Ongoing Radio Space-Weather Science Studies Using the LOw Frequency ARray (LOFAR) and Three-Dimensional (3-D) Modelling Techniques

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Brief Introduction to the Multi-Site Interplanetary Scintillation (IPS) Experiment (Radio Heliospheric Imaging)

UCSD 3-D Computer Assisted Tomography

IPS Developments with LOFAR

Heliospheric Faraday Rotation (FR) Determination and Verification Developments with LOFAR

Radio Heliospheric Modelling Developments: MHD and 3-D Tomography

HELCATS WP7 – T7.1

Brief Summary
Brief Introduction to the Multi-Site Interplanetary Scintillation (IPS) Experiment (Radio Heliospheric Imaging)

Multi-Site IPS

Radio signals received at each site are very similar except for a small time-lag.

The cross-correlation function can be used to infer the solar wind velocity(s) across the line of sight (LOS).

IPS is most-sensitive at and around the P-Point of the LOS to the Sun and is only sensitive to the component of flow that is perpendicular to the LOS; it is variation in intensity of astronomical radio sources on timescales of ~0.1s to ~10s that is observed.
IPS (g-level/density)

Density Turbulence

- Scintillation index, m, is a measure of level of turbulence
- Normalized Scintillation index, \( g = m(R) / \langle m(R) \rangle \)

- \( g > 1 \rightarrow \) enhancement in \( \delta Ne \)
- \( g \approx 1 \rightarrow \) ambient level of \( \delta Ne \)
- \( g < 1 \rightarrow \) rarefaction in \( \delta Ne \)

(Courtesy of Periasamy K. Manoharan)

Scintillation enhancement with respect to the ambient wind identifies the presence of a region of increased turbulence/density and possible CME along the line-of-sight to the radio source.
UCSD 3-D Computer Assisted Tomography

Heliospheric C.A.T. Analyses: example line-of-sight distribution for each sky location to form the source surface of the 3D reconstruction.
IPS Developments with LOFAR
The LOw Frequency ARray (LOFAR)

LOFAR High-Band observes 110 MHz to ~250 MHz and LOFAR Low-Band observes ~10 MHz to ~90 MHz. Map (below) of operational (green) and upcoming (yellow) LOFAR stations across Europe. Pathfinder to the Square Kilometre Array (SKA).
IPS with LOFAR: The First CME Detection


STEREO COR2-B CME Observations

- STEREO COR2 imagery of the CME seen to be going to the South-West from this viewpoint, i.e. South and Mars/Earth-ward (to the right of each image). Left: COR2-B on 14/11/11 at 21:54:59UT and Right: COR2-B on 14/11/11 at 23:54:59UT.
STEREO-A HI imagery shows the Northern-most flank of the CME (inside the ellipse) crossing over the line of sight (*) to the radio source at the same time as the LOFAR observation of IPS.
The First CME with LOFAR…

- Observations of J1256-057 (3C279) detecting a CME with LOFAR on 17 November 2011 and (briefly) its comparison so far with other remote-sensing observations and modelling.

Fully-consistent Results!

<table>
<thead>
<tr>
<th>Model Used</th>
<th>Best Fit in Radial Velocity (km s(^{-1}))</th>
<th>Error in Radial Velocity (km s(^{-1}))</th>
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</table>
Our Second Coronal Mass Ejection (CME) with LOFAR...

- Investigations are ongoing.
LOFAR Observations of IPS on 03 June 2013

20130603 : 07:50:00 : 3C147 : F06-U608

108.0 Rs at 45.9° Lat.

W-Limb
442 km s⁻¹

E-Limb
496 km s⁻¹ behind CME

146.1 Rs at 28.1° Lat.

W-Limb
522 km s⁻¹

20130603 : 08:40:00 : 3C98.2 : D605-U608

109.5 Rs at 33.0° Lat.

W-Limb
585 km s⁻¹ behind CME

20130603 : 09:26:00 : 3C67 : D605-U608

115.5 Rs at 26.3° Lat.

W-Limb
522 km s⁻¹ behind CME
Heliospheric Faraday Rotation (FR) Determination and Verification Developments with LOFAR
LOFAR heliospheric Faraday rotation (FR) observations to date are as follows…

Crab Nebula/3C144 (15 minutes of FR each time, plus 60 minutes of IPS on 02 July 2014 only):

✶ 02 July 2014 (10:40UT) – P-Point of 69 Rs, 16.2°, Heliocentric Lat. -4.4°.
✶ 11 July 2014 (10:00UT)) – P-Point of 104 Rs, 24.8°, Heliocentric Lat. -2.8°.
✶ 22 July 2014 (12:00UT) – P-Point of 146 Rs, 35.3°, Heliocentric Lat. -1.8°.

PSR J1022+1001:

✶ 13 August 2014 (13:00UT) – P-Point of 43.6 Rs, 11.6°, and an extended observation of 140 minutes split into 20-minute intervals yet to be fully investigated in terms of the context of the observation.
Combined IPS (60 minutes) and FR (15 minutes) Observations of the Crab Nebula (3C144/PSR B0531+21/PSR J0534+2200) a few Degrees North of the Ecliptic on the Sky Using LOFAR International Stations Plus the Core, Respectively, on 02 July 2014 Commencing at 10:40UT

- Work in progress – publications soon to be in preparation.
Density at Mercury from the UCSD tomography (using STELab IPS and Wind data) with the $1/R^2$ put back in (since the below image is normalised to 1 AU) provides $n = 31.9 \text{ cm}^{-3}$ (low).

Left-hand Image courtesy of the STEREO Science Center – Where is STEREO? (http://stereo-ssc.nascom.nasa.gov/cgi-bin/make_where gif)
MESSENGER data (courtesy of Dan Gershman, and Jim Raines) for context verification show a velocity \( \sim 400 \text{ km s}^{-1} \), but density information is, unfortunately, not available for this period here.
ENLIL MHD modelling using the UCSD IPS tomography as input to drive the model (IPS-driven ENLIL) as opposed to using the traditional WSA as input.

Very-preliminary results suggest this provides an improved background solar-wind environment in the MHD modelling.
LOFAR Observing Characteristics

- Central observing frequency: 149.609375 MHz ($\lambda \sim 2$ m).
- Observing bandwidth: 78.125 MHz.
- IPS analyses over 15-minute integration times (10:40UT-10:55UT) – only the first 15 minutes used here to match the time of the pulsar observation.

- Pulsar observation analysed by folding the whole data set to obtain the polarised pulse profiles and then these are modelled using an RM fitting routine.
- RM is thus calculated on the integrated 15-minute observation.
- Implications for Space-Weather forecasting at the Earth.

- LOFAR observations of IPS using the international stations yielded a velocity of around 285 km s$^{-1}$. 
Preliminary RM and FR (back-of-envelope calculations)

- The observed RM was: \(-42.0571 \pm 0.02\) rad m\(^2\).
- The expected RM of the Crab (at this frequency range) is expected to be: \(-45.50848\) rad m\(^2\) (based on anti-solar observations taken during February 2014).
- The modelled ionospheric RM was: \(3.11127 \pm 0.12935\) rad m\(^2\).
- The remaining RM, assumed due to be from the slow solar wind, is: \(-0.34011 \pm 0.15589\) rad m\(^2\), i.e. \(-0.34 \pm 0.16\) rad m\(^2\) (high?).
- Thus, using \(FR = \lambda^2 RM\) (and just using the central frequency), the resulting FR is roughly: \(-1.36\) rad.
- UCSD model RM result is \(~-0.3\)° m\(^2\) (factor \(~1/57\) of LOFAR)?
- Simplification: \(RM = 0.002 \times n_e [cm^{-3}] \times B [nT] \times L [AU] \times 2\)(° m\(^2\))
  where \(L\) is the contributing integration length along line of sight
  \(= 0.002 \times 80 \times -150 \times 0.4 = -9.6° m^2 (-0.168 rad m^2)\) (high?).
Radio Heliospheric Modelling Developments: MHD and 3-D Tomography
Inclusion of *in-situ* data into the UCSD Tomography and using the Tomography Source Surface to Drive MHD Models

Model results by D. Odstrcil (GMU) ENLIL; C.-C. Wu (NRL) HAF-3DMHD; and T. Kim (University of Alabama) MS-FLUXSS.

Model Boundaries: UCSD (Kinematic) at 15 $R_S$, ENLIL (MHD) at 21.5 $R_S$, HAF-3DMHD at 40 $R_S$, and MS-FLUXSS (MHD) at ~54 $R_S$. 
Note, however, that the UCSD kinematic model is both iterative and data-assimilative – these MHD models are not at present.

The IPS/\textit{in-situ} kinematic best-fit solution is the one back-projected to the necessary source-surface distance as required in each MHD model.
Propagation of Magnetic Fields to 1AU

- Other publications in preparation.
And Magnetic-Field Developments (1)

- With the ability to propagate out ambient magnetic fields from the Sun using the CSSS model, and obtain a reconstruction of $B_n$ (as well as $B_t$ and $B_r$ as previously been obtained) at the Earth, we can compare with *in-situ* data as well as prepare for potential forecasting of RTN magnetic fields near the Earth. This should provide improved inputs for ENLIL and other MHD modelling. In addition, $B_z$ can now be determined at Earth using the UCSD tomography.
And Magnetic-Field Developments (2)
And Magnetic-Field Developments (3)

(a) 2015/01/04 03 UT

(b) correlation 0.599

(c) Estimated Planetary K index (3 hour data)
And Magnetic-Field Developments (4)

(a) ACE and CSSS Field

(b) Correlation 0.357

(c) B normal field

Resolution:
Tomo = 0.5 day
ACE = 0.5 day
HELCATS WP7 – T7.1
HELCATS WP7:
Assessing the complementary nature of radio measurements of solar wind transients – Interplanetary Scintillation (IPS) (T7.1)
Task 7.1 Objectives

- Started at month 10 (February 2015) for 19.5 months equivalent effort between months 10 and 36.
- Development of a catalogue of CMEs observed using IPS during the STEREO mission time line and comparison with white-/visible-light observations where geometry allows.
- As above but for SIRs/CIRs.
- Requires HI catalogues with non-changing event IDs.
- Primary aspect: EISCAT/ESR and LOFAR individual observations used primarily in conjunction with the HI catalogues.
- Secondary aspect: where feasible and other IPS data are available (e.g. from STELab in Japan), use UCSD tomography and IPS-driven ENLIL on a case-by-case basis for a fuller comparison.
- Explore how IPS can aid to the investigations of interacting CMEs seen in the STEREO HIs.
Brief Summary
Summary

- IPS is an extremely powerful and unique technique for making heliospheric imaging observations of the inner heliosphere.

- Outlook to constraining ENLIL with improved radio heliospheric imaging which might include the background-propagated magnetic-field components: $B_x$, $B_y$, and $B_z$...

- IPS/FR on LOFAR is progressing very well with good solar wind/CME results, and preliminary heliospheric RM/FR determination – but much more work to be done and some help needed???

- The UCSD 3-D tomography should provide an excellent platform for obtaining 3-D magnetic-field values from combined radio observations of FR and IPS and integrating them into the current IPS, closed-loop fields, and L$_1$ *in-situ* data (and input to ENLIL).