The RPW Low Frequency Receiver (LFR) on Solar Orbiter: in-situ LF electric and magnetic field measurements of the solar wind expansion

- LFR science objectives
- Instrument description and data products
- Examples of first observations during the commissioning phase (Solar Obiter has been launched successfully February 10, 2020)

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LFR Science Objectives

- Study the **electromagnetic/electrostatic activity** in the extended corona and the near-Sun solar wind, **from near DC to 10 kHz**.

- Will **cover the electron gyrofrequency** and most of the **Doppler-shifted frequencies** of the low frequency/small scale plasma waves, structures & turbulence.

  - Kinetic or inertial Alfven waves
  - Ion cyclotron waves
  - Ion acoustic waves
  - Magnetosonic or whistler mode waves
  - ...

  ➔ Their characterization and the determination of their respective role in heating and accelerating the solar wind, **during its expansion**, is the main scientific issue addressed by LFR.

  ➔ Role of the low frequency/small scale plasma waves & structures associated to solar wind disturbances, **e.g. interplanetary shocks**, **current sheets**...
RPW Instrument Overview

Will allow the characterization of the electric and magnetic fields associated to the dynamics of the near-Sun heliosphere from near DC up to 20 MHz

Low Frequency Receiver

Electric Antennas (ANT)
- V₁
- V₂
- V₃
- V₄
- V₅
- V₆
- V₇
- V₈

Search Coil Magnetometer (SCM)
- B₁LF
- B₂LF
- B₃LF
- B₁HF
- B₂HF
- B₃HF

Main Electronic Box (MEB)
- Bias Unit
  - Floating voltage driver
- TNR-HFR
  - Auto & cross-spectra (4kHz-20MHz)
- TDS
  - Waveform @ 500kS/s + LFR Redundancy
- LFR
  - Waveform up to 25kS/s + Auto & cross-spectra + k-vector (~DC-10kHz)

LVPS-PDU
- 28 V from S/C
- 3.3V, 2.5V, 5V, +/-12V

RPW-DPU
- Nom. SpW to/from S/C
- Red. SpW to/from S/C
When BIAS is off LFR electric field measurements can be performed from the ANT HF preamps
LFR Decimation and Processing Strategy

8 ADCs @ 98 304 Hz
decimation down to 24 576 Hz (F0)

8 ADCs ideally

14 bits

FFT

Spectral matrices (ASM)

Basic parameters (BP)

256 Hz

4 096 Hz

FFT

Spectral matrices (ASM)

Basic parameters (BP)

16 Hz

256 Hz

FFT

Spectral matrices (ASM)

Basic parameters (BP)

16 Hz

256 Hz

FFT

Spectral matrices (ASM)

Basic parameters (BP)

16 Hz

256 Hz

FFT

Spectral matrices (ASM)

Basic parameters (BP)
### BIAS 5 outputs in the different modes

<table>
<thead>
<tr>
<th>MODE</th>
<th>V1_{BIAS}</th>
<th>V2_{BIAS}</th>
<th>V3_{BIAS}</th>
<th>V4_{BIAS}</th>
<th>V5_{BIAS}</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>V1_{DC}</td>
<td>V12_{DC}/V13_{DC}</td>
<td>V23_{DC}</td>
<td>V12_{AC}/V13_{AC}</td>
<td>V23_{AC}</td>
<td>Standard operation</td>
</tr>
<tr>
<td>1</td>
<td>V2_{DC}</td>
<td>V3_{DC}</td>
<td>V23_{DC}</td>
<td>V12_{AC}/V13_{AC}</td>
<td>V23_{AC}</td>
<td>Operation if antenna 1 fails</td>
</tr>
<tr>
<td>2</td>
<td>V1_{DC}</td>
<td>V3_{DC}</td>
<td>V13_{DC}/V12_{DC}</td>
<td>V13_{AC}/V12_{AC}</td>
<td>V23_{AC}</td>
<td>Operation if antenna 2 fails</td>
</tr>
<tr>
<td>3</td>
<td>V1_{DC}</td>
<td>V2_{DC}</td>
<td>V12_{DC}/V13_{DC}</td>
<td>V12_{AC}/V13_{AC}</td>
<td>V23_{AC}</td>
<td>Operation if antenna 3 fails</td>
</tr>
<tr>
<td>4</td>
<td>V1_{DC}</td>
<td>V2_{DC}</td>
<td>V3_{DC}</td>
<td>V12_{AC}/V13_{AC}</td>
<td>V23_{AC}</td>
<td>Calibration mode 0</td>
</tr>
<tr>
<td>5</td>
<td>2.5V Ref</td>
<td>2.5V Ref</td>
<td>2.5V Ref</td>
<td>V12_{AC}/V13_{AC}</td>
<td>V23_{AC}</td>
<td>Calibration mode 1</td>
</tr>
<tr>
<td>6</td>
<td>GND</td>
<td>GND</td>
<td>GND</td>
<td>V12_{AC}/V13_{AC}</td>
<td>V23_{AC}</td>
<td>Calibration mode 2</td>
</tr>
</tbody>
</table>
BIAS 5 outputs and the LFR R-parameters

DC $V$ (G=1/15)

DC $dV \sim E$ (G=1)

AC $dV \sim E$ (G=5 or 100, cutoff~8Hz)
LFR current set of Basic Parameters

"Instantaneous" 5 x 5 spectral matrix (256-point FFT)

\[
\begin{bmatrix}
B_1 \ast B_1 & B_1 \ast B_2 & B_1 \ast B_3 & B_1 \ast E_1 & B_1 \ast E_2 \\
cc & B_2 \ast B_2 & B_2 \ast B_3 & B_2 \ast E_1 & B_2 \ast E_2 \\
cc & cc & B_3 \ast B_3 & B_3 \ast E_1 & B_3 \ast E_2 \\
cc & cc & cc & E_1 \ast E_1 & E_1 \ast E_2 \\
cc & cc & cc & cc & E_2 \ast E_2
\end{bmatrix}
\]

Time Averaged Spectral Matrix (ASM)

\[
ASM \left( \omega_j^{(m)} \right) = \frac{1}{N_{SM}^{(m)}} \sum_{k=1}^{N_{SM}^{(m)}} SM_k \left( \omega_j^{(m)} \right) = \langle SM \rangle_{time}
\]

Frequency average ...

\[
S \left( \omega_j^{(m)} \right) = \langle ASM \rangle_{frequency}
\]

... before computations of the BPs (i.e. wave parameters)

Mono-k assumption:

- (Means, JGR, 1972)
- (Samson & Olson, GJRA, 1980)

\[
n \times E = \frac{\omega}{k} B
\]

BP1 set 1: Power spectrum of the magnetic field \((B)\)
BP1 set 2: Power spectrum of the electric field \((E)\)
BP1 set 3: Wave normal vector (from \(B\))
BP1 set 4: Wave ellipticity estimator (from \(B\))
BP1 set 5: Wave planarity estimator (from \(B\))
BP1 set 6: \(X_{SO}\) (radial)-component of the Poynting vector
BP1 set 7: Phase velocity estimator

\[
\frac{S_{ij}}{\sqrt{S_{ii} S_{jj}}}
\]

BP2 set 1: Autocorrelations
BP2 set 2: Normalized cross correlations
LFR spectral frequencies

(1) Depending on the frequency channel, selection of 96, 104 or 88 consecutive frequency bins among 128 ($N_{\text{FFT}} = 256$) of the time averaged spectral matrices.

(2) Then, the ASMs are averaged over packets of $N_{\text{freq}}$ (8 or 4) consecutive bins:

\[ \Delta f^{(m)} = \frac{f_m}{N_{\text{FFT}}} \times N_{\text{freq}} \]

Where:
- $f_3 = 16$ Hz => waveform [DC, 8Hz] \[ f_3 / 2.5 = 6.4 \text{ Hz} \]
- $f_2 = 256$ Hz => 12 frequencies [6.5Hz, 102.5Hz] \[ \Delta f^{(2)} = 8 \text{ Hz} \; \; f_2 / 2.5 = 102.4 \text{ Hz} \]
- $f_1 = 4096$ Hz => 13 frequencies [88Hz, 1752Hz] \[ \Delta f^{(1)} = 128 \text{ Hz} \; \; f_1 / 2.5 = 1638.4 \text{ Hz} \]
- $f_0 = 24576$ Hz => 11 frequencies [1584Hz, 10032Hz] \[ \Delta f^{(0)} = 768 \text{ Hz} \; \; f_0 / 2.5 = 9830.4 \text{ Hz} \]
**LFR Normal Mode (1)**

**Basic Parameters**

- **Sampling frequency**
  - $f_0 = 24576 \text{ Hz}$ ...
  - $f_1 = 4096 \text{ Hz}$ ...
  - $f_2 = 256 \text{ Hz}$ ...
  - $f_3 = 16 \text{ Hz}$ ...

- **Continuous WF**
  - $T_{BP_{1,0}} = 4 \text{ s}$ ...
  - $T_{BP_{1,1}} = 4 \text{ s}$ ...
  - $T_{BP_{1,2}} = 4 \text{ s}$ ...

- **Time**
  - $4 \text{ s}$
  - $20 \text{ s}$
LFR Normal Mode (2)

Wave Forms & Averaged Spectral Matrices

- Sampling frequency
  - $f_0 = 24576$ Hz
  - $f_1 = 4096$ Hz
  - $f_2 = 256$ Hz
  - $f_3 = 16$ Hz

- Time intervals:
  - $T_{WF} = 300$ s
  - $T_{ASM} = 3600$ s

- Spectral Matrices:
  - BP1
  - ASM
  - BP1
  - WF

- Number of Spectral Matrices (SMs):
  - 4 SMs
  - 64 SMs
  - 384 SMs

- Sampling intervals:
  - 8 s
  - 1/2 s
  - 1/12 s

- Continuous Waveform (WF)
LFR Selected Burst Mode 1

- $f_0 = 24576$ Hz
- $f_l = 4096$ Hz
- $T_{BP1,0} = 0.25$ s
- Continuous WF

Sampling frequency

24 SMs

BP1

BP1 & BP2

BP1

BP1

BP1 & BP2

BP1

24 SMs

24 SMs

24 SMs

24 SMs

24 SMs

24 SMs

24 SMs

24 SMs

0.25 s

1 s
LFR Selected Burst Mode 2 & BURST mode

$f_0 = 24576$ Hz ...

$f_1 = 4096$ Hz ...

$f_2 = 256$ Hz ...

$T_{BPL_0} = 1$ s ...

$T_{BPL_1} = 1$ s ...

continuous WF ...

$1$ s

$5$ s

sampling frequency

time

16 SMs 16 SMs 16 SMs 16 SMs 16 SMs 16 SMs 16 SMs 16 SMs
Electromagnetic wave event at frequencies ~ 5-25Hz: Whistler waves?

27/02

ASM from SWF @F2

full day

BP1 from SWF @F2

2020
Electromagnetic wave event
at frequencies ~ 5-25Hz: Whistler waves?

27/02
ASM from SWF @F2

2020
BP1 from SWF @F2

zoom
Electromagnetic wave event at frequencies ~ 5-25Hz: Whistler waves?

27/02

onboard BP2 @F2

zoom

onboard BP1 @F2

2020
Electromagnetic wave event at frequencies ~ 5-25Hz: Whistler waves?

27/02

- Looking at time \((2020, 2, 27, 5, 50, 0)\) and frequency of 18 Hz

- One observes a normal wave vector expressed in the SCM reference frame:

  \[
  \mathbf{n} = [0.10533082, -0.57960344, 0.80806266]_{\text{SCM}}
  \]

- Which expressed in the Spacecraft Reference Frame gives:

  \[
  \mathbf{n} = [0.82970735, 0.55613863, 0.04791182]_{\text{SRF}}
  \]

- From first exchange with the MAG team this vector would make an angle of \(~1-2°\) with the DC magnetic field

- Together with the fact that the local electron gyrofrequency would be \(~100\) Hz, it is likely that the observed waves are whistler waves
Short plasma perturbation possibly seen by PAS at ~15:30 (Continuous WF)

15/04  CWF @F3 = 16Hz  =>  PSD

E1 = V12_DC

E2 = V23_DC

V = V1_DC
Short plasma perturbation possibly seen by PAS at ~15:30 (Snapshot WF)

For all SWFs one has AC channels:

E1 = V12_AC
E2 = V23_AC

15/04/2020
Conclusion / Summary

✔ LFR is one of the subsystems of the Solar Orbiter Radio and Plasma Waves (RPW) instrument.

✔ Performs the on-board digital processing of the low frequency electromagnetic field & wave data (1V, 2E, 3B), measured in the extended corona and the near-Sun solar wind.

✔ Frequency range of investigation: $\sim 0.1 \text{ Hz} < f < 10 \text{ kHz}$.

[ microphysics of the SW (heating, turbulence, VDF, …) ]

✔ Combines different output data: from low-level (WF) to high-level (ASM & BP) processed data.

[ assessment of $k$ => dedopplerization possible ]

✔ Allows to increase the scientific return for a given telemetry by implementing different strategies for analyzing and transmitting the data.

✔ These first observations during the near-Earth commissioning phase are encouraging and show a good consistency of the data.