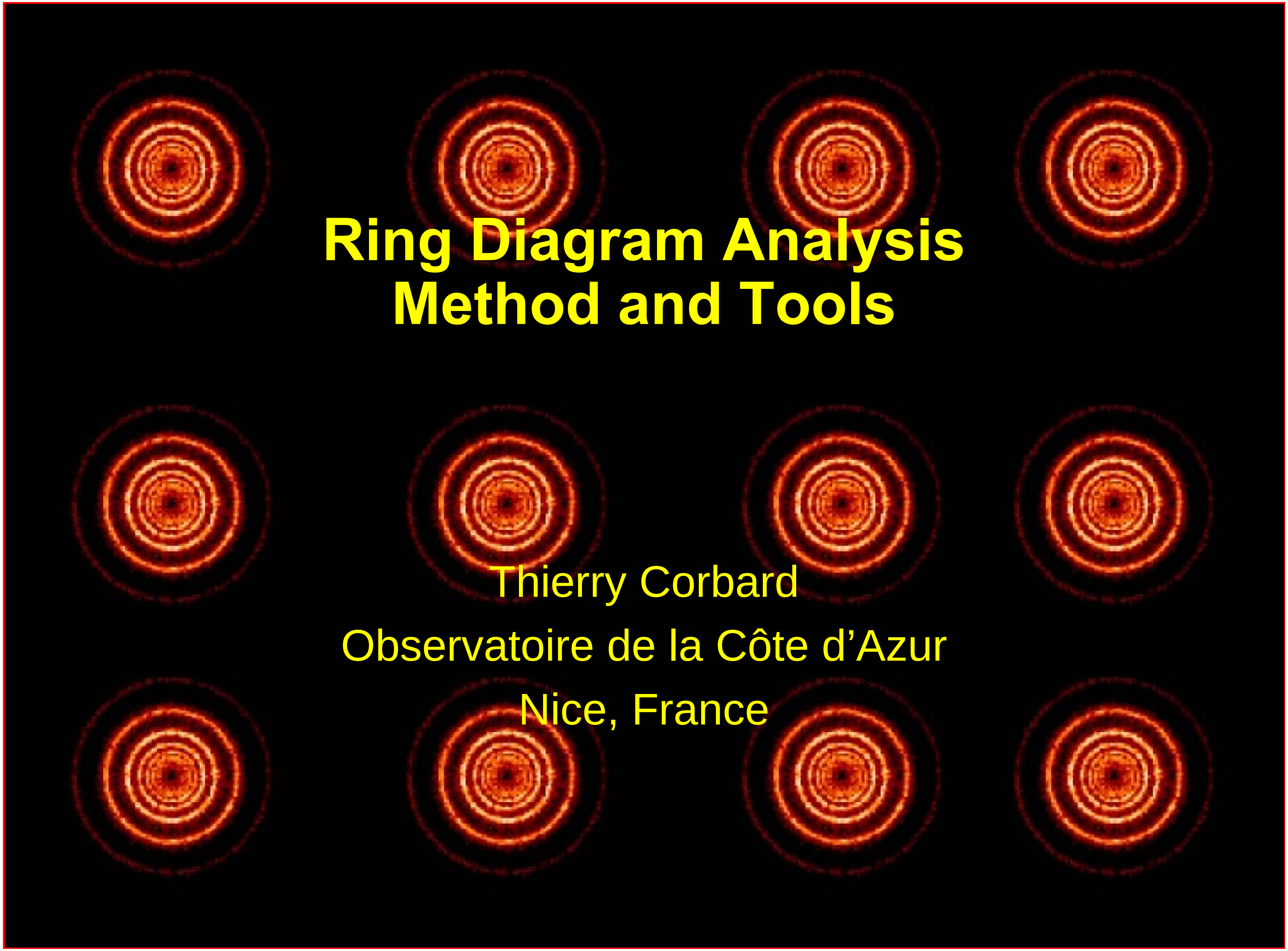
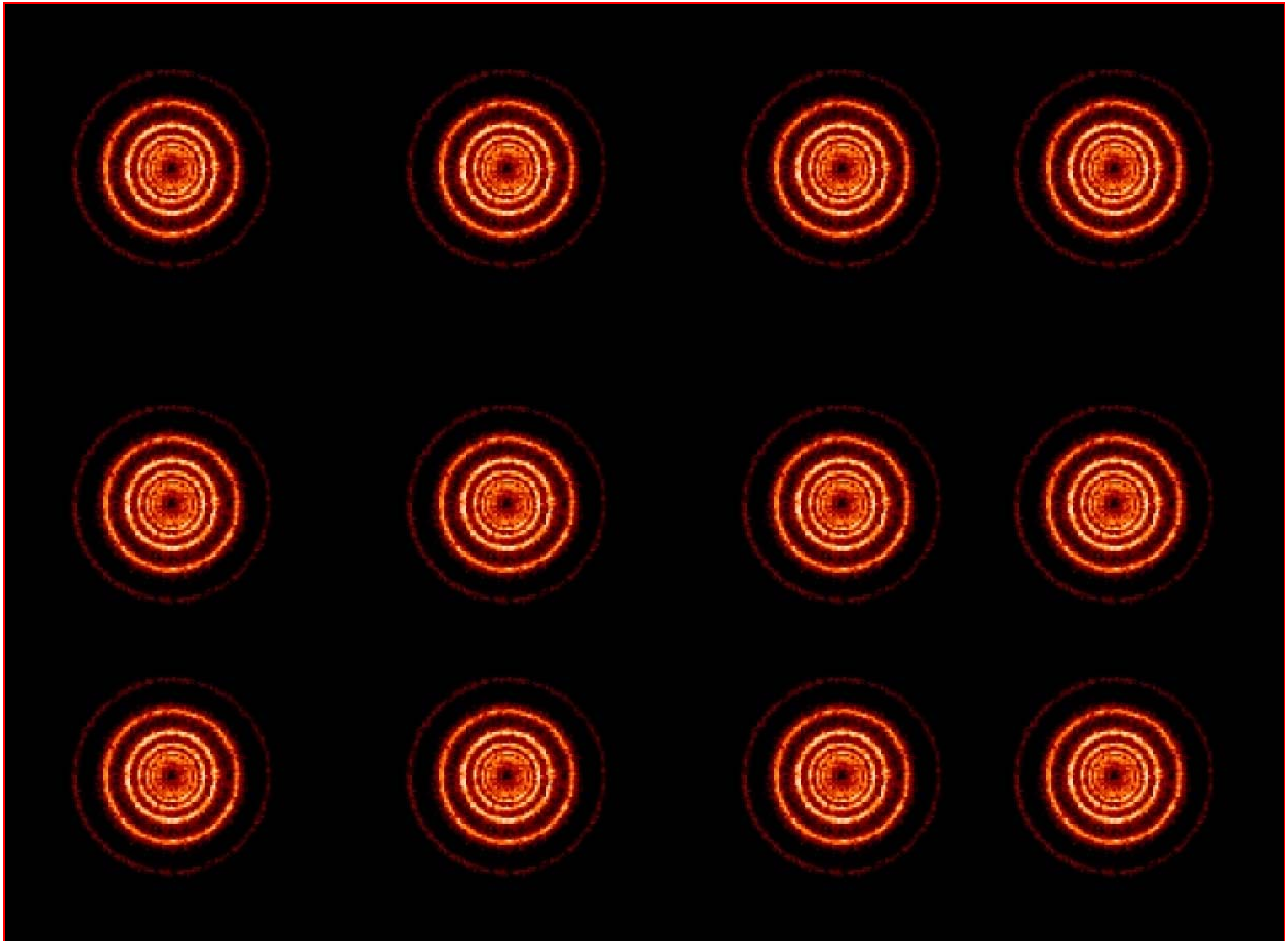
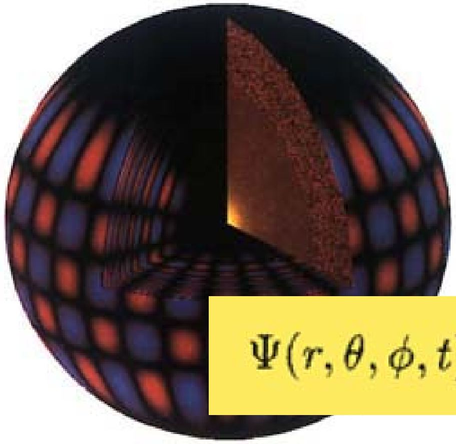


Ring Diagram Analysis Method and Tools

Thierry Corbard
Observatoire de la Côte d'Azur
Nice, France



Ring Diagram Analysis
Motivations and Historical Background



Global Modes

$$\Psi(r,\theta,\phi,t) = V_n(r)\ Y_\ell^m(\theta,\phi)\ e^{-2\pi i\nu t}$$

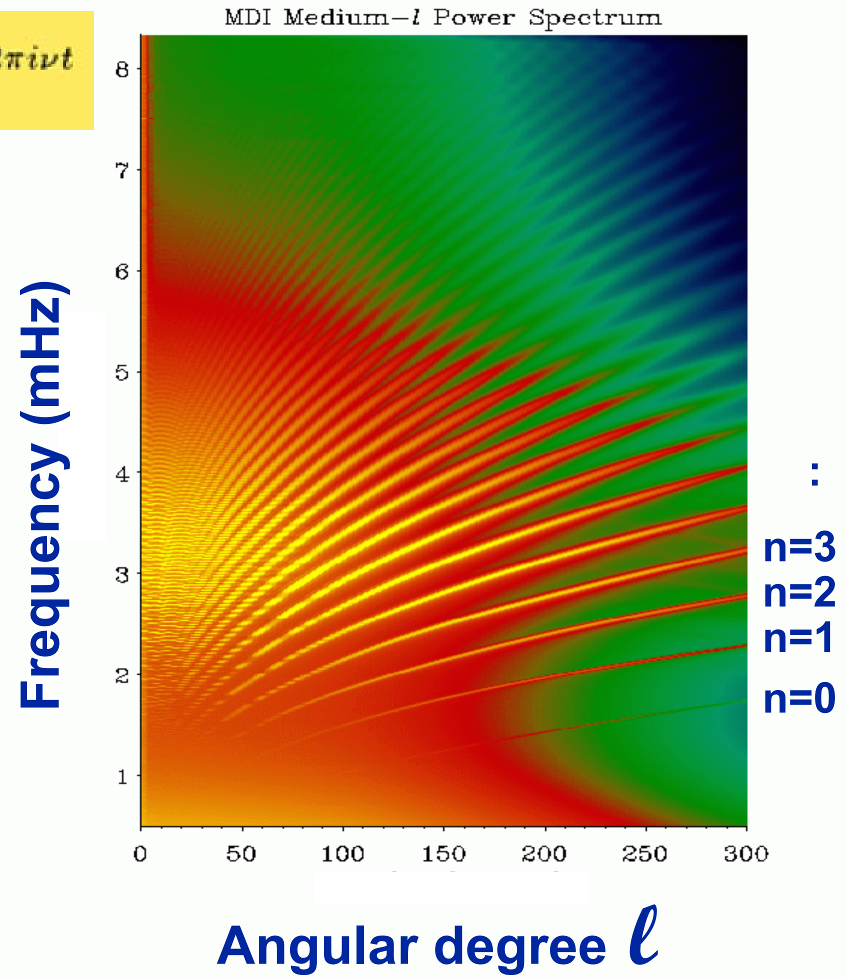
Internal Rotation breaks spherical symmetry

=> Multiplets of $2\ell+1$ frequencies

$$\frac{\omega_{nl\text{-}m} - \omega_{nlm}}{m} = \iint K_{nlm}(r,\theta)\,\Omega(r,\theta)\,dr\,d\theta$$

observed **Standard Solar Model** **Unknown**

=> 2D Inverse Problem



Global Helioseismology Limitations

- Sensitive only to the part of the rotation that is symmetric about the equator.
- Kernels Independent of longitude (e.g. cannot infer interaction between an active region and sub-surface flows)
- Impossible to separate the spherically asymmetric effects other than rotation (meridional circulation, magnetic fields, structural asphericity)
- Limited access to the polar zone

Ring Diagram: Historical Background

Solar Physics **82** (1983) 401–410.

ON THE DETECTION OF SUBPHOTOSPHERIC CONVECTIVE VELOCITIES AND TEMPERATURE FLUCTUATIONS*

D. O. GOUGH

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and

J. TOOMRE

Joint Institute for Laboratory Astrophysics, and Department of Astrophysical, Planetary and Atmospheric Sciences, University of Colorado, Boulder, Colo., U.S.A.

Abstract. A procedure is outlined for estimating the influence of large-scale convective eddies on the wave patterns of five-minute oscillations of high degree. The method is applied to adiabatic oscillations, with frequency ω and wave number k, of a plane-parallel polytropic layer upon which is imposed a low-amplitude convective flow. The distortion to the $k-\omega$ relation has two constituents: one depends on the horizontal component of the convective velocity and has a sign which depends on the sign of ω/k; the other depends on temperature fluctuations and is independent of the sign of ω/k. The magnitude of the distortion is just at the limit of present observational sensitivity. Thus there is reasonable hope that it will be possible to reveal some aspects of the large-scale flow in the solar convection zone.

VARIABILITY IN THE POWER SPECTRUM OF SOLAR FIVE-MINUTE OSCILLATIONS*

Solar Physics **82** (1983) 411–425. *(Invited Review)*

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and

LAURENCE J. NOVEMBER

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Abstract. Two-dimensional power spectra of solar five-minute oscillations display prominent ridge structures in (k, ω) space, where k is the horizontal wavenumber and ω is the temporal frequency. The positions of these ridges in k and ω can be used to probe temperature and velocity structures in the subphotosphere. We have been carrying out a continuing program of observations of five-minute oscillations with the diode array instrument on the vacuum tower telescope at Sacramento Peak Observatory (SPO). We have sought to establish whether power spectra taken on separate days show shifts in ridge locations; these may arise from different velocity and temperature patterns having been brought into our sampling region by solar rotation. Power spectra have been obtained for six days of observations of Doppler velocities using the Mg I λ5173 and Fe I λ5434 spectral lines. Each data set covers 8 to 11 hr in time and samples a region $256'' \times 1024''$ in spatial extent, with a spatial resolution of $2''$ and temporal sampling of 65 s. We have detected shifts in ridge locations between certain data sets which are statistically significant. The character of these displacements when analyzed in terms of eastward and westward propagating waves implies that changes have occurred in both temperature and horizontal velocity fields underlying our observing window. We estimate the magnitude of the velocity changes to be on the order of 100 m s^{-1}; we may be detecting the effects of large-scale convection akin to giant cells.

THE ASTROPHYSICAL JOURNAL, **311**:1015–1024, 1986 December 15

THE INTERACTION OF SOLAR *p*-MODES WITH A SUNSPOT. I. OBSERVATIONS

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AND

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Received 1986 April 14; accepted 1986 June 17

ABSTRACT

Time series of velocity maps of two isolated sunspots and their surroundings were recorded in Fe I λ6302.5 and the umbral line Ti I λ6303.8. Both 3 minute and 5 minute umbral oscillations were detected at photospheric heights. The 5 minute oscillations have reduced amplitude in the umbra, which appears to act as a filter in transmitting selected frequencies in the power spectrum of 5 minute *p*-mode oscillations of the surrounding convection zone. The *k*-*ω* power spectrum of the umbral oscillations shows this selective transmission and also shows a shift of power to longer horizontal wavelengths. This behavior is exhibited by a simple theoretical model of the interaction of *p*-modes with a sunspot. The 3 minute umbral oscillations are concentrated in the dark central part of the umbra. In both sunspots, the kinetic energy density of the 3 minute umbral oscillation in the photosphere is much greater than the corresponding kinetic energy density at chromospheric heights measured in other sunspots, in agreement with the results of Lites and Thomas.

Subject headings: Sun: atmospheric motions — Sun: oscillations — Sun: sunspots

THE ASTROPHYSICAL JOURNAL, **333**:996–1013, 1988 October 15

RINGS AND TRUMPETS—THREE-DIMENSIONAL POWER SPECTRA OF SOLAR OSCILLATIONS

FRANK HILL
National Solar Observatory, National Optical Astronomy Observatories[1]
Received 1987 December 18; accepted 1988 April 12

ABSTRACT

Characteristic "trumpet" surfaces are visible in three-dimensional power spectra of the Doppler shifts observed on the solar surface, where the three dimensions are ω, the temporal frequency, and k_x and k_y, the x and y components, respectively, of $\boldsymbol{k}$, the spatial wavenumber vector. When slices of these surfaces are taken at constant temporal frequency, the cross sections of the trumpets form "rings." Analysis of the shape and position of these rings provides information on the horizontal flow field and the thermodynamic structure below the solar photosphere. The relationship between the parameters of an elliptical approximation to the rings and the subphotospheric state is derived, and a numerical simulation is presented. A preliminary application to real data suggests the presence of a flow of 100 m s^{-1} directed from the equator toward the south pole. This flow may be solar, but could also be partially produced by systematic observational errors. A comparison of the velocities inferred from a single ring obtained at different longitudes shows variations of 20–40 m s^{-1}, suggesting that large-scale convection is not azimuthally symmetric. However, the noise in the measurement from a single ring is of the same order as the observed variation, precluding a definitive conclusion until many more rings are examined.

Ring Diagram: Historical Background

- Jesús Patrón, PhD 1994 (IAC) "Tridimensional distribution of horizontal velocity flows under the solar surface"
- Main actors since
  - MDI Team: R. Bogart, J. Schou
  - JILA Team: D. Habber, B. Hindman, J. Toomre
  - GONG Team: I. Gonzalez-Hernandez, F. Hill, R. Komm, J. Leibacher, C. Toner
  - Indian Team: H.M. Antia, S. Basu, S. Tripathy
- The method has developed very fast with high resolution data becoming available: TON, MDI, GONG++

Ring Diagram Analysis Principles

Ring Diagram Analysis Principles

- Général Dispersion Relationship for global modes:

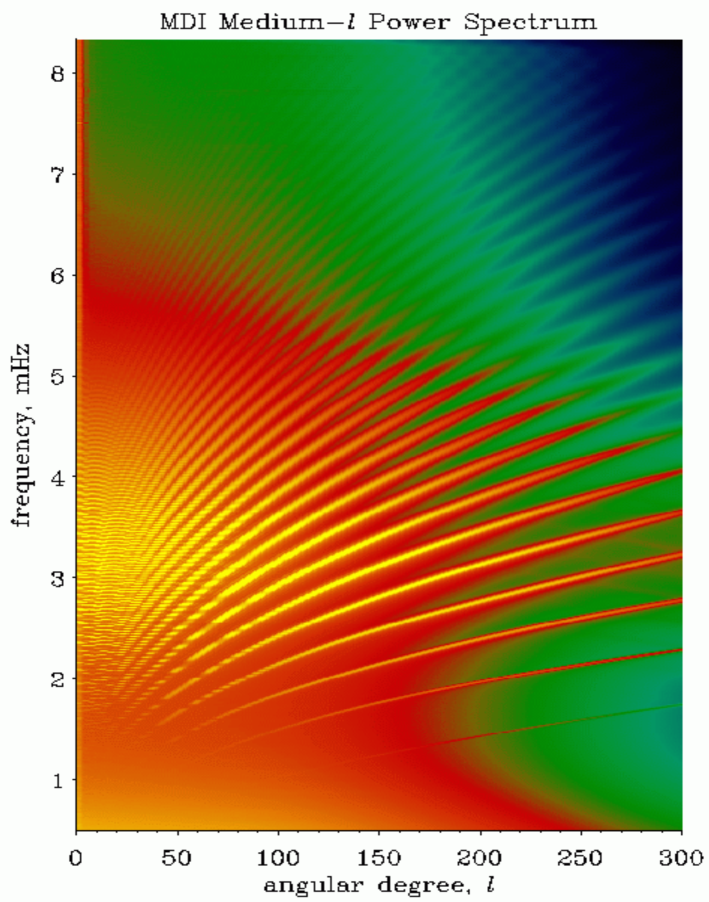
$$k_r^2 + k_h^2(1-N^2/\omega^2) = (\omega^2-\omega_c^2)/c^2 \qquad K_h^2=\ell(\ell+1)/r^2=K_\theta^2+K_\varphi^2$$

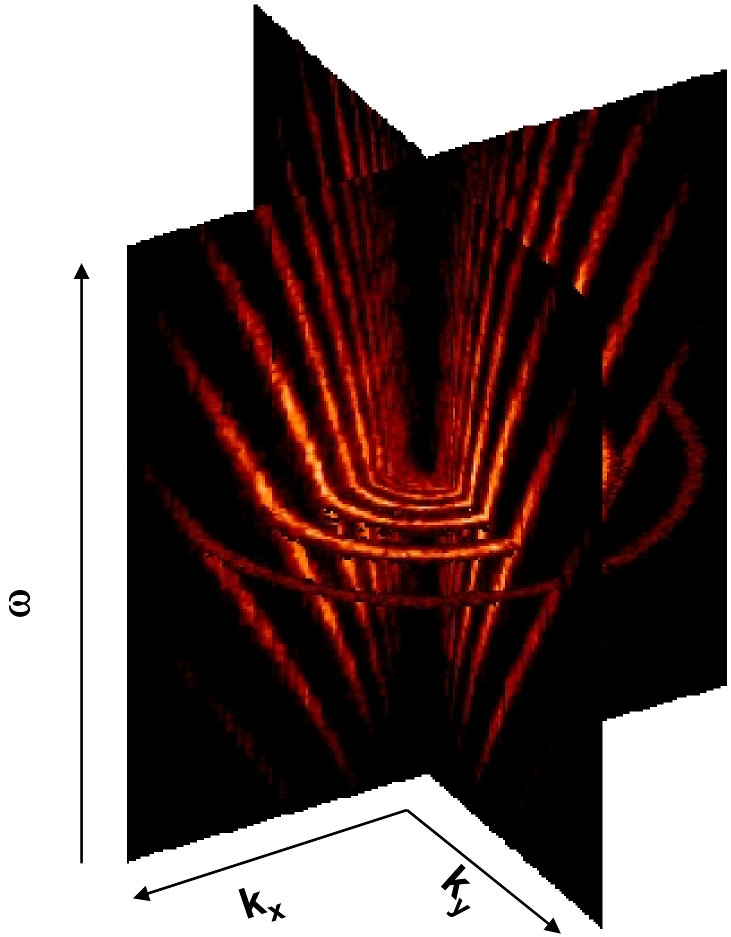
- Because the wavelength of high order modes is small compared with the typical scale over which equilibrium structure changes, the modes can be approximated locally by plane sound waves

$$\Rightarrow \qquad k^2=k_z^2+k_h^2=\omega^2/c^2 \qquad K_h^2=K_x^2+K_y^2$$

- High degree (ℓ >300) acoustic waves are damped and cannot travel around the full circumference of the sun. Their horizontal wave number isn't quantized anymore and their frequencies are local measures of the sun's properties.

Ring Diagram Analysis Principles





Global mode spectra

Local power spectra

Ring Diagram Analysis Principles

The presence of a velocity field, $\boldsymbol{U}$, will perturb the frequency by advecting the wave front and producing an apparent Doppler shift $\Delta\omega$, given by

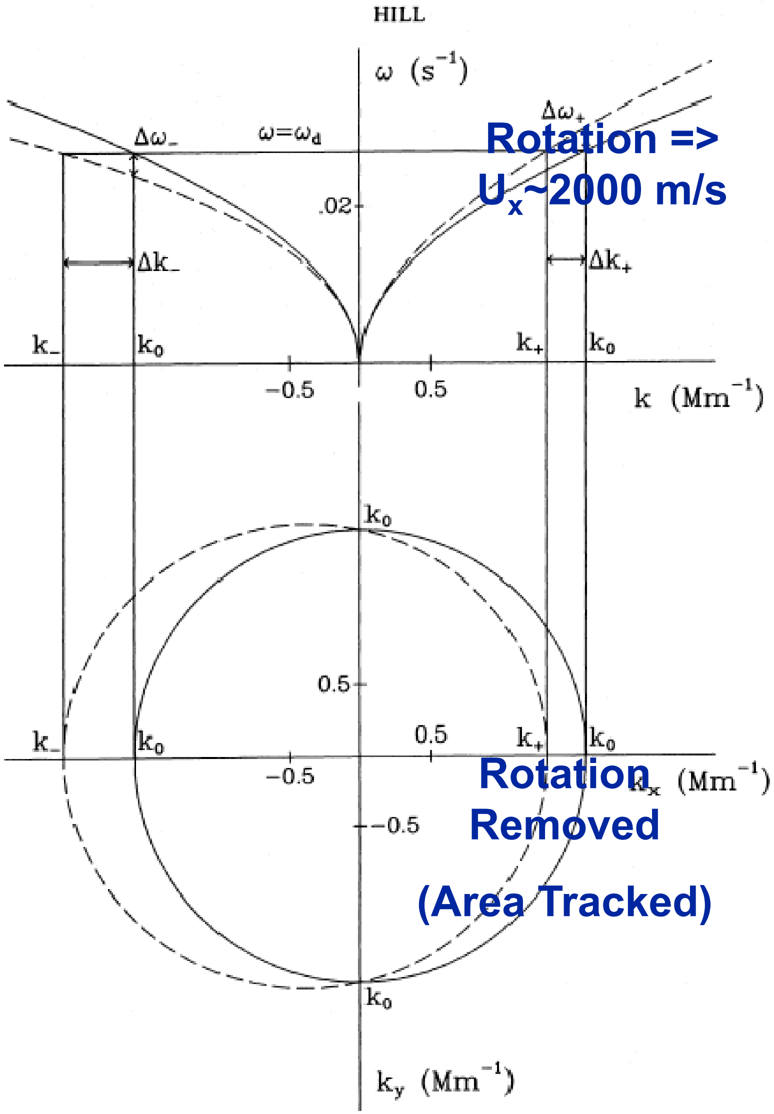
$$\Delta\omega = \boldsymbol{k} \cdot \boldsymbol{U} = k_x U_x + k_y U_y \,, \tag{2}$$

where U_x and U_y are the x and y components of the velocity vector $\boldsymbol{U}$. More precisely, $\boldsymbol{U}$ is an average over depth of the velocity with a weighting given by an average of the kernels of the modes contained in the ring.

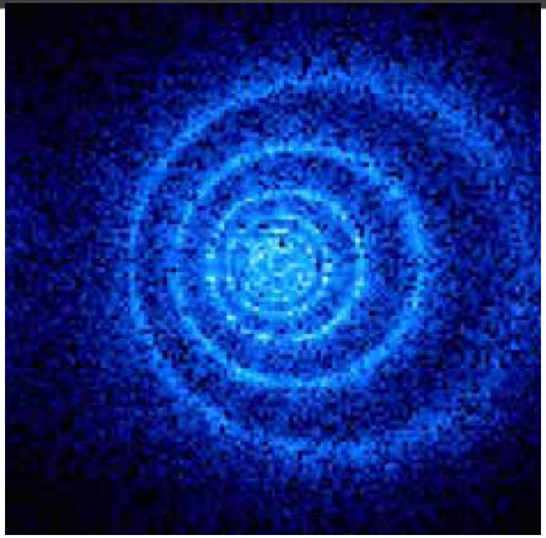
Hill, 1988

=> $\omega = \omega_0 + \Delta\omega = c\,k + k_x U_x + k_y U_y$

Ring Diagram Analysis Principles

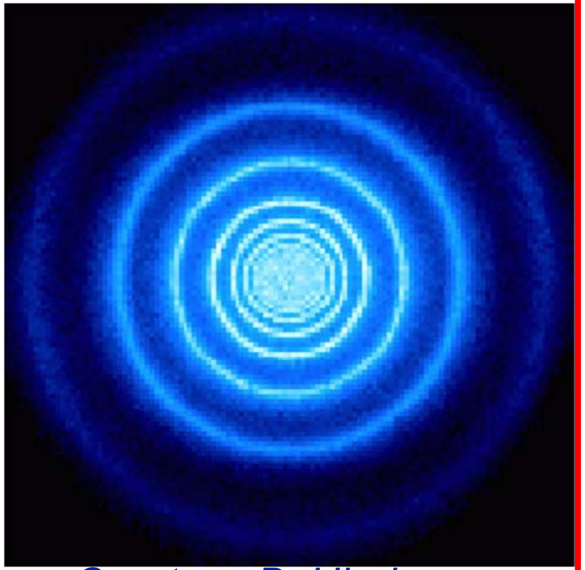


Rotation => U_x~2000 m/s



Rotation Removed

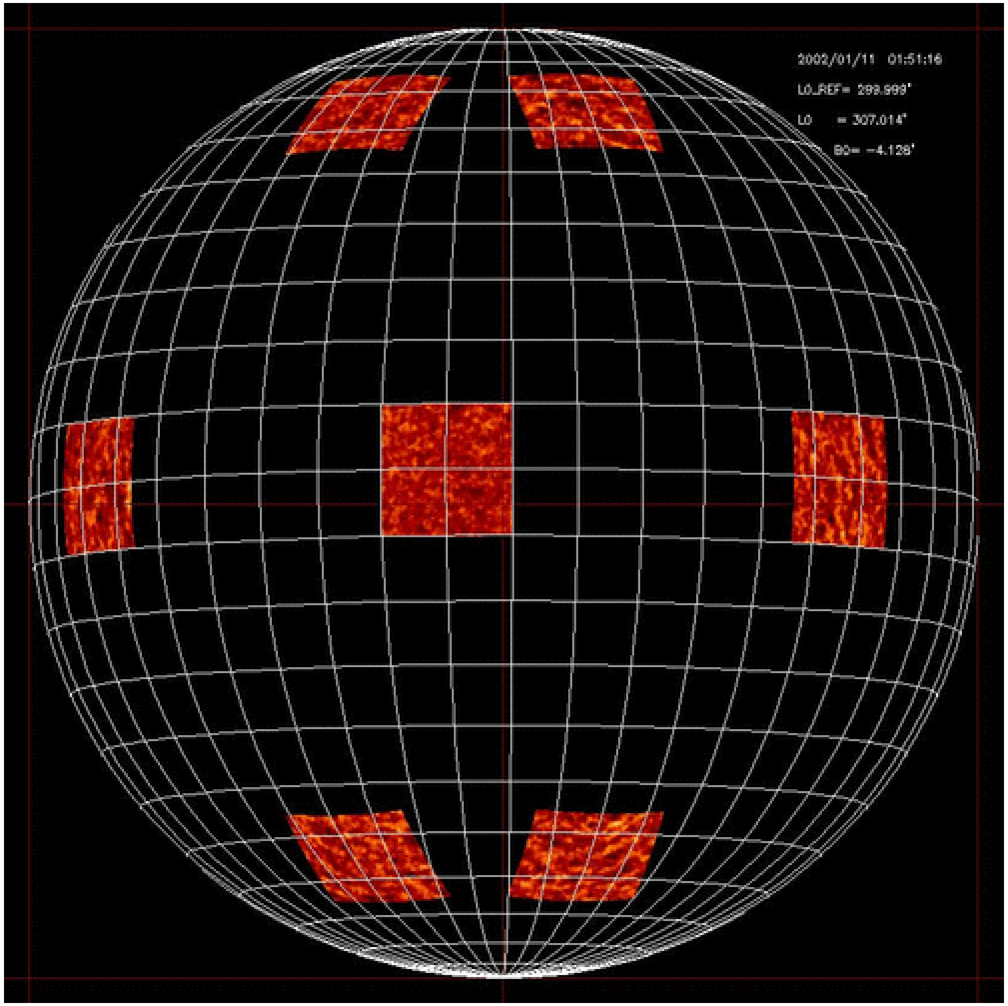
(Area Tracked)



Courtesy B. Hindman

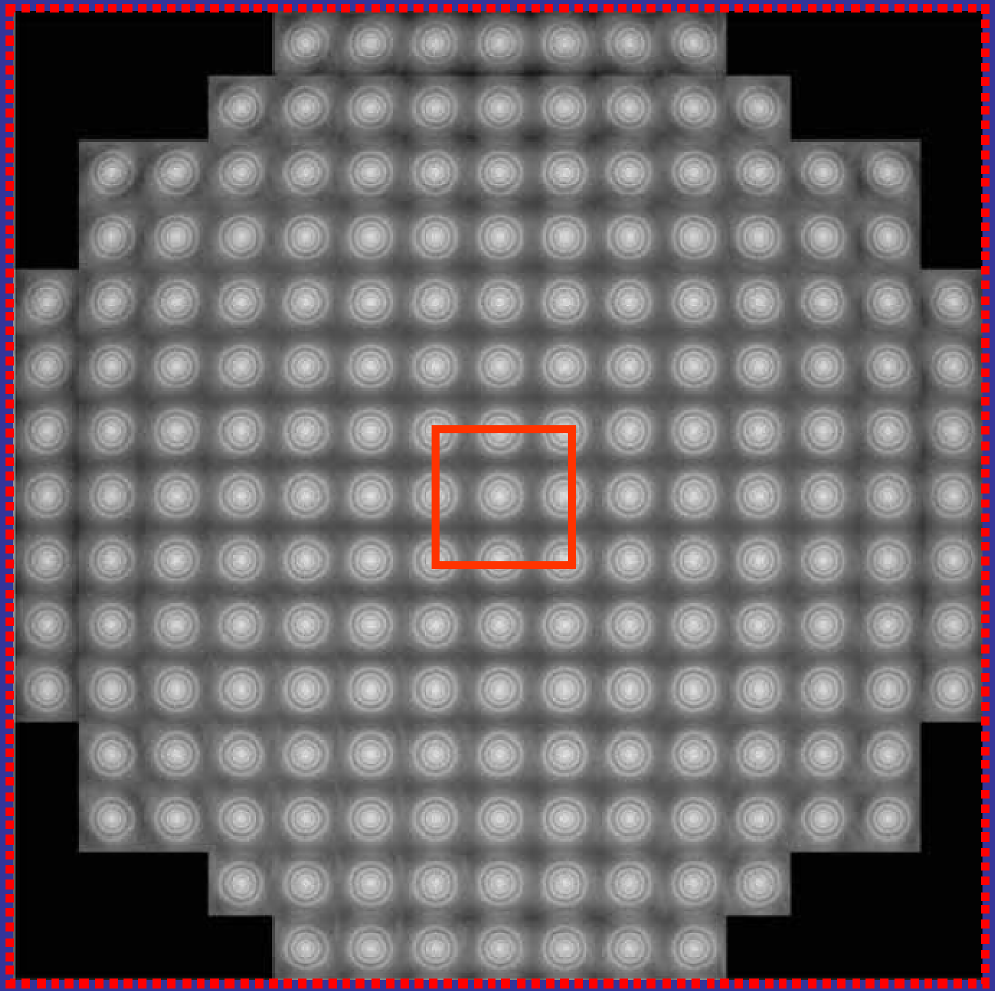
PRACTICAL ASPECTS:
The Ring Diagram Analysis Pipeline

Step 1 : Tracking



- Small areas (16ºx16º) are tracked (typically 1664 mn) over the solar disk at a rate depending on the latitude of their center.
- These areas are remapped using a Postel or transverse cylindrical projection that tend to preserve the distance along great circles.
- => Data cubes (Latitude – Longitude – time)

Dense Pack: Simultaneous Tracking of 189 tiles



Dense-Pack

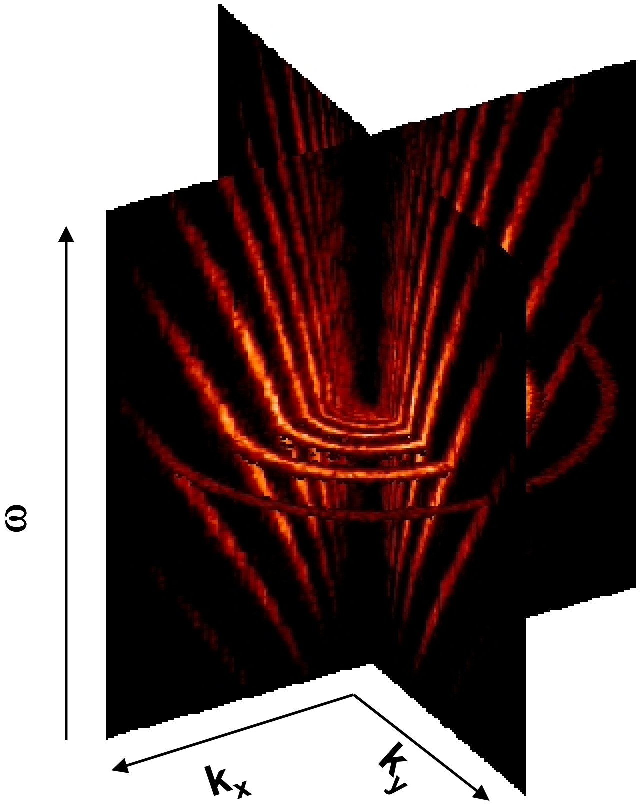
- 189 overlapping tiles
- 16 degrees on a side
- Tile centers are separated by 7.5 degrees.
- Tracked at the surface rotation rate for roughly 1 day.
- The analysis is repeated daily.
- The tiles fill the solar disk to within 30 degrees of the limb.

Courtesy B. Hindman

Steps 2-3-4

3D FFT → **3D Power spectra Fitting**

$(\theta,\varphi,t) \rightarrow (k_x,k_y,\omega)$



$$P = \frac{A}{(\omega - \omega_0 + k_x U_x + k_y U_y)^2 + \Gamma^2} + \frac{b_0}{k^3}$$

2 x 1D Inversions

$$U_{x,y}(\omega_o, k_h) = \int K(\omega_o, k_h, z)\, v_{x,y}(z)\, dz$$

V_z may then be computed using the divergence of the horizontal flow and assuming mass conservation.
(Komm, Corbard et al. 2004)

GONG++ Pipeline Components

For each step

•PERL Wrapper

•Main code in Fortran 95 / 77

•IDL tools for visualization

- Dense Cube production: splitup Process
  - \- Fortran 95
  - \- Projection: Transverse Cylindrical
  - \- Tracking: $\cos^2$, $\cos^4$ law
  - \- Sidereal-synodic correction
  - \- Interpolation: Spline/Sinc

F. Hill, C. Toner, T. Corbard, I. Gonzalez-Hernandez

- 3-D Power Spectra: map2power process
  - \- Fortran 95
  - \- Spatial apodization by cos bell taper
  - \- Temporal apodization by Multipaper
  - \- Remove the weighted mean before the FFT

T. Corbard

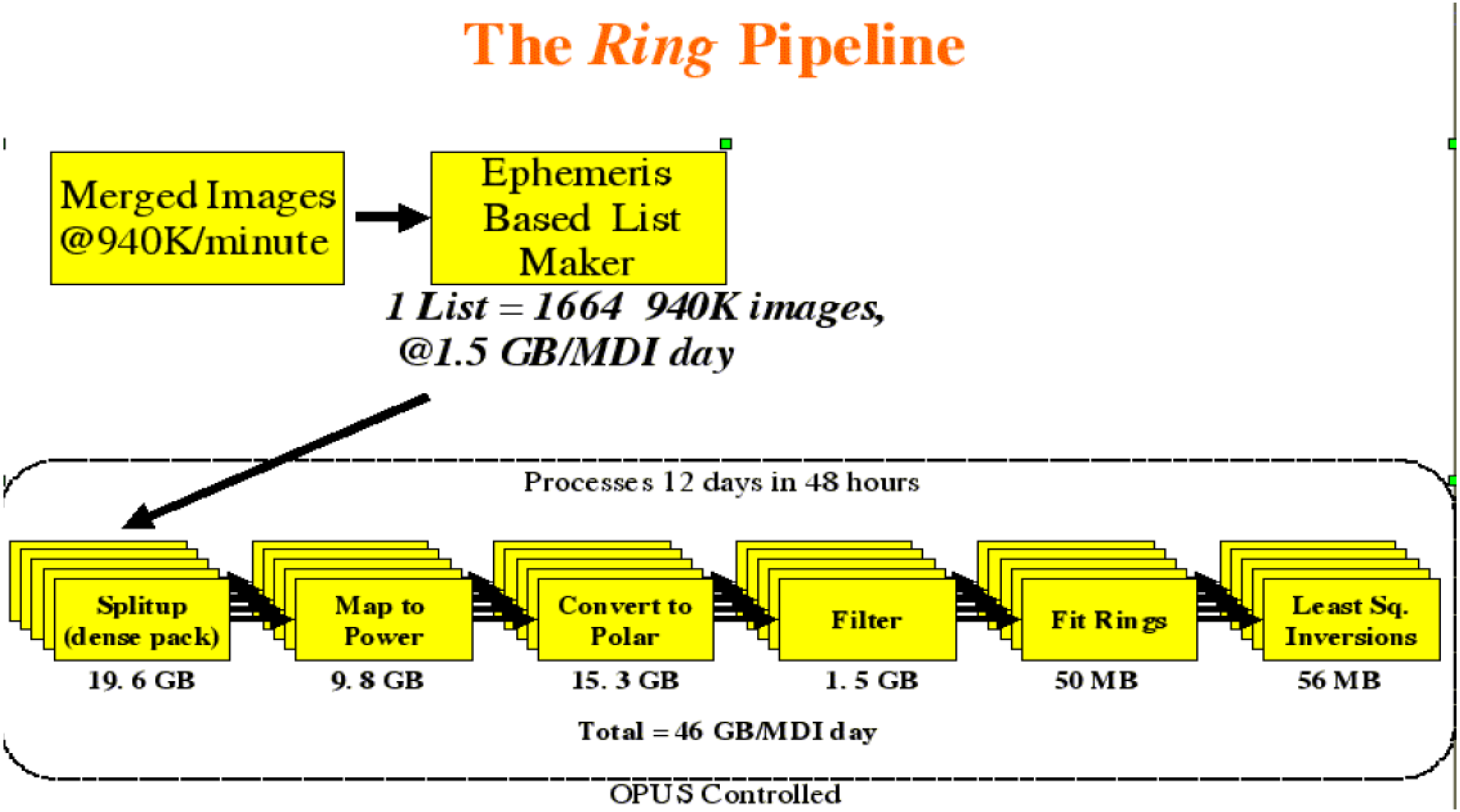
- Fitting of the rings
  - \- Conversion from Cartesian to Polar coordinates
  - \- Fourier filter
  - \- Fitting

B. Hindman, D. Haber, R.M. Larsen, R. Bogart, J. Schou

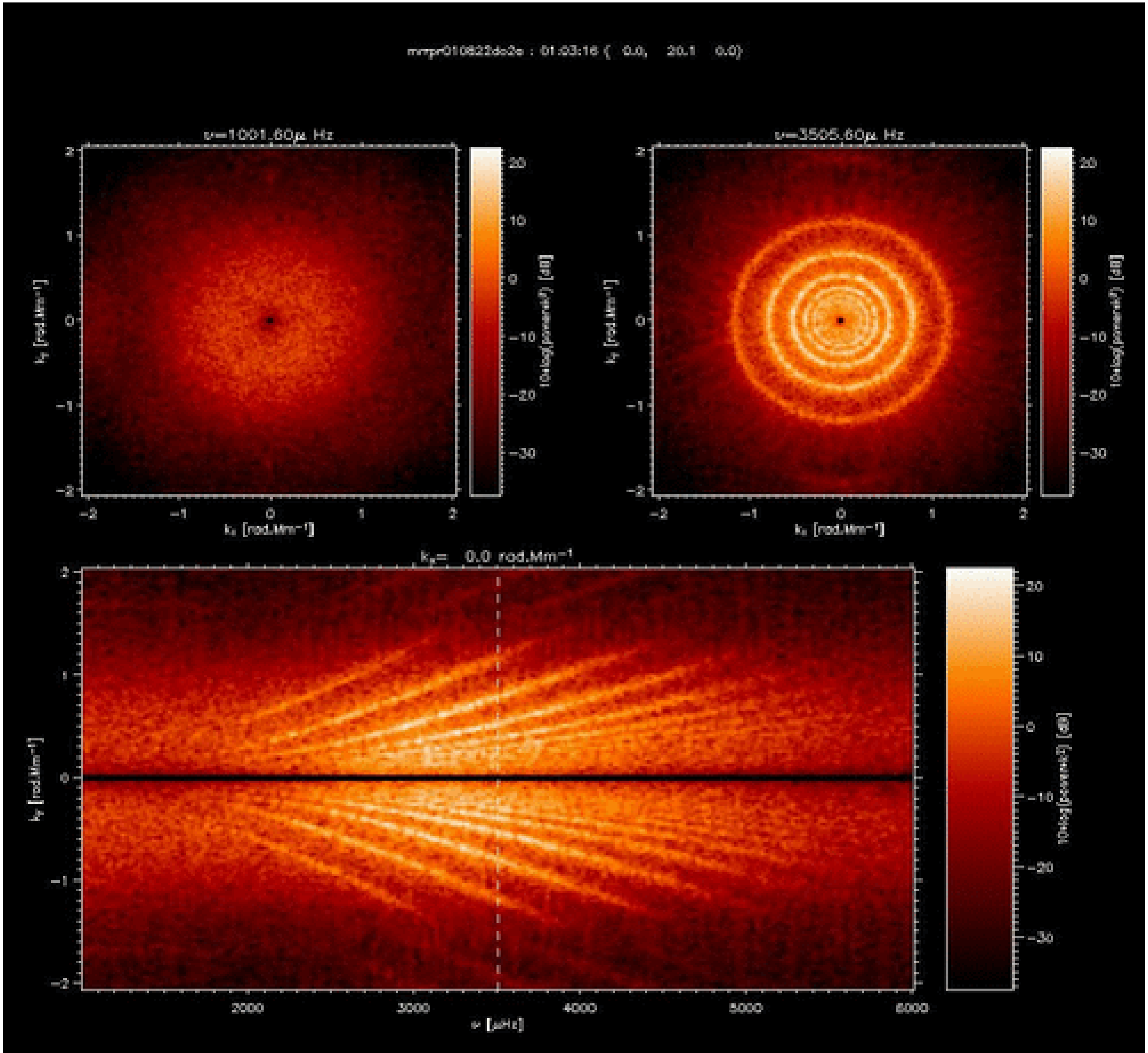
- Inversion
  - **RLS / OLA**

F. Hill, D. Gough, T. Corbard

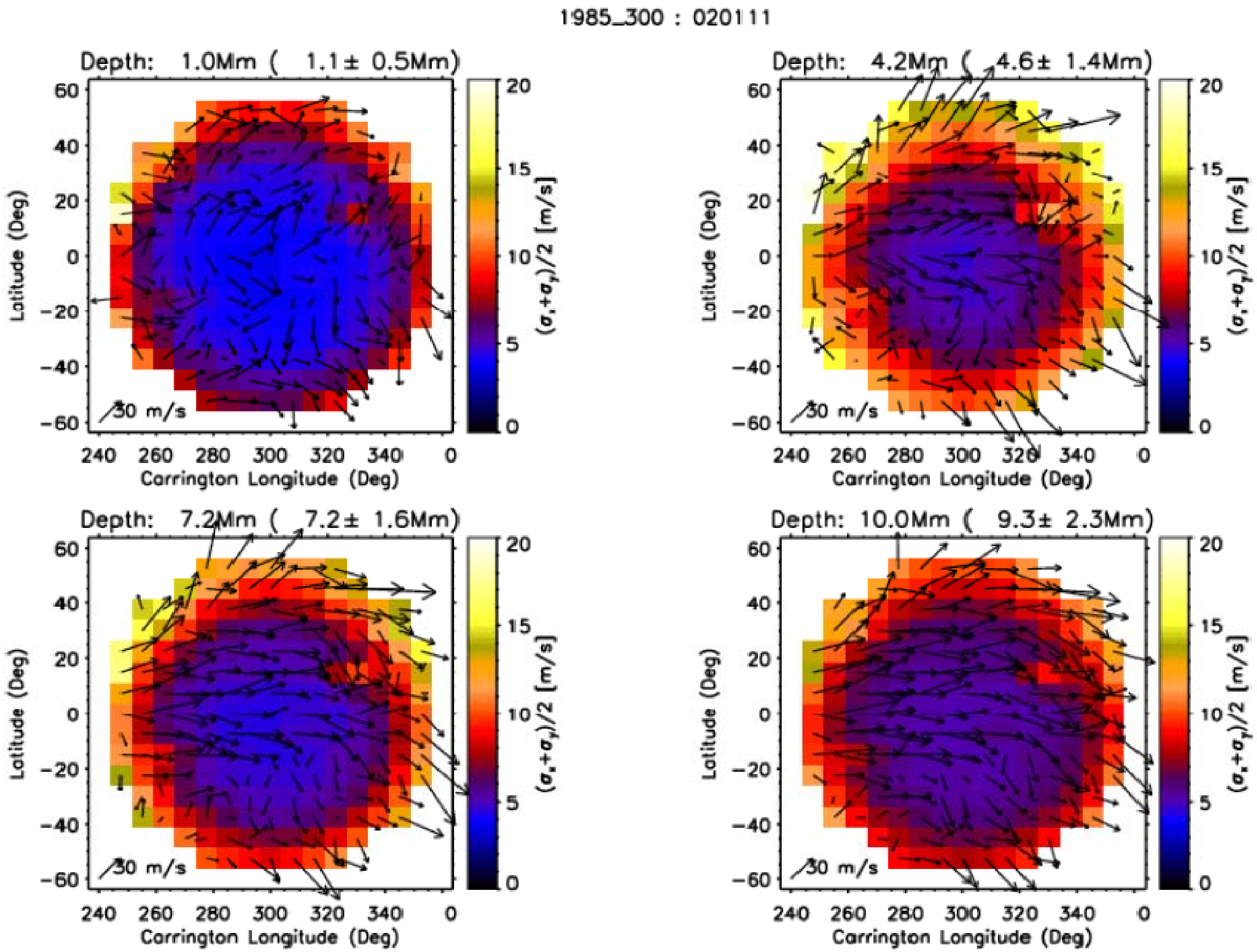
GONG++ Pipeline Components



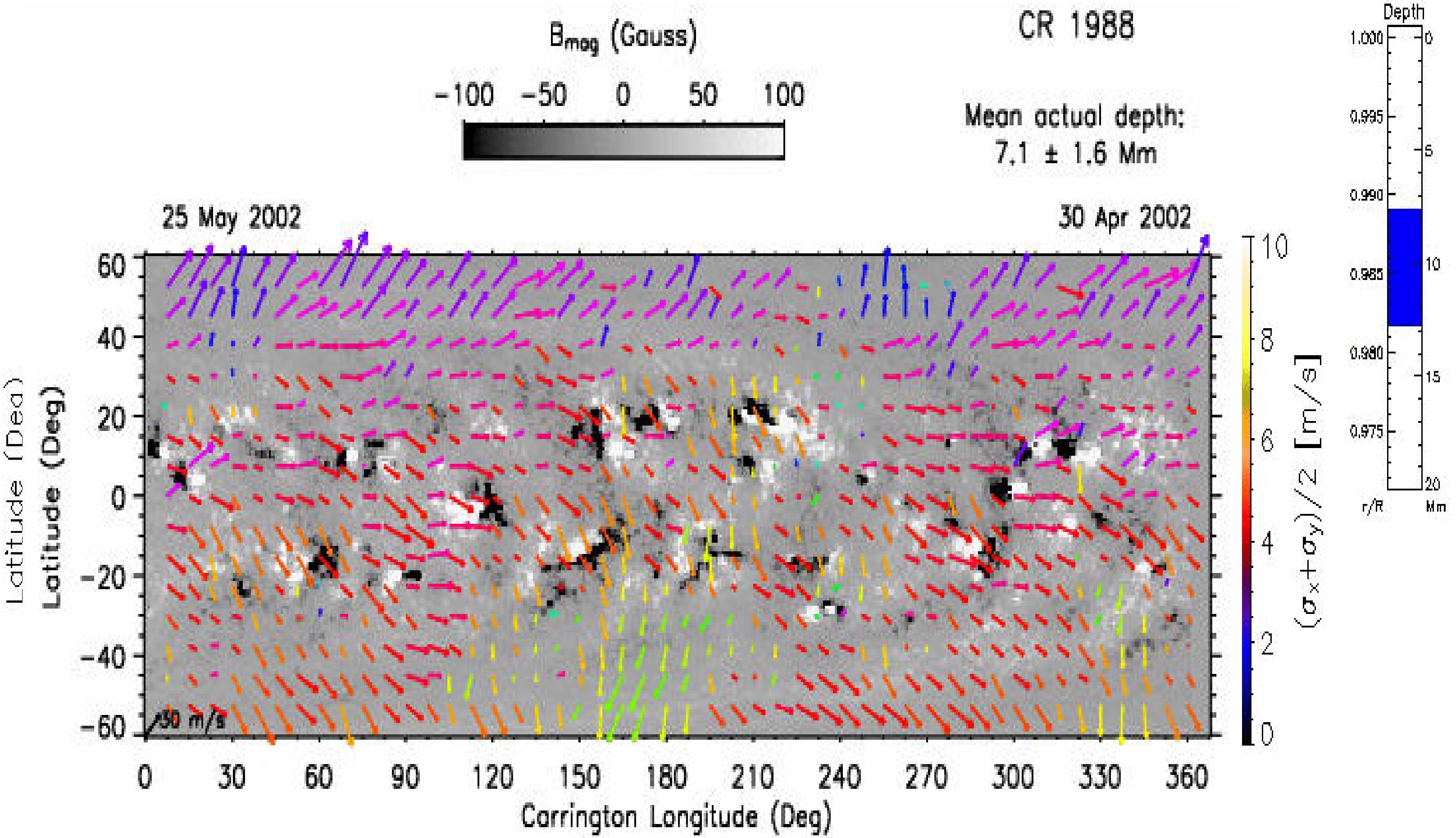
Courtesy I Gonzalez Hernandez / J. Bolding


ν=1001.60μ Hz
ν=3505.60μ Hz
k_x [rad.Mm⁻¹]
k_y [rad.Mm⁻¹]
k_x= 0.0 rad.Mm⁻¹
ν [μHz]

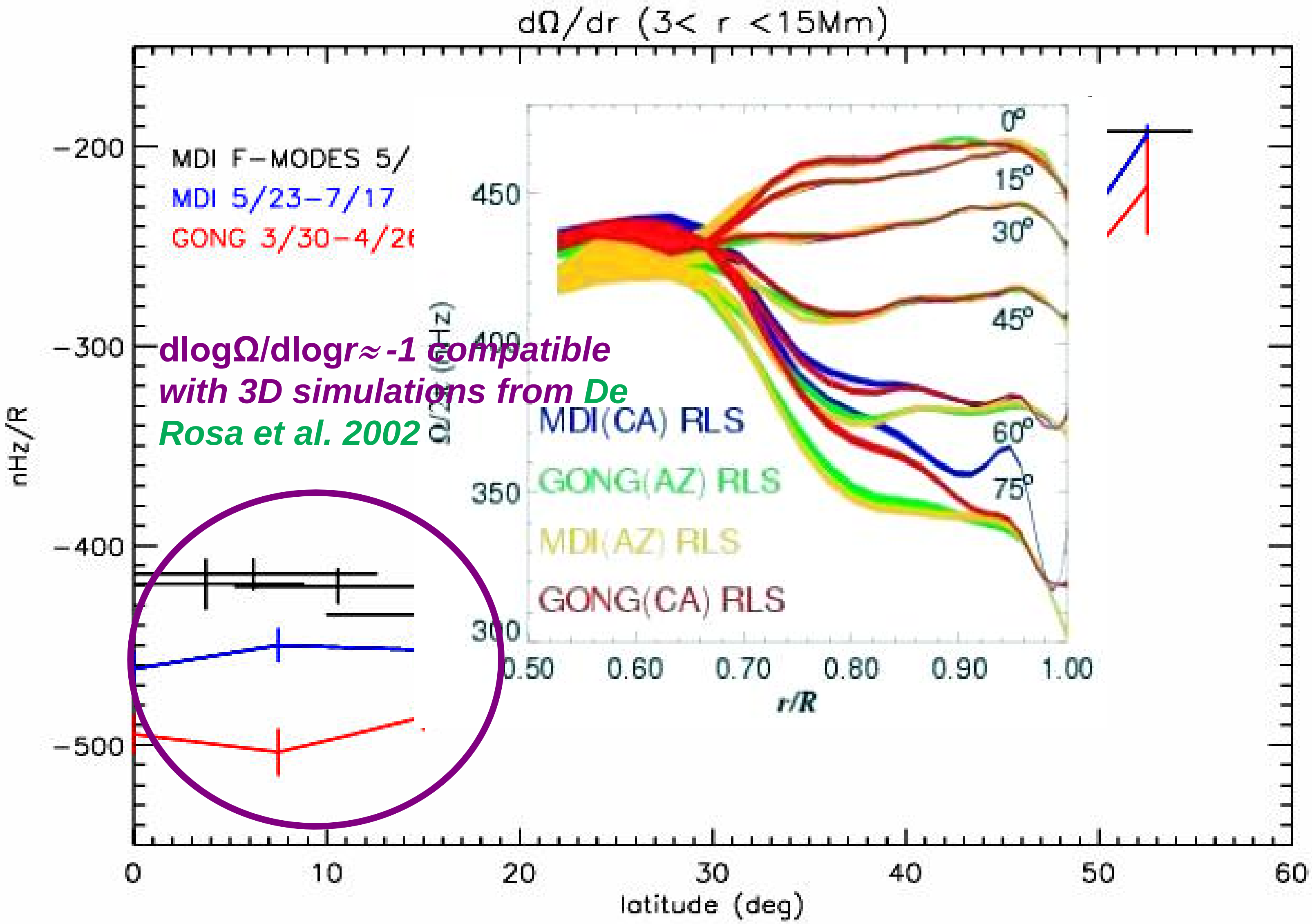
First results: the flow maps at different depths from a dense–pack analysis of GONG+ merged images



Synoptic Flow Maps



Subsurface radial Shear



dlogΩ/dlogr≈-1 compatible with 3D simulations from De Rosa et al. 2002

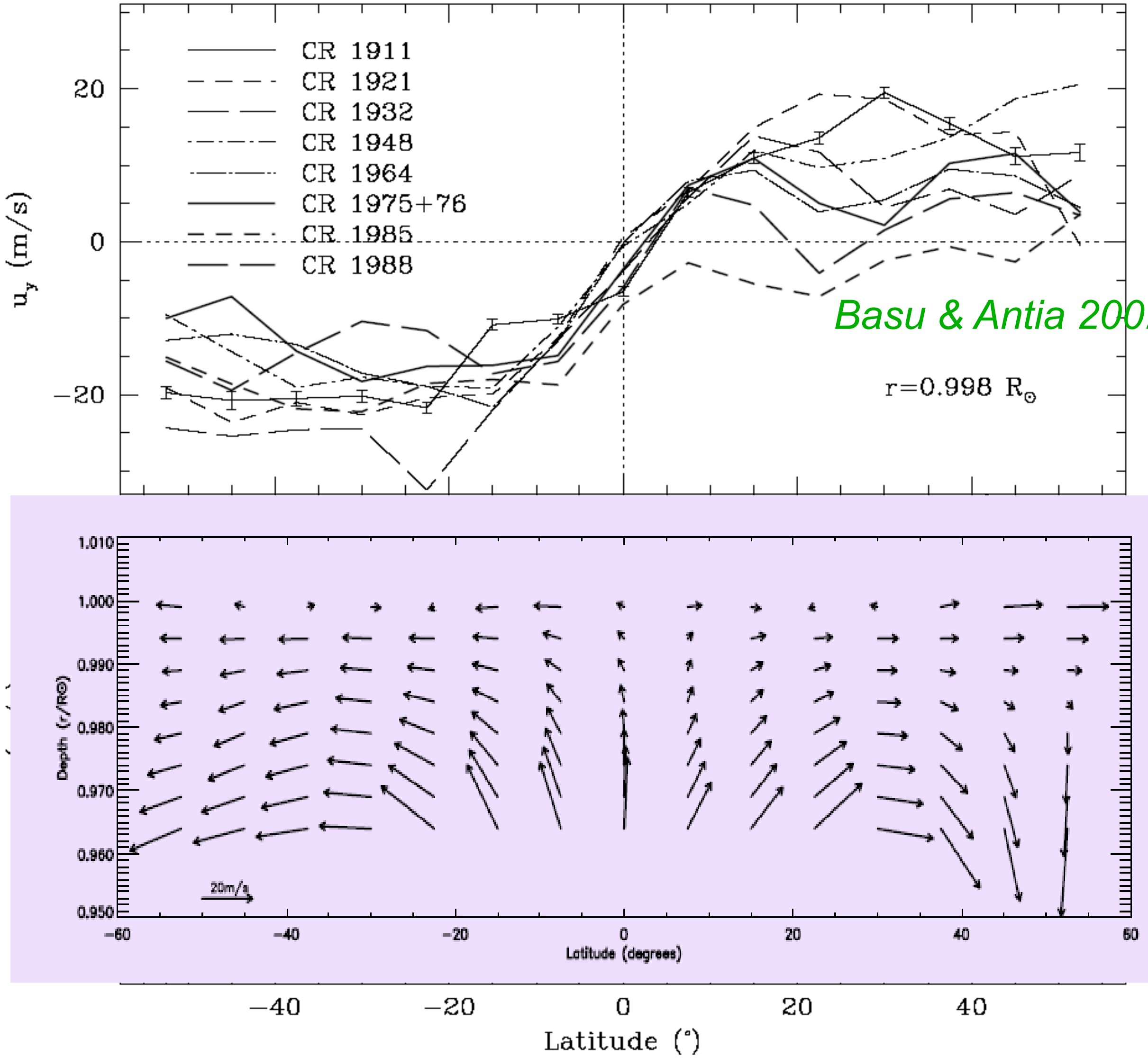
Meridional Circulation: Time and depth variation

Polward flow ~10 -20m/s, incresing with depth + secondary flow that converges toward the mean latitude of activity (Haber et al. 2002, Zhao & Kosovichev 2004, Komm et al. 2005)

Counter cells at high latitude (Haber et al. 2002) ?

González Hernández et al. 2006:* Geometric *Calibration issue?

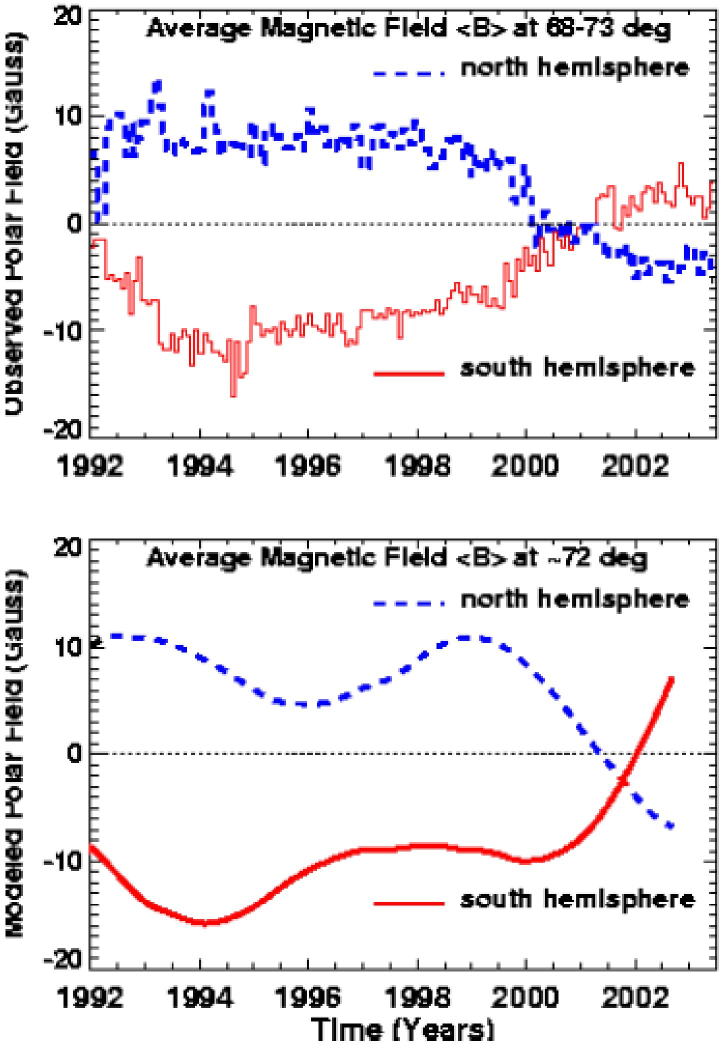
***Zaatri et al. (2006):* The N/S asymmetry of the flow reflects the N/S assymetry of the magnetic flux.**



González Hernández et al. 2004

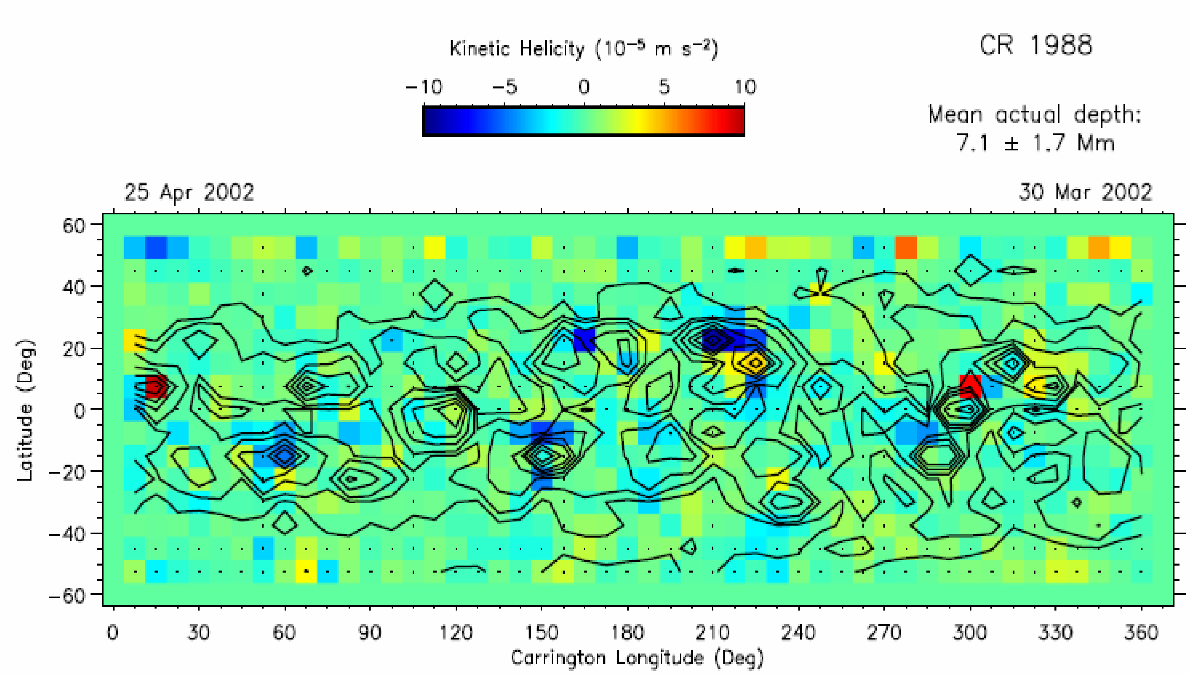
Dynamo Models and Meridional Circulation

N-S asymmetry in meridional flow speed during 1996-2002 and the appearance of a reverse, high-latitude flow cell in the N-hemisphere during 1998-2001 caused the N-pole to reverse ~1 yr before the S- pole



Dikpati et al. 2003

Synoptic Maps of Vorticity – Kinetic Helicity etc..



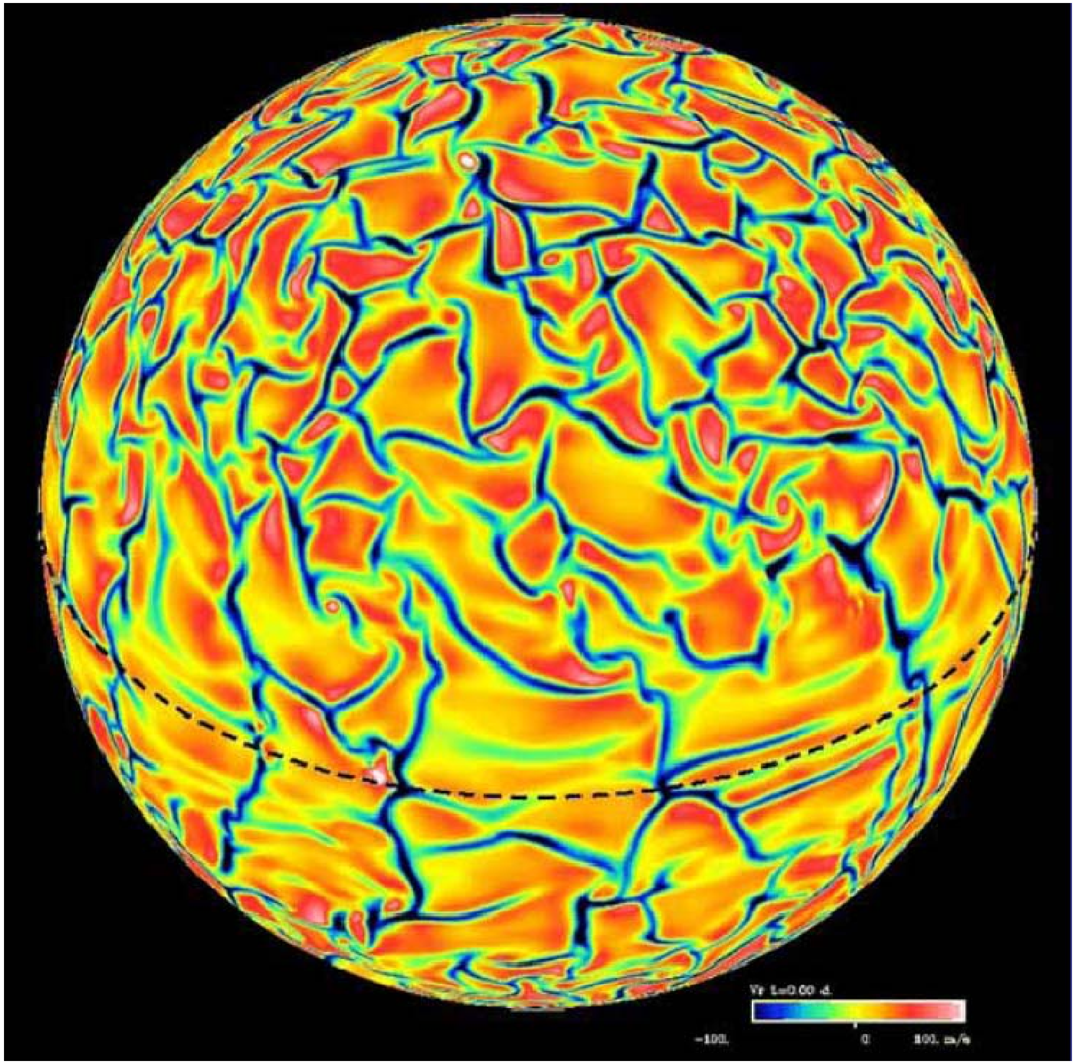
Komm, Corbard et al. 2004 (ring diagrams)

Zhao & Kosovichev 2003 (time-distance)

Conclusions

- A lot of efforts have been made during the last few years in:
  - Making comparison between the different Methods (group LoHCO)
  - Understanding errors, methods resolution and correlations
  - Understanding effects of image misalignment / geometric effects (P-angle / Bo angle)
  - MDI, GONG+, TON and soon SDO, Solar B, Solar Orbiter….
  - First attempt of "archeo-helioseismology" using Mt Wilson data in order to infer the meridional circulation in the past two solar cycles
- New developments
  - High resolution Ring Analysis using f-modes *(B. Hindman, D. Haber et al.)*
  - Deeply penetrating Ring techniques *(I. Gonzalez-Hernandez et al.)*
  - 3D Kernels and inversion procedure

But….by the way where are the Giant Cells?



Toomre et al.