Experiments and First Results with HELLRIDE

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*with most work done by*

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2D Spectrometer HELLRIDE – HELioseismic Large Region Interferometric DEvice

- Instrument developed and built by Joachim Staiger at KIS (Staiger, A&A 2011)
- Built on experience with GFPI at the VTT
- Fabry-Perot interferometer based device equipped with filter matrix
- Development and testing during the last years
  - Sequential scanning through up to 16 spectral lines (<2 s per line with ~35 scan steps)
**2D Spectrometer HELLRIDE – HELioseismic Large Region Interferometric DEvice**

- Etalon Producer: IC Optical, London
- Plate distances: ET-70: 1.125 mm  
  ET-50: 0.125 mm
- Filter Unit: 7 x 7 Matrix;  
  i.e. 49 filter positions  
  (quickly movable)
- Field of View: 100” x 100”
- CCD Camera: Andor Zyla
- Optical Layout: Collimated Beam

**Advantages:**  
Only a few optical surfaces  
High light throughput  
Simple Adjustment  
Easy maintenance
Endless List of Scientific Questions

- **Structure of solar atmosphere**
  - Quiet sun
  - Active regions

- **Seismology of active regions**
  - Effect of magnetic field needs to be corrected
  - Structure of atmosphere

- **Course of transient events (flares)**
  - Triggering, Onset, Propagation

- **Chromospheric heating**
  - Energy transport in the solar atmosphere

- **Synoptic magnetic fields**

- **Space Weather**
Multi-height Spectroscopy with HELLRIDE

- Provide multi wavelength observations
- Investigating the propagation of acoustic waves to understand the structure of the quiet and magnetized atmosphere
- Analysis of the kinematic energy transfer within the solar atmosphere at high temporal and spatial resolution.
- Confirmation of formation heights of the spectral lines
Observational Campaigns

HELLRIDE is installed at the Vacuum Tower Telescope (VTT) in Izana, Tenerife
• 2014: First scientific data were taken
• 2015: Instrument was opened to the community via the Solarnet Access Programme
   • Two campaigns took place in September 2015:
     • Arnold Hanslmaier
     • Rekha Jain
• 2016: Instrument is available again
Data Processing Pipeline

- Raw data suffers from systematic effects
- Interference stripes
- Dust on optics
- Shadowing of field-of-view
- Image motions

Original record. Fe I 617.33 nm
Movie of Raw Data

Example: Fe I 543.29 nm
Data Pre-Processing

- Flat-field correction $C = R/F$ removes
  - Dark spots (dust)
  - Intensity gradients
  - Weakens interference stripes

Example: Fe I 617.33 nm
Correction of Interference Fringes

• Origin:
  With narrow-band observations the glass window of the CCD (non-parallel surfaces) can cause interferences

• Removal by 2D Fourier filtering at each time step:
  • Identifiable structure in the power spectrum
Corrected Data

• Further correction: image motion removed by cross-correlation in the Fourier domain

• Image after fringe correction. Fe I 617.33 nm
Movie of Corrected Data

Example: Fe I 543.29 nm
Wave Propagation on the Sun

„Sonography“ of the Sun – Helioseismology

• Solar interior – low-frequency waves < 5.3 mHz
• Solar atmosphere – higher frequency waves > 5.3 mHz
First Concept of Cutoff Frequency

Sir Horace Lamb (1849-1934),

English applied mathematician
Author of several texts on classical physics e.g. Hydrodynamics (1895), Dynamical Theory of Sound (1910).

Cutoff frequency for acoustic waves in isothermal atmosphere

\[ \omega_{ac} = \frac{C_s}{2H_p} \]

+ non-isothermal atmosphere case, with uniform temperature gradient
**Further Theories on the Cutoff Frequency**

Lamb’s original cutoff frequency (Lamb 1910)

\[ \Omega_1(z) \equiv \omega_a(z) = \frac{C_s(z)}{2H_\rho(z)}, \]

Deubner & Gough (1984) –
Cowling approximation; most used in asteroseismology

\[ \Omega_2(z) = \frac{C_s(z)}{2H_\rho(z)} \left[ 1 - 2 \frac{dH_\rho(z)}{dz} \right]^{1/2}, \]

Schmitz & Fleck (1998) –
inclusion of 1st and 2nd derivatives of sound speed

\[ \Omega_3(z) = \omega_a(z) \left[ 1 + 2 \frac{\omega_s(z)}{\omega_a(z)} \right]^{1/2}, \]

\[ \Omega_4(z) = \left[ \Omega_3^2(z) + \frac{1}{4} \omega_s^2(z) - \frac{1}{2} C_s(z) \omega_s'(z) \right]^{1/2}, \]

Musielak et. al (2006) –
inclusion of pressure perturbations

\[ \Omega_5(z) = \Omega_{tp}(z) = \left[ \Omega_{crit}^2(z) + \Omega_{tau}^2(z) \right]^{1/2} \]

Acoustic cutoff frequencies are determined for the acoustic wave equations for velocity perturbations.
Models of the Quiet-Sun Atmosphere

Start of structure investigations:

Calculate theoretical cut-off frequencies by making use of an atmospheric model

We start with the VAL C model (Vernazza et al. 1981)
Functional Dependence of Theoretical Cutoff Frequencies

![Graph showing functional dependence of theoretical cutoff frequencies](image)

- $T_{\text{min}}$
- Height above the solar surface [km]
- Frequency $\nu$ [mHz]
Observations 2015 of Quiet Sun

9 spectral lines
Cadence of 30 sec.
Total time 8 hours

Fully covered photosphere and lower chromosphere
from ~200 to ~1700 km
## Formation Heights of Spectral Lines

<table>
<thead>
<tr>
<th>Spectral line</th>
<th>Wavelength [Å]</th>
<th>Landé g-factor</th>
<th>Formation height [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe I</td>
<td>6301</td>
<td>1.669</td>
<td>337</td>
</tr>
<tr>
<td>Fe I</td>
<td>5434</td>
<td>0.0</td>
<td>556</td>
</tr>
<tr>
<td>Fe I</td>
<td>5433</td>
<td>0.0</td>
<td>268</td>
</tr>
<tr>
<td>Na I D₂</td>
<td>5890</td>
<td>-</td>
<td>927</td>
</tr>
<tr>
<td>Hα</td>
<td>6562.7</td>
<td>1.048</td>
<td>1200 - 1700</td>
</tr>
<tr>
<td>Mg I b₂</td>
<td>5172</td>
<td>-</td>
<td>595</td>
</tr>
<tr>
<td>Fe I (HMI)</td>
<td>6173</td>
<td>2.499</td>
<td>276</td>
</tr>
<tr>
<td>Fe I</td>
<td>7090.1</td>
<td>0.0</td>
<td>284</td>
</tr>
<tr>
<td>Fe I</td>
<td>5576</td>
<td>0.0</td>
<td>310</td>
</tr>
</tbody>
</table>
Phase Differences of Acoustic Waves between Two Heights

**Standing wave:**
phase difference = 0

**Propagating wave:**
phase difference ≠ 0

Spectral line that forms highest (H$\alpha$ core) as reference

$$C_{ij}(\omega) = \langle F_{V_i}(\omega, k, \lambda_i) \cdot (F_{V_j}(\omega, k, \lambda_j))^* \rangle_k = \hat{C}_{ij} \cdot e^{-i(\phi_{V_i} - \phi_{V_j})}$$
HELLRIDE: Seismology of Solar Atmosphere

(Wisniewska, Musielak, Staiger, Roth, 2016, ApJL)
Vertical Cut through the Phase Spectra

\[ l = 301 \]
Vertical Cut through the Phase Spectra

$l = 301$

$180 < l < 301$
Theory vs Observations
Cutoffs $\Omega_1$ & $\Omega_3$ inconsistent with the observational data in the entire range of heights.

$\Omega_2$, $\Omega_4$ and $\Omega_5$ match the observational results between approx. 350 to 500 km.

For the photospheric heights (below 350 km) and the chromospheric level (above 500 km) none of the models is in agreement with observations.
Observational evidence for variations of the acoustic cutoff frequency with height in the solar atmosphere

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ABSTRACT

Direct evidence for the existence of an acoustic cutoff frequency in the solar atmosphere is given by observations performed by using the HELioseismological Large Regions Interferometric DEvice (HELRLIDE) operating on the Vacuum Tower Telescope (VTT) located on Tenerife. The observational results demonstrate variations of the cutoff with atmospheric heights. The observed variations of the cutoff are compared to theoretical predictions made by using five acoustic cutoff frequencies that have been commonly used in helioseismology and asteroseismology. The comparison shows that none of the theoretical predictions is fully consistent with the observational data. The implication of this finding is far reaching as it urgently requires either major revisions of the existing methods of finding acoustic cutoff frequencies or developing new methods that would account much better for the physical picture underlying the concept of cutoff frequencies in inhomogeneous media.

Subject headings: Sun: atmosphere — hydrodynamics — waves
Future Work on Probing Solar Atmosphere

**Quiet Sun**

![Graphs showing phase differences between different wavelengths and harmonic degrees for the quiet Sun at various depths.]

- $\Delta z = 1400\text{km}$
- $\Delta z = 1300\text{km}$
- $\Delta z = 1100\text{km}$
- $\Delta z = 1000\text{km}$
- $\Delta z = 900\text{km}$
- $\Delta z = 800\text{km}$

**Pore**

![Graphs showing phase differences between different wavelengths and harmonic degrees for pores at various depths.]

**Sunspot**

![Graphs showing phase differences between different wavelengths and harmonic degrees for sunspots at various depths.]

Photosphere

Chromosphere
Sunspot Observations

• Three observing days following a stable sunspot
• 10 spectral lines

14.09.2015  15.09.2015  17.09.2015

Example here: Fe I 543.29 nm
# Observed Wavelengths

<table>
<thead>
<tr>
<th>Origin</th>
<th>Wavelength [nm]</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosphere</td>
<td>630.15</td>
<td>Fe I</td>
</tr>
<tr>
<td></td>
<td>543.29</td>
<td>Fe I</td>
</tr>
<tr>
<td></td>
<td>537.96</td>
<td>Fe I</td>
</tr>
<tr>
<td></td>
<td>709.04</td>
<td>Fe I</td>
</tr>
<tr>
<td></td>
<td>557.61</td>
<td>Fe I</td>
</tr>
<tr>
<td></td>
<td>617.33</td>
<td>Fe I</td>
</tr>
<tr>
<td></td>
<td>684.13</td>
<td>Fe I</td>
</tr>
<tr>
<td></td>
<td>684.27</td>
<td>Fe I</td>
</tr>
<tr>
<td>• Lower chromosphere</td>
<td>543.45</td>
<td>Fe I</td>
</tr>
<tr>
<td>• Upper chromosphere</td>
<td>589.00</td>
<td>Na D2</td>
</tr>
</tbody>
</table>
Study of structure of sunspots – e.g. Evershed flow, acoustic halos, ...
Acoustic Halos

- Velocity power is \(~60\%\) higher around magnetic activity compared to quiet Sun

- Power suppression in the center
Possible Origin of Halos

• Alterations of turbulence due to magnetic field (Brown 1992)

• Fast mode reflection leading to downward propagation of acoustic waves (Donea et al. 2000, Khomeko & Collados 2009)

• Trapping of high frequency waves in canopy of network (Kuridze, Zaqarashvili, Shergelashvili, Poedts 2009)

• Scattering of waves leads to redistribution of power from low degree to high-degree modes (Hanasoge 2008 & 2009)
Acoustic Halos

Frequency dependence:
Halos appear above the acoustic cutoff frequency

HMI data
HELLRIDE Observations of Acoustic Halos

- Same frequency range as before (~6 mHz)
- From photosphere to chromosphere

Very preliminary: halos appear different in different lines
Flare Observations

Power maps allow identifying the **dominant frequencies** of the triggered waves.
Understanding Sunquakes

A sunquake in 1998, caused by a flare

Waves propagate on and inside the Sun

(Kosovichev et al., Nature 1998)
HELLRIDE als as Demonstration Instrument for SPRING Desing Study

- Development of a concept for a ground-based network for continuous synoptic observations of the Sun
- Ambition:
  - High spatial (1"")
  - High temporal (~10 s) resolution
- Many wavelengths!
Further HELLRIDE Experiments 2016
ESO Laser Guidestar with VTT

Goal: Usage of adaptive optics for daylight observations in the thermal infrared at the ELT (future grant telescope with 40m-diameter mirror).
Expectations: Doubling of observing time
Further Application: Corona observations at DKIST.

Laser over Izana
Further HELLRIDE Experiments 2016
ESO Laser Guidestar with VTT

Laser beam with VTT Coelostat.
Further HELLRIDE Experiments 2016
Mercury transit on May 9, 2016

Several spectral lines to be observed with HELLRIDE (Na, K, ...) for investigation the composition of the Mercury atmosphere
Further HELLRIDE Experiments 2016
Mercury transit on May 9, 2016
Summary & Outlook

• HELLRIDE is an instrument for whole solar physics

• A lot of work needs to be done
  • E.g. data pre-processing to be further developed to remove image distortions
  • Inversions of spectral lines

• Desired (& Planned) Instrumental Upgrades
  • Broad-band channel
  • Polarimeter