

# Low Frequency Radio Astronomy and the VO

## MASER

An Open Toolbox for Low Frequency Radio Astronomy

*Measure, Analyze, Simulate Emissions in Radio range*

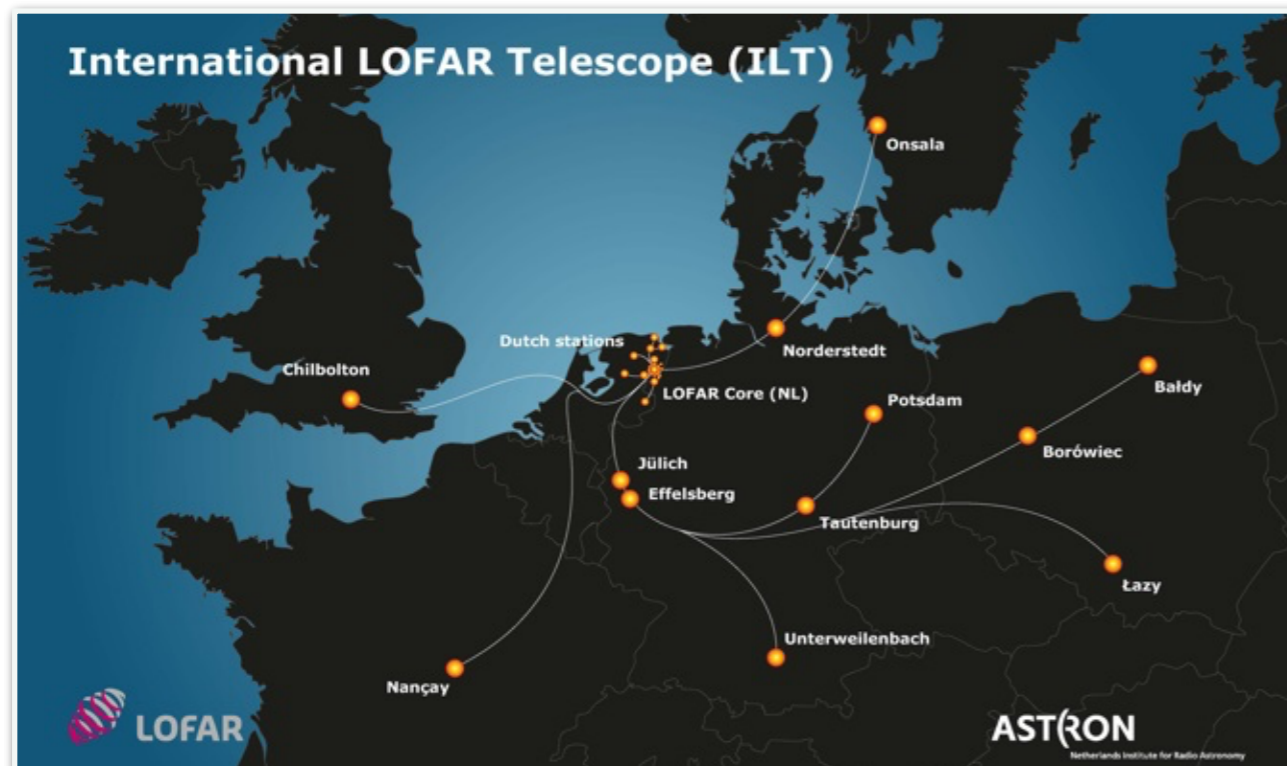
**Baptiste Cecconi<sup>1,2</sup>, Pierre Le Sidaner<sup>3</sup>, Renaud Savalle<sup>3</sup>, Xavier Bonnin<sup>1</sup>, Philippe Zarka<sup>1,2</sup>,  
Corentin Louis<sup>1</sup>, Andrée Coffre<sup>2</sup>, Stéphane Aicardi<sup>3</sup>, Laurent Lamy<sup>1,2</sup>, Laurent Denis<sup>2</sup>,  
Jean-Mathias Grießmeier<sup>4</sup>, Jeremy Faden<sup>5</sup>, Chris Piker<sup>5</sup>, Nicolas André<sup>6</sup>, Vincent Génot<sup>6</sup>,  
Stéphane Erard<sup>1</sup>, Joseph N Mafi<sup>7</sup>, Todd A King<sup>7</sup>, Mark Sharlow<sup>7</sup>, Jim Sky<sup>8</sup>,  
Markus Demleitner<sup>9</sup>**

<sup>1</sup>LESIA, Observatoire de Paris, CNRS, PSL, Sorbonne Université, Meudon, France, <sup>2</sup>Station de Radioastronomie de Nançay, Observatoire de Paris, CNRS, PSL, Université d'Orléans, Nançay, France, <sup>3</sup>DIO, Observatoire de Paris, CNRS, PSL, Paris, France. <sup>4</sup>LPC2E, CNRS, Université d'Orléans, Orléans, France. <sup>5</sup>Dep. Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA. <sup>6</sup>IRAP, CNRS, Université Paul Sabatier, Toulouse, France. <sup>7</sup>IGPP, UCLA, Los Angeles, California, USA. <sup>8</sup>Radio Sky Publishing, USA. <sup>9</sup>Heidelberg Universität, Heidelberg, Germany.



# Radioastronomy from ground

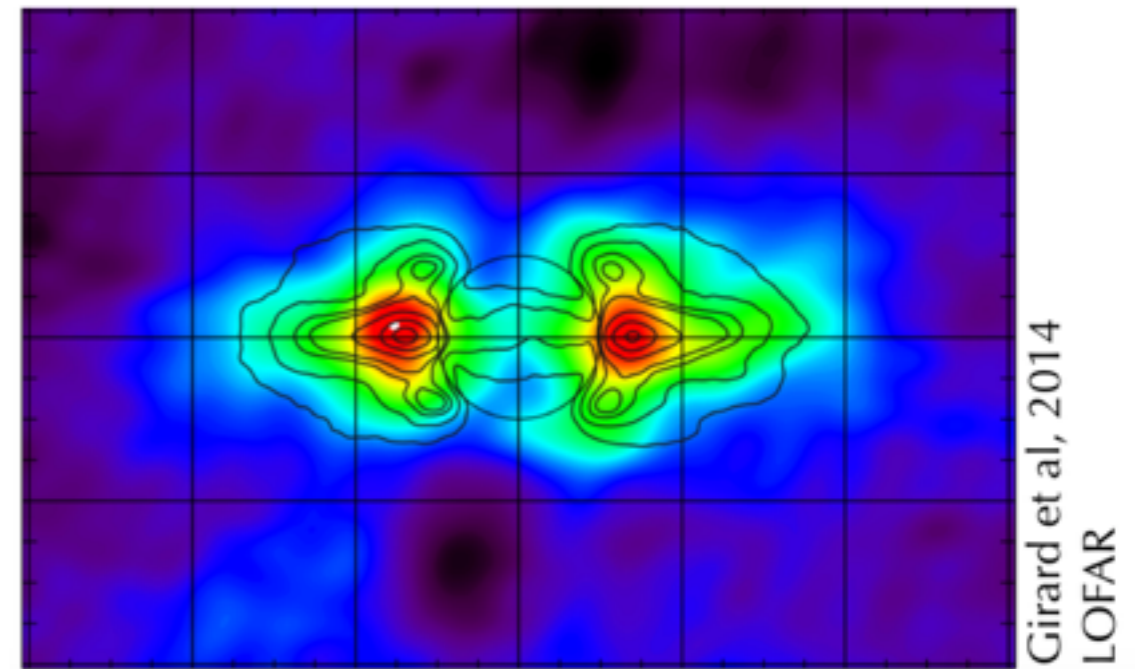
- Low frequencies from ground:
  - Interferometers
  - Phased arrays
- Example: LOFAR (Low Frequency Array)



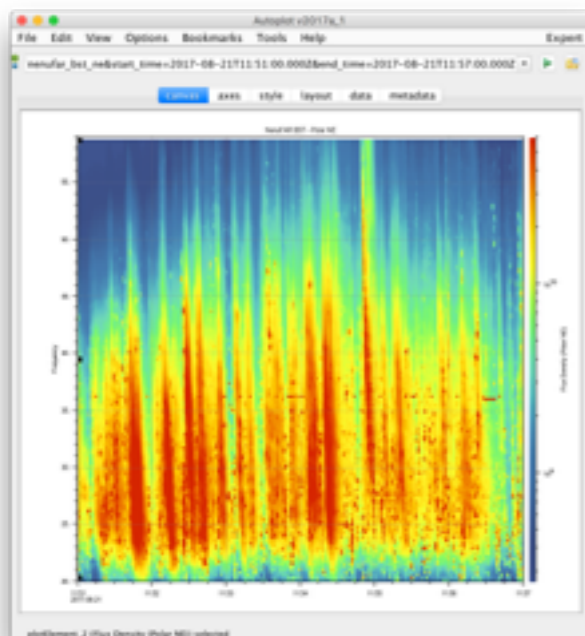
# Radioastronomy from ground

- 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...

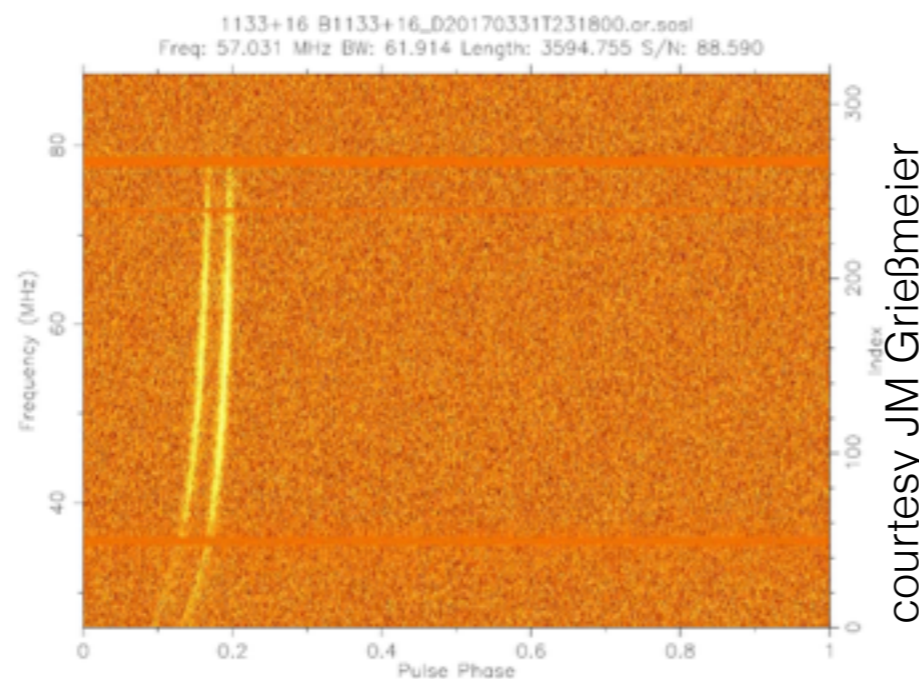
Jovian Radiation Belts at ~150 MHz



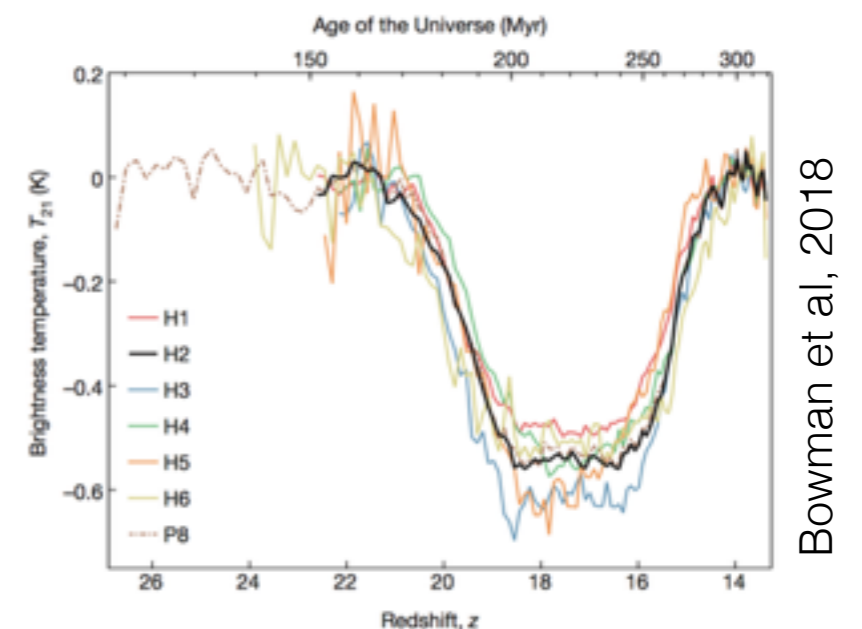
Solar Radio Storm



B1133+16 pulsar phase spectrogram



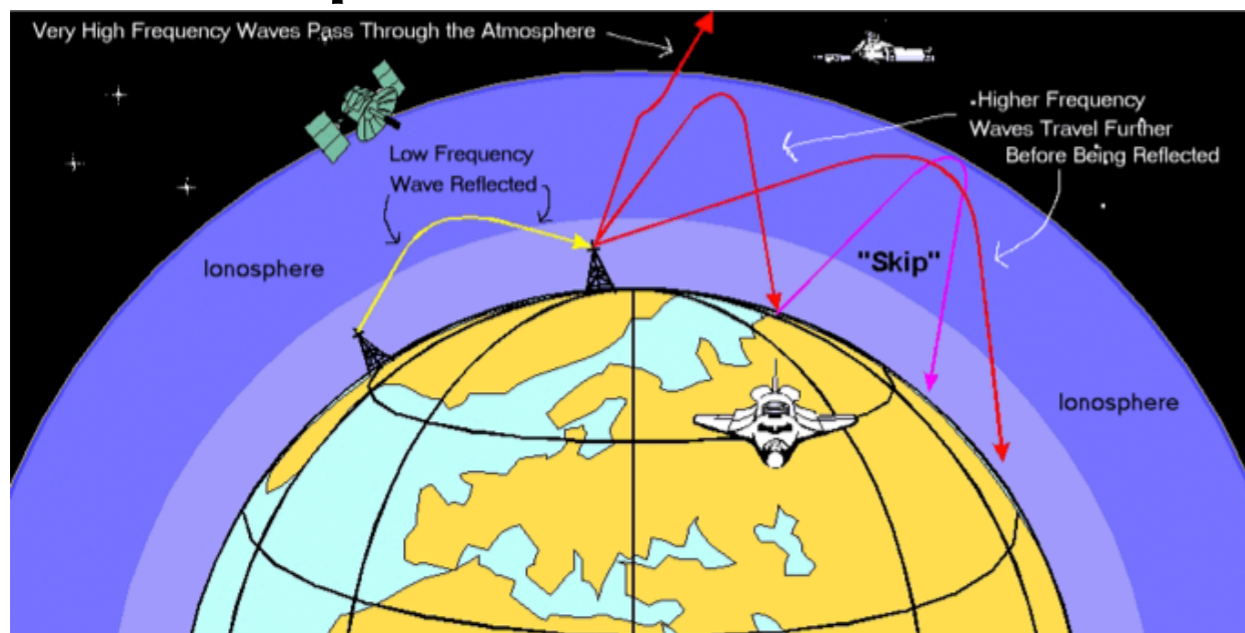
Cosmic Dawn signal



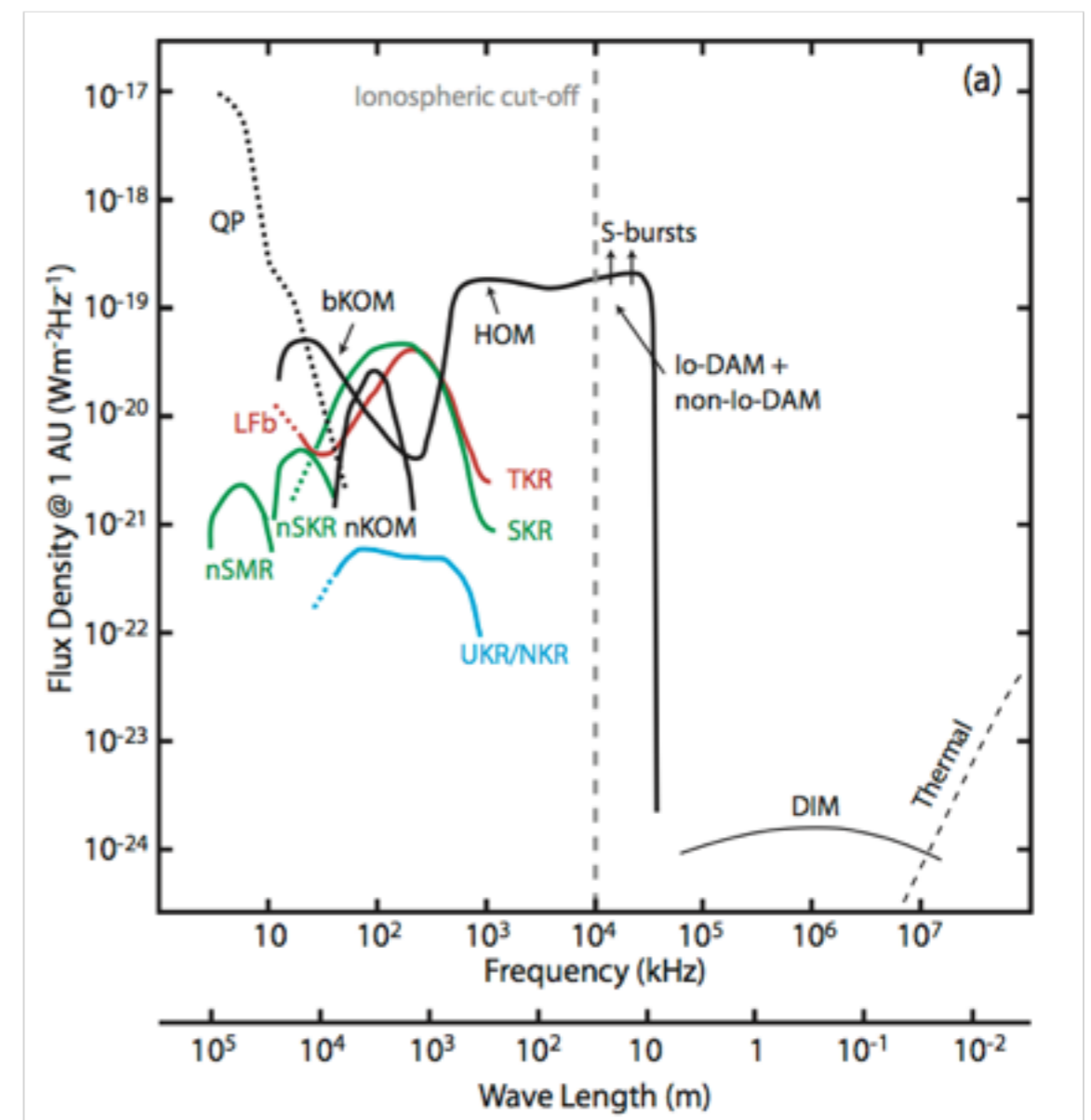
# Radioastronomy from space

- 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

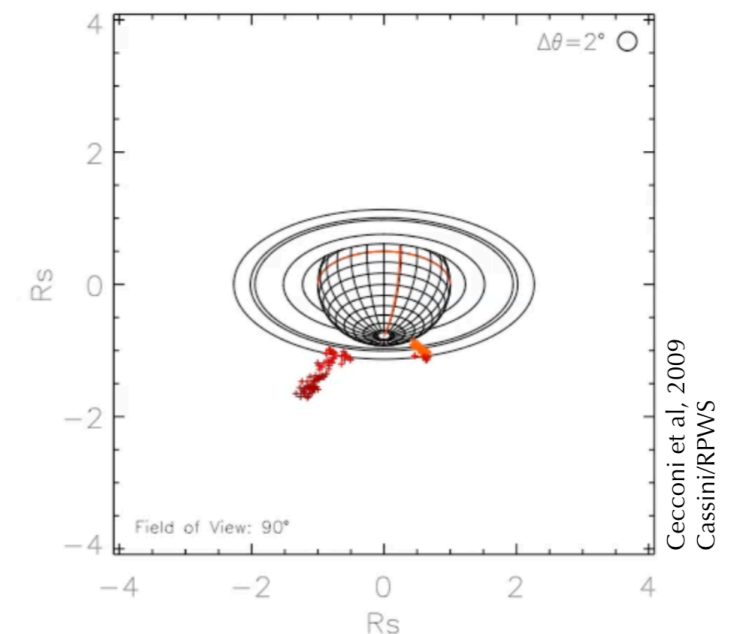
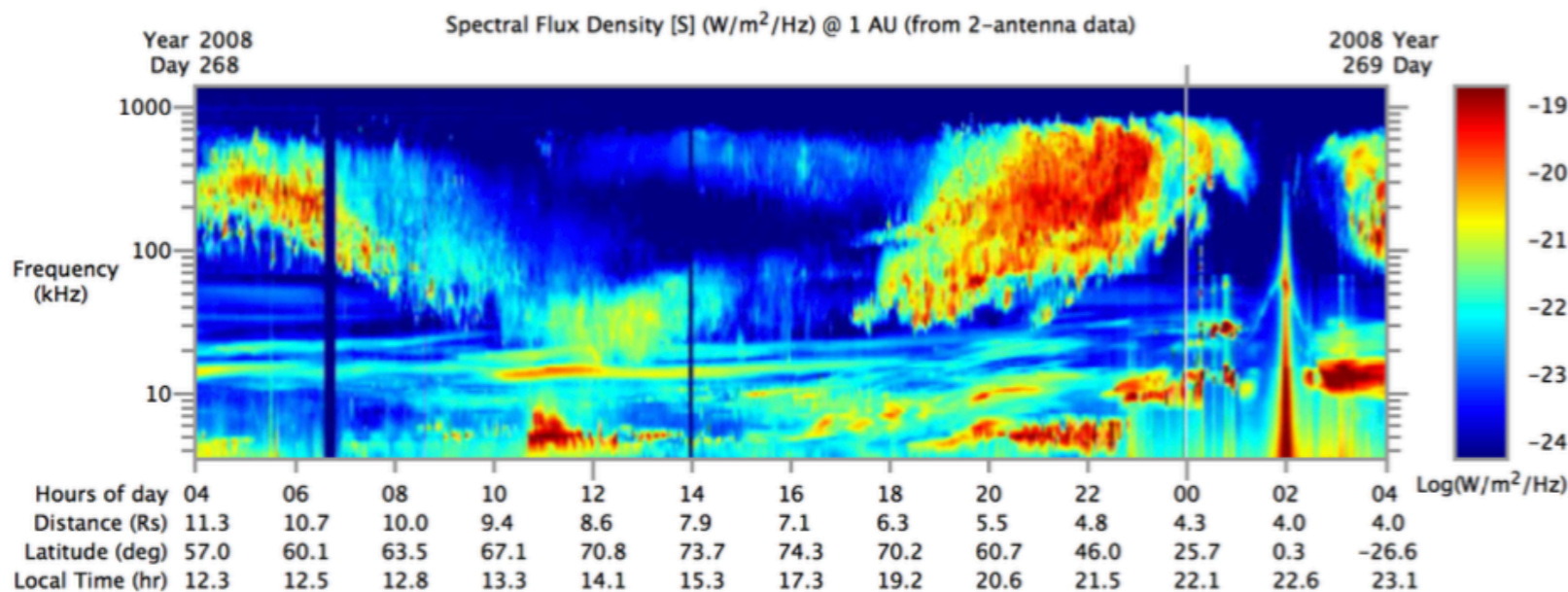
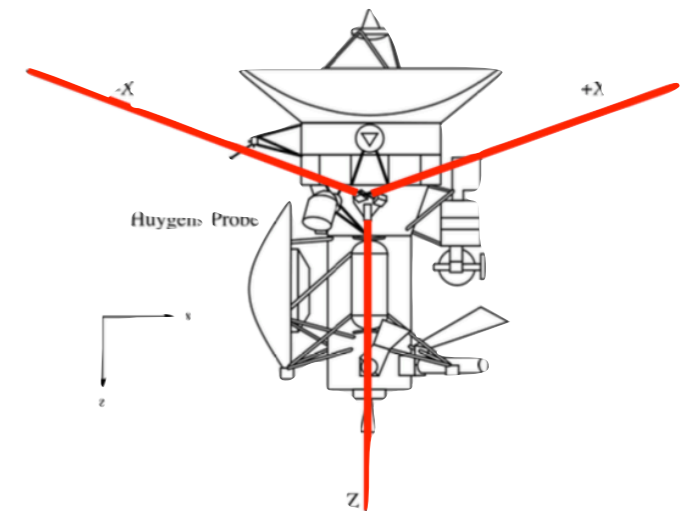


## Planetary Radio Emissions



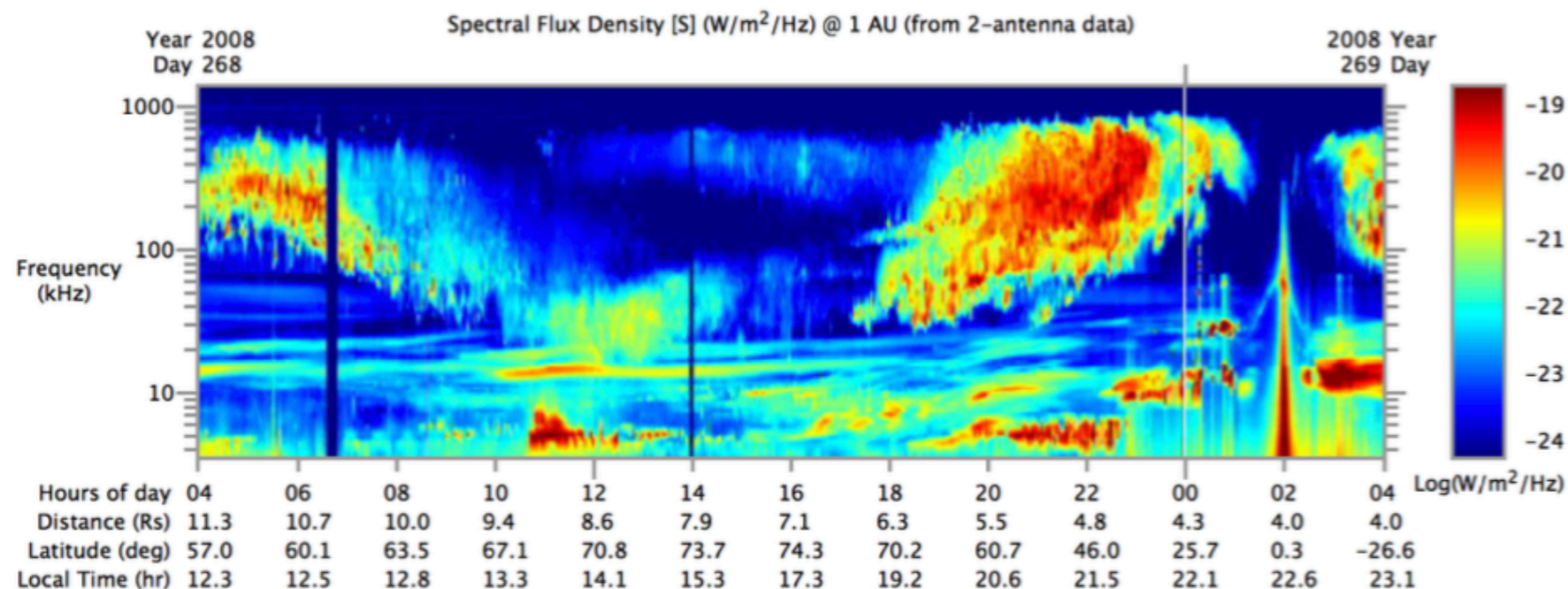
# Radioastronomy from space

- 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



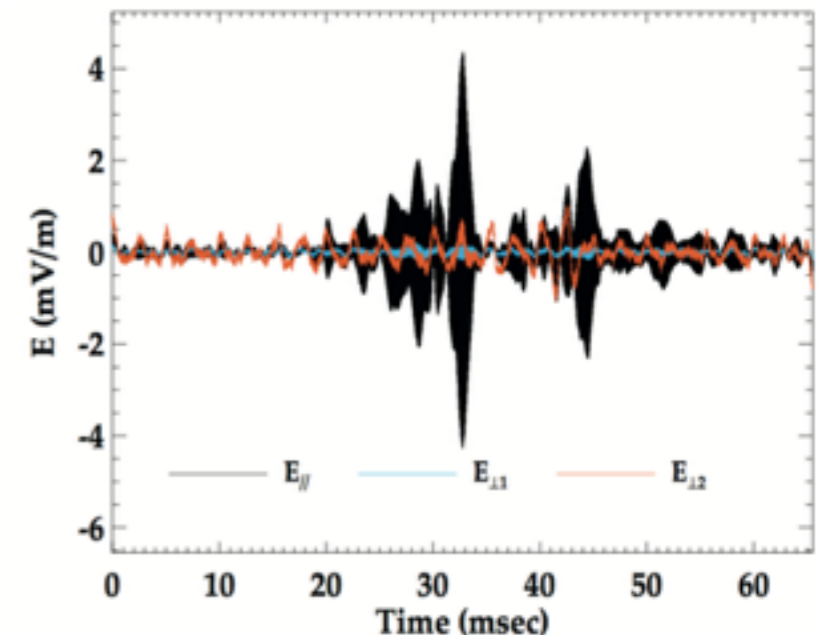
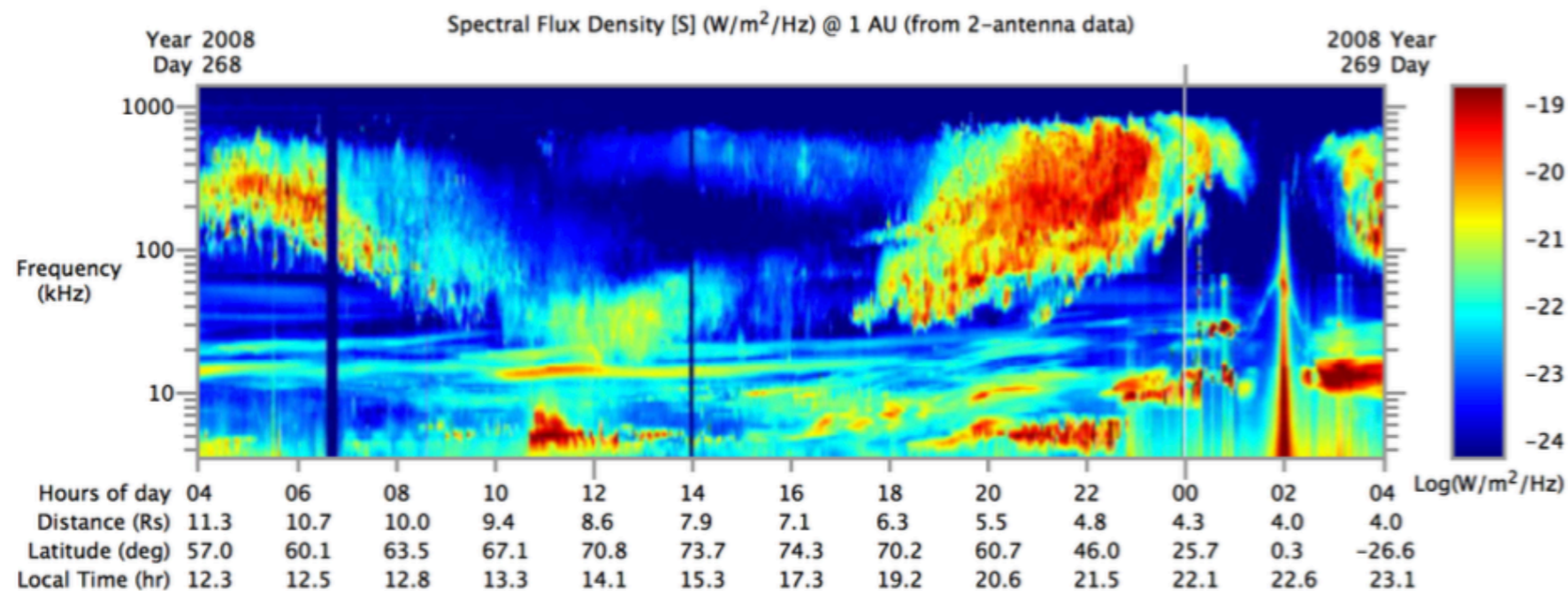
# MASER Data product types

- 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*



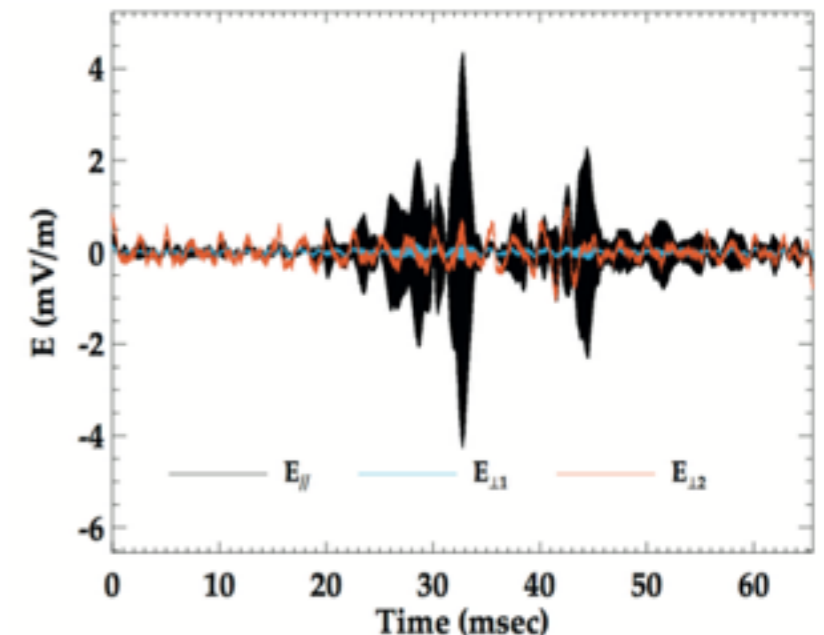
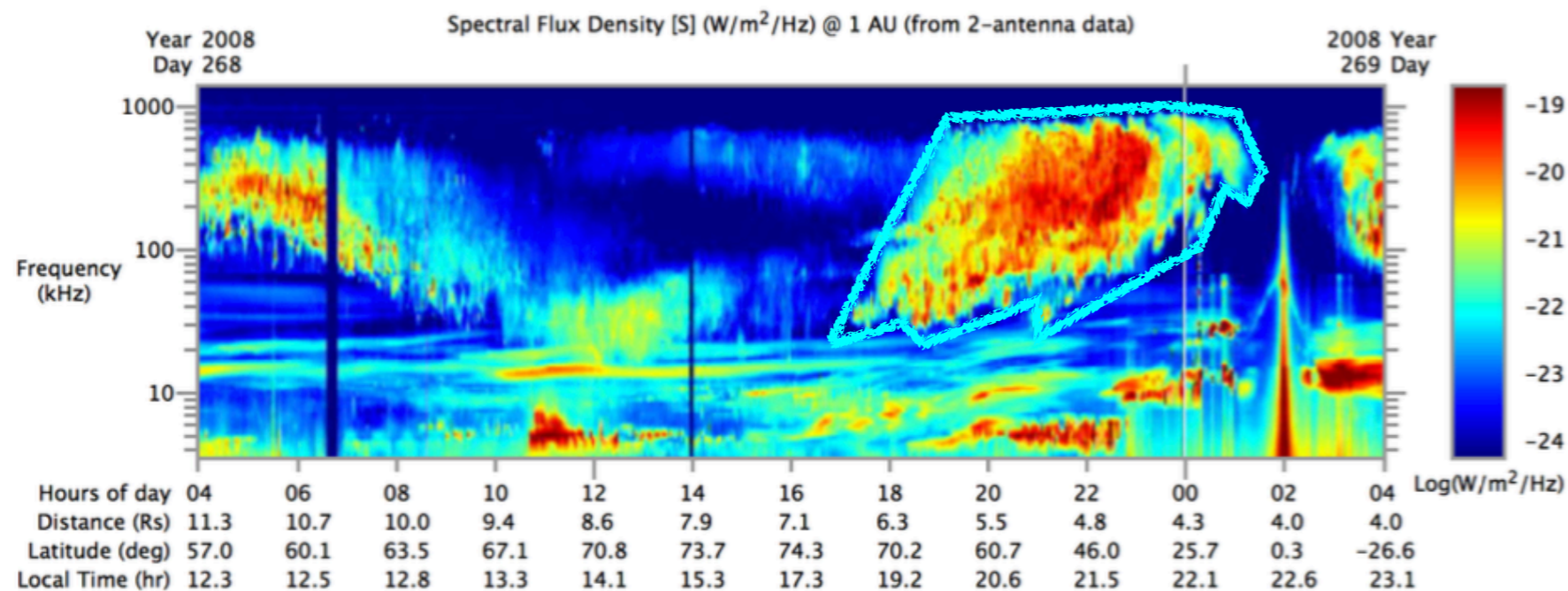
# MASER Data product types

- 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*



# MASER Data product types

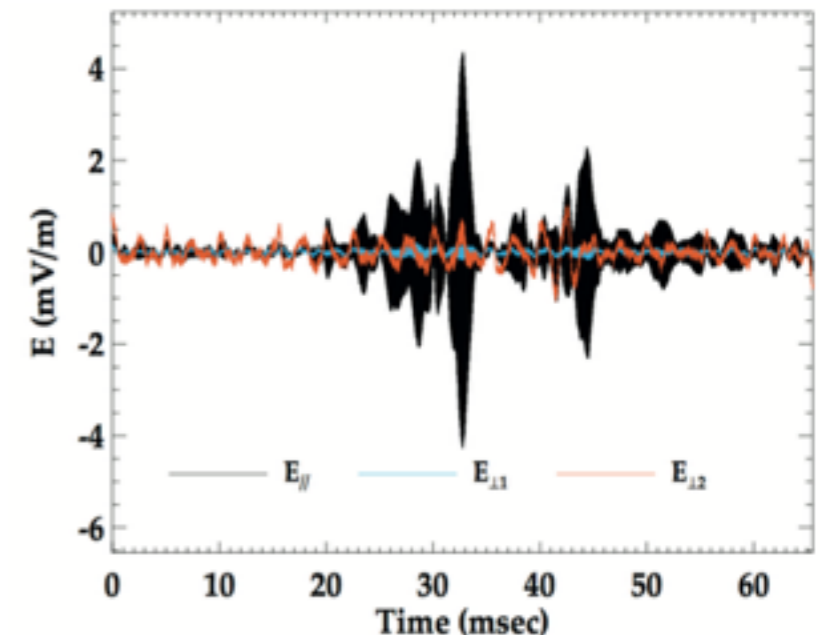
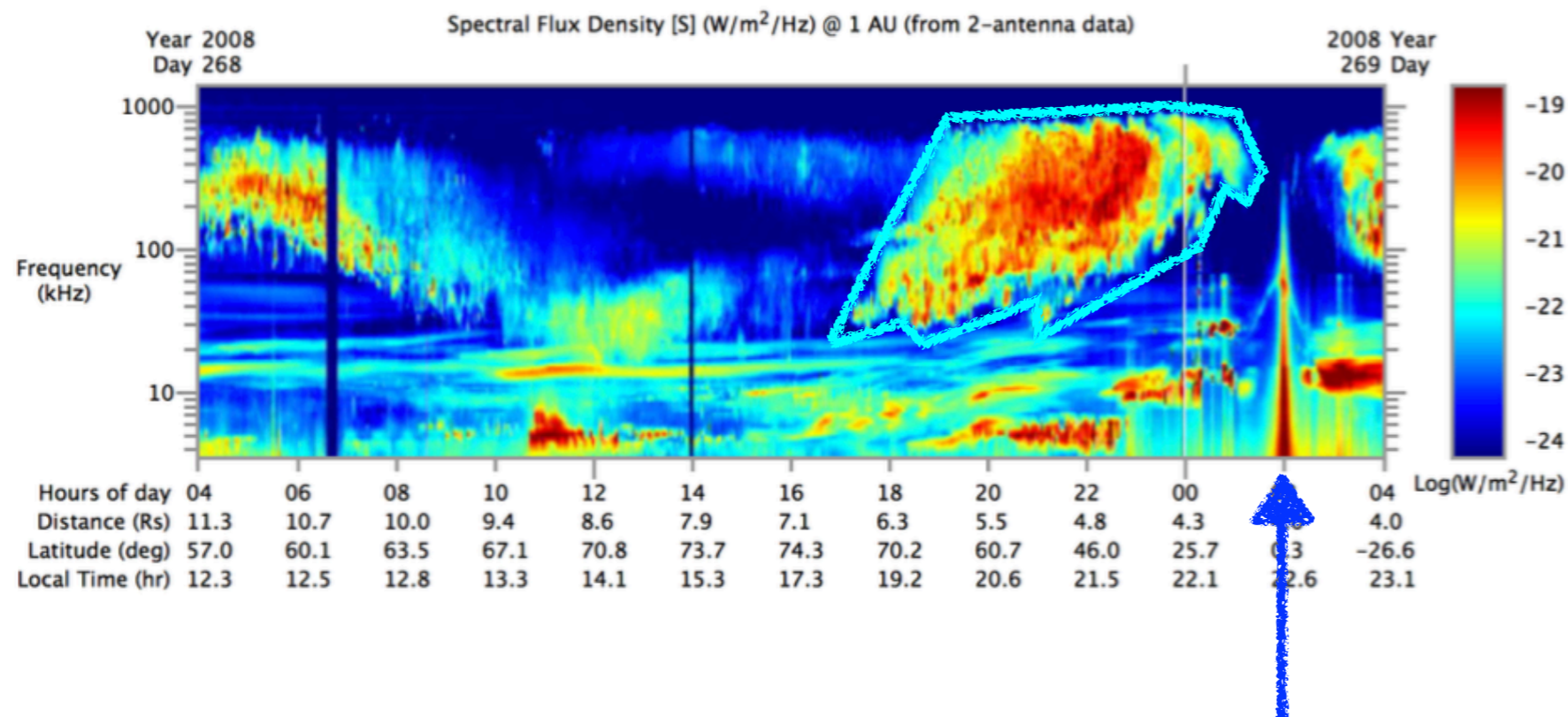
- Mostly **spectrograms**. Measured parameter (flux, polarization...) depending on time and frequency.
- Sometime: “**waveform**” (direct sampling of electric signal temporal fluctuations). Much higher data rate needed.
- also, **events**. timestamp + label + parameters (coverage) + data ? waveform snapshot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





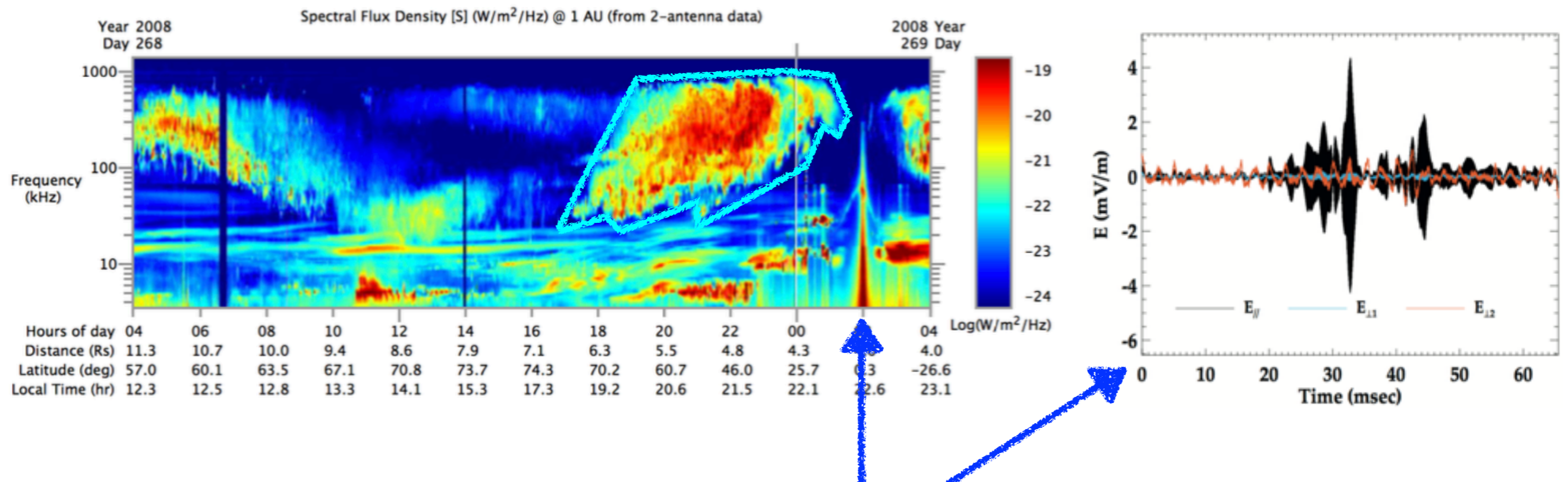
# MASER Data product types

- 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*



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

# Data volumes

- **Space data:**

about 1 spectrum ( $\sim 250$  steps \* 8 Bytes) / minute

=>  $\sim 35$  B/sec, or  $\sim 3$  MB/day

(space constraints: power, telemetry rate...)

Several decades of continuous coverage (Cassini, STEREO, Wind) are “easy” to store and share ( $\sim 20$  GB for 20 years)

Rich datasets: many processing levels

=>  $\sim 10$  TB for the Cassini/RPWS/HFR instrument full mission dataset

- **Ground data:**

about 100 spectra (15000 steps \* 16 Bytes) / second

=>  $\sim 30$  MB/sec, or  $\sim 2$  TB/day

Specific solutions needed for remote access of data.

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

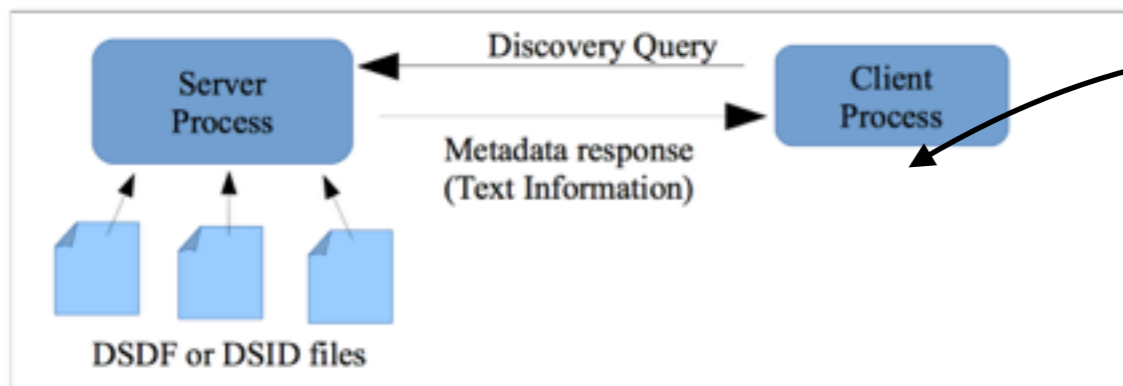
# Software library: MASER

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

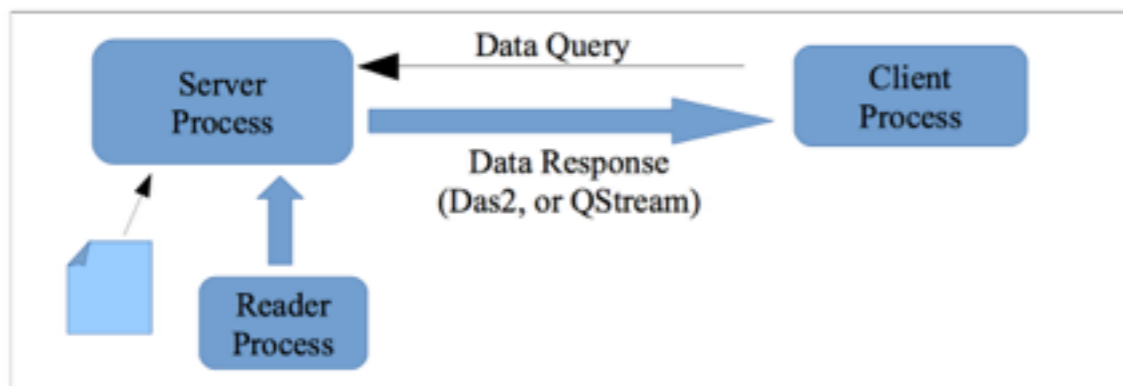
# Data on demand

- **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>

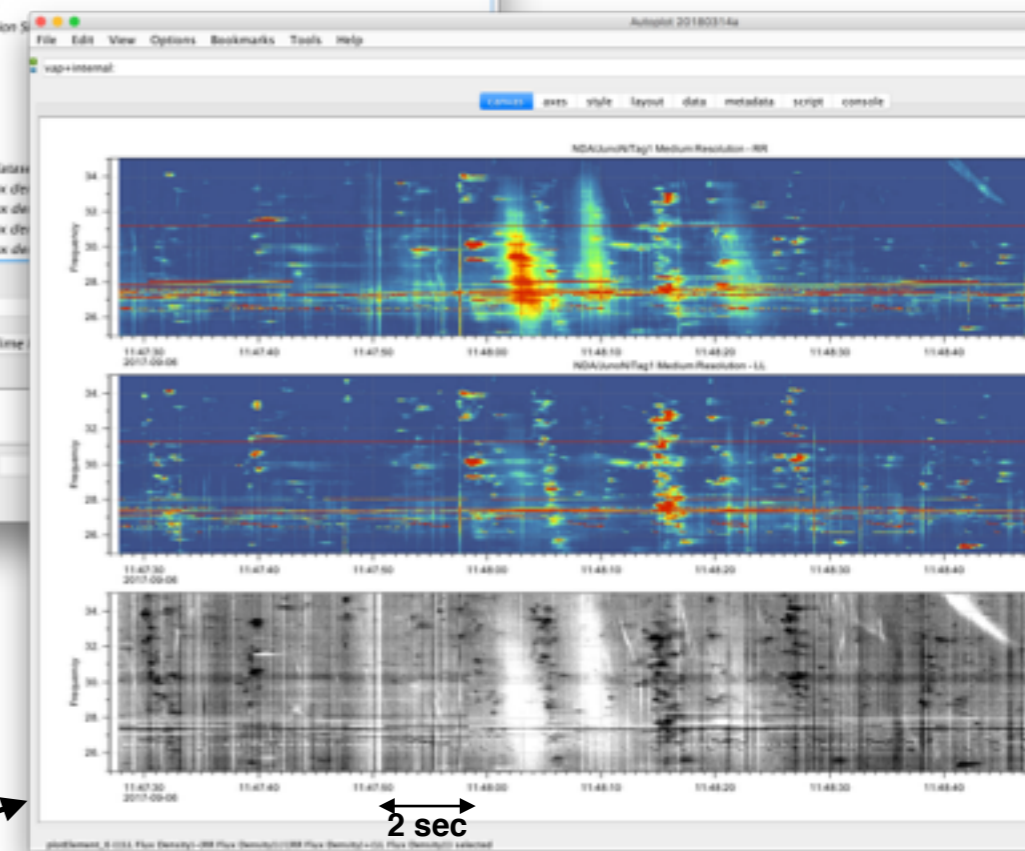
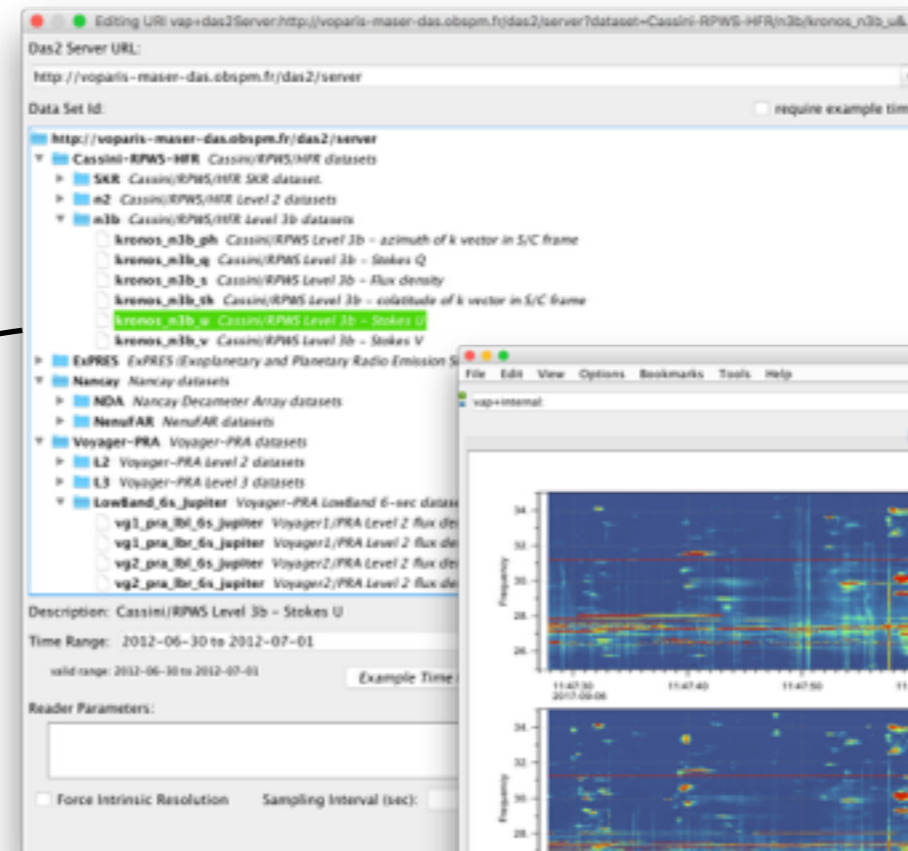
# Das2 / Autoplots process



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



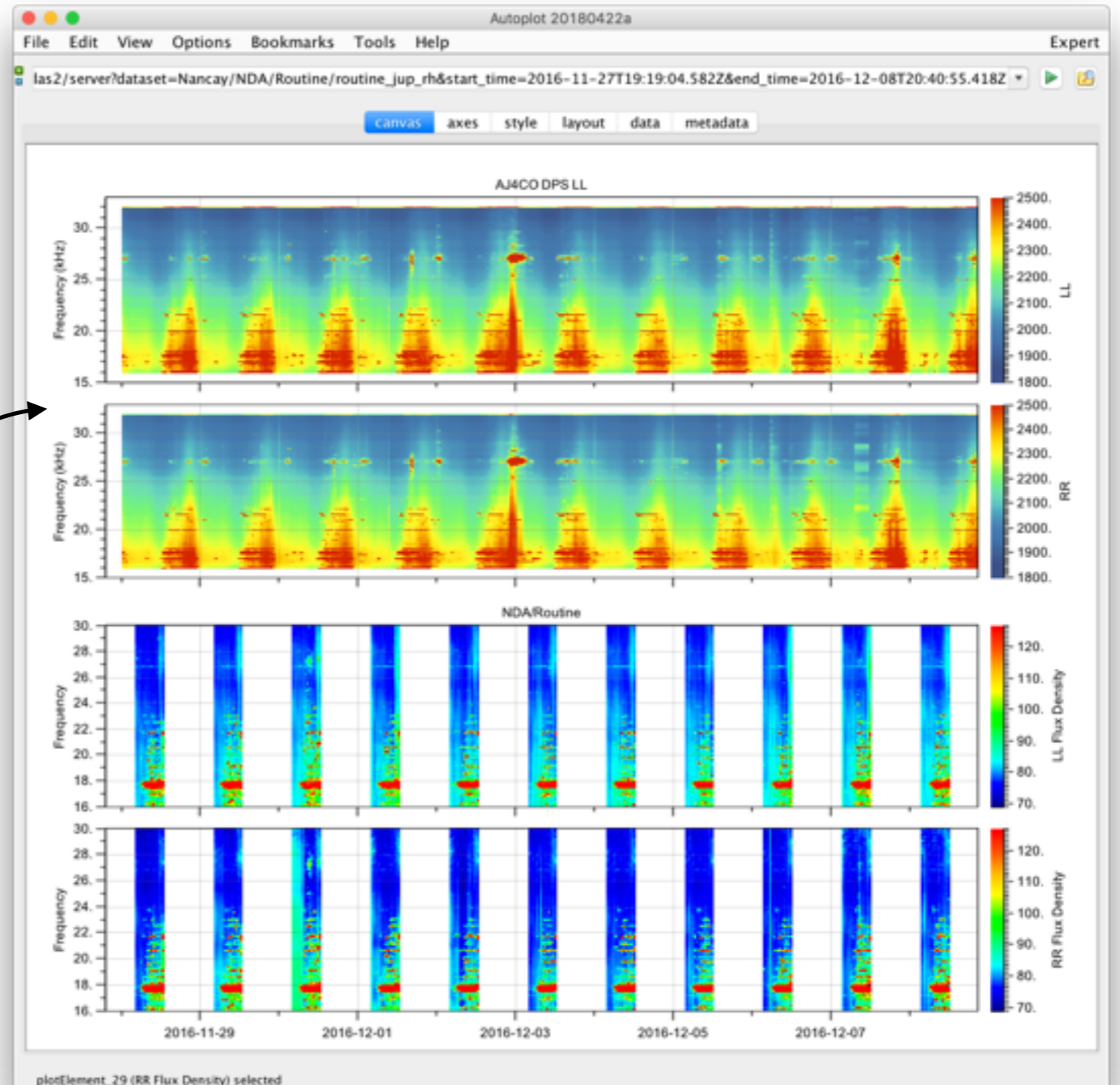
# Examples

- Pro + Amateurs
- Ground + Space
- Old missions

# Examples

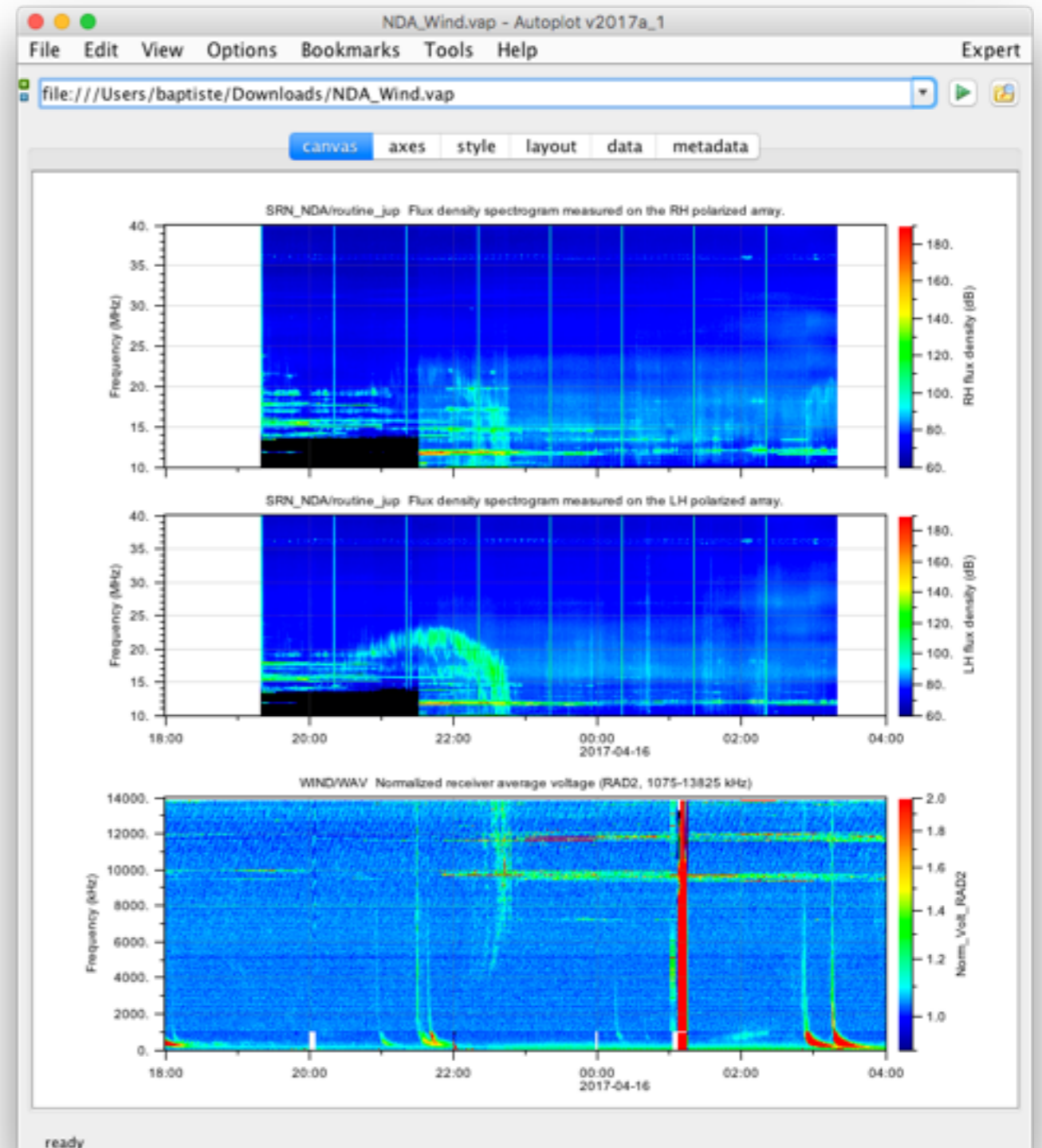
- Pro + Amateurs
- Ground + Space
- Old missions

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



# Examples

- Pro + Amateurs
- Ground + Space
- Old missions

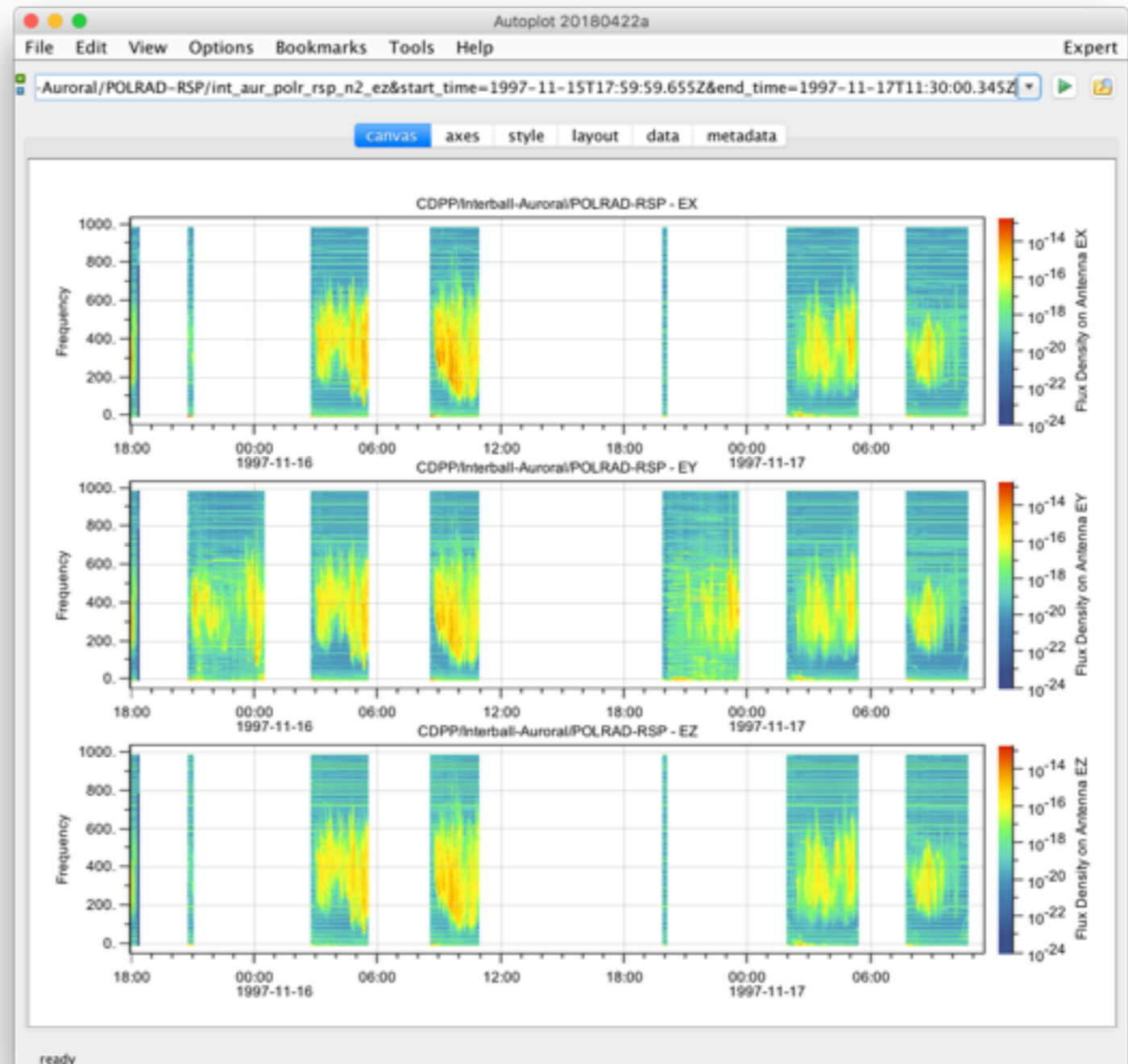


Nançay Decameter Array

Wind/Waves

# Examples

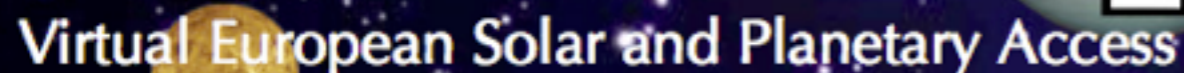
- Pro + Amateurs
- Ground + Space
- Old missions



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...)

The logo for VESPA, consisting of the letters 'VESPA' in a bold, white, sans-serif font.The full name of the project, 'Virtual European Solar and Planetary Access', written in a smaller white font below the logo.

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

**Results in service NDA Obs. Database**

Show 10 entries

Column visibility Show all Hide all

Select All in current page Reset Selection

granule_uid	dataproduct_type	target_name	time_min (d)	time_max (d)	access_url
J991231_rt1	dynamic_spectrum	Jupiter	1999-12-31T14:48:00.219	1999-12-31T22:47:59.280	http://realtime.obs-...
J991231_pdf	dynamic_spectrum	Jupiter	1999-12-31T14:48:00.219	1999-12-31T22:47:59.280	http://realtime.obs-...
J991231_cdf	dynamic_spectrum	Jupiter	1999-12-31T14:48:00.219	1999-12-31T22:47:59.280	http://realtime.obs-...
J991230_rt1	dynamic_spectrum	Jupiter	1999-12-30T14:51:00.199	1999-12-30T22:50:59.260	http://realtime.obs-...
J991230_pdf	dynamic_spectrum	Jupiter	1999-12-30T14:51:00.199	1999-12-30T22:50:59.260	http://realtime.obs-...
J991230_cdf	dynamic_spectrum	Jupiter	1999-12-30T14:51:00.199	1999-12-30T22:50:59.260	http://realtime.obs-...
J991229_rt1	dynamic_spectrum	Jupiter	1999-12-29T14:55:00.090	1999-12-29T22:54:59.140	http://realtime.obs-...
J991229_pdf	dynamic_spectrum	Jupiter	1999-12-29T14:55:00.090	1999-12-29T22:54:59.140	http://realtime.obs-...
J991229_cdf	dynamic_spectrum	Jupiter	1999-12-29T14:55:00.090	1999-12-29T22:54:59.140	http://realtime.obs-...
J991228_rt1	dynamic_spectrum	Jupiter			

Showing 1 to 10 of 26,046 entries 1 row selected

Data Selection Metadata Selection All Data All Meta

© Paris Observatory 2012  
Contact : support.apnta

of 2605  
Previous Next Last  
Footprints-  
eur PLANET

**Plotting tools**

- TOPCAT
- Aladin
- SPLAT
- CASSIS
- 3DView

**Example queries**

Saturn in March 2012

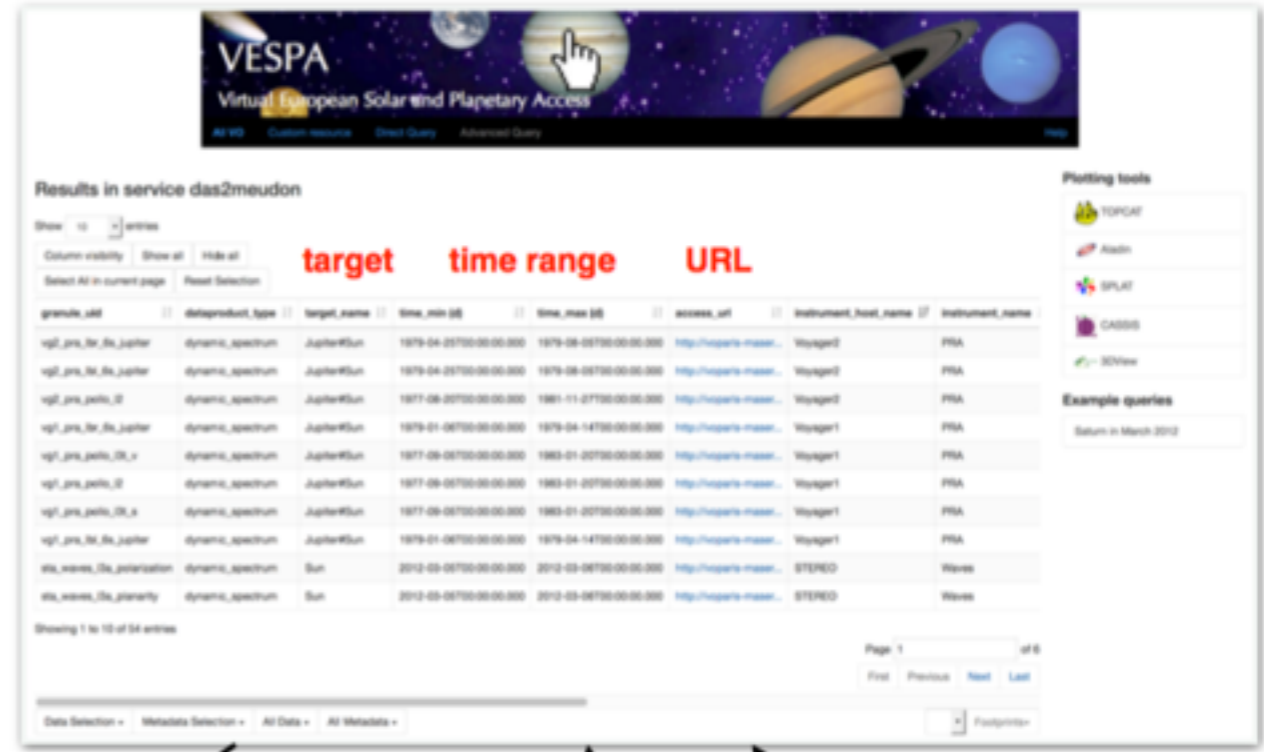
## Sharing data products:

- data files
- quicklook images
- data access webservice

VESPA result page in Nançay/NDA EPN-TAP service



VESPA result page for all das2server dataset in Meudon



`mtype=load.table.cdf`

`mtype=load.table.das2`

next: distribute .vap files

SAMP hub

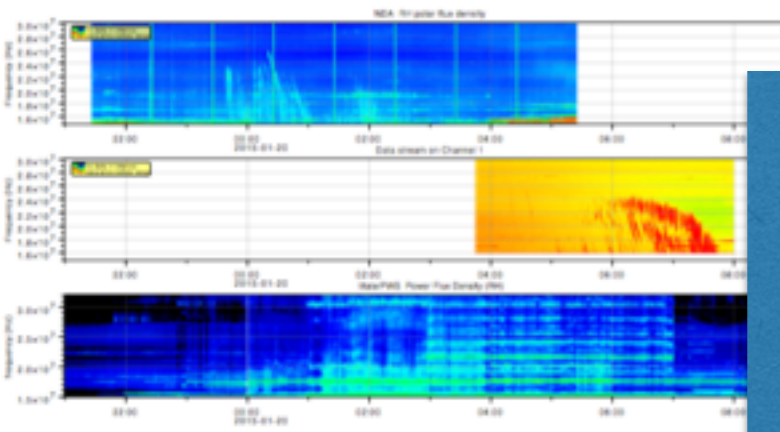
das2 dataset discovery feature

das2 dataset publication through VESPA

Das2 server catalog in Autoplot

Data Selector

Plot

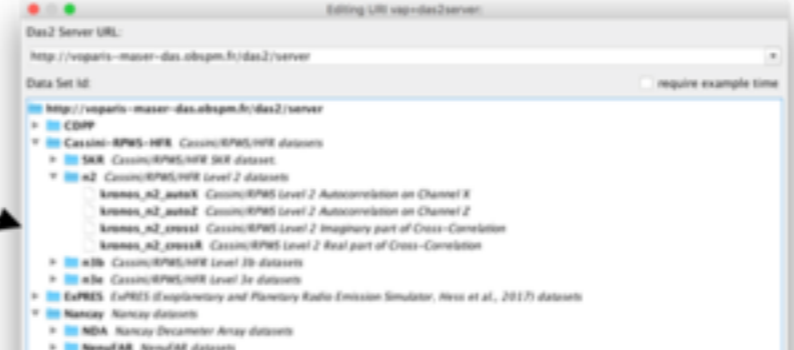


Sharing data products:

- data files
- quicklook images
- data access webservice



Das2 server block diagram



VESPA result page in Nançay/NDA EPN-TAP service



VESPA result page for all das2server dataset in Meudon



`mtype=load.table.cdf`

`mtype=load.table.das2`

next: distribute .vap files

SAMP hub

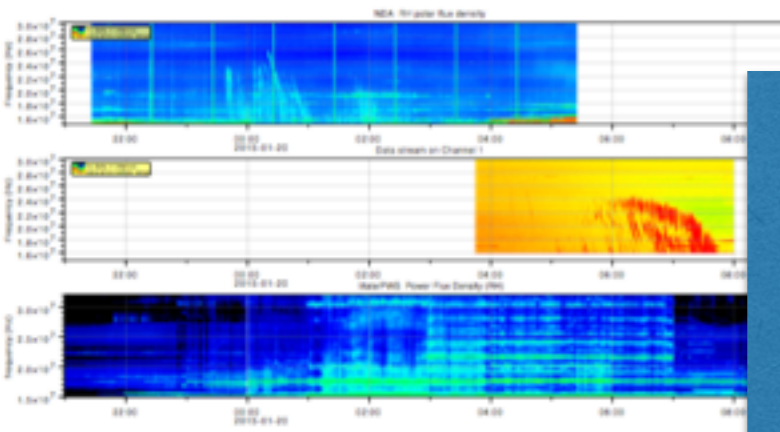
das2 dataset discovery feature

das2 dataset publication through VESPA

Das2 server catalog in Autoplot

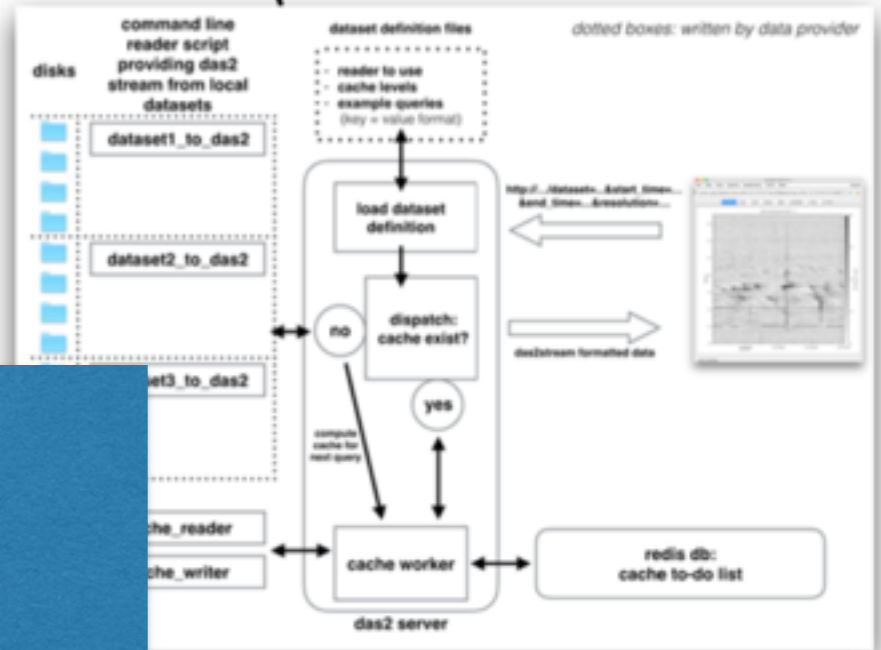
Data Selector

Plot



**Sharing data products:**

- data files
- quicklook images
- data access webservice



Das2 server block diagram



VESPA result page in Nançay/NDA EPN-TAP service



VESPA result page for all das2server dataset in Meudon



mtime=load.table.cdf

mtime=load.table.das2

next: distribute .vap files

SAMP hub

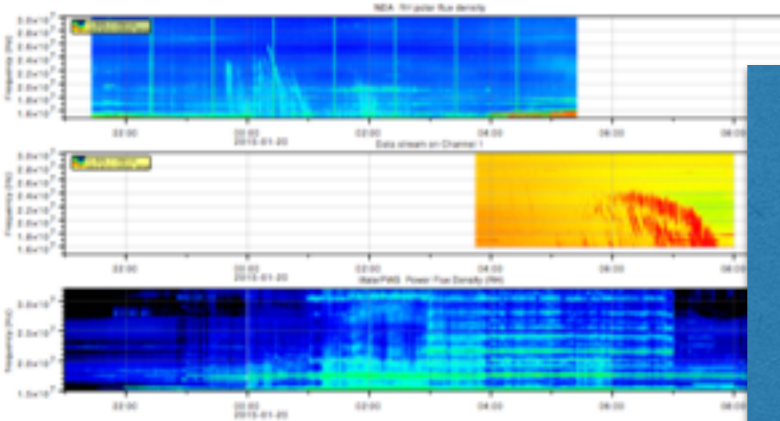
das2 dataset discovery feature

das2 dataset publication through VESPA

Das2 server catalog in Autoplot

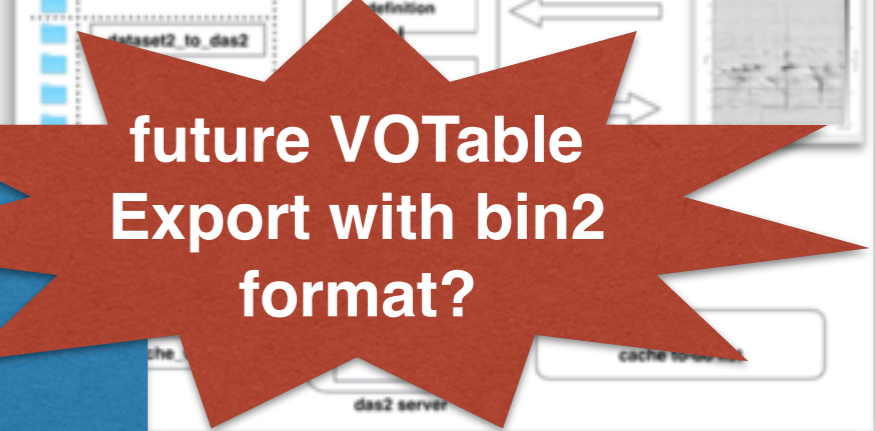
Data Selector

Plot



Sharing data products:

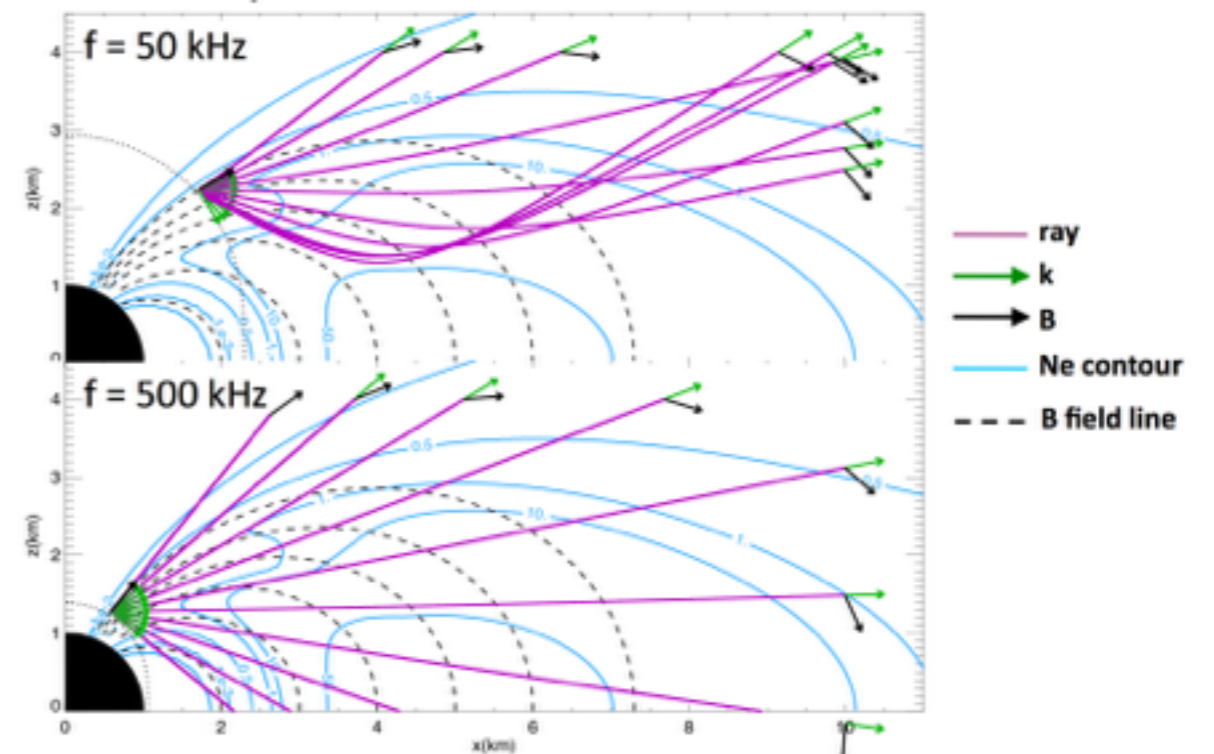
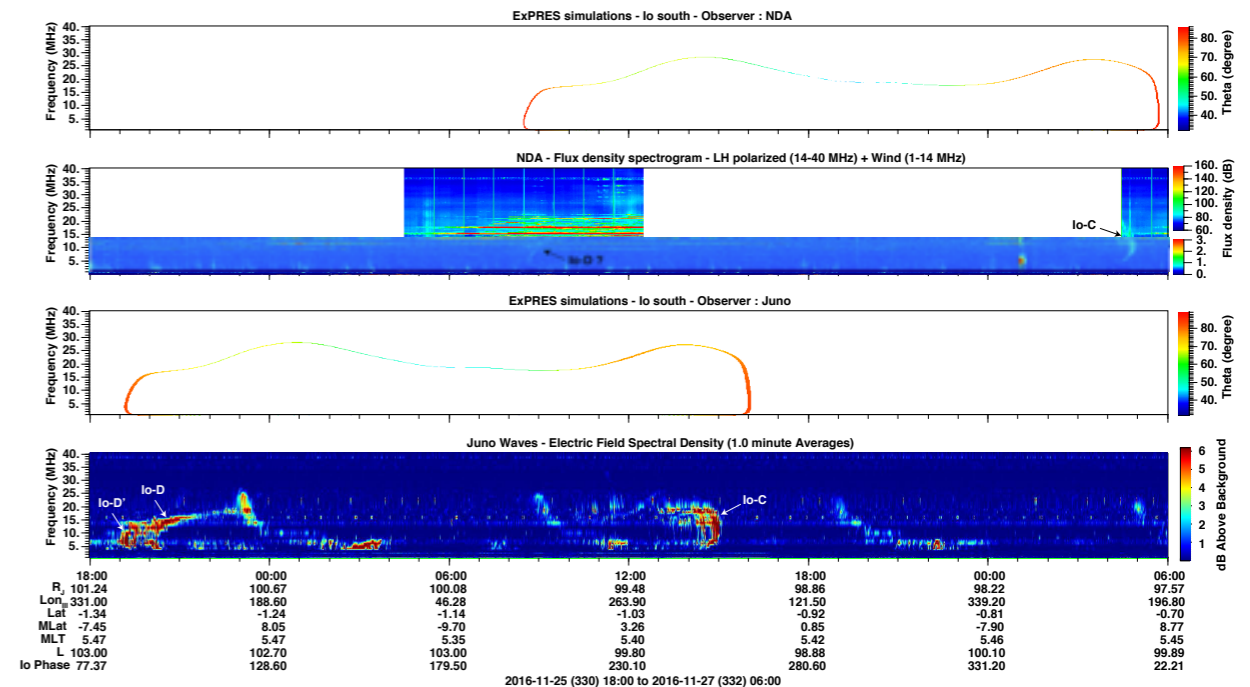
- data files
- quicklook images
- data access webservice



Das2 server block diagram

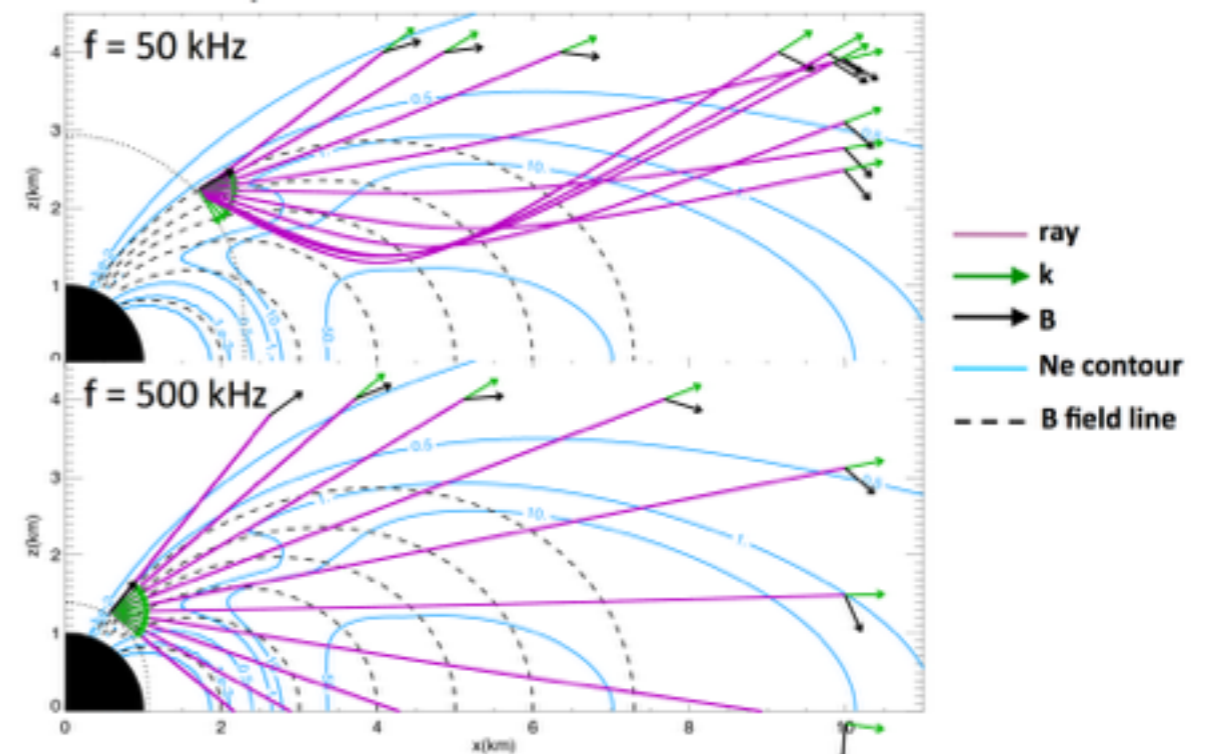
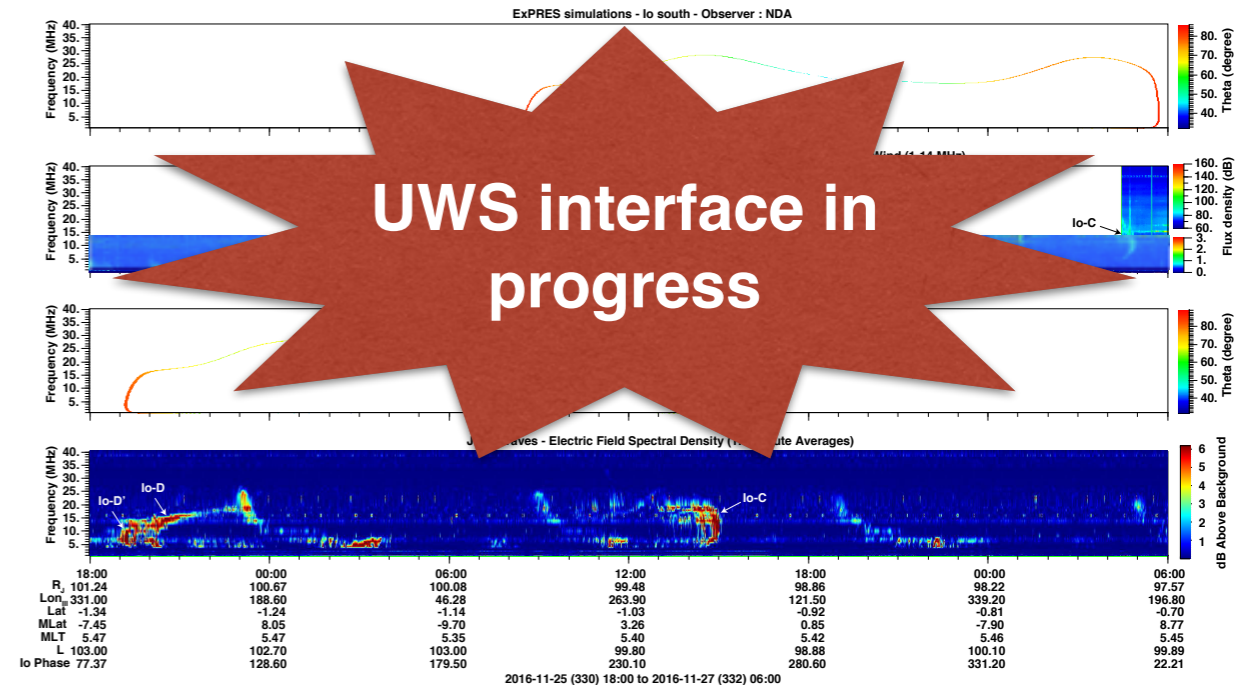
# Simulation and modeling

- 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)*



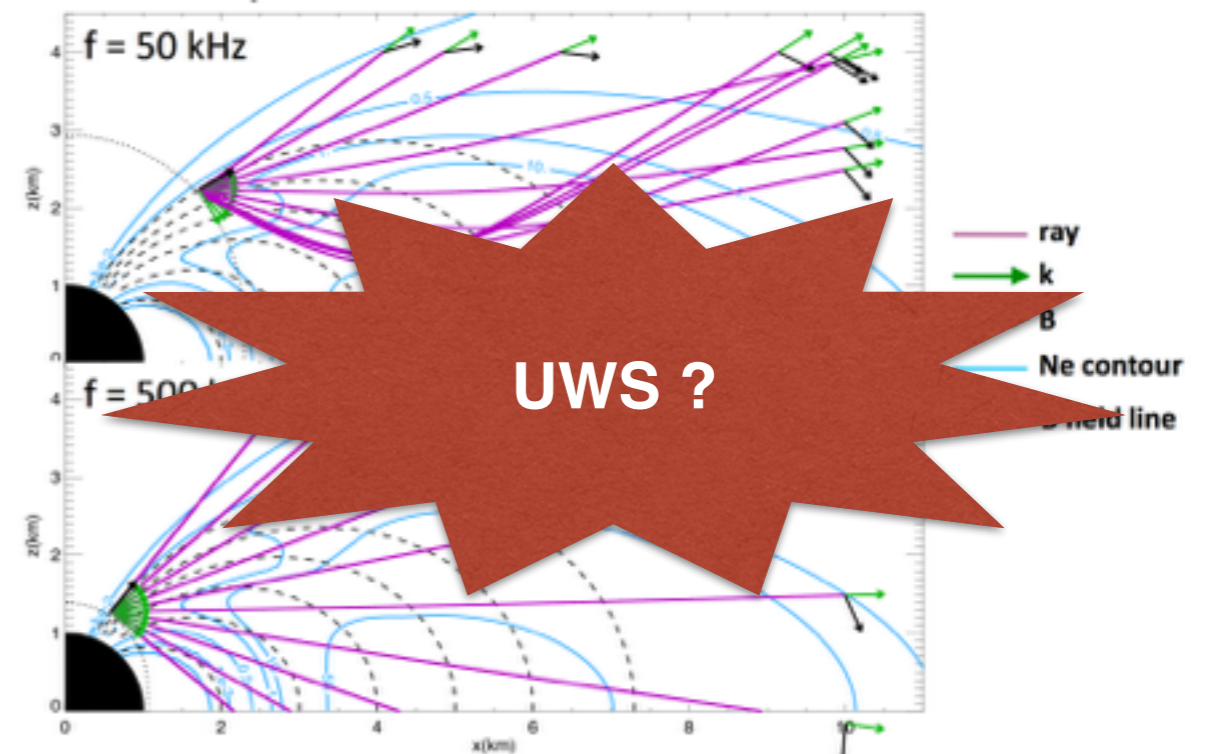
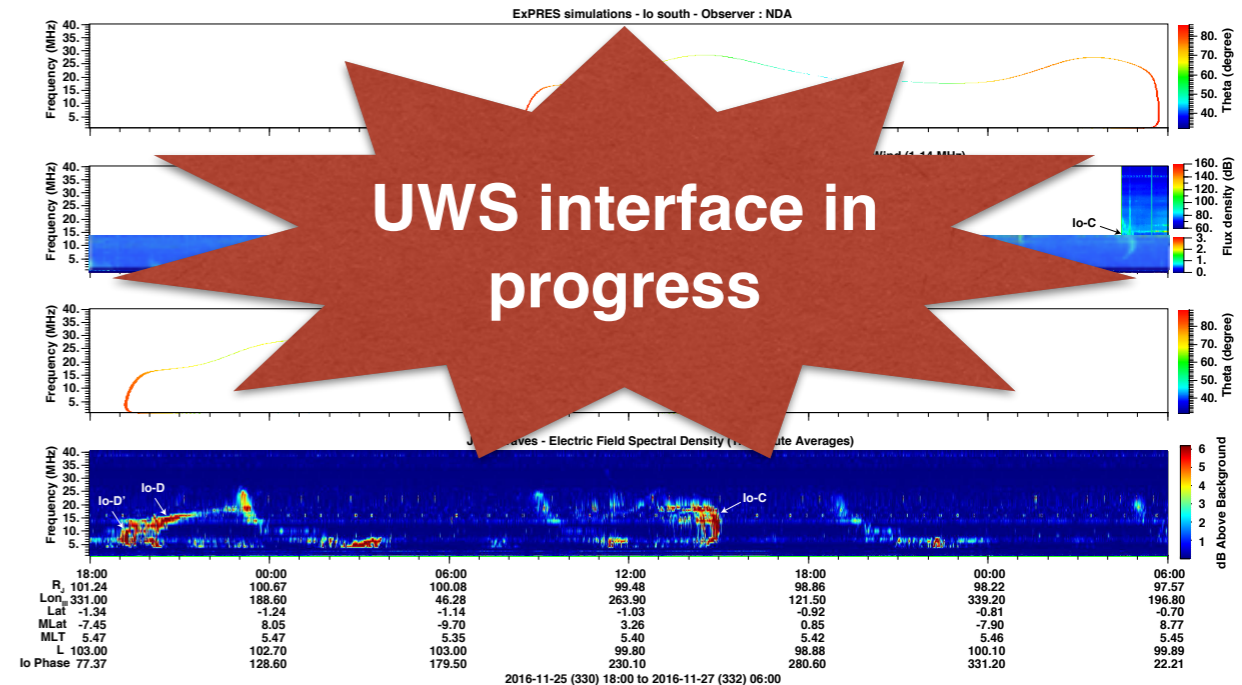
# Simulation and modeling

- 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)*



# 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)*

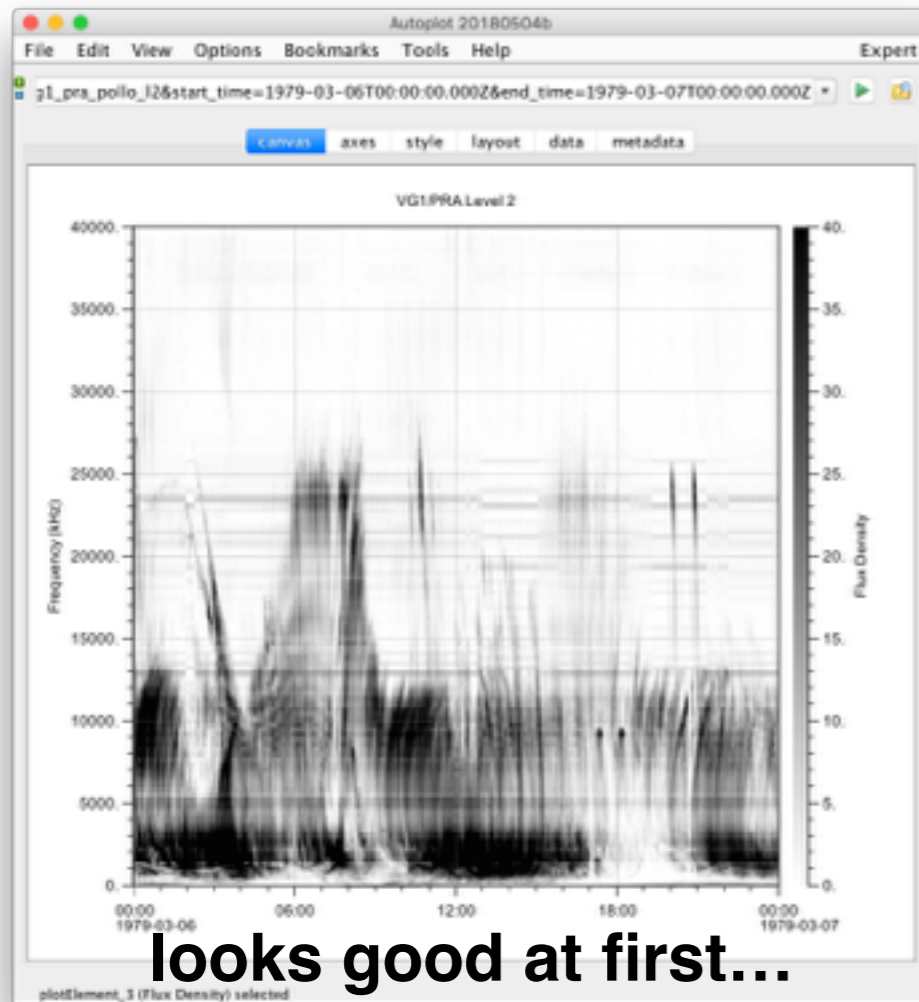


# Applications

- 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

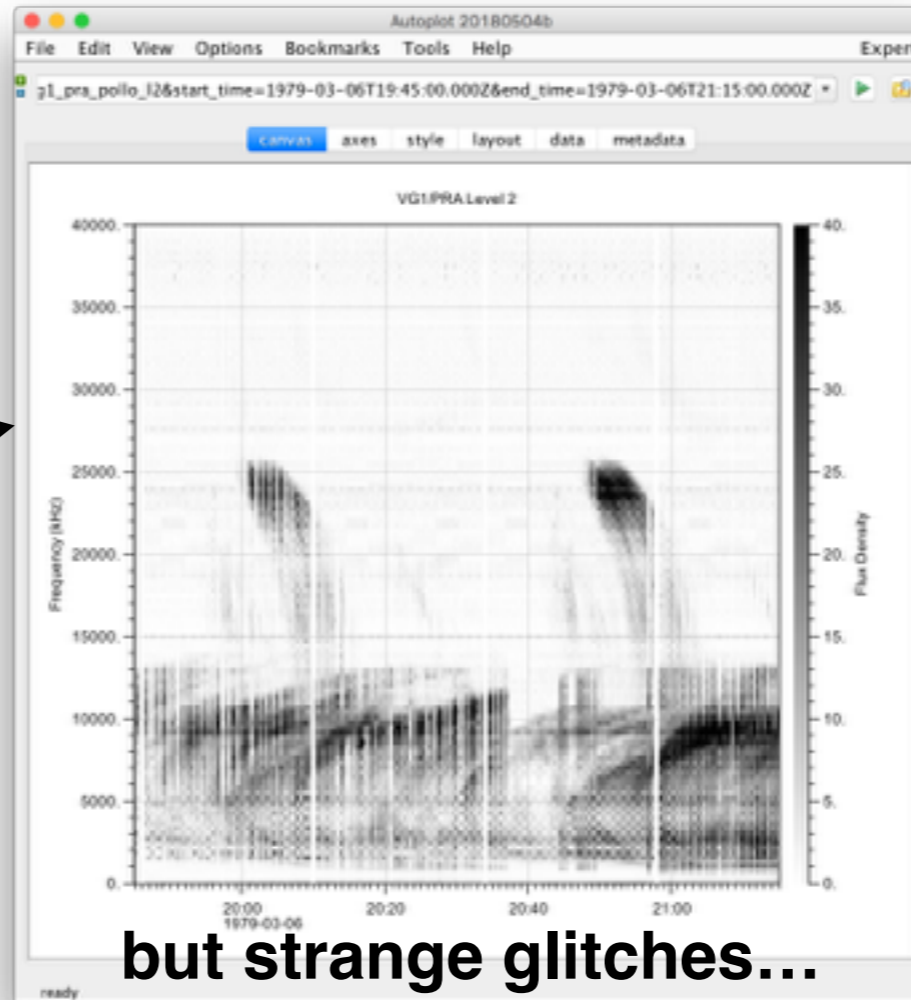
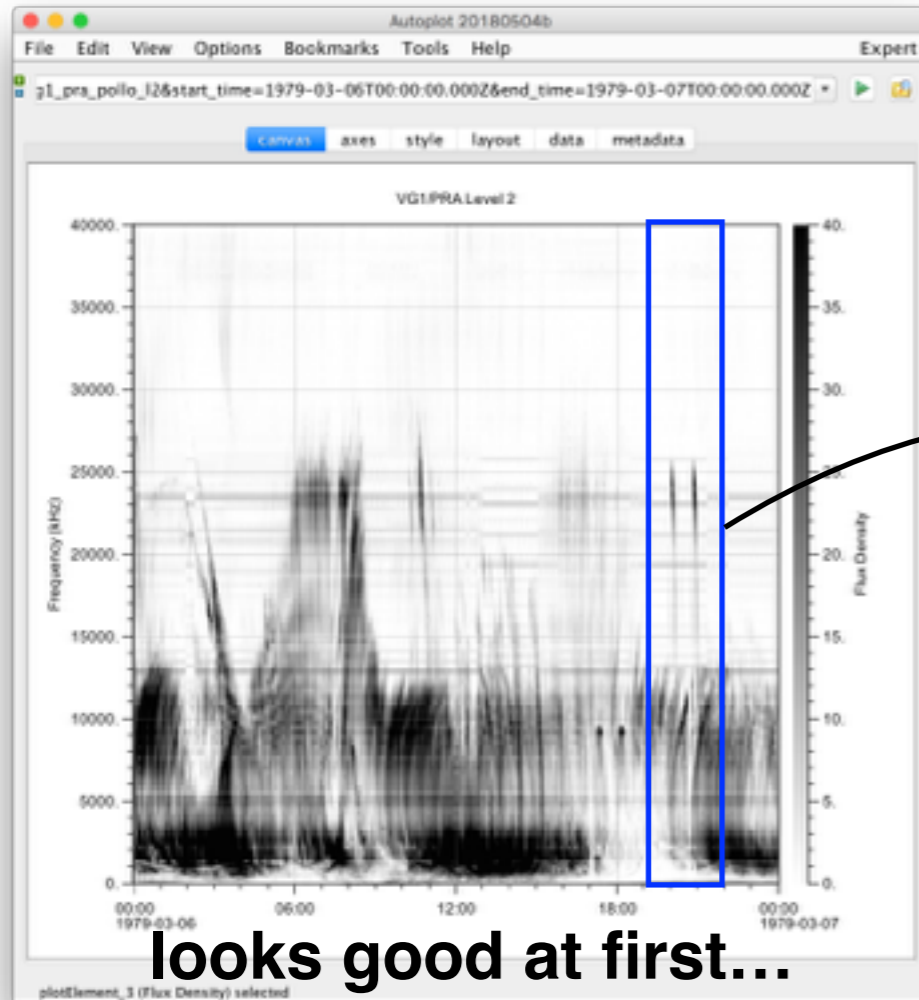
# Validation of CNES Voyager-PRA data

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



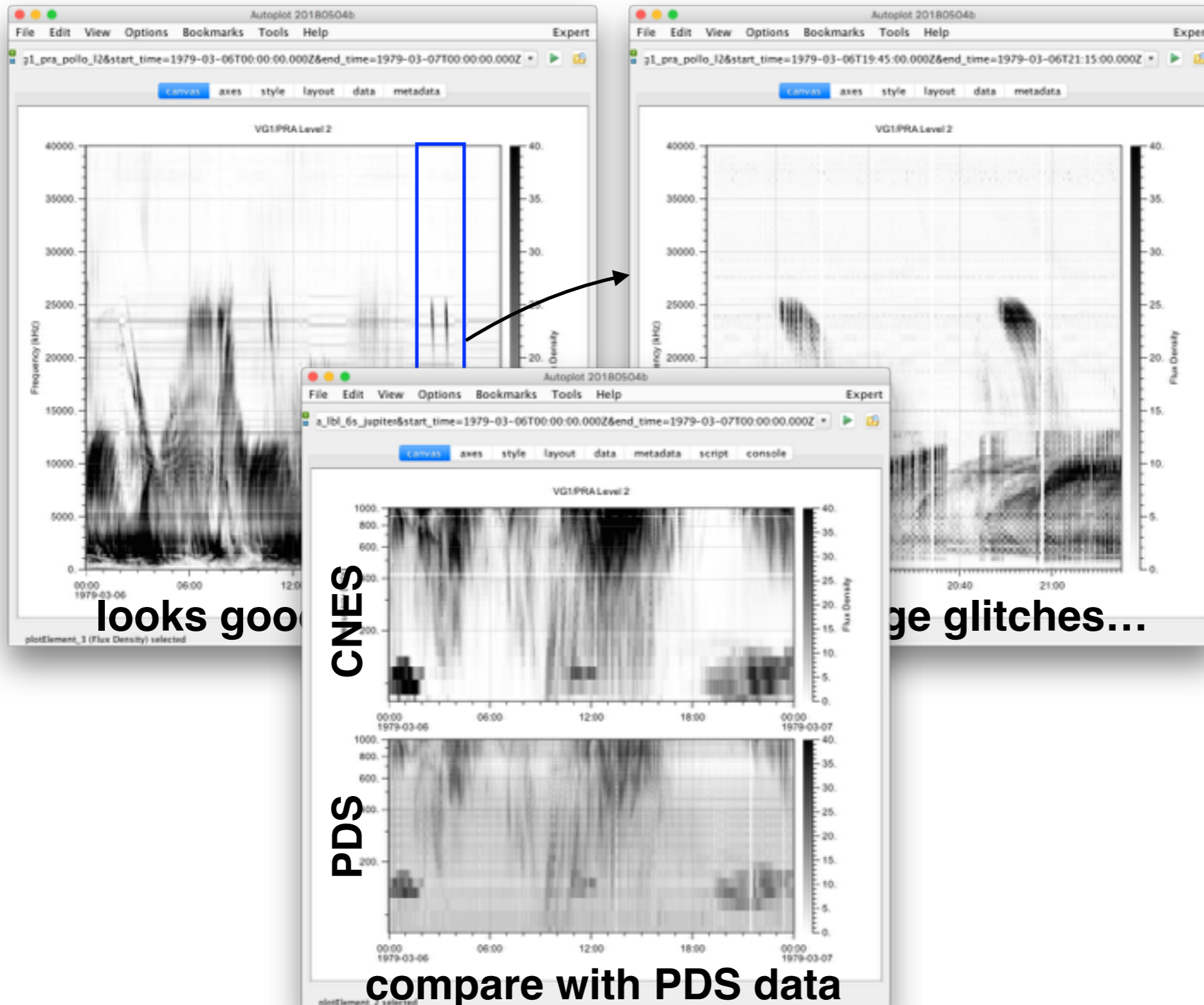
# Validation of CNES Voyager-PRA data

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



# Validation of CNES Voyager-PRA data

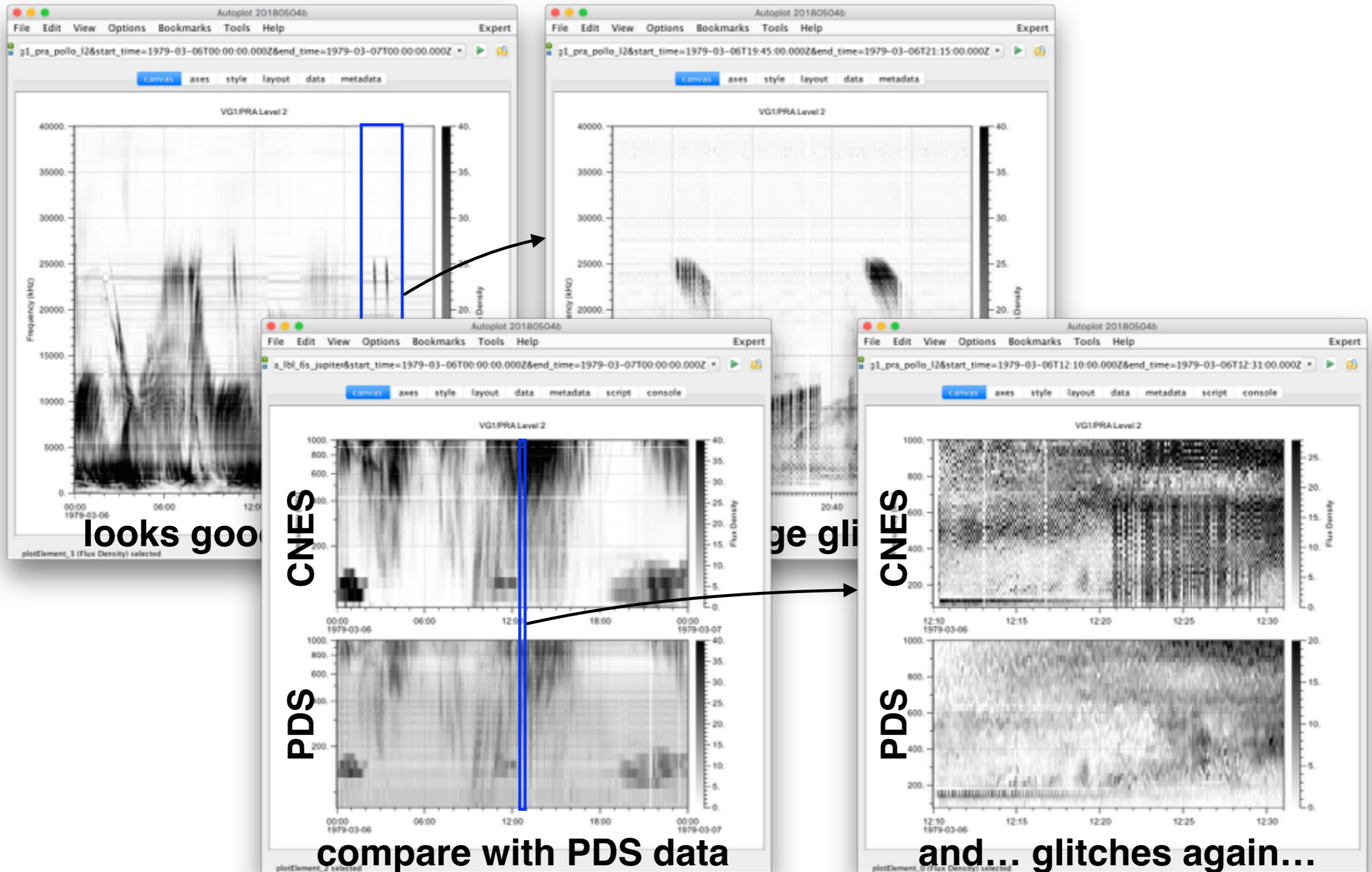
Using *Das2/Autoplot* + *Maser4py* reader modules for *CNES* and *PDS* datasets





# Validation of CNES Voyager-PRA data

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

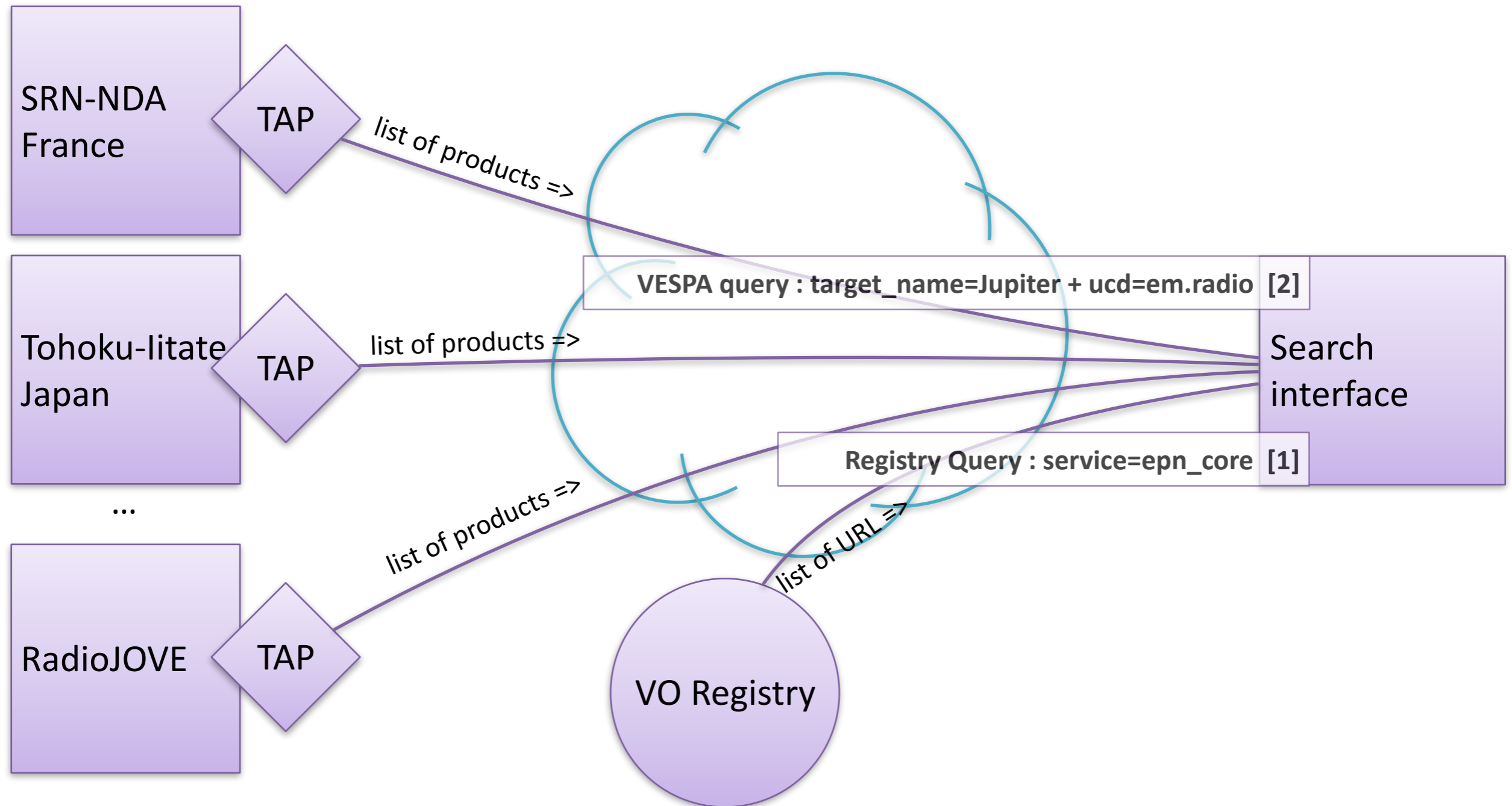


# Juno-Ground-Radio observation support group

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

## Data providers

## Users

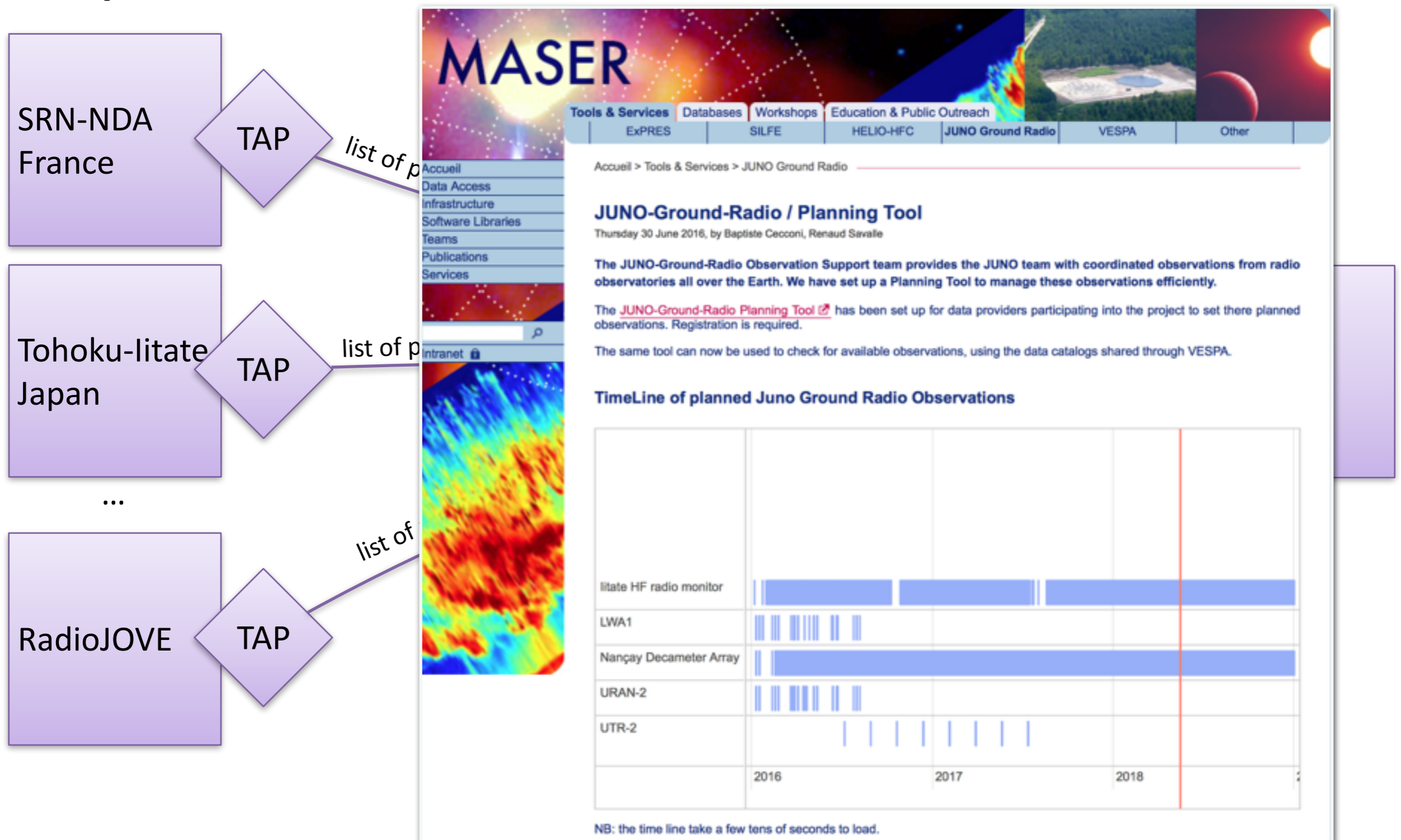


# Juno-Ground-Radio observation support group

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

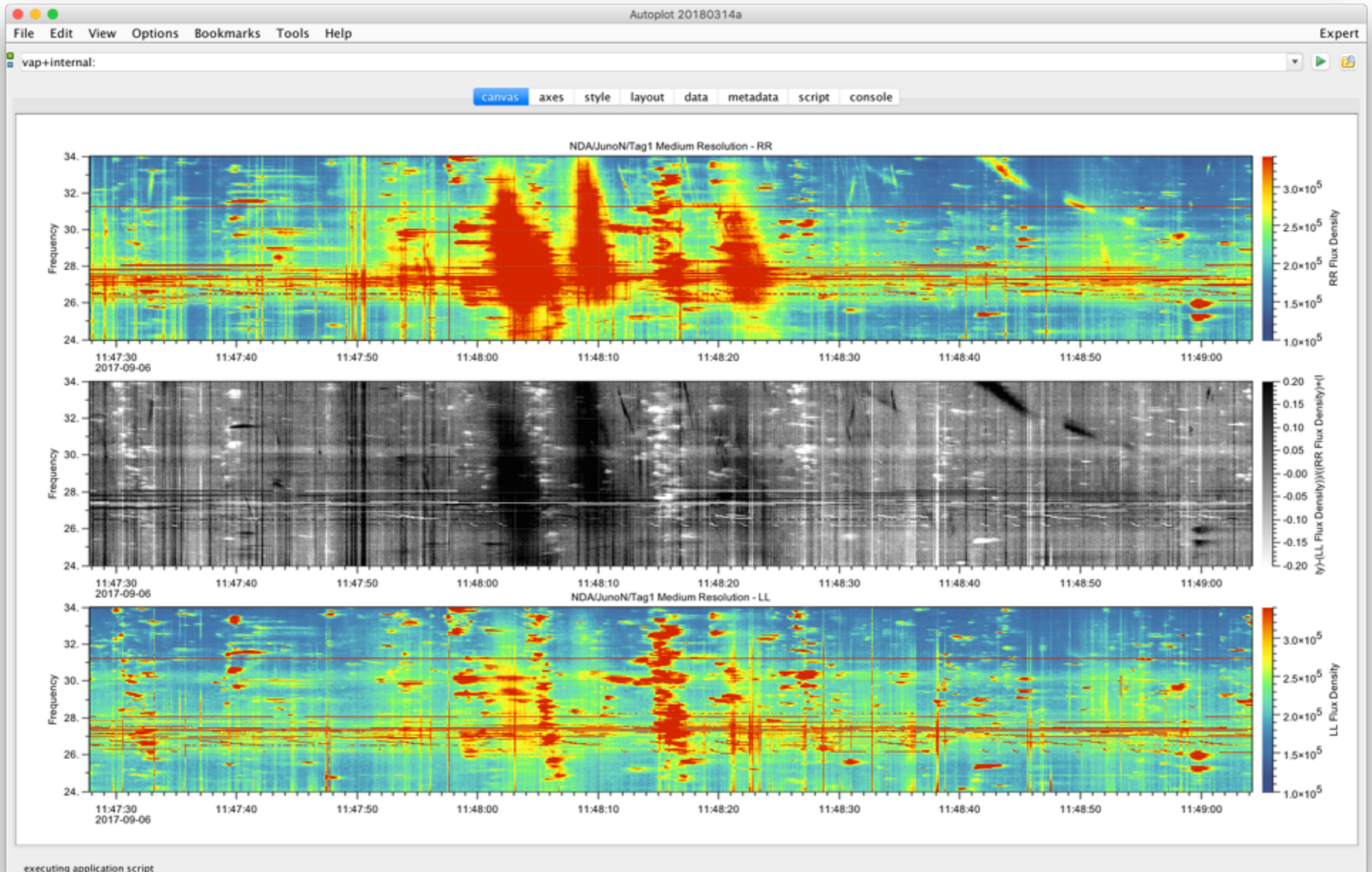
## Data providers

## Users



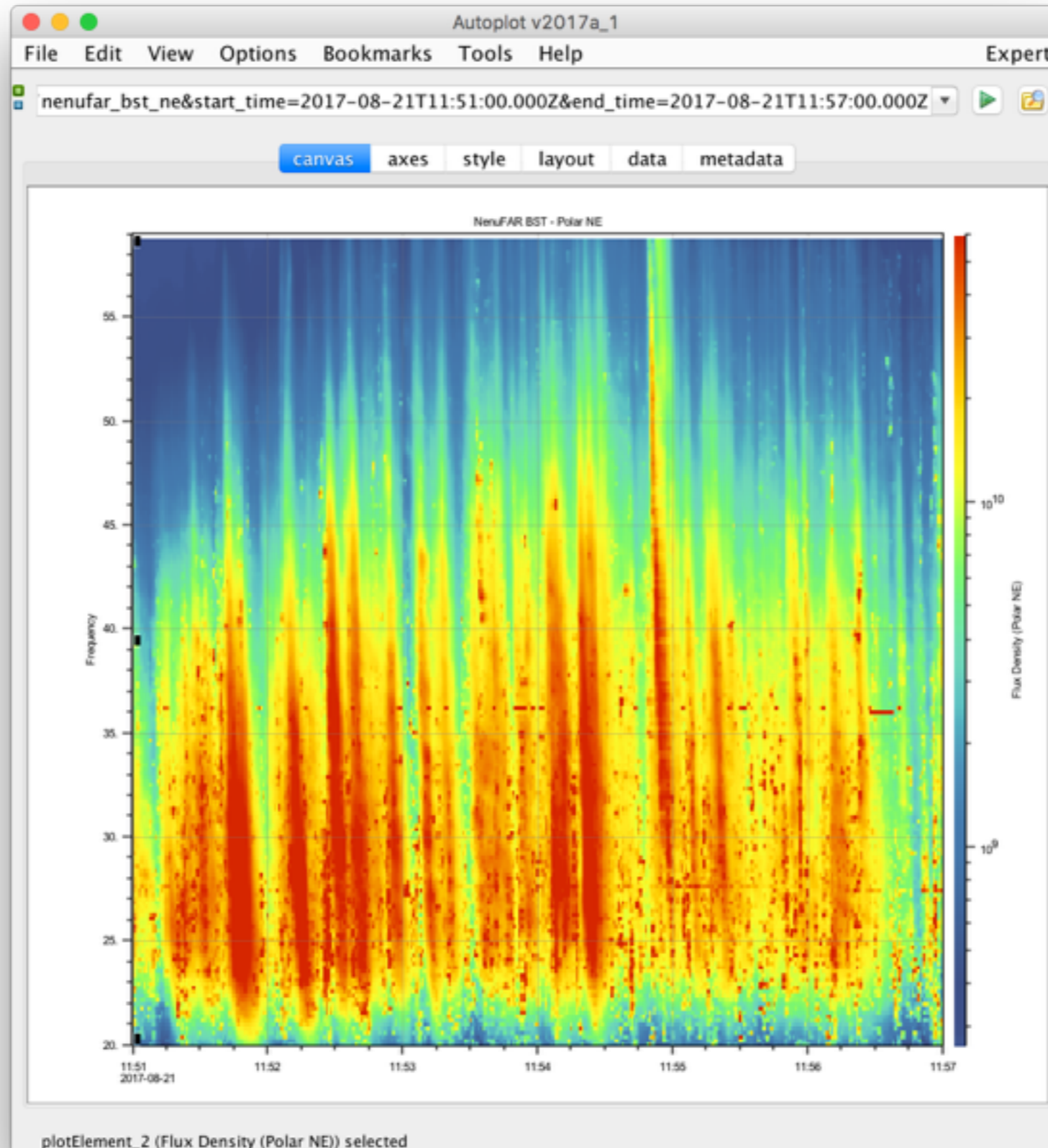
# Browse high resolution datasets

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



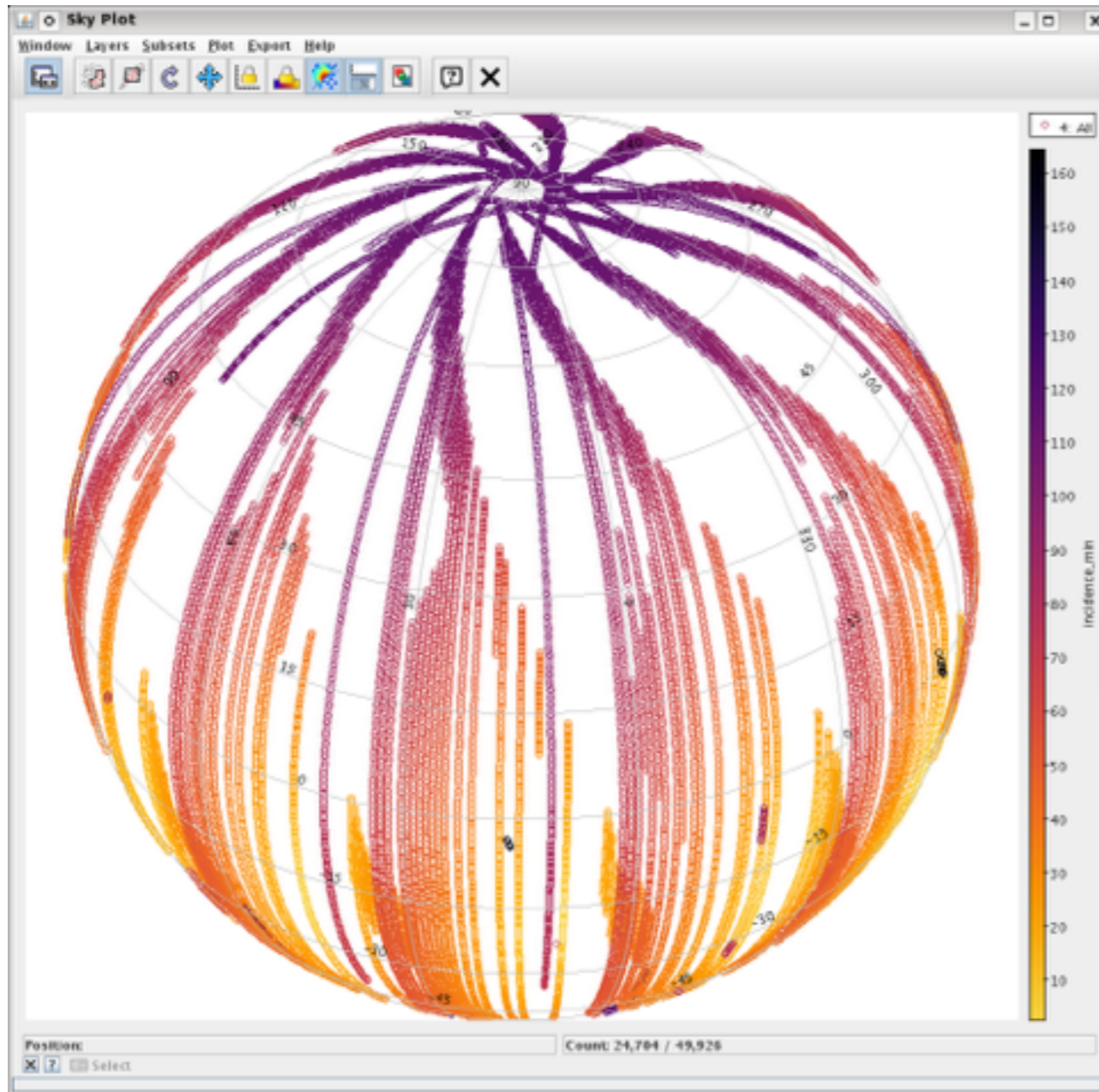
# NenuFAR (a SKA precursor) commissioning phase

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

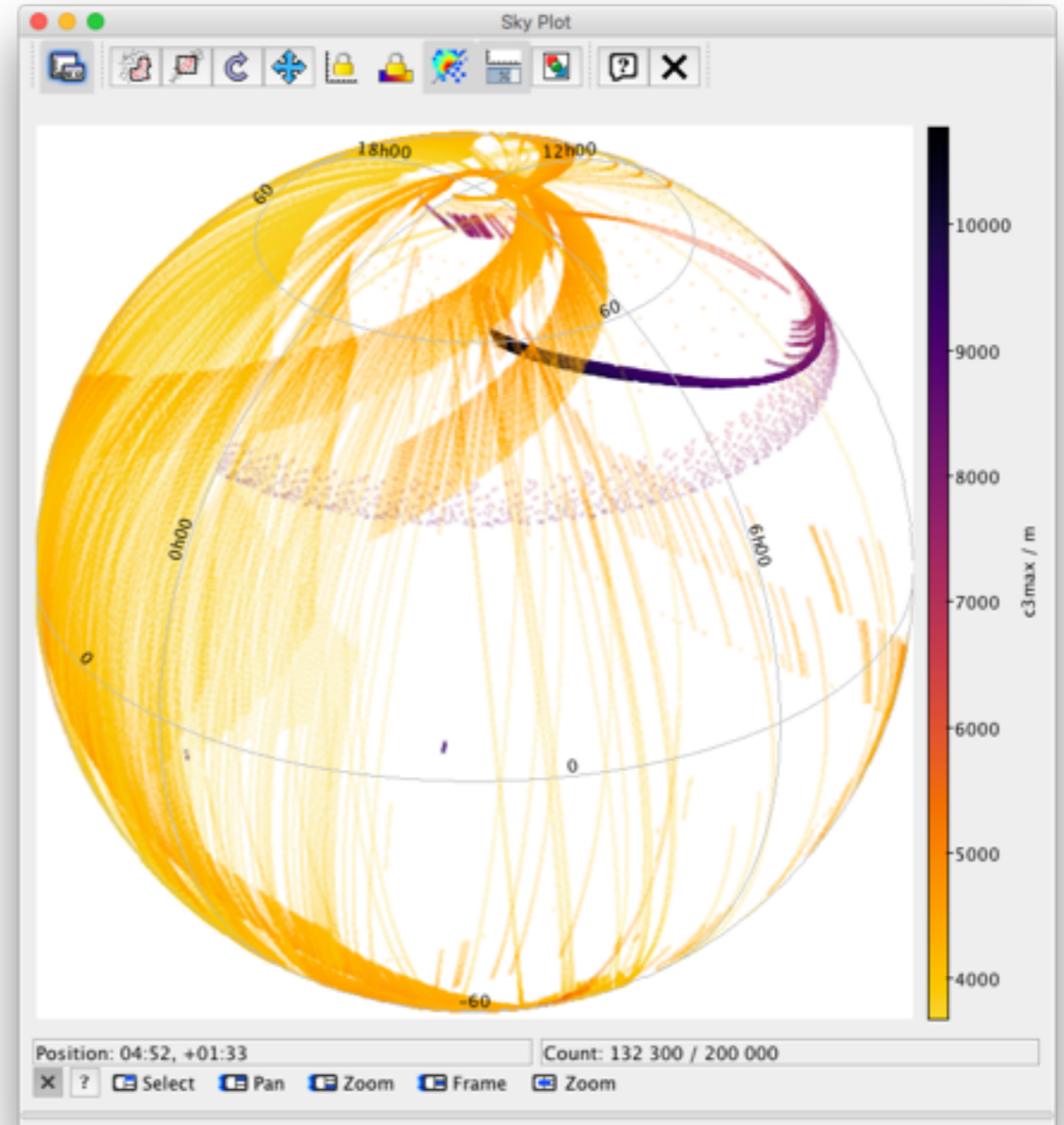


# Mars Express MARSIS footprint on Mars

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**