LOFAR observations of the quiet Sun

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LOw Frequency ARray

LOFAR structure:
• Central core (Exloo, NL) 24 stations
• 14 remote Stations (NL)
• 9 (+4) International Stations

Frequency range:
• Low Band: 10 – 90 MHz
• High Band: 110 – 250 MHz

New setup: Software telescope
LOFAR: Simple antennae, LBA

Low Band antennae:

- Low frequencies: 30 – 80 MHz
- Simple dipoles
- 2 polarizations
LOFAR: Simple antennae, HBA

High Band antennae:

- High frequencies: 120 – 240 MHz
- 16 dipole together
- 2 polarizations
- In Styrofoam block, covered with foil
Antenna fields: Potsdam-Bornim

Completion of fields:

LBA: December 2009
HBA: May 2010
Data processing: Station level

Station container:

- Antennae signals are combined
- Digitized
- Frequency channels
- Combined to “station beam”
- Reduction of data rate to 4 Gbit/s

Data are send to central correlator in Groningen
Data processing: Groningen

Central correlator:

• “Cobalt” GPU cluster
• Data from all stations
• Interferometer
• Real-time processing
• Radio maps of the sky
• Further processing
• Long-term Archive

Enormous versatility and flexibility
Quiet Sun studies

Objectives:

• Structure of the solar corona
• Density profile in LOFAR’s low band range
• Corresponds to upper corona: \( \omega > \omega_p = \sqrt{\frac{Ne^2}{m_e e_0}} \)
• Transition into solar wind

Observations:

• Dataset from cycle 0
• Discrete frequencies with 5 MHz separation, 19 – 79 MHz
Quiet Sun observations

Solar observations:
• The Sun is very dynamic
• Short-lived features associated with radio bursts
  → Snapshot imaging, e.g. 1 s or 0.25 s cadence

Quiet Sun:
• Solar radio emission is fairly constant
• Take advantage of changing baselines in the uv plane
  → Aperture synthesis imaging
The Sun on 08 August 2013

SDO:
The Sun on 08 August 2013

NRH:
Solar corona

Image:
- 79 MHz
- 3 h
Solar corona

Image:
- 74 MHz
- 3 h
Solar corona

Image:
- 69 MHz
- 3 h
Solar corona

Image:
- 64 MHz
- 3 h
Solar corona

**Image:**
- 59 MHz
- 3 h
Solar corona

**Image:**
- 54 MHz
- 3 h
Solar corona

**Image:**
- 49 MHz
- 3 h
Solar corona

**Image:**
- 44 MHz
- 3 h
Solar corona

**Image:**
- 39 MHz
- 3 h
Solar corona

**Image:**
- 34 MHz
- 3 h
Solar corona

Image:
- 29 MHz
- 3 h
Solar corona

**Image:**
- 24 MHz
- 3 h
Observed intensity profiles

Profiles:

• Average over azimuth
• Normalized to image center

79 MHz
Observed intensity profiles

Profiles:

• Average over azimuth
• Normalized to image center

![Graph showing the intensity profile for 74 MHz]
Observed intensity profiles

Profiles:

• Average over azimuth

• Normalized to image center

![Graph of intensity profiles](image)
Observed intensity profiles

Profiles:

- Average over azimuth
- Normalized to image center
Observed intensity profiles

Profiles:

• Average over azimuth
• Normalized to image center

\[ \frac{i(\alpha)}{i(\alpha=0)} \]

\[ \alpha \text{ ['}'] \]

59 MHz
Observed intensity profiles

Profiles:

• Average over azimuth

• Normalized to image center

![Graph showing the intensity profile with a peak at 54 MHz.](image)
Observed intensity profiles

Profiles:

- Average over azimuth
- Normalized to image center

49 MHz
Observed intensity profiles

Profiles:

- Average over azimuth
- Normalized to image center
Observed intensity profiles

Profiles:

- Average over azimuth
- Normalized to image center

Graph showing intensity profiles at 39 MHz.
Observed intensity profiles

Profiles:

• Average over azimuth

• Normalized to image center
Observed intensity profiles

Profiles:
- Average over azimuth
- Normalized to image center

![Graph showing observed intensity profiles with a peak at 29 MHz.](image)
Observed intensity profiles

Profiles:

- Average over azimuth
- Normalized to image center

![Graph showing observed intensity profiles](image)

24 MHz
Coronal intensity profiles

Radio wave ray path:
- $n = (1 - \omega_p^2 / \omega^2)^{1/2} = 1$ in IP space
- $n \to 0$ near plasma freq.
- Total reflectance

Free-free emission:
- Proportional to $N^2$
- Line-of-sight integral
Simple model

Assumptions:
• Intensity dominated by highest density
• Snell’s law leads to
\[
\sin(\theta) = n_{\text{source}}
\]

Resulting intensity model:
\[
\log \left( \frac{i(\alpha)}{i(\alpha = 0)} \right) \propto \left( \frac{\alpha \times 1\text{AU}}{R_\omega} \right)^2
\]
Resulting solar radii $r = R\omega$
Resulting solar radii $r = R\omega$

![Graph of Sun_74MHz_3h_profile showing the relationship between $r$ (solar radii) and $\alpha$ (in minutes)].
Resulting solar radii $r = R \omega$
Resulting solar radii $r = R\omega$

Sun_64MHz_3h_profile

$r$ [solar radii] vs. $\alpha$ ["]

Graph showing the relationship between $r$ and $\alpha$ with two lines:
- A solid line representing $r$.
- A dotted line indicating $R\omega$.

October 2015
12th Potsdam Thinkshop – The Dynamic Sun
Resulting solar radii $r = R\omega$
Resulting solar radii $r = R\omega$
Resulting solar radii $r = R\omega$

Sun_49MHz_3h_profile

$r$ [solar radii] vs. $\alpha$ ["]
Resulting solar radii $r = R\omega$

![Graph showing solar radii vs. alpha](image_url)
Resulting solar radii $r = R\omega$

Sun_39MHz_3h_profile

$r$ [solar radii] vs. $\alpha$ ["]

$0 \leq \alpha \leq 2500$

$1 \leq r \leq 4$
Resulting solar radii $r = R\omega$
Resulting solar radii \( r = R\omega \)
Solar radius from LOFAR data

Fit with density model:

• Hydrostatic model
  (Mann et al., 1999)

• Model parameters:
  - $T = 1.3 \cdot 10^6$ K
  - $N_0 = 6.0 \cdot 10^{15}$ m$^{-3}$

LOFAR imaging provides coronal density models
The model is too simple…

Local maxima for small $\alpha$

**Increasing $\alpha$:**

- Curvature of ray path leads to longer path length
- Line-of-sight integral yields higher values
- Absorption of radio waves in the corona also has to be considered
Coronal parameters:

- $T = 1.4 \cdot 10^6$ K
- $R \omega = 2 R_{\text{Sun}}$
- $f = 60$ MHz
- beam size: 150”
Next step: Inversion problem

Multiple dependencies:
- Mainly $R\omega$, which is sought for
- But also coronal temperature
- Search for best fit
Summary and conclusions

Quiet Sun observations:

• Improve uv coverage by aperture synthesis
• Example: 8 August 2013, 3 h observation time

Analysis of solar images:

• Refraction is important in the corona
• Simple wave propagation model leads to a surprisingly good density profile
• More accurate approach is still necessary