Bilateral Workshop on Astrophysics
V.N. Karazin Kharkiv National University – INAF

Space mission BRAUDE-M. Radio telescope on the farside of the Moon

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22-23, March 2018, Rome, Italy

Space mission BRAUDE-M.
Radio telescope on the farside of the Moon (FRT).

- The new generation of low frequency radio telescope has high sensitivity due to

- a wide, broadband antenna element;
- an amplifier, which is intrinsic part of an antenna element;
- a parallel receiver – spectrum analyzer.

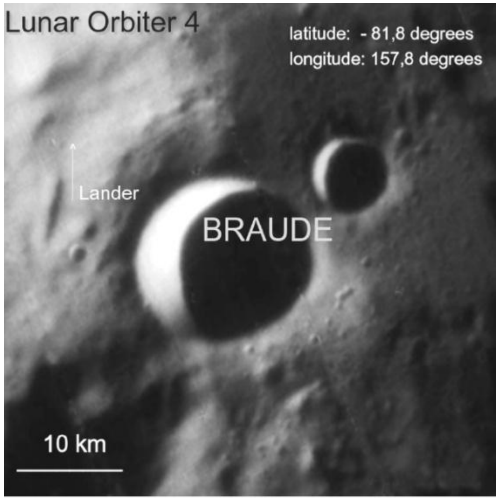
Telescope efficiency is much higher than that of the whip antenna onboard the spacecraft.

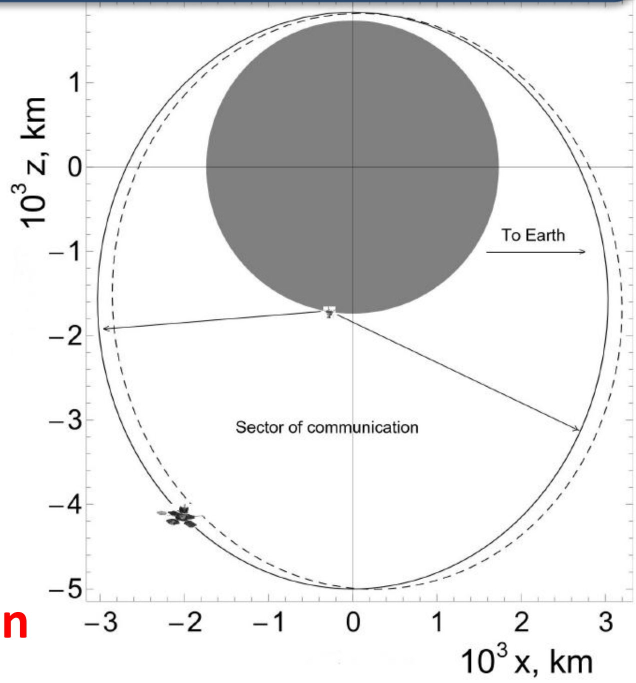
- Wide range of astronomical tasks:

- The Sun, SME, bursts of various types at a distance of several radii, space weather;
- Jupiter: kilometer, decameter radiation, as a model of exoplanet radio emission;
- Io-, Ganymede-, etc. controlled radiation;
- Saturn: SKR, lightning, Great White Spot;
- pulsars, long-term emission and dispersion measure variations; pulses as test signals;
- RRL at low frequencies, high-z red-shifted HI line, Dark Ages;
- interferometry with base up to 380 000 km, Solar system objects, scattering.

- What do we mean when say "telescope of new generation“?

Mission overview



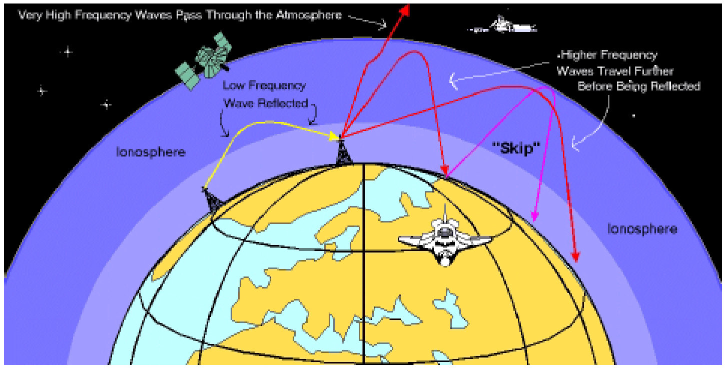


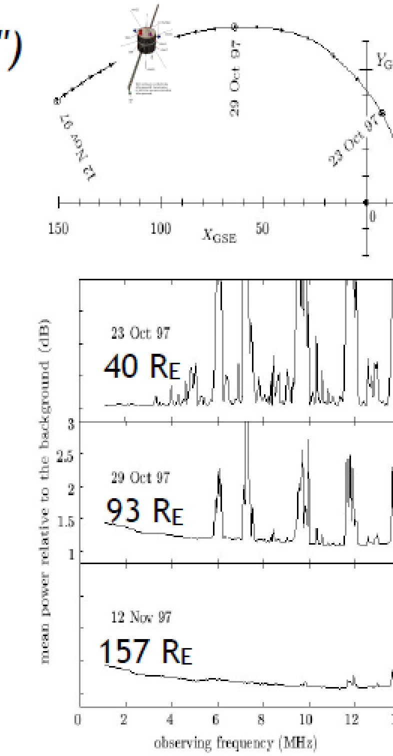
"Braude-M“ : Big Radio Astronomy Universe, DEmonstration from the Moon

Highlights:

- The mission includes a lander with radio astronomy antennas located on the lunar farside
- Low-frequency antennas shielded by Moon from Earth radio interference allow unique observations
- A relay orbiter uses a 5-hour polar orbit with pericenter near the north pole at a height of 100 km
- The orbiter is equipped with a 3-mm radar for surface mapping with 100-m resolution
- The orbiter payload also includes an IR spectrometer to study OH/H_2O compounds in regolith

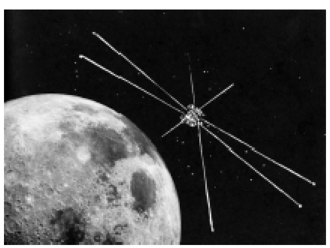
- Radioastronomy on the Moon is an Old idea. First proposals pre-date Apollo missions !
- The Moon (Far side especially) has been long recognized as unique astronomical platform, and a radio quiet zone by International Telecommunications Union
- No place on/near Earth is dark at Low Frequencies *(LF radio "smog")*

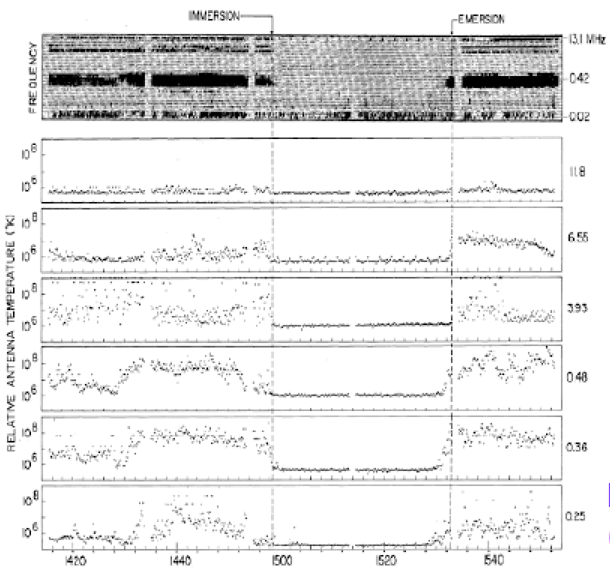




24h averages from Wind/WAVES

- RAE-2 : 1100 km circular orbit inclined by 59° / lunar equator

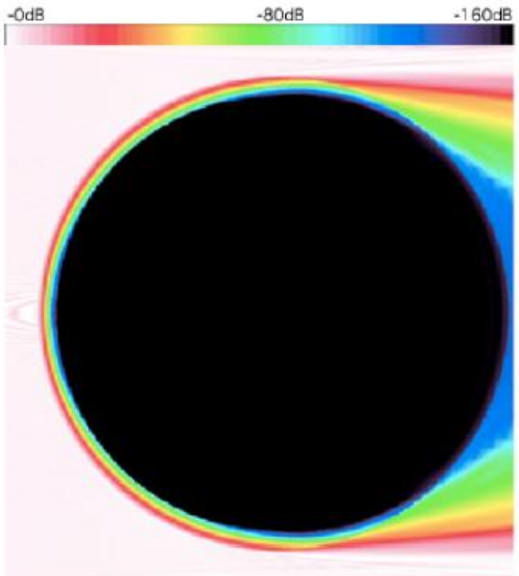




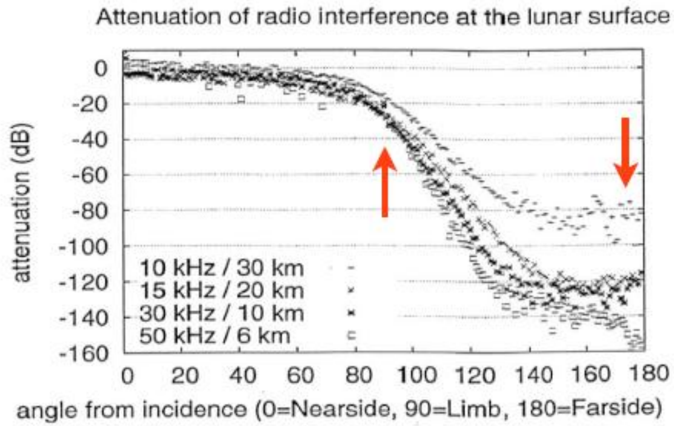
RAE-2 occultation of Earth (1973)

- Far-side of the Moon and eternally-dark craters at the lunar poles shielded from natural and man-made terrestrial RFI

→ AT NIGHT the most radio-quiet locations in the vicinity of the Earth.



Attenuation of a 60 kHz radio wave due to propagation around the Moon with subsurface penetration and a lunar density model (Takahashi, 2003)



- Sensitivity limitation = *Background sky temperature always high (~$10^{4\text{-}6}$ K)*

→ sensitivity can be increased by long integrations

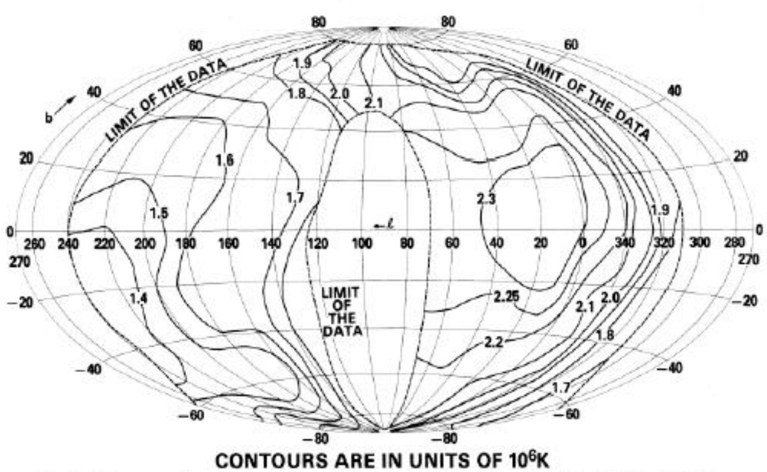


Fig. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

T_{sky}	freq (MHz)	
3.3×10^5	10	galactic synchrotron emission
2.6×10^6	5	
2.0×10^7	1	
2.6×10^7	0.5	free-free absorption
5.2×10^6	0.25	

RAE-2 observations (Novaco & Brown, 1978) : → no individual source identified

Wideband with high sensitivity

Octave :

$$f_{\text{high}} / f_{\text{low}} = 2$$

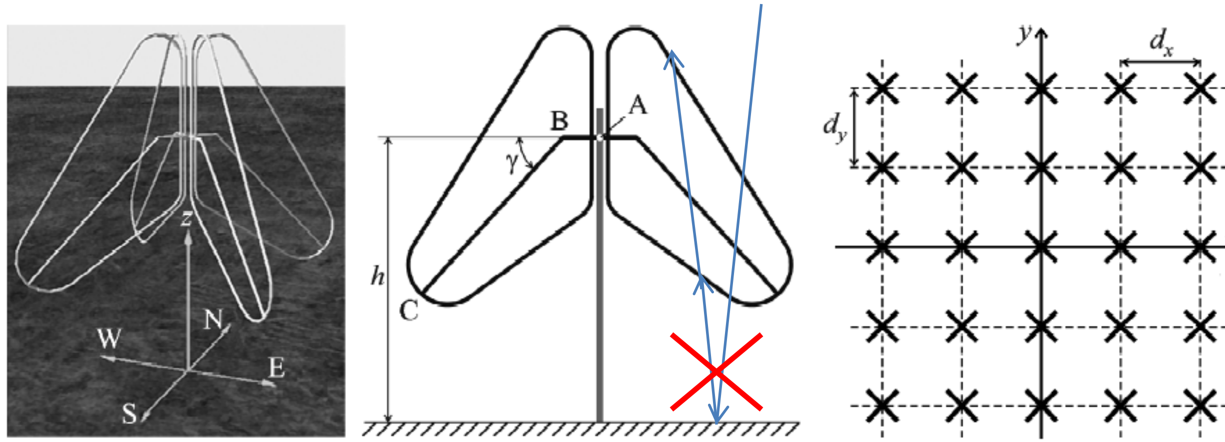
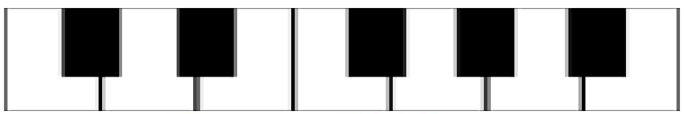
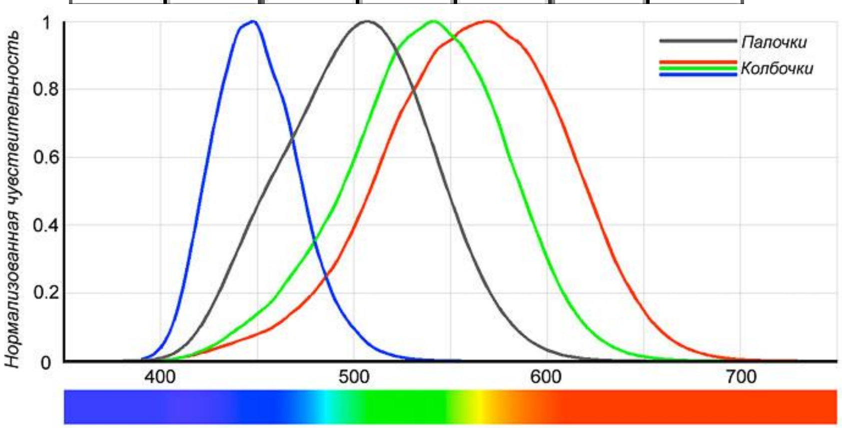
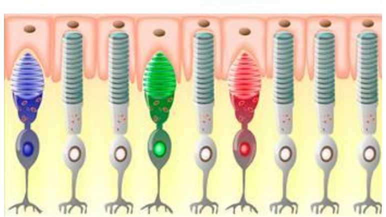
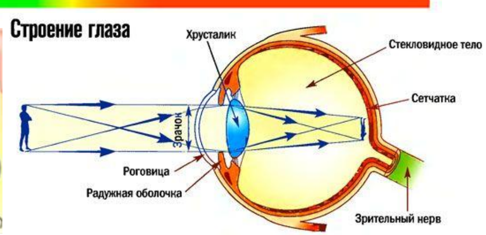


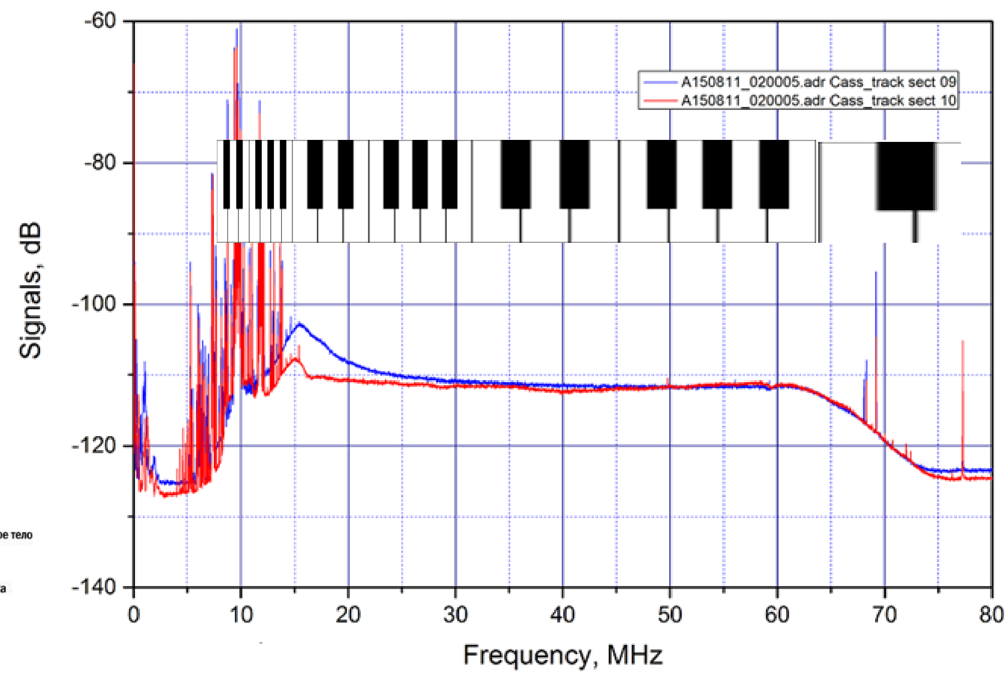
Рис. 1. Геометрия элементов и субрешетки ГУРТ: *а* – модель элемента субрешетки из двух скрещенных плоских диполей, *б* – геометрия плоского диполя ГУРТ, *в* – геометрия субрешетки ГУРТ









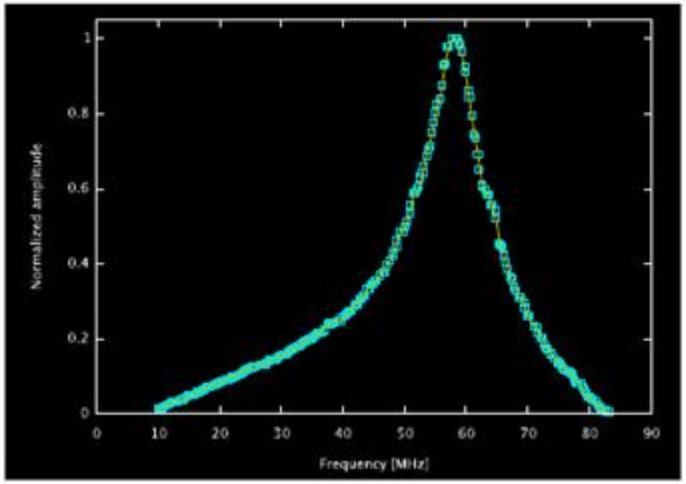


GURT transfer function

Low Frequency array (LOFAR)

LBA

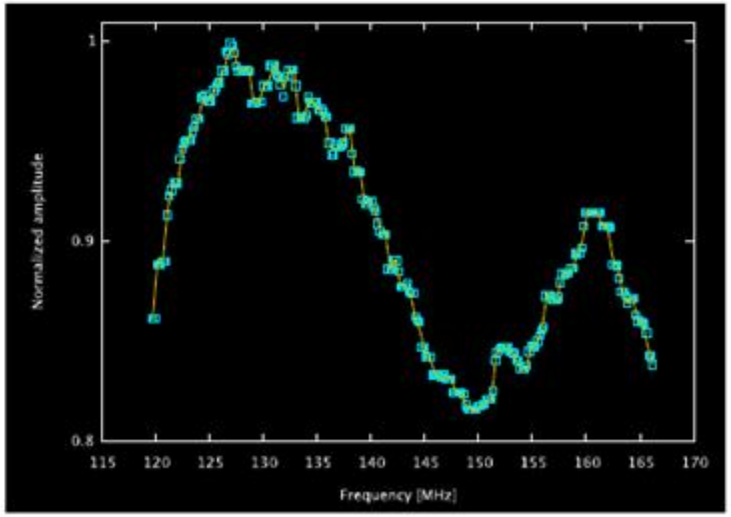
Sensitivity: low, only stronger sources (>1Jy?)



Bandpass is strongly peaked: strategy is frequency dependent

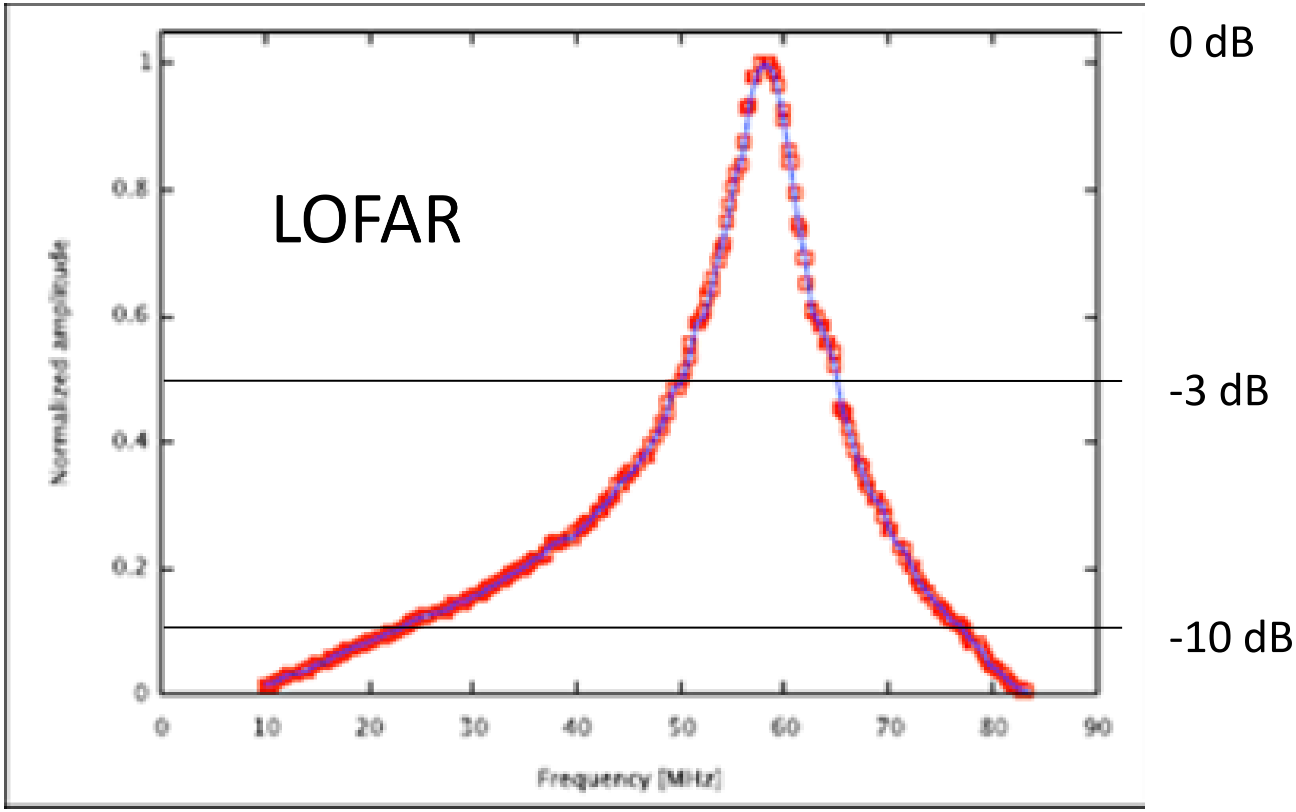
HBA

Sensitivity: good, can correct against 0.1 Jy



Bandpass varies by <20%: strategy is frequency independent

Slide courtesy: F. de Gasperin



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Low Frequency array (LOFAR)

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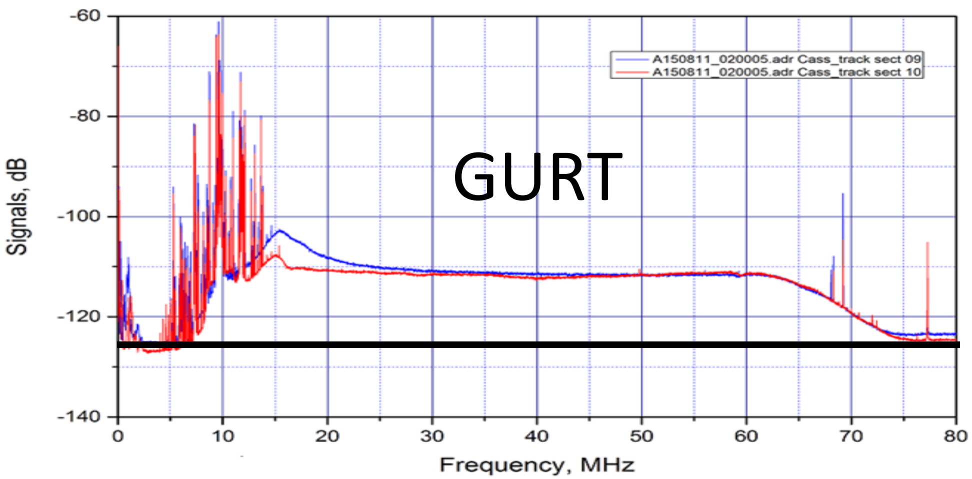
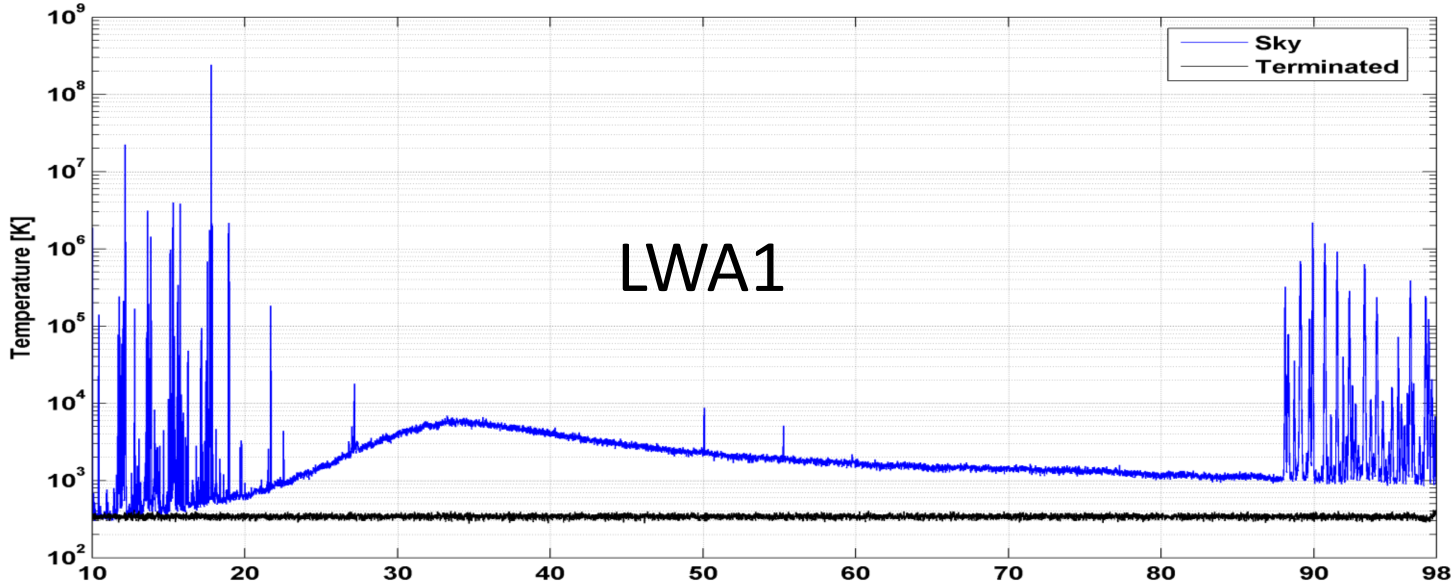


Рис. 7. АЧХ секции ГУРТ с эквалайзерами и контурным корректором

Sensitivity comparison of the of GURT and LWA1. Available area >1 km²



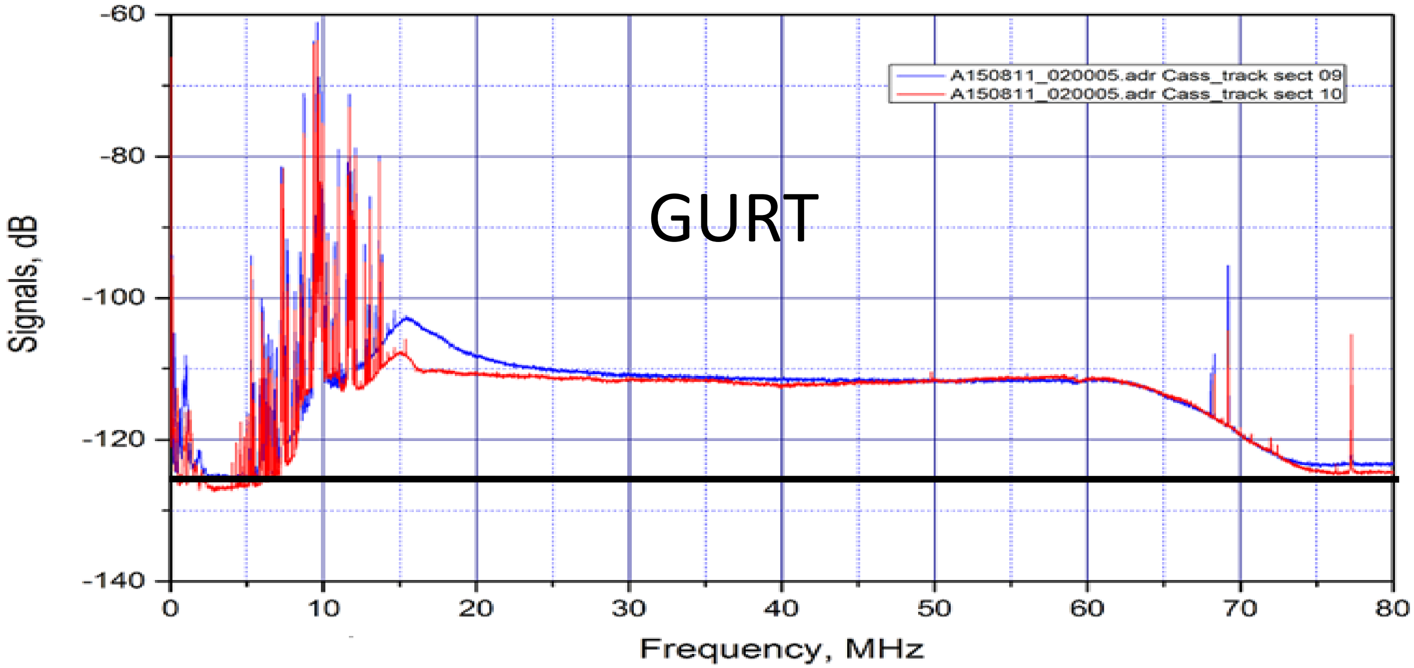
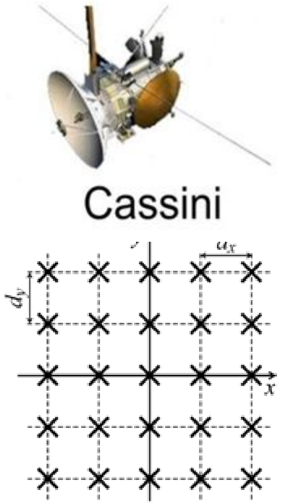
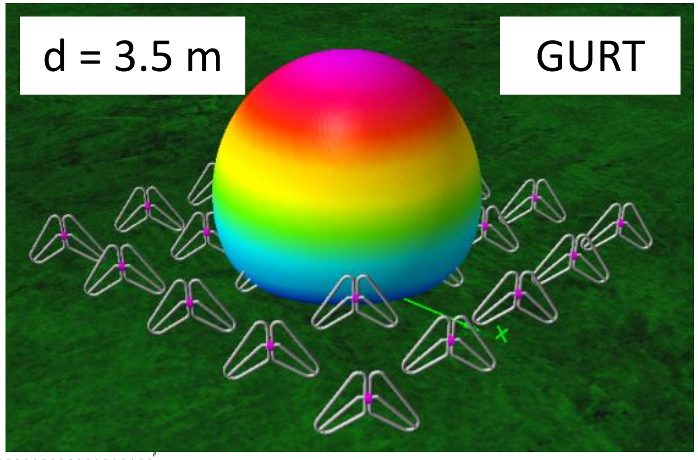
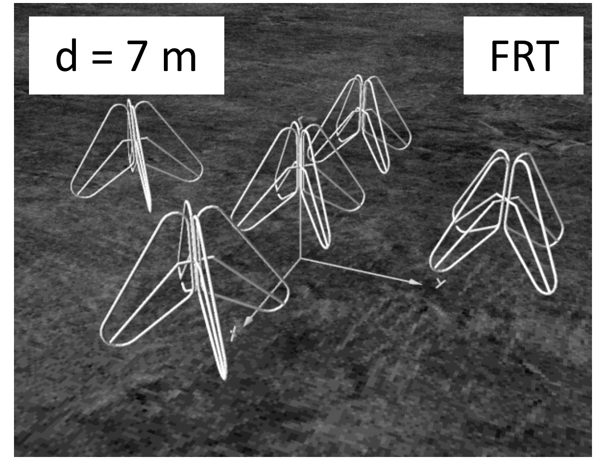


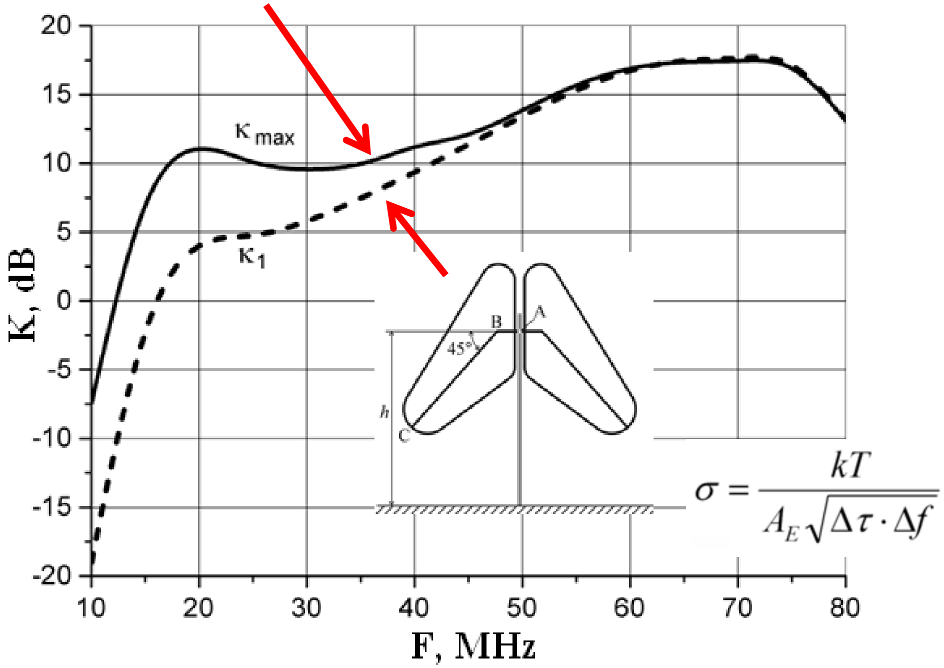
Рис. 7. АЧХ секции ГУРТ с эквалайзерами и контурным корректором

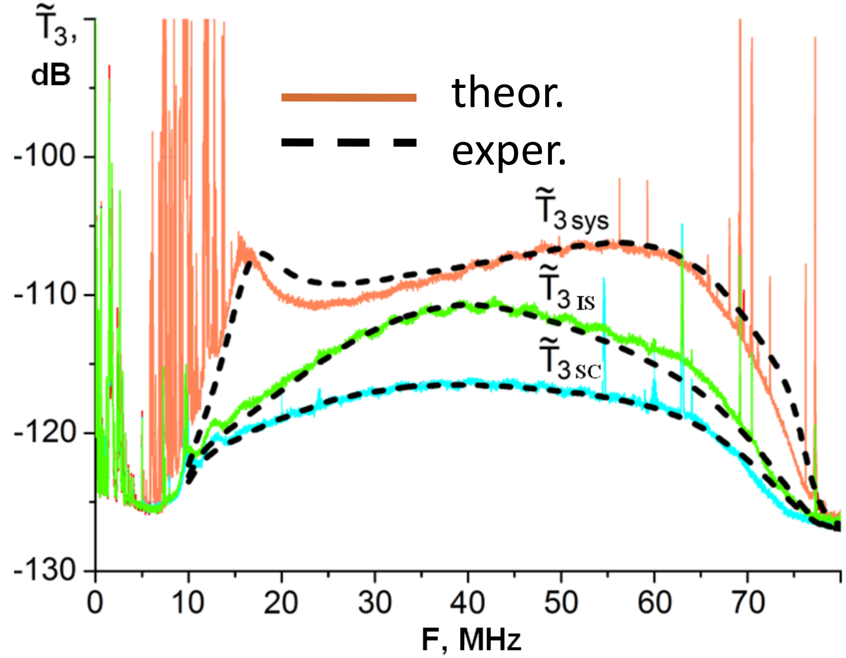
From GURT (8…80 MHz) to FRT 4…40 MHz, A_E = 400 m^2@ 25 MHz







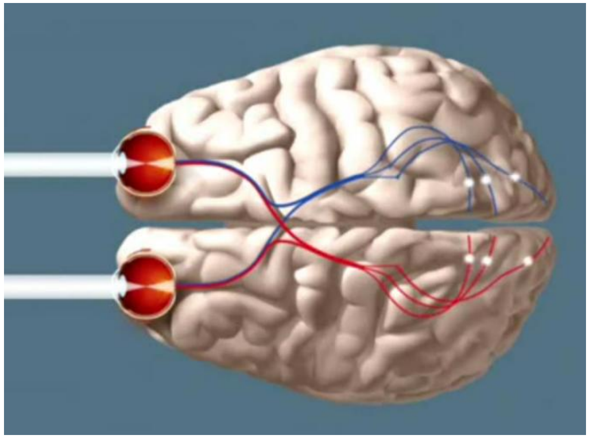




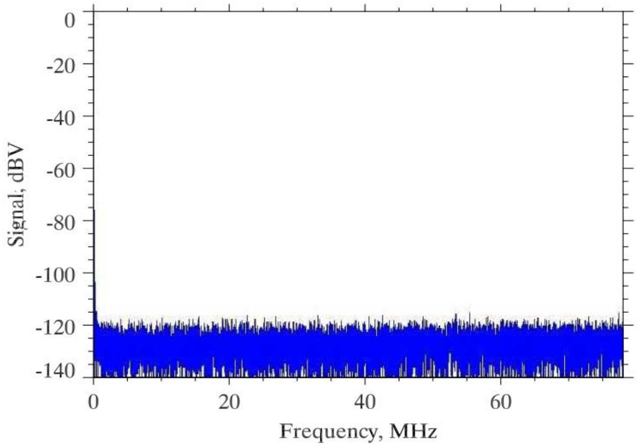
4 40 4 40

"Love looks not with the eyes but with the mind."

A Midsummer Night's Dream (I, i, 234), Shakespeare



We See With our Brains - Not with Our Eyes



Digital receivers for UTR-2, URAN and GURT

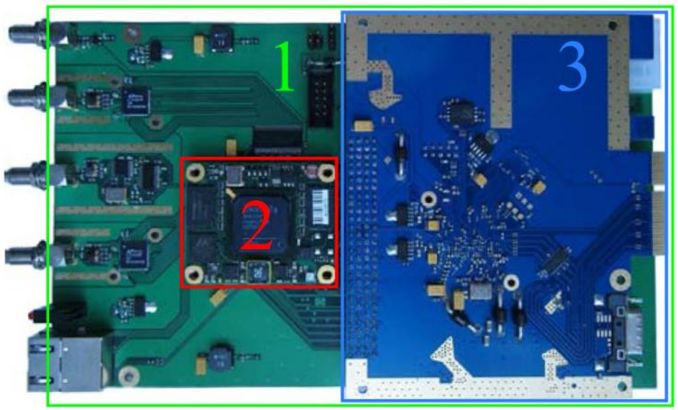


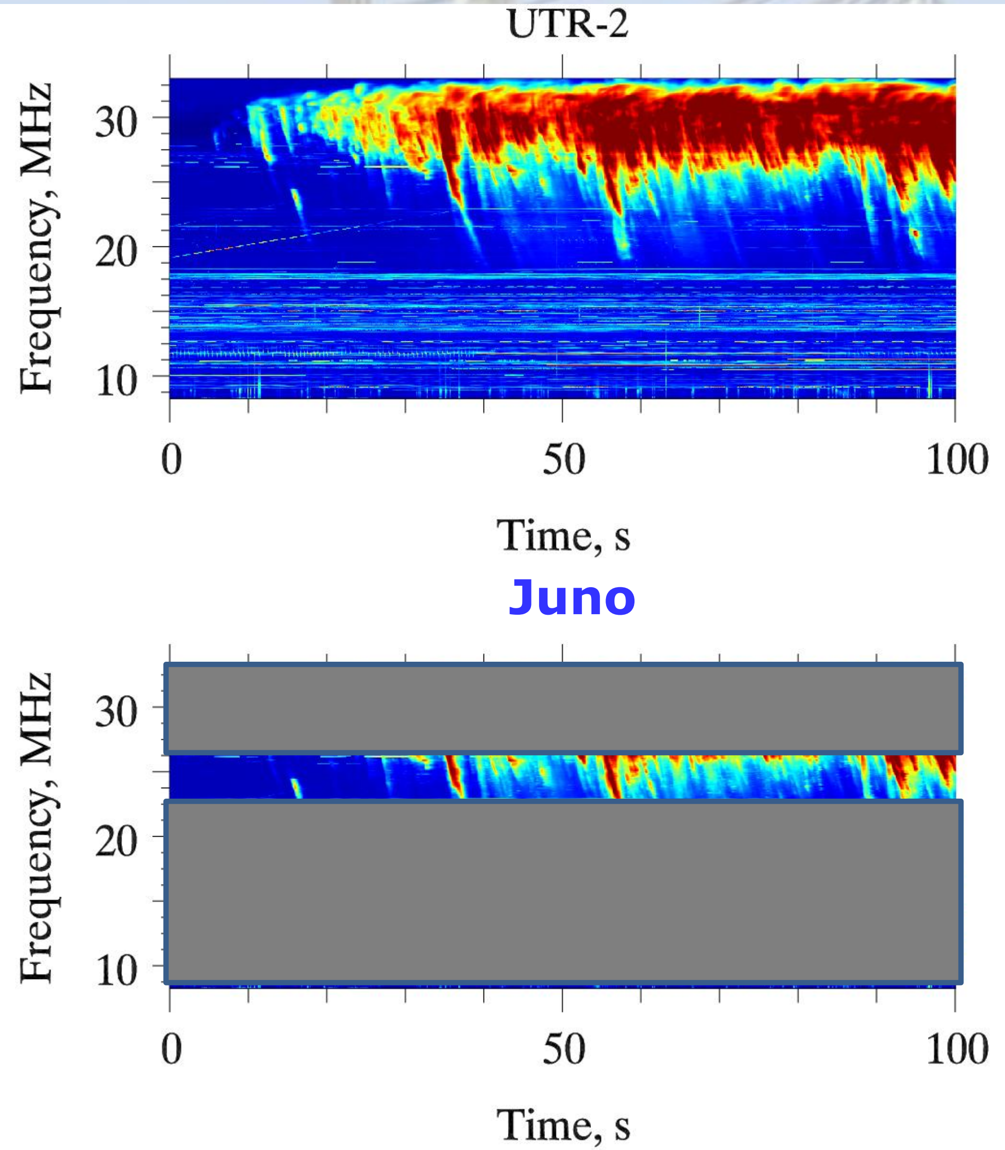
Fig. 8. ADC board (1), FPGA module (2) and high-speed waveform data transfer module (3).

Fig. 9. Front view of the ADR box, that contains the boards displayed in Fig. 8. The input labels correspond to those of Fig. 6 (with for A = input 1 and B = input 2). The receiver can operate independently in a section of the radio telescope or installed in the ADR Server).

Table 4. Parameters of digital baseband receiver DSPZ.

Number of input channels	2
Analog input bandwidth	180 MHz
Input impedance	50 Ohm
Input voltage	1 V
ADC sampling frequency	internal: 156 MHz/external: 20–160 MHz
ADC resolution	16 bits
ADC intrinsic dynamic range	73 dB
SFDR (spurious free dynamic range) (16,384 samples per FFT)	112 dB
Intrinsic noise level (16,384 samples per FFT)	−117 dB
Digital DC bias compensation	No
Dithering option (for an increasing SFDR value)	Yes
FFT size (samples or spectral channels)	2,048, 4,096, 8,192, 16,384 and 32,768
Output FFT samples resolution	32 bit
Speed of processing	4,800 complex 32,768 points FFT per second
Count of averaged spectra	16 - 32,768
Selectable frequency band output	by groups of 1,024 spectral channels
"Spectrometer" sub-modes	1. A channel spectrum output 2. B channel spectrum output 3. A and B channels spectrum output 4. A+B and A-B channels spectrum output 5. A and B channels spectrum and cross-correlation between A and B channels spectra
Waveform sub-modes	1. A channel waveform output 2. B channel waveform output 3. A and B channels waveform output 4. A+B and A-B channels waveform output
Output type (for spectrometer mode)	1 Gb Ethernet
Connection cables (for spectrometer mode)	Cat.5 UTP
Output type (for waveform mode)	10 Gb Ethernet
Maximal data rate to host PC (waveform mode)	650 MB/s
Maximal data rate to host PC (spectrometer mode)	80 MB/s
Control interface	TCP/IP
Data interface	UDP/IP

Even Juno's receiver – modern parallel spectrum analyzer have small frequency range



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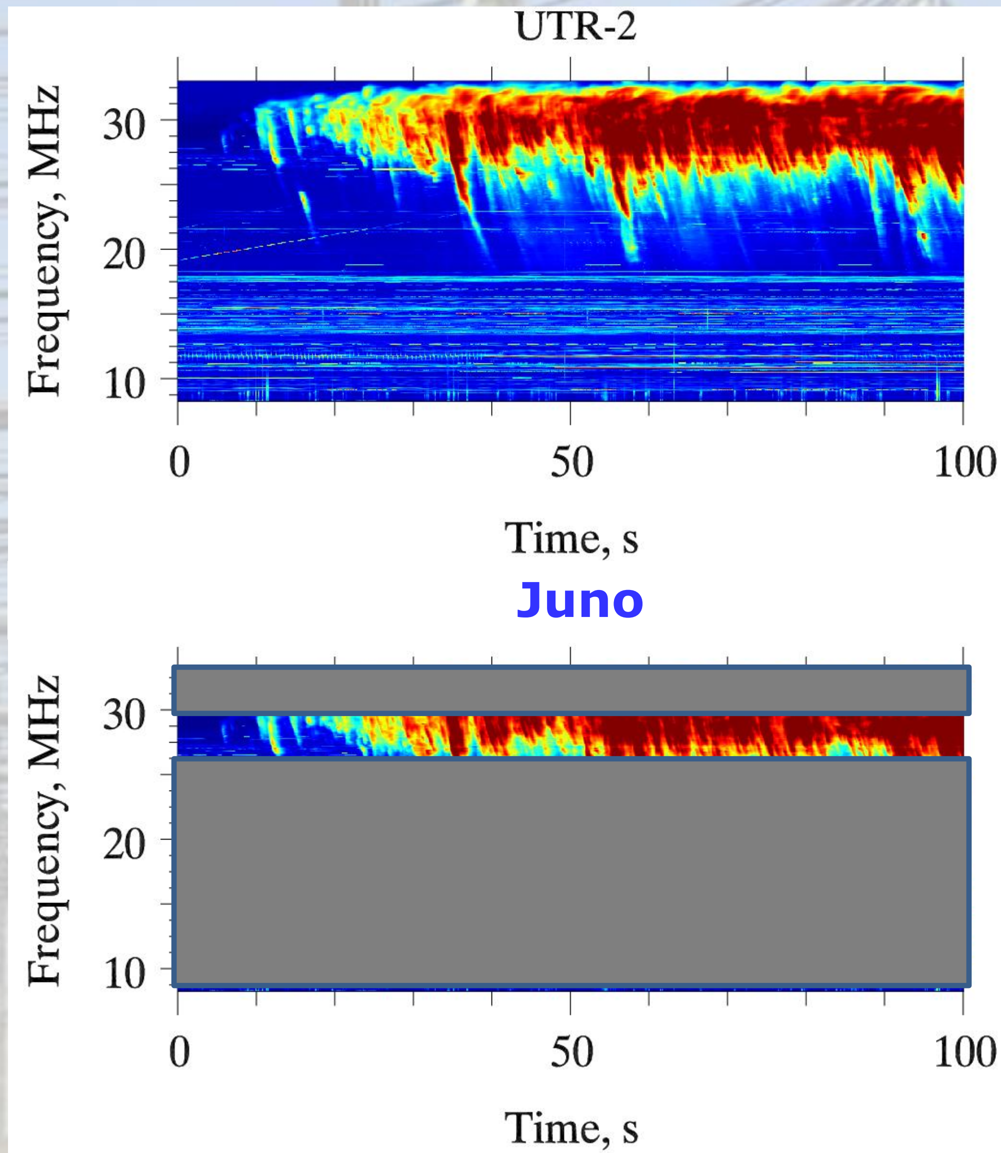
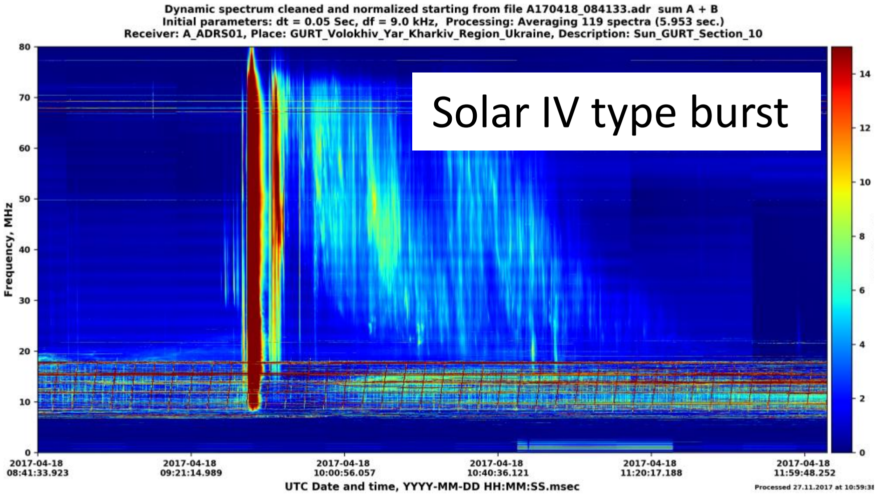
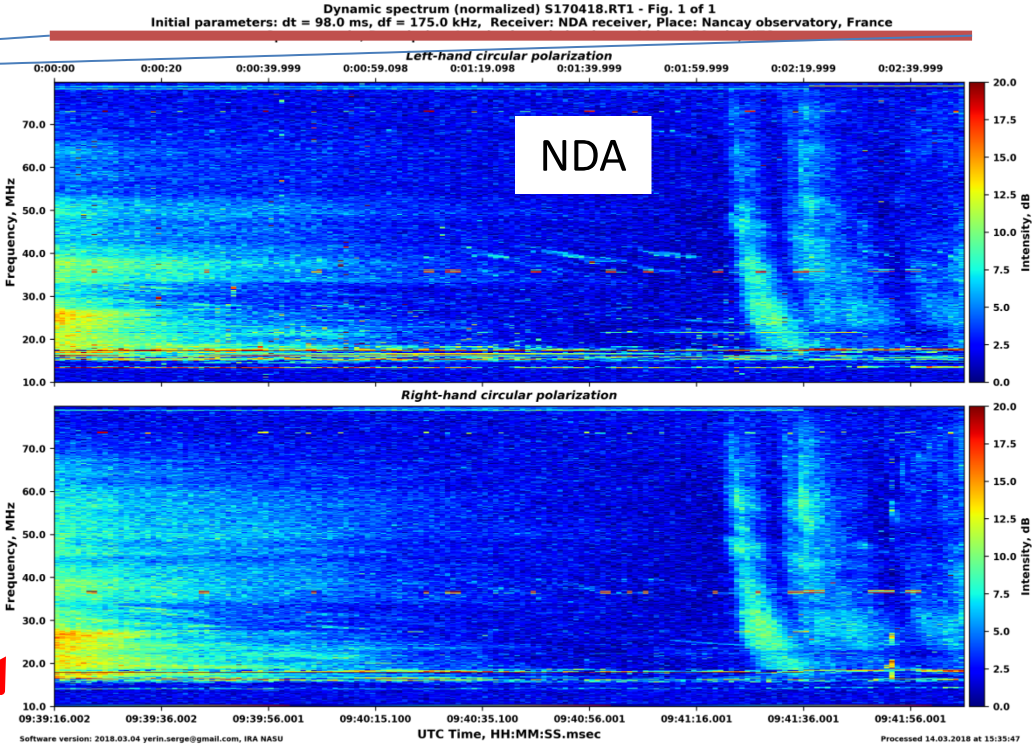
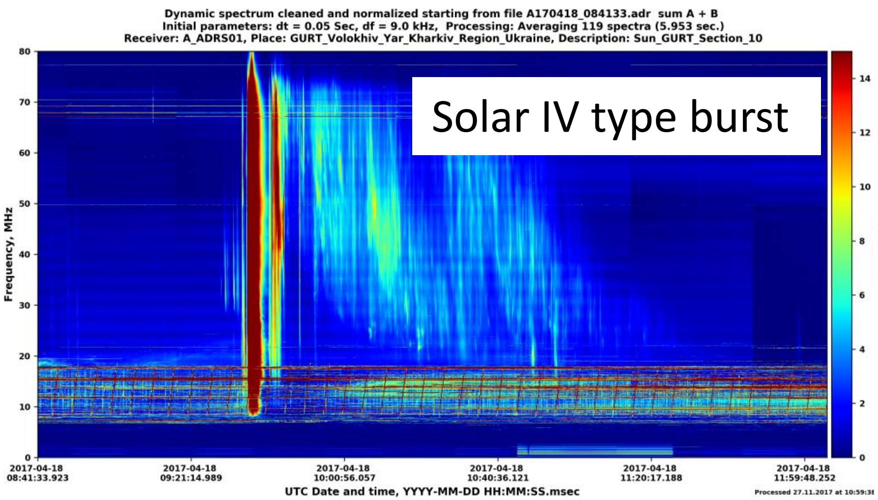


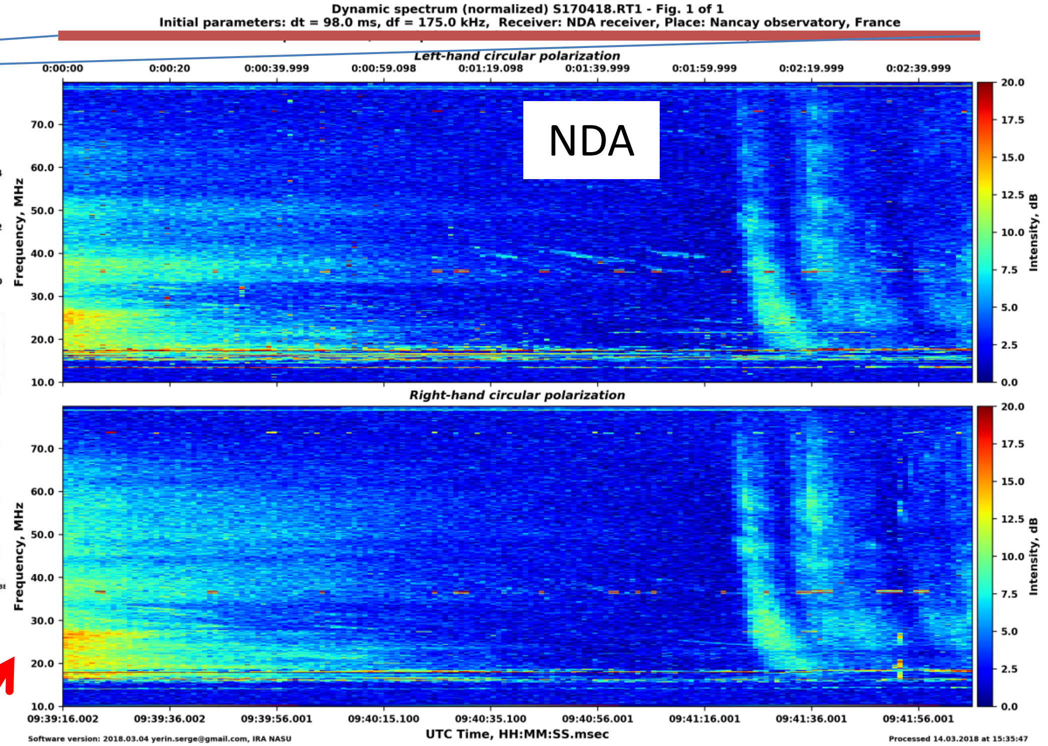




Nancay Decameter Array, $A_E > 2000\ m^2$

Sensitivity comparison





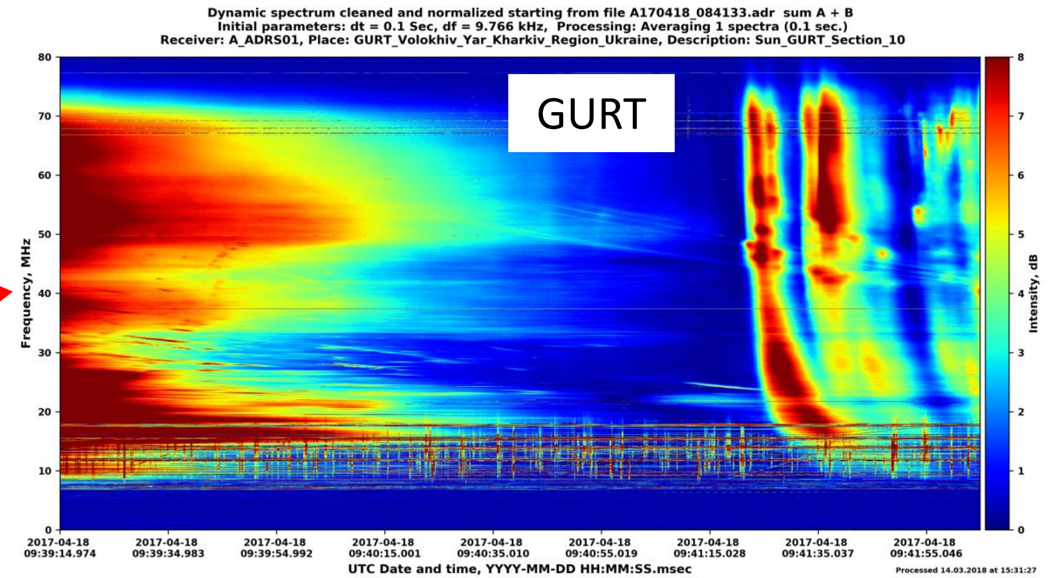


Fig. 9. Front view of the ADR box, that contains the boards displayed in Fig. 8. The input labels correspond to those of Fig. 6 (with for A = input 1 and B = input 2). The receiver can operate independently in a section of the radio telescope or installed in the ADR Server).

Solar radio emission

Solar Orbiter

RPW: DC-20 MHz

UTR-2, URAN: 8-33 MHz

GURT: 8-80 MHz

FRT 4…40 MHz

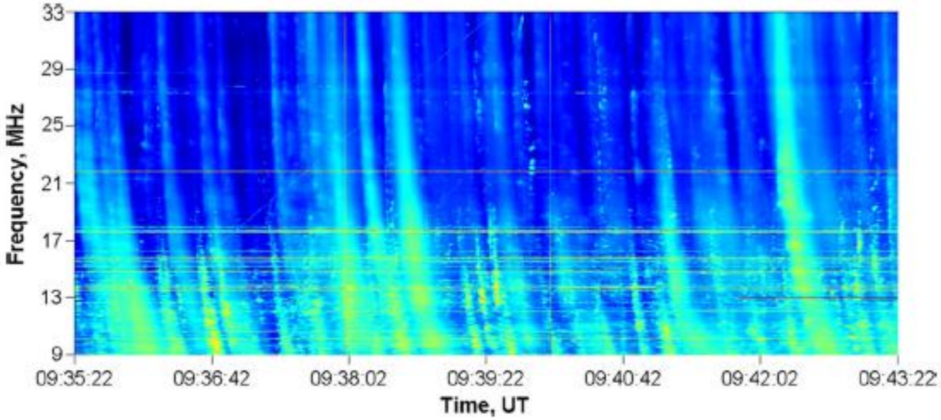


Fig. 7 Dynamic spectrum with a sequence of solar bursts of type III and IIIb-III obtained by the DSPZ connected to the South arm of UTR-2 on July 8, 2014

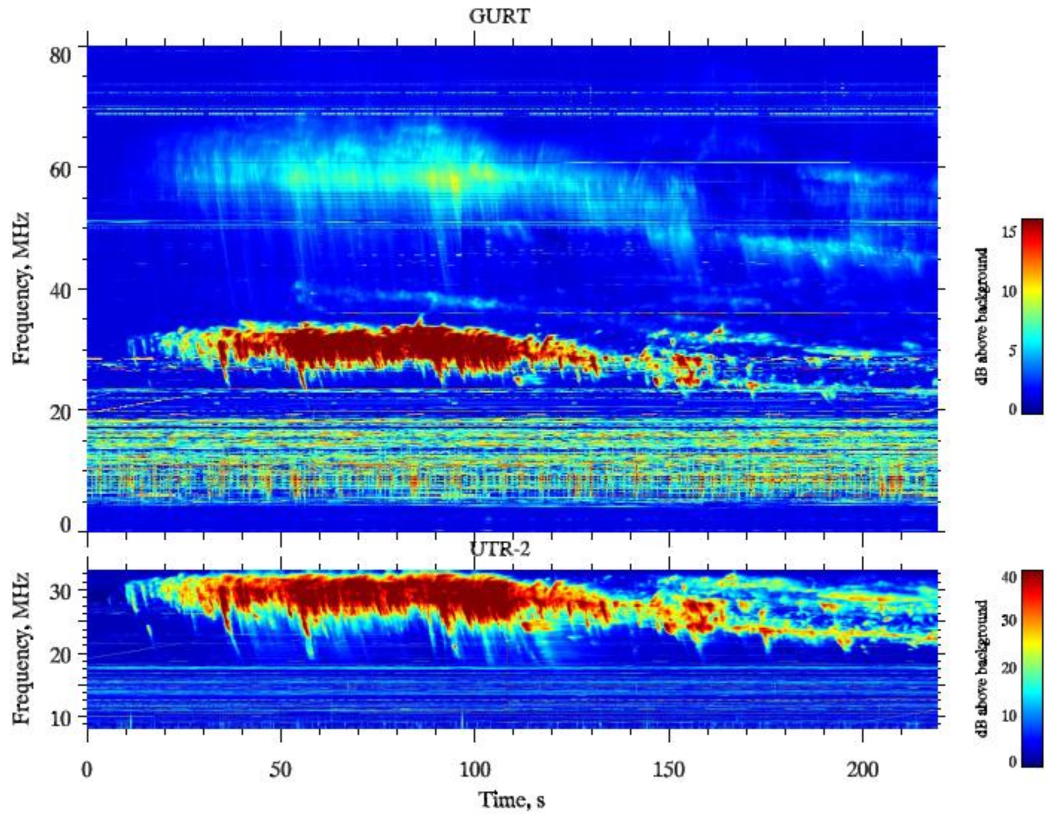
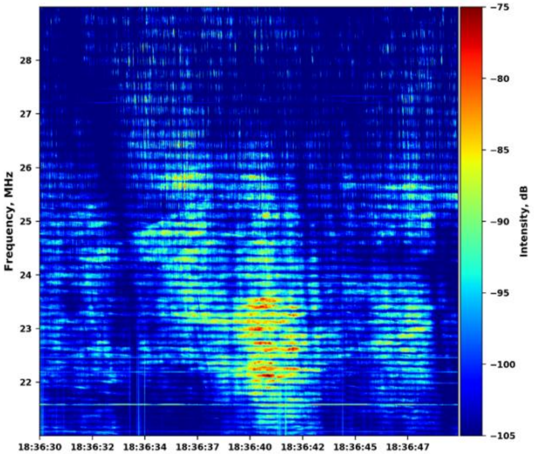
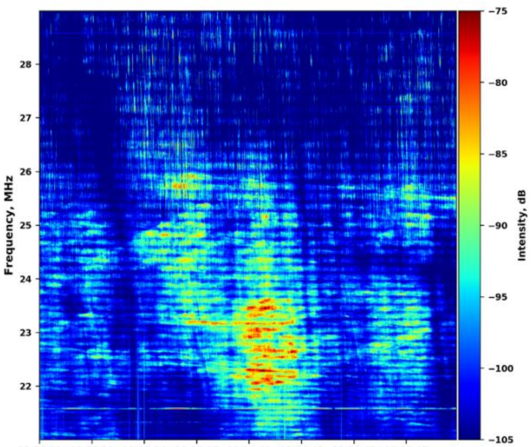
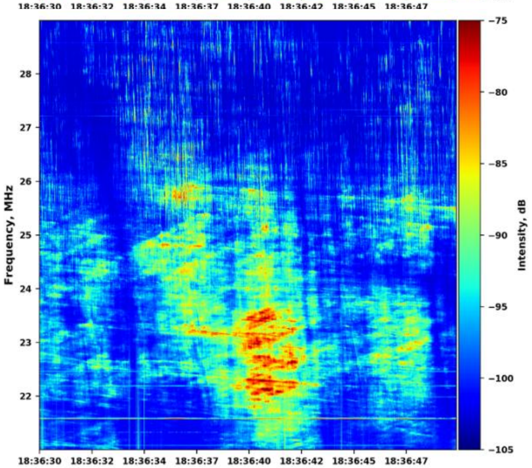


Fig. 10. Observations of a type II burst. UTR-2 frequency band 8.25 ÷ 33 MHz frequency and time resolution of 4 kHz and 100 ms, respectively. Recording was conducted on subarray GURT in the range 8 ÷ 80 MHz with the same time resolution and frequency resolution of 20 kHz. Start recording corresponds to 07:11:15 UT.

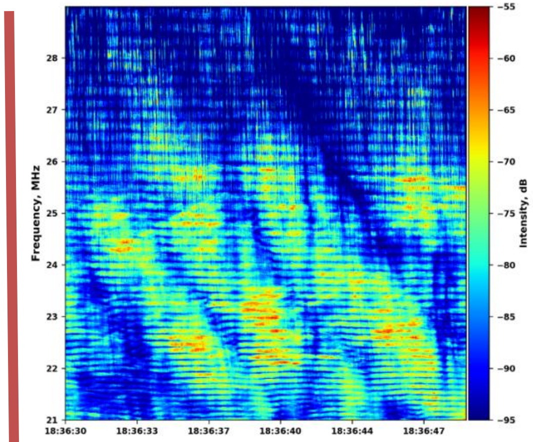
Jupiter radio emission

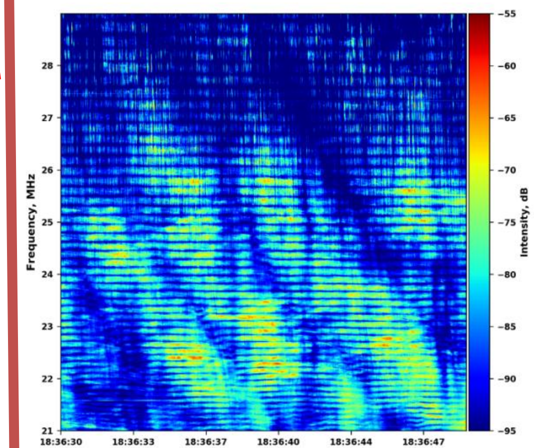


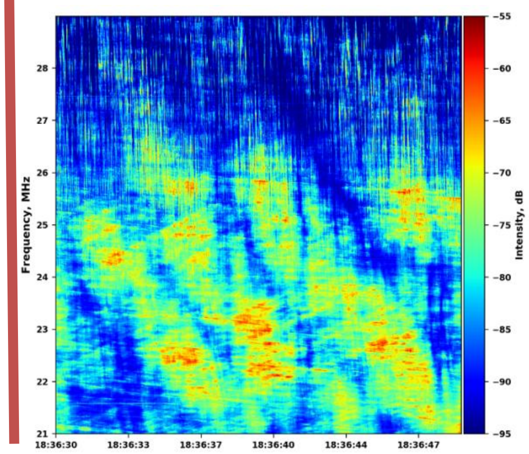


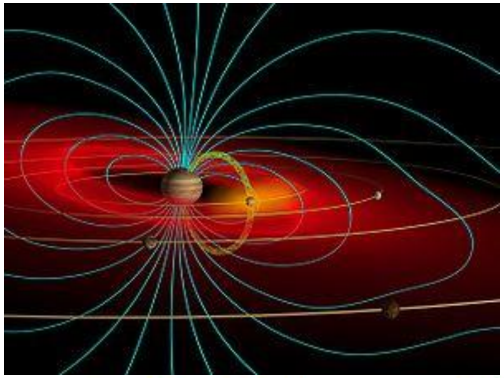


URAN-2, A_E = 28000 m^2









Non-Io radio emission

Louis, C. K., L. Lamy, P. Zarka, B. Cecconi, and S. L. Hess (2017), Detection of Jupiter decametric emissions controlled by Europa and Ganymede with Voyager/PRA and Cassini/RPWS, *J. Geophys. Res. Space Physics*, *122*, doi:10.1002/2016JA023779.

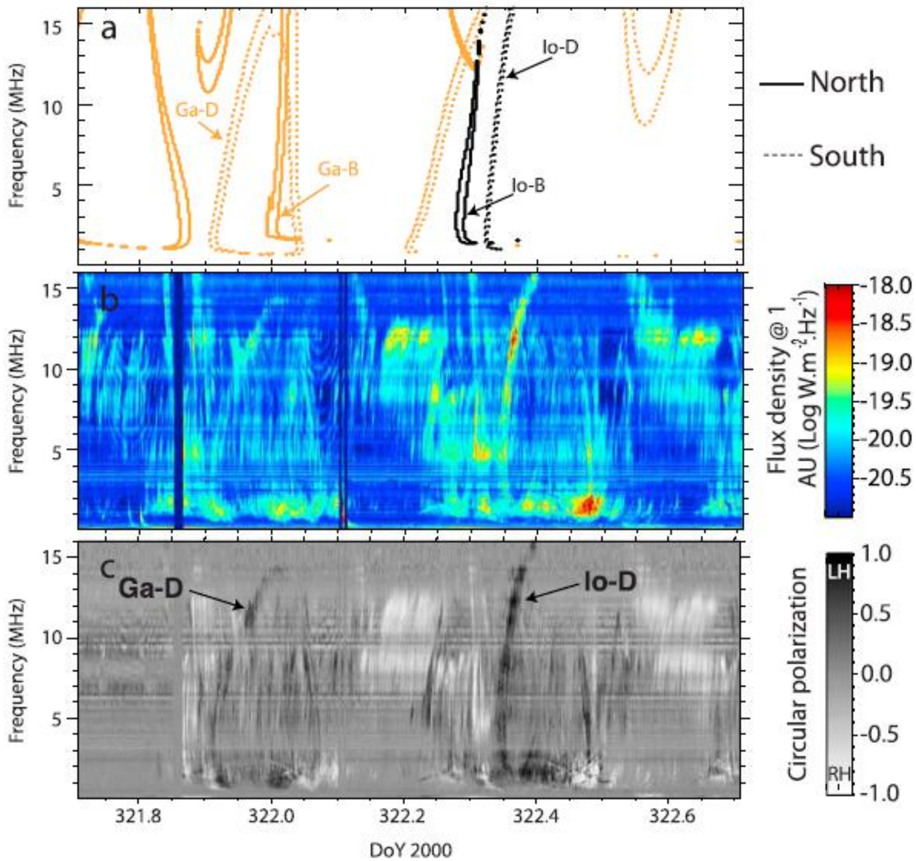


Figure 5. Cassini observations of an Io and a Ganymede arc. (a) ExPRES simulations (Io in black and Ganymede in orange—thick line, northern emissions; dotted line, southern emissions), (b) intensity flux and (c) the circular polarization—LH, left handed (emission from the southern hemisphere); RH, right handed (emission from the northern hemisphere). This time interval was chosen because of the presence of an Io arc and a Ganymede arc.

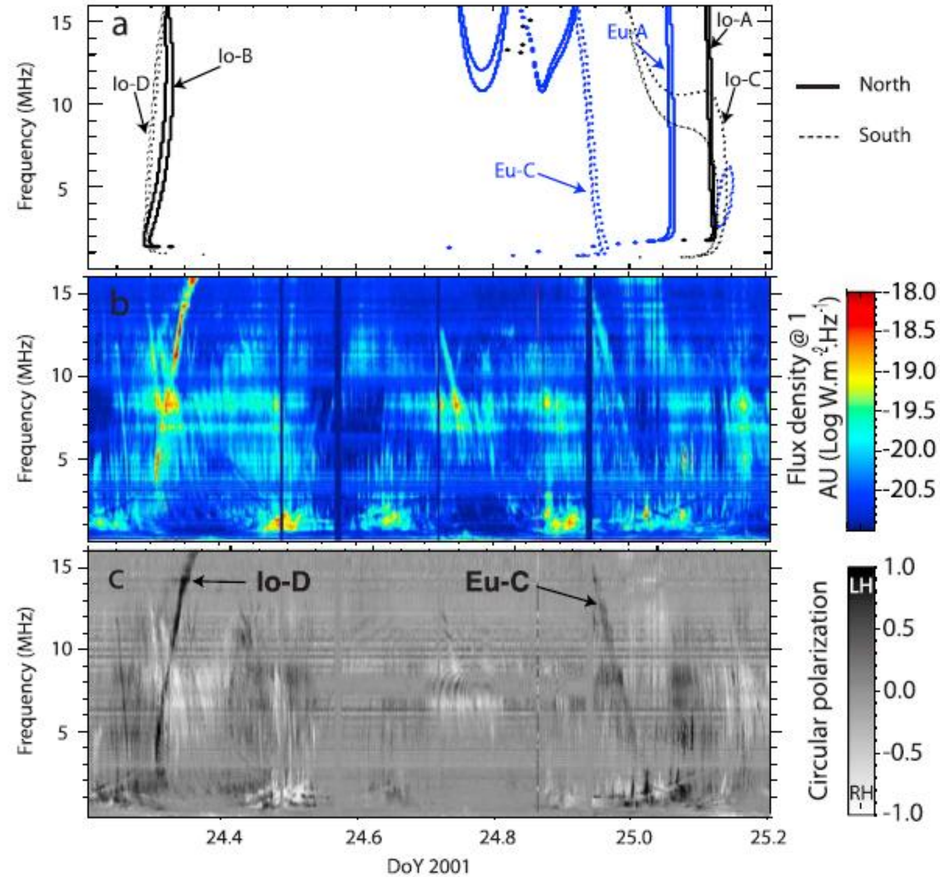
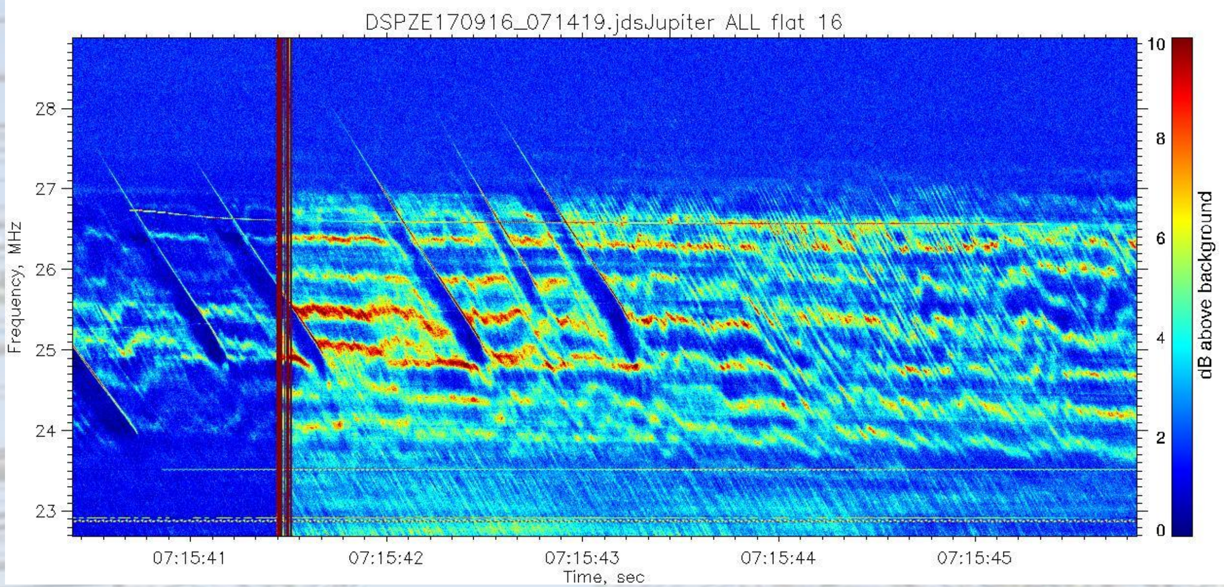
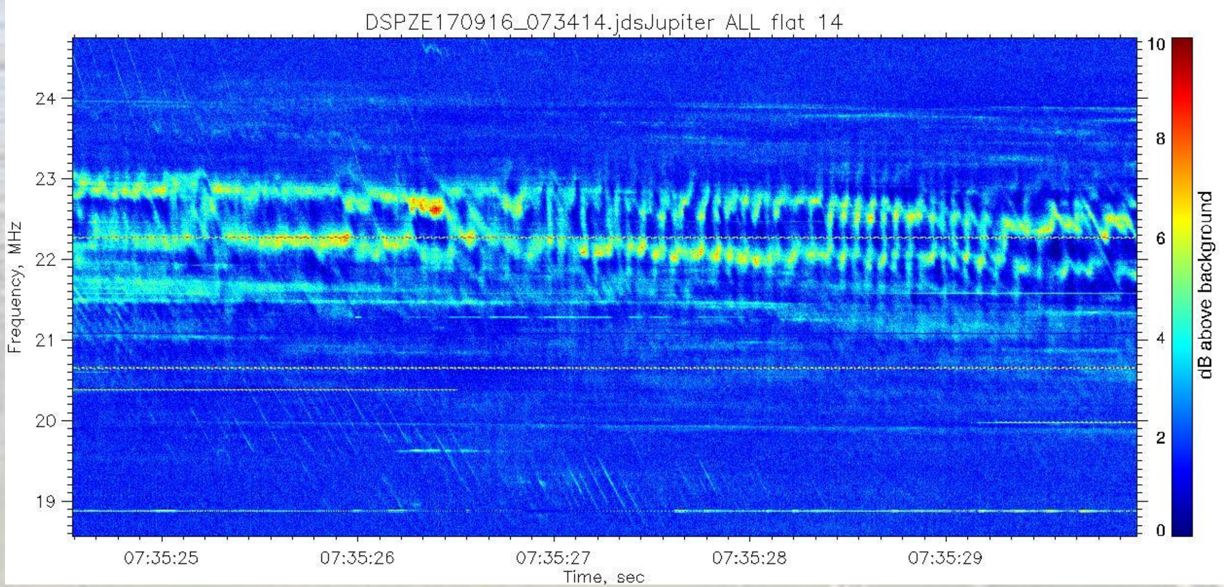


Figure 2. Cassini observations of an Io and a Europa arc. (a) ExPRES simulations (Io in black and Europa in blue—thick line, northern emissions; dotted line, southern emissions), (b) Intensity flux and (c) the circular polarization—LH: left handed (emission from the southern hemisphere); RH: right handed (emission from the northern hemisphere). This time interval was chosen because of the presence of an Io arc and a Europa arc.

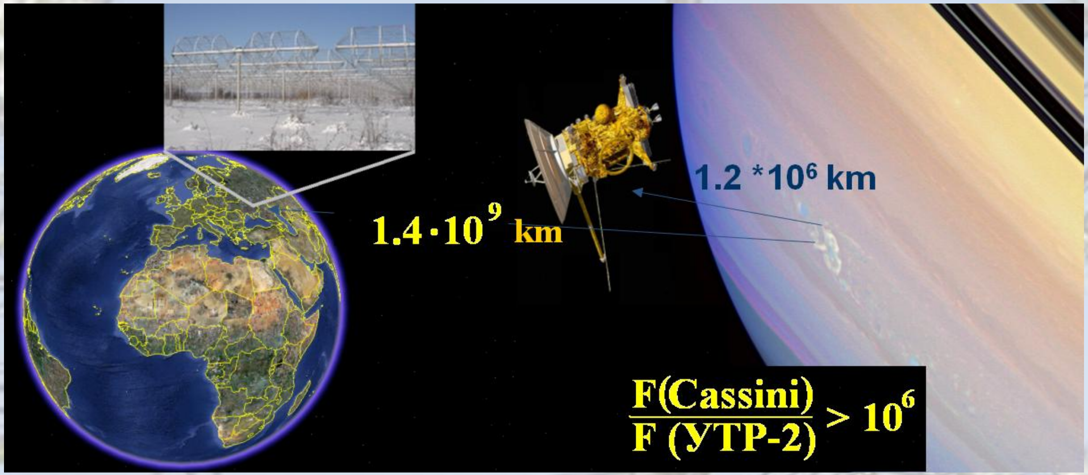
Different types of Jupiter radio emission

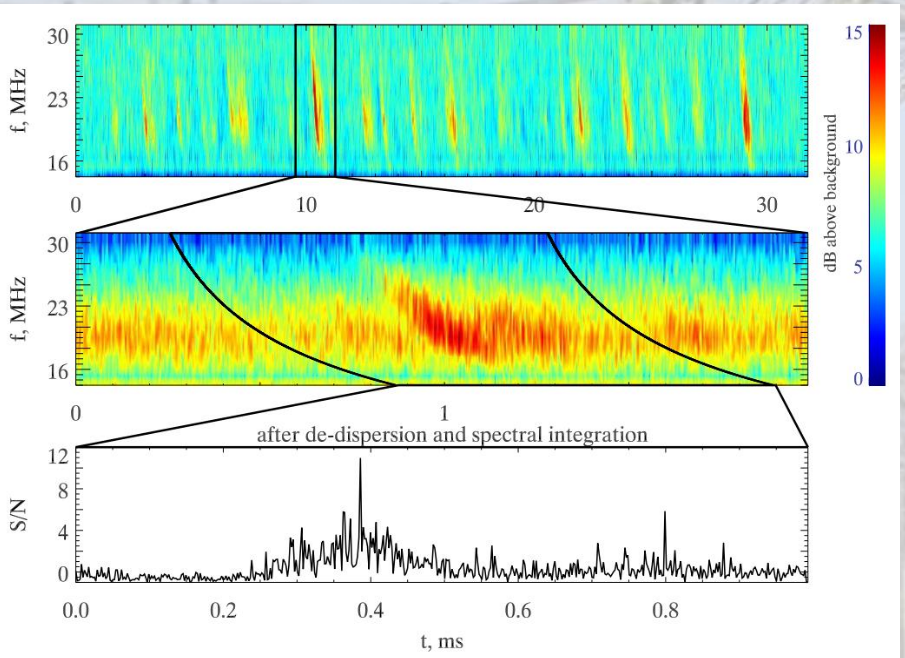
New types of Jupiter radio emission: "zebra" - structures and burst of absorption (observation of UTR-2 within the framework of ground support of the Juno mission)

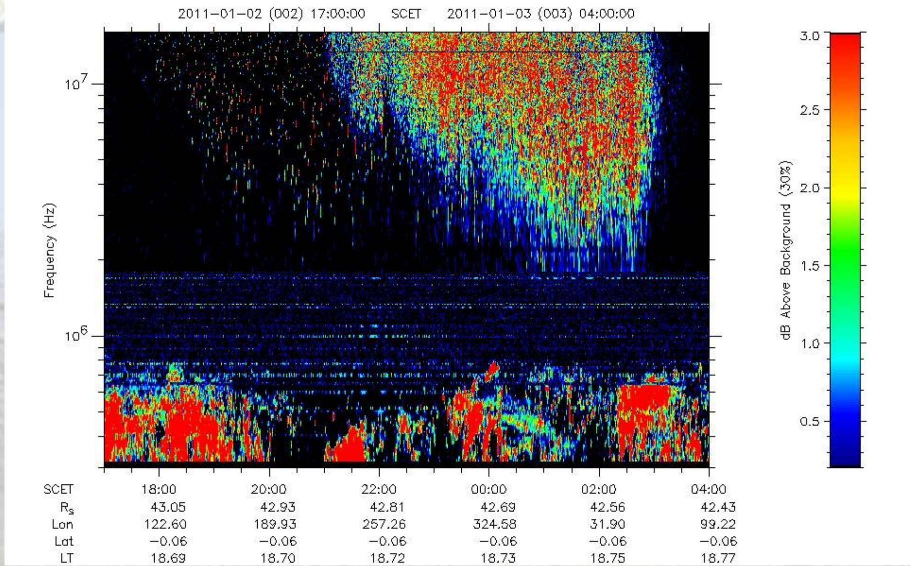




Lightning in Saturn’s atmosphere and Great White Spot

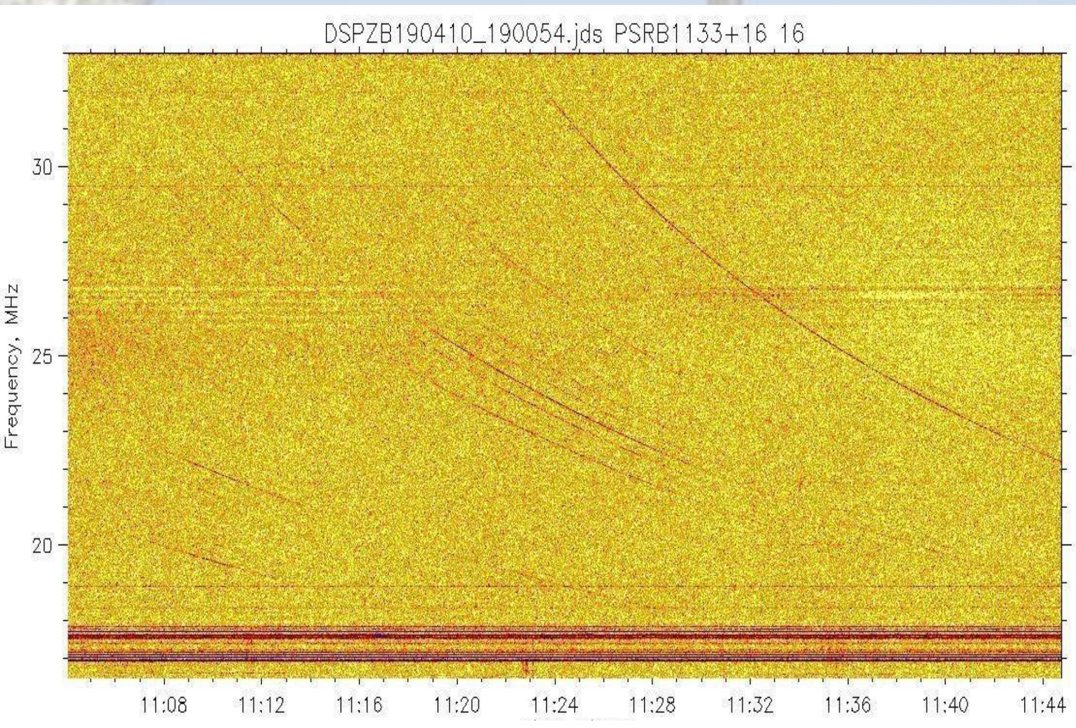






The time resolution of UTR-2 receivers (~ 15 ns) is approximately **10,000** higher than that of Cassini and Voyager (~ 30 ms)

Pulsars: long-term emission and dispersion measure variations



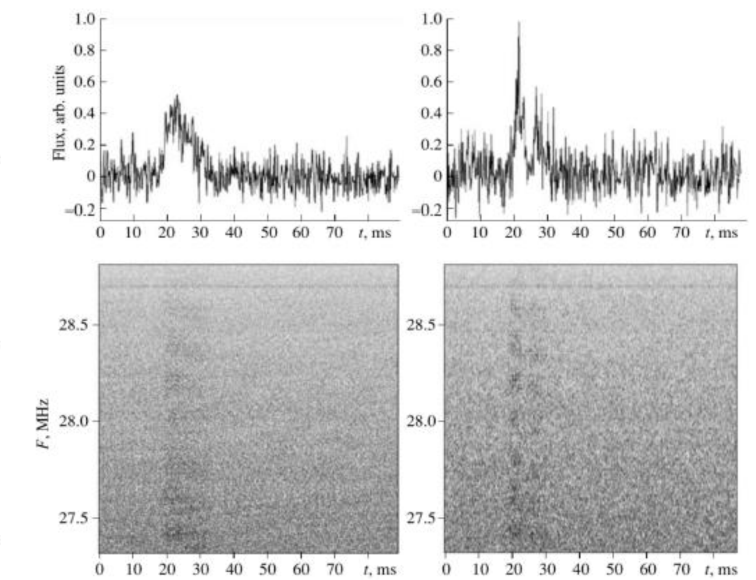
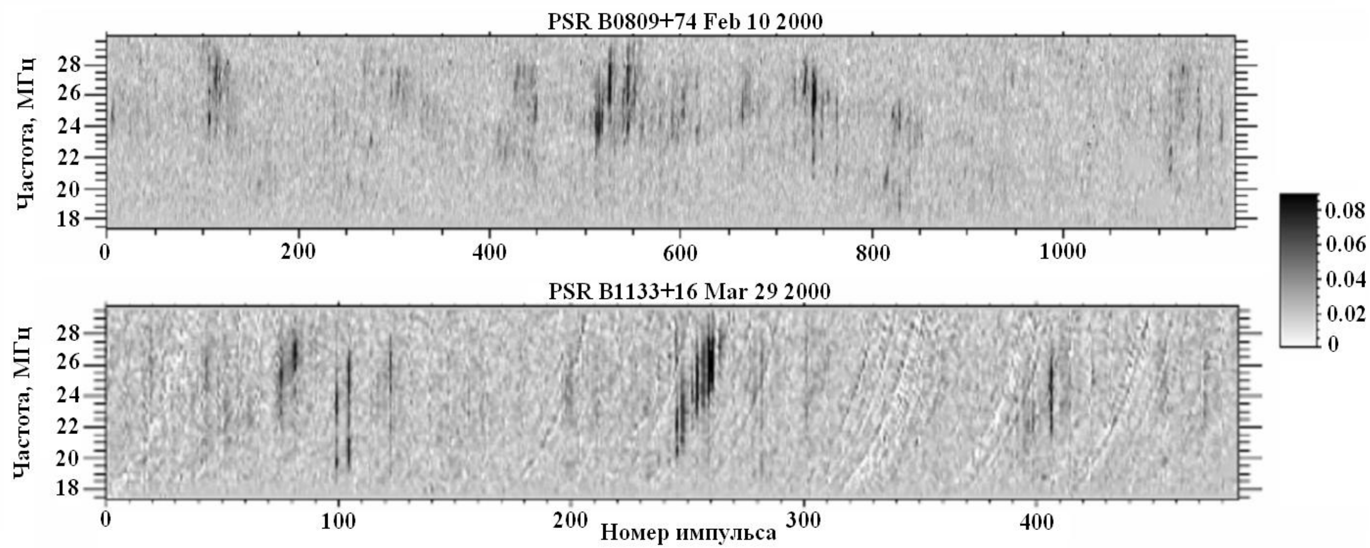
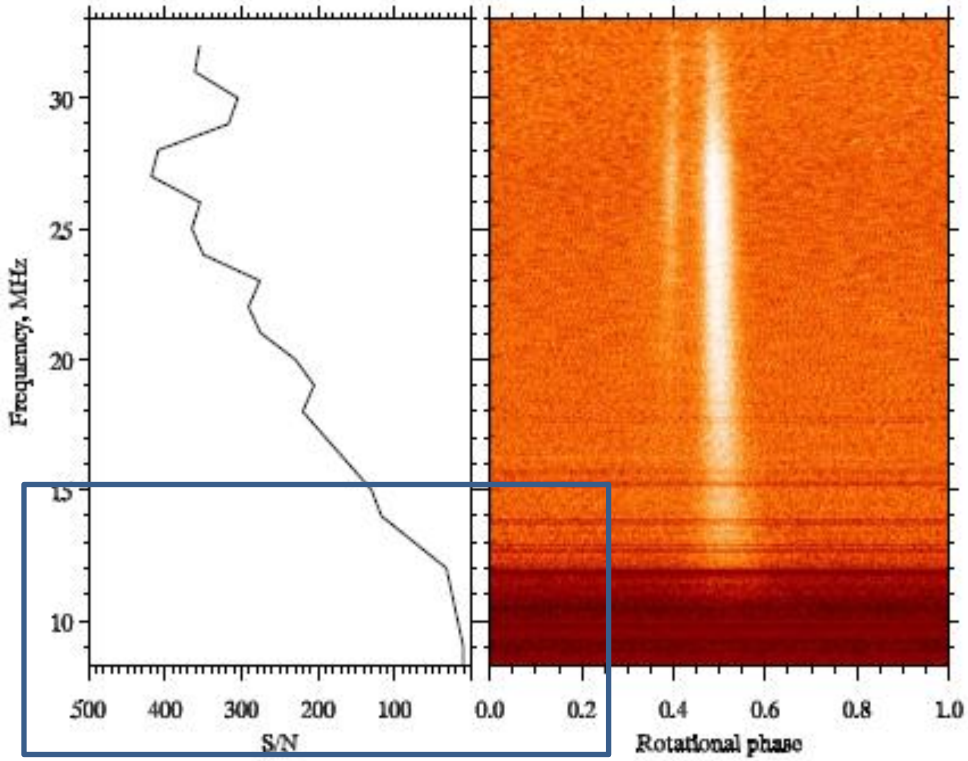


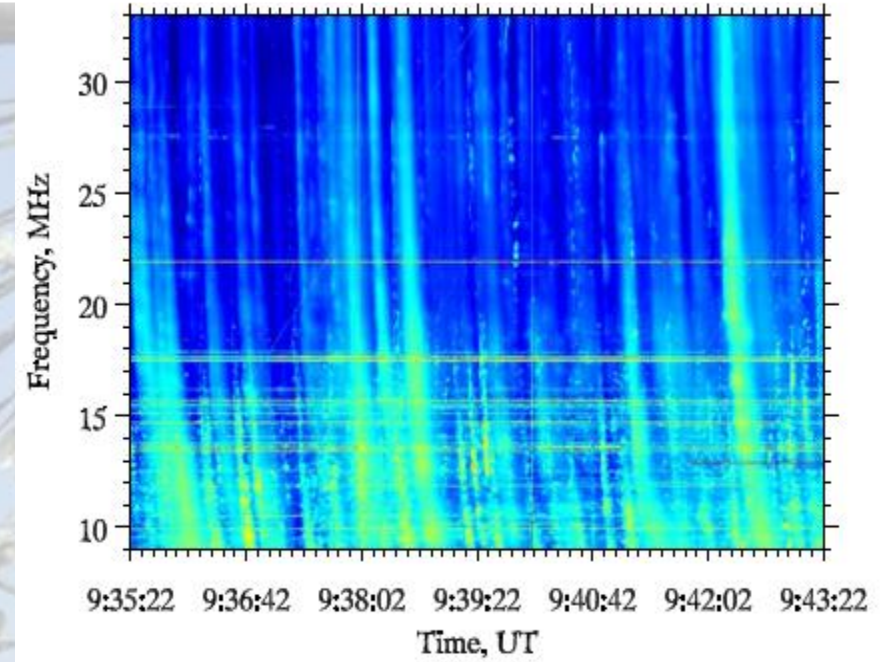
Рис. 1. Постдетекторний метод компенсації впливу дисперсійної затримки (ліва панель) та когерентний метод компенсації дисперсійної затримки (права панель). Обидва методи були застосовані для відтворення форми одного й тогож імпульсу PSR B0950+08.
O. M. Ul'yanov and V. V. Zakharenko Energy of Anomalously Intense Pulsar Pulses at Decameter Wavelengths // Astronomy Reports, 2012, Vol. 56, No. 6, pp. 417–429.

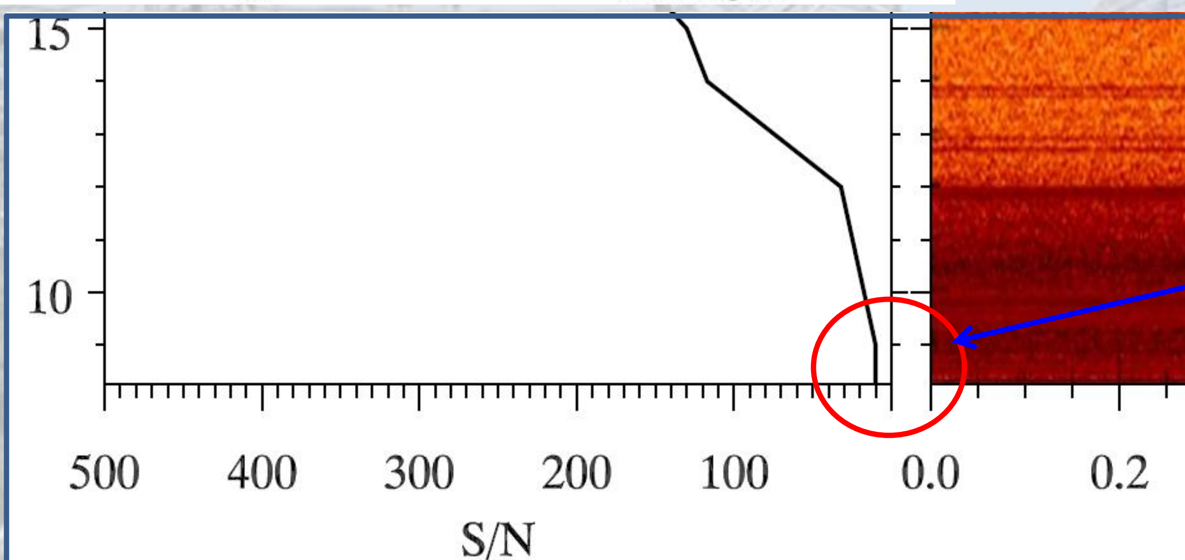
The details of an average pulsar profile of 1-10 ms with total dispersion delay of 100-1000 s allow determining the DM of with an accuracy of 10^{-5} -> ISM tomography with high precision



Possibilities of RFI mitigation.





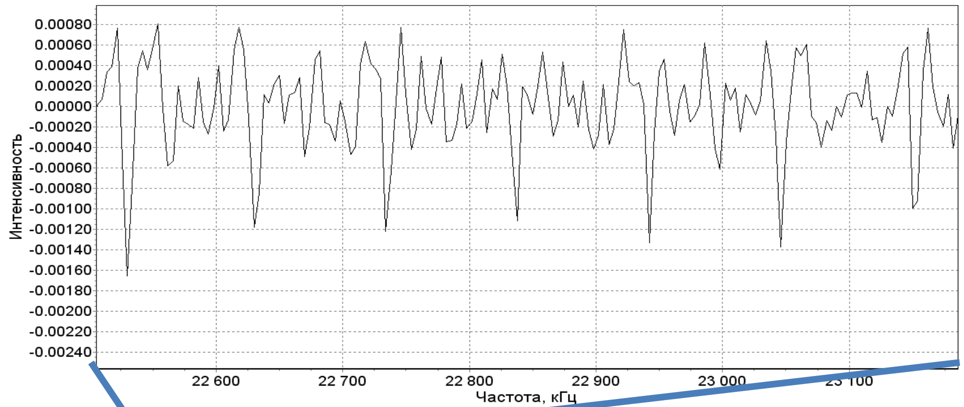


High temporal and frequency resolution and advanced RFI mitigation methods :

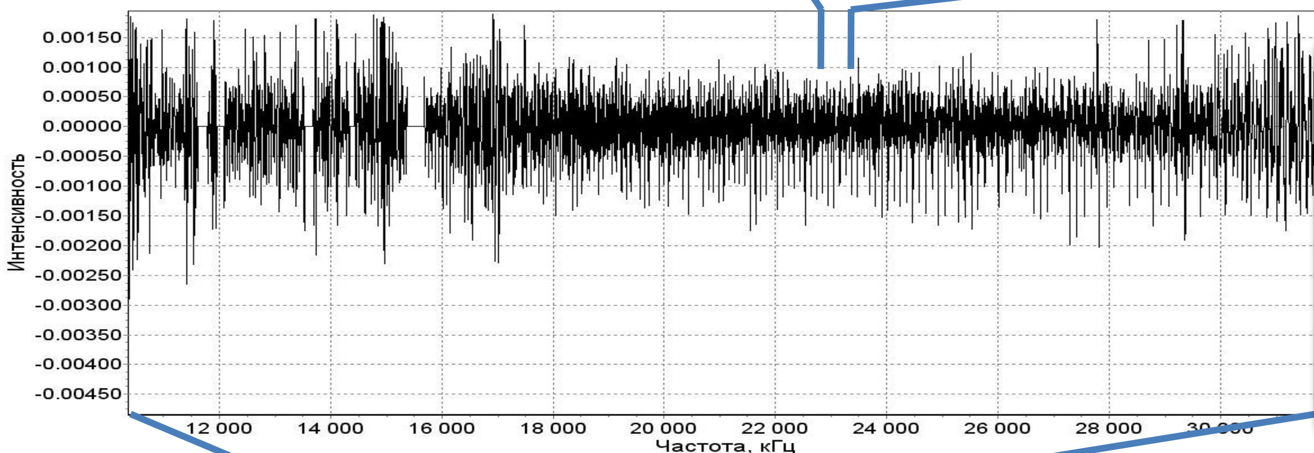
Signal/Noise = 10

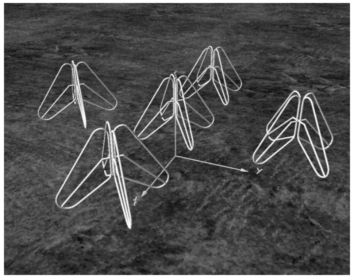
In hard interference conditions

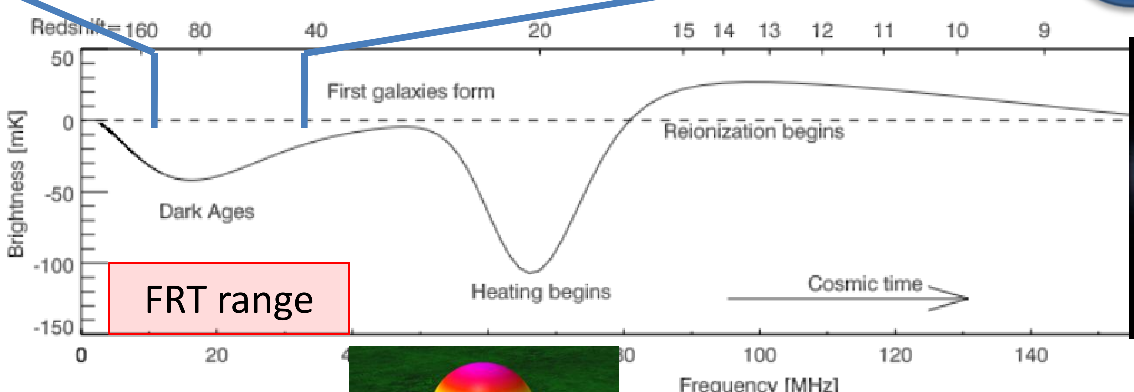
Radio recombination lines.
Dark Ages:
HI, z ~ 100

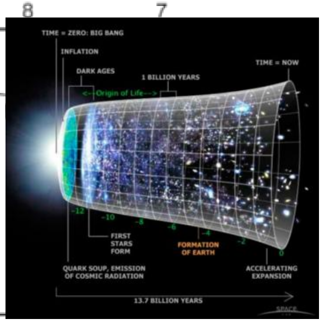


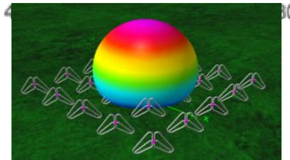
UTR-2.
Direction - Cas A. In the range 10.5 - 31 MHz there are Carbon RRL C854α ... C596α. Integration time – 55 min.
With ~100 h int. time -> $dT/T \sim 2*10^{-6}$





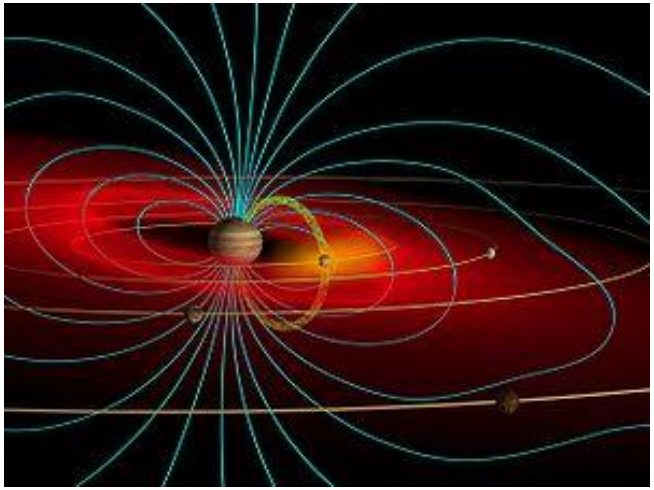


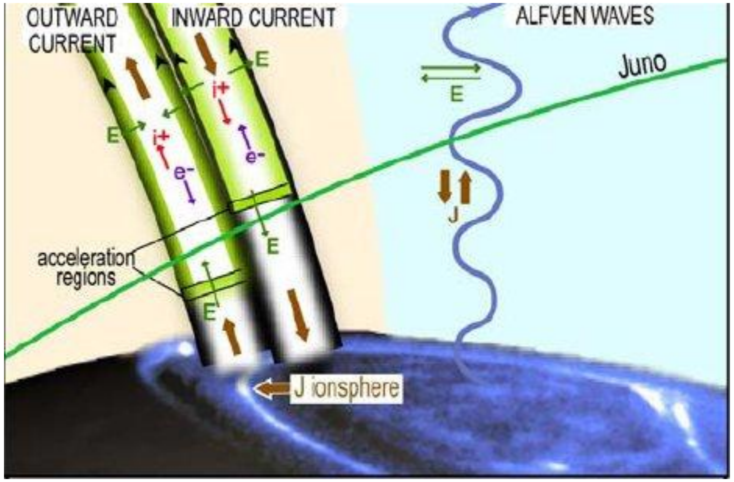


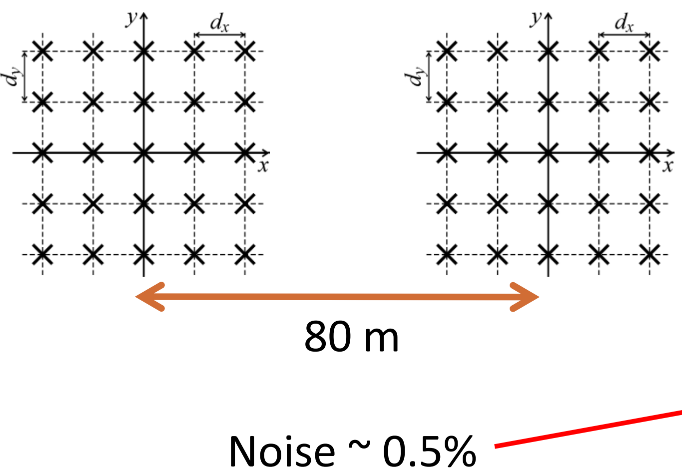


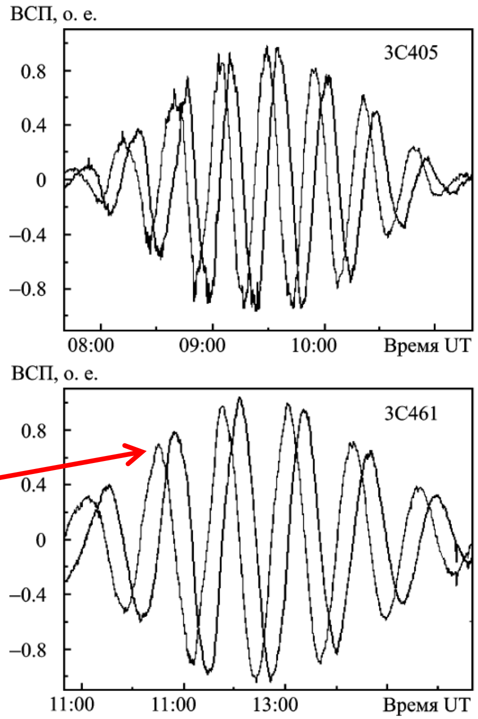
[Liu, Pritchard, Tegmark & Loeb arXiv:1211.3743v3]

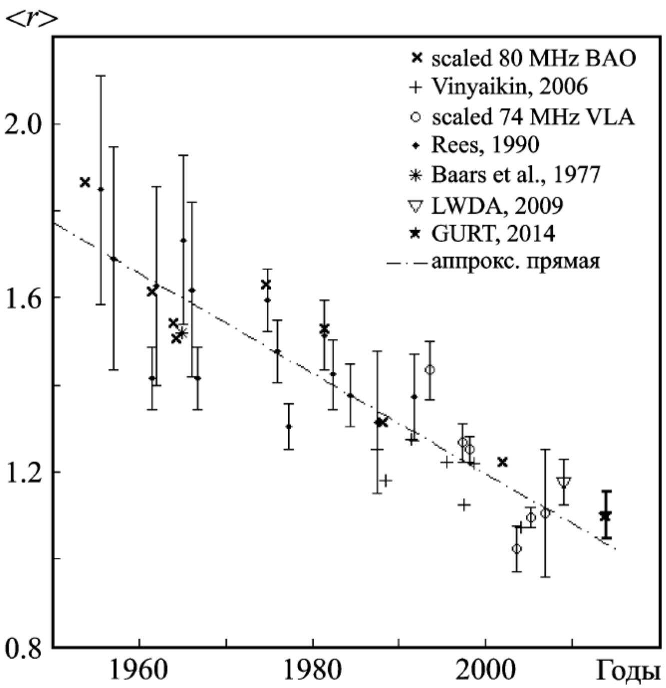
Interferometer up to 380 000 km.











A twofold mission to the Moon: objectives and payloads

Decision Letter - Revise: 13 February 2018
Mr Johnson
Special Issue Managing Guest Editor (**Acta Astronautica**)

-**Reviewer 3:**

"Many of the pioneering steps…"

- This proposal carefully stepped through the MANY genuinely interesting scientific questions that can be addressed by
- 1) getting away from the Earth's ionosphere, and
- 2) getting away from the Earth's RFI.

Many of the pioneering steps have been taken by this group:

- both on the technical side with electrically short, active antennas working in a regime of Galactic background dominance,
- in being pioneers for many of the most interesting scientific questions, including RRLs,
- and emission from solar system bodies.

Conclusion

- “So I really like this paper a lot, **it is based on LOTS of experience!”**

- “The **key** is to get in **contact with other groups** that are pushing similar missions, and to **work together**. You have a very strong background in technology and REAL science at low frequencies, so you can be a real asset to other groups that have much less REAL experience.”

- Low frequency radio telescope of new generation: high sensitivity part of a wide flexible telescope net with (at each section) different mode of observations, possibilities of RFI mitigation, preliminary data process and work in different combinations of net parts.

Thank you for your attention !