SPACEINN WP4 Helioseismology

Deliverable D4.12

Report on local helioseismology working group meeting #3

Coordinated by Kiepenheuer-Institut für Sonnenphysik (KIS) and
Max-Planck-Institut für Sonnensystemforschung (MPG)

The third SPACEINN local helioseismology working group meeting was held at Novotel Freiburg am Konzerthaus in Freiburg, Germany, on 4 September, 2015.

Purpose of the local helioseismology working group meeting #3:

The SpaceInn project plans to provide archival data and analyses tools for local helioseismology. A collection of data sets is already available through the project for carrying out various helioseismic studies. Providing such a standard data set also allows comparison between different techniques used in local helioseismology. Additionally, a basic set of tools to handle the data is also being made available for researchers and novices in the field. The project ultimately aims to build a comprehensive and easily accessible toolkit that will enable the community to fully exploit the data provided by space- and ground-based observations. The objective of this meeting was to review the status of the tools that are currently available through SpaceInn. The finalization of these tools in an opensource/access framework and in a more collaborative environment was discussed in connection with the setting of benchmarks for comparison and reproducibility of results. The meeting was publicly announced in order to open it to other researchers willing to share/contribute their expertise/tools and to those who want to explore the data for their specific studies.

Programme:

Friday, Sep 4, 2015; Conference Room "Basel" left

14:00 - 14:15 Introduction to tools on the SPACEINN WP4 - Kaori Nagashima (MPG)

14:15 – 14:45 Fourier-Hankel/Legendre pipeline - Vigeesh Gangadharan (KIS)

Fourier-Hankel/Legendre analysis is one of the helioseismic techniques employed to infer the internal properties of the Sun. It has been successfully applied to study p-mode interaction with sunspots and to measure sub-surface meridional flow. As part of SpaceInn project, we have implemented a new Fourier-Hankel/Legendre analysis module on the SDO/HMI JSOC dataanalysis pipeline. We will present the details of the module and some preliminary results. We will also discuss on its applicability to meridional flow, differential rotation measurements and active region seismology.

* *Presentation files of these two talks are found as attachments of this document.*

14:45 – 16:00 Discussion

The main goals of the discussion session:

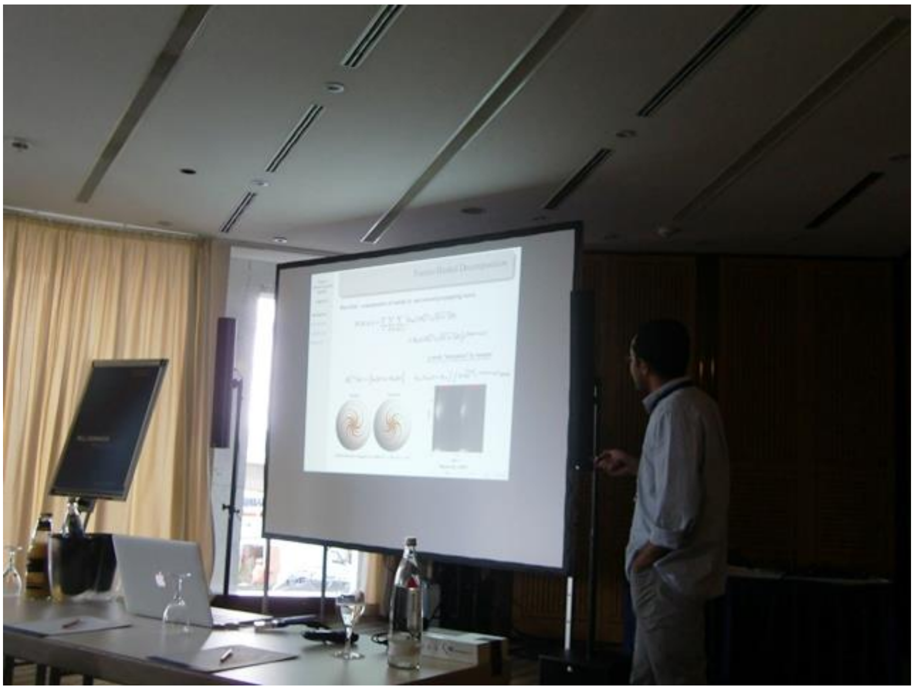
- To review the collection of dataset and tools provided by the SpaceInn project available at: http://www2.mps.mpg.de/projects/seismo/SpaceInn/index.html . To get feedback on issues and suggestions for improvement of these dataset and tools. To compile a list of requested updates and additional tools (e.g. mode fitting and inversion routines) for future use. To discuss updates to the information collected on systematic effects

- To provide an overview on how these tools can be used for local helioseismology. To identify other science goals and to obtain relevant resources (codes from other researchers) needed to address them and to provide them as part of the project. To discuss on copyright and other issues of providing these resources in an open-access/source platform
- To plan on migrating to a public repository (e.g. git) in order to maintain all the current and planned codes and their future updates. To discuss on developing these tools into a more comprehensive toolkit

Attendees

Kevin Belkacem (Observatoire de Paris-LESIA, France)
Rick Bogart (Stanford University, USA)
Ruizhu Chen (Stanford University, USA)
Khalil Daiffallah (Observatory of Algiers, CRAAG, Algeria)
Alina Donea (Monash University, Australia)
Vigeesh Gangadharan (KIS, Germany)
Kolja Glogowski (KIS, Germany)
Jan Langfellner (MPG, Germany)
John Leibacher (National Solar Observatory, USA)
Björn Löptien (Universität Göttingen)
Eric Michel (Observatoire de Paris-LESIA)
Kaori Nagashima (MPG, Germany)
Charly Pinçon (Observatoire de Paris – LESIA, France)
Damien Przybylski (Monash University, Australia)
Markus Roth (KIS, Germany)
Irina Thaler (KIS, Germany)
Jacobo Varela (CEA Saclay, France)
Junwei Zhao (Stanford University, USA)

Photos of the meeting



Vigeesh Gangadharan (KIS) is giving a talk about the Fourier-Hankel analysis.

Photo of the meeting room.

Discussions at the sessions:

1. Discussion about the Standard Product of the Fourier-Hankel/Legendre pipeline

- The codes for pipeline are ready and have been tested and running at KIS (D4.11).
- Data products are made available at local data storage system (the Data Record Management System, DRMS) at KIS, and they will installed at the German Data Center for SDO (GDC-SDO) at MPS by the end of 2015 (MS45).
- There was a question of whether other datasets can be analyzed by the pipeline.
    - Currently the pipeline has been tested and can be analyzed only for the SDO/HMI datasets. However, it is possible for the present code to use the datasets of the SDO/AIA and GONG. Since the code uses the data cube provided by *mtrack* as the input, any dataset handled by *mtrack* can be easily used with the present version of the code.
- What types of products do we need as standard products of the pipeline? What types of data are the users interested in?
    - Synoptic maps for meridional flow study might be useful. However, the intermediate data products such as the mapped/tracked data cubes will consume large amount of storage space. Also, the optimal geometry of the regions required for the construction of the synoptic maps needs to be studied.
    - Active Region and/or Sunspot datasets are useful, for example, for mode conversion study, and as a supplementary dataset for the target active region information HMI Active Region Patches (HARPs), which is used in the ring diagram pipeline for SDO datasets.
    - This analysis can also be useful for emerging active regions, which are not covered by HARPS.
    - In order to construct a standard dataset for the active regions, what kind of geometry should be considered?
        - For the sunspot, at least we need the area about three times of the penumbra radius.
    - Some people are also interested in the application to the supergranule study. While this has not been attempted before, the current version of the code can be easily applied for Legendre/Hankel analysis of supergranules, if the mapped/tracked data cube of the supergranule along with the coordinates of the cell center is provided.
    - It might be good if we could set up the web interface to get the data product so that we can choose the parameters, i.e., the location on the Sun, the area size, etc.?
        - Currently this is not provided. However, a webpage with the details of code and how to run the module along with other pipeline modules will be made available.
    - How about the intermediate products? Should we provide them as well as the main standard products?
        - For the ring-diagram pipeline case, the intermediate products are archived, but not available online.

        - In the case of Fourier-Legendre analysis, especially for meridional flow study, this pipeline produces a large amount of intermediate dataset as a result of mapping/tracking longitudinal patches across the solar surface. This will have to be archive/cleared as no other modules use these data for their analysis.

2. Some Feedback from the people who saw and/or used the SPACEINN WP4 website

- It would be nice, if standard tools/packages for the helioseismology analysis are available.
    - Test exercise codes and small test data cubes for new beginner students, for example.
    - But it might be too much for maintenance? (May need too much manpower to maintain or support the users.)
    - In the past such packages were constructed at a GONG/MDI/NSO summer school? Are they available?
- Some obsolete information is found on the website.
    - The webmasters will try to make it up-to-date.
- It would be nice to have some comparison results analyzing specific datasets with various helioseismology techniques.
- Any pieces of information about the simulation datasets useful for helioseismology and systematics of any helioseismology-related data are always welcome and are open to all at the website.
- It might be good to have a wiki webpage or a mailing list to interact between the users?
    - The issue being how to engage users to update the wiki with the latest on systematics that are available with only a selected number of people in the community.
    - The issue in identifying proper personal to set up and maintain such a wiki.
- How to make the codes available through open repository that will help in collaborative development of these codes?
    - There is a problem of users willing to share their analysis routines and making it available to a wider community
    - The issue of licensing of parts of certain codes used in the pipeline and other analysis routines, which prohibit users to go to an open platform.

Outcomes:

- The SPACEINN WP4 website was updated as much as possible.
- The description about the Fourier-Hankel/Legendre module on the SDO JSOC data-analysis pipeline is available online, and the link is included in the SPACEINN WP4 website as well.
  http://vigeesh.github.io/spaceinn/

Attachment:

1. Presentation file 1:
    - “Introduction to tools on the SPACEINN WP4” Kaori Nagashima (MPG)
2. Presentation file 2:
    - “Fourier-Hankel/Legendre pipeline” Vigeesh Gangadharan (KIS)
3. Screenshots of the webpage describing the Fourier-Hankel/Legendre module on the SDO JSOC data-analysis pipeline

Attachment file 1: Presentation file 1
“Introduction to tools on the SPACEINN WP4” Kaori Nagashima

Introduction to tools on the SPACEINN (WP4.2)

Kaori Nagashima

Max-Planck-Institut für Sonnensystemforschung

What is SPACEINN?

SPACEINN: “Exploitation of Space Data for Innovative Helio- and Asteroseismology”

- http://www.spaceinn.eu/
- Successor to the HELAS project. Since 2013.
- Funded by EU under FP7.
- Scientific Coordinator: M. Roth (KIS)
- Consists of 17 institutes around Europe and USA.
  – KIS, IAC, CEA, MPG, INAF, KU Leuven, OBSPARIS, CAUP, UAUP, UOB, AU, UPS, CSIC, KB MTA CSFK, AURA, UCAR, UPST
- Main goal: *“the full exploitation of space data and complementary ground-based data to allow for innovative approaches in helio- and asteroseismology.”* (cited from the SPACEINN poster)

SPACEINN WP4 *Helioseismology* workpackage

- WP Leader: L. Gizon (MPG)
  http://www2.mps.mpg.de/projects/seismo/SpaceInn/index.html
  – WP4.1: Global helioseismology
  – *WP4.2: Local helioseismology*

SPACEINN WP4 websites

http://www2.mps.mpg.de/projects/seismo/SpaceInn/index.html

SPACEINN WP4 *Helioseismology* workpackage

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  – WP4.1: Global helioseismology
  – *WP4.2: Local helioseismology*
- WP4.2
  – One of the goals : to maintain a local helioseismology data archive along with related tools for analysis

WP4.2 Local Helioseismology Tasks (according to DoW)

- T4.5) Explore **systematic effects** present in the analysis of space observations, e.g., geometrical distortions, instrumental errors and changes, foreshortening, and line-of-sight effects. (collect and document) [KIS, MPG, UCAR, AURA] *Meeting #2 in 2014*
- T4.6) Make available and exploit **numerical simulations of seismic waves** and their interactions with internal heterogeneities and magnetic regions. [KIS, MPG, UCAR, AURA, UPS] *Meeting #1 in 2013*
- T4.7) Implement **Fourier-Hankel/Legendre analysis** (FH), which is the most natural technique to study cylindrically-symmetric structures like sunspots. [KIS, MPG, UCAR, AURA] *Meeting #3 in 2015*
- T4.8) Develop fast, automated data processing by implementing efficient workflows to process historical data sets (MDI and GONG) and for the continued analysis of SDO-HMI data. [KIS, MPG, UCAR, AURA]

Open tools available on SPACEINN WP4 websites

- Simulated datasets
- Systematics

- Observation datasets
- Helioseismology tools
- Modeling tools

and more....

Website providing access to simulated data (1/3)

http://www2.mps.mpg.de/projects/seismo/SpaceInn/SimData/index.html

If you have any other simulated data (possibly) useful for analyses, let us know! We would like to add them!

Website providing access to simulated data (2/3)

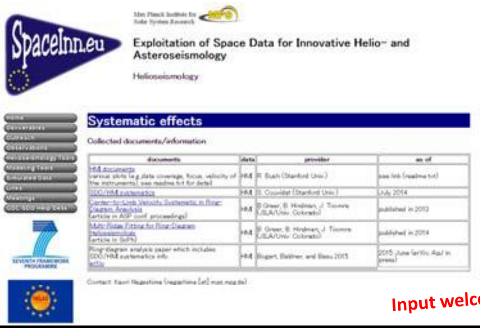
If you have any other simulated data (possibly) useful for analyses, let us know! We would like to add them!

Website providing access to simulated data (3/3)

If you have any other simulated data (possibly) useful for analyses, let us know! We would like to add them!

Systematics

http://www2.mps.mpg.de/projects/seismo/SpaceInn/systematics.html



Input welcome!

Fourier-Hankel analysis

- See Vigeesh's talk!

Other open tools related to SPACEINN: Seismic Plus Portal

http://voparis-spaceinn.obspm.fr/seismic-plus/

This site is preliminary, and your comments are welcome!

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Also, some tools and data are available from SPACEINN website

http://www.spaceinn.eu/

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Also, some tools and data are available from SPACEINN website

http://www.spaceinn.eu/

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Summary

- SPACEINN: http://www.spaceinn.eu/
- SPACEINN WP4 Local Helioseismology, tools and data (Simulated data, systematics, and more) : http://www2.mps.mpg.de/projects/seismo/SpaceInn/index.html
- Fourier-Hankel analysis: see next talk!
- Spaceinn *Seismic Plus* portal: http://voparis-spaceinn.obspm.fr/seismic-plus/

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Attachment file 2: Presentation file 2
“Fourier-Hankel/Legendre pipeline” Vigeesh Gangadharan

Fourier-Hankel/Legendre module
for SDO/HMI data analysis pipeline

Vigeesh Gangadharan
Kiepenheuer-Institut für Sonnenphysik

Outline

- Introduction
- Fourier-Hankel/Legendre module
- Applications

Techniques of Local Helioseismology

- Fourier-Hankel spectral decomposition (Braun et al., 1987)
- Ring-Diagram analysis (Hill, 1988)
- Time-Distance analysis (Duvall et al., 1993)
- Acoustic Holography (Lindsey & Braun, 1998)

Fourier-Hankel Decomposition

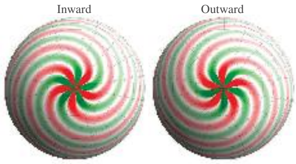
Wave field - a superposition of radially in- and outward propagating waves.

$$\delta V_z(\theta,\phi,t) = \sum_n \sum_{l\geq 0} \sum_{|m|\leq l} \Big[A_{lm}(t) H_m^{(1)}(\sqrt{l(l+1)}\theta) + B_{lm}(t) H_m^{(2)}(\sqrt{l(l+1)}\theta)\Big] e^{i(m\phi+\omega_{nl}t)}$$

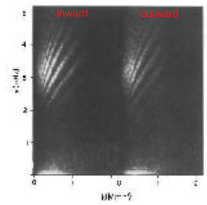
p mode "absorption" by sunspot

$$H_m^{(1,2)}(kr) = \Big[J_m(kr) \pm iY_m(kr)\Big]$$

$$A_{l,m}, B_{l,m}(t) = N_{l,m} \int\int \delta V\, H_m^{(1,2)} e^{-i(m\phi+\omega_{nl}t)} d\theta d\phi$$



Hankel functions mapped on a sphere ($l = 20$, $m = +5$)



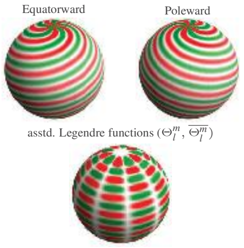
Braun et al. (1987)

Fourier-Hankel/Legendre Decomposition

Wave field - a superposition of radially in- and outward propagating waves.

$$\delta V_z(\theta,\phi,t) = \sum_n \sum_{l\geq 0} \sum_{|m|\leq l} \Big[A_{lm}(t)\Theta_l^m(\theta,\phi) + B_{lm}(t)\overline{\Theta_l^m}(\theta,\phi)\Big] e^{i(m\phi+\omega_{nl}t)}$$

$$\Theta_l^m(\theta,\phi) = N_l^m \Big[P_l^m(\cos\theta) - \frac{2i}{\pi} Q_l^m(\cos\theta)\Big]$$

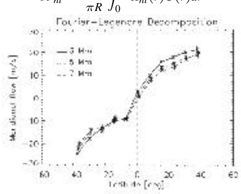


asstd. Legendre functions (Θ_l^m, $\overline{\Theta_l^m}$)

Spherical harmonics ($l = 20$, $m = +5$)

meridional flow measurements

$$\delta\nu_{nl} = \frac{l}{\pi R}\int_0^R K_{nl}(r)\overline{U(r)}dr$$

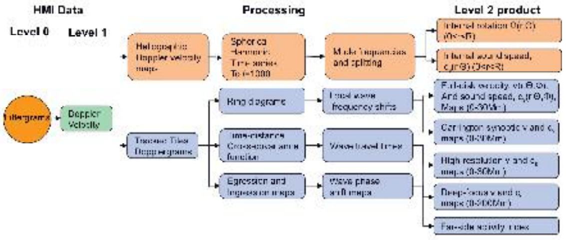


Doerr et al. (2010)

Fourier-Hankel/Legendre Decomposition

- interaction of p-modes with sunspots
  k_h dependence on absoption
  Fourier-Hankel (Braun et al., 1988; Braun & Duvall, 1990; Braun et al., 1990, 1992)
  Fourier-Legendre (Bogdan et al., 1993)
- meridional flow measurements
  Braun & Fan (1998); Krieger et al. (2007); Doerr et al. (2010); Glogowski (2011)
  validation using aritificial data (Roth et al., 2015)
- wave propagation in the solar atmosphere
  multi-height obs., support mode conversion scenario (Couvidat, 2013, 2014)
- study the scattering of f- and p-modes using numerical simulation
  sunspot structure (Felipe et al., 2012, 2014)

HMI Data Analysis Pipeline



Fourier-Hankel/Legendre pipeline
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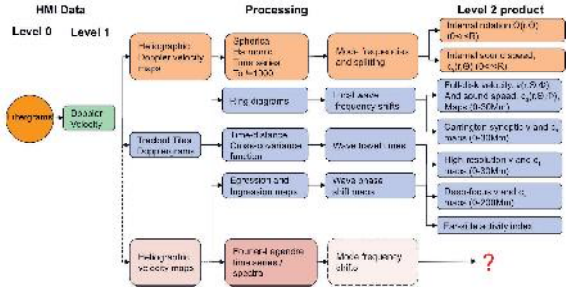
HMI Data Analysis Pipeline



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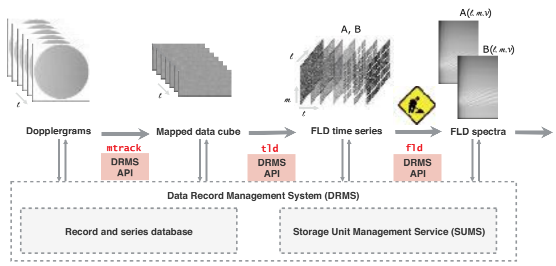
Pipeline workflow



Data managed by a system developed by the Joint Science Operations Center (JSOC).
DRMS processes, archives, and distributes data.
Data series contain *data record*, and are described by keywords.
Actual data is stored in SUMS.
Applications Programming Interface (API) to communicate with the database.

Bogart (2007)

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Pipeline workflow

`mtrack` - Mapping and Tracking

- creates small patches of mapped (& tracked) data cube: *Starttime, Duration*
- centered at different Θ_{HG}, Φ_{HG}
- size (*rows* and *cols*) and *mapscale* (degree/pixel)

```
[vigeesh@halo ~]$ mtrack in='hmi.v_45s[2010.06.01_00:00:00_TAI/4d]'       \
                  out='kis_vigeesh.hmi_fldvtrack_4d' scale=0.125           \
                  lat="{-40,-30,-20,-10,0,10,20,30,40}" lon="{200.}"     \
                  map='carree' rows=160 cols=800 -n -v -o -r
```

```
[vigeesh@halo ~]$ show_info ds='kis_vigeesh.hmi_fldvtrack_4d[2010.06.08_00:00:00_TAI]' \
                  key=LatHG,LonHG,Duration,Mapscale,Width,Height -A -P

LatHG LonHG     Duration   Mapscale   Width    Height    V
+40   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00009/V.fits
+30   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00008/V.fits
+20   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00007/V.fits
+10   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00006/V.fits
+00   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00005/V.fits
-10   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00004/V.fits
-20   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00003/V.fits
-30   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00002/V.fits
-40   -200.0    1382400.0  0.125      100.00   20.00     /SUMS/SUM5/D84864/S00001/V.fits
```

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Pipeline workflow

`tld` - Fourier-Hankel/Legendre time series

- Reads mapped data cubes from DRMS for specific: *Midtime*, Θ_{HG}, Φ_{HG}
- Computes the FLD coefficients: $l = 0$ to $l_{\max}$, $m = -m_{\mathrm{abs}}$ to $+m_{\mathrm{abs}}$
- Stores the data to DRMS with the appropriate keywords

```
[vigeesh@halo ~]$ mpirun -np 5 tld \
                  in=kis_vigeesh.hmi_fldvtrack_4d[2010.06.08_00:00:00_TAI][+200][+10] \
                  out=kis_vigeesh.hmi_tldcoeff_4d m_abs=25 l_max=1000
```

```
[vigeesh@halo ~]$ show_info ds='kis_vigeesh.hmi_tldcoeff_4d[2010.06.08_00:00:00_TAI]' \
                  key=LatHG,LonHG,Duration,Cadence,lMax,mAbs -A -P

LatHG LonHG     Duration   Cadence    lMax  mAbs  lmg
+40   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM3/D84909/S00000/lmg.h5
+30   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM5/D84956/S00000/lmg.h5
+20   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM6/D84908/S00000/lmg.h5
+10   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM5/D84952/S00000/lmg.h5
+00   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM4/D84910/S00000/lmg.h5
-10   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM6/D84873/S00000/lmg.h5
-20   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM6/D84957/S00000/lmg.h5
-30   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM4/D84958/S00000/lmg.h5
-40   +200.0    1382400.0  45.0       1000  25    /SUMS/SUM4/D84913/S00000/lmg.h5
```

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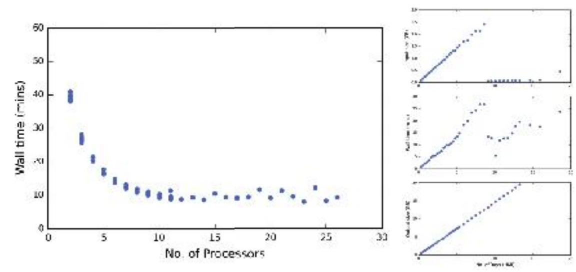
Performance

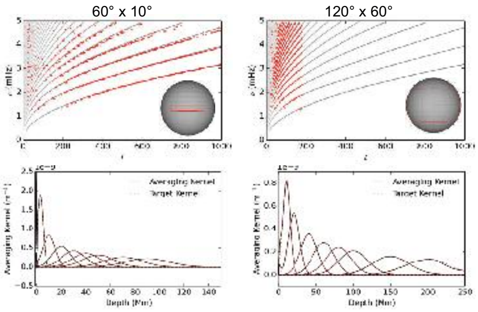
- uses Message Passing Interface (MPI)
- parallel I/O (utilising the HDF5 file format)
- scales well upto 10 proc. (limited by I/O, latency)
- issues with input file size (`mtrack` output)



100° x 20° x 4 days of HMI data (i.e. 800 x 160 pixels x 7680 maps)

Case 1: Meridional flow

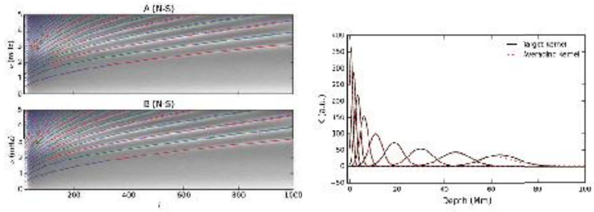
FLD time series for different geometries:
- Power spectra (FFT, Periodogram, Multitaper)
- Peak fitting (least square)
- SOLA inversion



possible to probe deeper, sacrificing latitudinal information

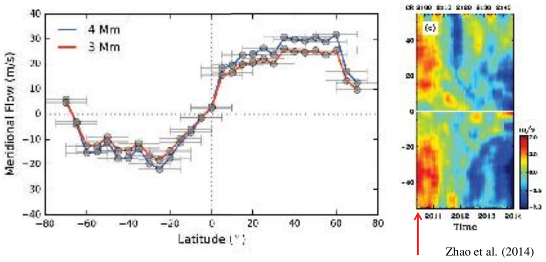
Case 1: Meridional flow

Data: from 2010.05.31 to 2010.06.04 (B-angle $\sim 0.4°$)
- input : `hmi.v_45s[2010.05.31_14:32_TAI/4d]'`
- Background : `bckgn=hmi.v_avg120[2097][180]`
- geometry : 100° x 20° (-40° to +40°), 80° x 20° (±50°) . . .
- Power spectra (Nth order sine multitaper, N=9)
- Peak fitting (least square)
- SOLA inversion (depth $\sim$ 50 Mm)



Case 1: Meridional flow

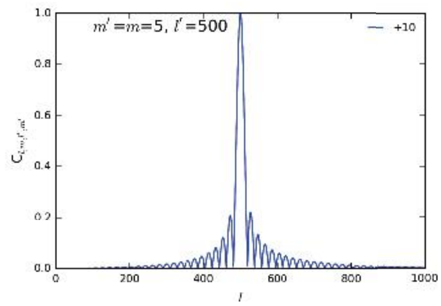
Data: from 2010.05.31 to 2010.06.04 (B-angle $\sim 0.4°$)
- input : `hmi.v_45s[2010.05.31_14:32_TAI/4d]'`
- Background : `bckgn=hmi.v_avg120[2097][180]`
- geometry : 100° x 20° (-40° to +40°), 80° x 20° (±50°) . . .
- Power spectra (Nth order sine multitaper, N=9)
- Peak fitting (least square)
- SOLA inversion (depth $\sim$ 50 Mm)



Zhao et al. (2014)

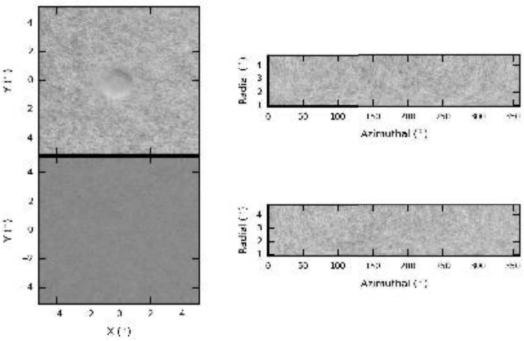
Case 1: Meridional flow

Leakage matrix
- for a given geometry
- at the specific Θ_{HG}, Φ_{HG}



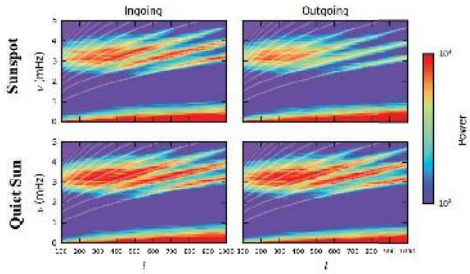
Case 2: Active Region

Data: AR 11084 - 2010.07.02_00:00 - 2010.07.02_23:59
- tracked AR 11084 ($\Theta_{HG} = -19°$) and a quiet Sun patch at $\Theta_{HG} = +19°$
- Postel to equi-angular remapping



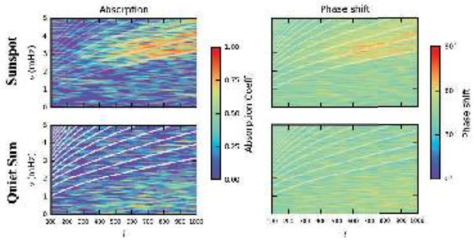
Case 2: Active Region

Data: AR 11084 - 2010.07.02_00:00 - 2010.07.02_23:59
- Power suppression of the outgoing wave

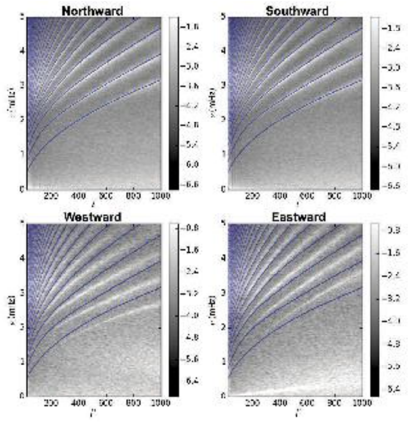


Case 2: Active Region

Data: AR 11084 and quiet Sun
- Absorption ($\sim 70\%$ for $l > 400$)
- Scattering phase-shifts ($< 90°$)



Case 3: Differential Rotation



Conclusion

- The pipeline is fully incorporated and working on the DRMS@KIS
- Provides Fourier-H/Legendre time series of the selected area
- Fast and optimized, utilizes other standard pipeline modules (mtrack)
- Tested for meridional flow measurements and sunspot seismology
- Fitting and Inversion methods needs to be improved and implemented
- Q: Should there be a standard data product?

Thank you

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Attachment file 3:
Screenshots of the webpage describing the Fourier-Hankel/Legendre module on the SDO JSOC data-analysis pipeline

Fourier-Hankel/Legendre Pipeline

Vigeesh Gangadharan

Table of Contents

Introduction

Among the various techniques currently used in local helioseismology (Ring- diagram analysis: Hill (1988); Time-distance analysis: Duvall et al. (1993); Acoustic holography: Lindsey & Braun (1998)), the Fourier-Hankel spectral decomposition was one of the earliest techniques used by helioseismologists to explore the subsurface regions of the Sun. It was first employed by Braun et al. (1987), and later followed up by a series of work (Braun et al., 1988; Braun & Duvall, 1990; Braun et al., 1990, 1992) to study the interaction of solar acoustic modes (p-modes) with isolated large scale magnetic structures like sunspots. Sunspots are local discontinuities in the near surface regions of the Sun. The p-modes sample these discontinuities and leave signature of their interaction on the oscillation spectra. Whereas, the spectra of the modes that have not encountered the sunspot remains unaltered. Fourier- Hankel method can be used to separate these two wave fields. This is done by decomposing the wave field into radially inward and outward propagating waves on an annular region centered in the sunspot.

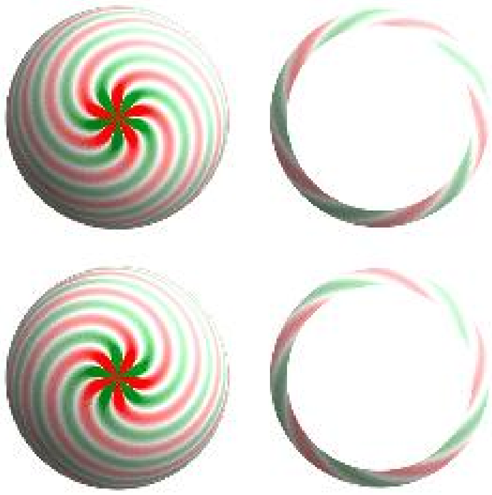


Figure 1. Hankel functions of the first and the second kind are used to describe the inward and outward propagating wave field.

Although, Hankel functions are good approximations, later studies also explored this method with the help of associated Legendre functions to account for the curvature of the solar surface.

Figure 2. Combinations of associated Legendre functions of the first and second kinds are used to describe the poleward and equatorward propagating wave field.

The application of Fourier-Hankel/Legendre technique was later extended to other helioseismic studies. Braun & Fan (1998) carried out meridional flow measurements using this technique by decomposing the wavefield into equatorward and poleward wavefields and measuring the frequency shifts between them. Further work carried out by Krieger et al. (2007) and Doerr et al. (2010) in this direction have resulted in the development of a fast and efficient code for the computation of Fourier-Hankel/Legendre transform which can be easily applied to a large amount of data (Glogowski, 2011). Preliminary results for meridional flow obtained from this work are comparable to the results obtained using ring- diagram analysis.

This document provides a description of the Fourier-Hankel/Legendre module on the

SDO/HMI JSOC data-analysis pipeline for processing HMI data.

Installing

Extract the archive to the local directory. Edit the Makefile with the appropriate paths to CFITSIO, HDF5 (requires hdf5-1.8.14 compiled with the **--enable-parallel** option), PostgreSQL, and DRMS libraries.

```
./configure
make
```

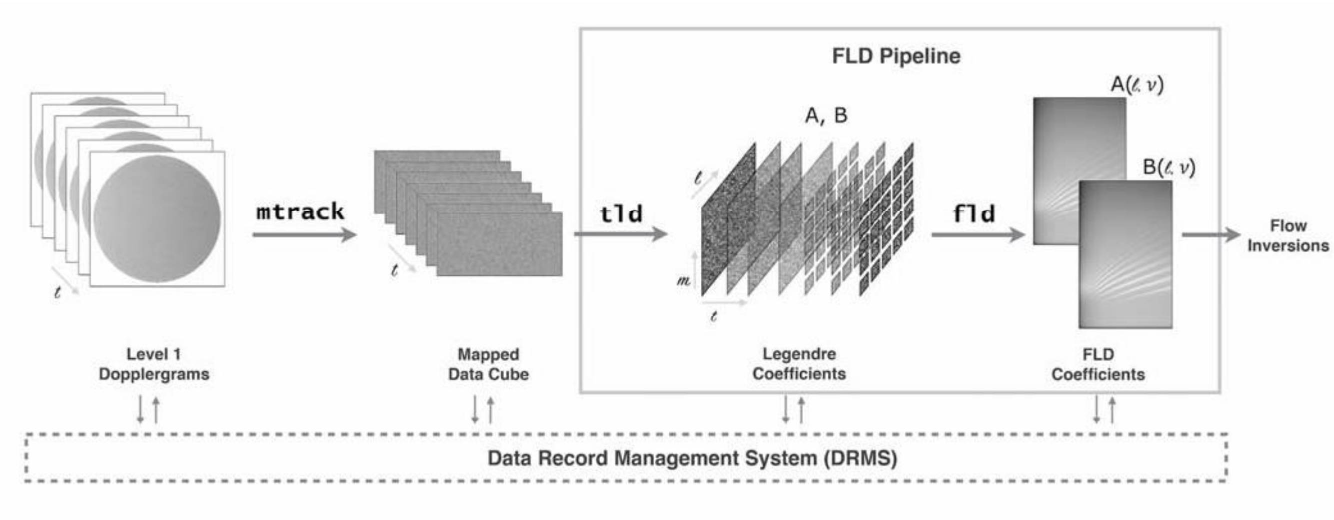
In case the libraries are not located in your default path. Configure it with the respective paths.

```
./configure --with-hdf5=<Path to the h5pcc executable> --with-cfitsio=<CFITSIO path>
--with-drms=<DRMS Path>
make
```

Make produces three executables: postel_remap, tld, fld.

Workflow

The Fourier-Legendre analysis are usually performed on small areas of the solar surface to infer the average properties beneath the selected region. For instance, to estimate the meridional flow as a function of latitude, rectangular patches are extracted from the Dopplergrams in the North-South direction along a specific longitude (usually the Stonyhurst $\varphi = 0^{\circ}$), centered at different latitudes. The Fourier-Hankel/Legendre decomposition gives the amplitude of the poleward and equatorward directed flow field. The difference in frequency between these two oppositely directed components can be attributed to a Doppler shift as a result of a flow in a particular direction. Assuming that the origin of this flow is be due to the meridional circulation, the frequency shifts can be inverted to get the magnitude of the meridional flow at different depths as a function of latitudes. For sunspot seismology, annular regions are selected centered in the spot and the decomposition gives the amplitude of the ingoing and outgoing waves within this annulus. The absorption coefficients and scattering phase-shifts can then be estimated from the amplitude of the two components. It should be noted that, for the meridional flow measurements the center is fixed on one of the poles, while in the case of sunspot it is the spot center. In both cases, the decomposition is carried out on a equi-angluar grid and therefore the first step is to select the region of interest and map it onto an appropriate grid. The Fourier-Hankel/Legendre decomposition is then carried on this tracked/mapped cube.



hmi.v_45s

↓

mtrack

↓

hmi_fldvtrack

↓

tld

↓

hmi_tldcoeff

Example run

```
create_series kis_vigeesh.hmi_fldvtrack.jsd

./mtrack in='hmi.v_45s[2010.06.01_00:00:00_TAI/8h]' out='kis_vigeesh.hmi_fldvtrack'
\
scale=0.125 lat="{0.}" lon="{200.}" map="carree" rows=400 cols=400 -n -v -o -r

show_info kis_vigeesh.hmi_fldvtrack[2010.06.01_00:00:00_TAI] -P
key=MidTime,LonHG,LatHG,Duration

create_series kis_vigeesh.hmi_tldcoeff.jsd

mpirun -np 9 tld in=kis_vigeesh.hmi_fldvtrack[2010.06.01_00:00_TAI][+200][0] \
out=kis_vigeesh.hmi_tldcoeff m_abs=25 l_max=1000

show_info kis_vigeesh.hmi_tldcoeff[2010.06.01_00:00_TAI] -P
```

```
key=MidTime,LonHG,LatHG,Duration,lMax,mAbs

create_series kis_vigeesh.hmi_fldcoeff.jsd

./fld in=kis_vigeesh.hmi_tldcoeff[2010.06.01_00:00_TAI][+200][0]
out=kis_vigeesh.hmi_fldcoeff

show_info kis_vigeesh.hmi_fldcoeff[2010.06.01_00:00_TAI] -P
key=MidTime,LonHG,LatHG,Duration,lMax,mAbs
```

---

1. Mapping and Tracking - `mtrack`

Each data set (e.g. Dopplergrams, Tracked cubes, SHT coefficients, etc.) is identified by a series in the DRMS (Data Record Management System).

Create a new data series

We start by creating a new data series in the DRMS that can hold the tracked cubes: $V_z(\Theta, \Phi, t)$. The data series is created using a series definition file, or a JSD file. A template is available under **kis_vigeesh.hmi_fldvtrack.jsd**.

To create a series that will hold the cube generated using mtrack:

```
create_series kis_vigeesh.hmi_fldvtrack.jsd
```

Note:

Unlike the usual pipeline data series, this definiton file does not specify the final pixel size and the time-length of the tracked data. This is set to be a variable.

Track the region

The next step is to track the desired region. The primary input to the module **mtrack** are the full-disk Dopplergrams available as the data series **hmi.v_45s**. We need to pass the **lat** and **lon** arguments to specify the Heliographic Latitude (Θ) and Longitude(Φ) of the center of the region to be tracked. The **scale** argument sets the desired MapScale in degrees/pixel. The **rows** and **cols** are the total number of pixel-rows and columns of the final mapped region. The FLD part can only process *PlateCarree* map projection currently, and so the **map** argument has to be set to '*carree*'. The tracked output will be stored in the data series that we just defined.

Example

To generate an untracked region (flag: **-n**) centered at $(\Theta, \Phi) = (0, 200)$ sapnning 8 hours, with the line-of-sight component of observer velocity (flag: **-o**) and solar rotation (flag: **-r**) removed,

```
./mtrack in='hmi.v_45s[2010.06.01_00:00:00_TAI/8h]' out='kis_vigeesh.hmi_fldvtrack' \
scale=0.125 lat="{0.}" lon="{200.}" map="carree" rows=400 cols=400 -n -v -o -r
```

There are several ways one can call **mtrack**.
To generate multiple sets of tracked regions, one can specify the **lat** and and **lon** as:
`lat="{0.,10.,-10.}" lon="{200.}"` - maps centered at
$(\Theta, \Phi) = (-10., 200.), (0., 200.), (+10., 200.)$.
`lat="{0.,10.,-10.}" lon="{200.,210.,195.}"` - maps centered at
$(\Theta, \Phi) = (0., 200.), (10., 210.), (-10., 195.)$
`lat="{0.,10.,20.,30.,40.}" lon="{200.,210.,195.}"` - maps centered at
$(\Theta, \Phi) = (0., 200.), (10., 210.), (20., 195.), (30., 195.), (40., 195.)$.

Note:

The current version of the **fld** can only process individual tracked cubes.
There is no correction/checking whether the Φ that is provided is out of the coverage, and hence the tracked output can be arrays of 'nan's.

Look at the series

The tracked cube is stored as fits file inside the DRMS - SUMS directory that can be viewed using the **show_info** command.

```shell
show_info kis_vigeesh.hmi_fldvtrack[2010.06.01_00:00:00_TAI/5m] -P
key=MidTime,LonHG,LatHG,Duration
```

The essential keywords that will be used by the next modules are:
MidTime, LonHG, LatHG, Duration, Cadence, MapScale, MapProj, Width, Height

---

2. Legendre time series - `tld`

Create a new data series

A template is available under **kis_vigeesh.hmi_tldcoeff.jsd**.

```
create_series kis_vigeesh.hmi_tldcoeff.jsd
```

An important thing to note here is that, unlike the other pipeline modules, the data format is set to 'generic' and the output file format is 'hdf5'. The reasons for this are the following.

Why generic file format

1. The number or *l*, *m* are not predefined, since we need to have the flexibility in choosing these values at runtime.
2. To avoid storing multiple FITS files (A_{lm}, B_{lm}) under the same data record.
3. Writing in parallel is not yet supported for FITS file (AFAIK), which would generate again multiple files for each coefficients depending on the number of processors used under the same data record.
4. We can get away with the *meat-grinder*, as we now have access to hyperslabs of data.

Do the **tld**

The input series is the tracked data cube from the **mtrack**. The Mapscale and other quatities are automatically passed on from the input series. The user provides the maximum *l* and the absolute maximum *m* that is desired. Presently, the code can only process individual sets of (Θ, Φ) as follows.

```
mpirun -np 3 tld in=kis_vigeesh.hmi_fldvtrack[2010.06.01_00:00_TAI][+200][0]
out=kis_vigeesh.hmi_tldcoeff m_abs=25 l_max=1000
```

The code runs as follows:

1. The master divides the whole data into chunks along the time axis, the number of chunks depend upon the number of processors assigned using the **-np**.
2. The master processor opens an hdf5 container file in the local directory and adds in the A_{lm} and B_{lm} data spaces to the **/lmg** group.
3. Each processor then fills in the hdf5 file at the specific location of their respective chunk with transformed complex values of A_{lm} and B_{lm}.
4. Finally the attributes are added to the hdf5 and the file is assigned to the data series where it gets its own SUMS location.

Look at the series

```
show_info kis_vigeesh.hmi_tldcoeff[2010.06.01_00:00_TAI] -P
key=MidTime,LonHG,LatHG,Duration,lMax,mAbs
```

The file can be viewd using **hdfview** command-line tool. Apart from the other keywords that are propagated from the **mtrack** module,

MidTime, LonHG, LatHG, Duration, Cadence, MapScale, MapProj, Width, Height the data series aquires two new keywords as defined below.

Table 1. Aquired Keywords

Keyword	Datatype	Purpose
lMax	int	Maximum l (l=0, l_{max})
mAbs	int	Absolute of the maximum m (m= -m_{abs}, m_{abs})

These keywords are then used by the next module without the need for specifying it at runtime.

Analysis

1. Reading the file

If we have the file from the FLD,

```
/SUMS/SUM2/D76331/S00000/freq_lmg.h5
```

IDL

```
file = '/SUMS/SUM4/D81848/S00000/freq_lmg.h5'
file_id = H5F_OPEN(file)
dataset_Alm = H5D_OPEN(file_id,'/lmg/Alm')
a = H5D_READ(dataset_Alm)
dataset_Blm = H5D_OPEN(file_id,'/lmg/Blm')
b = H5D_READ(dataset_Blm)
alm = complex(a.real,a.imaginary)
blm = complex(b.real,b.imaginary)
```

Python

```
import h5py
f = h5py.File('/SUMS/SUM2/D76331/S00000/freq_lmg.h5',"r")
a=f['/lmg/Alm']
b=f['/lmg/Blm']
```

```
alm=a['real']+ 1j * a['imaginary']
blm=b['real'] + 1j * b['imaginary']

plot(alm[0,2,:]['real'])
```

References

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Braun, D. C., Duvall, Jr., T. L., Labonte, B. J., Jefferies, S. M., Harvey, J. W., & Pomerantz, M. A. 1992, ApJ, 391, L113

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