The WIBAR Spectrometer and RFI mitigation

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Need for a new spectrometer

- **Scientific needs** for broad band, high spectral spectral resolution and high dynamics radio observations in RFI polluted bands;
- extend the **technical characteristics of the NRT correlator**.
- Instrumentation studies : continuous spectral coverage, RFI elimination algorithms working on-line (GPUs) and off-line,
- including RFI elimination algorithms based on robust statistics.

Main science programs

Examples of programs which may conducted with the WIBAR spectrometer and benefit from its characteristics and software pipelines.

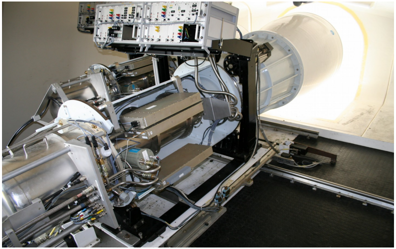
- **Extragalactic HI** in emission (∼1360 MHz to 1420 MHz) or in absorption (with the Nançay decimetric radio telescope - NRT).
- **Extragalactic OH masers** with redshifts up to $z = 0.45$
- **Galactic spectral observations** of OH and HI lines;
- **radio continuum** observation and monitoring of radio sources (e.g. HESS Blazars and in the future CTA Blazars).
- Peculiar projects like fast acquisition spectra (200 μs/spectrum) of giant pulses of Crab PSR; up to 16 Hz spectral resolution spectra with the standard setup.

The Nançay Radio Telescope

The Nançay Radio Telescope

The focal and receivers systems FORT

WIBAR : WIde **BA**nd **R**eceiver for NRT



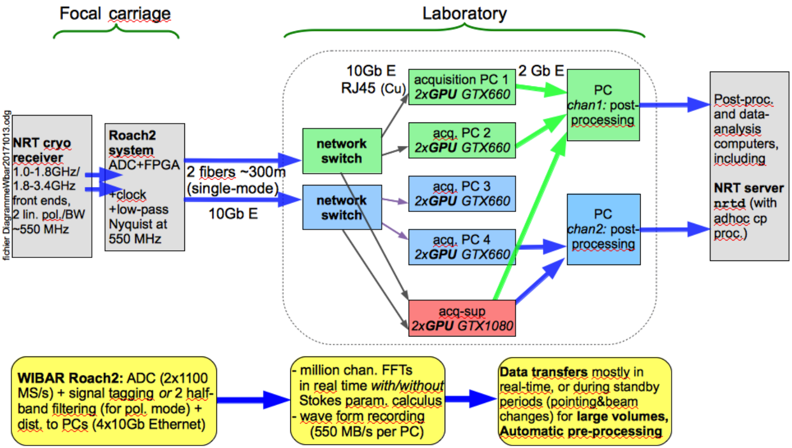
2 receivers are located in FORT Carriage :
- Low-Frequency System : 1.1 - 1.8 GHz
- High-Frequency System : 1.7 - 3.5 GHz

Horns can be rotated by +/- 90°

Specifications summary for the WIde BAnd spectrometer for the Radio telescope (WIBAR)

Name	Value (unit)	Comments
Sampling	2×1100 MS/s	Roach2/katADC
Bandwidth	2×550 MHz 8×275 MHz	For the spectroscopic and waveform modes For the Stokes mode (2 linear+2 cross-pol, x 2 sub-bands)
Input channels	2	The Wibar Roach2/katADC is connected to the linear outputs of the NRT receiver, in the carriage.
Digitization levels	8 bits	
Number of spectral channels	2^{16} to 2^{26}	Minimum stacking of spectra of 2

WIBAR technical description



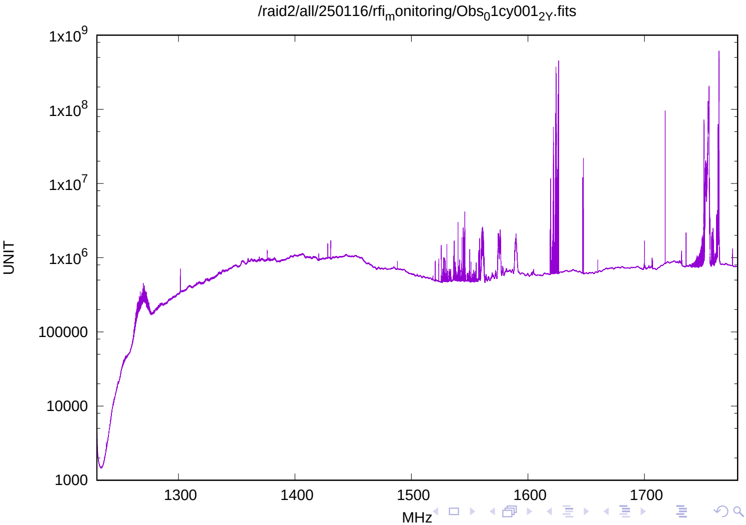
Technical description: the two Roach2 firmwares

1. **firmware passthru** (with counter)
   Roach sends:
   digitized chan1 voltages to PCs 1&2
   digitized chan2 voltages to PCs 3&4

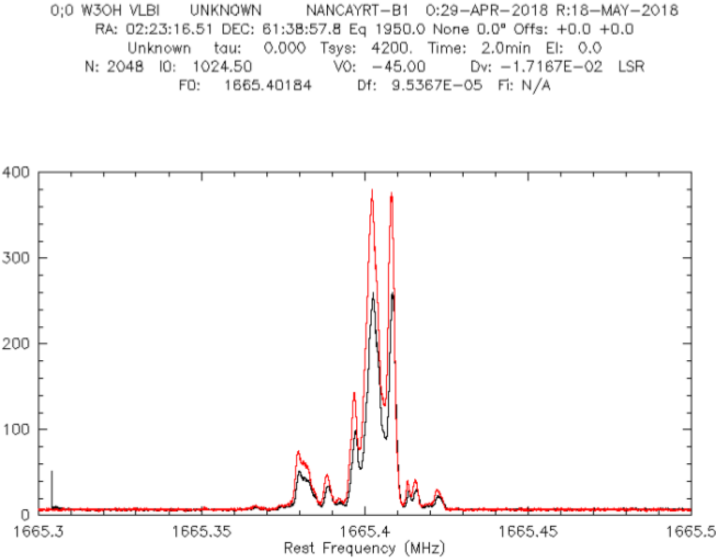
   PCs 1&2 and 3&4 produce averaged power spectra for channels 1 and 2 respectively.
2. **firmware FIR filter** (two half-bands x two lin. pol. inputs)
   Roach sends:
   both digitized ch. of subband1 to PCs 1&2 (with counter)
   both digitized ch. of subband2 to PCs 3&4

   Each group of PCs produces averaged power spectra for channels 1 and 2, and averaged cross-corr. spectra.

L band spectrum

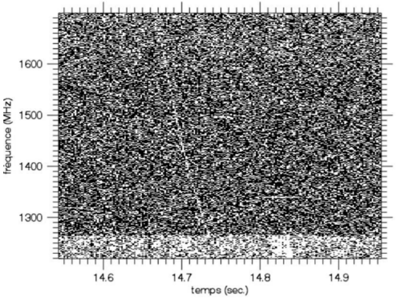


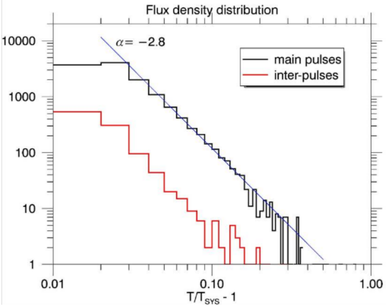
W3(OH) Stokes I: WIBAR (*red*) & correlator spectra (*black*)



Crab PSR giant pulses

- 10h data
- 22000 pulses found incl. 1800 interpulses
- similar properties as those published by Majid et al.2011





Conclusions for WIBAR

- **WIBAR is working** and is a team project, it is open to collaboration work.
- **Tools** for general users in development (python scripts/library, and dedicated tools exist).
- RFI mitigation in GPU is under test,
- in order to analyse the data aquired for an extragalactic HI absorption lines survey, a dedicated robust pipeline has been developed (C.Belleval, PhD Thesis, September 2019).

We hereafter present the ROBEL package which has been developed at Paris Observatory and tested with NRT WIBAR data.

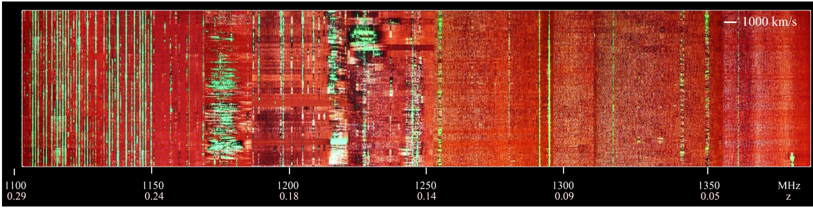
Automated processing

It is now impossible to handle large survey data manually. Thus, **processing must be automated** as far as possible.

- **data quality analysis and noise filtering**: noise reduction must be pushed as far as possible;
- **Automated detection of spectral lines** is compulsory.

Example of various kinds of RFI in a broadband spectrum observed at the Nançay Radio Telescope. (Correlator 50 MHz bands stacked)

credits: Lehnert & van Driel (in prep.)



The need for data quality assessment

Main assumption: any artificial signal carries information which by definition is not randomly distributed. **Only natural sources exhibit normally distributed power spectral values** (Central Limit Theorem applied to the χ^2 law with enough degrees of freedom).

To discriminate between "good" and "bad" outliers, data quality estimators must be applied on time-series of flux densities for each frequency channel.

What are robust statistics?

The term "**robust**" is often used in the literature but seldom pertinent. The compact **definition** is: **statistical tools which are immune from outliers** (up to 50%). For power spectral data, these are:

- **estimators of location**, i.e., a typical central value that best describes the data, such as the **median**, as opposed to the mean;
- **estimators of scale** which measure data spread, such as the median absolute deviation (**MAD**) or **Sn** (Rousseuw and Leroy, 2003) as opposed to standard deviation;
- **regression tools** for baseline fitting, such as the **Least Trimmed Squares (LTS)** as opposed to non-robust Least Squares (LS).

The ROBust Elusive Line detection (ROBEL) post-processing software

ROBEL has been designed for **spectral line detection in a strong RFI environment**. Its **paradigms** stipulate that:

- **automated blind line detection** is compulsory especially in the context of wide-band surveys;
- the only common point between **RFI** is that their power spectral data **are not normally (Gaussian) distributed on a time-line basis**;
- **robust statistics are appropriate algorithms** in this context.

The ROBEL data processing steps

ROBEL produces 1D spectra through the following steps:

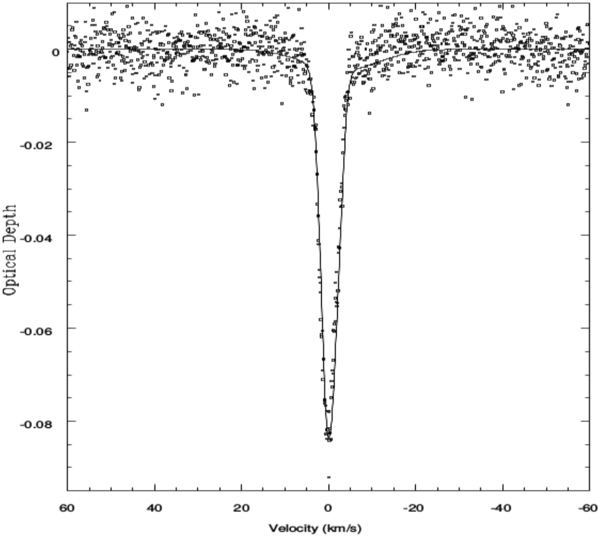
1. frequencies are corrected for solar system barycentric Doppler effects;
2. n-**robust binning** may be applied (i.e., concatenating all power spectral values of *n* frequency channels);
3. for each frequency channel, non robust as well as **robust estimators of location and scale are calculated**, plus **skewness** and **kurtosis**;
4. in each frequency channel, power spectral data are then filtered (5x3*disp* **clipping** where *disp* is respectively std deviation, MAD and *Sn*);
5. same calculations are done on **filtered data** (reassessment);
6. **1D spectra** are **fitted using LTS** which give **residuals per frequency channels**;
7. **detection of spectral lines** is performed by flagging frequency channels which residuals exceed a defined threshold.

B0738+313 HI line IGM absorber at $z = 0.2212$

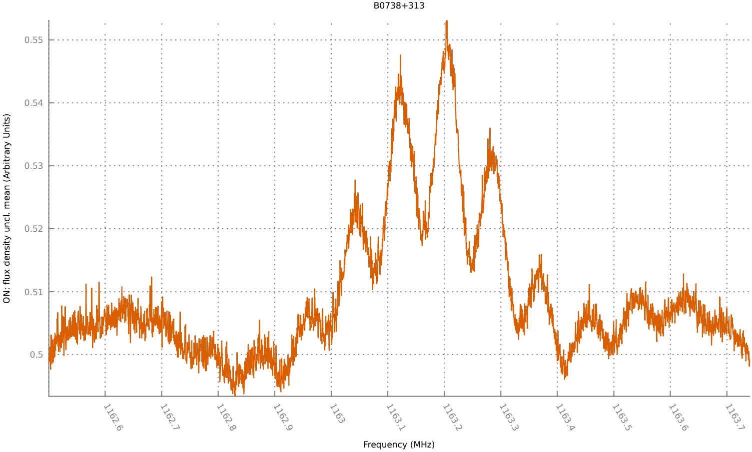
B0738+313 is a quasar (QSO) at $z = 0.63$:

- with a high 21 cm continuum flux density of 2 Jy;
- selected as one of the test cases for the Nançay Absorption Program;
- retained as a test target for WIBAR broadband observations and ROBEL data analysis;
- there are two documented absorbers at $z = 0.0912$ (B1) and $z = 0.2212$ (B2);
- B2 was observed by Kanekar et al. (2001) during 9 hours at Arecibo with no RFI;
- B2 was observed at NRT with WIBAR, only 1.8 hours were usable.

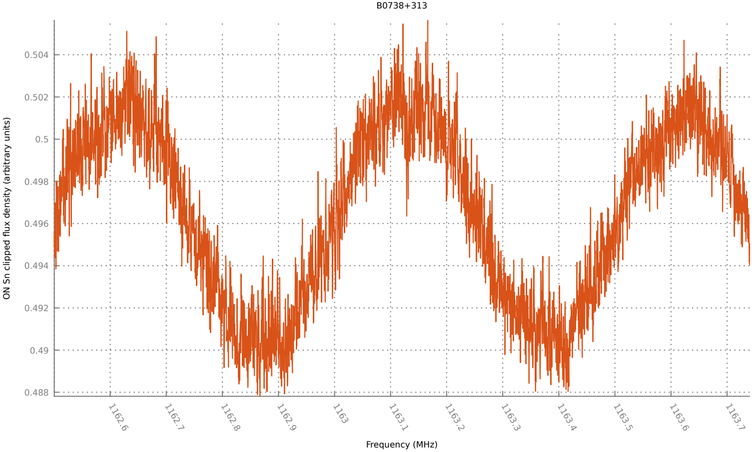
B0738+313 B2 absorber observed at Arecibo (Kanekar et al. 2001)



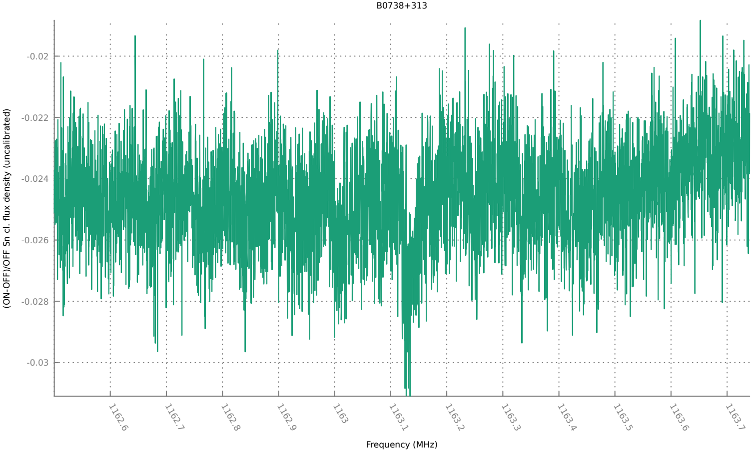
B0738+313 B2 absorber: unclipped *ON* spectrum observed at NRT



B0738+313 B2 absorber: *Sn*-clipped median of the *ON* spectrum observed at NRT



B0738+313 B2 absorber: *Sn*-clipped median of the $(ON - OFF)/OFF$ spectrum observed at NRT



B0738+313 B2 absorber: summary of results

With the *Sn*-clipped $(ON - OFF)/OFF$ spectrum:

- the frequency *rms* after *Sn*-clipping around B2 is $28mJy$ (vs. $27mJy$ in the $1421 - 1421.5$MHz protected band)
- the *B*2 absorber peak is detected at 3.22σ;
- $FWHM = 3.04 \pm 0.33\ \mathrm{km\,s^{-1}}$ (vs. 3.85 ± 0.30 for Kanekar et al.);
- peak optical depth $\tau_{peak} = 0.076 \pm 0.009$ (vs. 0.080 ± 0.002 for Kanekar et al.)

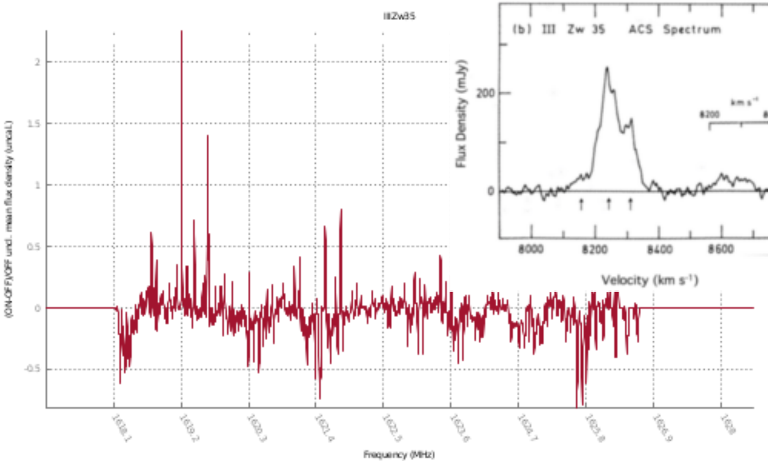
Observation of the III Zw 35 OH megamaser

III Zw 35 is a two nuclei Luminous Infrared Galaxy (LIRG). It contains an **OH megamaser**:

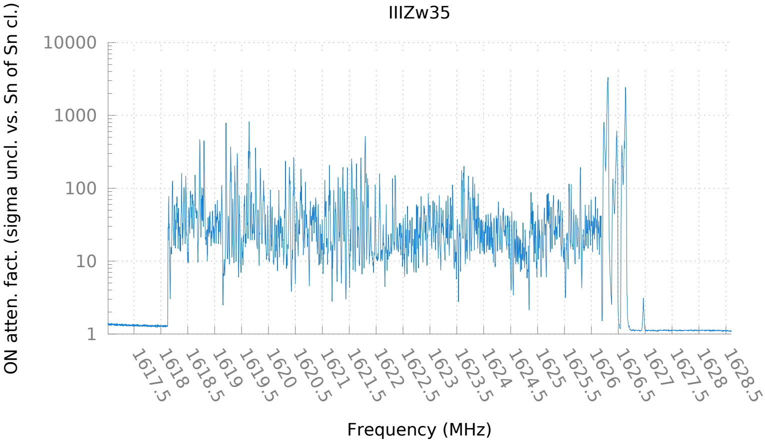
- **OH 1667 MHz line:** three components were observed by Staveley-Smith et al. (1987):
  1. the first at 8240 $\mathrm{km\,s^{-1}}$ (1622.756 MHz LSR), with a 245 mJy peak,
  2. the second at 8310 $\mathrm{km\,s^{-1}}$ (1622.388 MHz LSR), with a 140mJy peak,
  3. the third at 8160 $\mathrm{km\,s^{-1}}$ (1623.178 $\pm$ 0.026 MHz LSR), with a 30 mJy peak;
- **OH 1665 MHz line:** observed at 8260 $\mathrm{km\,s^{-1}}$ (1620.736 MHz LSR), with a 30 mJy peak.

Observation of III Zw 35 at NRT in 2018: $(ON - OFF)/OFF$ spectrum before clipping

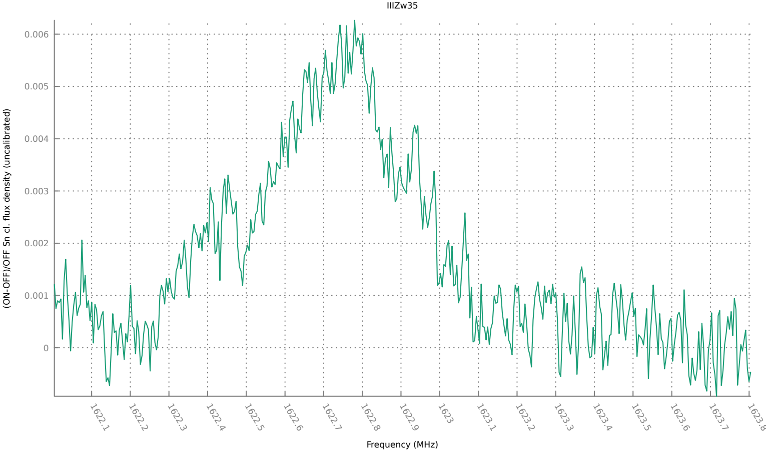
Now swamped by Iridium satellite constellation RFI (inserted spectrum from Staveley-Smith et al. (1987))



III Zw 35 at NRT in 2018: *EoS* attenuation factor on the *ON* spectrum after *Sn*-clipping



III Zw 35 at NRT in 2018: $(ON - OFF)/OFF$ OH 1667 line spectrum after Sn-clipping



Results on RFI mitigation (1)

The ROBEL RFI excision algorithm (*Sn*-clipping) has proven its efficiency on a variety of artificial signals. For *Sn*-clipped $(ON - OFF)/OFF$ spectra:

- B0738+313 absorption line visible after filtering, temp.noise/3 and *rms* **brought back to a level similar to the protected band**;
- the **III Zw 35 megamaser OH emission line restored** with a temporal noise attenuation factor of 30 on average (up to 3500);

Results on RFI mitigation (2)

With integration time of 1h47 minutes, and sampling time of 0.2s:

- **RFI mitigation of the strongest radar** operating in the $1300 - 1400$ MHz range decreased the frequency *rms* by more than 87% (to 6 mJy at $10\,\mathrm{km\,s^{-1}}$ resolution);
- **GNSS** RFI mitigation decreased the frequency *rms* up to 41% in various frequency bands between 1175 and 1298 MHz (to $5 - 12$ mJy at $10\,\mathrm{km\,s^{-1}}$ resolution);
- but GNSS RFI mitigation has to be tested further with actual spectral lines.

***Sn* is better suited than MAD for RFI mitigation** (more efficient and unbiased even with non-nil skewness).

Next steps

Now that **ROBEL algorithms have been validated** by extensive testing on the Nançay Radio Telescope with the WIBAR broadband fast sampling spectrometer:

- to use ROBEL with NRT and WIBAR for future surveys (semester 2020A at NRT)
- to test ROBEL post-processing on data produced by **other single dish RTs**;
- to **adapt the post-processing to interferometers in cooperation** with other teams, especially in the SKA context.

Thank you !

Credits: WIBAR team at Observatoire de Paris: Jean Borsenberger, Eric Gérard, Christophe Belleval, Jean-Michel Martin, Jean-François Roig and Wim van Driel (GEPI, Meudon) ; Pierre Colom, Alain Lecacheux (LESIA, Meudon), Guy Kenfack (USN, Nançay)
ROBEL package: Christophe Belleval