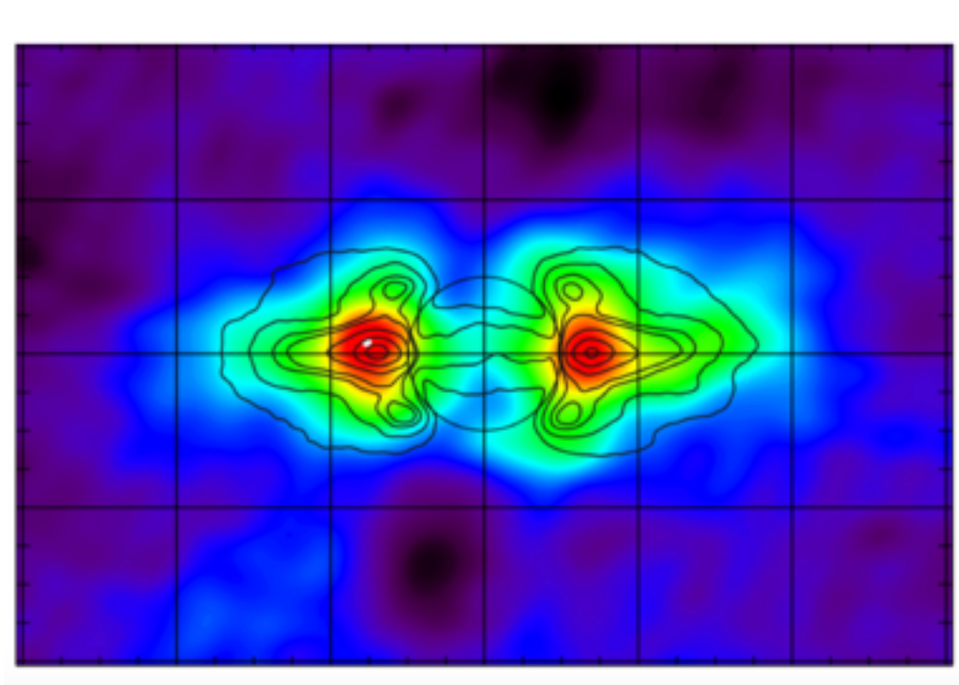
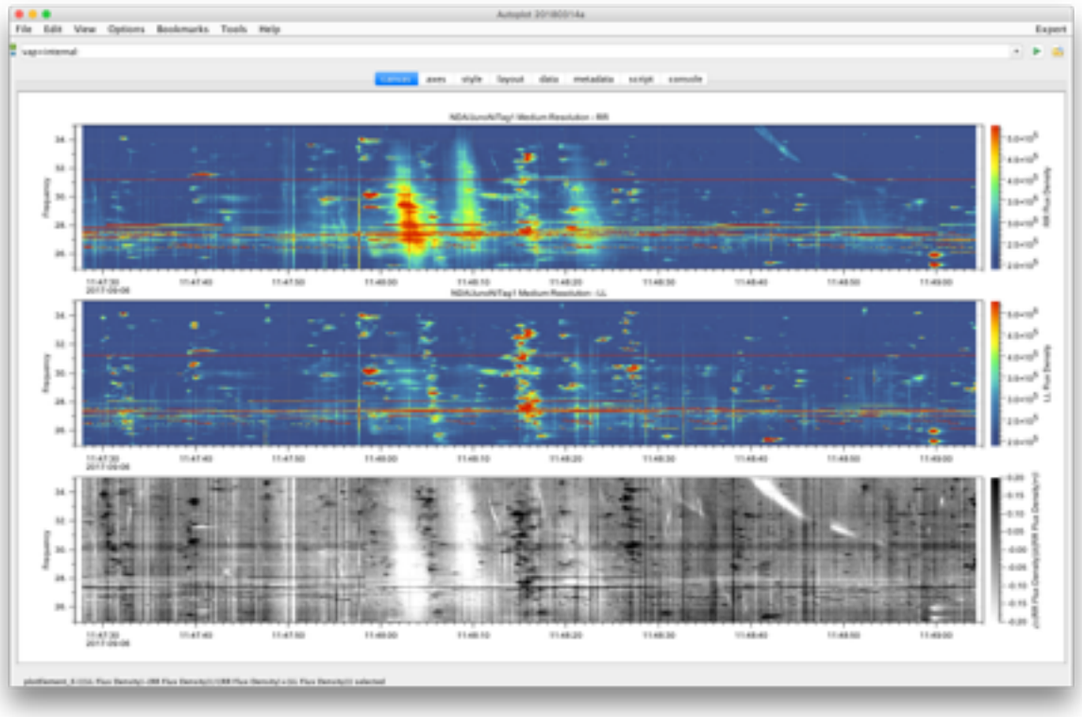
# Low Frequency Radio Astronomy and the VO

B. Cecconi
A. Loh, E. Tremou, F. Bonnarel, (et al.)



Girard et al, 2014
LOFAR

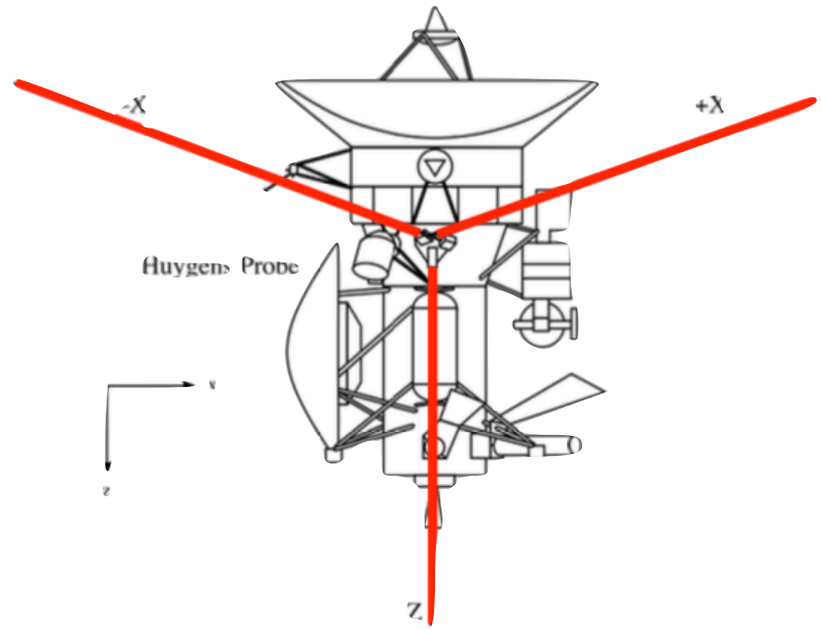


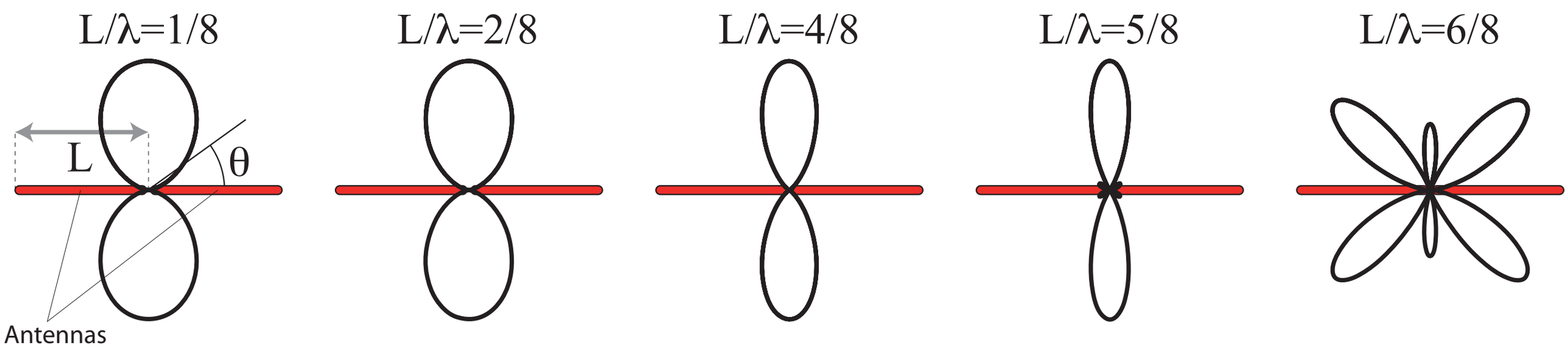
# Radio Astronomy: what do we measure

- **Single antenna** (in space): no directivity,
  => spectro-temporal information.

- **Phased array**: coherent sum, beam forming.
  => spectro-temporal information within beam.

- **Interferometer**: phased correlations.
  => spectro-temporal + spatial frequencies



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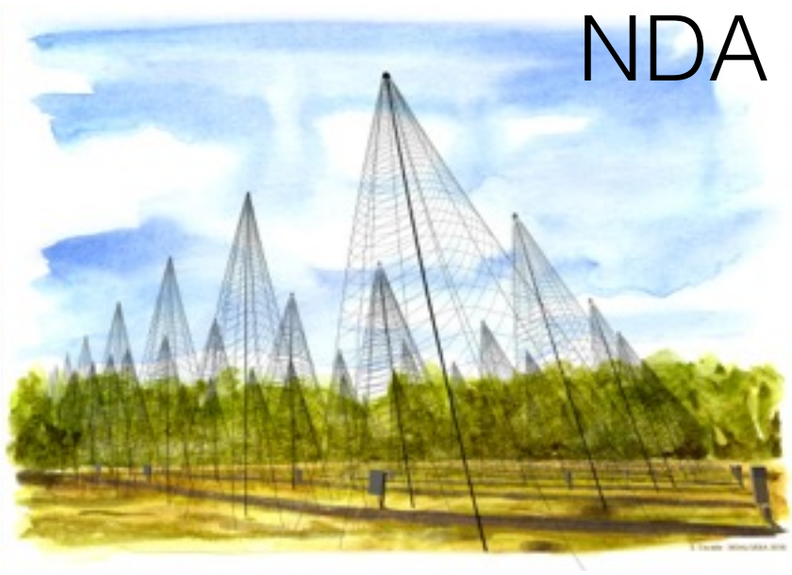


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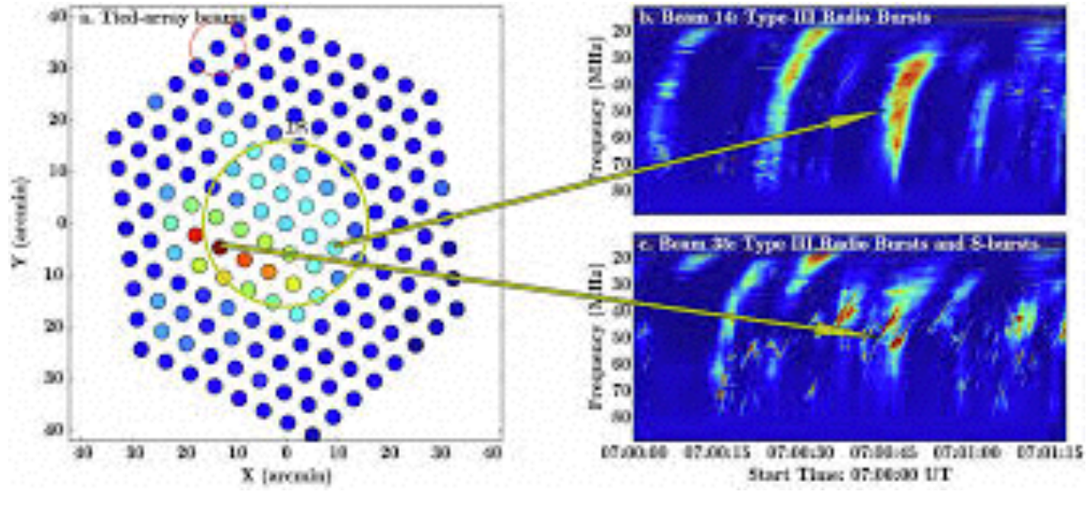


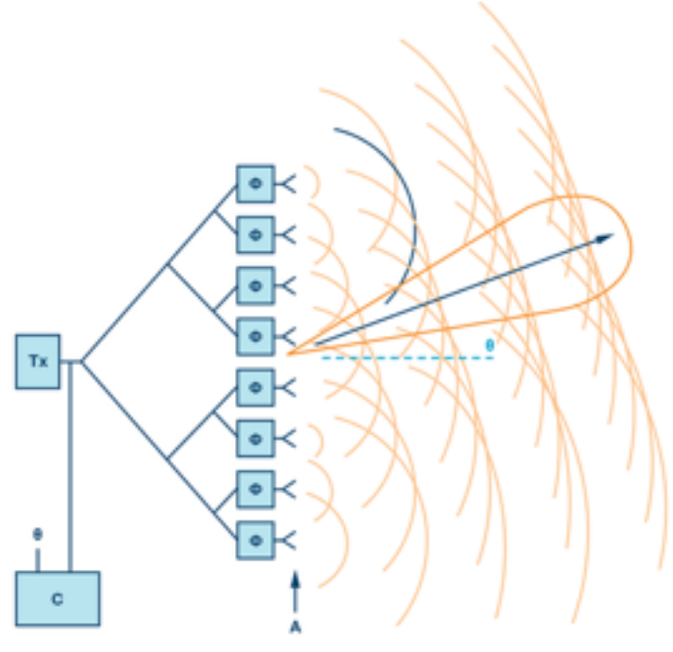

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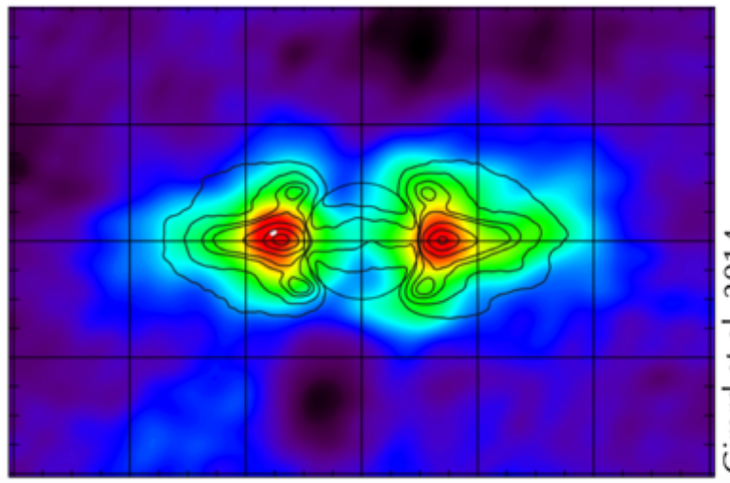
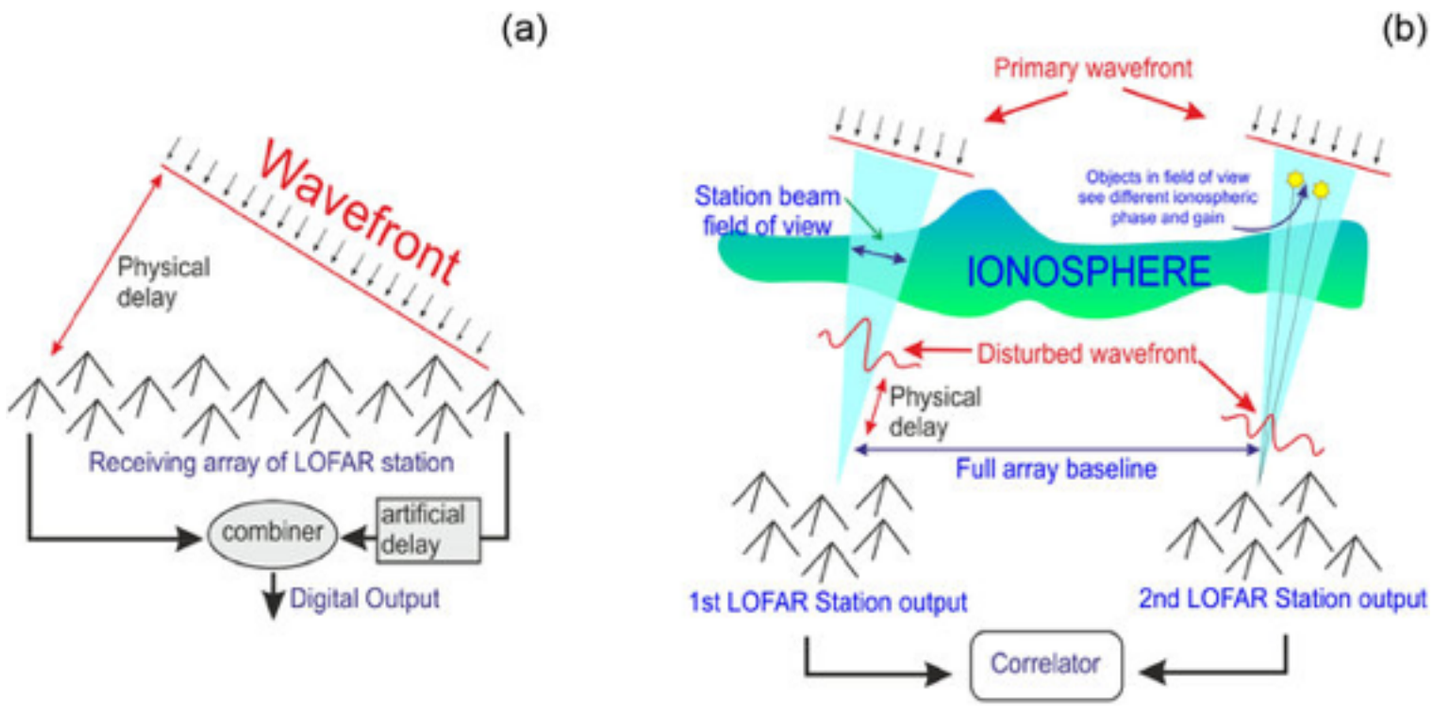
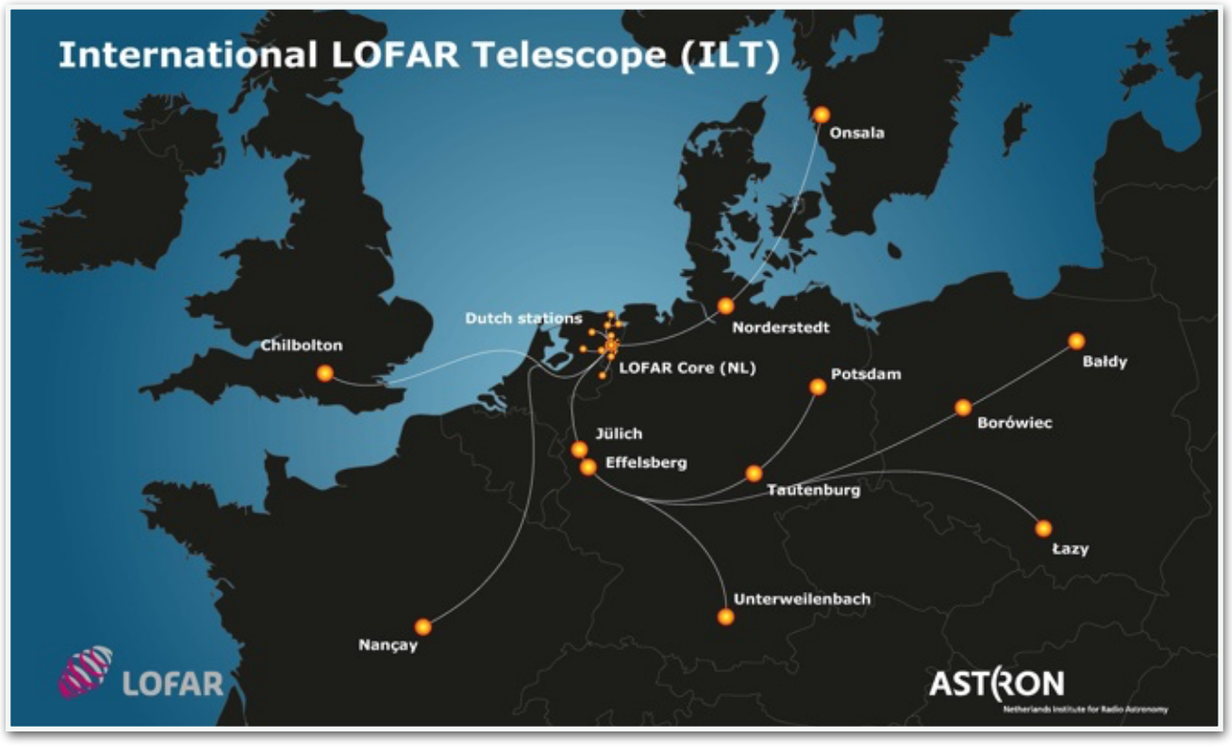


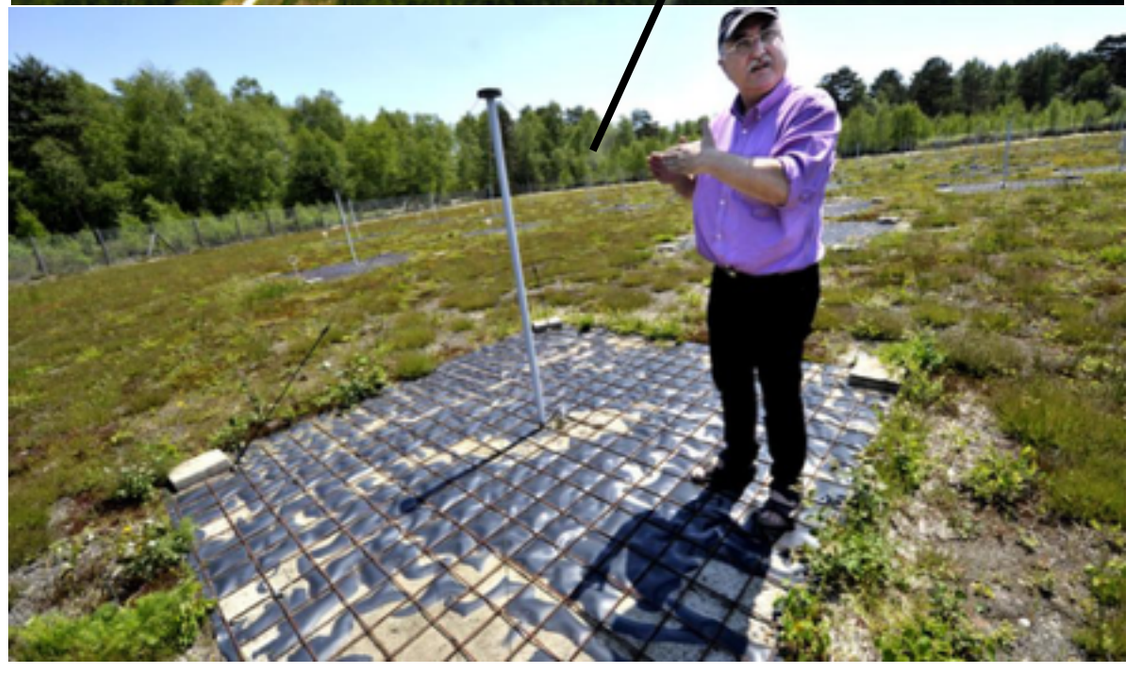



# Radioastronomy from ground

- Low frequencies from ground:
  - Interferometers
  - Phased arrays

- Example: LOFAR (Low Frequency Array)



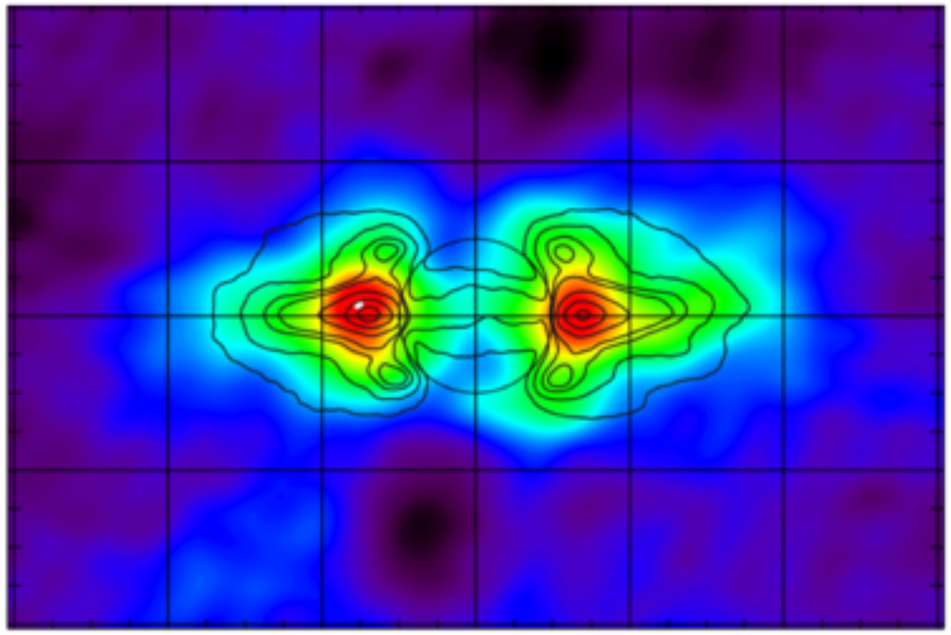


# Radioastronomy from ground

- Sensors:
  - phased array: NDA (France), UTR2 (Ukraine), each LOFAR station (Europe), LWA1 (USA), each MWA antenna (Australia)…
  - interferometer: LOFAR, MWA

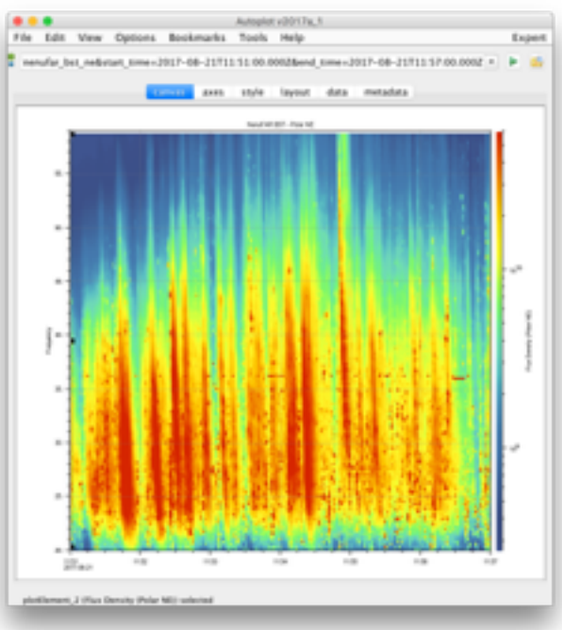
- Measurements: spectra, spectrograms of intensity, polarization, imaging…

Jovian Radiation Belts at ~150 MHz



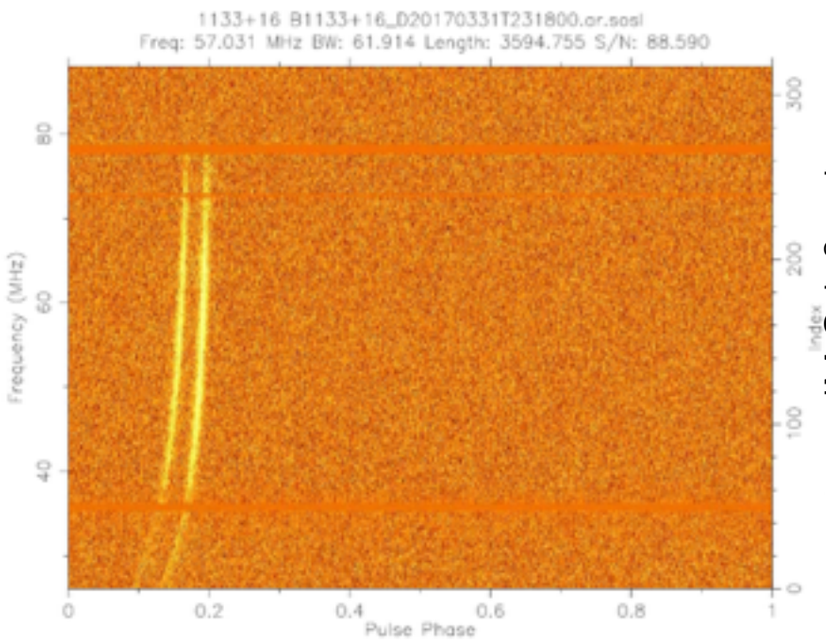
Girard et al, 2014
LOFAR

Solar Radio Storm



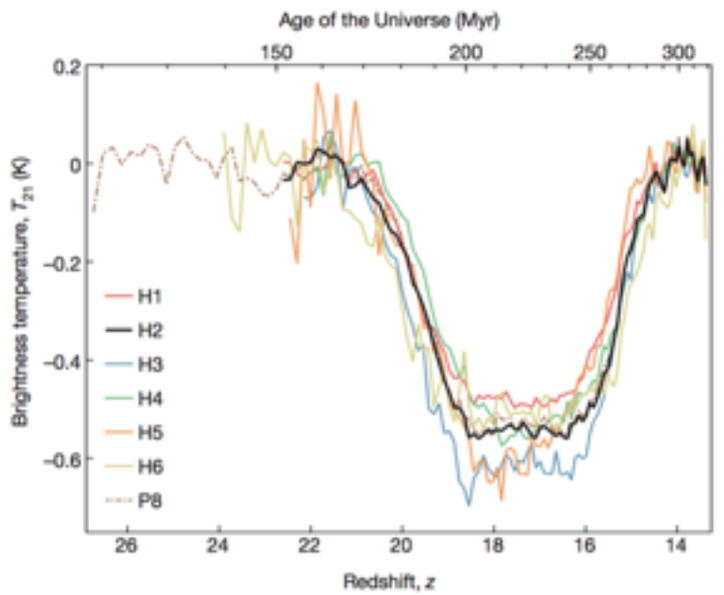
NenuFAR commissioning

B1133+16 pulsar phase spectrogram




courtesy JM Grießmeier

Cosmic Dawn signal

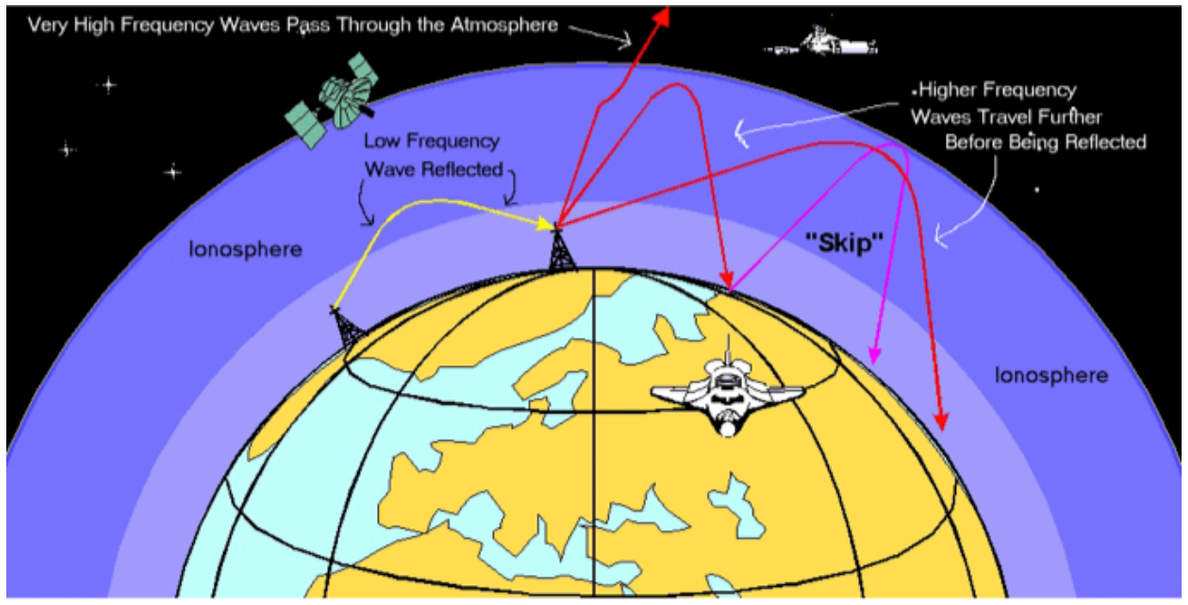



Bowman et al, 2018

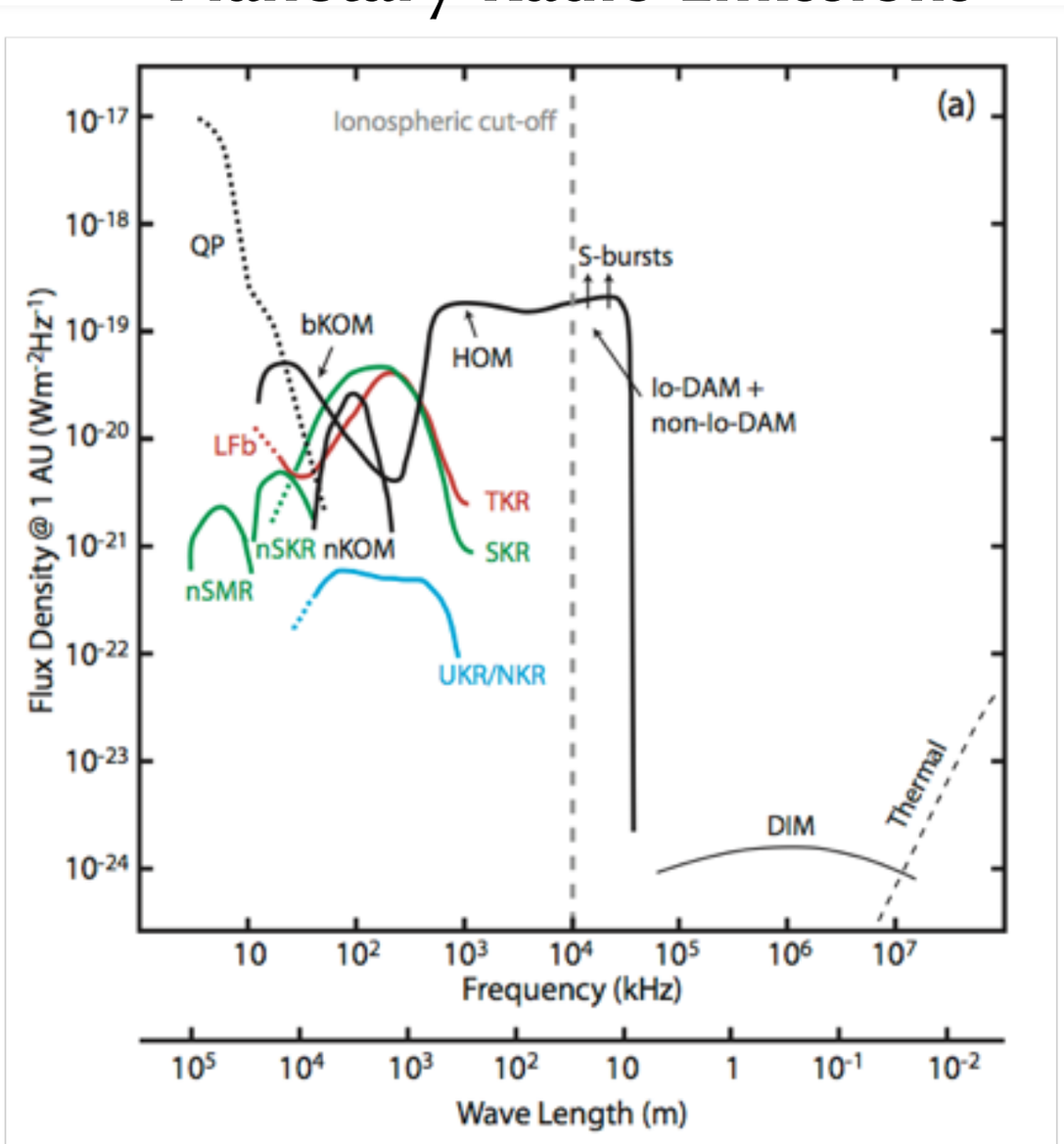
# Radioastronomy from space

- Earth's ionosphere reflects radio waves below 10 MHz
- Except with Jupiter, planetary radio sources are observed below 1 MHz
- Radio frequency interferences: (human activity): we have to get away from Earth

**Ionospheric cut off at 10 MHz**

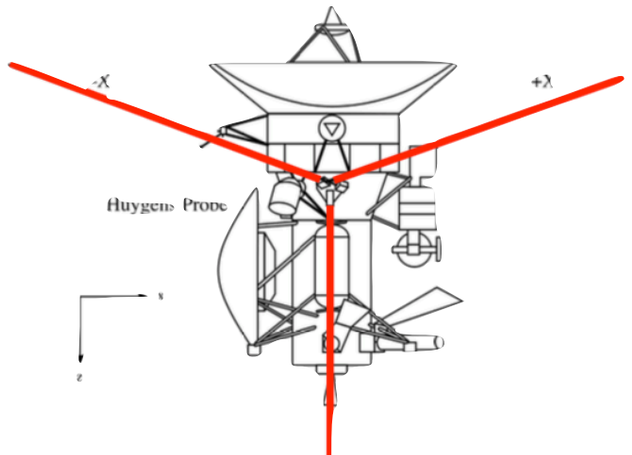



**Planetary Radio Emissions**

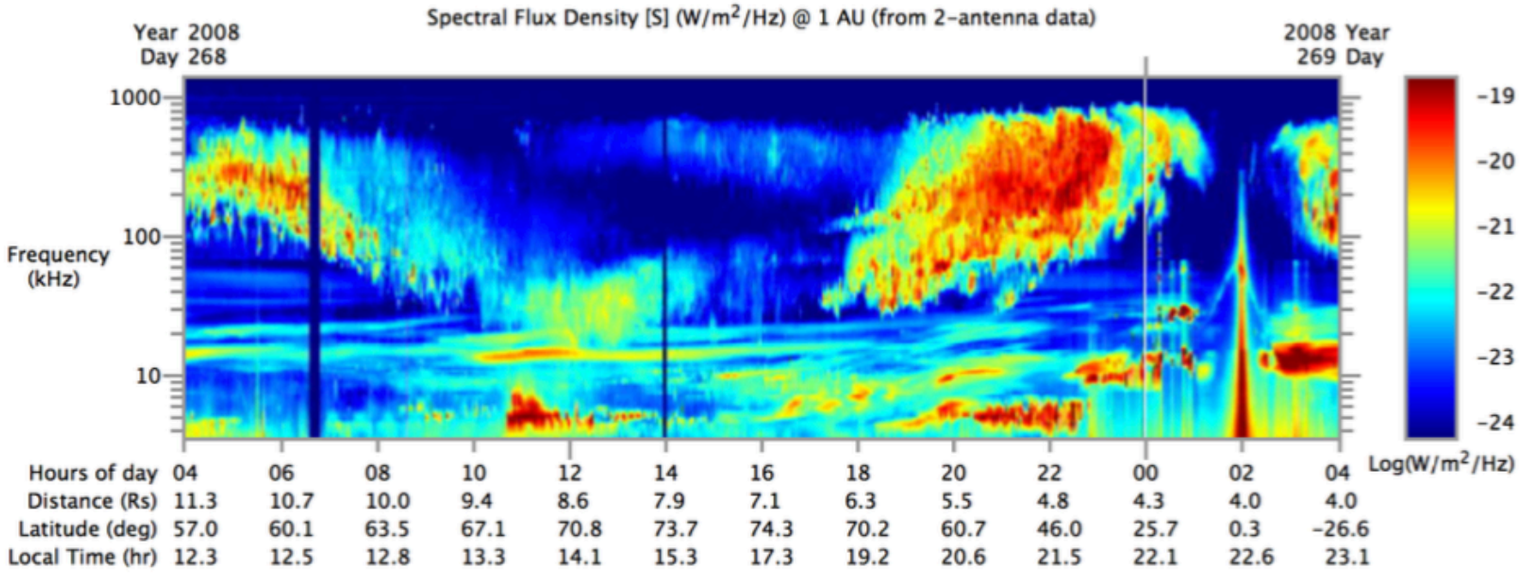


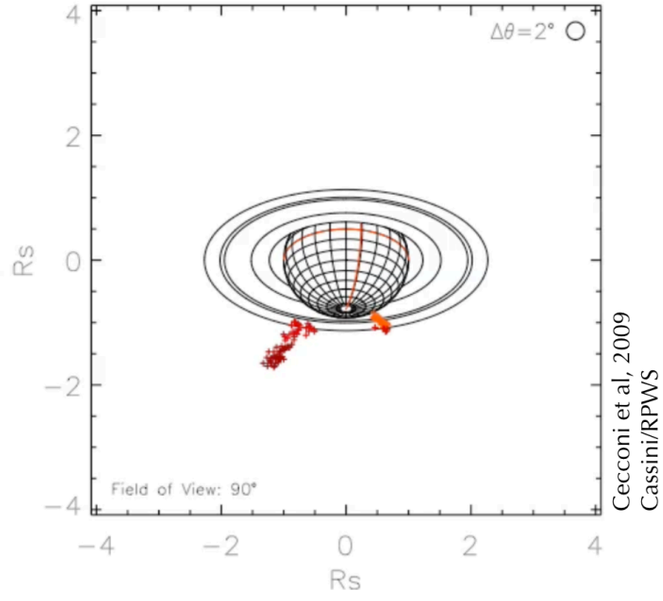
# Radioastronomy from space

- Sensors: linear antenna (same as on kitchen radio sets, but often longer)
- Measurements: spectrograms of intensity, polarization direction of arrival.




- Example: Cassini Mission at Saturne

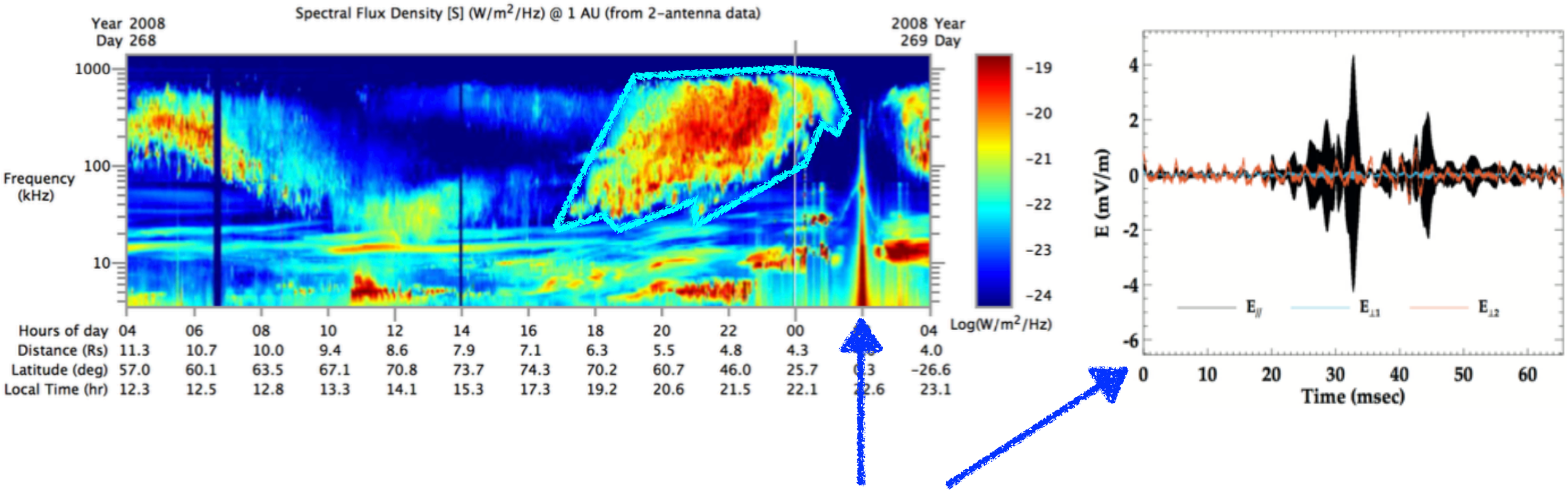



Cecconi et al, 2009
Cassini/RPWS

# MASER Data product types

- Mostly **spectrograms**. Measured parameter (flux, polarization…) depending on time and frequency.
- Sometime: "**waveform**" (direct sampling of electric signal temporal fluctuations). Much higher data rate needed.
- also, **events**. timestamp + label + parameters (coverage) + data ? waveform snapshot can be considered as an event.
- NB: *images not in the scope of MASER*



# Data Collections

- **Large archives for space missions**
  - NASA/HPDE (NASA - heliophysics)
  - NASA/PDS (NASA - planetary sciences)
  - CDPP (CNES - space plasma physics)
  - DARTS (JAXA - all sciences)

- **Ground based data collections**:
  - Nançay Decameter Array (Nançay, France)
  - URAN-UTR-2 (Kharkov, Ukraine)
  - Iitate Radio observatory (Iitate, Japan)

- Plenty of other observatory/laboratory/team data collections, not comprehensively distributed yet.

- **Catalogue of events**, from published papers (from the 70's to last year): solar and jovian events.

# Data format and metadata

- NASA Heliophysics, archive format = **CDF** (common data format), with ISTP standard.
  Recommended by CDPP and JAXA too.
  NASA/PDS now accepts CDF as archive format.

- Other standard formats in use:
  - Solar community: **FITS**
  - Modern ground interferometers (LOFAR, LWA): **HDF5, MS**

- Other (again): **raw binary** streams, with custom descriptions (most of the data collections…)

# Data volumes

- **Space data**:
  about 1 spectrum (~250 steps * 8 Bytes) / minute
  => ~35 B/sec, or ~3 MB/day
  (space constraints: power, telemetry rate…)
  Several decades of continuous coverage (Cassini, STEREO, Wind) are “easy” to store and share (~20 GB for 20 years)

  Rich datasets: many processing levels
  => ~10 TB for the Cassini/RPWS/HFR instrument full mission dataset

- **Ground data**:
  about 100 spectra (15000 steps * 16 Bytes) / second
  => ~30 MB/sec, or ~2 TB/day
  Specific solutions needed for remote access of data.

- Very different needs for architecture, infrastructure, archive and distribution systems, but: similar needs.

# Software library: MASER

- **MASER** (Measure, Analyse, Simulate Emissions in the Radio range): github.com/maserlib

- Maser4py: Python 3.5+ modules
  - current developments: reading data collections in various data formats (specifically raw binary formats), using homogeneous classes (same interface)

- Currently implemented data collections:
  - from LESIA: Cassini/RPWS, Voyager/PRA, SolarOrbiter/RPW;
  - from CDPP: Demeter, Interball, Viking (Swedish auroral mission), ISEE3, Wind
  - from NASA/PDS: Cassini/RPWS, Voyager/PRA
  - from Nançay: Nançay Decameter Array, NenuFAR
  - from Radio amateurs: RadioJOVE

- Open source development, GPLv3

# Data on demand

- **Large data rate or long times intervals**
  => need for optimized client/server distribution system.

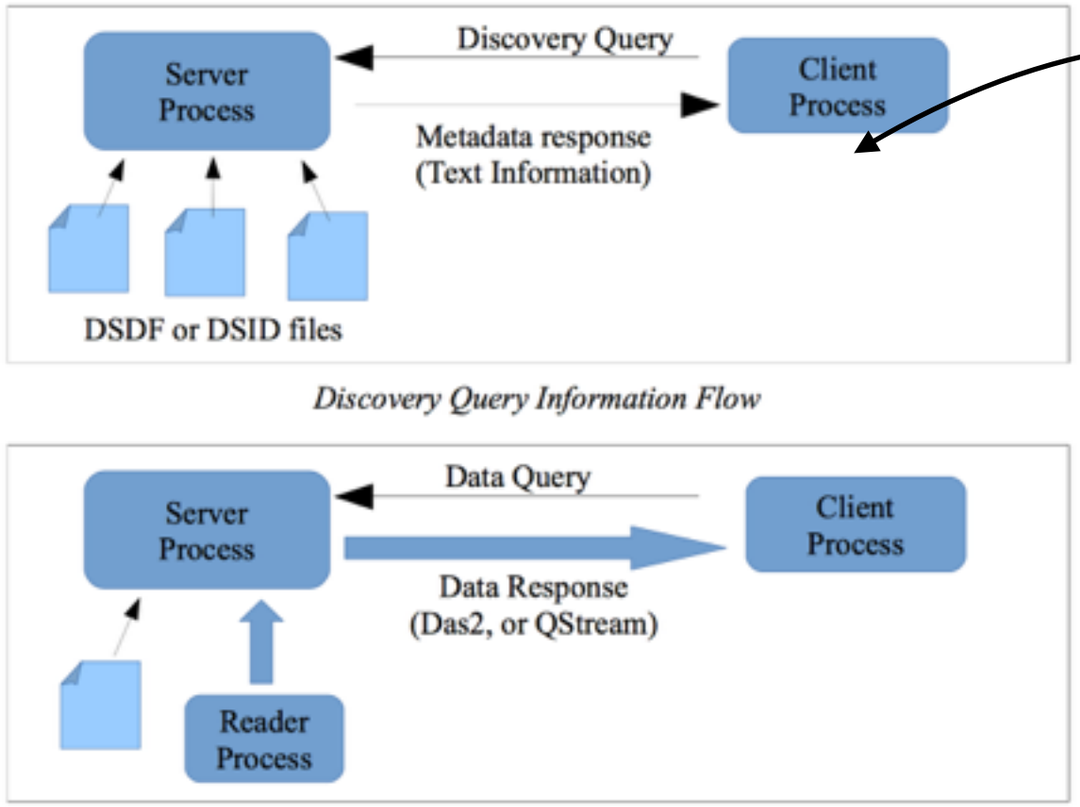
- Existing solution developed by University of Iowa (USA):
  server=**Das2** (http://das2.org) and client=**Autoplot** (http://autoplot.org)

- **Built for space data** (low data rate), but capable of serving long **resampled** times series.
  **Tested with success on ground Nançay datasets:** adapted also for ground based high data rate collections.

- Very simple configuration:
  data collection description files + data reader that produces “das2stream” formatted data.

- Implemented on LESIA, CDPP, and Nançay data collections (using the Maser4py modules):
  - LESIA: http://voparis-maser-das.obspm.fr/das2/server
  - Nançay: https://das2server.obs-nancay.fr/das2/server

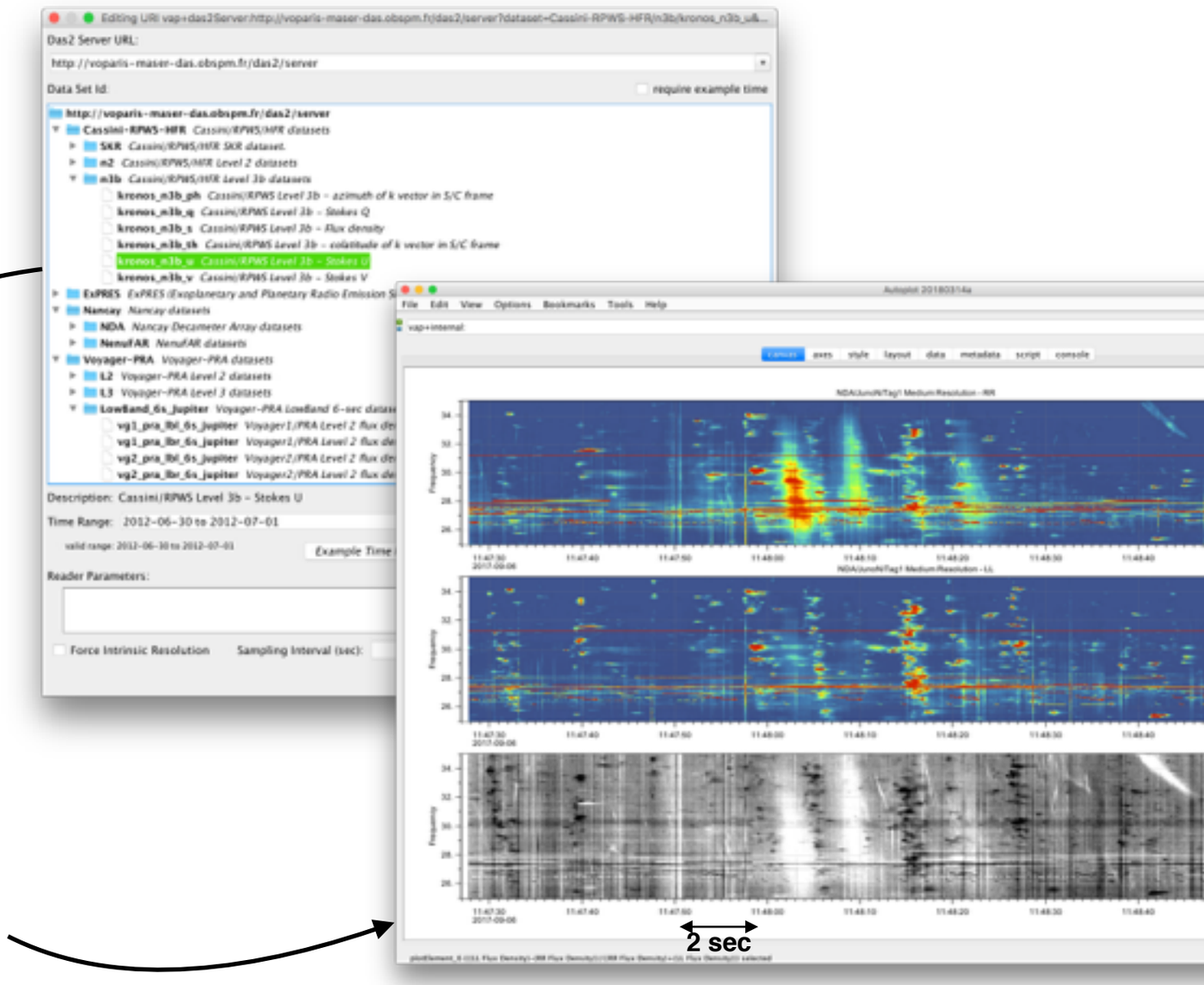
# Das2 / Autoplot process




*Discovery Query Information Flow*




*Data Query Information Flow*



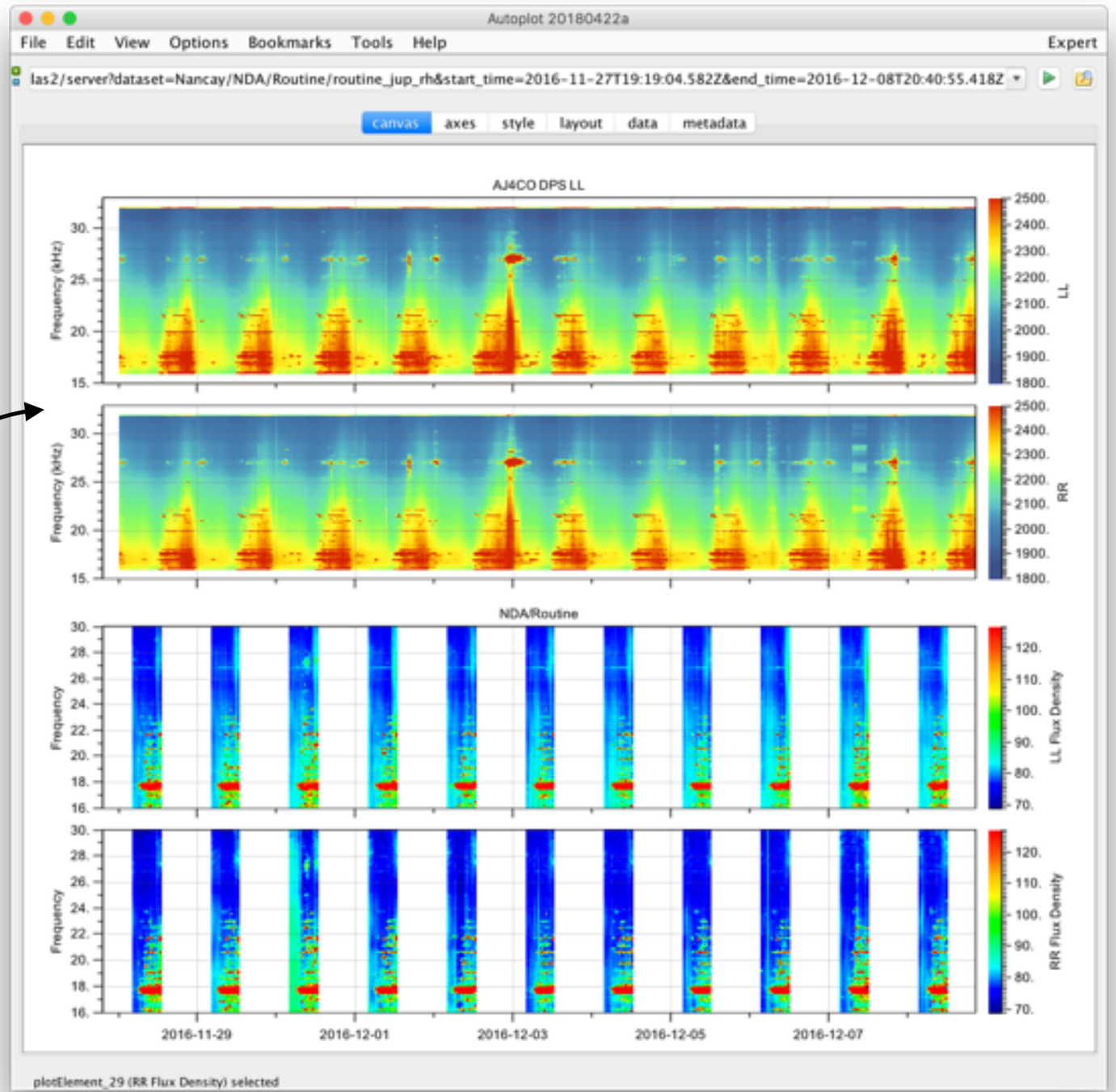

NDA/JunoN dataset (3TB/day)

- Das2 = **data distribution** system for time series + **on demand resampling** (averaging on the fly).
  HTTP REST Query: data collection + time interval + temporal resolution

# Examples

- Pro + Amateurs
- Ground + Space
- Old missions

2 top rows : ~7 GB raw data,
only 760kB dowloaded for display



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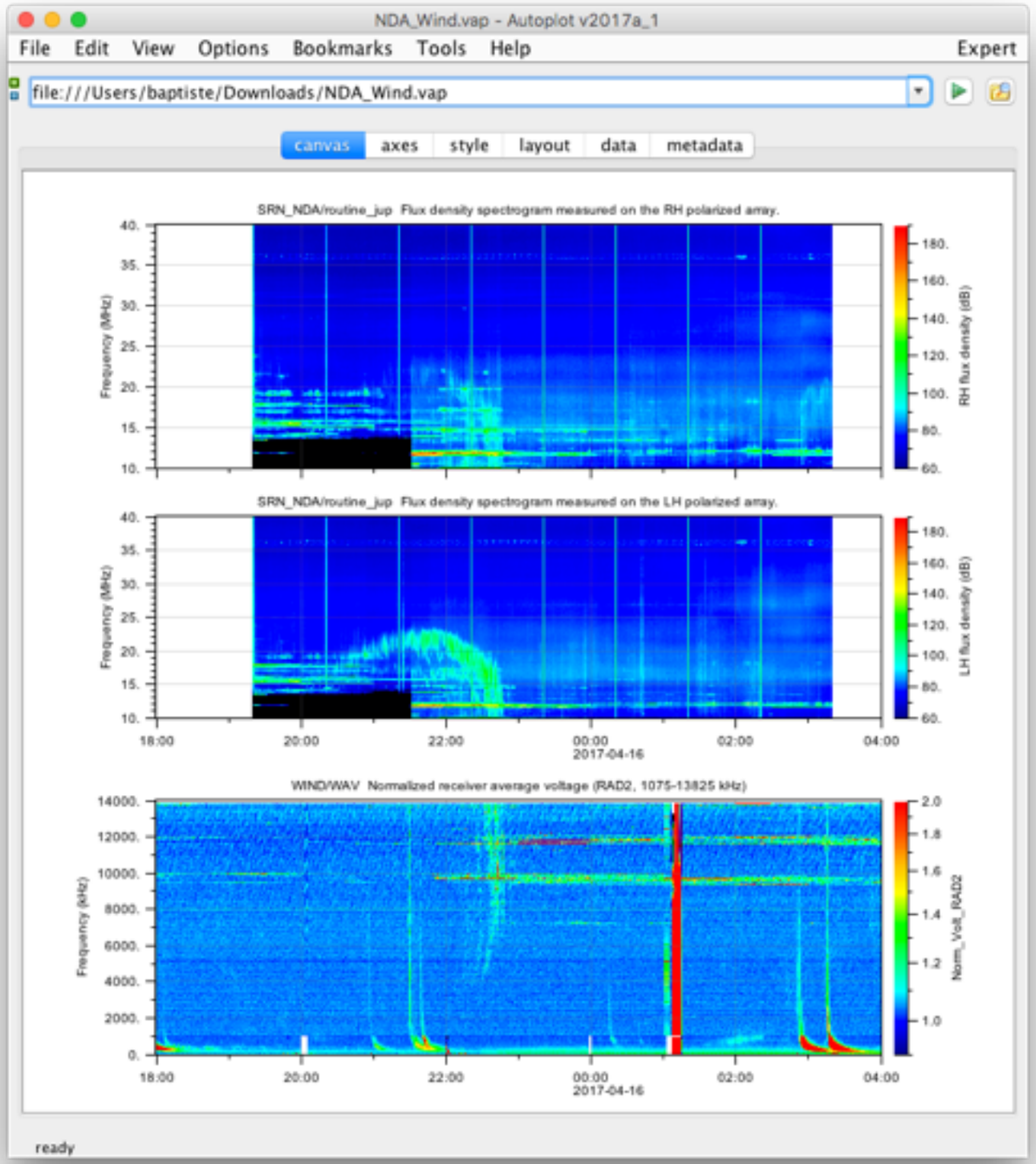

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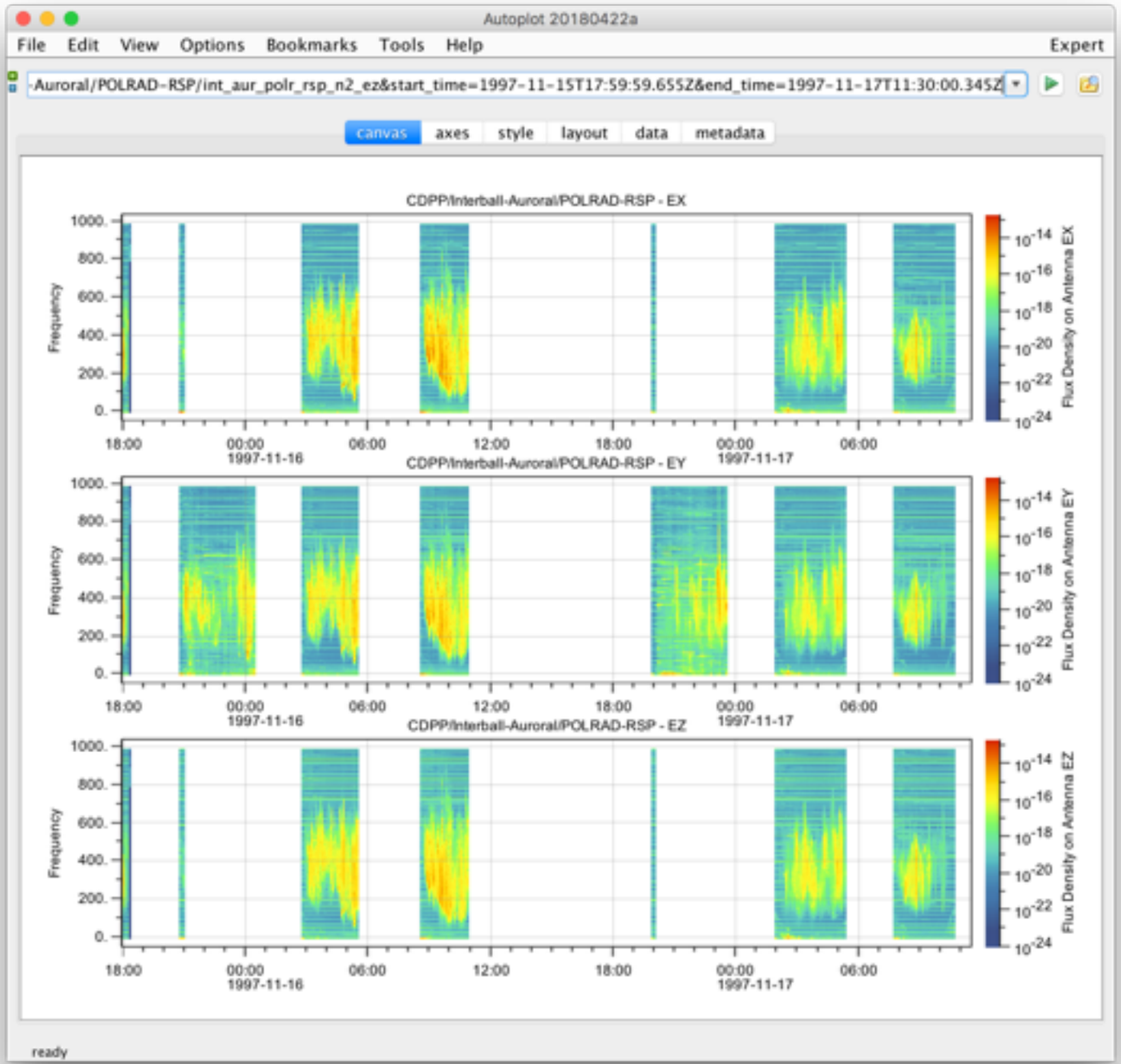


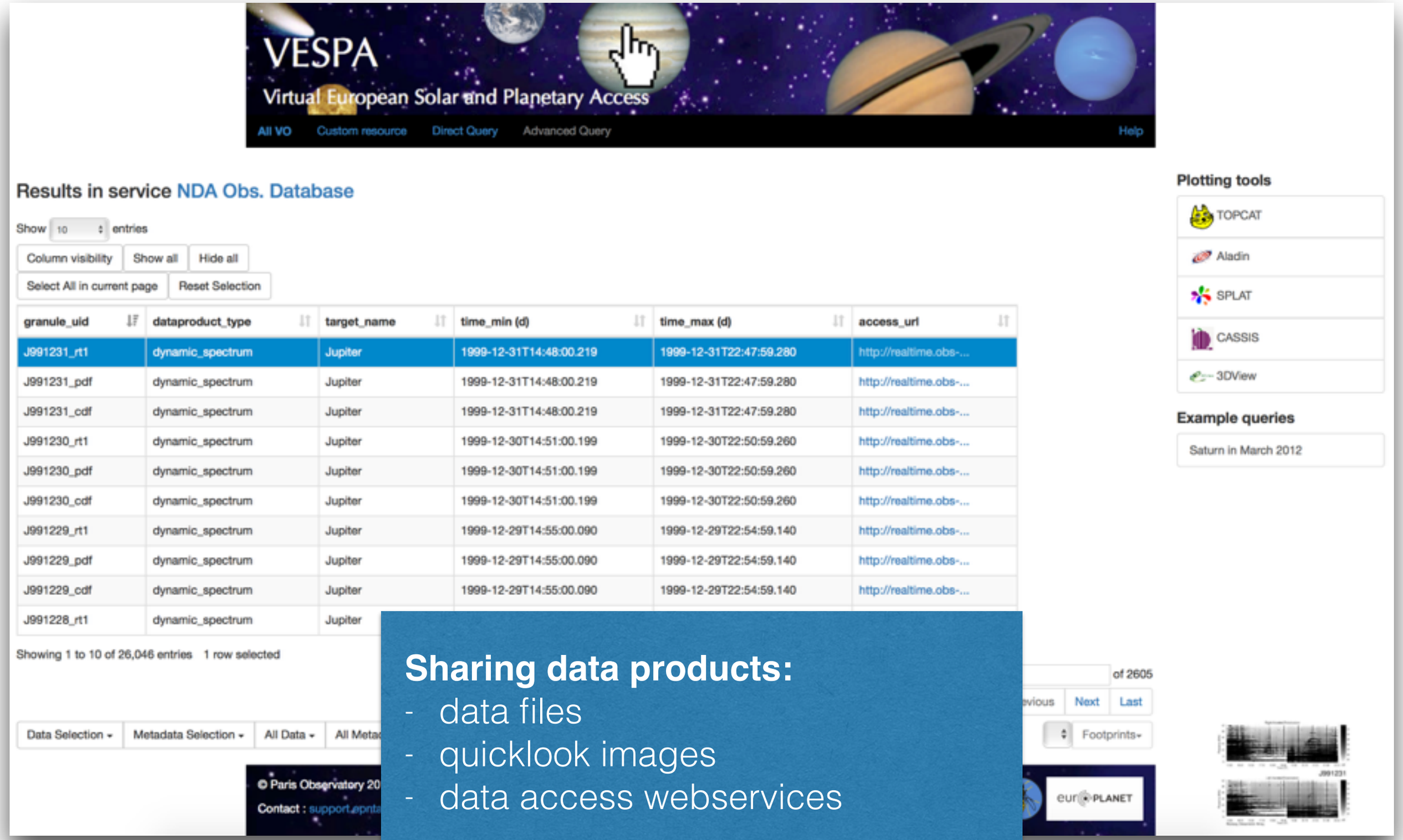

**Interball/POLRAD**

# Data discovery

- Data collection catalogue with standard metadata forged for solar system sciences (EPNcore)
  Same protocol for all catalogues (TAP, from IVOA)
  => VESPA (see Erard et al., talk)

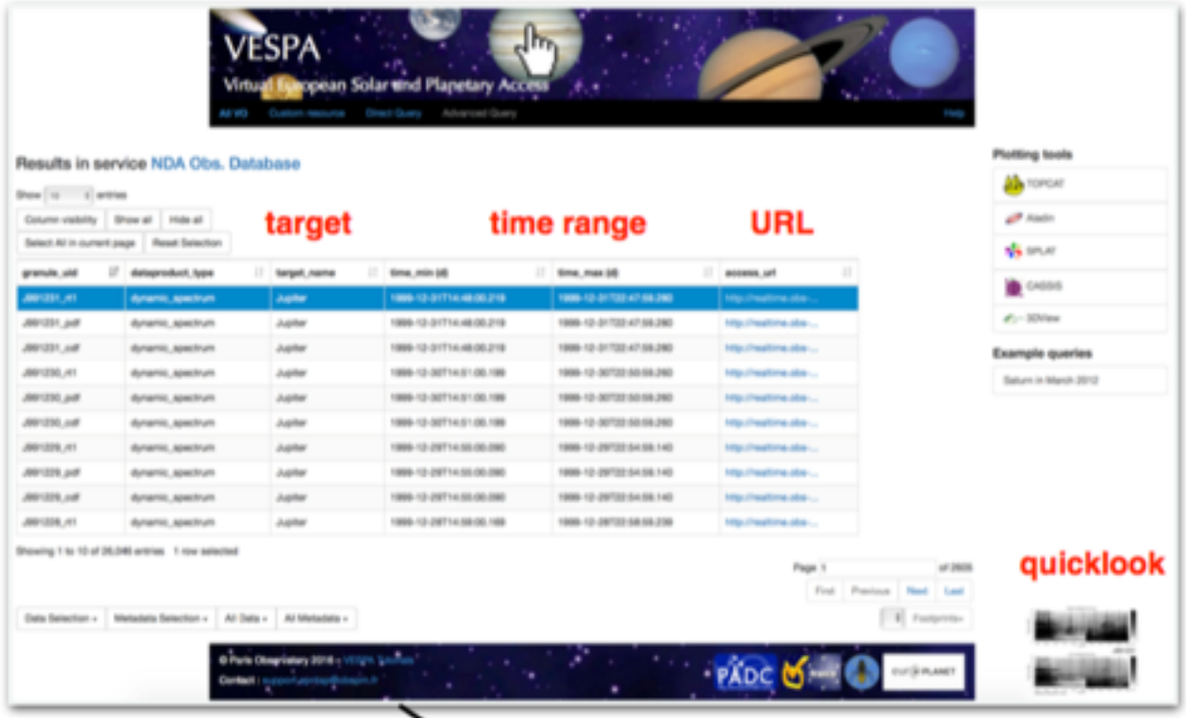
- Discovery of data products with content metadata (coverage, observation…)

- Solar System Virtual Observatory (http://vespa.obspm.fr/)




**Sharing data products:**
- data files
- quicklook images
- data access webservices

VESPA result page in Nançay/NDA EPN-TAP service




VESPA result page for all das2server dataset in Meudon

DATALINK on test server

mtype=load.table.cdf

mtype=load.table.das2

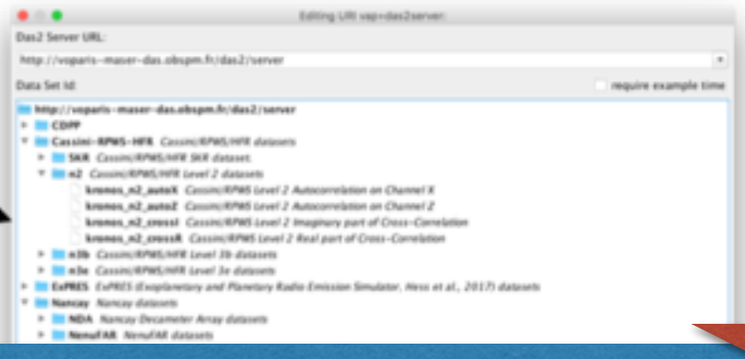
SAMP hub

das2 dataset discovery feature

next: distribute .vap files

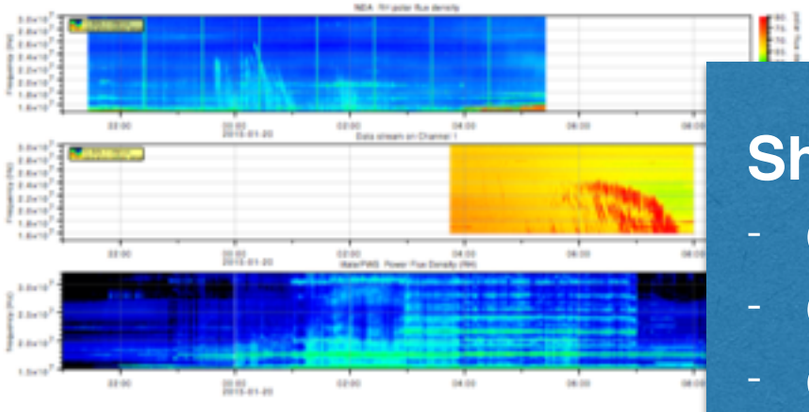
das2 dataset publication through VESPA

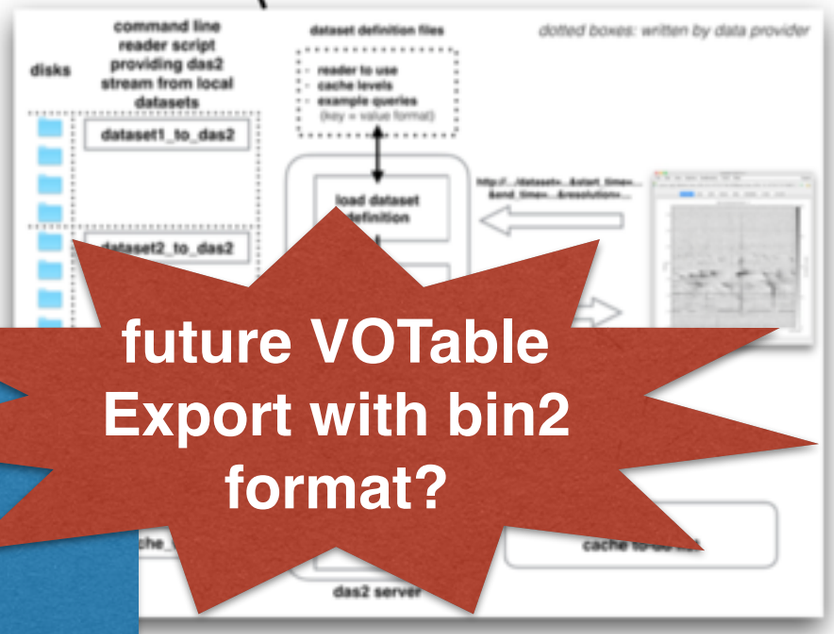
Das2 server catalog in Autoplot




Data Selector

Plot






Das2 server block diagram

future VOTable Export with bin2 format?

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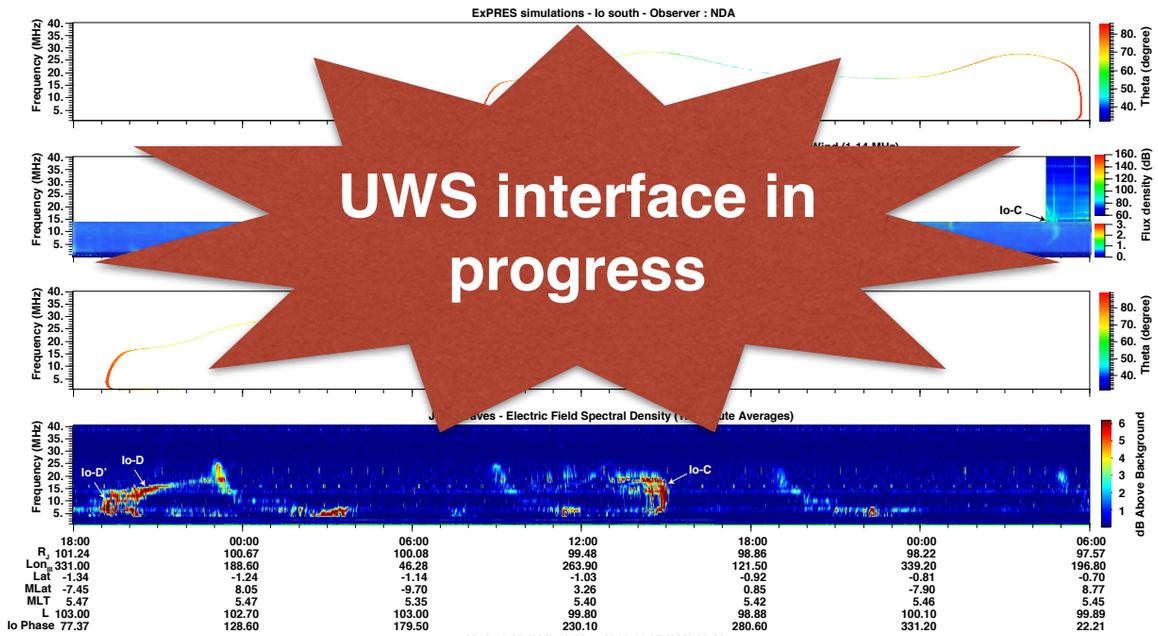
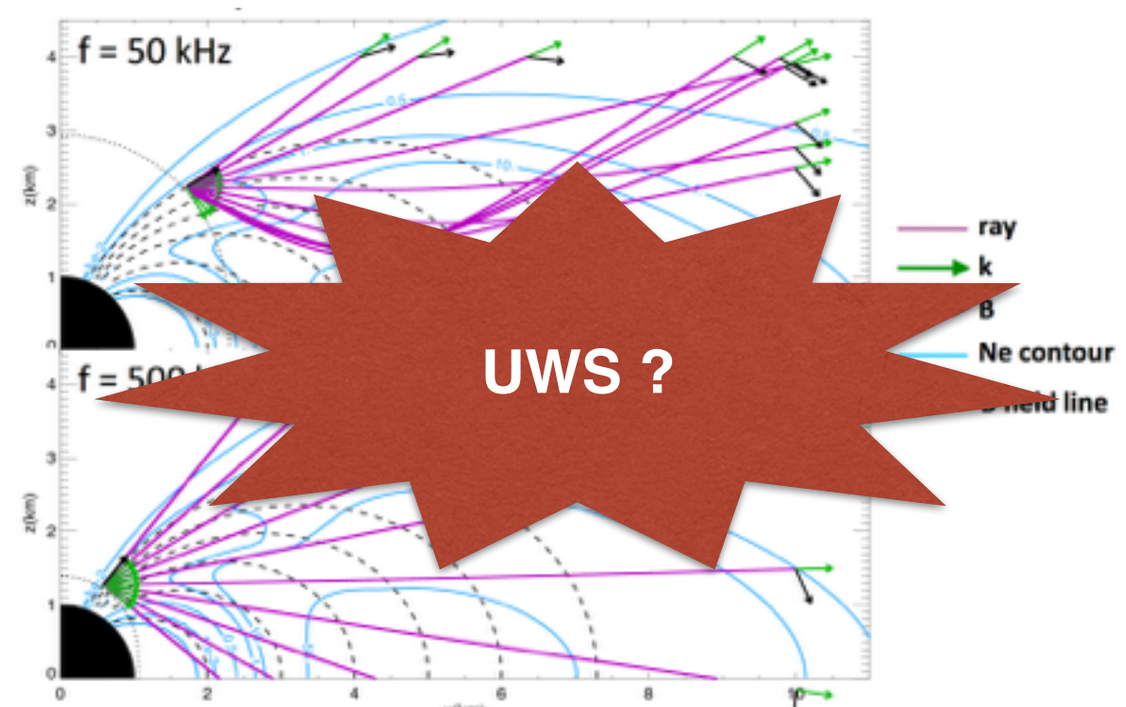
# Simulation and modeling

- Modeling of planetary radio emissions spectrograms
  *ExPRES (Exoplanetary and Planetary Radio Emission Simulator)*

- Modeling low frequency radio wave propagation with ray tracing
  *ARTEMIS-P (Anisotropic Ray Tracing code for Electromagnetic waves in Magnetospheres, Ionospheres and Solar wind, including Polarization)*



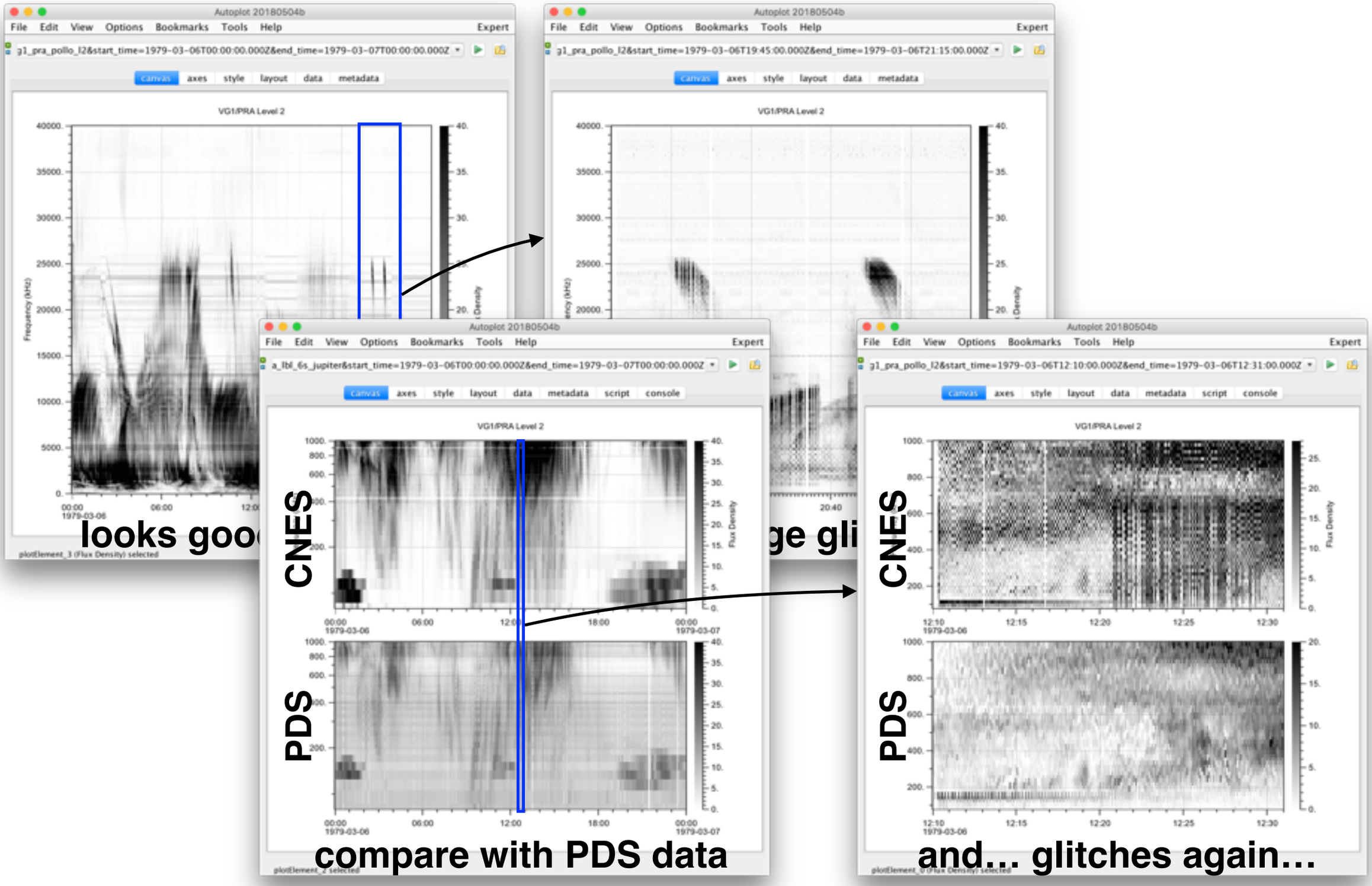



# Applications

- Old data recovery: Voyager/PRA
- Juno-Ground-Radio support group
- Browse high resolution datasets
- NenuFAR (SKA precursor) commissioning phase
- Mars Express MARSIS footprint on Mars

# Validation of CNES Voyager-PRA data

*Using Das2/Autoplot + Maser4py reader modules for CNES and PDS datasets*



# Juno-Ground-Radio observation support group

*France (Nançay) + USA (RadioJOVE, LWA), Ukraine (Kharkov), Japan (Iitate)…*
*Using: VESPA+CDF (now); das2+autoplot (soon)*

**Data providers**

**Users**

SRN-NDA France

TAP

Tohoku-Iitate Japan

TAP

…

RadioJOVE

TAP

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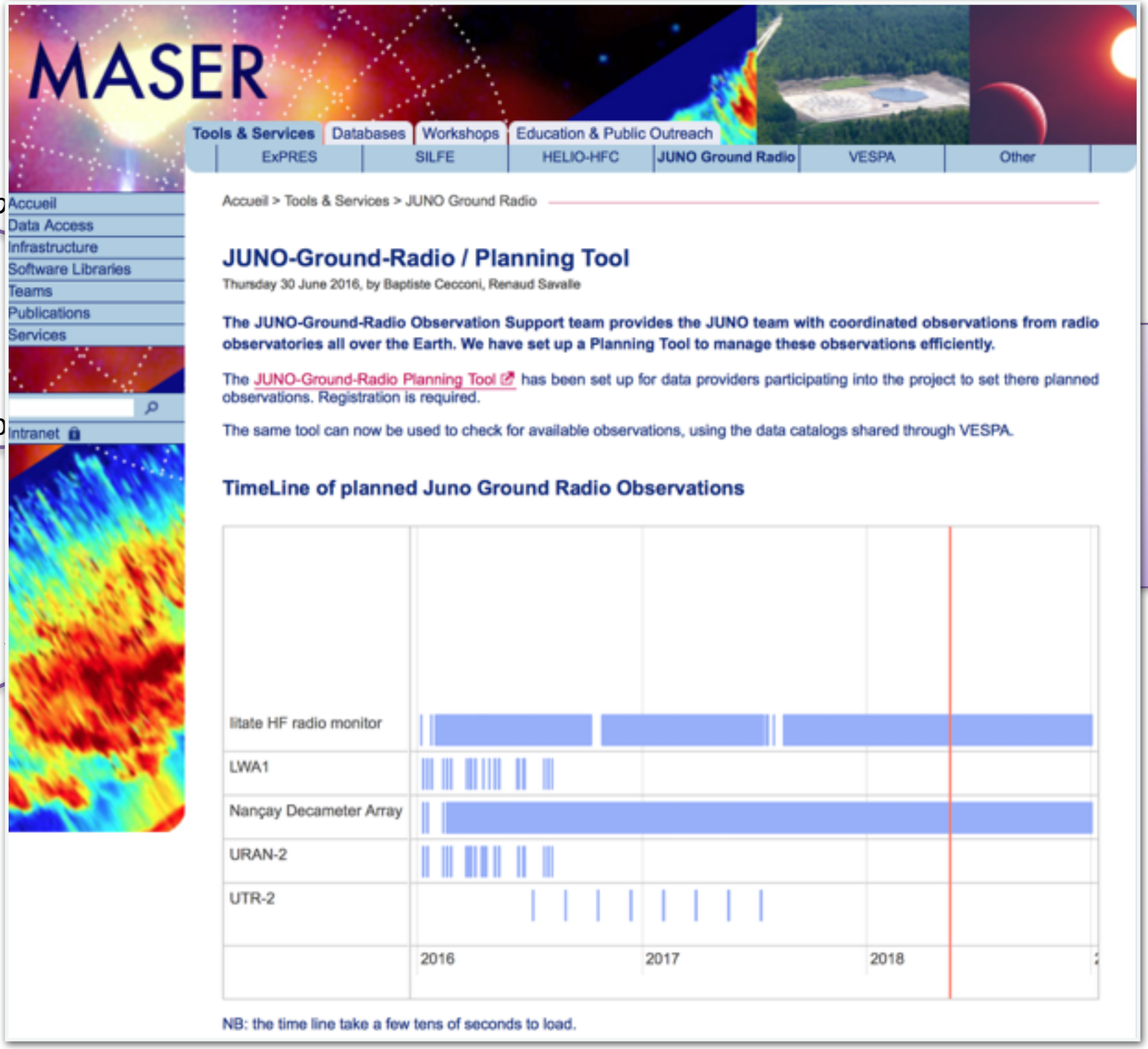
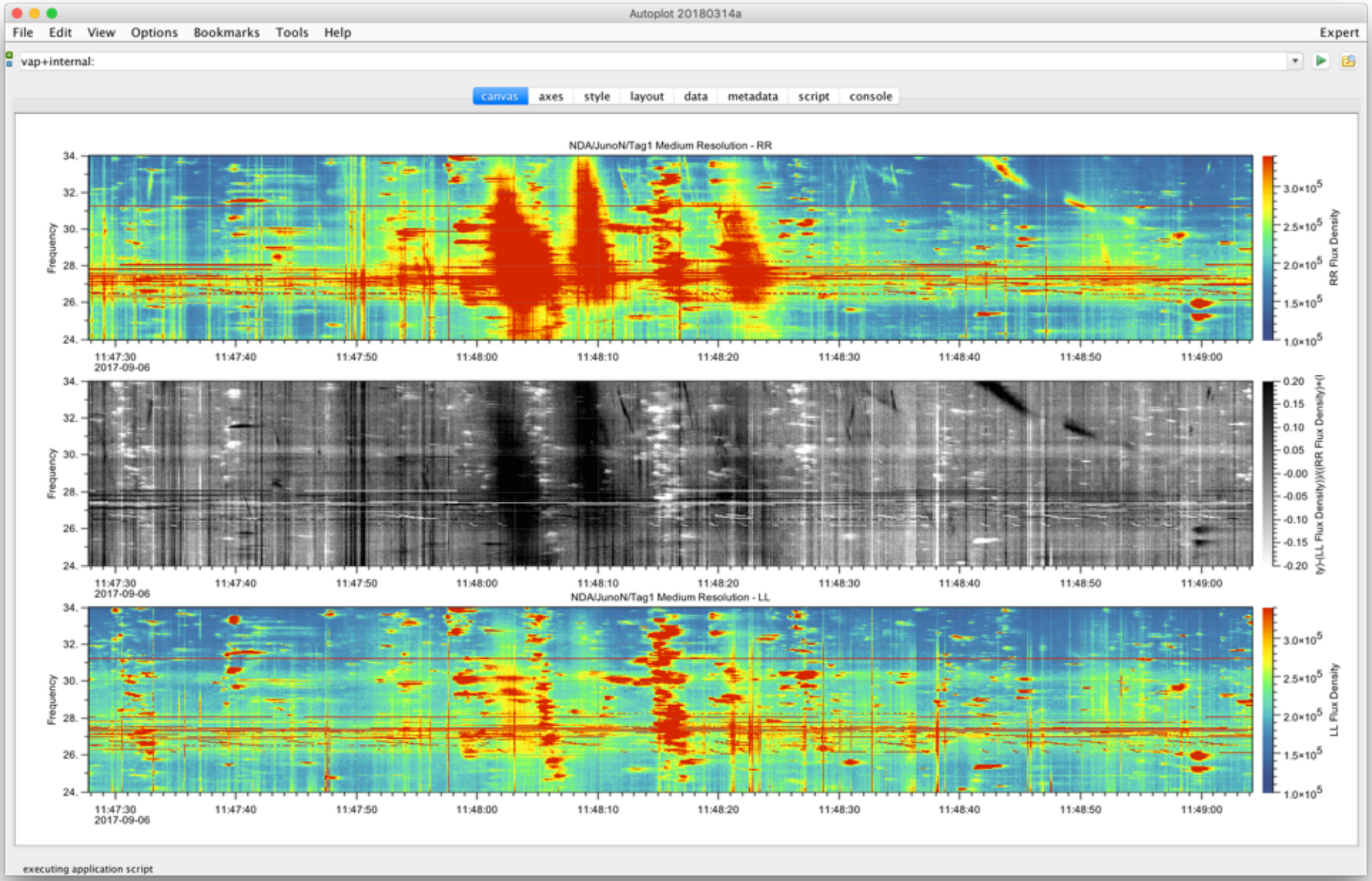


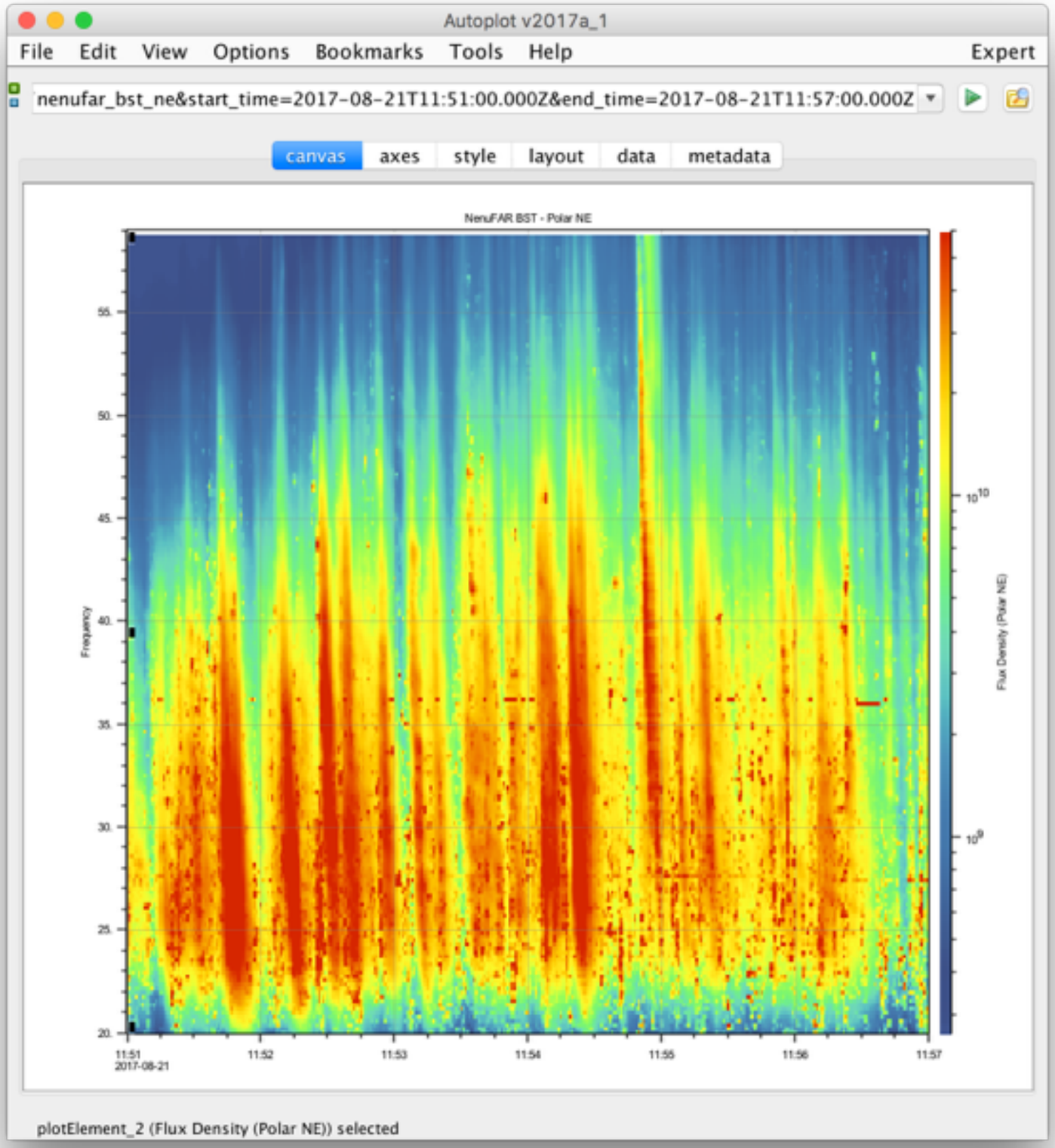
# Browse high resolution datasets

*Using: das2+autoplot, EPN-TAP on NDA/JunoN dataset (here, solar bursts)*



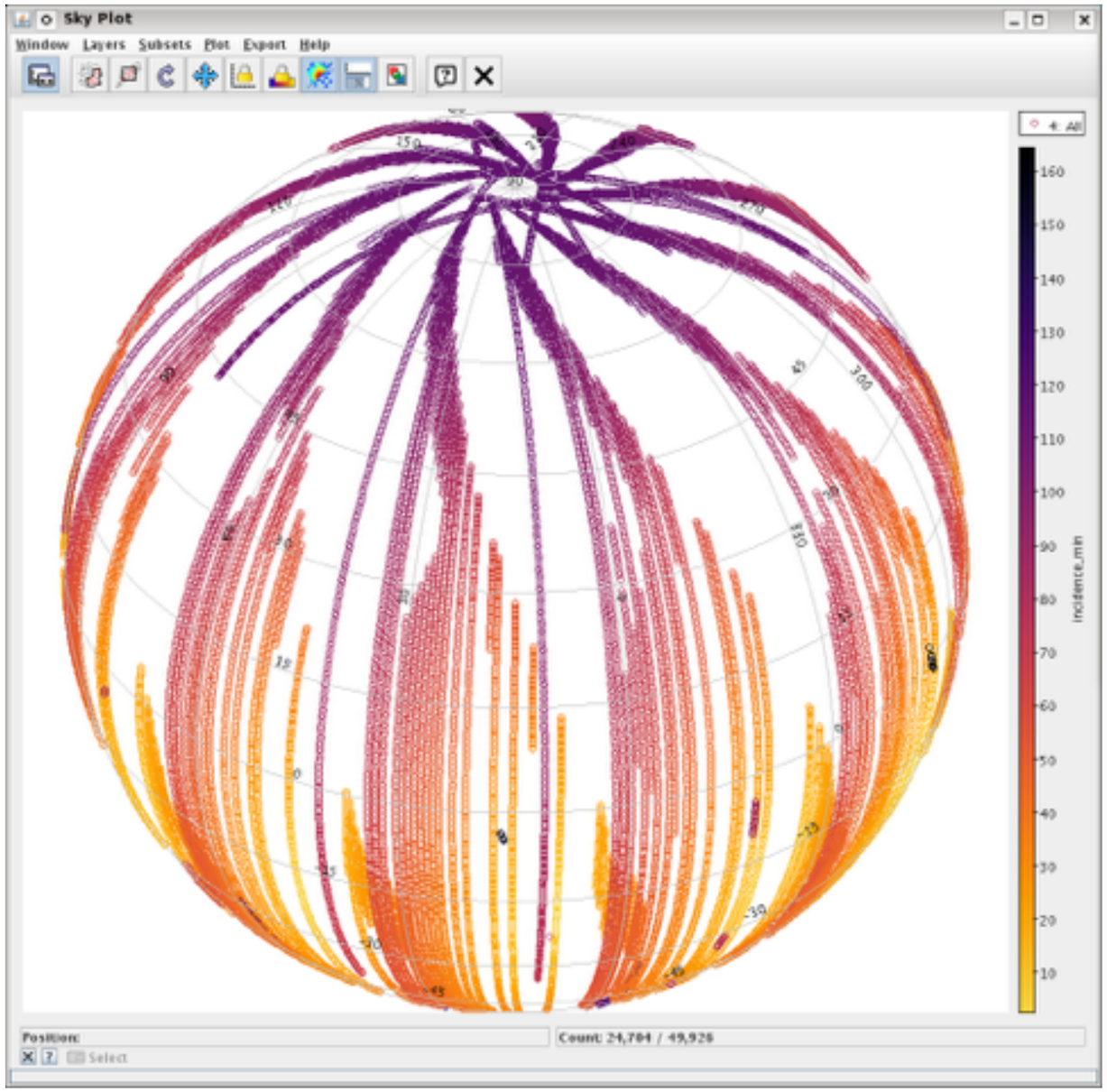
# NenuFAR (a SKA precursor) commissioning phase

*Using: FITS, das2+autoplot (now), EPN-TAP+ObsTAP (soon), FITS+Aladin (next);*

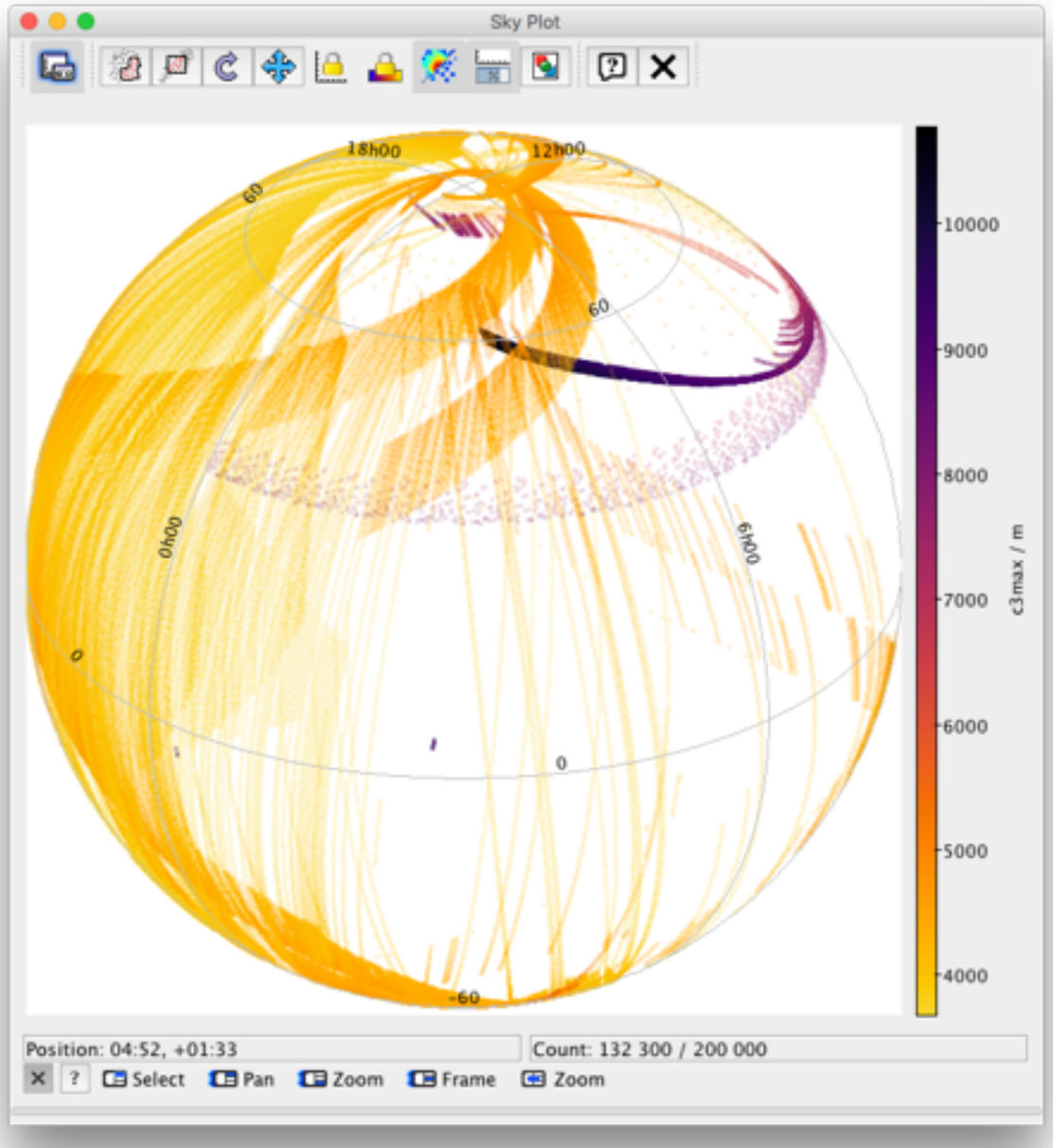


# Mars Express MARSIS footprint on Mars

*Using: EPN-TAP (Univ. Iowa) + TOPCAT*




**MEx/MARSIS footprint location (lat, long)**
colorbar = solar incidence angle




**MEx/MARSIS location (lat, LT)**
colorbar = altitude

# Future (sooner to later)

- More data modules and features to **maser4py**, cleaner interfaces, improve **Datalink** and **SAMP**
- Distribution of **event catalogues** (published Solar radio bursts, Jovian radio bursts catalogues…)
- Launch **machine learning** activities/studies for radio spectrograms feature recognition
- **Citation** of data collections/products/events
- ESA Solar Orbiter / NASA Parker Solar Probe **ground support** (as currently done for Juno)
- Better integration of **modeling tools** with visualization
- Extension to **astronomical observations** (pulsars…)
- Connection with **SPASE** (NASA Space Physics registry)
- Improve Das2 interface for adaptive **spectral resampling**