Vision of Chapter 1 ”Novel techniques in coronal seismology data analysis“

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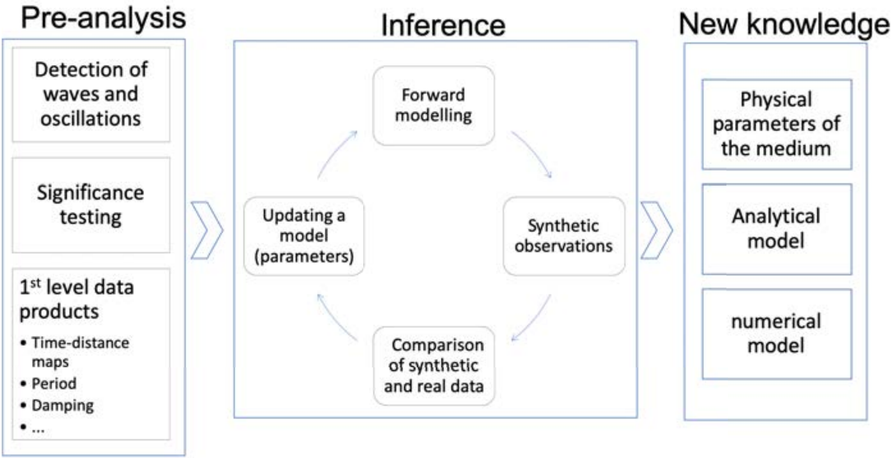
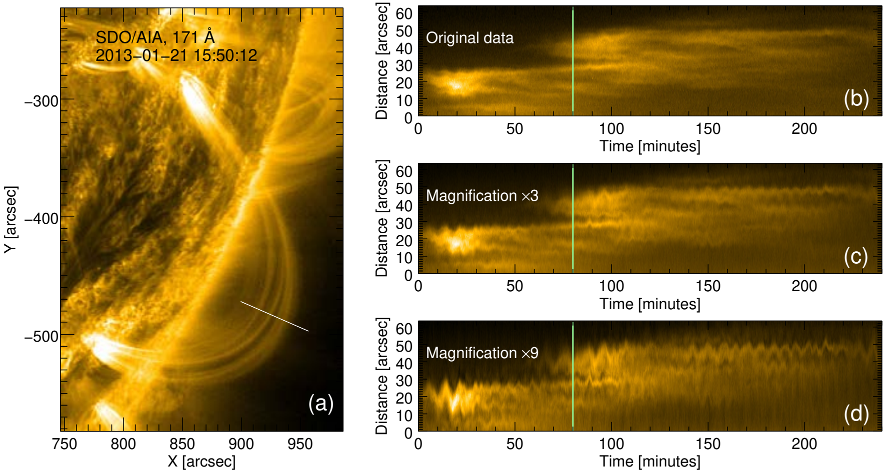
Data analysis workflow



Detection of waves and oscillations

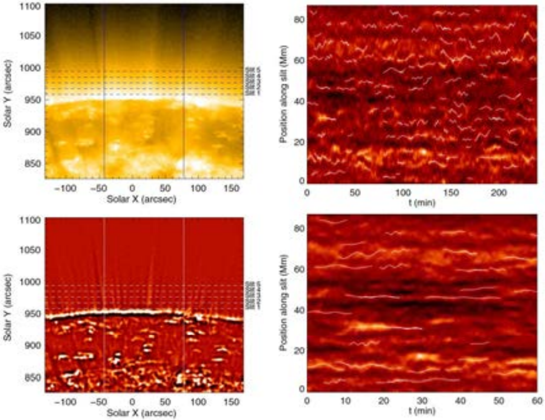
Motion magnification [1]



1

Detection of waves and oscillations

Automated wave-tracking with NUWT [2] [3]



[2] Northumbria University Wave Tracking code

[3] Anfinogentov and Nakariakov (2016); Weberg et al. (2018); Thurgood et al. (2014)

Detection of waves and oscillations

AFINO[4] code by Andrew Inglis

<u>Andrew Inglis</u>

The AFINO approach to finding oscillations in solar and stellar flares: latest results and updates

The Automated Flare Inference of Oscillations (AFINO) code provides a novel, statistically conservative approach to identifying oscillatory signals in solar and stellar flare data. This tool enables large sample studies of flares and other coronal phenomena. AFINO has also been used in wider contexts to search for discrete ULF waves in the magnetosphere. We present the AFINO methodology and discuss the main results obtained so far using this approach, as well as its advantages and disadvantages compared to other methods. Finally, we discuss expected updates and improvements to the analysis code.

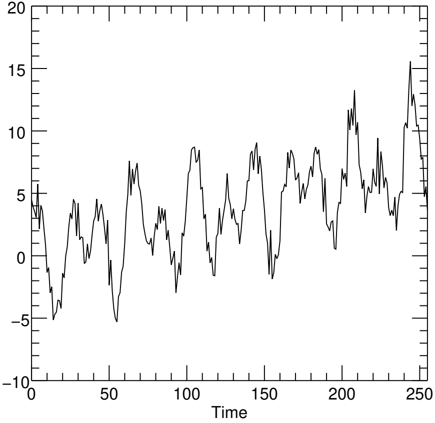
Waiting for Andrew Inglis talk...

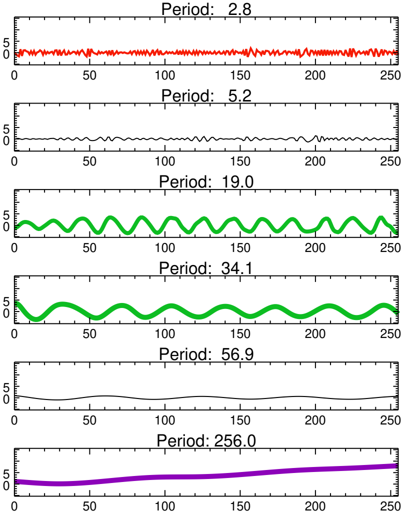
[4] Automated Flare Inference of Oscillations

First level data products

Empirical mode decomposition

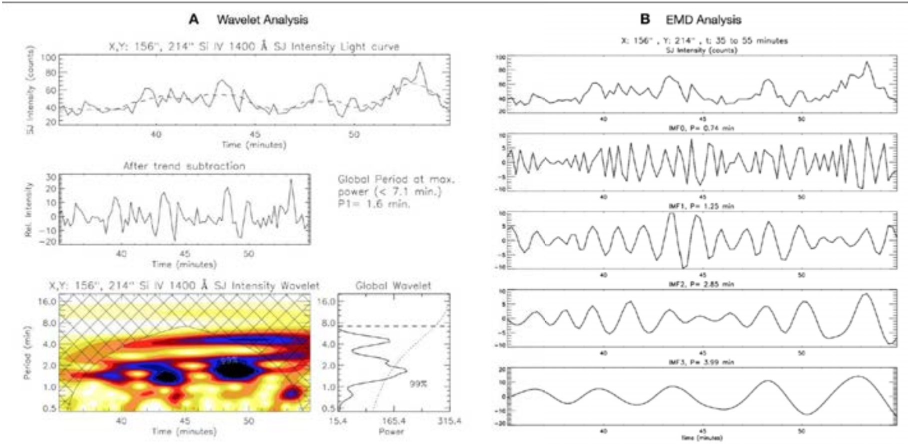
$$x(t) = 3\sin\frac{2\pi t}{20} + 2.5\cos\frac{2\pi t}{35} + 0.03t + N(0,1)$$





First level data products

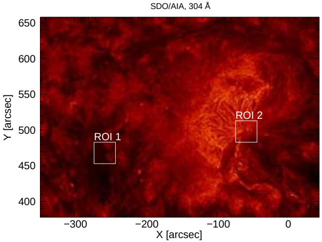
Empirical mode decomposition[5]

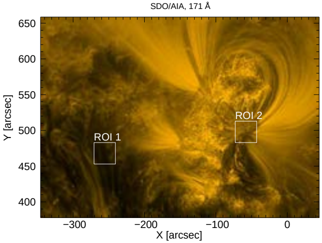


[5] Narang et al. (2019); Kolotkov et al. (2015)

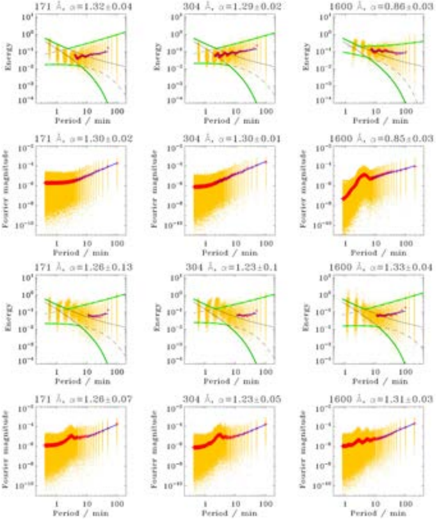
Significance testing

Significance of EMD modes[6]





ROI 1

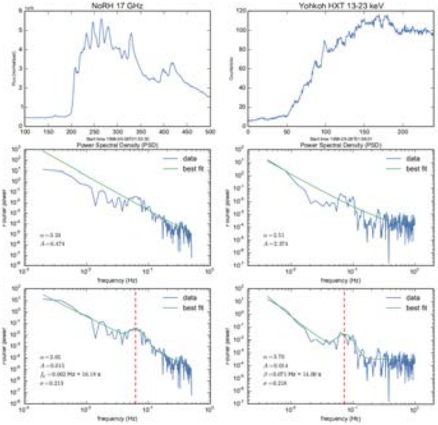


ROI 2

[6]Kolotkov et al. (2016)

Significance testing

Significance testing Bayesian analysis of Fourier decomposition[7]



Bayesian model comparison

1. Power law + white noise
2. Power law + white noise + oscillation
3. Broken power law + white noise+ oscillation

[7] Inglis et al. (2015, 2016)

Inference methods

Best fitting

- **Input**: data + model
- **Output**: best fit (the highest mountain in the parameter space)
- **Model comparison**: comparison of the best fits (based on a single point in the parameter space)

Bayesian inference

- **Input**: data + model + a priory knowledge
- **Output**: PDF (full landscape of the parameter space)
- **Model comparison**: Bayes factor (based on full parameter space)

Inference methods

Bayesian inference[8]

Bayesian Coronal Seismology

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Abstract

In contrast to the situation in a laboratory, the study of the solar atmosphere has to be pursued without direct access to the physical conditions of interest. Information is therefore incomplete and uncertain and inference methods need to be employed to diagnose the physical conditions and processes. One of such methods, solar atmospheric seismology, makes use of observed and theoretically predicted properties of waves to infer plasma and magnetic field properties. A recent development in solar atmospheric seismology consists in the use of inversion and model comparison methods based on Bayesian analysis. In this paper, the philosophy and methodology of Bayesian analysis are first explained. Then, we provide an account of what has been achieved so far from the application of these techniques to solar atmospheric seismology and a prospect of possible future extensions.

Keywords: magnetohydrodynamics (MHD); methods: statistical; Sun: corona; Sun: oscillations

[8] Arregui (2018)

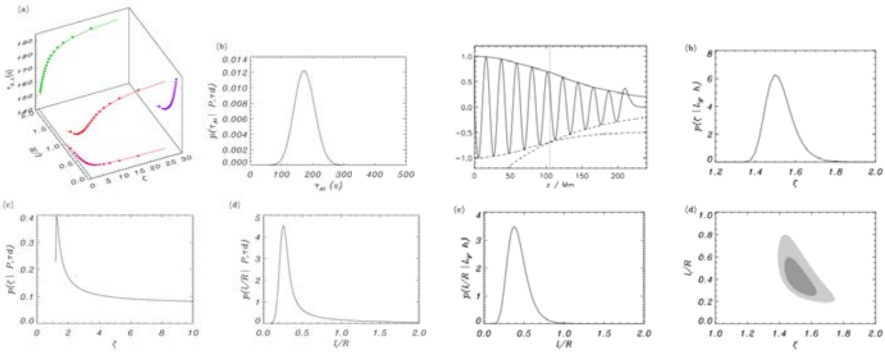
Inference methods

Bayesian inference

- Bayesian analysis of QPP spectra: Inglis et al. (2015, 2016)
- MHD seismology by kink oscillations (mainly analytical approach):Montes-Solís and Arregui (2019); Arregui and Soler (2015); Arregui et al. (2015, 2019)
- MHD seismology by kink oscillations (numerical analysis with MCMC) Pascoe et al. (2017a,b, 2018); Goddard et al. (2018)

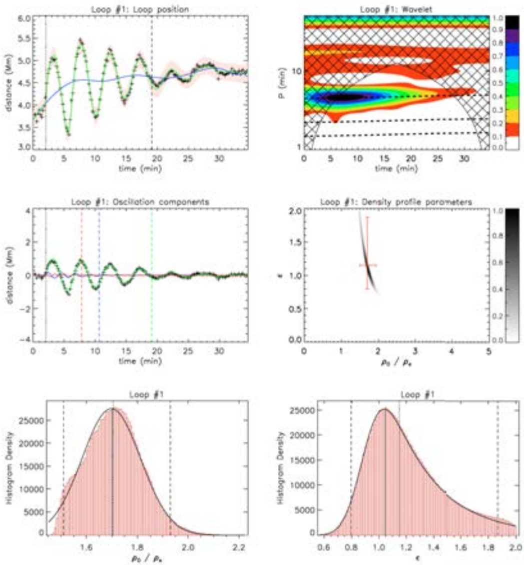
Inference methods

Bayesian inference, (semi)analytical



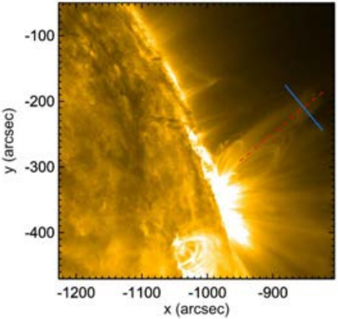
Inference methods

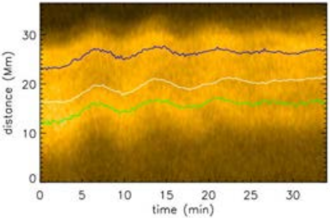
Bayesian inference, MCMC[9]

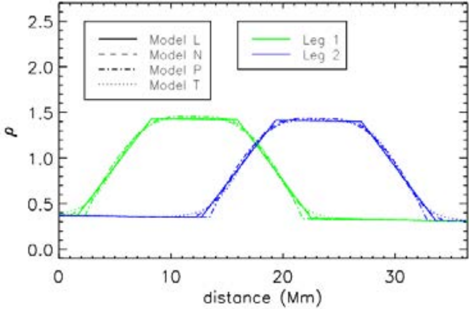


Inference methods

Bayesian inference, loop tracking

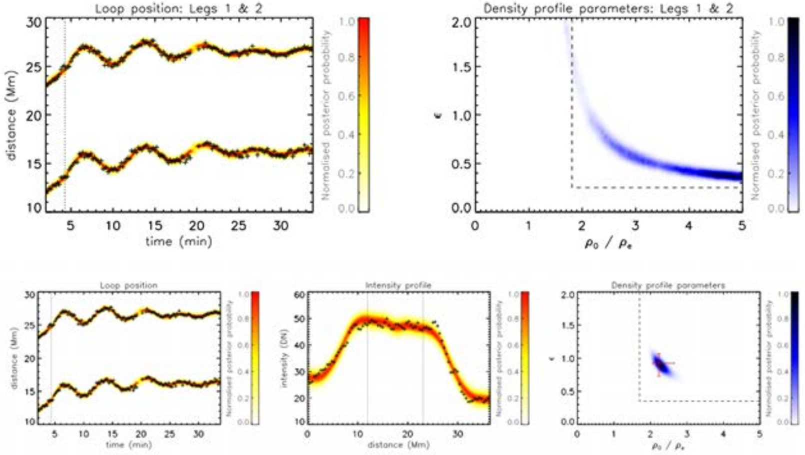






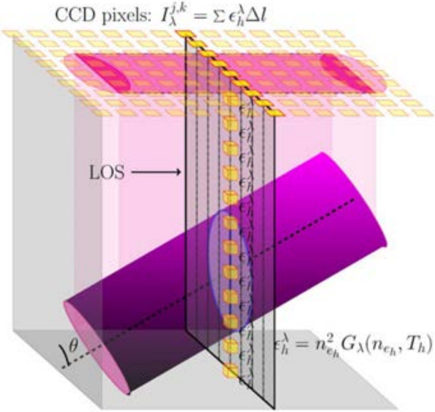
Inference methods

Bayesian inference, spatial + temporal information



Forward modelling

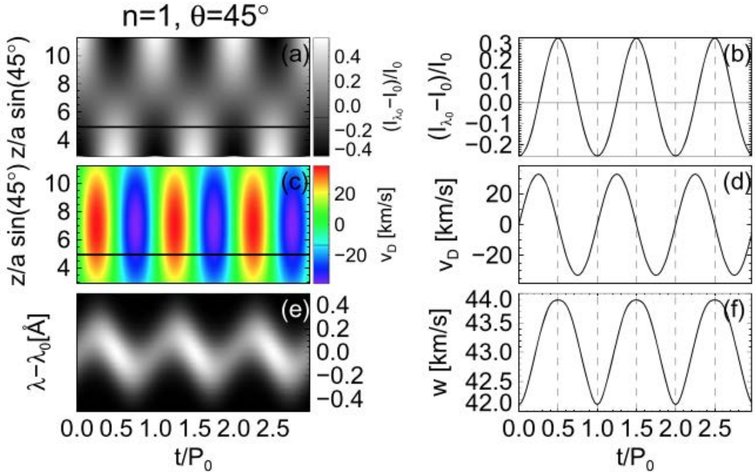
Forward modelling EUV emission with FoMo[10]



[10]Van Doorsselaere et al. (2016)

Forward modelling EUV

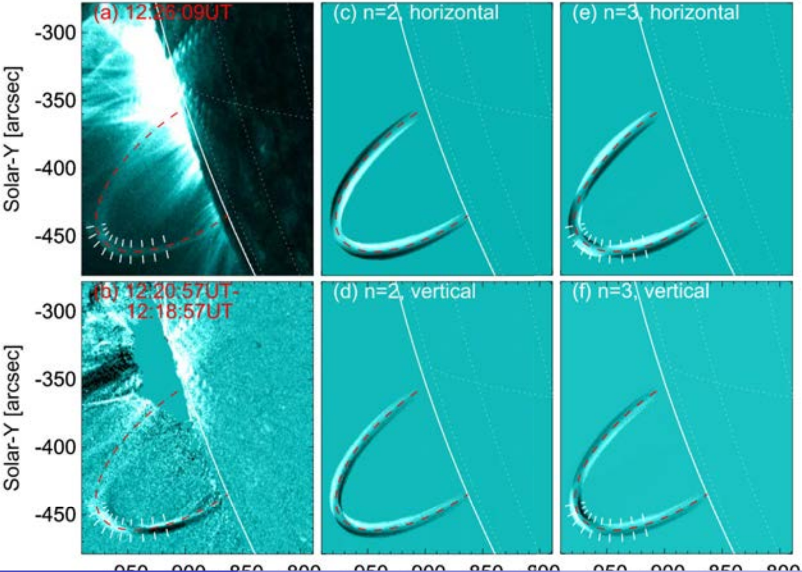
Slow waves[11]



[11] Pascoe et al. (2018)

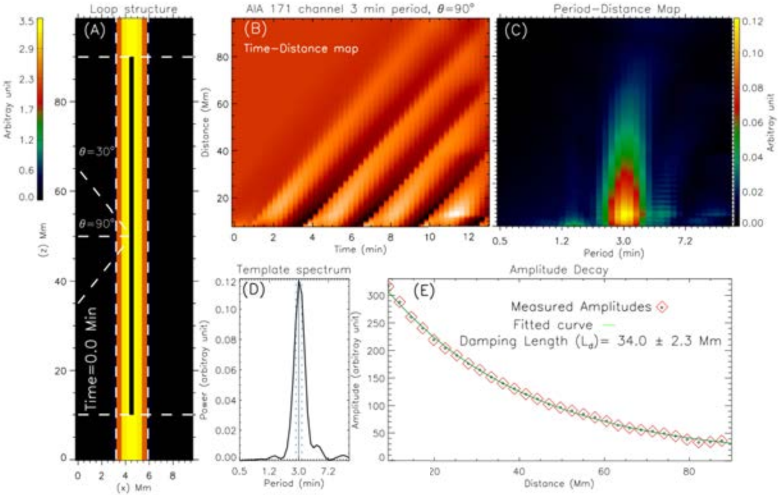
Forward modelling EUV

Standing kink waves waves[12]



Forward modelling EUV

Propagating slow waves waves[13]



[13] Mandal et al. (2016)

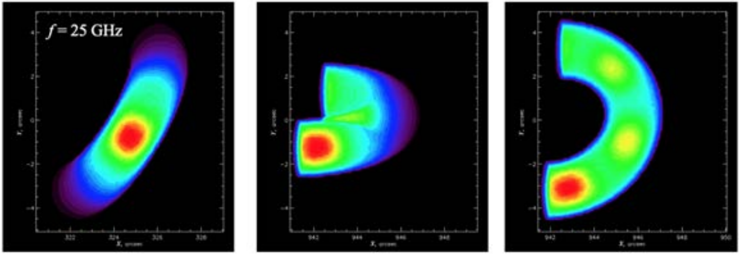
Forward modelling

Forward modelling radio emission with fast GX and GR codes[14]

Curved semi-circular loop; sausage mode; low-density model.

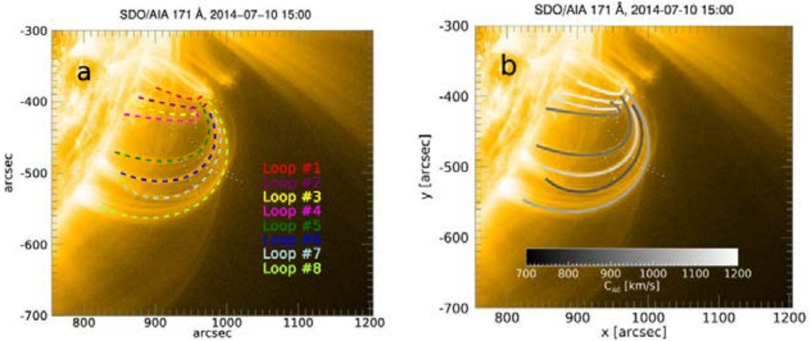
- Optically thick and optically thin emissions oscillate in phase.
- Slightly below the spectral peak, the oscillations are shifted by ~$\lambda/4$.
- The oscillation amplitude is the highest:
  - in the optically thin range – at $\theta \approx 90°$;
  - in the optically thick range – at small viewing angles.

Kuznetsov et al. (Solar Phys., 290, 1173, 2015)



[14] Kuznetsov et. al 2015

MHD seismology by decay-less kink oscillations



MHD seismology by decay-less kink oscillations

Loop No	Loop length [Mm]	Slit width [px]	Period (s)	Intensity contrast	Density contrast	Kink speed [km/s]	C_{A0} [km/s]	C_{Ae} [km/s]
1	224	1	$276^{+2.8}_{-2.5}$	0.23	$0.04^{+0.35}_{-0.03}$	1622^{+15}_{-17}	1173^{+182}_{-23}	4313^{+7935}_{-2156}
2	231	5	334^{+40}_{-49}	0.46	$0.07^{+0.40}_{-0.05}$	1395^{+226}_{-163}	942^{+338}_{-35}	2765^{+4221}_{-1076}
3	244	11	$321^{+11}_{-7.8}$	0.66	$0.11^{+0.52}_{-0.04}$	1525^{+38}_{-52}	1140^{+240}_{-38}	2122^{+2156}_{-384}
4	235	5	382^{+18}_{-15}	0.70	$0.12^{+0.57}_{-0.04}$	1228^{+49}_{-58}	927^{+218}_{-43}	1549^{+1514}_{-184}
5	292	28	475^{+10}_{-10}	0.50	$0.08^{+0.42}_{-0.06}$	1229^{+26}_{-25}	903^{+161}_{-27}	1974^{+3578}_{-466}
6	329	5	435^{+12}_{-11}	0.43	$0.07^{+0.43}_{-0.05}$	1512^{+39}_{-42}	1110^{+201}_{-38}	2624^{+5352}_{-769}
7	343	15	$580^{+6.7}_{-6.6}$	0.42	$0.06^{+0.43}_{-0.04}$	1184^{+14}_{-14}	866^{+155}_{-21}	1948^{+4051}_{-489}
8	391	13	$547^{+9.0}_{-8.5}$	0.26	$0.04^{+0.37}_{-0.03}$	1429^{+22}_{-23}	1030^{+174}_{-19}	3353^{+6682}_{-1478}

Preliminary structure of the chapter

- Detection of waves and oscillations
  - Motion magnification
  - NUWT
  - AFINO?
- Significance testing
  - focus on the presence of power law "noise" in solar data
- Forward modelling
  - EUV
  - Radio
- Bayesian inference
  - focus on research not covered by Arregui (2018)
- Did I miss something important?

Thank you for your attention!

References

Anfinogentov, S. and Nakariakov, V. M. (2016). Motion Magnification in Coronal Seismology. Sol. Phys., 291(11):3251–3267.

Arregui, I. (2018). Bayesian coronal seismology. *Advances in Space Research*, 61(2):655–672.

Arregui, I., Montes-Solís, M., and Asensio Ramos, A. (2019). Inference of magnetic field strength and density from damped transverse coronal waves. A&A, 625:A35.

Arregui, I. and Soler, R. (2015). Model comparison for the density structure along solar prominence threads. A&A, 578:A130.

Arregui, I., Soler, R., and Asensio Ramos, A. (2015). Model Comparison for the Density Structure across Solar Coronal Waveguides. ApJ, 811(2):104.

Goddard, C. R., Antolin, P., and Pascoe, D. J. (2018). Evolution of the Transverse Density Structure of Oscillating Coronal Loops Inferred by Forward Modeling of EUV Intensity. ApJ, 863(2):167.

Inglis, A. R., Ireland, J., Dennis, B. R., Hayes, L., and Gallagher, P. (2016). A Large-scale Search for Evidence of Quasi-periodic Pulsations