



# NEW FRONTIERS FOR LOW FREQUENCY RADIO ASTRONOMY IN UKRAINE AND IN THE WORLD

International Workshop  
“RT-32 ZOLOCHIV: FIRST RESULTS, EU  
COLLABORATION, RADIO ASTRONOMY FRONTIERS”  
October 3-5, 2019, Zolochiv, Ukraine

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# **New Opportunities of Ukrainian and World Low Frequency Radio Astronomy**

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## **Abstract**

There is a rapid progression of low-frequency radio astronomy (8-80 MHz band) around the world. Giant new generation instruments LOFAR, NenuFAR, LWA, MWA, SKA are being built and used. But for half a century, Ukraine has remained the world leader in this current field of fundamental and applied science, thanks to the creation and use of the world's largest UTR-2, URAN, GURT radio telescopes. Recently, a careful analysis has shown that the reserves of these unique tools and related research have not yet been exhausted. This concerns the further development and modernization of experimental means and observation methods that will radically increase the sensitivity of measurements, resolution, noise immunity. The integration of Ukrainian radio astronomy potential and related facilities into the worldwide network of radio research of the Universe is also an additional opportunity for progress.

**President of the NASU B. Paton with Academic of the NASU S.Braude at the meeting of the Presidium of the Ukraine Academy of Sciences during the inauguration of the UTR-2 Radio Telescope (June, 1971).**



# The State Prize of Ukraine in the Field of Science and Technology for 2018:

## “The Universe Radio Emission at Decameter Wavelength”

*Konovalenko A.A., Zakharenko V.V., Kalinichenko N.N., Melnik V.N., Sidorchuk M.A.,  
Stanislavsky A.A., Stepkin S.V., Ulyanov O.M., (IRA NASU, Kharkiv)*



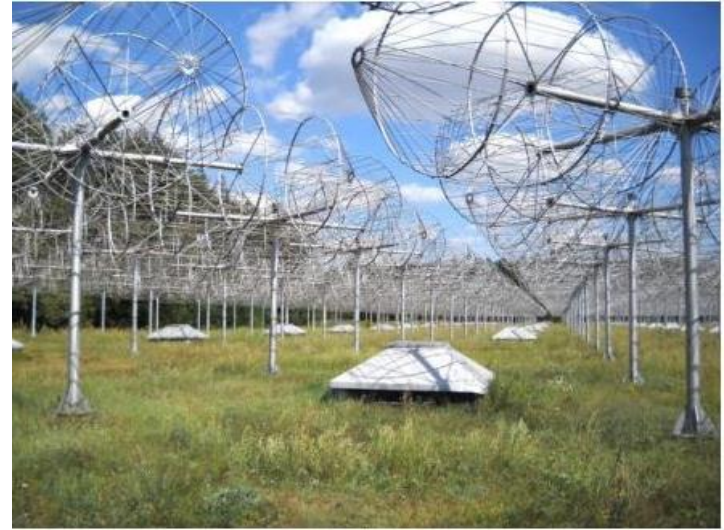
Solemn meeting at the National Academy of Sciences of Ukraine (NASU),  
**June 5, 2019**



**The world's largest UTR-2 radio telescope (N-S arm, 1.9 km x 60 m)  
Frequency range - 8... 32 MHz; number of elements - 2040;  
effective area - 150,000 square meters.**



**The UTR-2 radio telescope, E-W arm (900m×60m)**



## URAN-1...URAN-4 radio telescopes

$\Sigma N$  (URAN) = 1000\*2;  $\Sigma N$  (total) = 4040;  $A_{\text{eff}}$  (total) = 200000 sq. m

# Low-frequency radio telescopes on the map of Ukraine





# Upgrade of the UTR-2 radio telescope during 2006-2016



## SYSTEM PARAMETERS AND REGIMES

### OLD

### NEW

#### *Antenna*

Frequency range	10-25 MHz	8 – 32 (40) MHz
Frequency band	6 x 1 MHz = 6 MHz	24 (32) MHz
Calibration, check-in, control, hardware, software	~	high - performance

#### *Back-end*

Number of channels	5 beams x 12 rec. = 60 ch.	5 x 2 x 8192 = 81920 ch.
Frequency band	10 kHz x 60 = 600 kHz	24(32) MHz
Time resolution	20 ms	0,25 ms (up to 1 mcs)
Frequency resolution	10 kHz	4 kHz (up to 0,1 kHz)
Dynamic range	40 dB	90 dB
Sensitivity	10 Jy	10mJy
Regimes of measurements	Power spectra; post detector registration	Power spectra; complex cross-spectra; real-time Fourier transform; wave-form

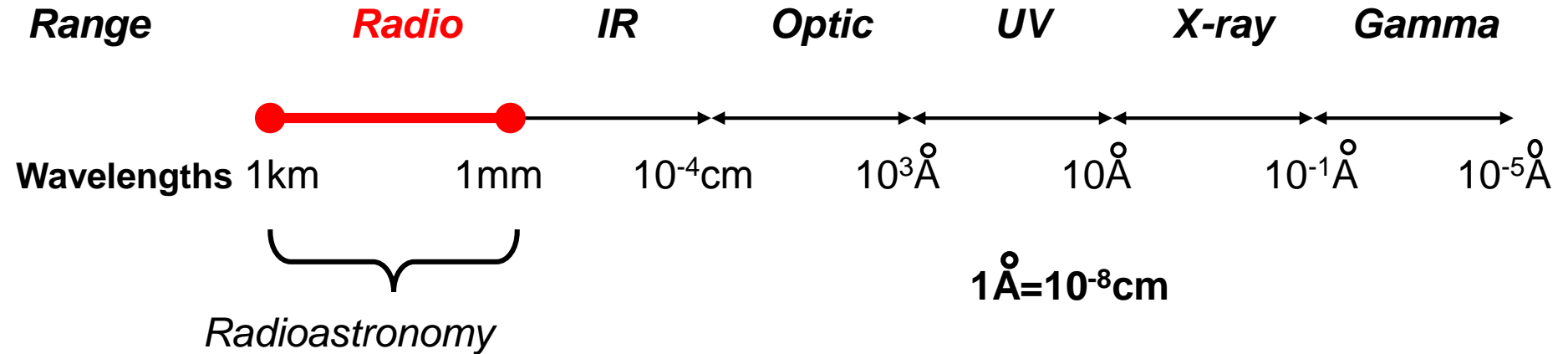
# Main parameters of Ukrainian low-frequency radio telescopes

Sky Noise Dominance for UTR-2 and URAN system is 4-8 dB, for GURT – 10 dB.

Main beam scan sector from zenith along both coordinates is  $\pm 70^\circ$  for UTR-2 and  $\pm 80^\circ$  for URAN and GURT

Radio telescope; institution; coordinates (longitude / latitude)	Frequency range, MHz	Dimensions, m; Max effective area, m <sup>2</sup>	Number of elements ( $l \times m = N$ ); polarization	Beamwidth at 25 MHz	Distance to UTR-2 (LOFAR), km	VLBI resolution at 25 MHz (UTR-2 – URAN)	Array spacing (d), suspension above ground (h)
UTR-2; IRA NASU (49° 39' / 36° 56')	8 – 32 (40)	1800 × 900 m 140 000 m <sup>2</sup>	2040 1 linear	0.4° × 0.4°	0 (~2000)	–	$dNS = 7.5$ m $dW = 9$ m, $h = 3.5$ m
UTR-2 North-South arm	8 – 32 (40)	1800 × 53 m 105 000 m <sup>2</sup>	6 × 240 = 1440 1 linear	0.3° × 12°	0 (~2000)	–	---//---
UTR-2 West arm	8 – 32 (40)	900 × 45 m 40 000 m <sup>2</sup>	6 × 100 = 600 1 linear	0.6° × 12°	0 (~2000)	–	---//---
URAN-1; IRA NASU (49° 40' / 36° 21')	8 – 32 (40)	200 × 29 m 5 500 m <sup>2</sup>	4 × 24 = 96 2 linear	5° × 30°	42 (~1950)	59"	$d = 7.5$ m $h = 3.5$ m
URAN-2; PGO NASU (49° 38' / 34° 50')	8 – 32 (40)	238 × 116 m 28 000 m <sup>2</sup>	16 × 32 = 512 2 linear	3.5° × 7.5°	150 (~1850)	16"	$d = 7.5$ m $h = 3.5$ m
URAN-3; PMI NASU (51° 29' / 23° 50')	8 – 32 (40)	238 × 58 m 14 000 m <sup>2</sup>	8 × 32 = 256 2 linear	3.5° × 15°	946 (~1100)	2.6"	$d = 7.5$ m $h = 3.5$ m
URAN-4; IRA NASU (46° 24' / 30° 16')	8 – 32 (40)	238 × 29 m 7 000 m <sup>2</sup>	4 × 32 = 128 2 linear	3.5° × 30°	613 (~1500)	4"	$d = 7.5$ m $h = 3.5$ m
GURT (single subarray); IRA NASU (49° 39' / 36° 56')	8 – 70 (80)	18 × 18 m 650 m <sup>2</sup> (at 10 MHz)	5 × 5 = 25 2 linear	30° × 30°	~1 (~2000)	–	$d = 3.75$ m $h = 1.6$ m

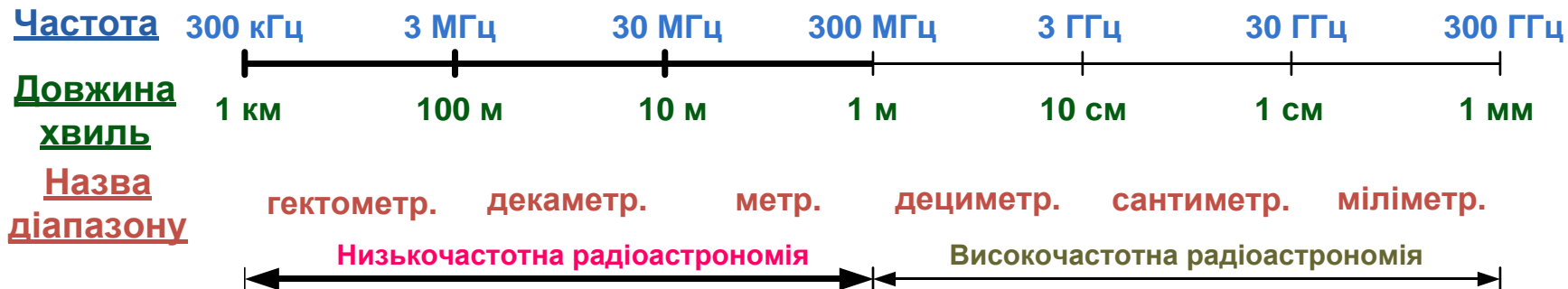
# Modern all-waves astronomy



**Frequency of electromagnetic radiation**      =       $\frac{\text{Light velocity}}{\text{Wavelength of radiation}}$

$\lambda = 10\text{ m}$       :       $f = \frac{300\,000\text{ km/s}}{10\text{ m}} = 30\text{ MHz}$

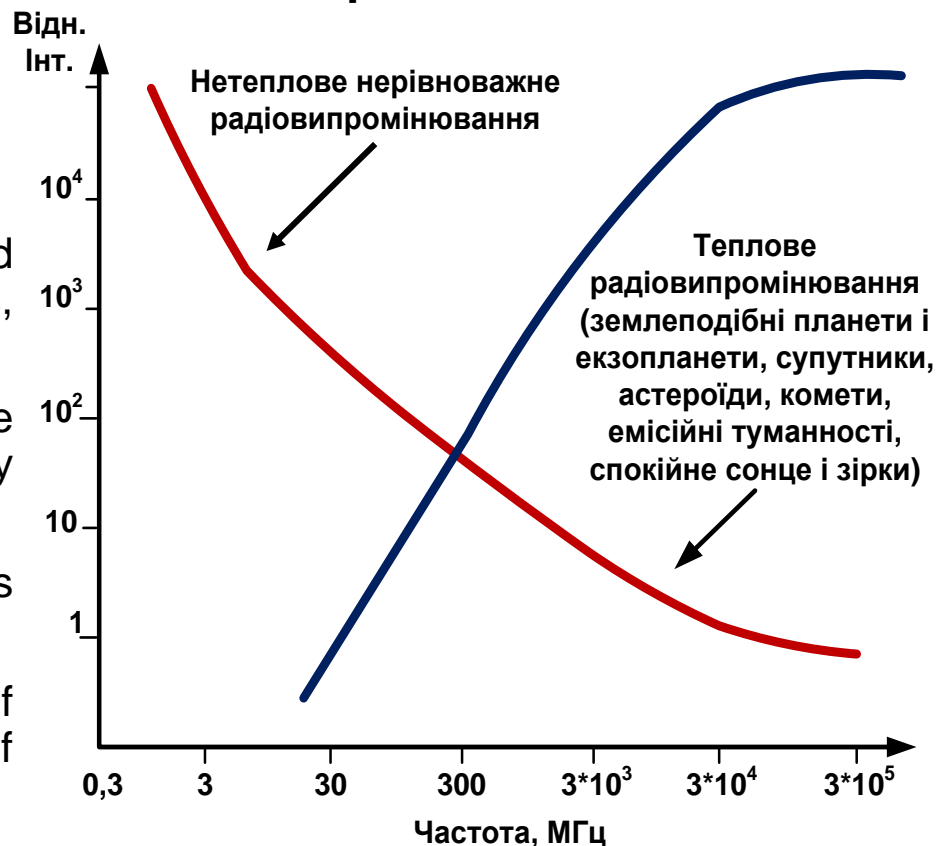
# Frequency bands of radio astronomical studies



## Non-thermal non-thermal radio emission mechanisms important for low-frequency radio astronomy

- Synchrotron radio emission (galactic and extragalactic background, radio galaxies, quasars);
- Coherent radioemission in magnetoactive plasma (active Sun and stars, pulsars, planetary giants and giant exoplanets);
- Radio emission of electrostatic discharges (lightning in planets and exoplanets);
- Monochromatic stimulated radioemission of highly excited atoms (recombination lines of interstellar atoms).

## Possible spectra of radio emission



# Equipment-methodical advantages of the low-frequency radio-astronomy

1. Informativeness of the astronomical observations in the certain range of spectrum rises with the increase of relative width of this spectrum that is determined as  $f_B / f_H$ . For low-frequency radioastronomy ( $f = 8 \dots 80$  Mhz)  $f_B / f_H = 10$ . (In an optics it equals only two). Thus the absolute band of frequencies folds only  $F = f_B - f_H = 80 - 8 = 72$  Mhz. Up-to-date digital technique such band it can be simply digitised "straight".
2. As a noise temperature of low-frequency of radio telescopes is determined by the temperature of the galactic background, then there is not a necessity to use cryogenic entrance receiver.
3. The number of required antenna elements (at a given effective area) decreases inversely in proportion to the square of the wavelength, so the price of the LF radio telescope is significantly reduced.
4. For low-frequency radio telescopes are built as antenna arrays in which it is possible to achieve simultaneously unlimited field of view, multi-beam and multi-section signal reception, flexibility in changing the configuration of the radio telescope.
5. Phased array antennas do not have mechanically moving parts, which increases the reliability and longevity of radio telescopes.
6. Low-frequency radio telescopes are scientific-capacitive, but not technologically-capacitive, so they are not very expensive.

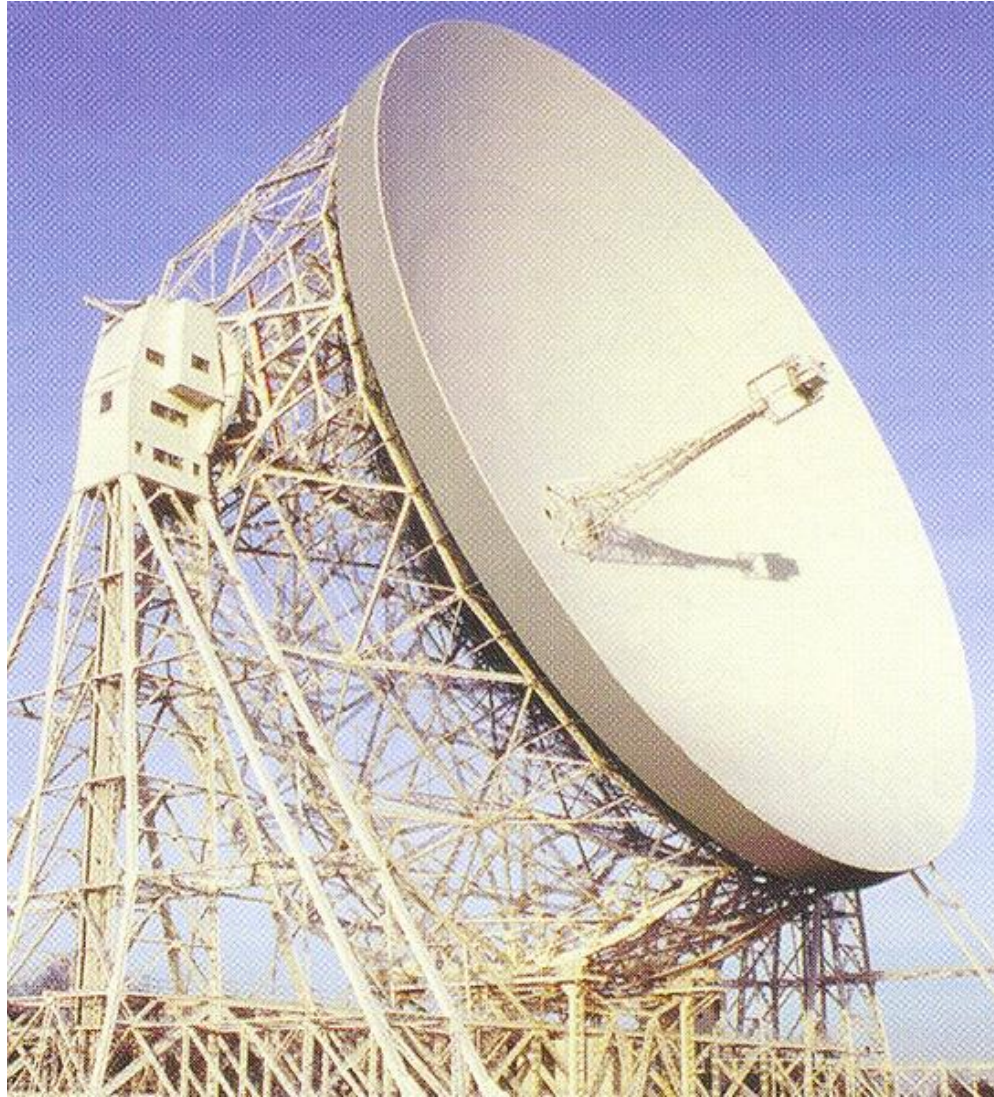
# The tasks of the ground-based (and space-born) low frequency radio astronomy in the solar system, galactic and metagalactic sciences (including UTR-2 and URAN observations)

The Earth	{	* Ionosphere	+	
		* Magnetosphere	~	
		* Air showers of cosmic rays	-	
		* Parameters of the surface	+	
Solar system	{	* The Moon: occultations	+	
		secondary emission of cosmic rays	-	
		screen	-	
		* The Sun: quiet	+	
		active	+	
		* Jupiter	+	
		* Planets (Saturn, Uranus etc.)	+	
		* Interplanetary media: scintillations	+	
		VLBI	+	
		* Comets	~	
Galaxy	{	* Pulsars	+	
		* Active stars	~	
		* Exoplanets	~	
		* Transients	~	
		Non-thermal background	+	
		Supernova remnants	+	
		HII regions	+	
		* Interstellar media (recombination lines)	+	
Metagalaxy	{	Galaxies	+	
		Radio galaxies	+	
		Quasars	+	
		Galactic clusters	+	
		Unidentified objects	+	
		* Transients	~	
		* Dark ages spectral features	-	

Lecacheux, Konovalenko,  
Rucker, P&SS, 2003;

Konovalenko et al., PRE VII, 2011

# 76-m Radio Telescope (Great Britain)



# The world's best low frequency radio telescopes ( $f \leq 300$ MHz)

( Existing modernized \*, New generation\*\*, Future\*\*\* ),  $K = T_N / (T_N + T_{sys})$

- 1.\* **UTR-2** :  $f = 8 \dots 32(40)$  MHz;  $A_{ef} \approx 150\ 000$  sq.m ( $K \approx 0,8$ ) – Ukraine
- 2.\* **URAN-1...URAN-4**:  $f = 8 \dots 32(40)$  MHz;  $\sum A_{ef} \approx 50\ 000$  sq.m ( $K \approx 0,8$ ) – Ukraine
- 3.\*\* **GURT**:  $f = 8 \dots 80$  MHz;  $A_{ef} \approx 400$  sq.m (1 субреши́тка) ( $K \approx 0,9$ ) – Ukraine
- 4.\* **NDA**:  $f = (10)20 \dots 80$  MHz;  $A_{ef} \approx 14\ 000$  sq.m ( $K \approx 0,7$ ) – France
- 5.\*\* **NenuFAR**:  $f = (8)20 \dots 80$  MHz;  $A_{ef} \approx 20\ 000$  (40 000) sq.m ( $K \approx 0,9$ ) – France
- 6.\*\* **LOFAR (LBA)**:  $f = (10)30 \dots 80$  MHz;  $A_{ef} \approx 50\ 000$  sq.m ( $K \approx 0,3$ ) – Europe  
**LOFAR (HBA)**:  $f = 110 \dots 240$  MHz;  $A_{ef} \approx 10\ 000$  sq.m ( $K \approx 0,5$ ) – Europe
- 7.\*\* **LWA**:  $f = (10)20 \dots 80$  MHz;  $A_{ef} \approx 7\ 000$  sq.m ( $K \approx 0,7$ ) – USA
- 8.\*\* **MWA**:  $f = 50 \dots 300$  MHz;  $A_{ef} \approx 10\ 000$  sq.m ( $K \approx 0,7$ ) – Australia
- 9.\*\*\* **SKA (Low-band)**:  $f = 200 \dots 1000$  MHz;  $A_{ef} \approx 10^6$  sq.m ( $K \approx 0,7$ ) – South. Africa

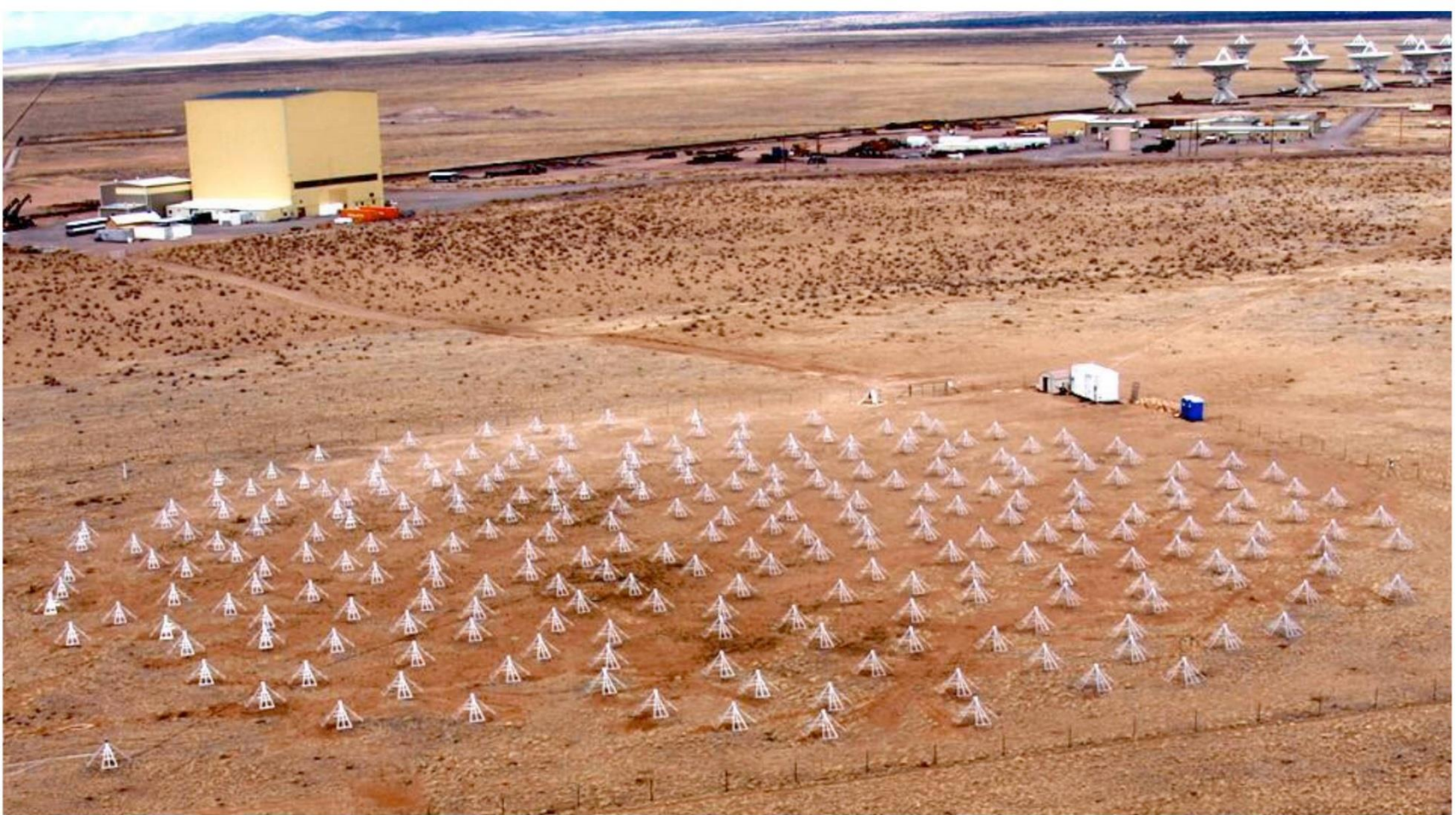


# ***First part of LOFAR core***

**LBA: 30...80 MHz; HBA: 110...240 MHz**

**The Netherlands, Exloo, 2010**





**New LF radio telescope LWA (Long Wavelength Array, USA, New Mexico)  $f = 20\text{--}80$  MHz**

**США, LWA:**  $f=30\text{--}80$  МГц;  $N=256$ ;  $B=16$  МГц;  $D=85$  дБ;  $\Delta T=6$  дБ ;  $b=12$  бит;  $\Sigma_1 = 400$  USD

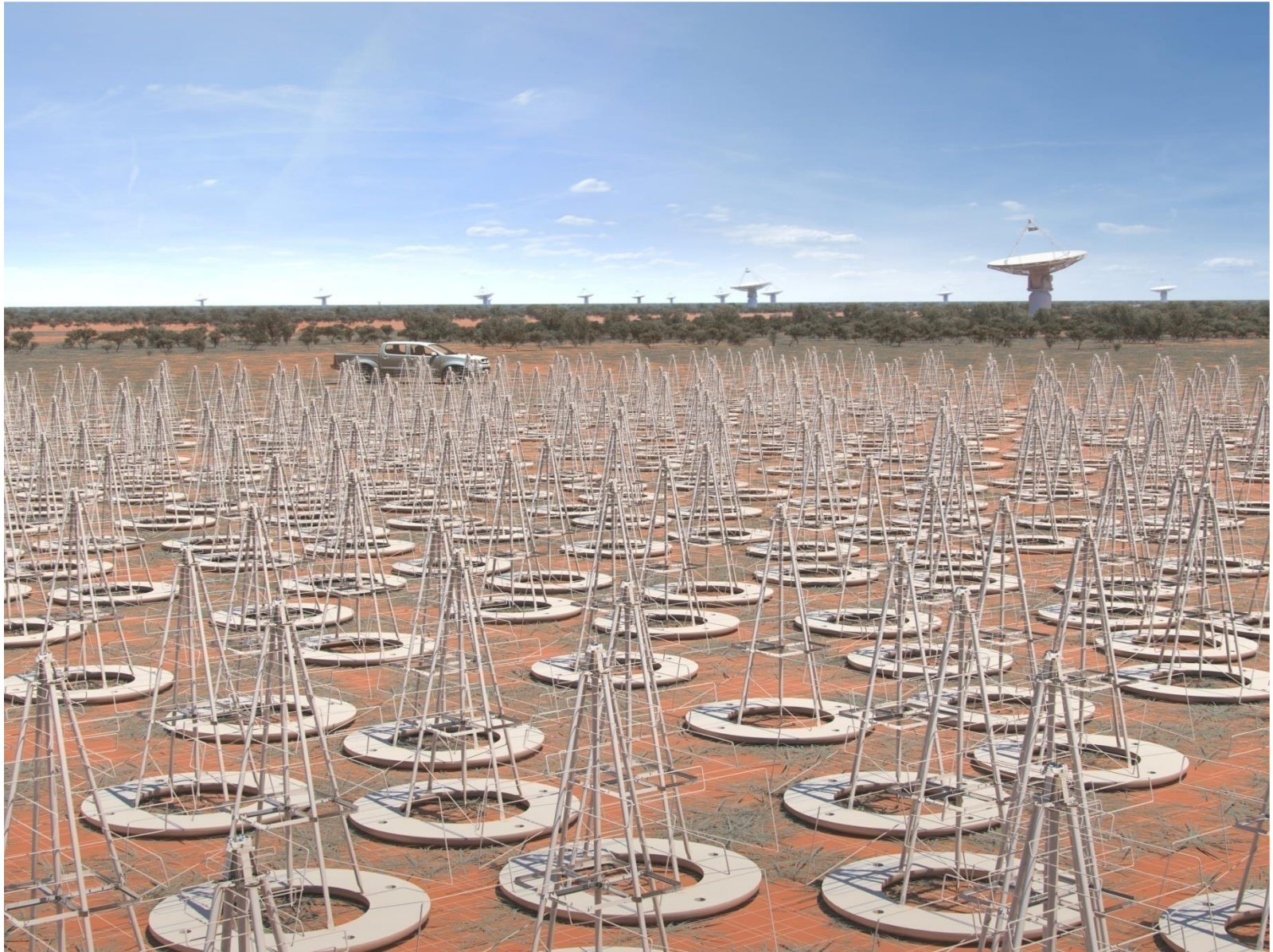
**Європа, LOFAR:**  $f=30\text{--}80$  МГц;  $N=96 \times 10$ ;  $B=16$  МГц;  $D=80$  дБ;  $\Delta T=4$  дБ ;  $b=12$  бит;  $\Sigma_1 = 350$  USD

**Україна, GURT:**  $f=10\text{--}80$  МГц;  $N=275$ ;  $B=70$  МГц;  $D=95$  дБ;  $\Delta T=9$  дБ ;  $b=16$  бит;  $\Sigma_1 = 150$  USD

# Radio Telescope MWA, 50-300 MHz, Australia



# Radio Telescope SKA, 200-1000 MHz, International

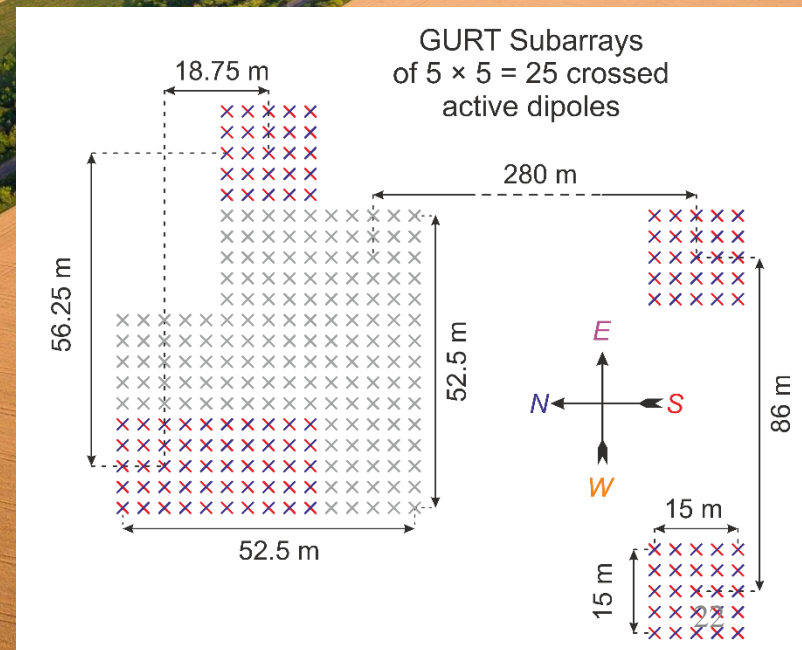
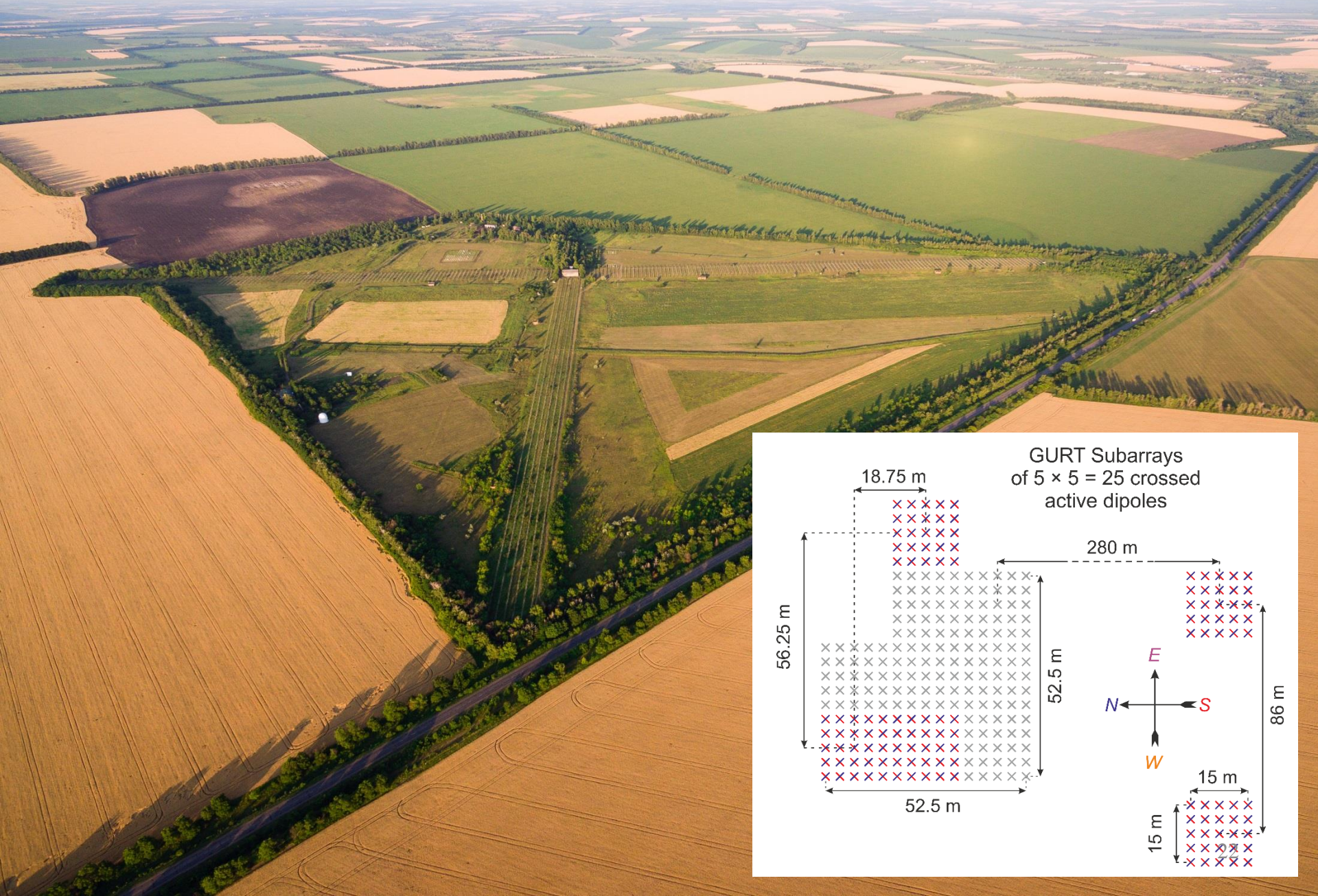


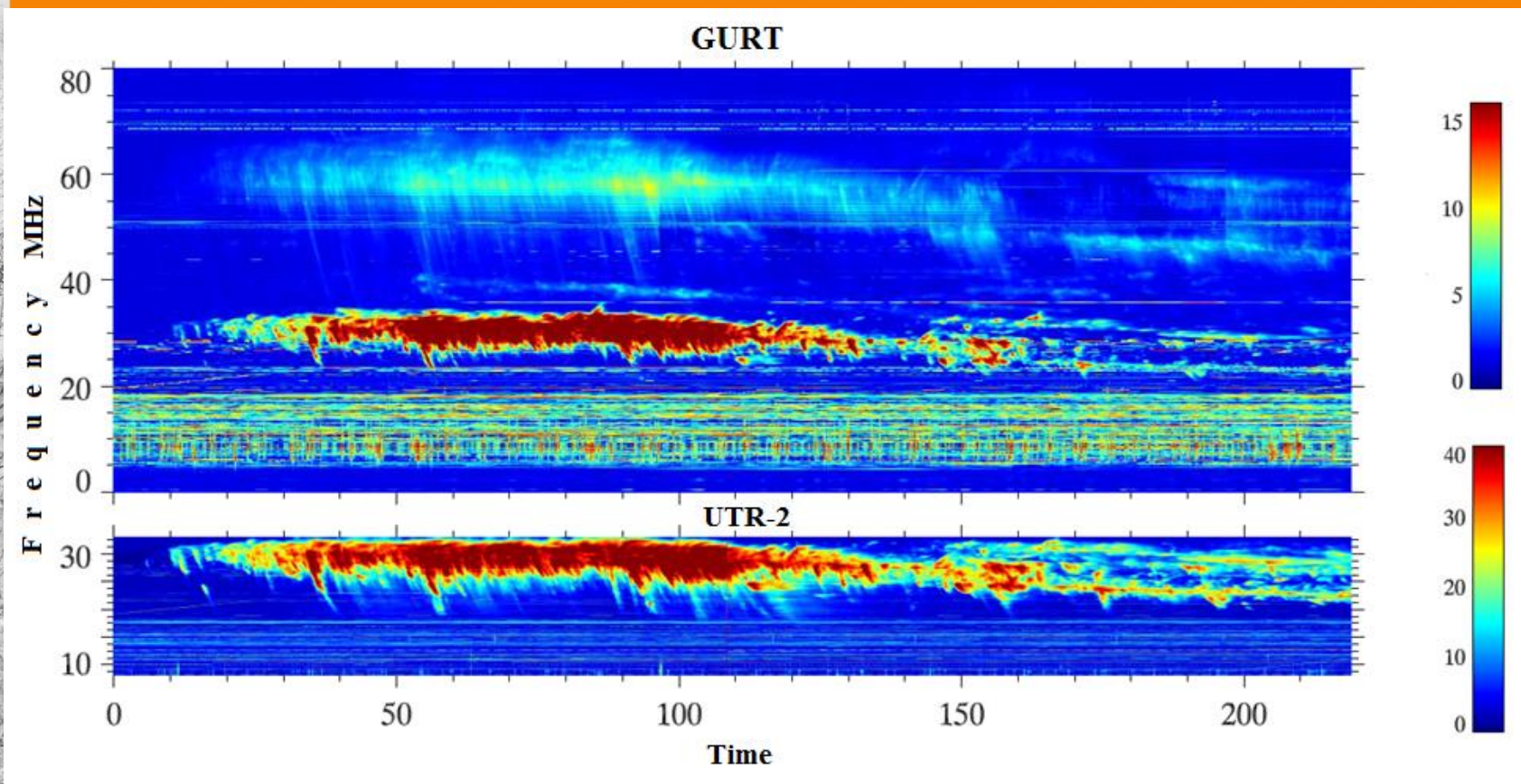
## Additional New Generation GURT Radio Telescope with the UTR-2 Radio Telescope at the Observatory of the name S.Y. Braude

- ✓ Frequency range – **8...80 МГц**;
- ✓ Number of crossed elements in the subarray – **25**;
- ✓ The total number of elements installed – **550**;
- ✓ Potential number of elements - up to **10,000**, which can provide an area of up to 1 sq. km!



# Observatory of the name S. Ya. Braude with UTR-2 and GURT Radio Telescopes (September, 2017)





**Type II Solar bursts observed by GURT (top)  
and UTR-2 (bottom) on 25.07.2014.  
The start is 07:11:15 UT**

# **High quality astrophysical studies by using of small size low-frequency new generation radio telescopes**

## **1. Advantages of new generation sub-array GURT (25 active antenna elements)**

- broad band;
- high sensitivity for brightness temperature;
- high time and frequency resolution;
- high dynamic range and interference immunity;
- electronic beam steering;
- polarimetric capabilities;
- high filling factor of antenna elements;
- continuous operation in automatic mode;
- optimal combination of analog and digital equipment;
- low costs of the development and maintenance;
- simple checking and repairing.

## **2. Astrophysical possibilities and tasks**

- The Sun and interplanetary medium;
- Earth ionosphere;
- Jupiter;
- Saturn electrostatic discharges;
- pulsars;
- galactic and extragalactic background;
- interstellar medium and radio recombination lines;
- cosmological spectral lines;
- secular decreasing of CasA flux density.



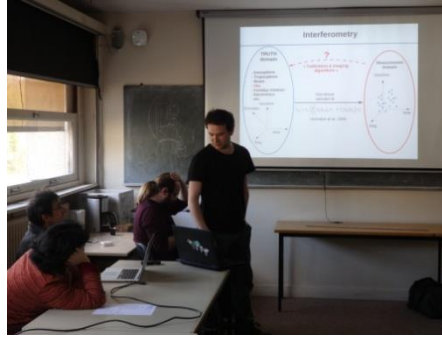
**Radio Astronomers of Ukraine in the Paris-Maidon Observatory (France)  
during the French-Ukrainian Scientific Meeting  
on the Development of Low-Frequency Radio Astronomy (March 2019)**



# Radio Astronomers of Ukraine during the reports about the new horizons of Low-Frequency Radio Astronomy



# Radio Astronomers from France during the reports about the NenuFAR Radio Telescope, Nancy Observatory, France



# New Generation Radio Telescope NenuFAR

(New Extension of Nancay Upgrading LOFAR), France,  $f=8\dots80$  MHz



# Radio telescope NenuFAR sub-arrays



**Nancay LF Radio Astronomy Meeting with the  
radio astronomers from France (10 people), from Ukraine (10 people)  
with the participation of radio astronomers from the Netherlands, Germany,  
the United Kingdom and others.**



# Director of the International Radio Telescope LOFAR R.Vermeulen presents the upgrade of the LOFAR 2.0



## Discussion of the prospects of LF radio astronomy





# The world's best low frequency radio telescopes ( $f \leq 300$ MHz)

( Existing modernized \*, New generation\*\*, Future\*\*\* ),  $K = T_N / (T_N + T_{sys})$

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- 8.\*\* **MWA**:  $f = 50 \dots 300$  MHz;  $A_{ef} \approx 10\ 000$  sq.m ( $K \approx 0,7$ ) – Australia
- 9.\*\*\* **SKA (Low-band)**:  $f = 200 \dots 1000$  MHz;  $A_{ef} \approx 10^6$  sq.m ( $K \approx 0,7$ ) – South. Africa

# The Contribution of Ukrainian Radio Astronomers to the development of the NenuFAR Radio Telescope, Nancay Observatory, France

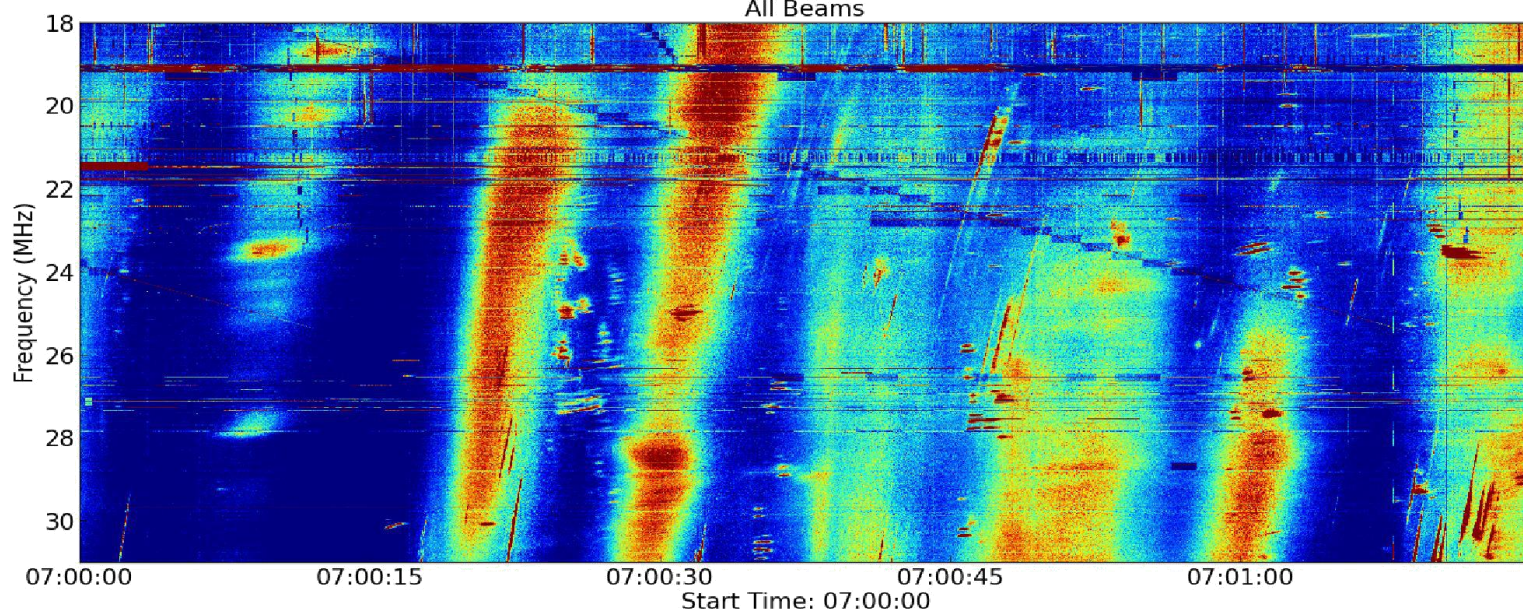
1. Girard J.N., Zarka P., Tagger M., Denis L., Charries D., **Konovalenko A.**, Boone F. Antenna design and distribution of the LOFAR superstation.// *Comptes Rendus Physique*. – 2012. – V.13 – P. 33-37.
2. Zarka P., Girard J. N., Tagger M., Denis L., Aghanim N., Alsac L., Arnaud M., Barth S., Boone F., Bosse S., Capayrou D., Capdessus C., Cecconi B., Charrier D., Coffre A., Cognard I., Combes F., Corbel S., Cornilleau-Wehrlin N., Cottet P., Dole H., Dumez-Viou C., **Falkovych I.**, Ferrari C., Floquet F., Garnier S., Georges G., Gond B., Grespier N., Griebmeier J.-M., Joly S., **Konovalenko A.**, Lamy L., Leh-nert M., Pommier M., Rucker H., Sandré P., Semelin B., Taffoureau C., Tasse C., Thétas E., Theureau G., **Tokarsky P.**, Van Driel W., Vimou J.-B., and Weber R.: LSS/ NenuFAR: The LOFAR Super Station project in Nançay //S. Boissier, P. de Laverny, N. Nardetto, R. Samadi, D. Valls-Gabaud, and H. Wozniak, eds. *SF2A 2012: Proc. of the Annual meeting of the French Society of Astronomy and Astrophysics*. – 2012. – P. 687–694.
3. Zarka P., Tagger M., Denis L., Girard J. N., **Konovalenko A.**, Atemkeng M., Arnaud M., Azarian S., Barsuglia M., Bonafede A., Boone F., Bosma A., Boyer R., Branchesi M., Briand C., Cecconi B., Célestin S., Charrier D., Chassande-Mottin E., Coffre A., Cognard I., Combes F., Corbel S., Courte C., Dabbech A., Daiboo S., Dallier R., DumezViou C., El Korso M. N., Falgarone E., **Falkovych I.**, Ferrari A., Ferrari C., Ferrière K., Fevotte C., Fialkov A., Fullekrug M., Gérard E., Griebmeier J.-M., Guiderdoni B., Guillemot L., Hessels J., Koopmans L., Kondratiev V., Lamy L., Lanz T., Larzabal P., Lehnert M., Levrier F., Loh A., Macario G., Maintoux J.-J., Martin L., Mary D., Masson S., Miville-Deschenes M.-A., Oberoi D., Panchenko M., Pandey-Pommier M., Petiteau A., Pinçon J.-L., Revenu B., Ri-ble F., Richard C., Rucker H. O., Salomé P., Semelin B., Serylak M., **Sidorchuk M.**, Smirnov O., Stappers B., Taffoureau C., Tasse C., Theureau G., **Tokarsky P.**, Torchinsky S., **Ulyanov O.**, van Driel W., **Vasylieva I.**, Vaubaillon J., Vazza F., Vergani S., Was M., Weber R., and **Zakharenko V.** NenuFAR: Instrument description and science case // *International Conference on Antenna Theory and Techniques (ICATT): Proc. conf.* – Kharkiv, Ukraine. – 2015. – P. 1–6. DOI: 10.1109/ICATT.2015.7136773

# Difficulties of the decameter wavelengths radio astronomy

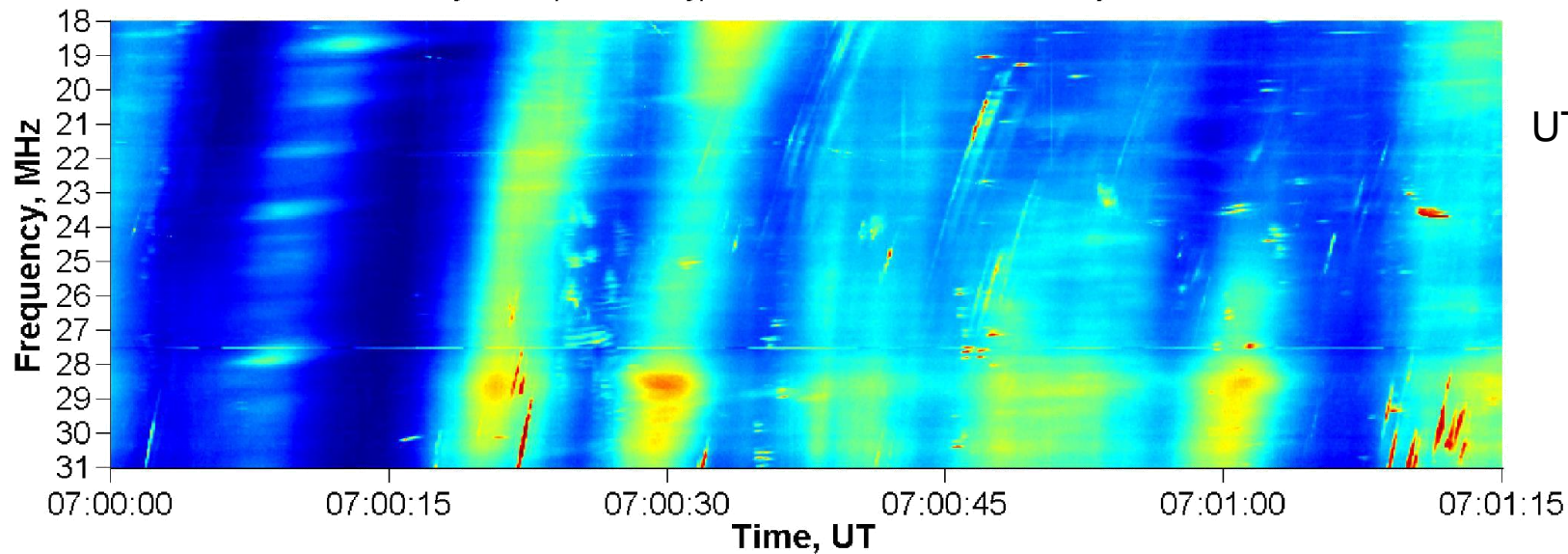
<i>Problems of low-frequency radio astronomy</i>	<i>Possible solution</i>
High temperature of the Galactic background	High effective area ( $10^4 \dots 10^6 \text{ m}^2$ ). The increasing of the integration time, frequency band, observational statistics. <b>Multi-telescope observations.</b>
Ground-based interferences (natural, artificial, narrow-band, broad-band)	High dynamic range of the front-end. High dynamic range and resolutions back-end. Broad-band antenna. High directivity, low side lobes of antenna. Special processing (clean). <b>Space-borne instruments.</b> <b>Multi-telescope observations.</b>
Ionosphere influence (refraction, scintillations, absorption)	Large field of view (multi-beams). Adaptive antenna. Special processing (clean). <b>Space-borne instruments.</b> <b>Multi-telescope observations.</b>
Low angular resolution in single-dish mode (low $D/\lambda$ ratio)	VLBI (ground-ground; ground-space). It is <b>Multi-telescope observations.</b>

# Advantages of the multi-telescope (ground-ground, ground-space) radio astronomy observations at low-frequencies (the distances between telescopes are from ~ 1 km up to ~ 3 000 km)

1. Improvement of the sensitivity (summarization of the effective areas in coherent mode).
2. Improvement of the angular resolution (VLBI mode).
3. Mutual positive complementarity (low effective area, sensitivity and resolutions, but broad frequency range + high effective area, sensitivity and resolutions but moderate frequency range).
- \*4. Reducing and/or identification of the interferences (inner, external, natural, artificial, broad-band, narrow-band) influences.
- \*5. Reducing and/or identification of the ionospheric influences.
6. Reducing and/or identification of the interplanetary medium influence.
7. In the frame of the previous point it is interesting to measure of the delay in the interplanetary inhomogeneous movements across of line-of-sigh.
8. Measurements of the directivity of the source pulse radio emission.
9. Improvement of the sporadic radio emission identification.
10. Identification of the negative instrumental effects.
11. Identification of the observational arte-facts what produced by the telescope side-lobes and diffrational lobes influence.
- \*12. Considerable improvement of the effectivity and realibility of the low-frequency radio astronomy investigation in general



*Dynamic spectrum of type S radio bursts recorded on 9 July 2013*



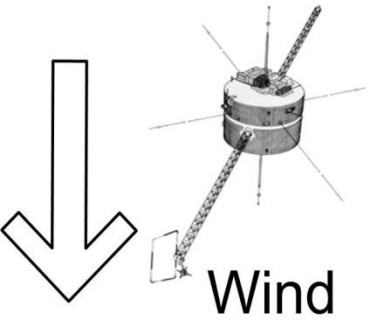
## Synchronized Solar bursts observations with LOFAR and UTR-2, 9 Jul. 2013-2014



**Low-frequency radio telescopes in Europe (UTR-2, URAN-1, URAN-2, URAN-3, URAN-4, GURT, LOFAR, E-LOFAR, Nenu FAR, NDA)**

**LF: 10...30 MHz (dkm); 30...300 MHz (m)**

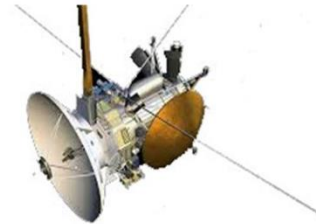
# Complementary character of space and ground-based low-frequency radio astronomy systems



Wind



Stereo



Cassini



Juno

SPACE:

$f < 10 \text{ MHz}$  (NOT IONOSPHERIC LIMIT):

$f=0,1 - 30 \text{ MHz}$ ;  $\Delta F=100 \text{ kHz}$ ;  $\Delta T=100 \text{ ms}$

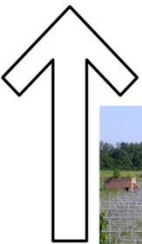
$N \approx 1$ ;  $A_{\text{eff}} \approx 100 \text{ m}^2$  (!)

$$\Delta S_{\text{min}} = 2kT / A_{\text{eff}} \sqrt{\Delta f \Delta T}; \quad A_{\text{eff}} \approx NA_1 \approx N \lambda^2 / 4$$

GROUND: (UTR-2, URAN1.....URAN4,GURT);  $F \geq 10 \text{ MHz}$  (IONOSPHERIC LIMIT):

$f=8-32 \text{ MHz}$  (8-80 MHz);  $\Delta F=1\text{kHz}$ ;  $\Delta T=1 \mu\text{s}$

$N=2040$  (UTR-2);  $N_{\Sigma}=4500$ ;  $A_{\text{eff}}$  (UTR-2)=  $140\,000 \text{ m}^2$ ;  $A_{\text{eff}\Sigma} \approx 300\,000 \text{ m}^2$  (!)



UTR-2



URAN-1



URAN-2



URAN-3

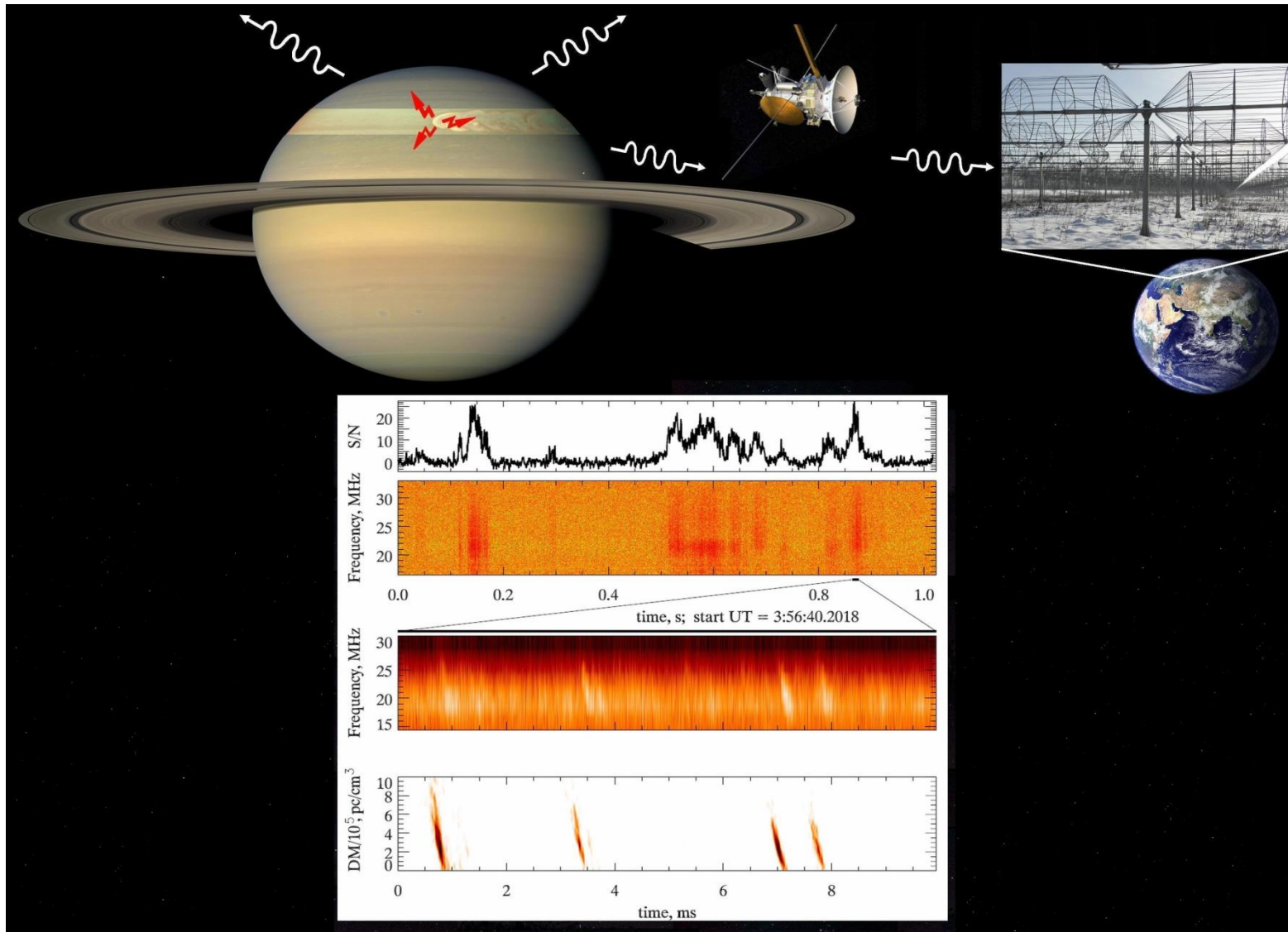


URAN-4



GURT

# Ground-based detection and studies of the Saturn electrostatic discharges with the UTR-2



V. Zakharenko, C. Mylostna, A. Konovalenko, et al. Ground-based and spacecraft observations of lightning activity on Saturn, *Plan. and Sp. Sci.*, 2012, v.61, p.53-59



# Huge Solar system – scale low-frequency radio telescope

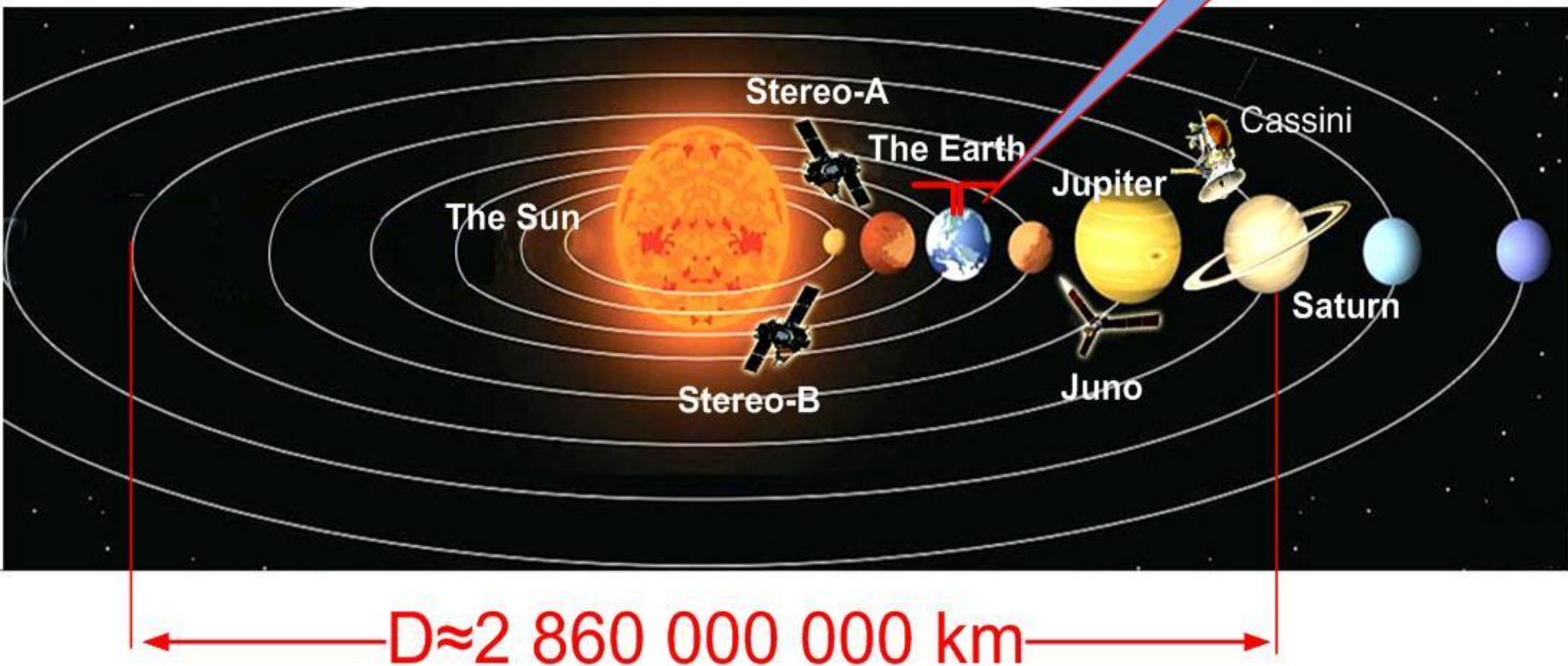
(It is in principal, it is a joke 🤪):

$f \approx 0.1 \dots 100$  MHz !

$N \approx 20000$  elements !

$D \approx 2\,860\,000\,000$  km !!!

Ground-based  
LF radio  
telescopes



# The sensitivity of the radio astronomy investigations

$$\Delta S_{\min} = 2 k T_{\text{sys}} / A_{\text{ef}} \sqrt{\Delta f \Delta t}$$

$k = 1,38 \times 10^{-23}$  – Boltzmann constant;

$T_{\text{sys}}$  – the noise temperature of the receiving system of the radio telescope;  
(cryogenic input amplifier);

$\Delta f, \Delta t$  – registration band (frequency resolution)  
and accumulation time (temporal resolution)

For high frequency radio astronomy (  $f > 300$  MHz):  $T_{\text{sys}} \sim 10$  K;  $A_{\text{ef}} \sim 3000$  sq.m.

$$2k T_{\text{sys}} / A_{\text{ef}} = \text{S E F D} \sim 1 \text{ Jy (System Equivalent Flux Density)}$$

For low frequency radio astronomy (  $f < 300$  MHz):

$$\Delta S_{\min} = 2 k T_{\text{sys}} / A_{\text{ef}} (T_{\text{N}} / (T_{\text{sys}} + T_{\text{N}})) \sqrt{\Delta f \Delta t} ;$$

$T_{\text{sys}} = 1000 - 1\,000\,000$  K! (temperature of the galactic background);

$T_{\text{N}} \sim 100$  K (noise temperature of the input antenna amplifier);

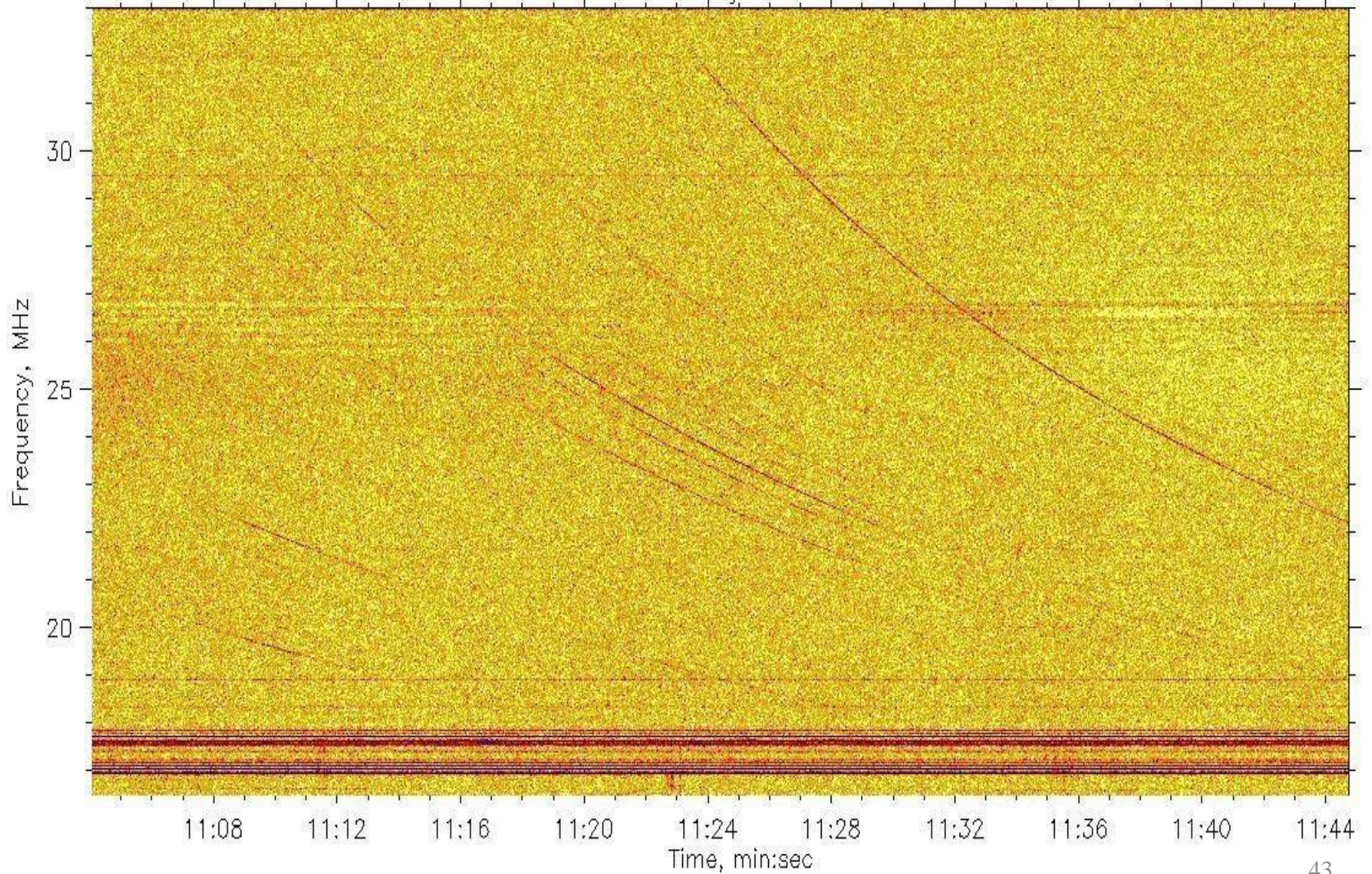
$A_{\text{ef}} \sim 1000 - 10\,000\,000$  sq.m.

*New low frequency radio telescope quality parameter  
introduced by Ukrainian radio astronomers:*

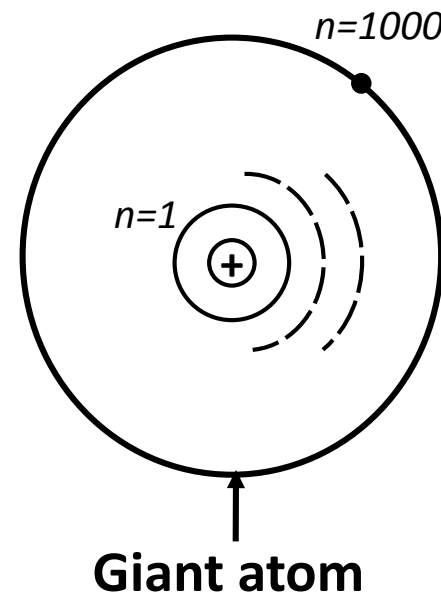
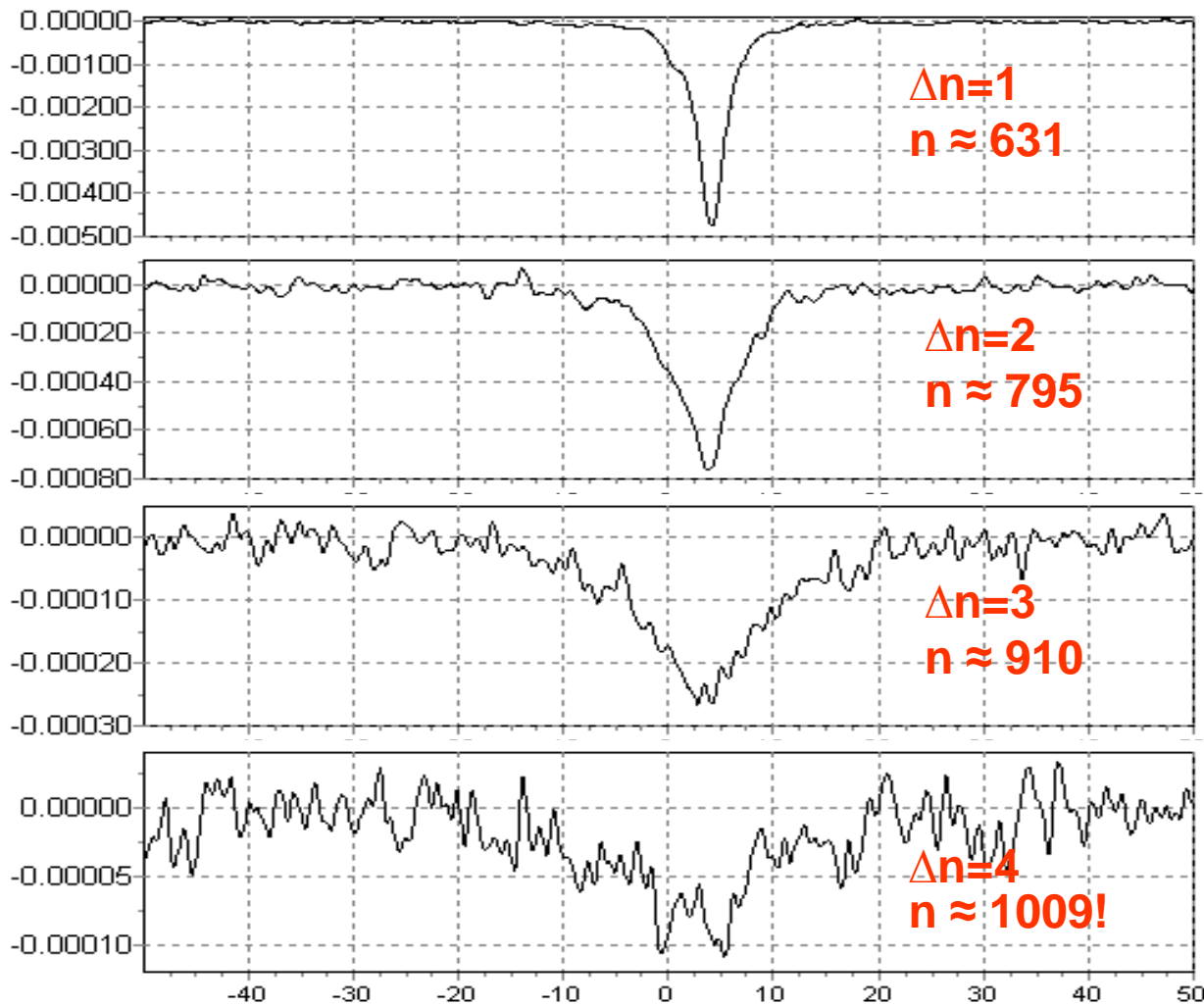
$$A_{\text{ef}} (T_{\text{N}} / (T_{\text{sys}} + T_{\text{N}})) = \text{S E E A} \sim 100\,000 \text{ sq.m. (System Equivalent Effective Area)}$$

# Dynamic spectra of PSRB1133+16

DSPZB190410\_190054.jds PSRB1133+16 16



# Detection of the recordly high excited quantum states ( $n > 1000$ ) on the interstellar atoms (UTR-2, $\nu \approx 30$ MHz, $\Delta n = 1...4$ , $n \approx 1009$ ) - 2007

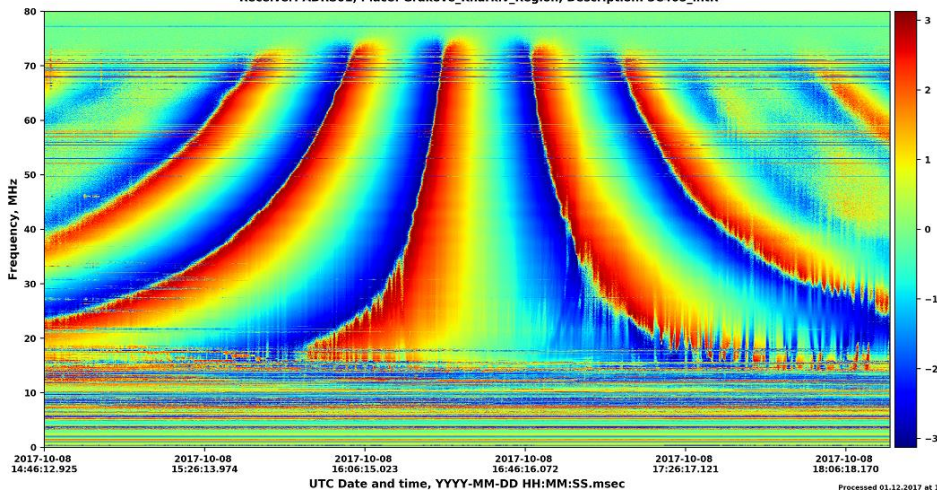


**$D \approx 0.1$  mm !**

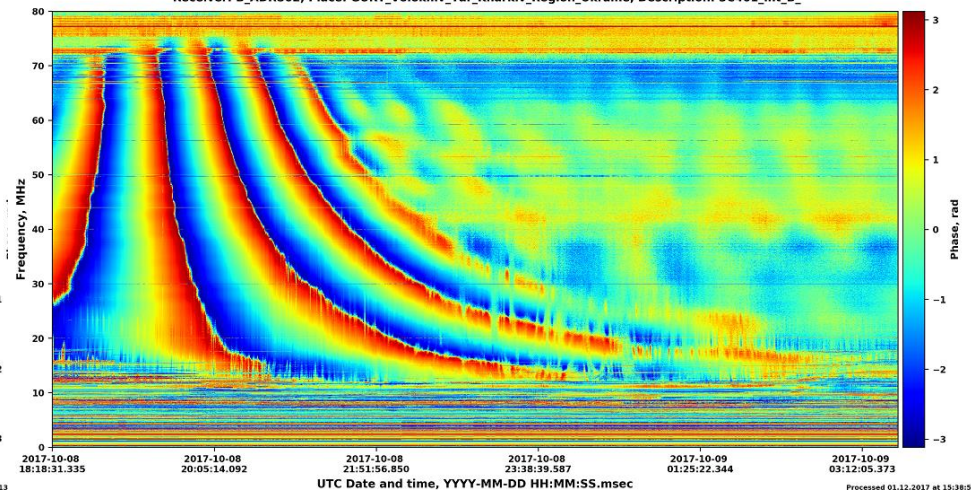


# Interferometric observations 3C405 and 3C461 (Oct, 2017)

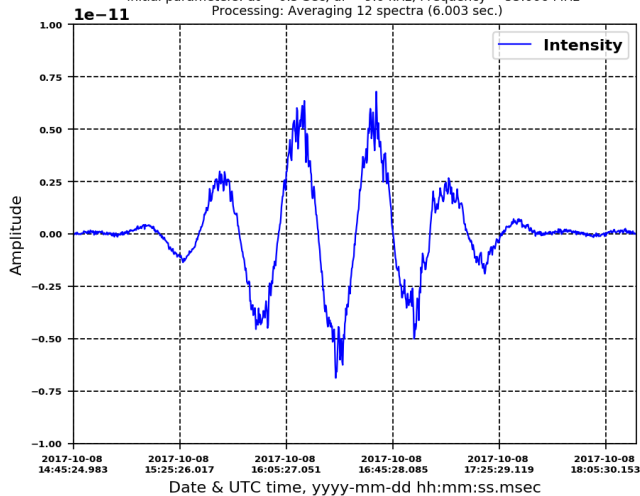
Dynamic spectrum starting from file A171008\_144612.adr correlation phase  
Initial parameters: dt = 0.5 Sec, df = 9.0 kHz, Processing: Averaging 12 spectra (6.003 sec.)  
Receiver: ADRS01, Place: Grakove\_Kharkiv\_Region, Description: 3C405\_intR



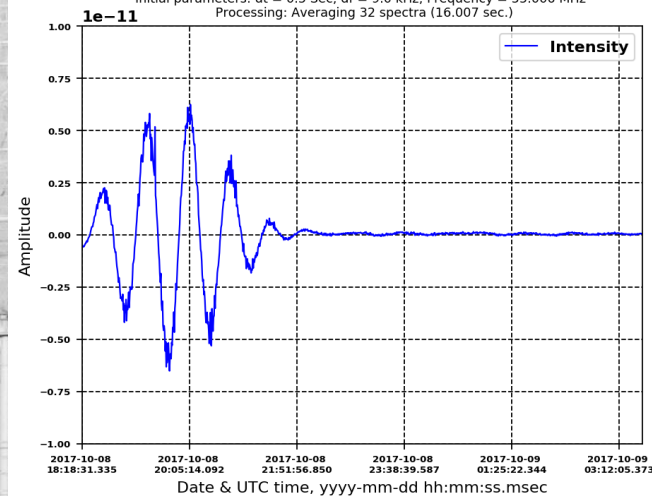
Dynamic spectrum starting from file B171008\_181831.adr correlation phase  
Initial parameters: dt = 0.5 Sec, df = 9.0 kHz, Processing: Averaging 32 spectra (16.007 sec.)  
Receiver: B\_ADR502, Place: GURT\_Volokhiv\_Yar\_Kharkiv\_Region\_Ukraine, Description: 3C461\_int\_B



Intensity variation B171008\_144524.adr correlation IM part  
Initial parameters: dt = 0.5 Sec, df = 9.0 kHz, Frequency = 55.006 MHz  
Processing: Averaging 12 spectra (6.003 sec.)



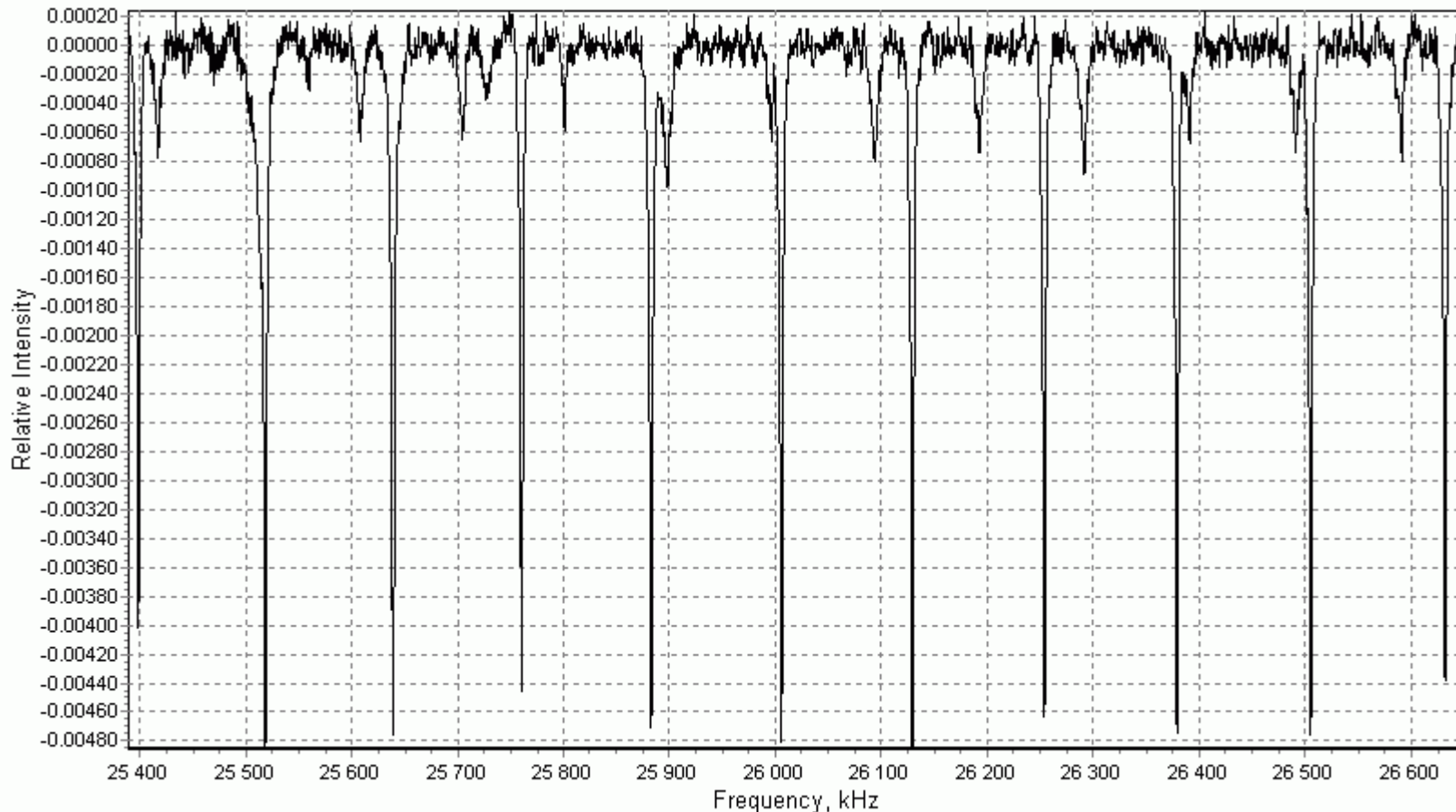
Intensity variation B171008\_181831.adr correlation IM part  
Initial parameters: dt = 0.5 Sec, df = 9.0 kHz, Frequency = 55.006 MHz  
Processing: Averaging 32 spectra (16.007 sec.)



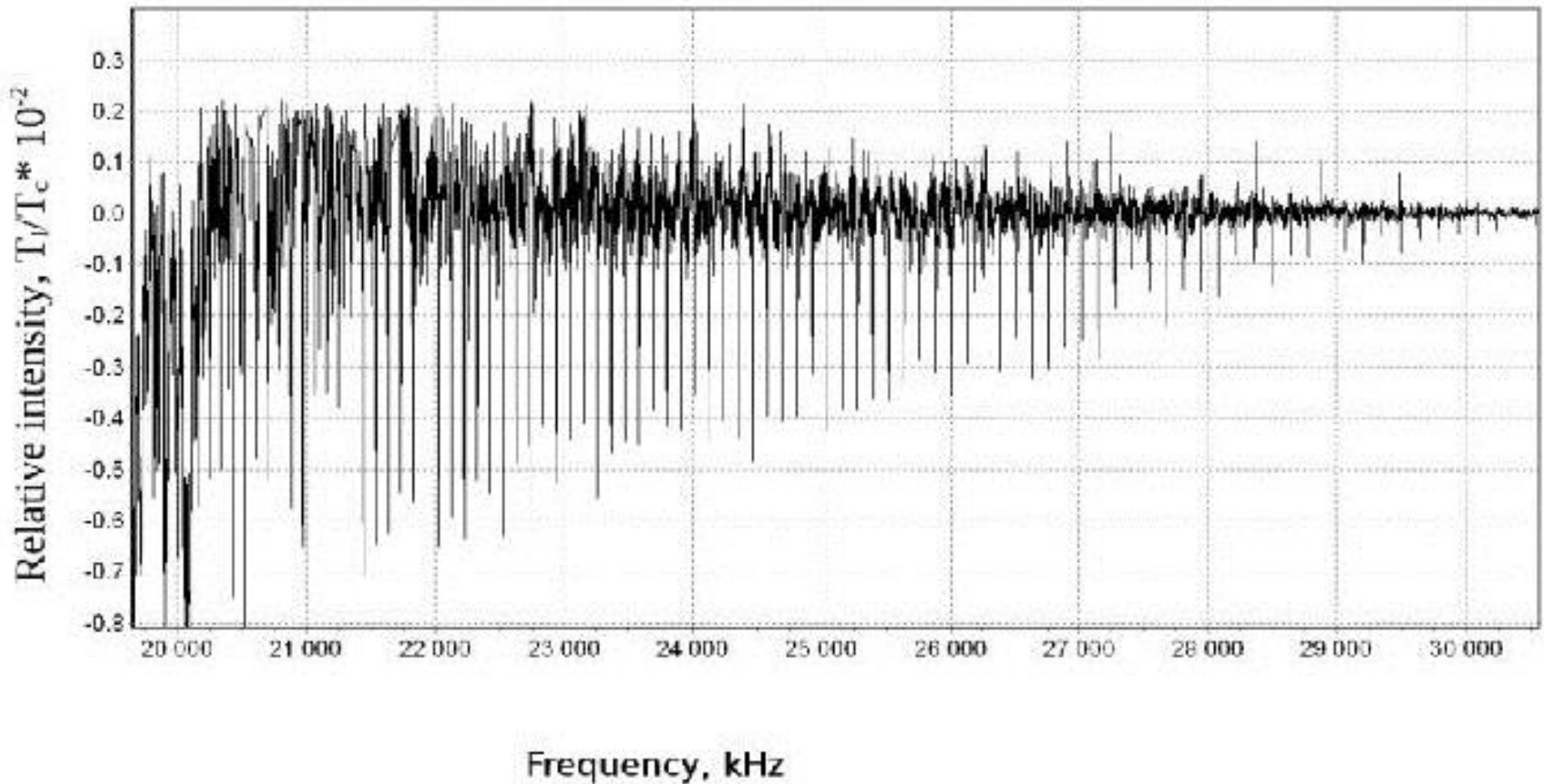
Interferometric responses when observing 3C405 and 3C461 sources  
on the interferometer of two GURT sub-arrays with a base of 56 m.

The upper panel is the signal correlation phase, the lower panel is the imaginary part of the correlation

# Radio recombination lines towards Cas A detected by UTR-2 with broad-band ( $B > 1$ MHz) and multi-channel ( $N=4096$ ) measurements

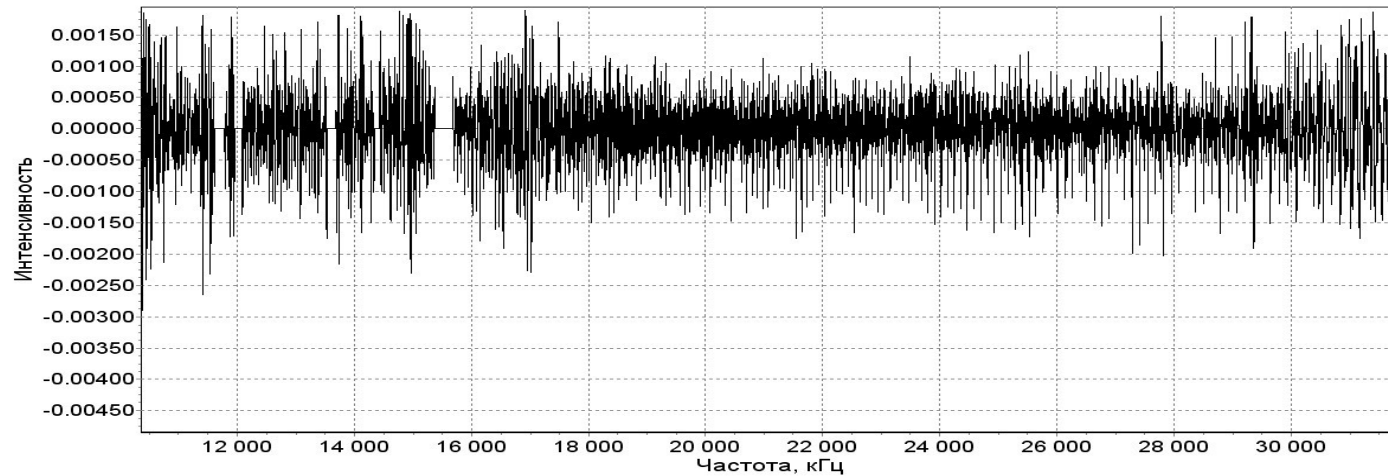


S.V. Stepkin, A.A. Konovalenko. Radio recombination lines from the largest atoms in space. **Monthly Notices of Royal Astronomical Society**, 2007, January, v. 374, issue 3, pp. 852-856.

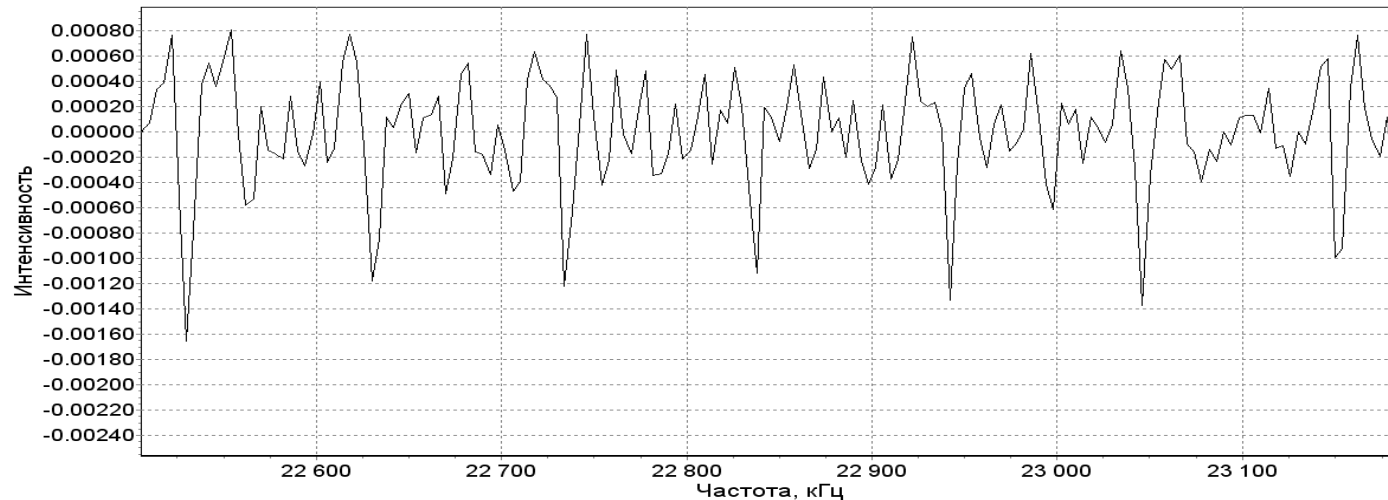


**Carbon RRLs towards Cas A,  
measured with the North – South arm of the UTR-2 array and  
new broad-band, multi-channel DSP (~100 lines simultaneously!)**

# First simultaneous registration a large number of recombination lines ( $\sim 250$ ) at UTR-2, Oct., 2017



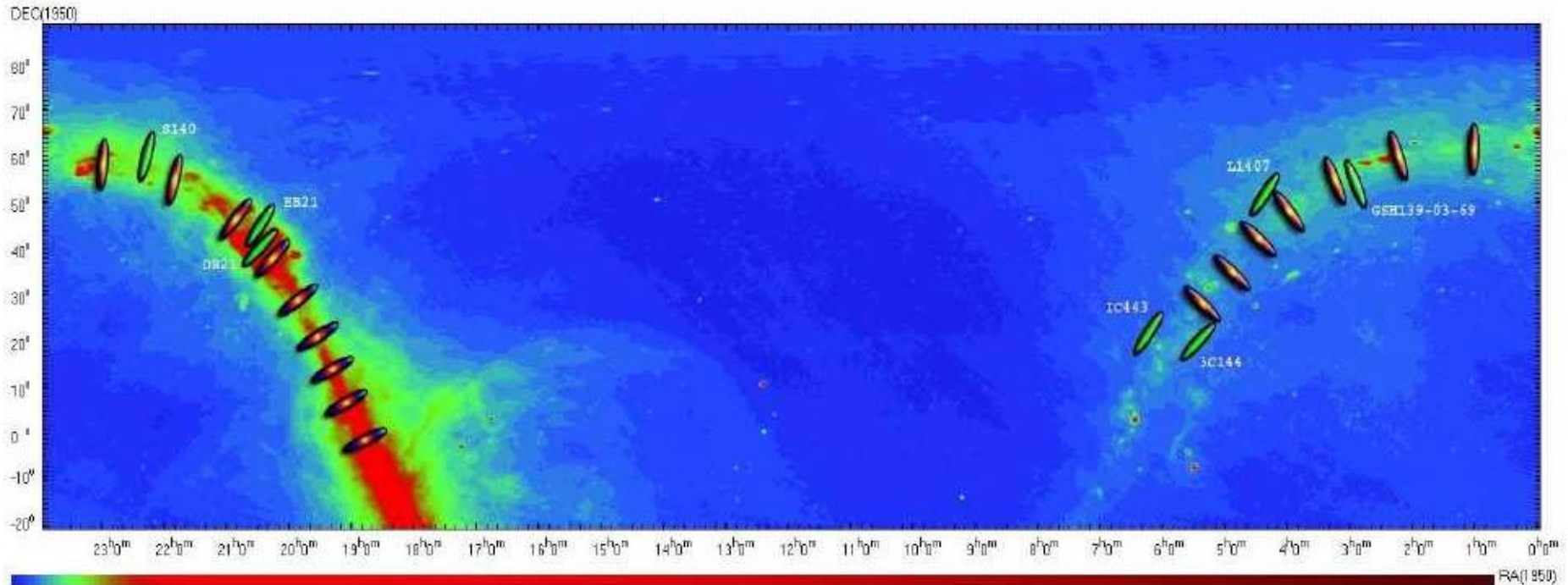
Normalized spectrum in the direction of Cassiopeia A containing a series of RRL carbon. C854 $\alpha$  ... C596 $\alpha$  lines fall in the range from 10.5 MHz to 31 MHz. The accumulation time was 55 minutes



A part of the spectrum with lines C663 $\alpha$  ... C657 $\alpha$



## Galactic plane survey in the LF carbon RRL's (2006-2016)

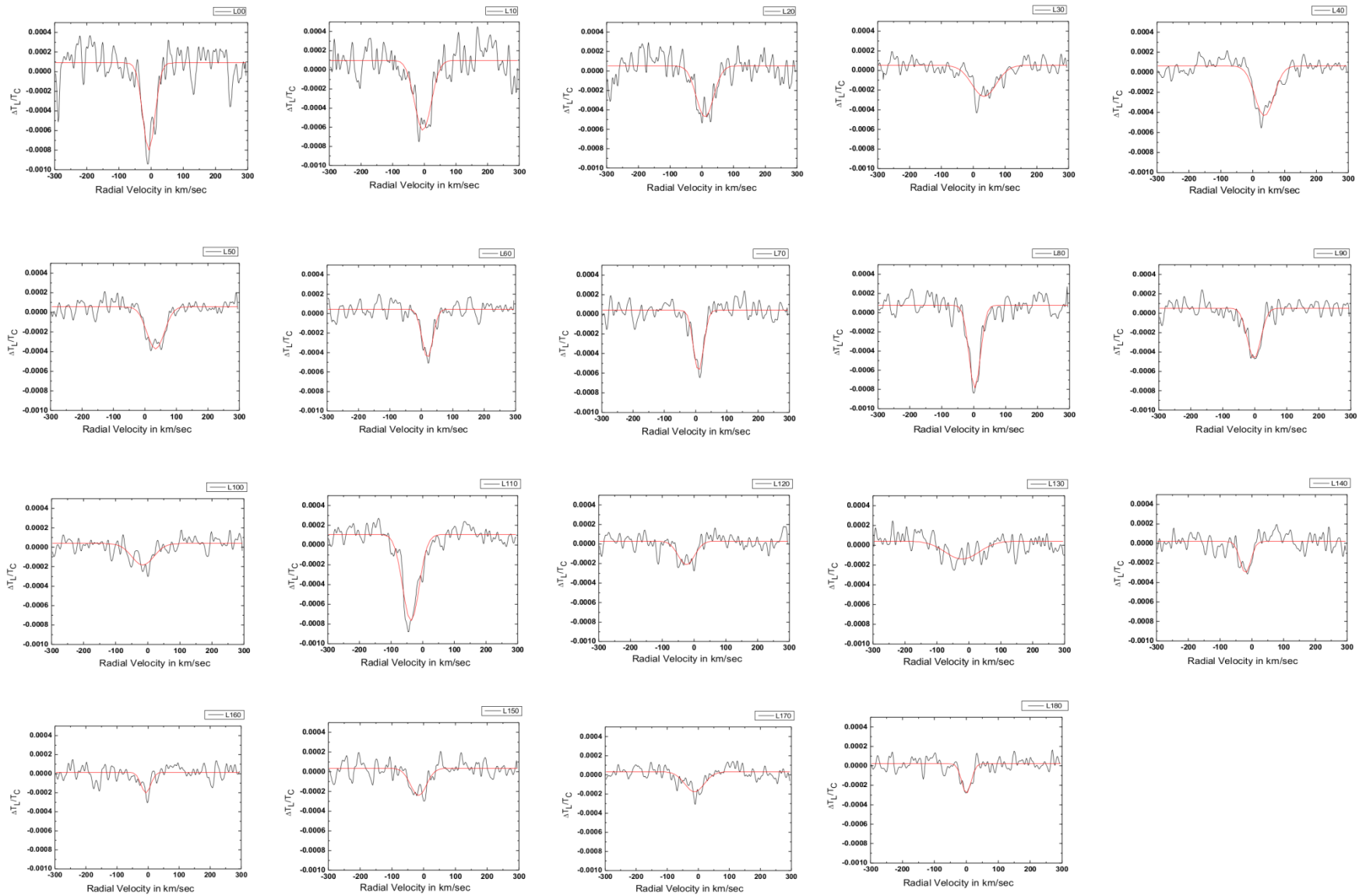


$b = 0^\circ (\pm 2^\circ, 4^\circ, \text{etc.})$        $n = 636-645$ ,       $B \sim 1 \text{ MHz}$ ,  $f \sim 25 \text{ MHz}$ ,

$l = 0^\circ \dots 180^\circ$  with the step  $10^\circ$

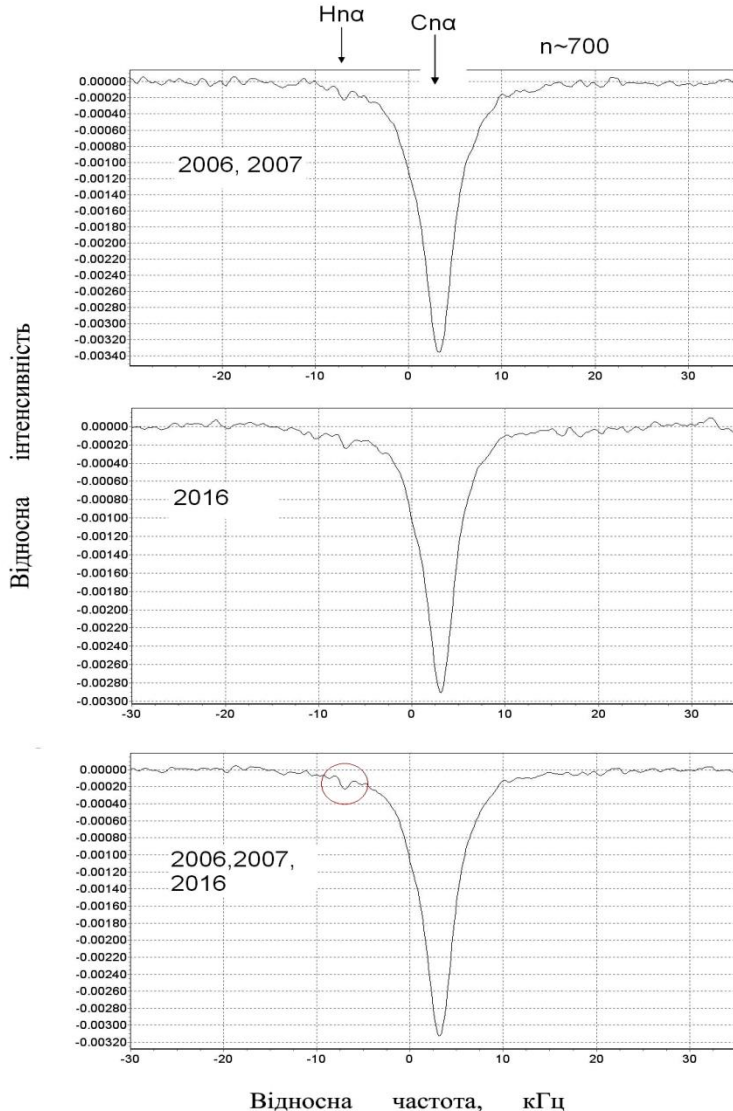
$t \sim 150 \dots 250 \text{ h}$  (for each point)

# LF carbon RRL's detection near the Galactic plane by UTR-2



# Detection of recombination absorption lines of highly excited atoms ( $n \sim 700$ ) hydrogen in cold interstellar plasma

(Institute of Radio Astronomy, National Academy of Sciences of Ukraine, Kharkiv, Ukraine)



$$\text{Частота ліній: } \nu_n = cZ^2 R \left(1 - \frac{m_e}{M_a}\right) \left(\frac{1}{n^2} - \frac{1}{(n + \Delta n)^2}\right),$$

де  $c$  - швидкість світла,  $Z$  - ефективний заряд ядра,  $R$  - стала Ридберга,  $m_e$  и  $M_a$  - маси електрона та атома,  $n$  - головне квантове число.

Відносний вміст елементів:  $C/H \approx 2 \cdot 10^{-4}$ .

Потенціал іонізації:  $C: E=11,2 \text{ eV}; H: E=13,6 \text{ eV}$ .

Інтенсивність ліній:

$$I_C \approx \frac{S \cdot N(C^+) \cdot N_e(C) \cdot b_n \cdot \beta_n}{T^{5/2}} \quad (b_n \cdot \beta_n \approx 100),$$

$$I_H \approx \frac{S \cdot N(H^+) \cdot (N_e(C) + N_e(H)) \cdot b_n \cdot \beta_n}{T^{5/2}} \quad (b_n \cdot \beta_n \approx 1).$$

$$N_e(C) \gg N_e(H) \approx N(H^+).$$

S.Stepkin, акад. A.Konovalenko

Invited talk at an international conference  
 "Planetary, Solar and Heliospheric Radio Emissions",  
 Austria, Graz, October 2016

# A New Method of Sensitive Search and Studies of the Low Frequency Radio Recombination Lines

$$(\Delta T_L / T_C)_{\min} = \pi / 2 \sqrt{\Delta f_{\text{ef}} \Delta t} N_1 N_2 N_3 N_4 N_5$$

**1978 :** detection of interstellar RRL at the decameter waves using UTR-2;

$\Delta t_{\text{ef}} = 4 \text{ год}$ ;  $N_1=1, N_2=1, N_3=1, N_4=1$ ;  $\Delta f=1 \text{ кГц}$ ;  $B=20 \text{ кГц}$ ;

$(\Delta T_L / T_C)_{\min} = 4 \times 10^{-4}$ ;  $(\Delta T_L / T_C)_{\text{det}} = 4 \times 10^{-3}$ ;  $S/N \approx 10$

**1978-1992 :** detection of the low-frequency RRL in selected galactic objects;

it is shown that the distance between the lines is significantly reduced at LF ( $\Delta F = 3 f / n$ )

$\Delta t_{\text{ef}} = 5 \times 4 \text{ год} = 20 \text{ hours}$ ;  $N_1=5, N_2=1, N_3=1, N_4=1$ ;  $\Delta f=1 \text{ кГц}$ ;  $B=20 \text{ кГц} \times 5$ ;

$(\Delta T_L / T_C)_{\min} = 1,8 \times 10^{-4}$ ;  $(\Delta T_L / T_C)_{\text{det}} \approx 1,5 \times 10^{-3}$ ;  $S/N \approx 10$

**1992-2005 :** detection of the recordly high excited states ( $n \sim 1000$ );

$\Delta t_{\text{ef}} = 10 \times 4 \text{ год} = 40 \text{ hours}$ ;  $N_1=10, N_2=1, N_3=1, N_4=1$ ;  $\Delta f=1 \text{ кГц}$ ;  $B=1,5 \text{ МГц}$ ;

$(\Delta T_L / T_C)_{\min} = 1 \times 10^{-4}$ ;  $(\Delta T_L / T_C)_{\text{det}} = 1 \times 10^{-3}$ ;  $S/N \approx 10$

**2005-2018 :** simultaneous observations of many RRL ( $\Delta n \sim 100 \dots 400$ );

$\Delta t_{\text{ef}} = 400 \times 4 \text{ hours} = 1600 \text{ hours}$ ;  $N_1=400, N_2=1, N_3=1, N_4=1$ ;  $\Delta f=1 \text{ кГц}$ ;  $B=12 \dots 24 \text{ MHz}$ ;

$(\Delta T_L / T_C)_{\min} = 2 \times 10^{-5}$ ;  $(\Delta T_L / T_C)_{\text{det}} = 1 \times 10^{-4}$ ;  $S/N \approx 5$

**2019:** simultaneous multilinear ( $N_1=400$ ), multi-section ( $N_2=100$ ), multi-antenna ( $N_3=3$ ),  
bipolarization ( $N_4=2$ ), many bits ( $N_5=2$ ) insensitive searches RRL;

!  $\Delta t_{\text{ef}} = 400 \times 100 \times 3 \times 2 \times 4 \text{ hours} = 480\,000 \text{ hours} \leftarrow 100 \text{ years} !$

!  $(\Delta T_L / T_C)_{\min} = 6 \times 10^{-7}$

# The Nature of the Observatory, Forge steppe (June, 2016)

