National Academy of Sciences of Ukraine
Institute of Radio Astronomy

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Solar emission and space weather monitoring system at meter and decameter wave ranges

Solar Influences on the Magnetosphere, Ionosphere and Atmosphere

June 3-7, 2019
Primorsko, Bulgaria

Outline

- *Our experience in low-frequency radio astronomy*

- *Motivation and challenges of sun and space weather observations at low frequencies*

- *Modern low-frequency radio telescopes*

- *Real data of observations and possible ways to overcome the challenges*

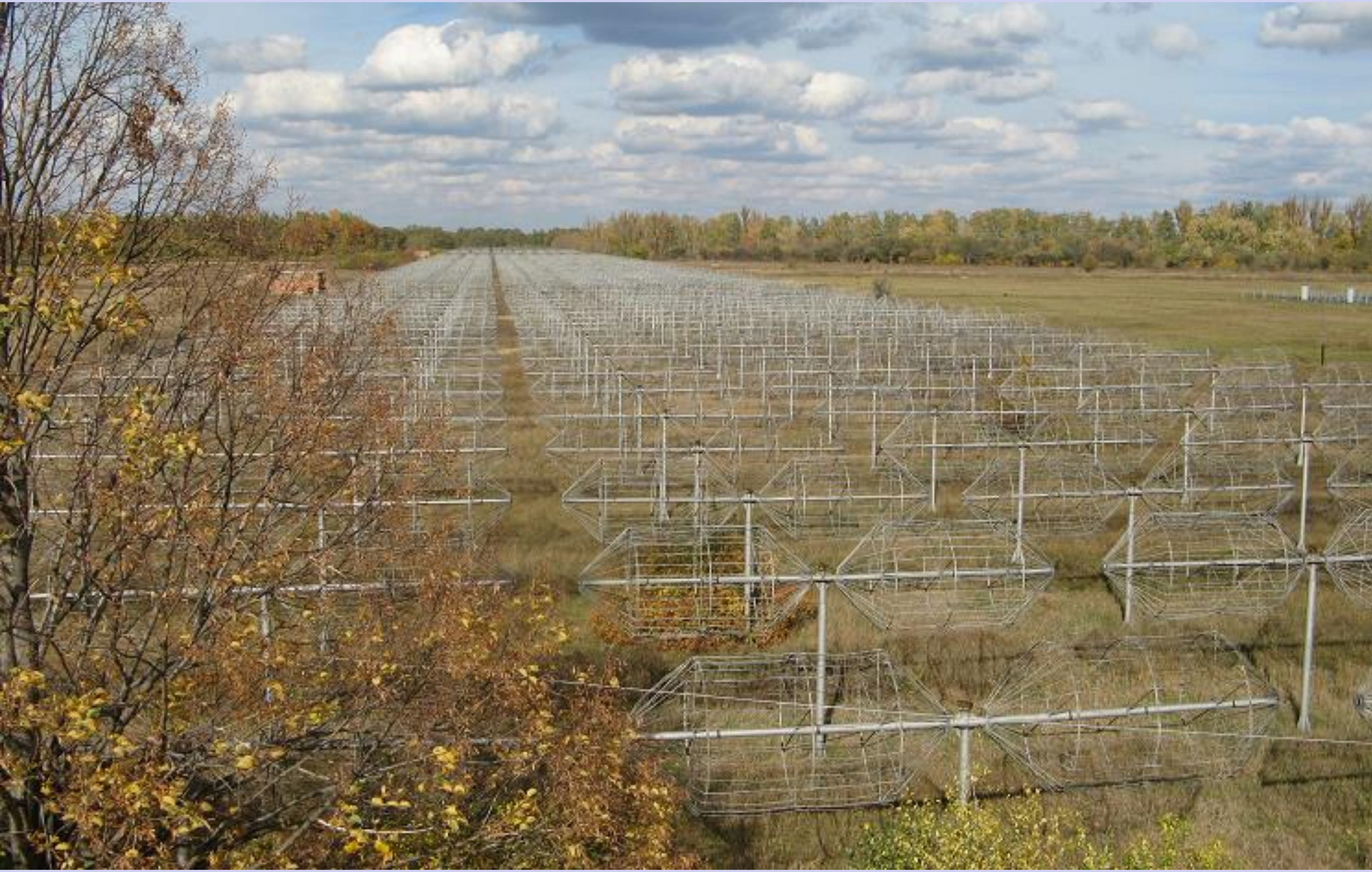
- *The idea of the project*

- *What has been already done*

Experience

Experience

UTR-2, Kharkiv region, Ukraine



UTR-2 antenna array structure

Frequency range: 8 - 33 MHz

Effective area: up to 150 000 sq. m.

Main beam HPBW: 0.5 sq. deg.

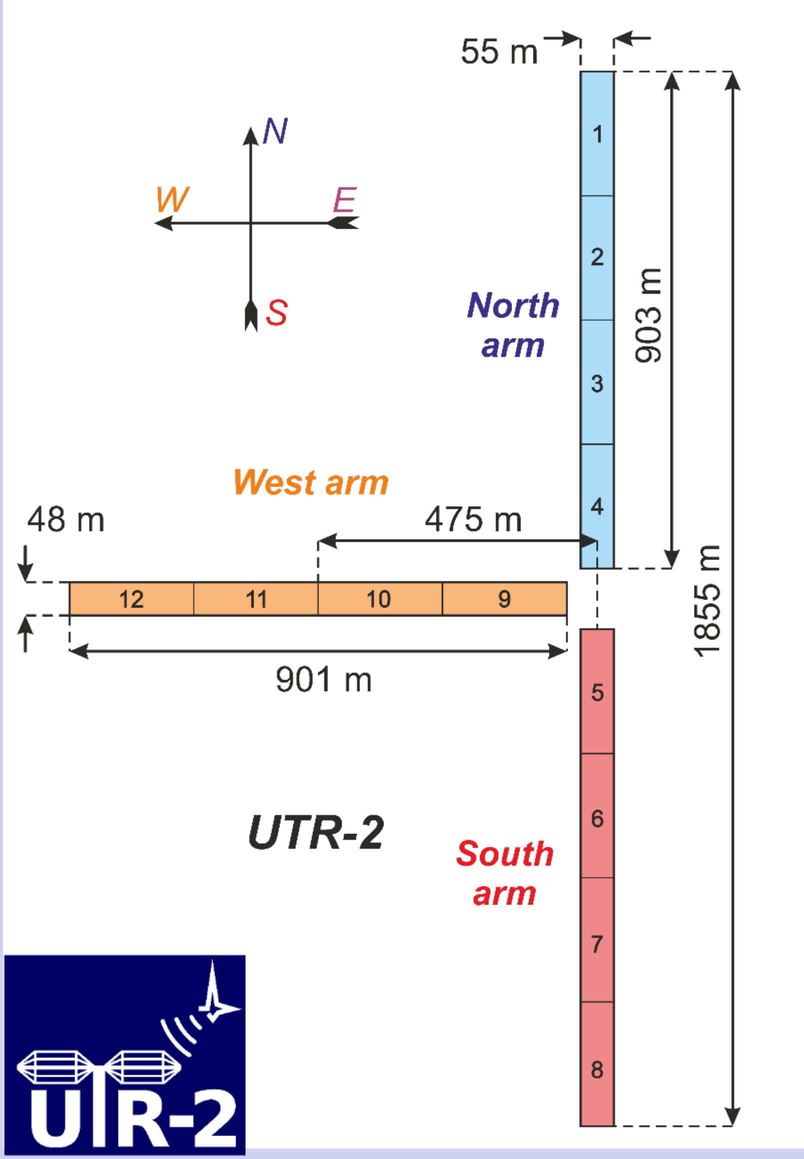
2040 dipoles arranged into 3 arms and 12 subarrays.

Antenna elements – fat dipoles of 8 m length for single linear polarization of EM waves.

Interelement spacing is 7.5 m along NS axis and 9 m along WE axis.

Fully analog beamforming on true time-delay lines.

Digital signal processing at radio telescope output.



Motivation

Solar sporadic radio emissions at low frequencies are very informative and essential to observe all-day-round to monitor the processes on the Sun and in the nearest surroundings up to 3 solar radii

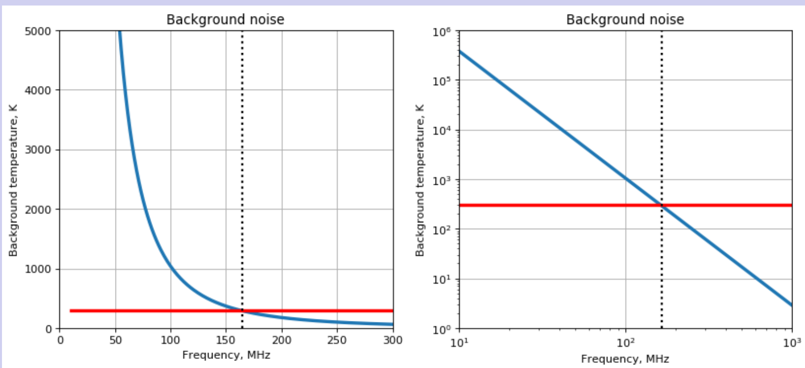
The monitoring of interplanetary scintillations of point radio sources at low frequencies is essential for space weather studies.

Detailed study of these emissions needs large instruments and much observation time, which are limited…

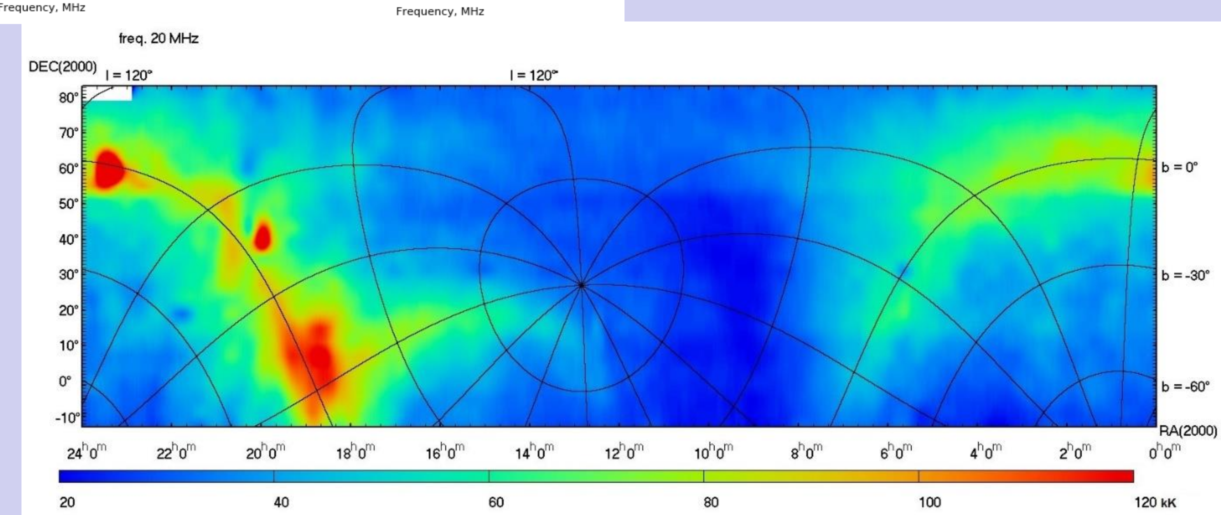
We do our best to make our new GURT radio telescope as useful and efficient as possible at low cost

Problems to be solved

Problem: ***High brightness temperature of galactic background emission***



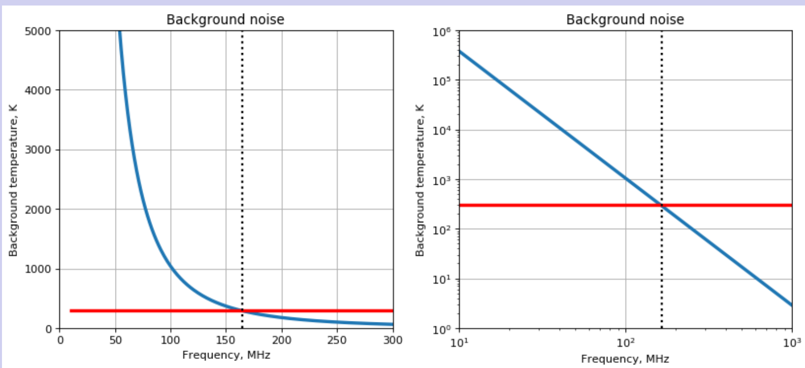
$$T_B(f) \approx 3.78 \cdot 10^5 (10/f\ MHz)^{2.56}$$



Problems to be solved

Problem: ***High brightness temperature of galactic background emission***

Solution: ***large sensitive radio telescopes with high spatial selectivity***



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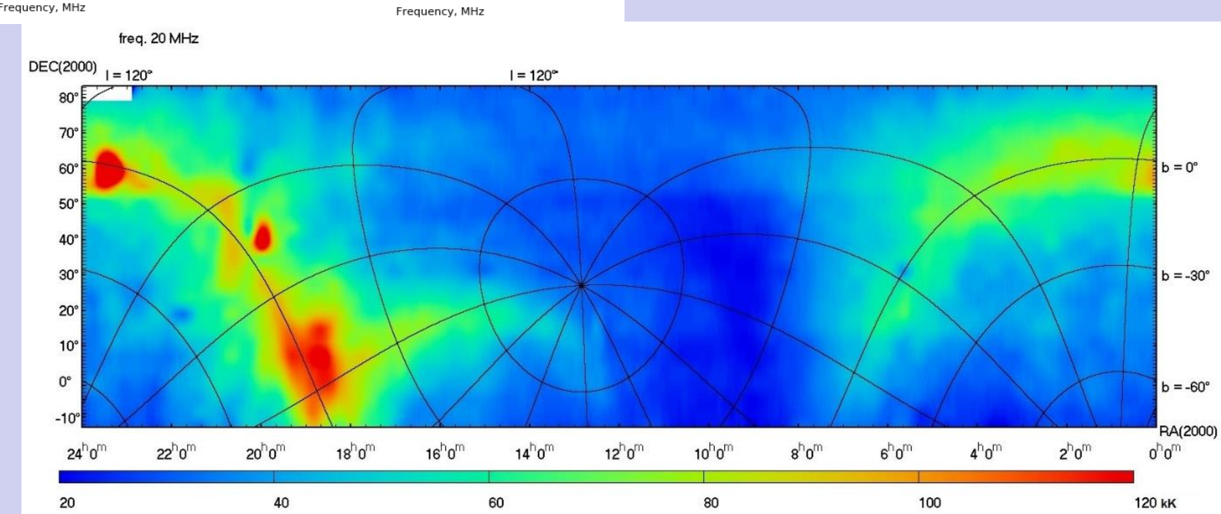

Problems to be solved

Problem: *High brightness temperature of galactic background emission*

Solution: *large sensitive radio telescopes with high spatial selectivity*

Problem: *Strong radio frequency interference (RFI)*

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Solutions: *large radio telescopes with high spatial selectivity*
high system dynamic range to prevent saturation

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Solution: *simultaneous observations of multiple sources (multiple digital antenna beams)*

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***Problem*:** *High brightness temperature of galactic background emission*

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***Problem*:** *Strong radio frequency interference (RFI)*

***Solutions*:** *large radio telescopes with high spatial selectivity*
high system dynamic range to prevent saturation

***Problem*:** *much observation time at large instruments*

***Solution*:** *simultaneous observations of multiple sources (multiple digital antenna beams)*

***Problem*:** *Enormous data rates to process on-the-fly and / or construction of new radio telescopes*

The best way*

Record raw digitized radio signals (waveform) from each single antenna of large radio telescope and form as many beams as needed for all research activities.

+ universal method

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*** Impossible now (due to high data rates)**

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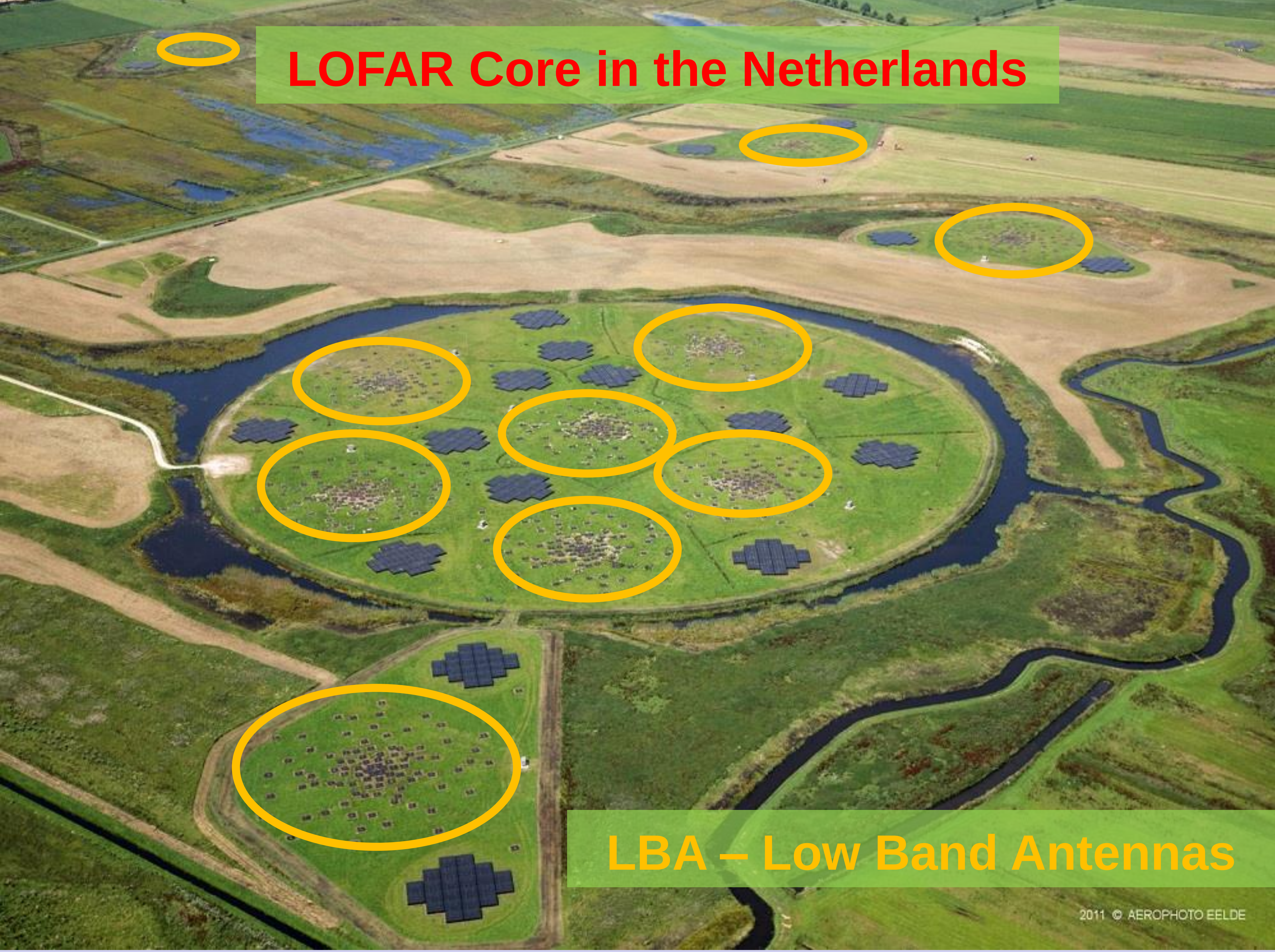
* Impossible now (due to high data rates)

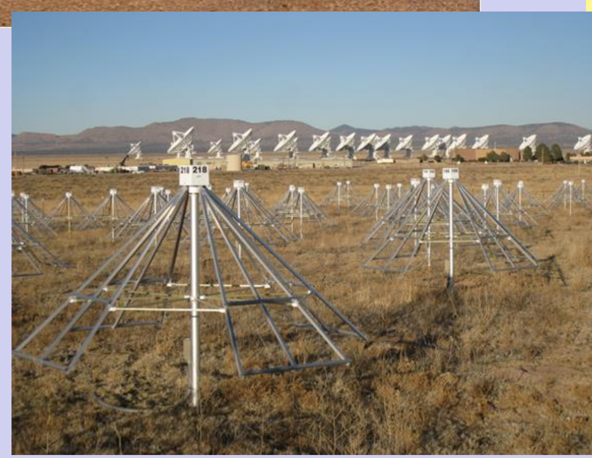
One ADC gives: 16 bit × 160 000 000 samples per second = 320 MB/s or 1.152 TB per hour of observations

Full telescope give:
number of antennas in array × 2 linear polarizations × 1.152 TB per hour

LOFAR Core in the Netherlands


LOFAR Core in the Netherlands
LBA – Low Band Antennas
2011 © AEROPHOTO EELDE

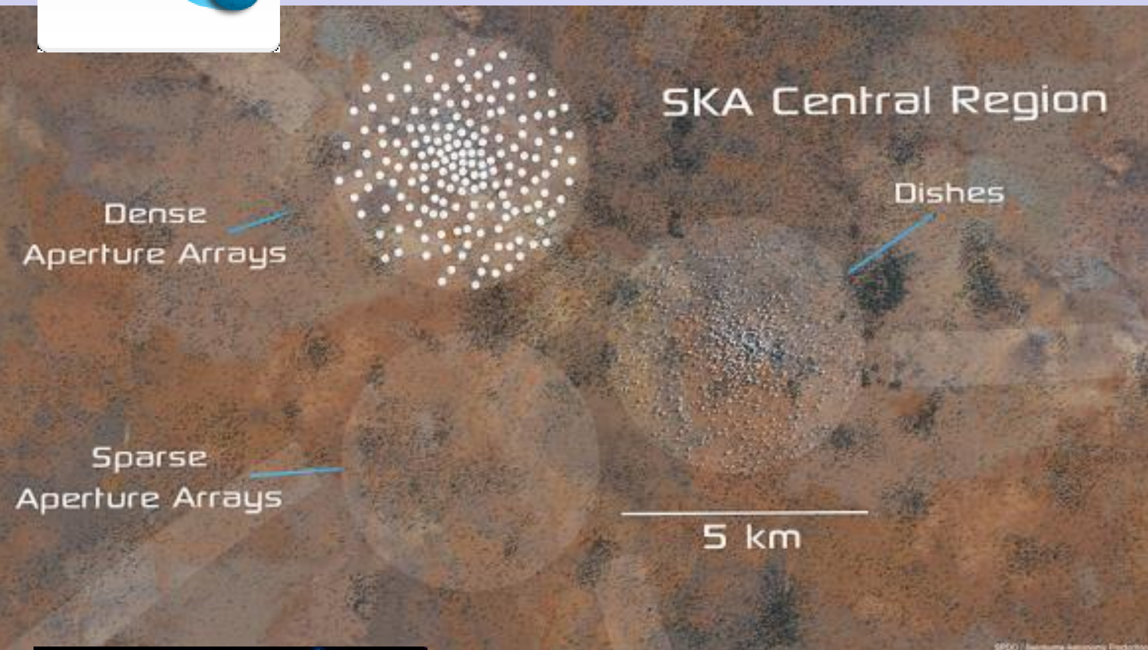
LWA (Long Wavelength Array), USA



Location: ***New Mexico (USA)***
Frequency range: ***10 - 88 MHz***
Telescope style: ***phased array of 50 stations, each with 256 dipole antennas.***
Collecting area: ***1 sq. km.***

www.lwa.unm.edu

Square Kilometer Array



www.skatelescope.org

Location of Low frequency aperture array stations: Australia
Frequency range: 50 - 350 MHz
Telescope style: Phased array
Collecting area: 1,000,000 m²

These radio telescopes try to do impossible:

- ***LOFAR LBA***

  most data are reduced on site during observations

  uses only half of dipoles at station simultaneously

  12-bit ADC which is not sufficient

- ***LWA1***

  most data are reduced on site during observations

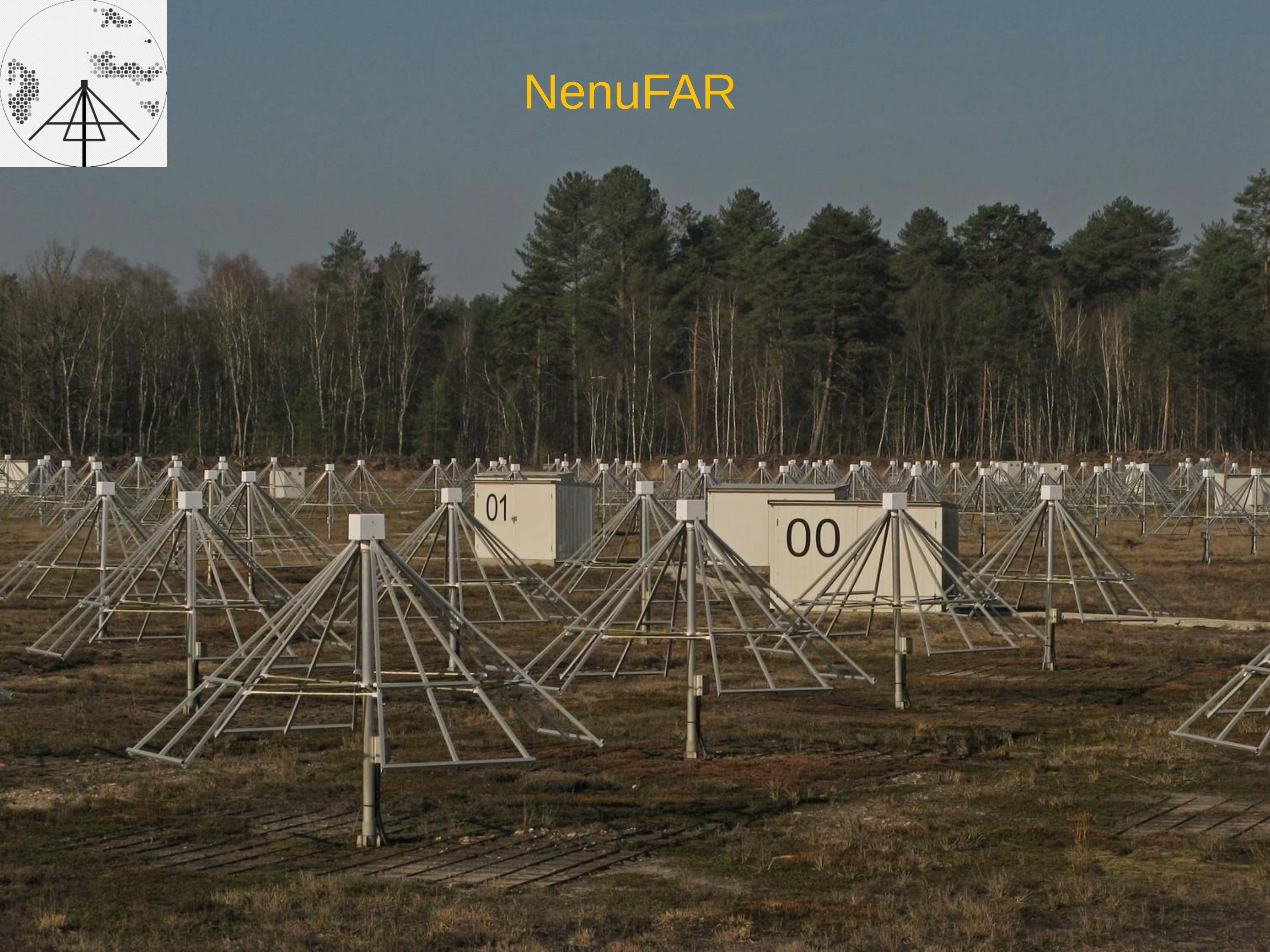
  uses all dipoles but there are only 512 dipoles built

- ***SKA***

  just a project now, has pathfinders


LOFAR Core in the Netherlands
HBA – High Band Antennas
2011 © AEROPHOTO EELDE

NenuFAR



NenuFAR

NenuFAR - New Extension in Nançay Upgrading LOFAR

Number of antennas : 1938 = 96 core + 6 remote MA of 19 antennas each

Frequency range : 10 – 85 MHz (λ = 3.5 – 30 m)

Time-Frequency resolutions : δf = 195.3125 kHz x δt = 5.12 μs

Full polarization (4 Stokes)

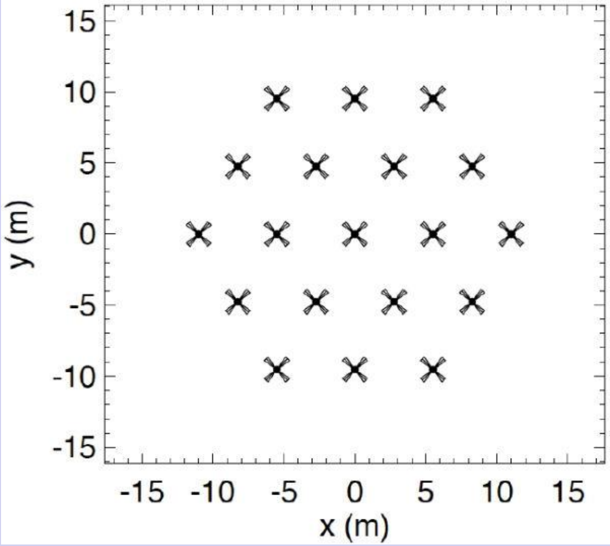
Effective area: from ~83 000 m2 at 15 MHz to ~7 500 m2 at 85 MHz the core
from ~88 000 m2 at 15 MHz to ~8 000 m2 at 85 MHz core+remote MA

Pointing : from declination δ = -23° to δ = +90°

Field of View : ~46° (1650°2) at 15 MHz to ~8° (51°2) at 85 MHz

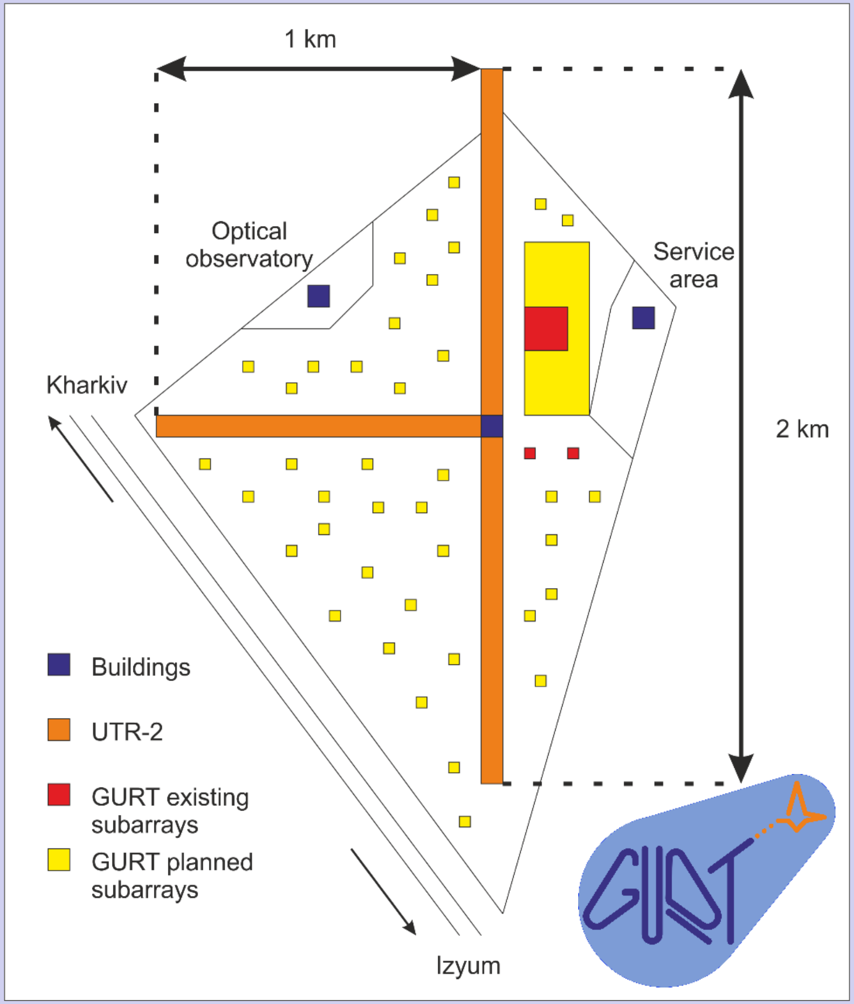
NenuFAR

MA (mini-array)



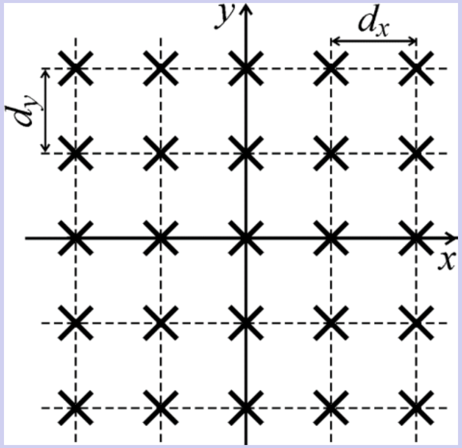
https://nenufar.obs-nancay.fr

Giant Ukrainian Radio Telescope (GURT)



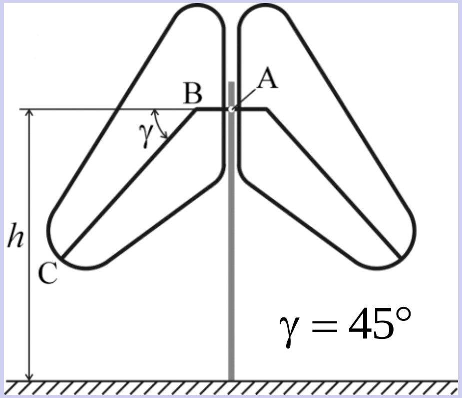
- Frequency range: 8 - 80 MHz.
- Up to several hundreds of subarrays.
- 5×5 element subarrays.
- Subarray dimensions 15×15 m.
- Interelement spacing 3.75 m.
- Subarray elements – active dipoles.
- Total area up to 2 sq. km.
- 2 orthogonal polarizations of incoming waves.
- Analog beamforming at subarray stage.
- Digital beamforming at entire antenna array stage.
- Digital signal processing.
- Low cost of dipoles and subarrays.
- Easy radio telescope extension.
- Construction in UTR-2 territory.

GURT Subarray



$$d_x = d_y = 3.75\ m$$

$$h = 1.6\ m \qquad ABC = 1.4\ m$$



These radio telescopes search the compromise:

- *LOFAR HBA*

  subarrays of 16 antennas

- *NenuFAR*

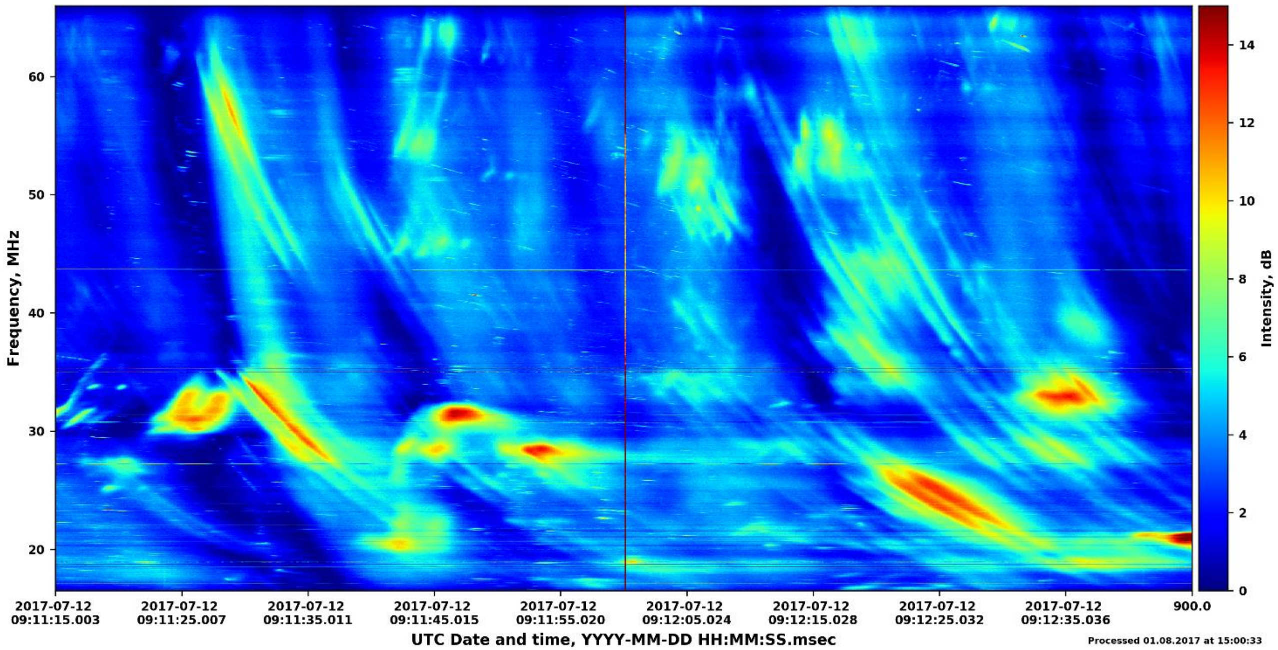
  subarrays of 19 antennas

- *GURT*

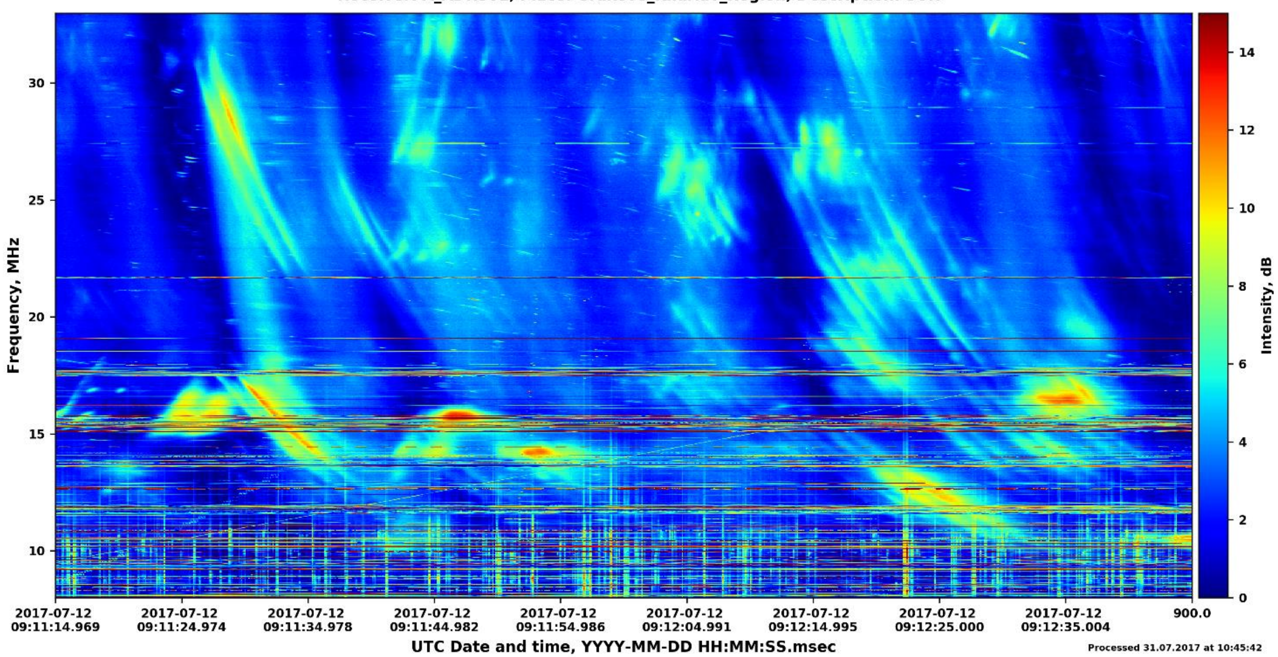
  subarrays of 25 antennas

This approach reduces the data rate times the number of antenna in the subarray but limits the immediate field of view

Dynamic spectrum cleaned and normalized starting from file D120717_090932.jds channel A
Initial parameters: dt = 0.1 Sec, df = 8.057 kHz, Processing: Averaging 1 spectra (0.1 sec.)
Receiver: D, Place: UTR-2_Volokhiv_Yar_Kharkiv_region_Ukraine, Description: Sun_2017-Ch1=Notrh-Ch2=West



Dynamic spectrum cleaned and normalized starting from file A170712_091055.adr channel A
Initial parameters: dt = 0.1 Sec, df = 9.0 kHz, Processing: Averaging 1 spectra (0.1 sec.)
Receiver: A_ADRS01, Place: Grakove_Kharkiv_Region, Description: SUN



UTR-2

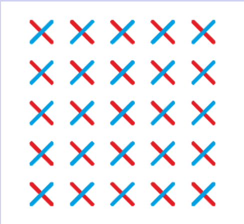
720 dipoles

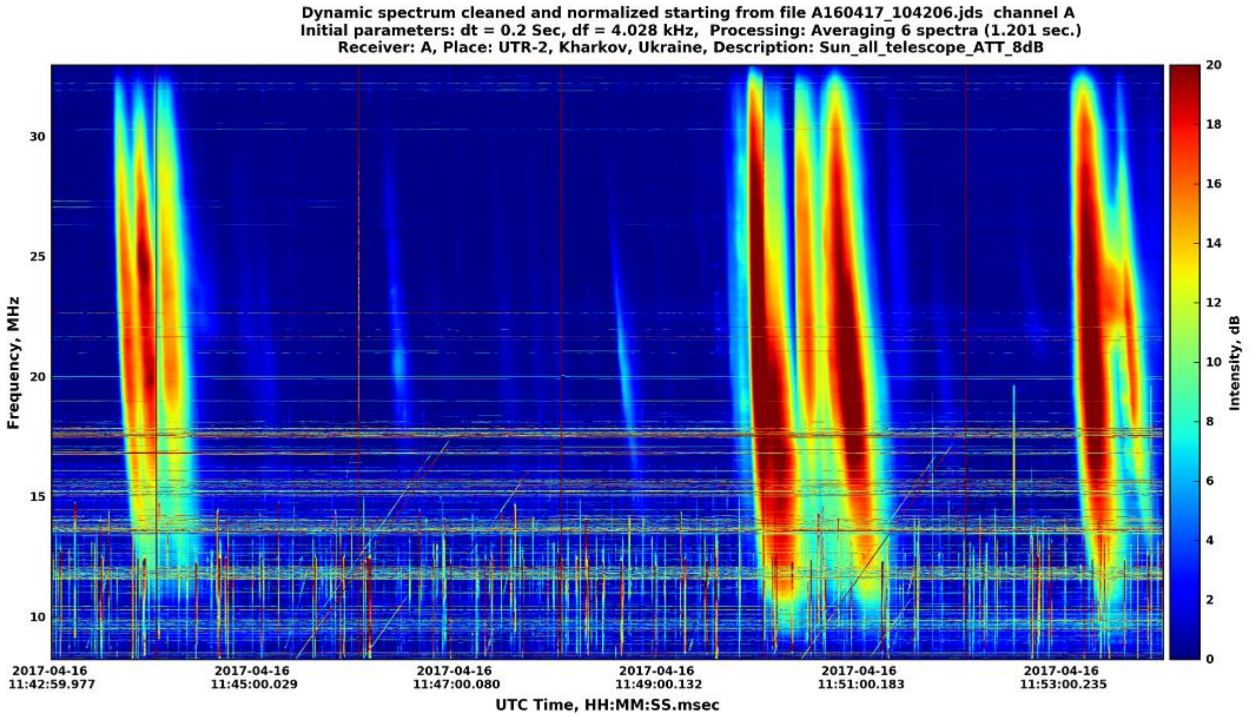
UTR-2 North Arm vs. GURT subarray

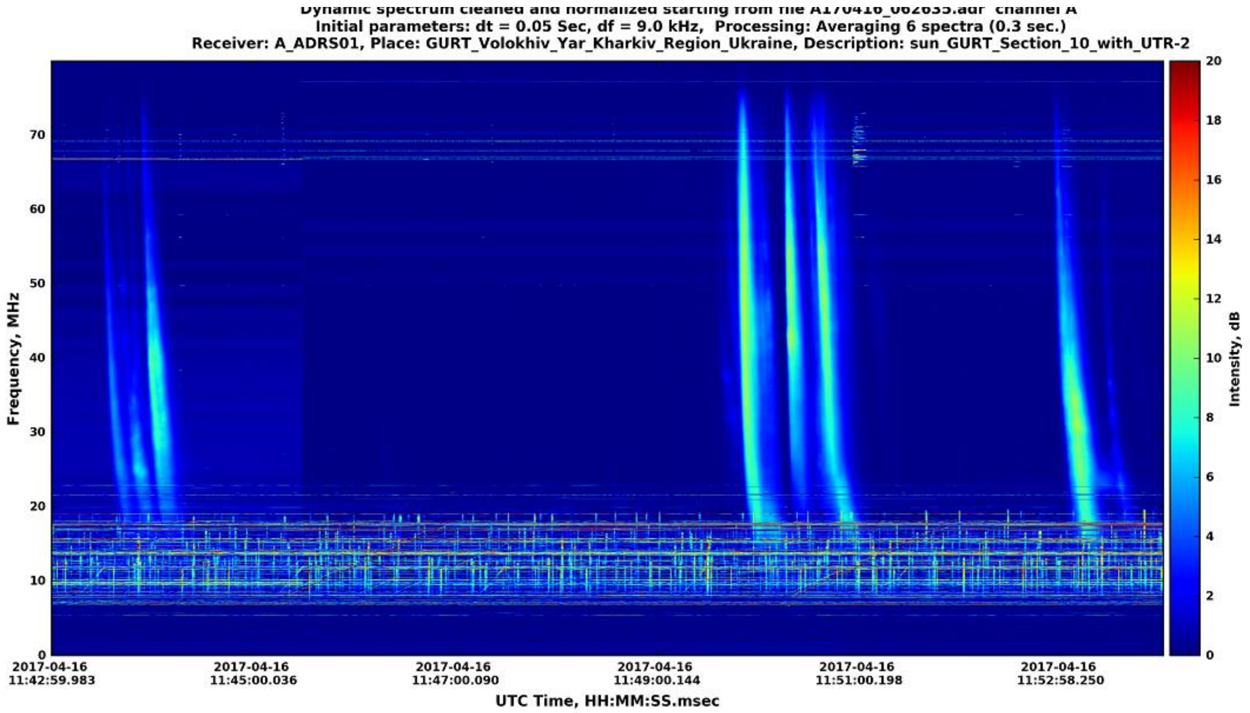
in 8 - 33 MHz range

GURT

25 dipoles



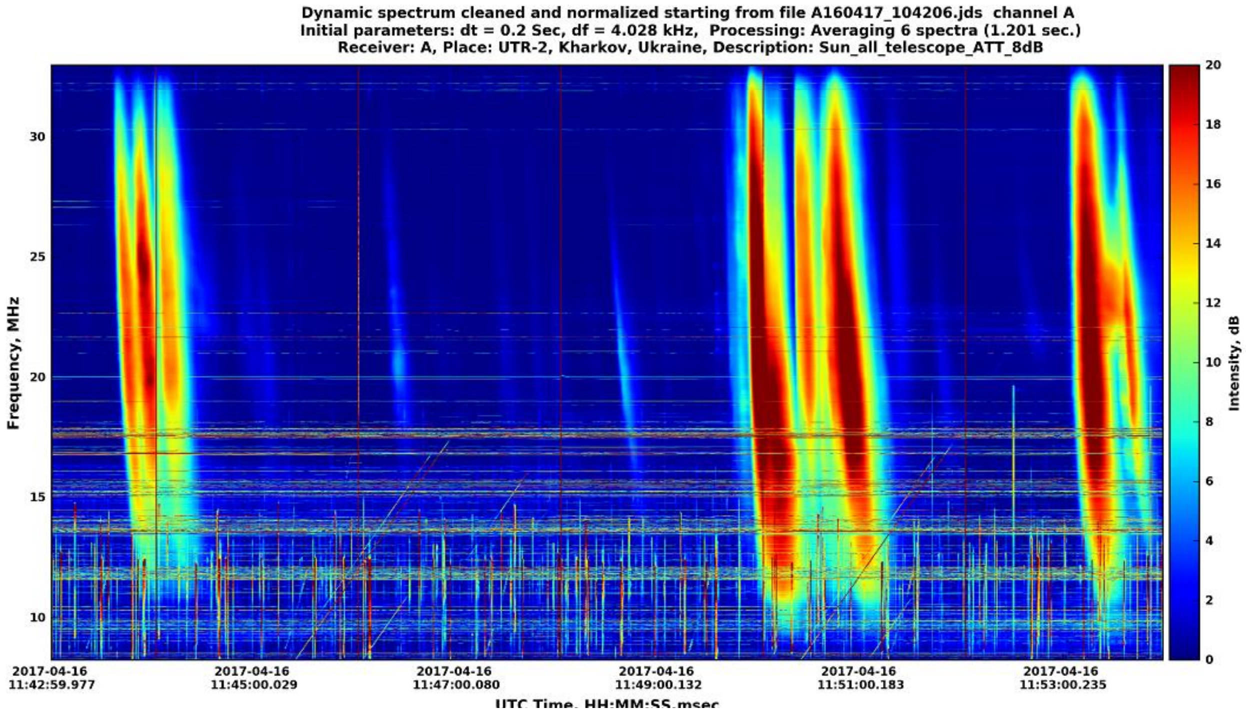


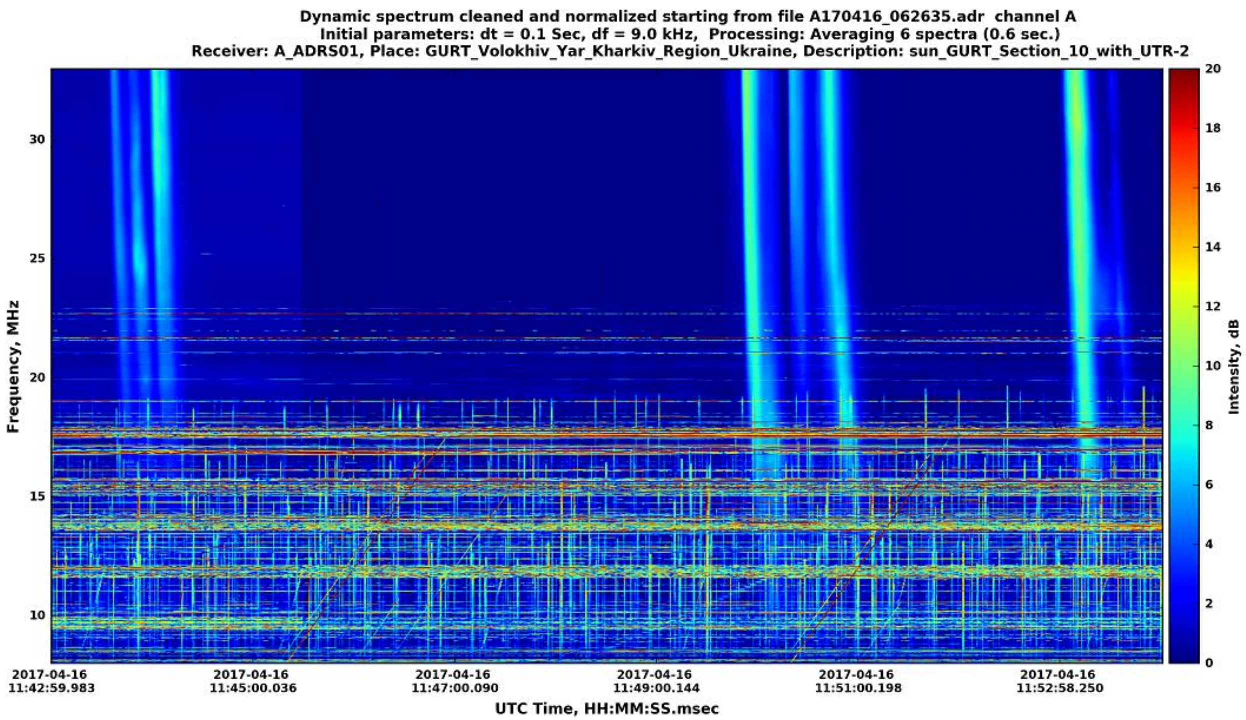


North-South arm (1440 dipoles)

in operational frequency range

Single subarray single linear polarization (25 dipoles)





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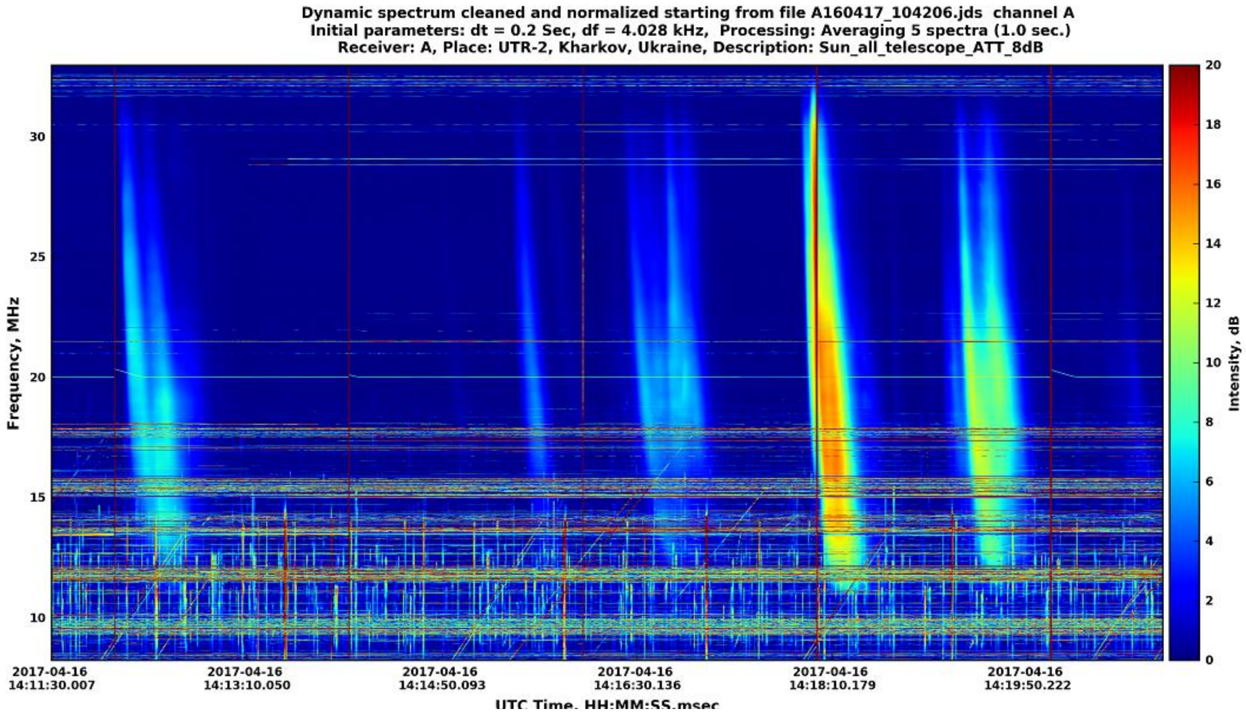

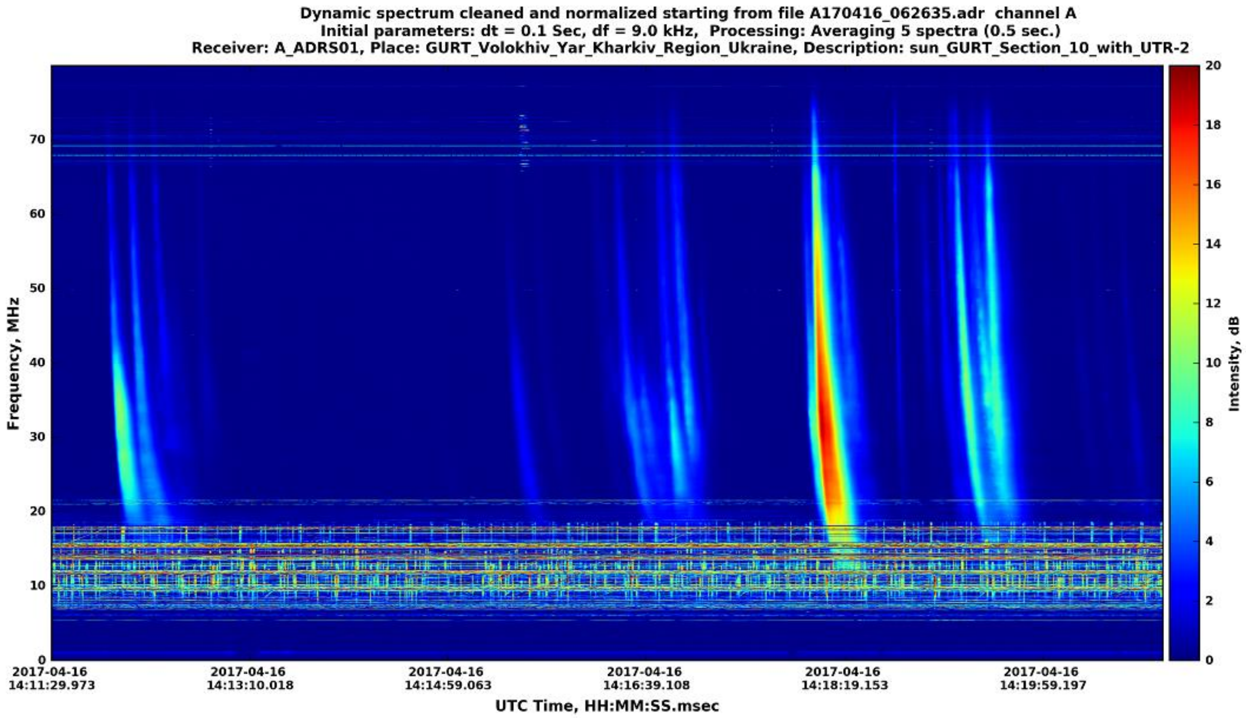

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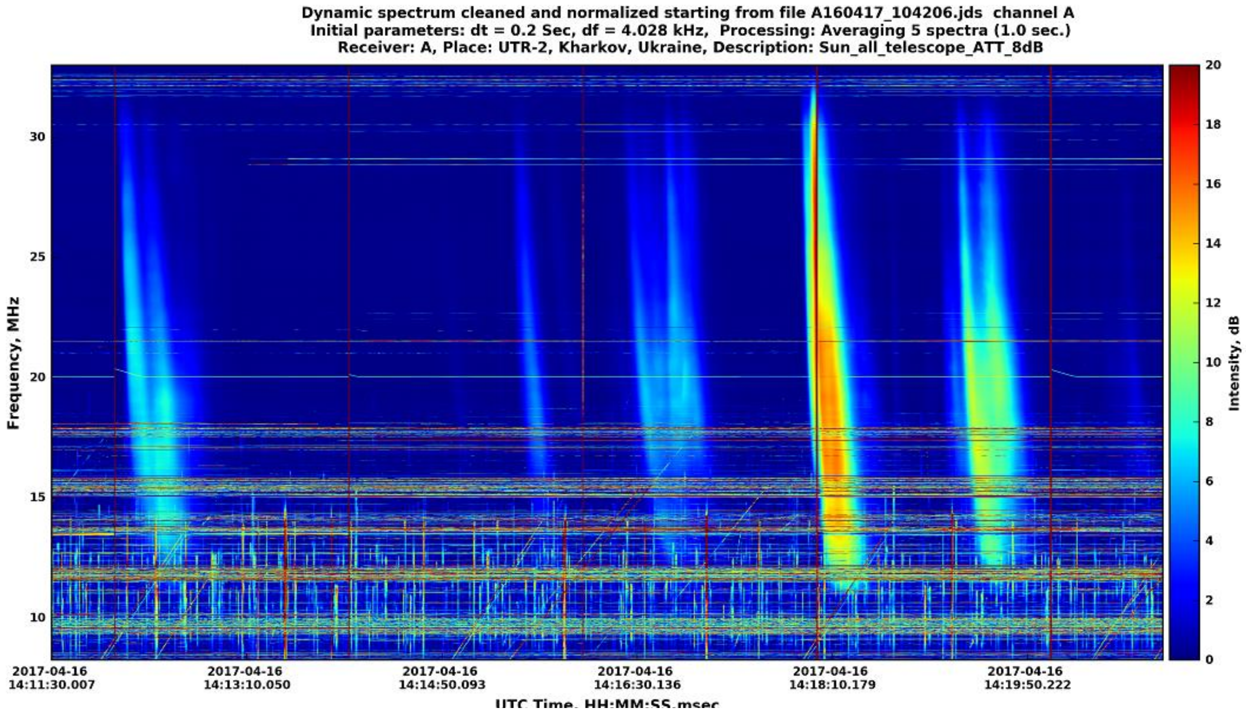

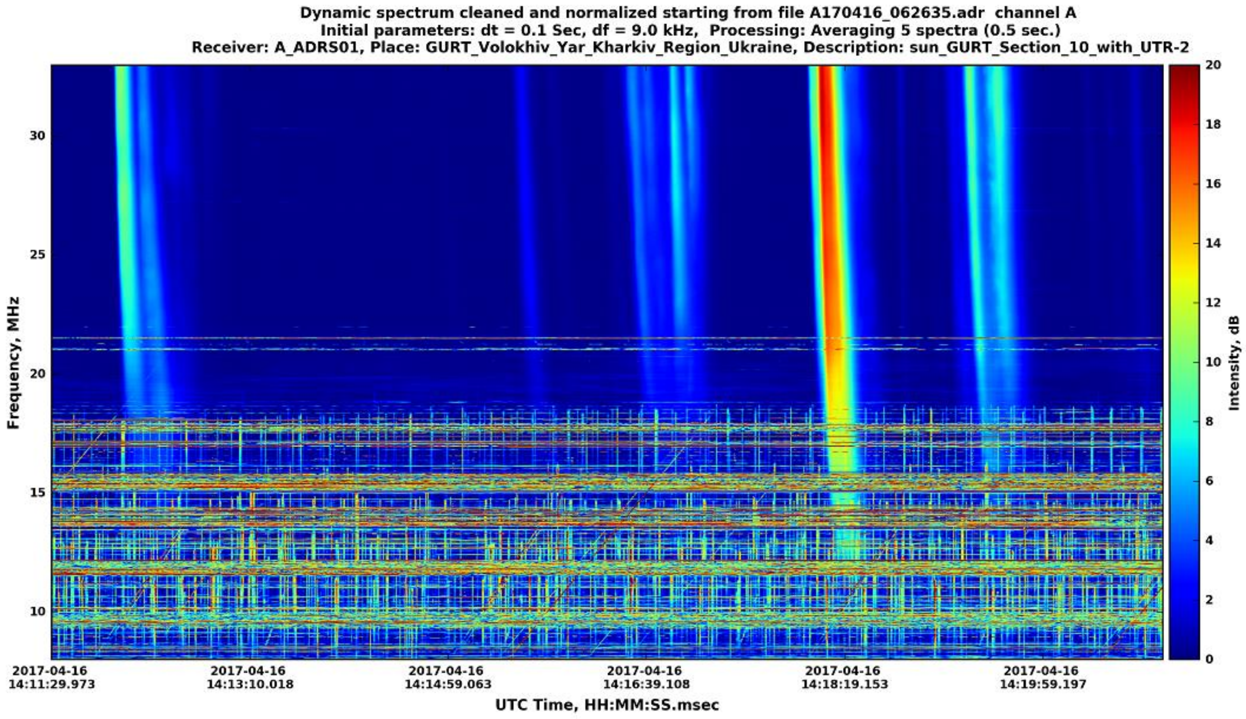

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Conclusions from the dynamic spectra

The solar radio observations at frequencies upper 30 MHz do not need very large antennas. The highest efficiency of large antenna is essential at lower frequencies.

That gives us a frequency criteria…

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The solar radio observations at frequencies upper 30 MHz do not need very large antennas. The highest efficiency of large antenna is essential at lower frequencies.

That gives us a frequency criteria…

Hints for the idea

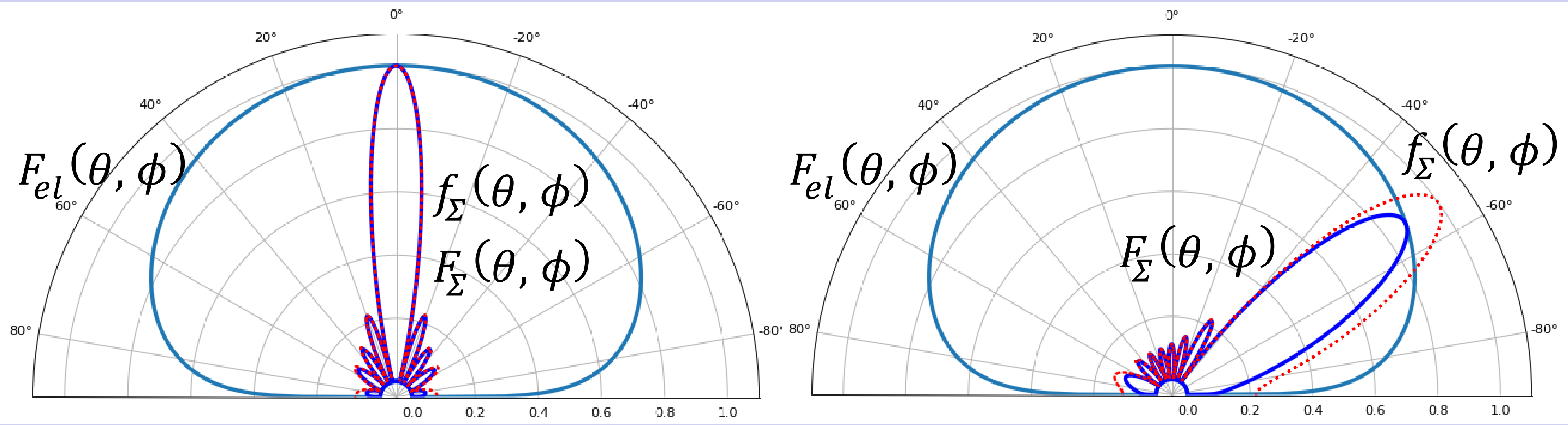
Some of new large low-frequency radio telescopes consist of many subarrays (stations, sections, tiles) which field-of-view (FoV) limits the possibilities of simultaneous observations.

The new low-frequency radio telescopes are wideband…

Pattern of phased array of identical antennas: is a product of two factors:

- single antenna pattern (FoV)
- factor of the array of antennas

$$F_{\Sigma}(\theta,\phi) = f_{\Sigma}(\theta,\phi) \times F_{el}(\theta,\phi)$$



Pattern of phased array of identical subarrays: is a product of two factors:

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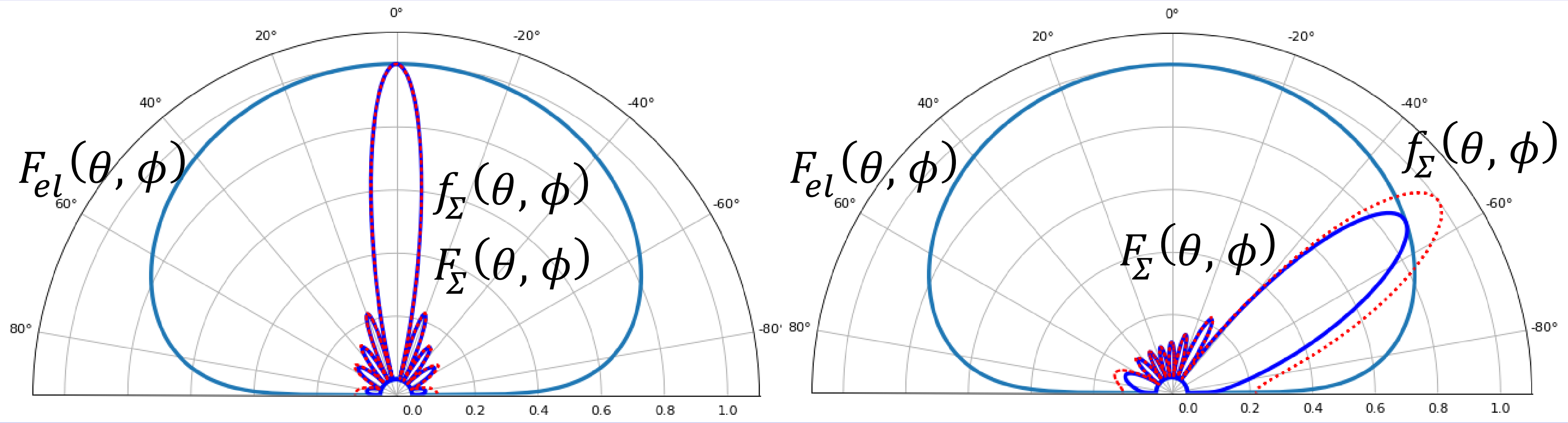
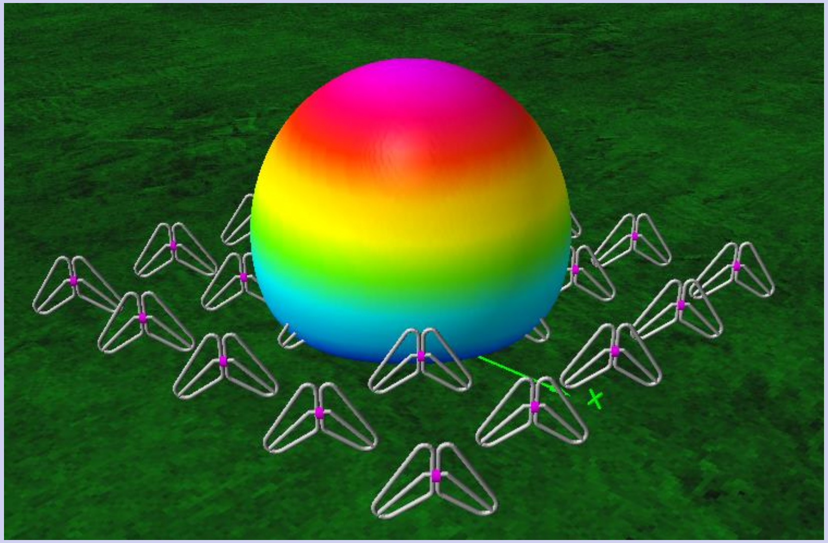
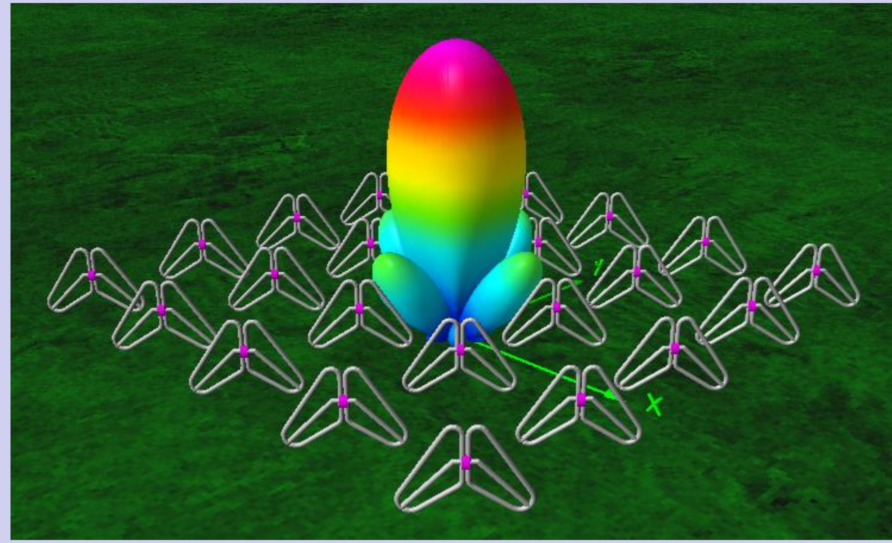


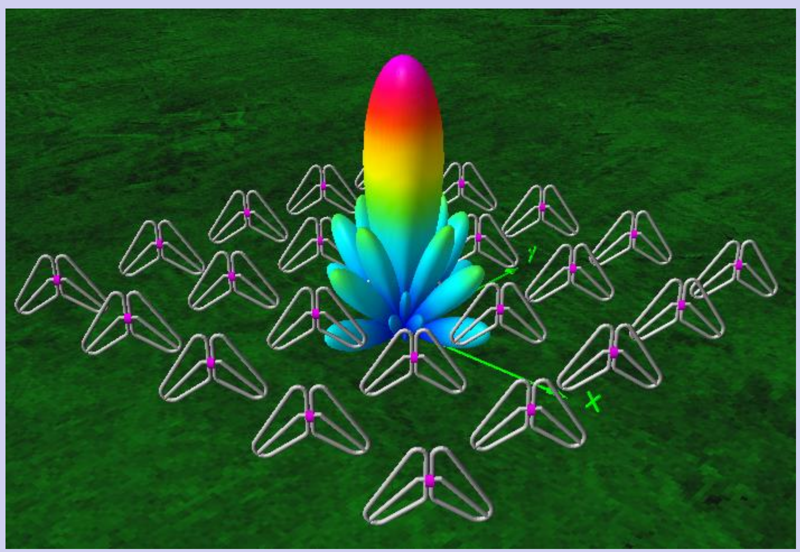
GURT subarray pattern vs. frequency



10 MHz

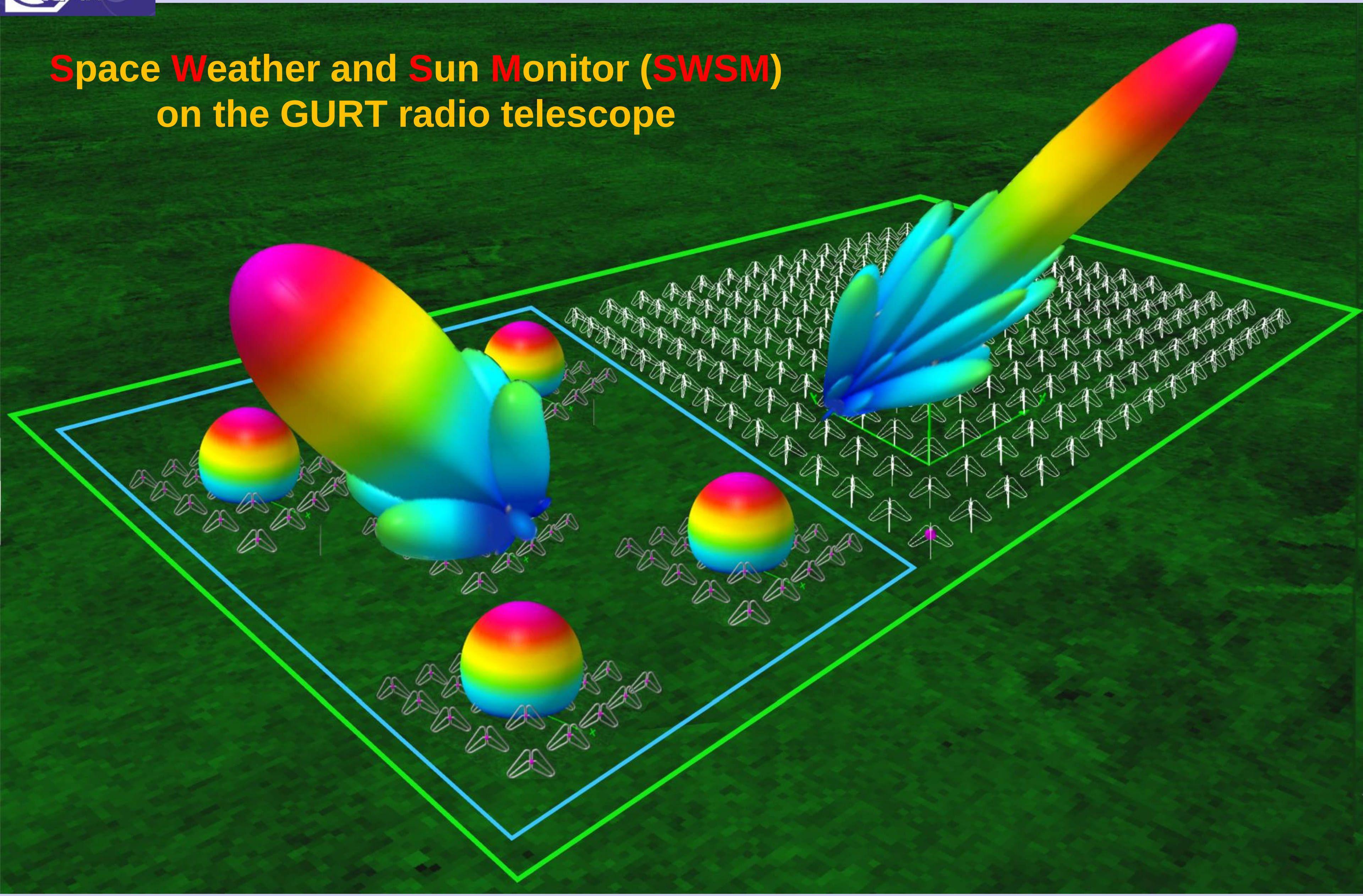


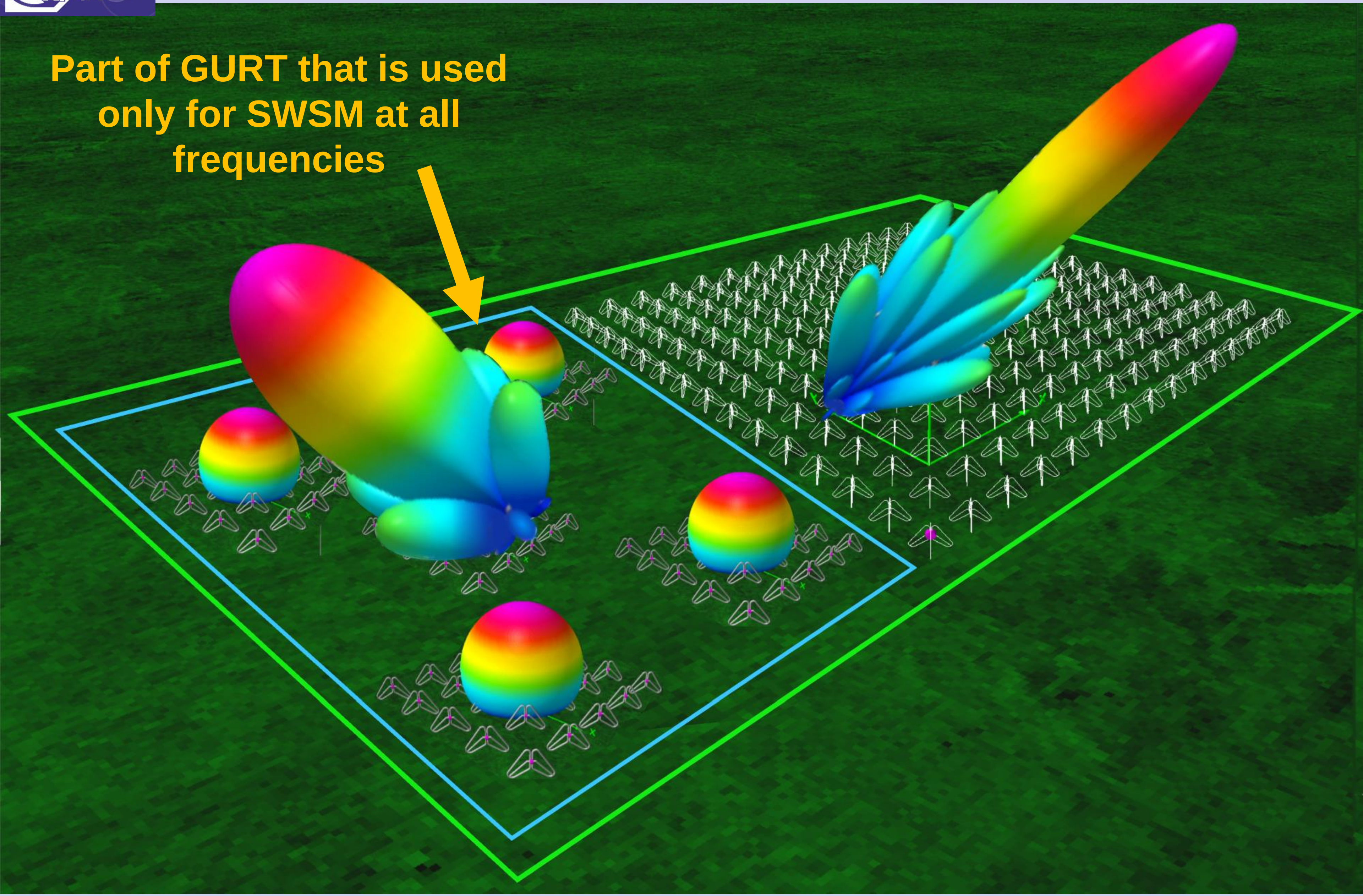
40 MHz



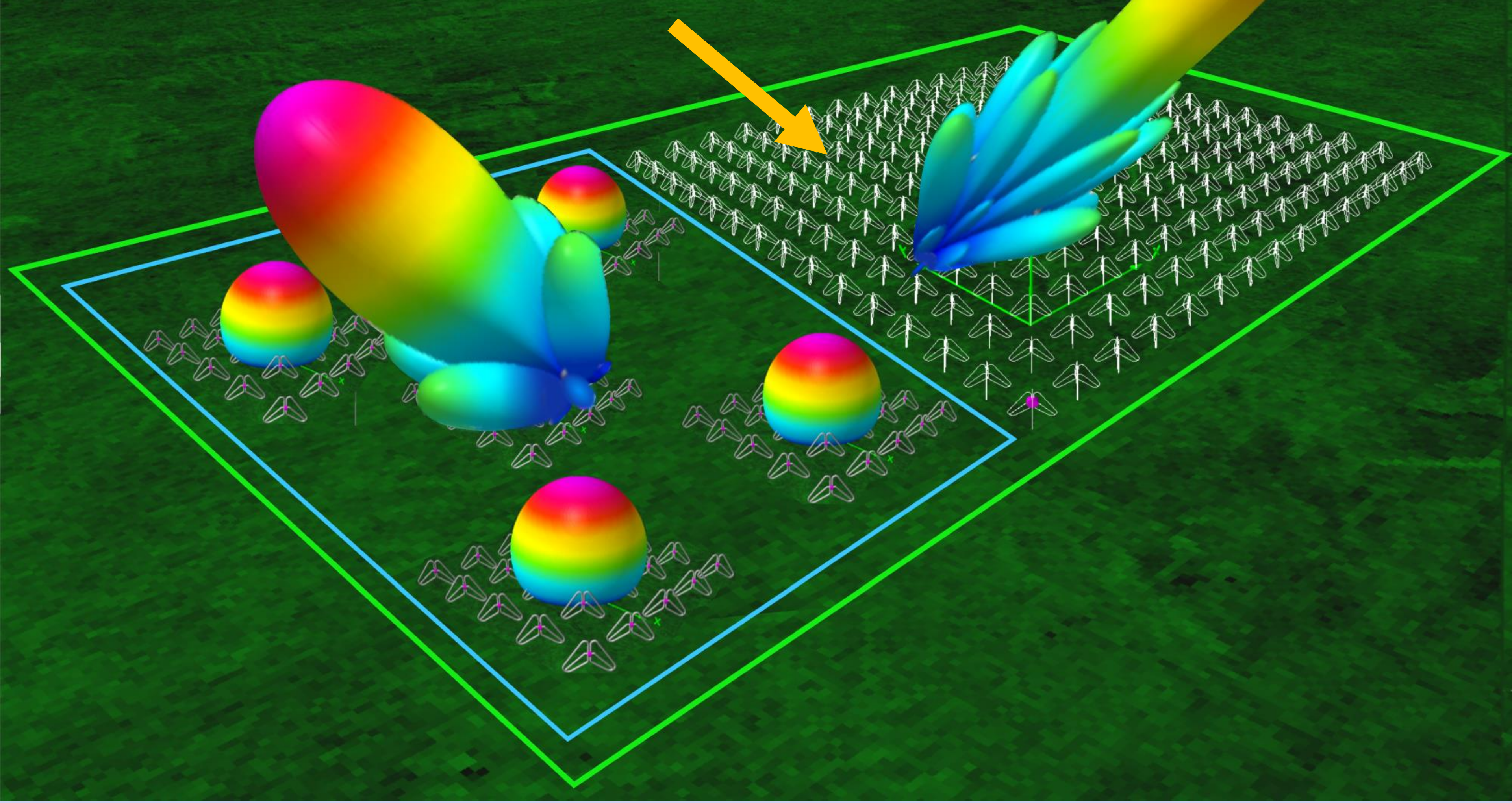
70 MHz

Space Weather and Sun Monitor (SWSM) on the GURT radio telescope




Part of GURT that is used
only for SWSM at all
frequencies

Part of GURT that observes other sources and used for SWSM at lower frequencies



Scientific goals

– detection of the CME start time before it can be viewed by space-born coronagraphs via type II bursts identification;

– finding the radial component of the CME velocity from the type-II bursts drift rates, what is essential in case of Earth-directed CMEs;

– finding the size of the CME from the analysis of the spatial properties of type IV bursts sources;

– estimation of CME mass from type IV bursts spectral and spatial analysis;

– more precise estimation of the CME direction from interferometric observations of type II and type IV bursts (especially important in the cases of Earth-directed CMEs).

GURT digital radio astronomy receiver ADR

Parameters	ADR – GURT
Frequency band (MHz)	80
Number of freq. channels	16 384 (tunable)
Frequency resolution (kHz)	4,8
Time resolution (ms)	2
ADC resolution (bits)	16
Dynamic range (dB)	90
Input channels	2
On-line real-time possibilities	
Fast Fourier transform	Yes
Wave-form	Yes
Auto- and complex cross-spectra	Yes
Sum-Subtraction mode	Yes
Signals normalization	yes
Signals delay	yes

Conclusion

The good data at low-frequencies (8-30 MHz) can be obtained only with big antennas, but it does not have to be a separate antenna.

The SWSM project does not require development and construction of new special antennas or using of low-grade antennas of common applications. At the same time the space weather monitoring will not affect the radio astronomical observations of other sources which means low cost of the project implementation.

Thank you for attention!
Q & A

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Alexander Stanislavsky,
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Mykola Kalinichenko

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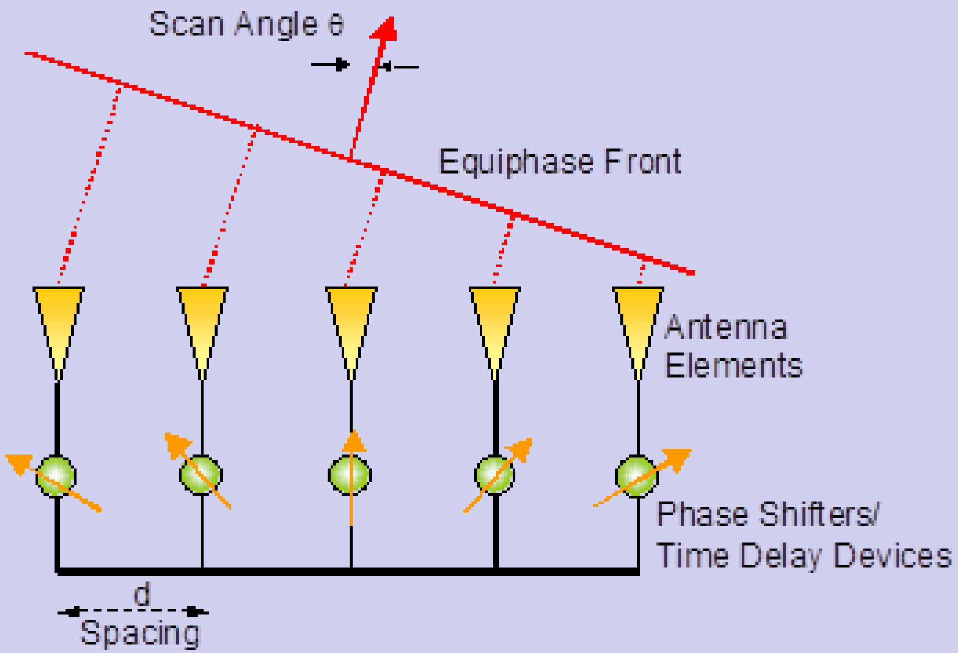
Phased array antenna
is an array of antenna elements where antenna pattern scanning is realized with insertion of variable phase delays between the currents feeding elements of the array



Our main publications related to the topic

Konovalenko, A., Sodin, L., Zakharenko, V., Zarka, P., Ulyanov, O., Sidorchuk, M., Stepkin, S., Tokarsky, P., Melnik, V., Kalinichenko, N., Stanislavsky, A., et al. 2016. **The modern radio astronomy network in Ukraine: UTR-2, URAN and GURT.** *Experimental Astronomy*, *42*(1), pp.11-48. DOI: 10.1007/s10686-016-9498-x

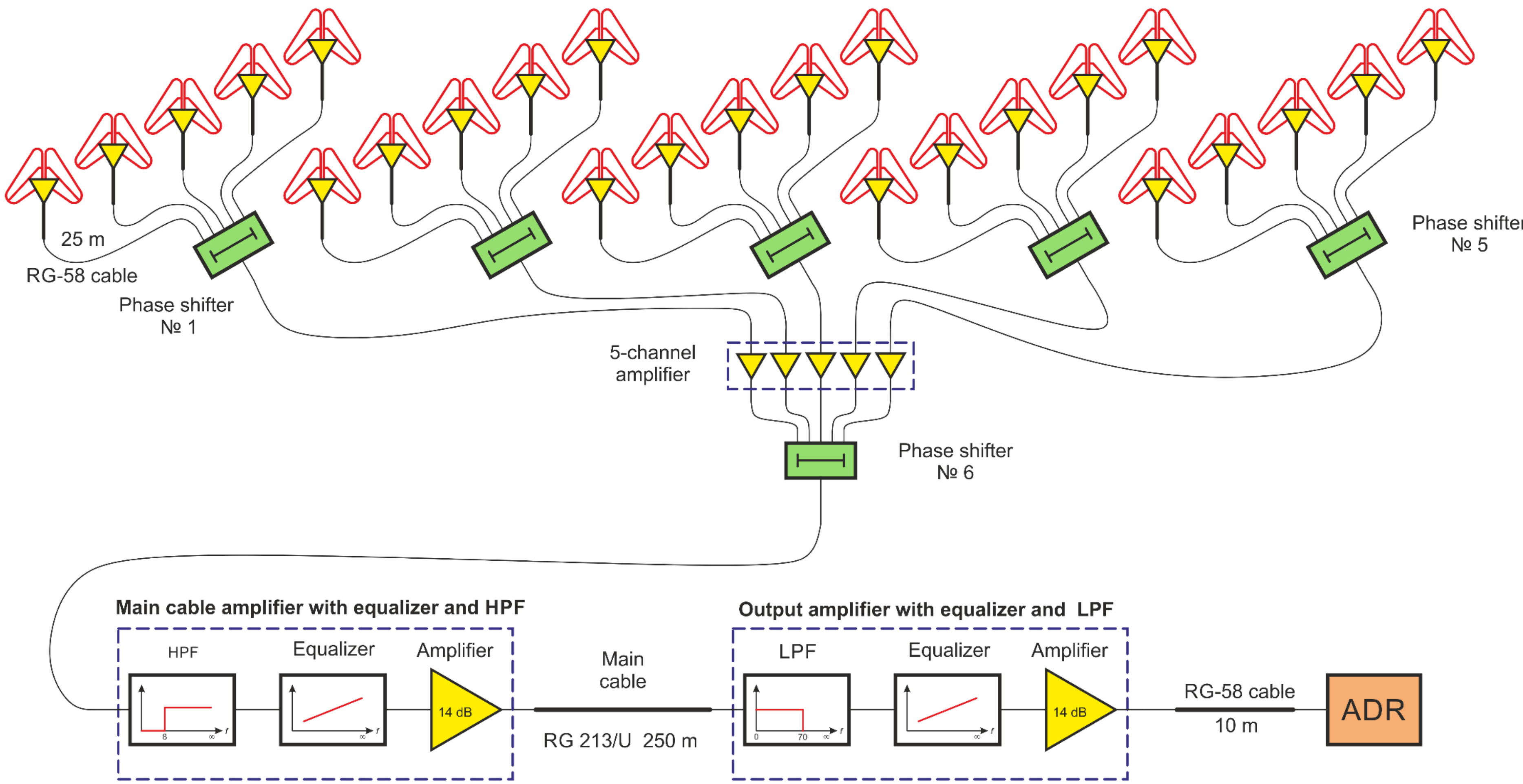
Zakharenko, V., Konovalenko, A., Zarka, P., Ulyanov, O., Sidorchuk, M., Stepkin, S., Koliadin, V., Kalinichenko, N., Stanislavsky, A., Dorovskyy, V., Shepelev, V., et al. 2016. **Digital receivers for low-frequency radio telescopes UTR-2, URAN, GURT.** *Journal of Astronomical Instrumentation*, *5*(04), p.1641010. DOI: 10.1142/S2251171716410105

Tokarsky P., Konovalenko, A., Yerin. S. 2017. **Sensitivity of an active antenna array element for the low-frequency radio telescope GURT.** *IEEE Transactions on Antenna and Propagation*, *65*(9), pp.4636-4644. DOI: 10.1109/TAP.2017.2730238

Tokarsky P., Konovalenko, A., Yerin. S., Bubnov I., 2019. **An Active Antenna Subarray for the Low-Frequency Radio Telescope GURT Part I: Design and Theoretical Model.** *IEEE Transactions on Antenna and Propagation*, *(Accepted)*

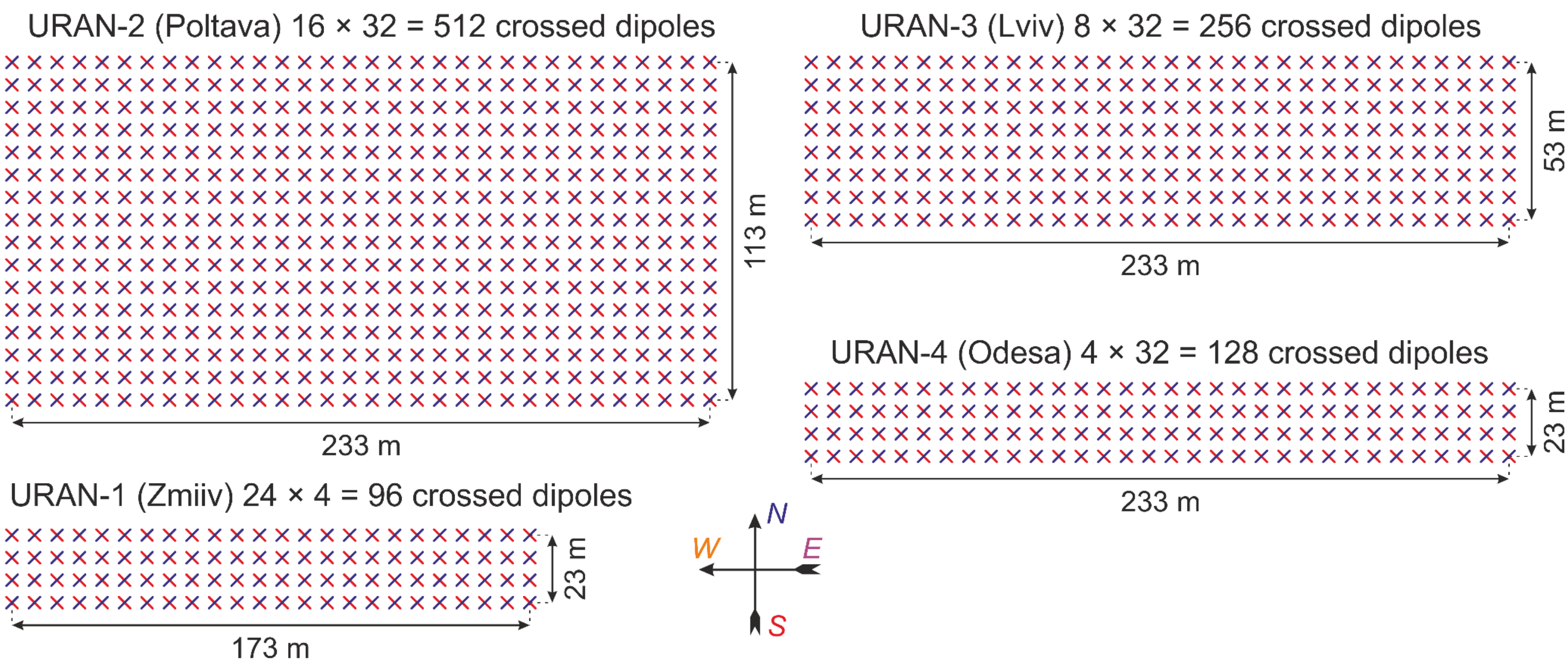
Tokarsky P., Konovalenko, A., Yerin. S., Bubnov I., 2019. **An Active Antenna Subarray for the Low-Frequency Radio Telescope GURT Part II: Numerical Analysis and Experiment.** *IEEE Transactions on Antenna and Propagation*, *(Accepted)*

GURT Subarray Structure

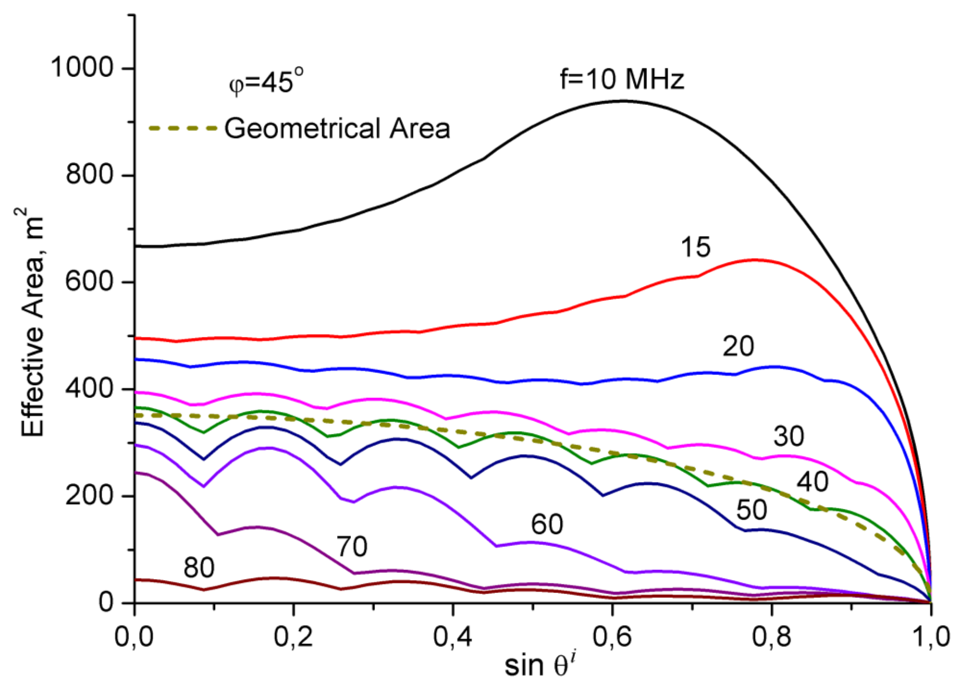


URAN-3
Kyiv
946 km
805 km
910 km
Lviv
Kharkiv
URAN-1
GURT
Poltava
URAN-2
UTR-2
735 km
U K R A I N E
495 km
613 km
Odesa
100 km
URAN-4
Kharkiv
URAN-1
42 km
GURT
Poltava
110 km
153 km
URAN-2
UTR-2

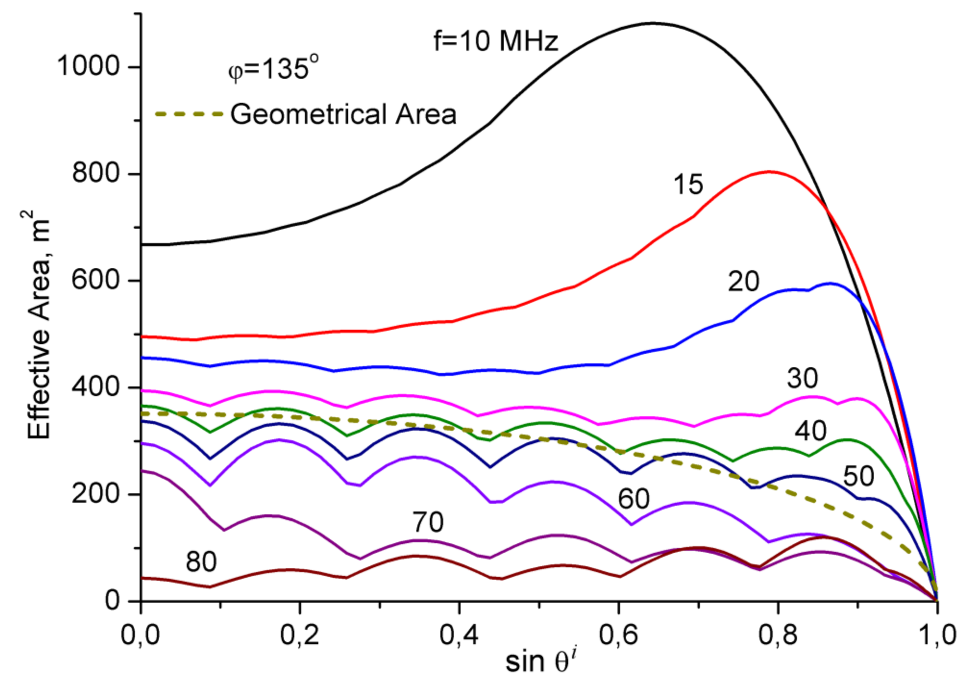
URAN decameter interferometer network



GURT subarray effective area for beam scanning in two principal planes of the array

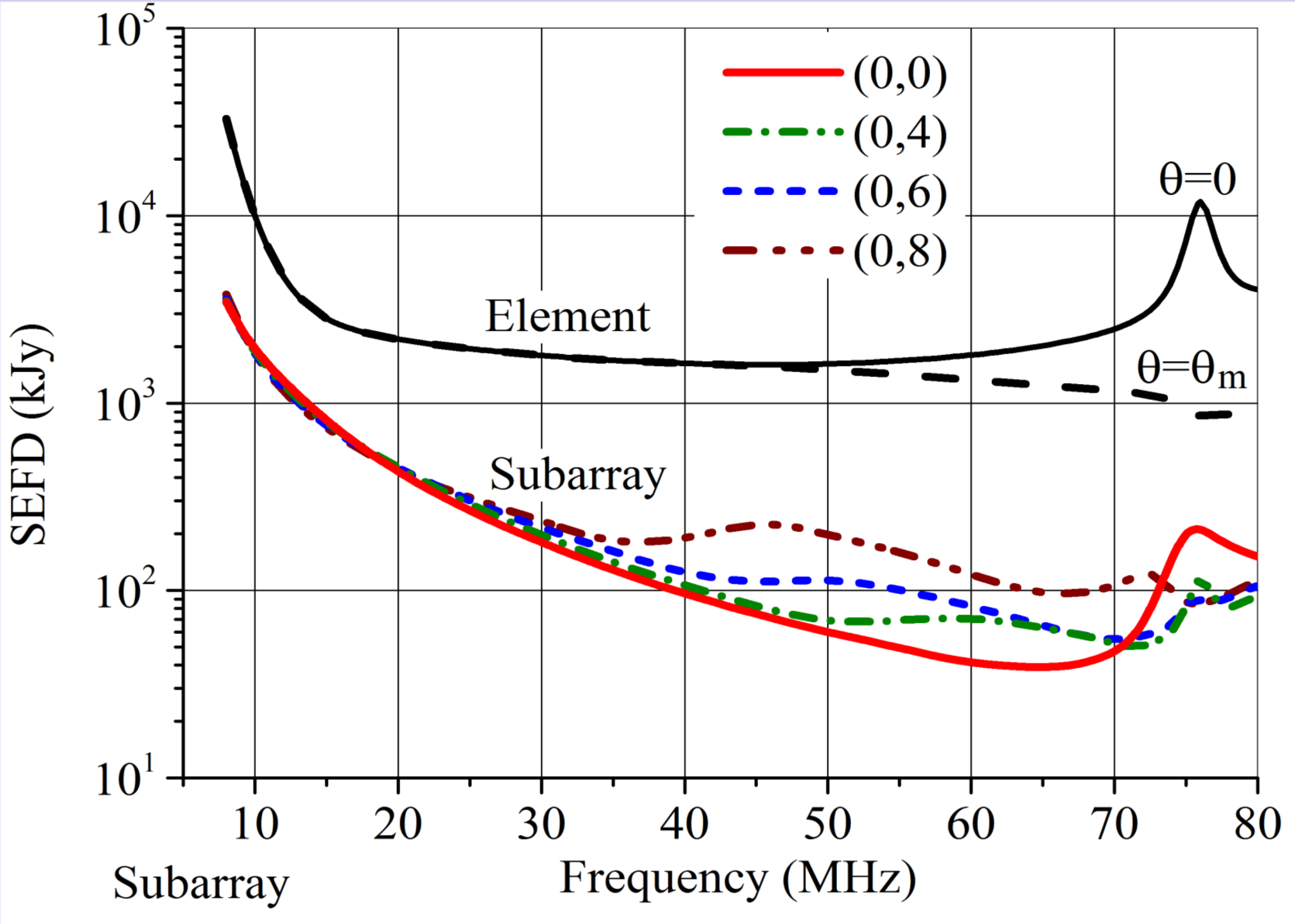


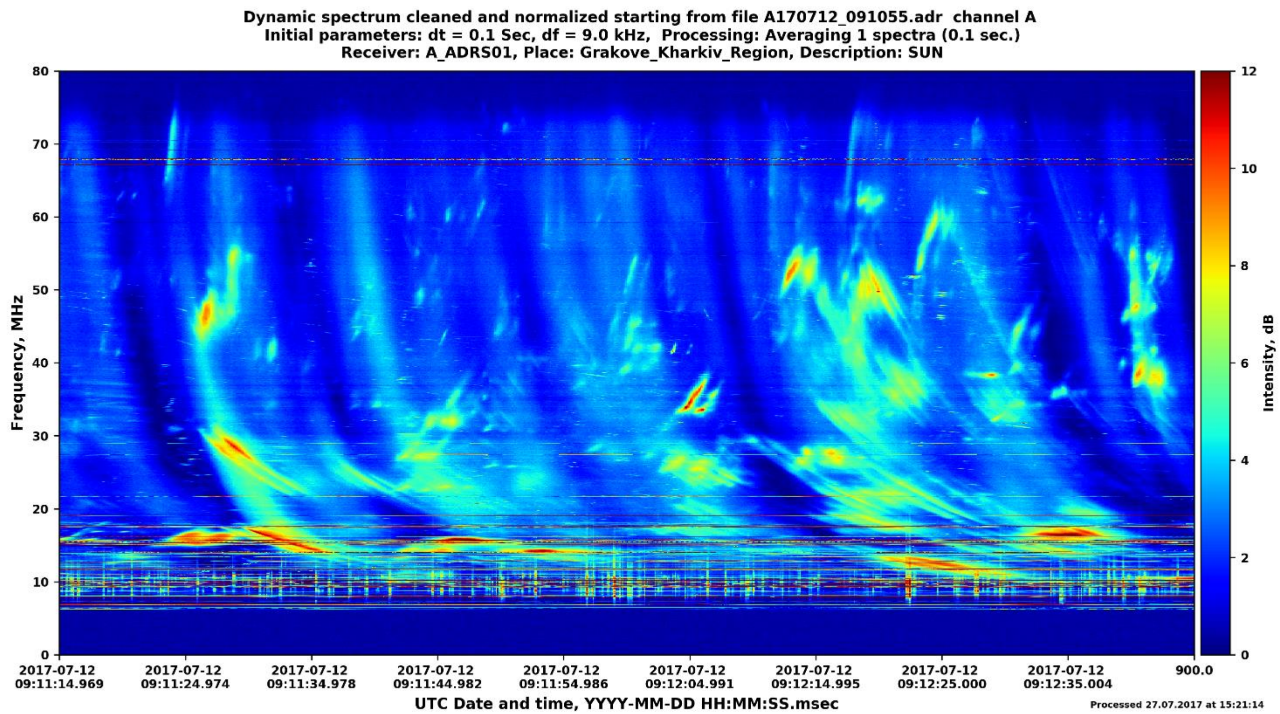
E-plane

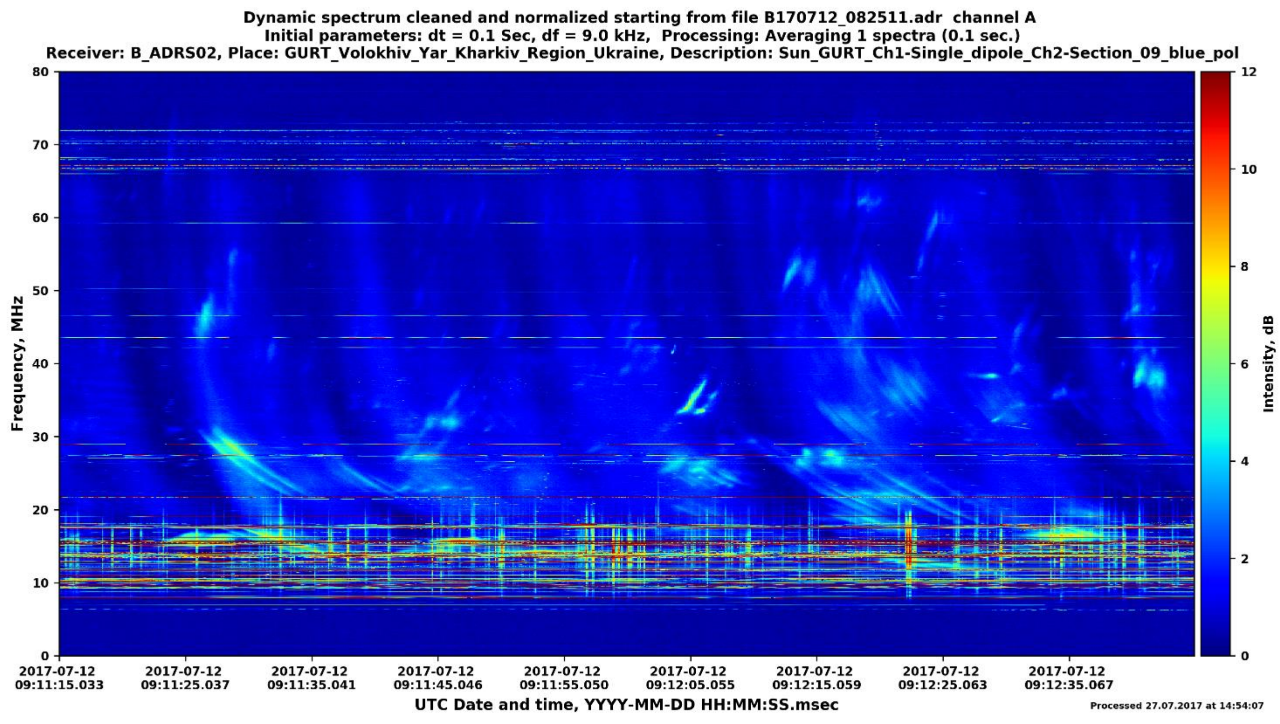


H-plane

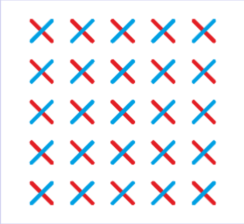
GURT system equivalent flux density (SEFD)







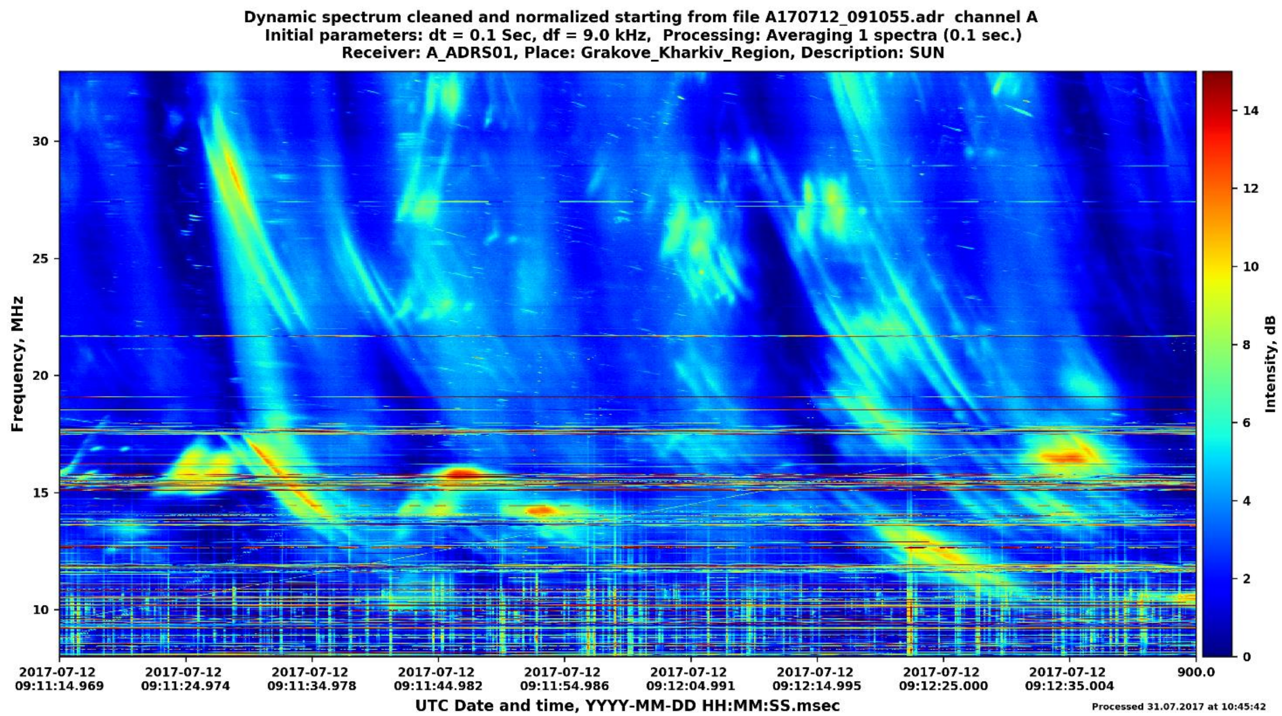
25 dipoles



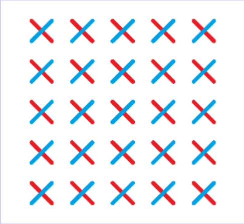
GURT subarray vs. GURT dipole

in 0 - 80 MHz range

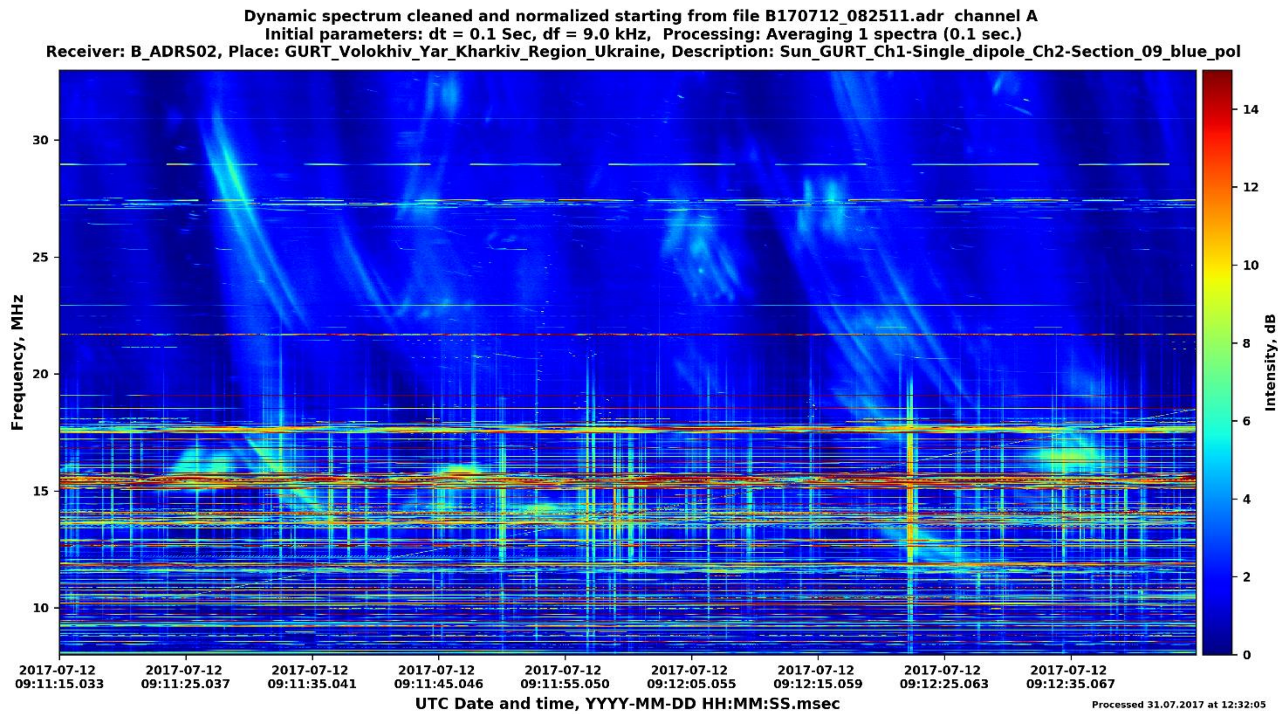
1 dipole



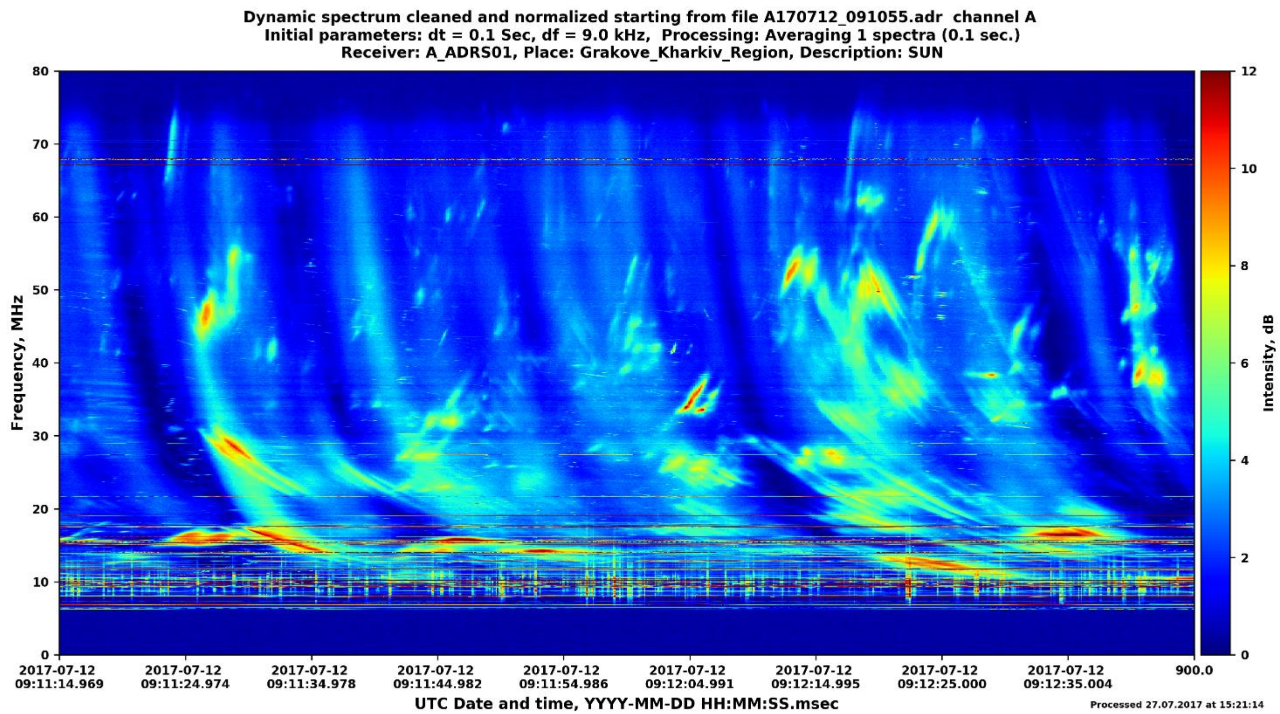
25 dipoles

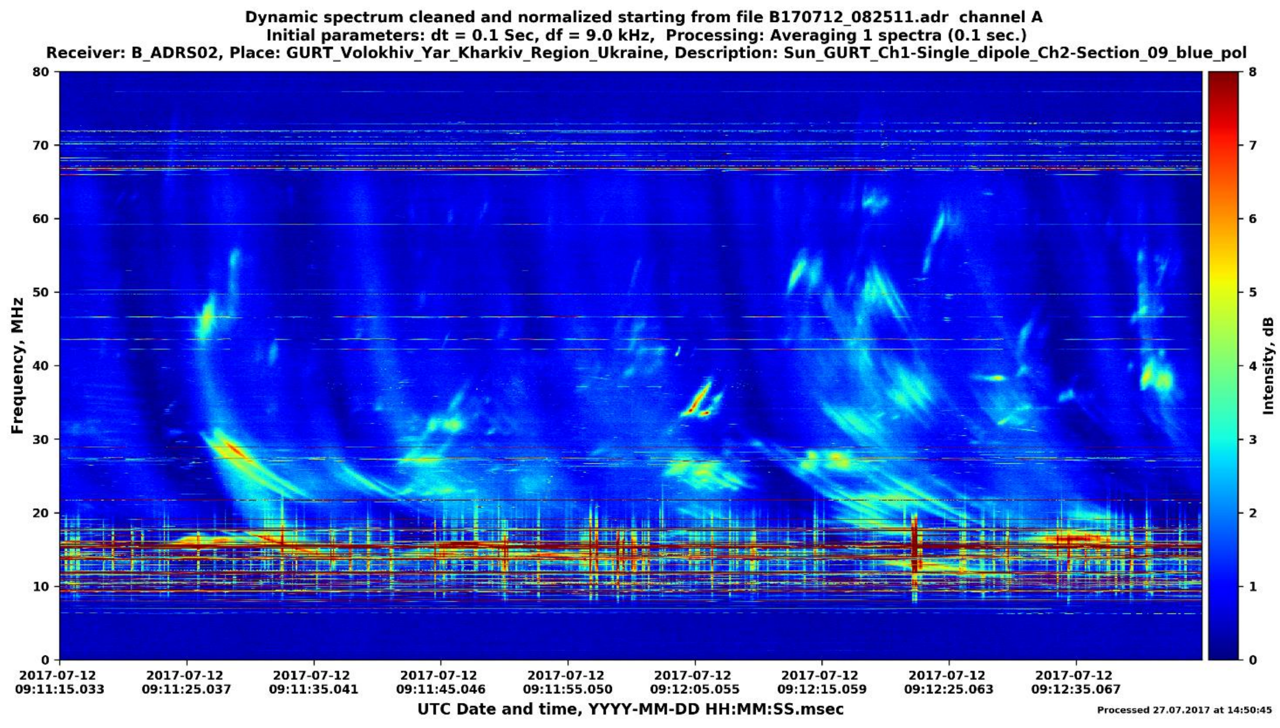


GURT subarray
vs.
GURT dipole
in 8 - 33 MHz range

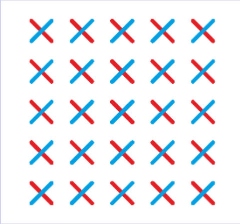


1 dipole





25 dipoles

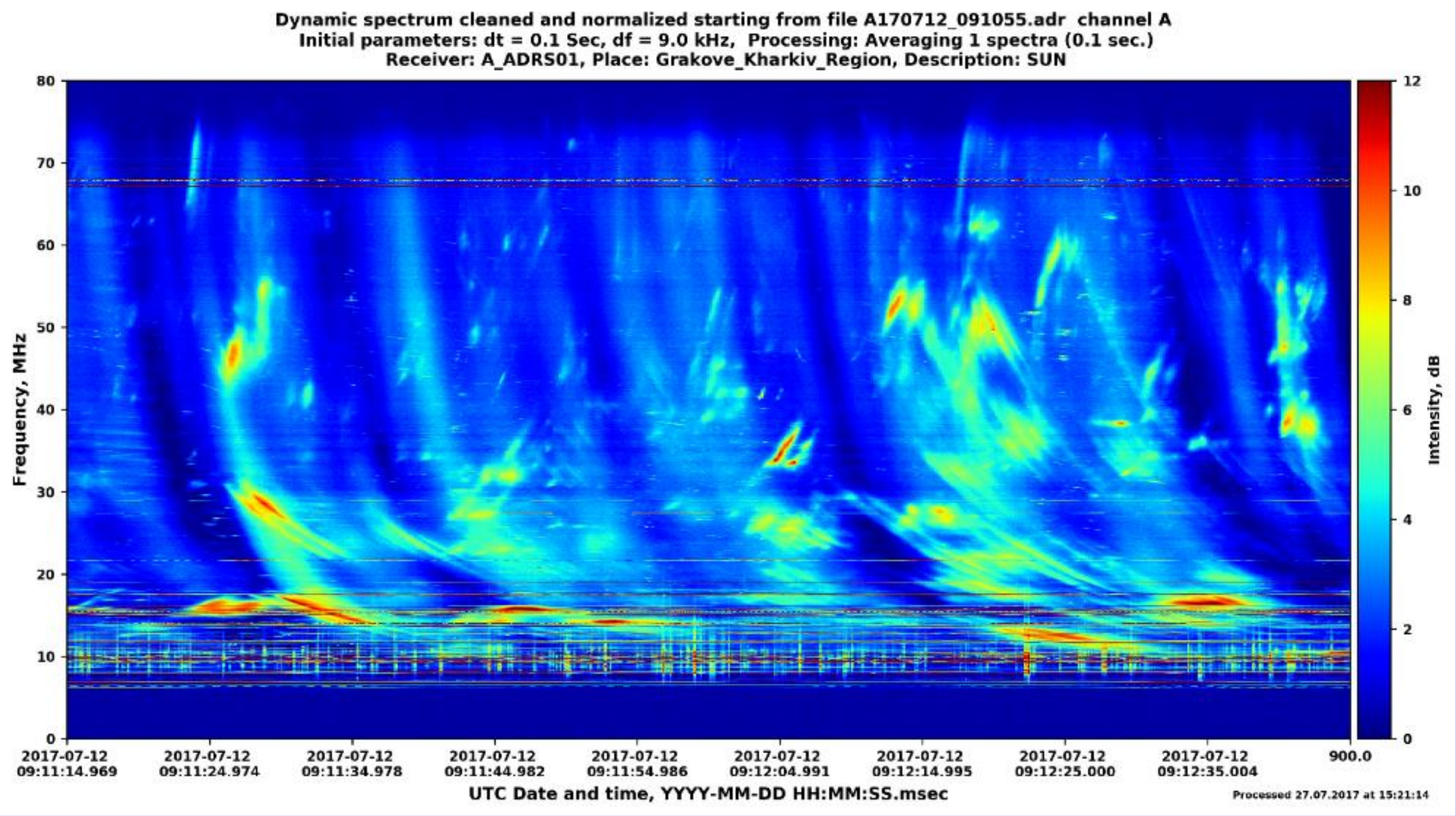


GURT subarray
vs.
GURT dipole
in 0 - 80 MHz range

1 dipole

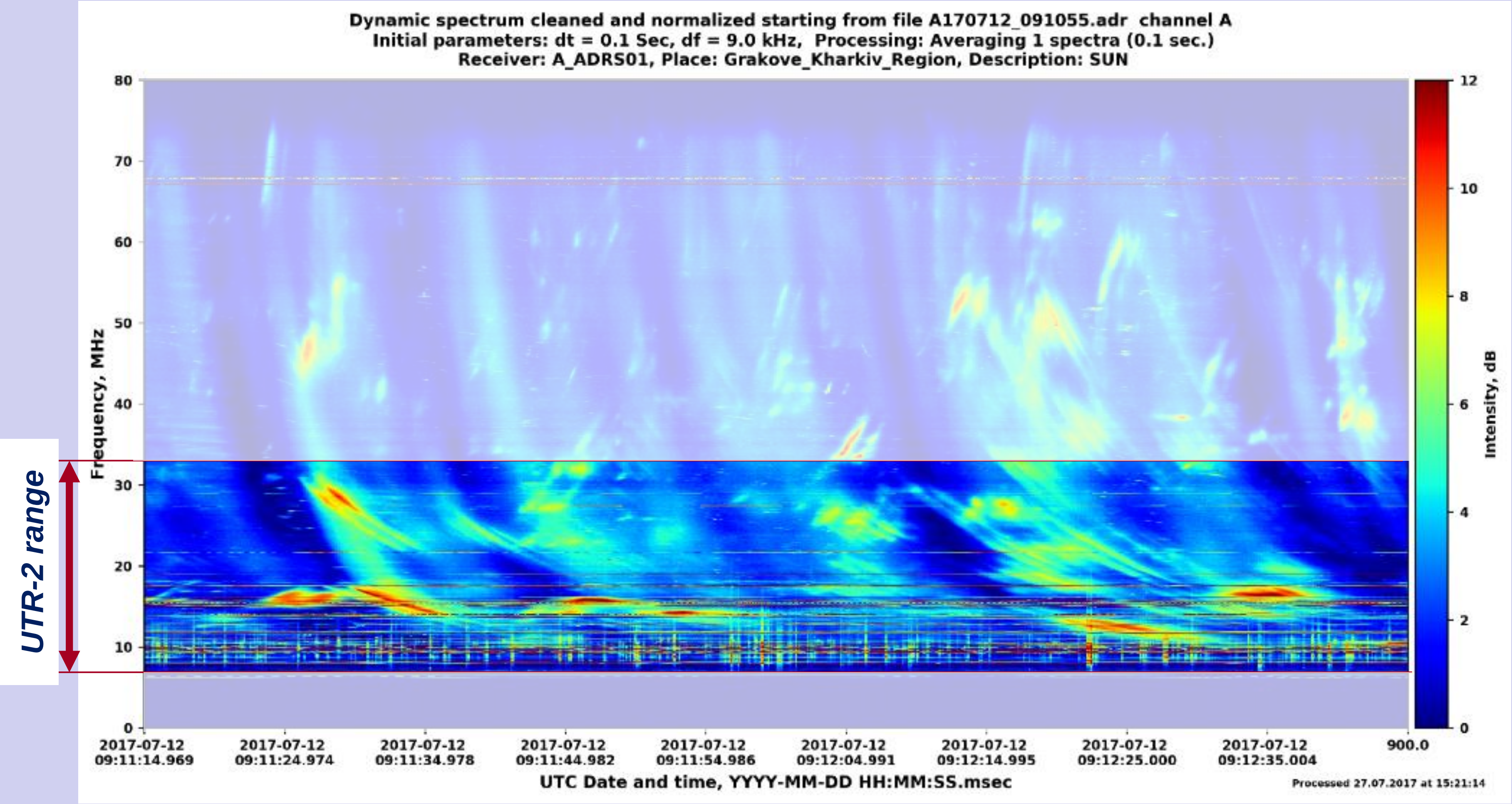
Drifting pairs solar radio emission observed on July 12, 2017

GURT subarray of 25 active dipoles



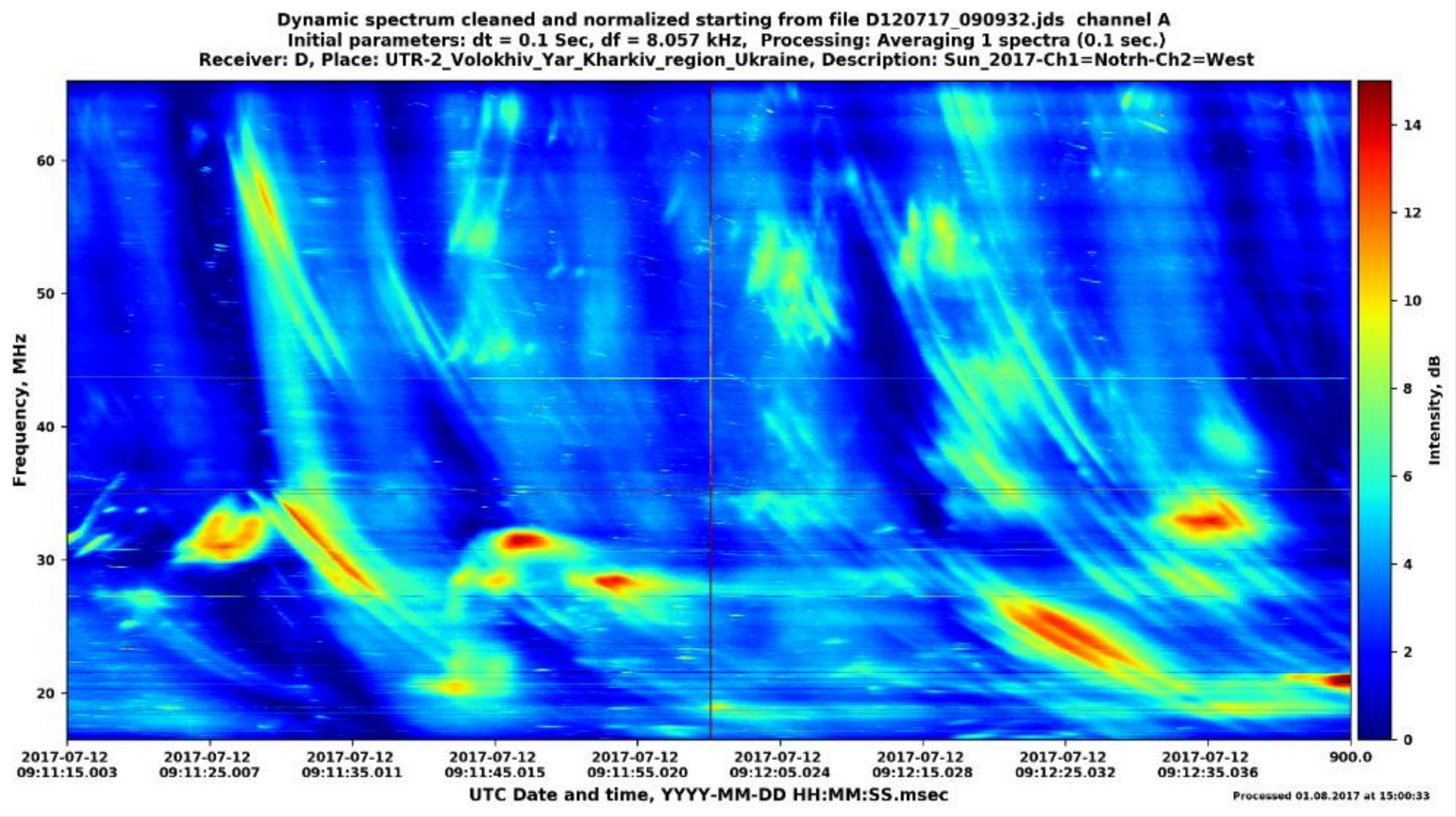
Drifting pairs solar radio emission observed on July 12, 2017

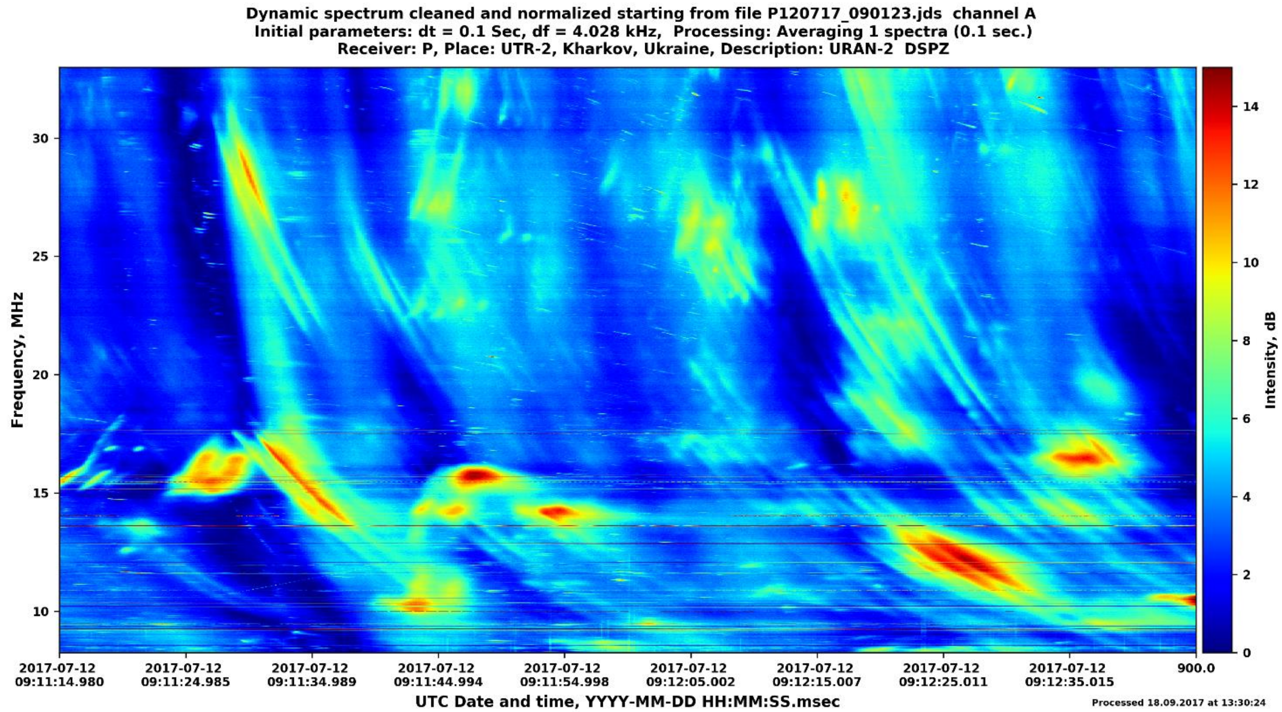
GURT subarray of 25 active dipoles

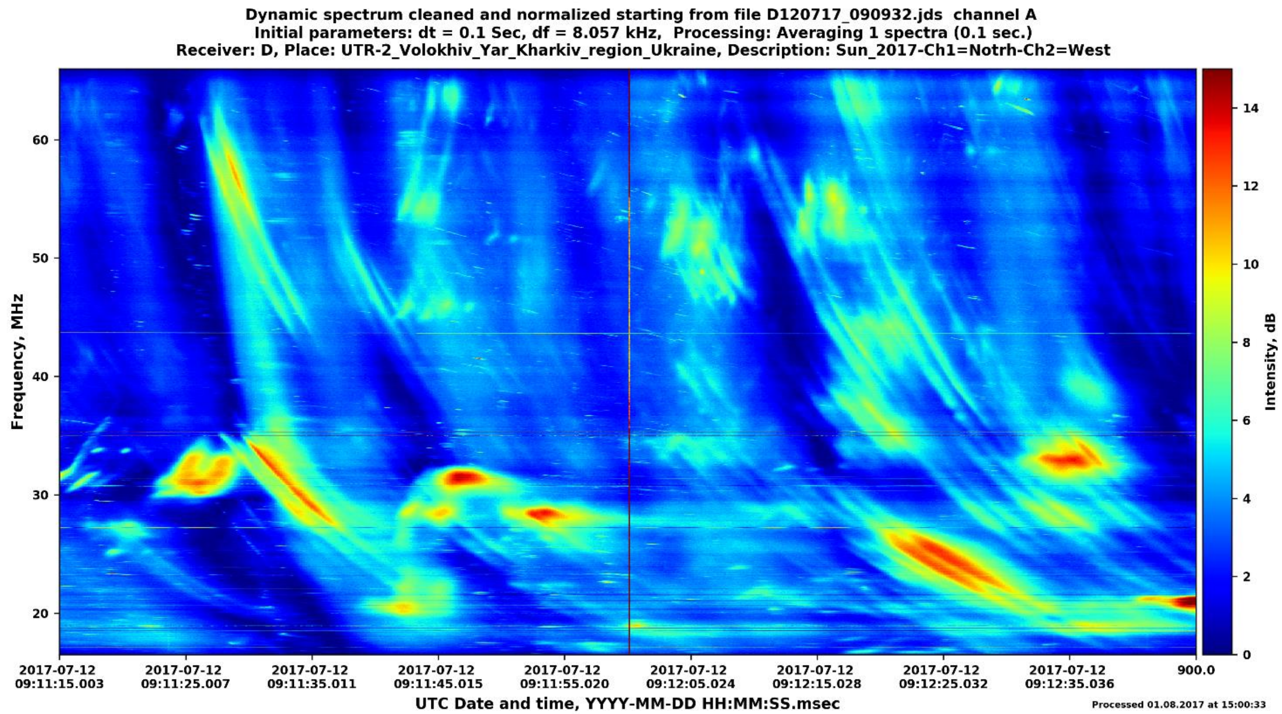


Drifting pairs solar radio emission observed on July 12, 2017

UTR-2 North arm (720 passive dipoles)







URAN

512 dipoles
(16 x 32)
Rectangular
configuration

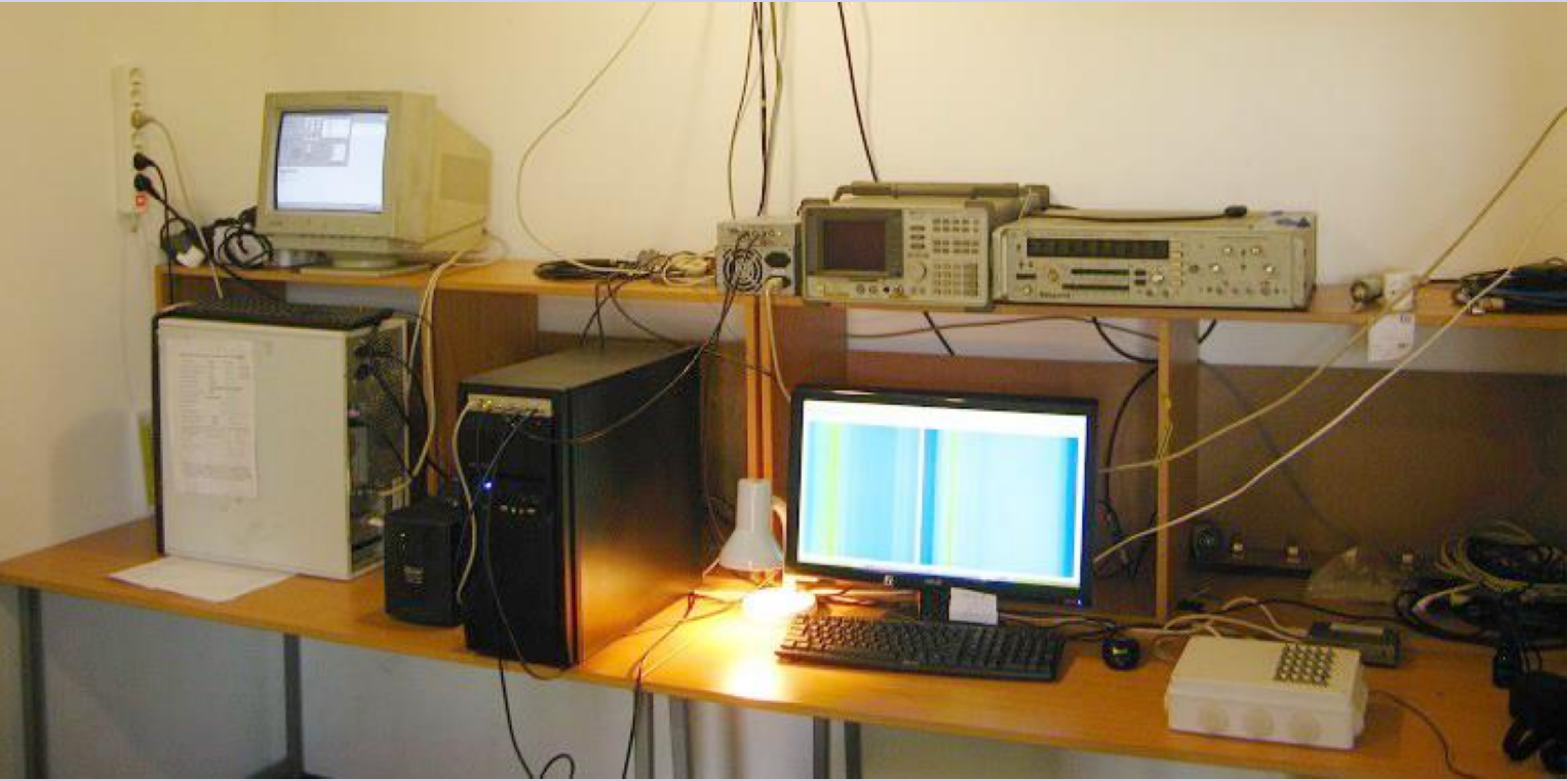
URAN-2 Full telescope vs. UTR-2 North Arm

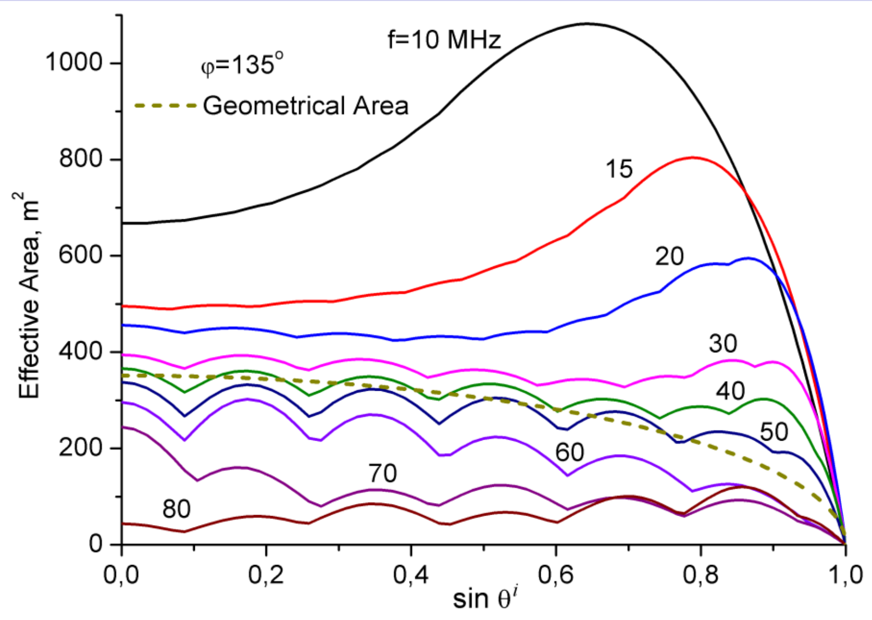
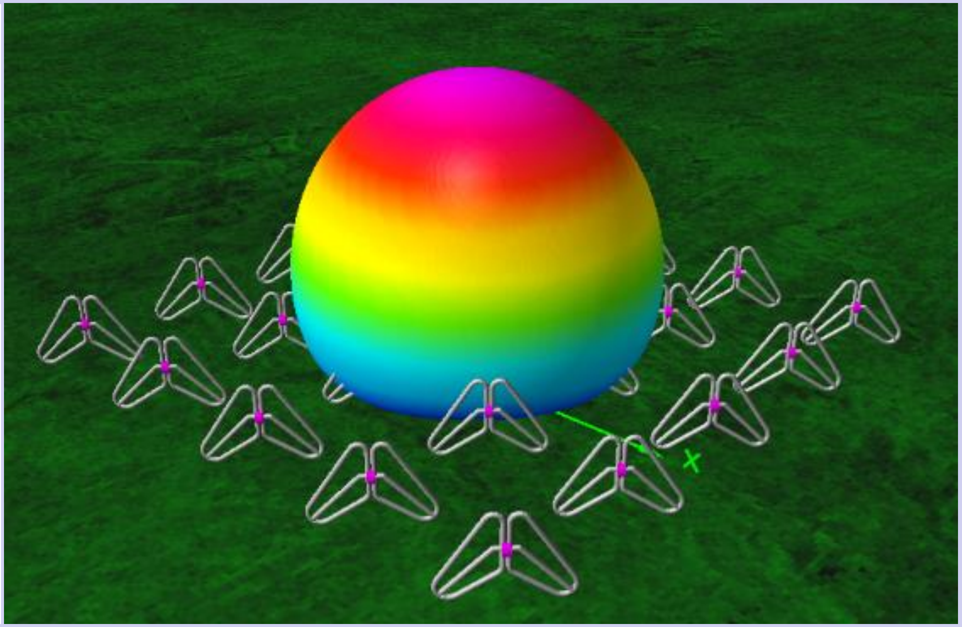
in 8 - 33 MHz range

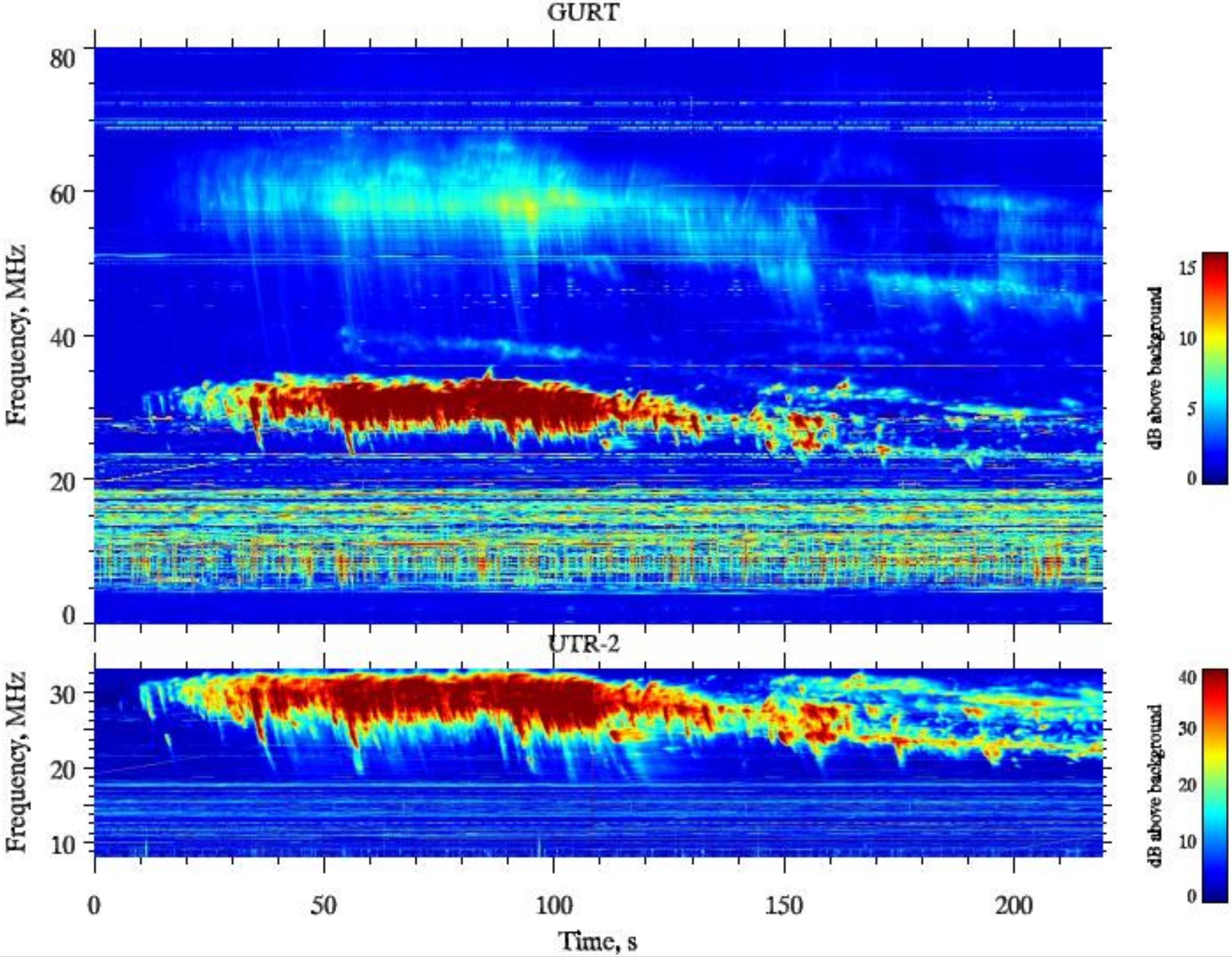
720 dipoles
(6 x 120)
Almost linear
array

UTR-2

Digital radio astronomy receivers DSPZ and ADR for UTR-2 and GURT radio telescopes




f=10 MHz
φ=135°
Geometrical Area
15
20
30
40
50
60
70
80
Effective Area, m²
sin θ^i
1000
800
600
400
200
0
0,0
0,2
0,4
0,6
0,8
1,0


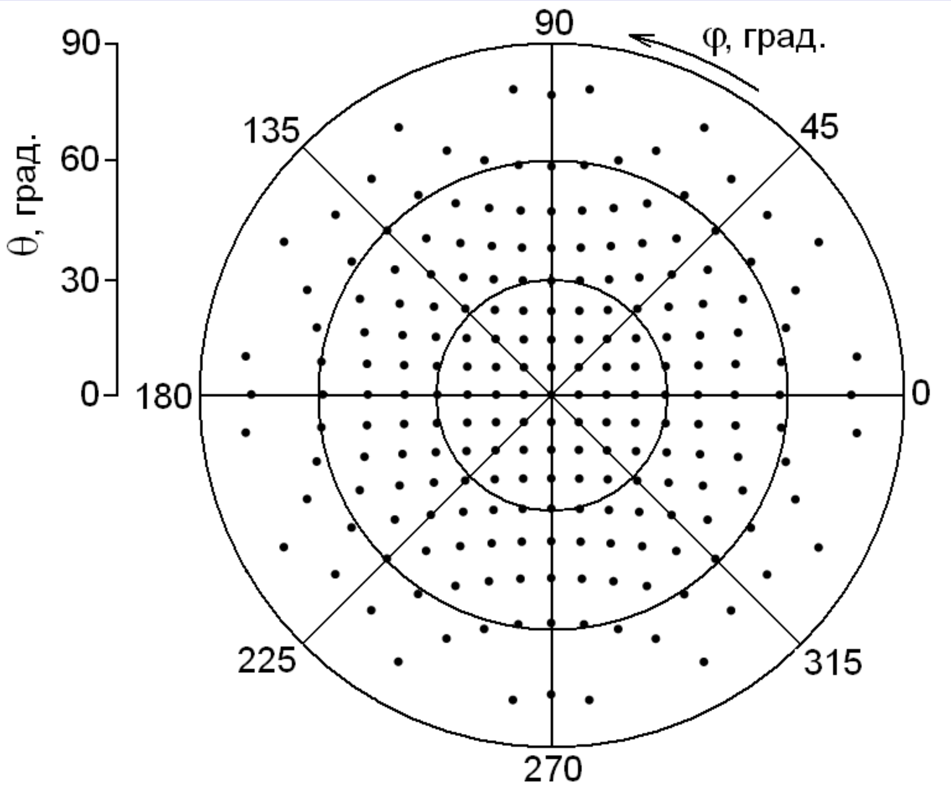

GURT
UTR-2
Frequency, MHz
Time, s
dB above background
80
60
40
20
0
30
20
10
50
100
150
200
15
5
40

Углы фазирования секции ГУРТ

i	0	±1	±2	±3	±4	±5	±6	±7	±8
θ_{0i}	0°	±7°	±14°	±21,3°	±29°	±37,4°	±46,7°	±58,2°	±76,1°
Коды управления	00000	00001 10011	00010 10110	00111 10101	00100 11100	01101 11111	01010 11110	01001 11001	01000 11000
ΔL_i, м	0	0,3	0,6	0,9	1,2	1,5	1,8	2,1	2,4

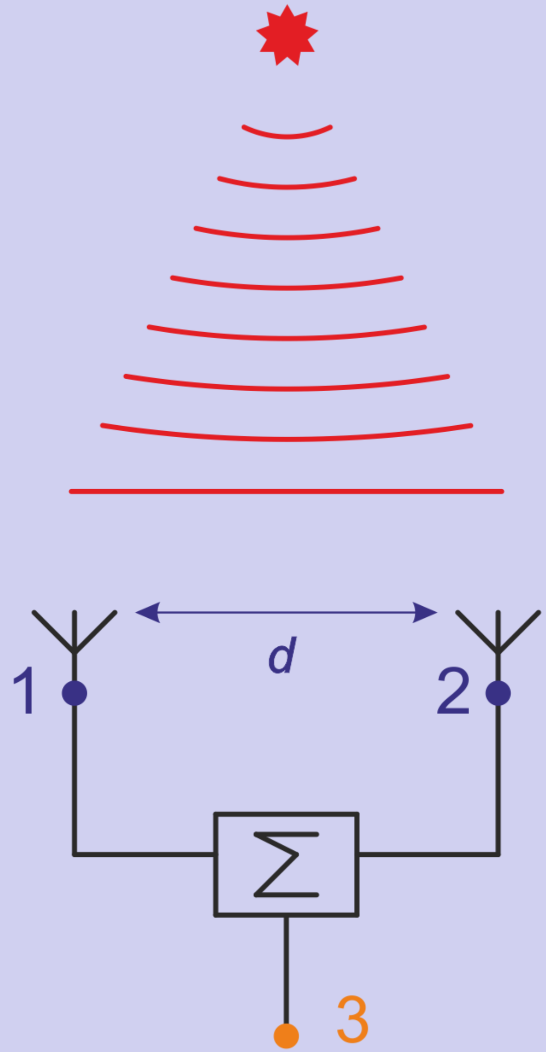
$L_{22} = 0{,}3\ м$ $\tau_{min} = 1{,}518\ нс$

Всего направлений фазирования в области реальных углов: 213



Секция радиотелескопа ГУРТ

Простейшая антенная решетка из двух элементов



Флуктуационная чувствительность

Флуктуационная чувствительность – минимальный сигнал, который можно различить на фоне шумов (для данного радиотелескопа).

$$\Delta S_{min} = \frac{SNR \cdot k_B \cdot T_{sys}}{A_{eff}\sqrt{\Delta f \cdot \Delta t}}$$

T_{sys} **- шумовая температура системы, на низких частотах может быть приравнена к яркостной температуре фона Галактики**

Чем ΔS_{min} **меньше, тем лучше радиотелескоп!!!**

Флуктуационная чувствительность

$$\Delta S_{min} = \frac{SNR \cdot k_B \cdot T_{sys}}{A_{eff}\sqrt{\Delta f \cdot \Delta t}} = SEFD$$

System equivalent flux density (SEFD)

SEFD – поток излучения, при котором отношение сигнал/шум на выходе системы равно единице.

$$SEFD = \Delta S_{min} \cdot \sqrt{\Delta f \cdot \Delta t} = \frac{k_B \cdot T_{sys}}{A_{eff}}$$ при $SNR = 1$

$SEFD$ определяется только характеристиками радиотелескопа и не зависит от параметров наблюдений!

Чем $SEFD$ меньше, тем лучше радиотелескоп!!!

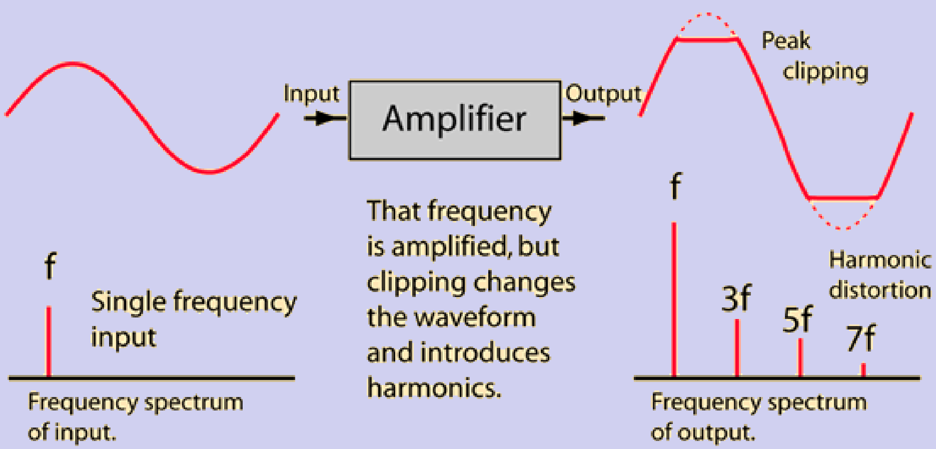
Динамический диапазон

Динамический диапазон – логарифм отношения максимального уровня входного сигнала при котором устройство работает в линейном режиме к чувствительности системы (уровню шумов).

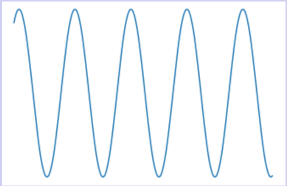
Динамический диапазон – ***Диапазон амплитуд входного сигнала при котором устройство работает в линейном режиме.***

Устройство можно считать линейным для данного уровня сигнала, если спектр сигнала не обогащается новыми гармониками при прохождении устройства и сигнал хорошо различим на фоне шума.

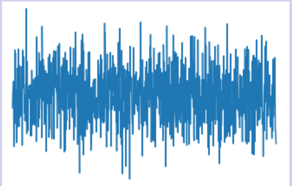
Верхняя граница – возникают гармоники из-за нелинейности



Нижняя граница – шумы системы

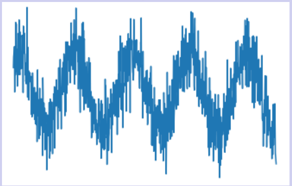


сигнал

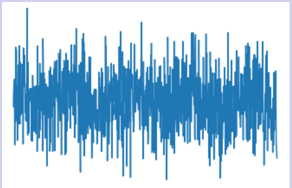


шум

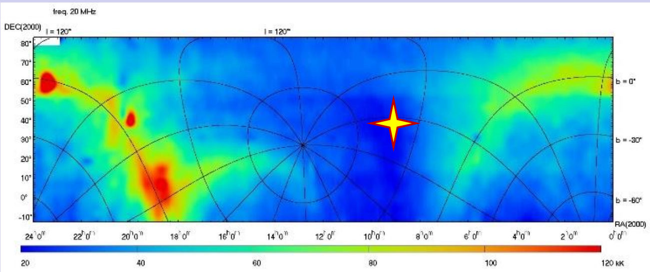
сигнал / шум = 2



сигнал / шум = 0,3

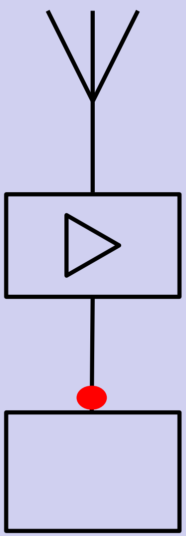


Смесь шумов на входе приемника



Шумовой сигнал источника — P_{signal}

Фоновое шумовое излучение Галактики — P_{bg}



Шумы антенны — P_{Nant}

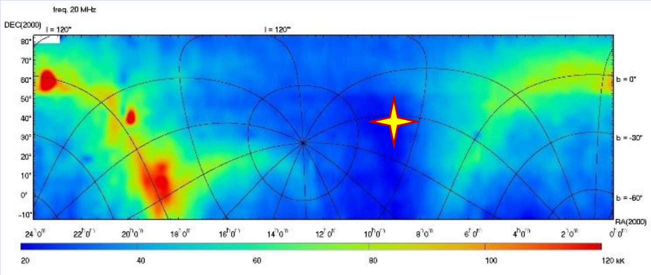
Шумы земли (и/или атмосферы) — P_{Ngnd}

Шумы приемно-усилительного тракта — P_{Namp}

Приемник

$$P_{in} = k_1(P_{signal} + \underbrace{P_{bg}) + k_2 P_{Nant} + k_3 P_{Ngnd} + k_4 P_{Namp}}_{P_{noise}}$$

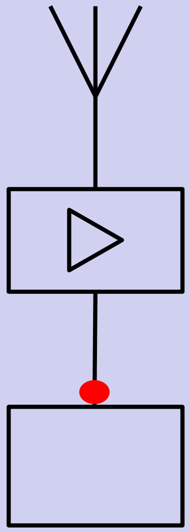
Соотношение сигнал / шум (С/Ш)
Signal-to-noise ratio (SNR)



P_{signal}

P_{bg}

$$SNR = \frac{P_{signal}}{P_{noise}}$$



P_{Nant}

P_{Ngnd}

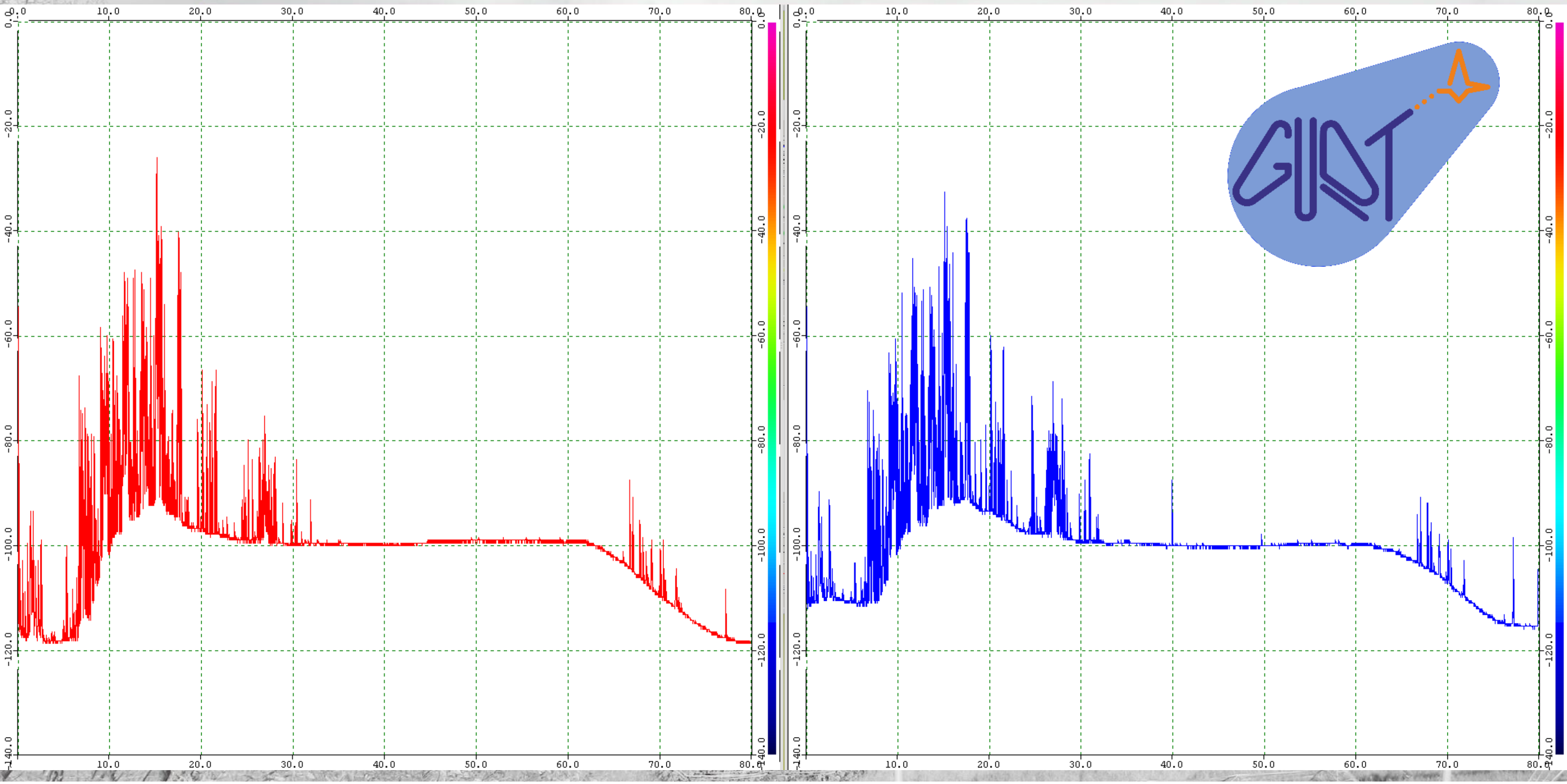
P_{Namp}

Приемник

Главная задача приемной системы обеспечить максимально возможное соотношение С/Ш на входе приемника (*такое же как и на входе самой приемной системы***) при этом обеспечить уровни сигнала приемлемые для приемника**

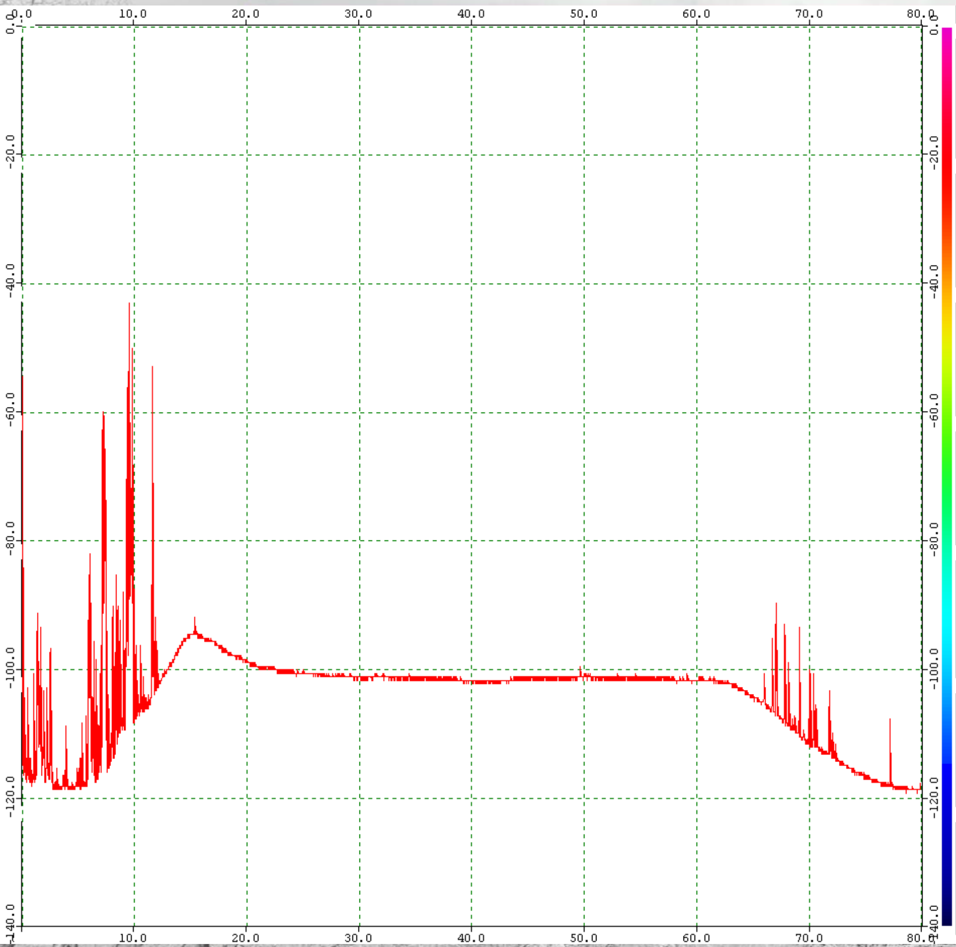
$$SNR_{sky} = \frac{P_{signal}}{P_{bg}}$$

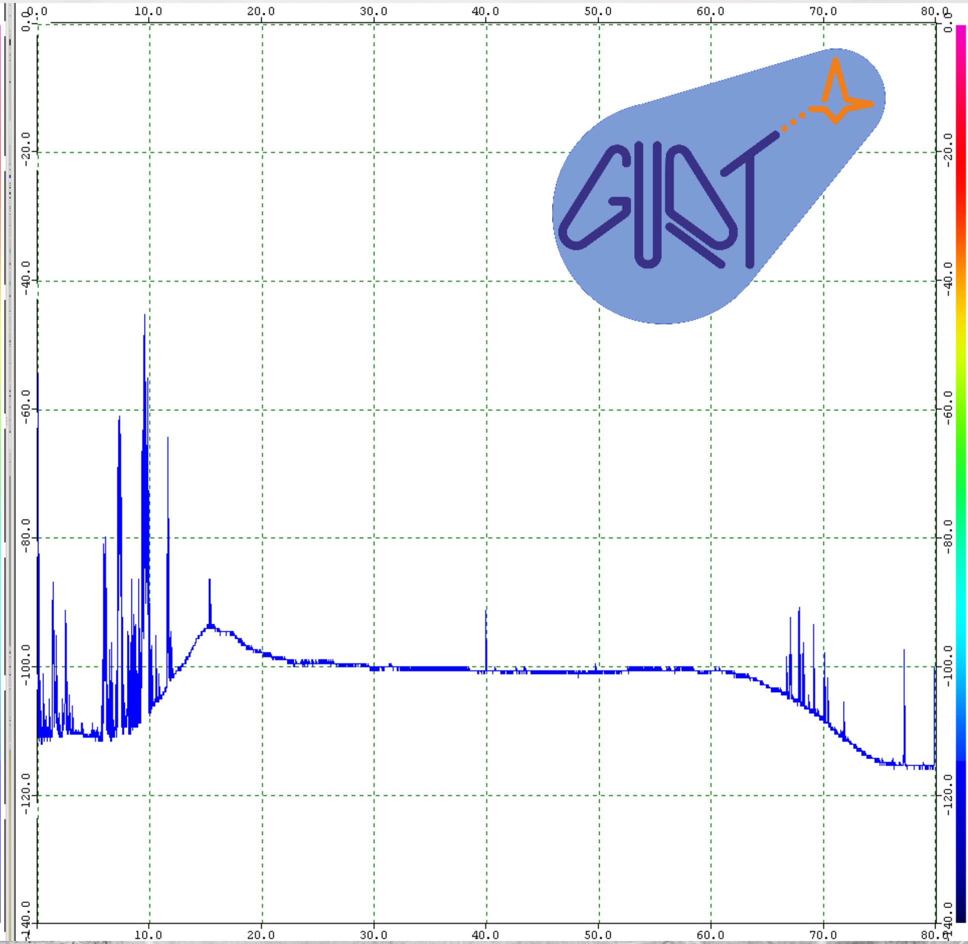
GURT spectrum



RFI and galactic background of GURT subarray phased to zenith direction (December 11, 2014 at 13-43 Local time)

GURT spectrum

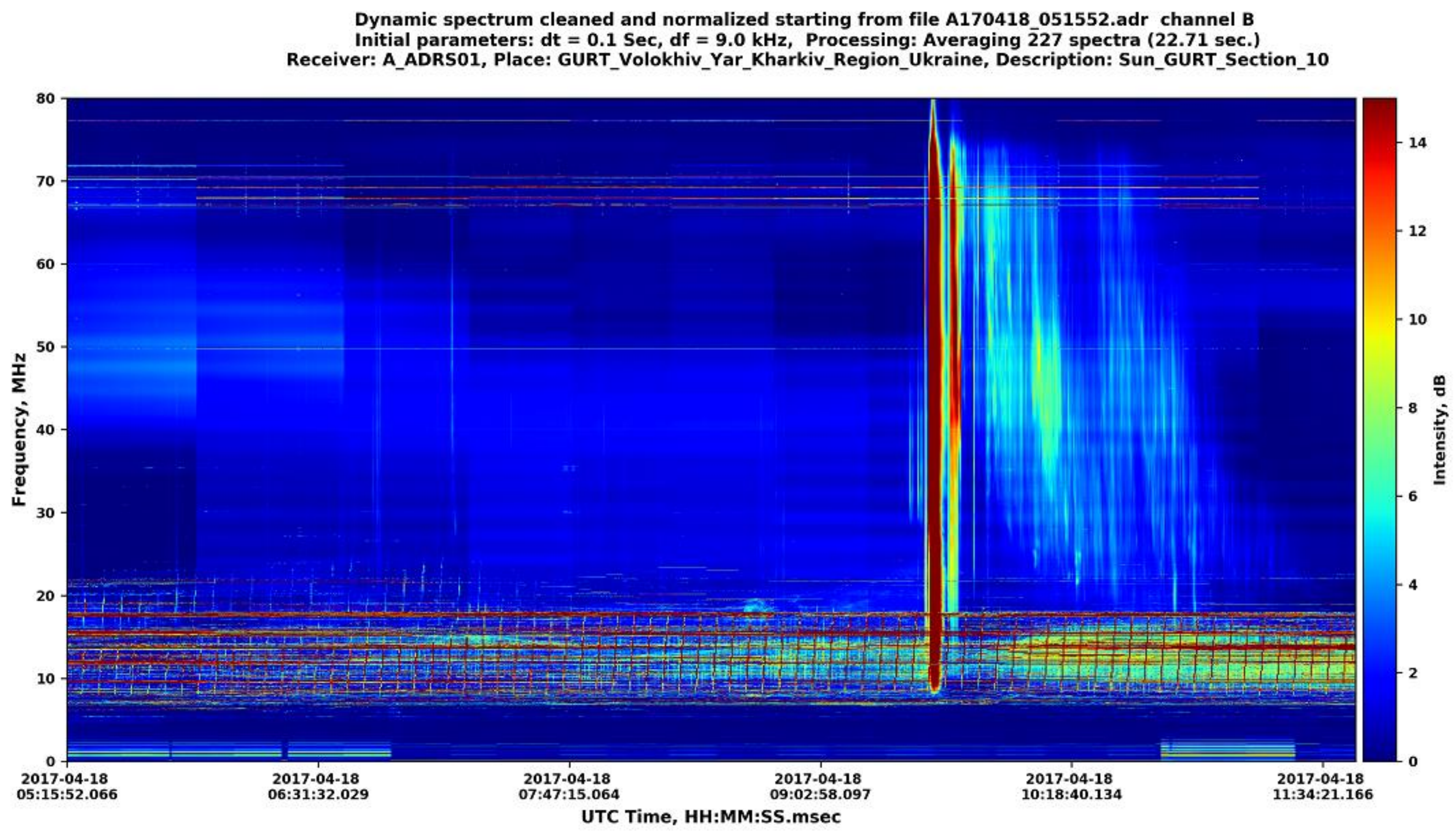




RFI and galactic background of GURT subarray phased to zenith direction (December 11, 2014 at 23-20 Local time)

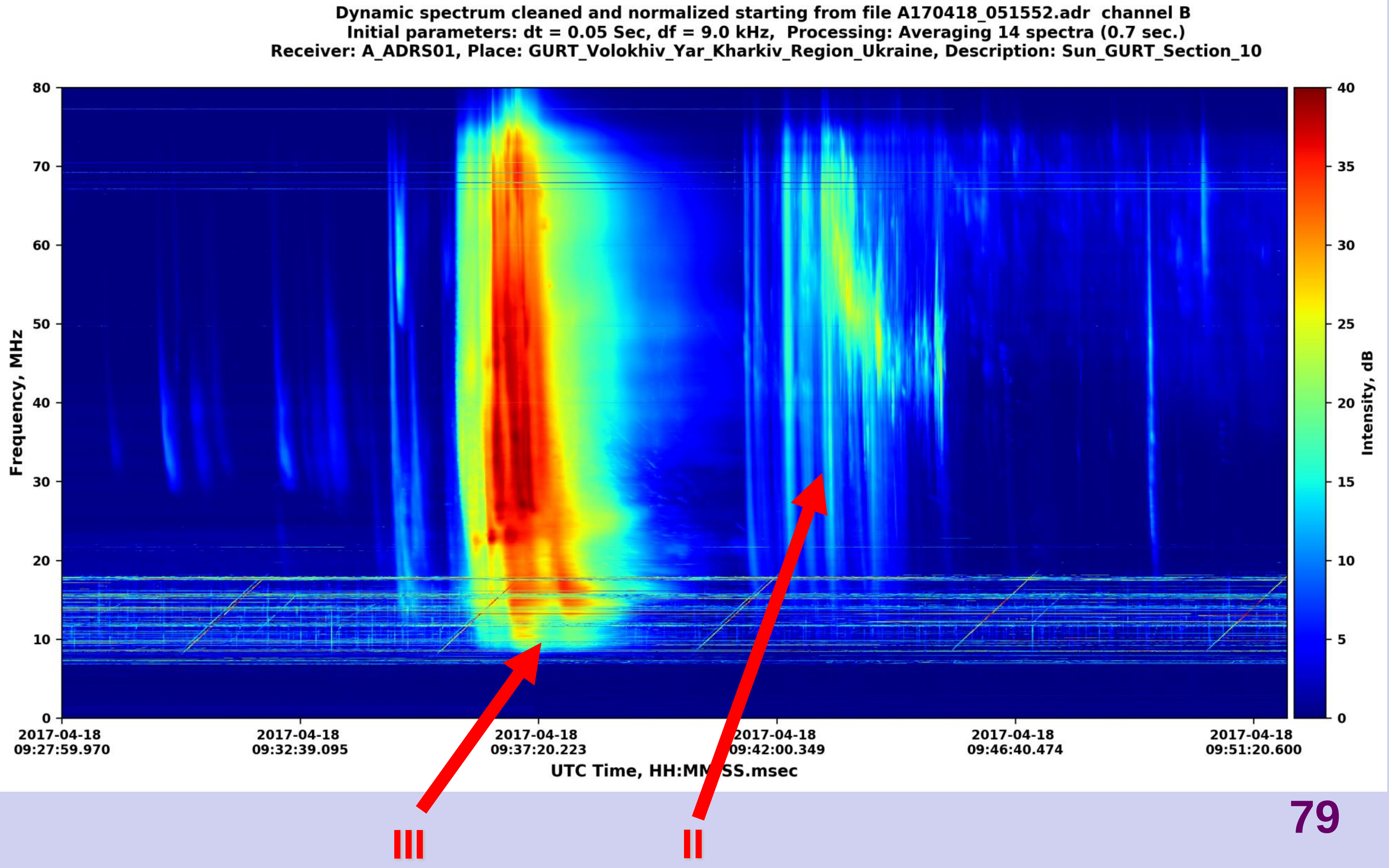
You should analyze events in various time scales

6,5 hours / picture scale



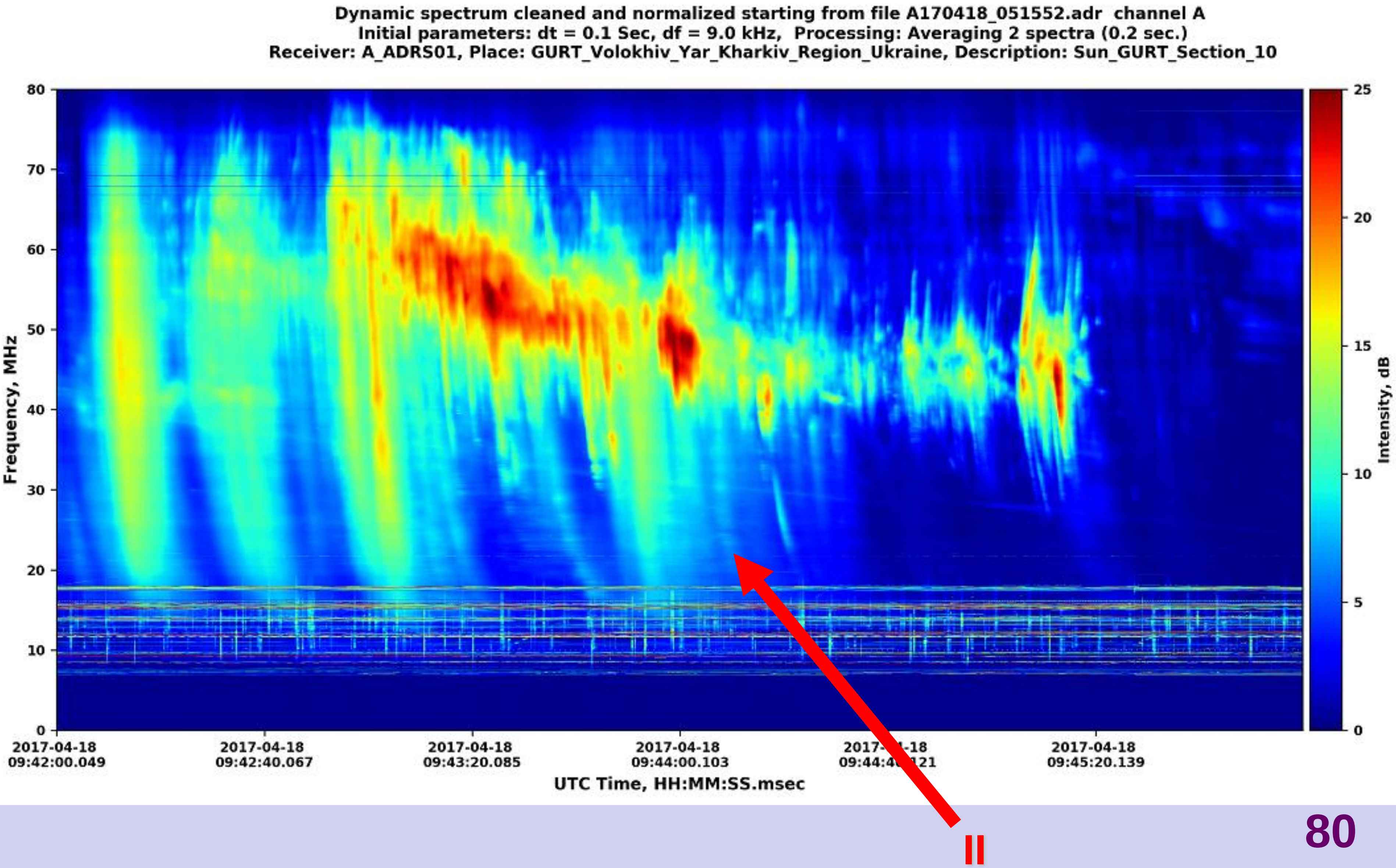
You should analyze events in various time scales

22 minutes / picture scale



You should analyze events in various time scales

4 minutes / picture scale



Digital radio astronomy receivers DSPZ and ADR for UTR-2 and GURT radio telescopes