UTILIZING EXISTING DECAMETER RADIO TELESCOPES AS PATHFINDERS TOWARDS LOFAR - LWA - LOIS SCIENCE AND TECHNOLOGY

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Abstract

Over the past years new opportunities for the ground-based solar system investigations at decameter wavelengths have been arisen both in the field of new instruments design (including modern back-end facilities) and in improving operating potential of the largest existing telescopes such as UTR-2, URAN, NDA, and SURA. Here we discuss obtained achievements as precursors of the new generation low-frequency instruments (LOFAR, LOIS, and LWA are among them) from astrophysical and methodological points. The wide spectrum of low frequency radio astronomical investigations is discussed and illustrated. It includes not only traditional investigations of the Sun and Jupiter, but also studies of the solar wind, the interplanetary medium, planets, active stars, and high sensitive investigations of the magnitosphere and ionosphere both by passive and radar approaches. The achieved levels of spectral, temporal, spatial, and polarization measurement quality are presented.

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1 Introduction

Today the the low frequency (ν < 100 MHz) range is considered to be very important for modern radio astronomy. We see now a vigorous progress in this field. Developments of new instruments include both ground based facilities (LOFAR - Low Frequency Array, LOIS - LOFAR Outtrigger In Scandinavia , and LWA - Low Wavelength Array) and space based ones (STEREO, SIRA, ALPHA, etc.). The importance of such approaches is illustrated, for example, by the Special Issue: "The Low Frequency Array (LOFAR) and (Extra-) Solar System Science" (eds I. de Pater, N. Kassim, H. O. Rucker; Planetary and Space Science, 52, 1339 - 1491, 2004). In the Netherlands and USA a consortium aimed to the development of new generation giant ground based systems has been created. In numerous countries (Ukraine, France, Austria, Russia, Sweden, Australia, etc.) these ideas are strongly supported. Thus, a new European project INTAS03-5727 "Using world largest decameter radio telescopes as probe and basis for development the LOFAR concept" (France-Austria-Ukraine-Russia) can be considered as a precursor of one of the most current line of development in modern radio astronomy. It consists in developing and installing new means and new methods which are specific for the low frequencies radio astronomy (particularly at decameter wavelengths) with the world largest long wavelength radio telescopes UTR-2, URAN1. . . URAN4, SURA, and Nancay Decameter Array. Also, it includes various astrophysical observations of different objects (among them those belonging to the Solar System). Some results of these studies are presented in this Paper.

2 The largest existing decameter wavelength radio telescopes and new back-ends, comparison with parameters of the future LOFAR and LWA

The main parameters of existing decameter wavelength radio telescopes are presented in Table 1. Here the UTR-2 array is the largest (the maximum effective area is about 150 000 m^2) [Braude et al., 1978; Konovalenko, 2000]. In Ukraine on the base of UTR-2 VLBI system URAN was build. It includes besides UTR-2 four additional telescopes with smaller dimensions and covers the bases from 40 to 950 km [Megn et al., 1997]. Nancay decameter array (NDA) is effectively used mainly for Sun and Jupiter investigations [Lecacheux, 2000]. SURA presents a receiving-transmitting antenna [Karashtin et al., 1999] and operates near ionospheric cut-off.

Recently, new back-end facilities have been installed at these observatories. Employment of various types of equipment is determined by investigation tasks. Digital Spectral Processor (DSP) and Waveform Receiver (WFR) [Lecacheux et al., 1998] are the most universal and effective. The existing radio telescopes were developed approximately 30 years ago, so their hardware including phase system is analogue. Now, it is possible to upgrade them with the modern digital equipment even at the level of a single dipole. Nevertheless, the old way with the structure of analogue antenna and digital-software back-ends is still relevant. It is clear that the future elements of antenna systems will be built using a great deal of various digital devices. In order to find optimum ways to new instrumentation design it is very useful to take into account already obtained experience. The current

Table 1: Main parameters of existing decameter wavelengths radio telescopes

Radio telescopes	Locations	Frequency range, MHz	Maximum effective area, m^2	Number of elements, polarization	Distance to UTR-2 (LOFAR), km	Angular resolution at 25 MHz
UTR-2	Kharkov, Ukraine	8 – 32	150 000	2040 1 linear	0 (∼ 2000)	$25' \times 25'$
URAN-1	Zmiev, Ukraine	8 – 32	5500	96 2 linear	42 (∼ 1900)	60”
URAN-2	Poltava, Ukraine	8 – 32	28 000	512 2 linear	120 (∼ 1800)	21”
URAN-3	Lviv, Ukraine	8 – 32	14 000	256 2 linear	915 (∼ 1000)	2.7”
URAN-4	Odessa, Ukraine	8 – 32	7300	128 2 linear	613 (∼ 1500)	4.0”
NDA	Nancay, France	8 – 88	2 × 4000	2 × 72 2 circular	3000 (∼ 500)	∼ 1.0” (potentially)
SURA	N.Novgorod, Russia	4 – 9	40 000	144 2 linear	1500	Trans. power ∼ 150 MWt

state of the knowledge about low frequency experiment methods can be very important in many aspects (among them are ionospheric and interference influences and their mitigation; the requirements to antenna and back-end parameters according to astrophysical tasks and receiving signal features; processing of huge data volumes; and, especially, the motivation of new scientific programs and investigations).
It is interesting to compare (see Table 2) the principal parameters of existing systems with those of the future giant ground-based radio telescopes such as LOFAR and LWA (they are being built by scientific organizations in the Netherlands and USA including by ASTRON and NRL) [van Haarlem et al., 2001; Kassim et al., 2004; Lazio et al., 2005]. Firstly, the new system will have considerably bigger number of stations. This will sharply improve their imaging capabilities. The bigger number of elements and larger effective area, as well as the broader frequency range will open new opportunities to experiments. In some works authors compared parameters of the existing and future instruments and concluded that the sensitivity and angular resolution will be better by several orders [Kassim et al., 2004; Lazio et al., 2005]. This conclusion needs to be specified. In particular, the really working VLBI system URAN has not be mentioned in these works. It includes 5 stations with dimensions comparable to those of LOFAR and provides maximum base up to 950 km. Full imaging (phase measurements) at the frequencies less than 30 MHz is still problematic because of insufficient number of stations, insufficient dimensions of them, and the ionospheric and interference influences. Nevertheless, the URAN system yields a useful information concerning radio source structures and component sizes and this have had high astrophysical and cosmological significance. Measurements consist in determination of amplitudes of visibility functions and their dependence on the base (40–950 km), frequency (15–30 MHz), and hour angle (±4 h). Then, the computer modeling and radio maps obtained at the highier frequencies are applied to fitting the experimental data. The system angular resolution reaches few arc seconds in these experiments (see paragraph 3.2). Also we have to mention that the first sub-arcminute resolution imaging below 100 MHz was achieved with the 74 MHz VLA system.

Rather high sensitivity of UTR-2 at so low frequencies (∼ 5 Jy) is realized in a rela-

Table 2: Comparison of existing and future low-frequency instruments principal parameters

Nr.	Parameter	UTR-2, URAN, NDA	LOFAR	LWA
1	Frequency range, MHz	8...32 (NDA-8...88)	10...240	20...80
2	Number of stations	6	100	50
3	Total number of elements	∼ 3000	∼ 13 000	∼ 12 500
4	Total number of antenna elements for one polarization	∼ 4000	∼ 26 000	∼ 25 000
5	Number of elements per station	96 ...1440	128	250
6	Station size, m	28 × 240...60 × 1900	∼ 100 × 100	∼ 100 diameter
7	Maximum baseline, km	950	∼ 350	∼ 400
8	Minimum baseline, km	∼ 0.1	∼ 0.1	∼ 0.1
9	Maximum angular resolution (25 MHz)	∼ 3”	∼ 6”	∼ 6”
10	Field of view, degree	2...20	all-sky	3...12
11	Electronic steering, degree	±80	multi-beaming	multi-beaming
12	Polarization	2 (5 stations)	2	2
13	Maximum observable bandwidth, MHz	10 ...20	32	3
14	Spectral resolution, kHz	0.1...12	< 1	< 1
15	Time resolution, ms	1...100	1	10
16	Summarized total effective area (25 MHz), m^2	∼ 200 000	350 000	900 000
17	Virtual core (VC) size, km	2×1 (UTR-2)	2×2	5×5
18	VC max. eff. area (25 MHz), m^2	150 000 (UTR-2)	100 000	300 000
19	VC stations number	12 (UTR-2)	∼ 25	∼ 17
20	VC elements number per station	150 and 180 (UTR-2)	128	250
21	Limit of the confusion effect sensitivity for the continuum point radio source (25 MHz)	< 1000 mJy	< 1 mJy	< 1 mJy
22	Sensitivity of radio emission without the confusion effect (25 MHz, $\tau = 1$ h, $B = 4$ MHz)	∼ 10 mJy	∼ 1.5 mJy	∼ 1.5 mJy

tively narrow bandwidth of 10 kHz with the time constant of 60 s. It is possible because of its large effective area. In the case of continuum radio source observations telescope sensitivity is restricted by the confusion effect, which is caused by the influence of background sources on the system temperature both through the side lobes and main beam (when such sources are not resolved and modeled). Having the UTR-2 beam width of 25’ at 25 MHz confusion comes to 1...5 Jy (for URAN system it is less and have to be re-estimated according to the new knowledge and observational methods). In the paper of Kassim et al., (2004) LOFAR virtual core (VC) size (angular resolution) and effective area are very similar to the existing virtual core (UTR-2), see Table 2. The estimated point source sensitivity of LOFAR VC at the frequencies 10–30 MHz (it is 12–6.5 mJy) have to be verified with taking into account the confusion noise. Meanwhile, there are many astrophysical objects and phenomena which can be observed without limitation of the confusion effect. In these cases the frequency band and/or integration time can be sharply increased (broad frequency range and long electronic steering allow this at UTR-2 and URAN antennas). The difference in sensitivities will be determined only by the difference in the effective areas or even by the difference in the numbers of antenna elements (if the distance between them is more than $\lambda/2$). For example, this is true for pulsars and

radio recombination lines. During real experiments the following parameters have been obtained at UTR-2: $\tau = 8$ h, $B = 12$ MHz (pulsars), and $\tau = 5000$ h, $B = 1$ kHz (lines). This gives the sensitivity of few mJy and provides reliable phenomenon detection with the high signal-to-noise ratio. In order to solve continuum radio source imaging problems at frequencies less than 30 MHz the sensitivity of new instruments should be 100 times better than those of UTR-2 and URAN. Reaching a potentially achievable sensitivity at these frequencies is problematic because of the ionosphere and interference influences.
When speaking about the current development of low frequency radio astronomy instrumentation it is needed to mention successful tests of some future system prototypes which were carried out in Ukraine, USA and the Netherlands [Falkovich et al., 2001; Konovalenko et al., 2005; Stewart et al., 2004; Nigl et al., 2005]. These tests included the Sun, Jupiter, ionospheric and interplanetary scintillations observations. By this way the efficiency and perspectives of active antenna element conception for the low frequency radio astronomy have been proved. Undoubtedly, the idea of building several huge telescopes having various configuration and situated in different places (the Netherlands, USA, may be Australia and Ukraine) is very important.
So we can conclude, as LOFAR and LWA surpass the existing systems over the whole set of parameters, their creation is actual and in time. Especially we have to emphasize a new ideology and observing paradigms of the future telescopes: "software" instruments and practically all-sky multi-beaming.
In any case, the existing low-frequency instruments are not so bad to play the role of a methodical and technical precursors because they give the useful examples for the future radio astronomical observational programs.

3 Current Solar system studies

Recently, combination of the existing instruments and new back-end devices has allowed us to carry out a great deal of observational programs [Konovalenko et al., 2001a; Rucker et al., 2001; Lecacheux et al., 2004; Mel'nik et al., 2004]. In Figure 1 the set of objects and tasks which are investigated with UTR-2, URAN-1...URAN-4 are briefly listed. It can be seen that this set is in good accordance with the future scientific programs of LOFAR and LWA. In Figure 1 the sign (+) corresponds to the fields where the big number of positive results have been obtained for a large amount of investigated objects; the sign ($\sim$) depicts the isolated cases of results; the sign ($-$) illustrates the absence of any results yet. The sign ($*$) marks the objects for which the confusion effect does not restrict the sensitivity. In these cases it can reach values from few to tens of mJy (see paragraph 2).
Many results connected to rather intensive decameter emission from the Sun and Jupiter were obtained using relatively small antennas. But implementation of the large telescopes opens new opportunities. Studying short-time and narrow-band processes needs very high frequency and temporal resolutions, so the high sensitivity (signal-to-noise ratio) can be reached only with large effective area. Besides, a big area and high antenna directivity increase the signal-to-interference ratio and also the signal-to-signal ratio (high value of the signal-to-signal ratio means the detectability of the fine signal structure against the background of strong emission). It is important for the decameter range which suffer from huge amount of interferences and very considerable variations of power, temporal

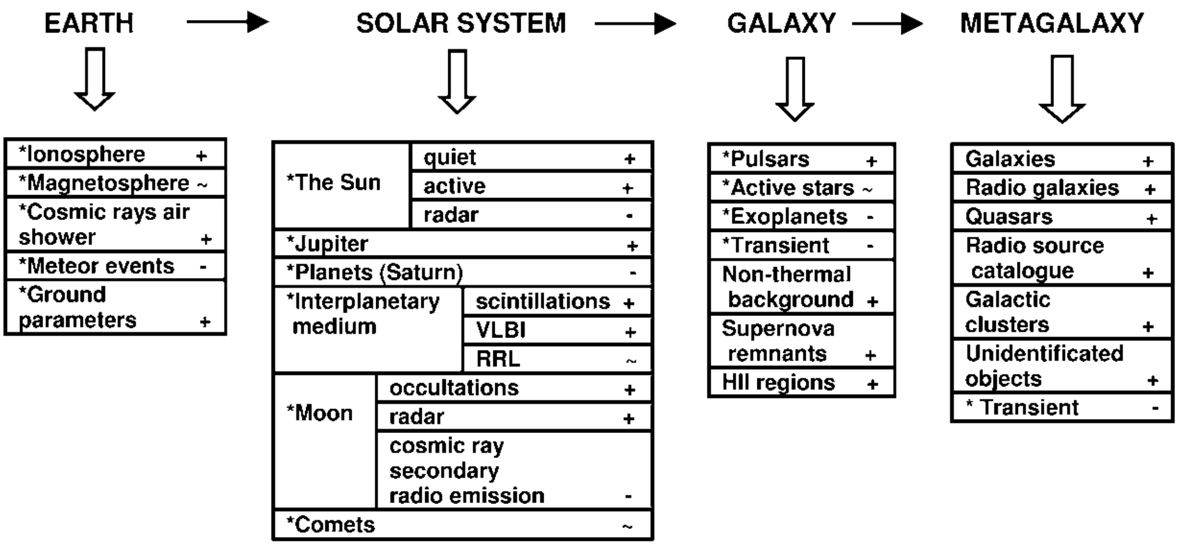

Figure 1: Objects investigated with UTR-2, URAN

and spectral signal features.
More detailed description of the recent results concerning the Sun, Jupiter and other magnetized objects obtained with the existing telescopes can be found in the present issue. In our work we concentrate on the other branches (less known and developed) of the Solar system decameter radio astronomy, which can be effectively studied with the future giant low frequency telescopes as well.

3.1 Interplanetary scintillations

Interplanetary scintillations (IPS) method is actively used for the estimation of radio source sizes and the Solar wind studies in the meter and decimeter wavelength ranges usually when elongations are small [Rickett and Coles, 1991]. We can expect this approach to be effective for the outer Solar Corona investigations at low frequencies, i.e. at decameter wavelengths. Until recently, this method has not been actively used at this range, except, may be, the case of some investigations of the Jovian radio emission [Douglas and Smith, 1967; Dulk, 1970]. Over the recent years, the IPS investigations have been carried out more frequently at UTR-2, URAN, and NDA radio telescopes due to introducing new experimental and theoretical approaches .
The IPS method implies that the solar wind parameters are usually obtained by fitting a model to the observed scintillation power spectra. For this purpose the phase screen model has been frequently used at the high frequency ranges . However, at large elongations and long wavelengths the scattering medium is essentially expanded and the mostly scattering layer is placed near an observer. In these conditions this leads to severe problems when using the phase screen theory . More correct ways at the decametric range are provided by multiple scattering theory methods such as the Feynman path-integral technique.
The developed method has been used for the model fitting of the experimental spectra at the radial distances $R \geq 1$ AU. For this we are using the spherical symmetry solar wind model with the mean velocity ν, inhomogenity spectral index n, $\sigma_N(\zeta) \propto R^{-b}$, $b \approx 2$,

and $R \equiv R(\zeta)$ where ζ is the coordinate along line of sight (it is the distance from the Sun) or, if required, two stream model. If a set of radio sources is observed, it is possible to investigate the space distribution and dynamics of the solar wind at large elongations. Figure 2 shows the scintillation spectra of 3C273 and 3C380 quasars obtained by UTR-2

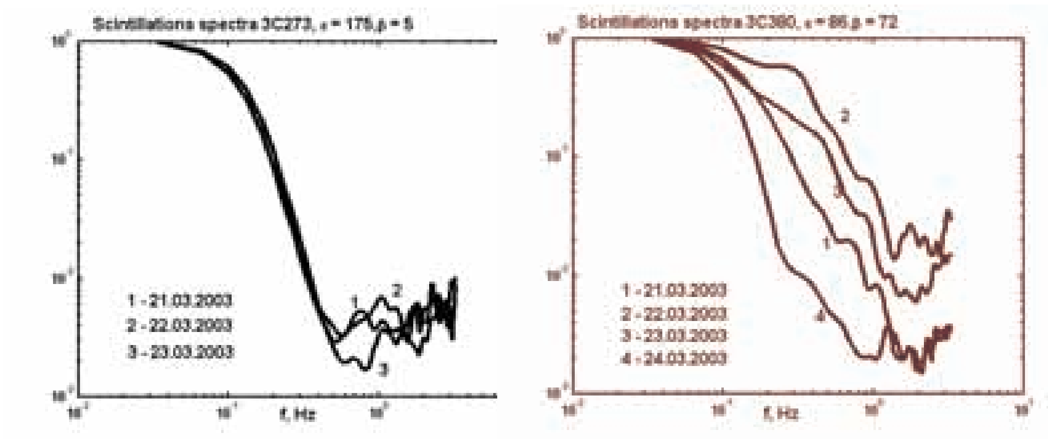

Figure 2: Experimental scintillation spectra for the different conditions.

on 21, 22, 23 and 24 of March, 2003. The spectra have the essentially different widths that generally is the result of the different parameters of the solar wind along the line of sight (sources have essentially different elongations ϵ and heliographic latitudes β). The variations of the spectrum width of 3C380 quasar in this period are, probably, the result of motion of a large scale interplanetary disturbance like shock wave across the line of sight. Also, it is necessary to take into account the influence of the ionosphere on radio source scintillations at decameter wavelengths in order to obtain the reliable parameters of the solar wind. We showed this by analyzing the experimental data when the frequency correlation interval of the ionospheric scintillations is not more than 6 MHz for daytime and nighttime observations. As the interplanetary scintillations of extragalactic radio sources are correlated in this range, the width difference of the frequency correlation intervals is often used for separating the interplanetary and ionospheric scintillations. The records with the larger time resolutions allow one to find a fine structure caused by the irregularities in the solar wind which have no frequency drift. Sensitivity of the existing systems allows one to apply the IPS method to about 100 radio sources. The confusion effect limitation plays the second role in this case. The time scale response for the usual continuum radio source with UTR-2 is about 1 min. The time scale response for scintilltions is less than 1 sec. Furthermore, compact objects which are suitable for IPS investigations constitute only small part of the known continuum radio sources. The future LOFAR and LWA instruments will provide the possibility to observe about 1000 appropriate compact sources and realize a tomography approach for the problem of Solar wind studies at any elongations [Oberoi and Kasper, 2004].

3.2 Scattering effects in the IP medium measured by VLBI

During the last 20 years an extensive program has been carried out with URAN VLBI system. Many astrophysical results have been obtained for a number of radio sources (up to several tens, see, for instance, the work of Megn et al., (2001)). The possibilities of high angular resolution at the decameter wavelength range have been investigated because of their astrophysical and cosmological significance.

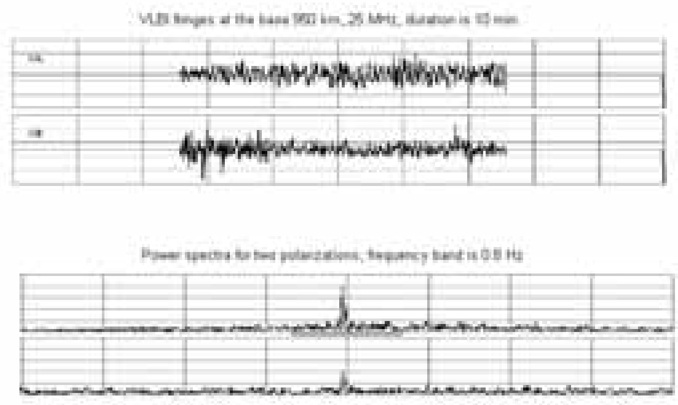

Figure 3: Interferometer fringes (top), and corresponding power spectra (bottom) for two polarizations measured by UTR-2 – URAN-3 interferometer towards 3C144.

One of the important methodical results is the detection of interferometric fringes at 25 MHz in the point source belonging to the Crab Nebula with the visibility function amplitude of ~ 1 and over a baseline of ~ 950 km (UTR-2 – URAN-3 interferometer). Figure 3 illustrates this result (ordinate scales are in relative units). This experiment has been carried out for elongations of about 180^o. As we can see, the IP scattering effect is absent for these elongations. The angular size of the point source in 3C144 (angular resolution) is approximately 1 arcsec and comes close to the theoretical limit imposed by the interstellar scattering at the frequencies less than 30 MHz.

The dependence of visibility function module (scattering effect) versus elongation has been measured with UTR-2 – URAN-1, URAN-2, URAN-3 interferometers. Corresponding results for UTR-2 – URAN-1 interferometer (baseline is 42 km, 3C144 radio source) are shown in Figure 4. The evident feature is the considerable depression at $\varepsilon \sim -125^0$. This is the result of the extra angular spectrum broadening when the line of sight is directed along magnetic lines.

Since the coronal plasma is partially involved in co-rotation with the Sun, the frozen-in field is bent away from the radial and remains so in the outer solar wind. This bending is also responsible for the asymmetry of visibility curves before and after solar transit.

The minimum of the in-bound feature is a sensitive indicator of the solar wind velocity and the amount of the anisotropy in the field-aligned inhomogeneities. If we use the electron density spatial spectrum, we can fit calculated visibilities to the experimental data. For the minimum position at $\varepsilon \sim -125^o$ the solar wind velocity is about 380 – 400 km/s. The depth of the minimum suggests the best agreement when axial ratios is of 7–10. The parameter n lies between 3.0 and 3.3, the parameter b is about 2.2. The inner scale of the inhomogeneities is less than 40 km.

Thus, the scattering effect (angular structure variation) measurements of compact radio

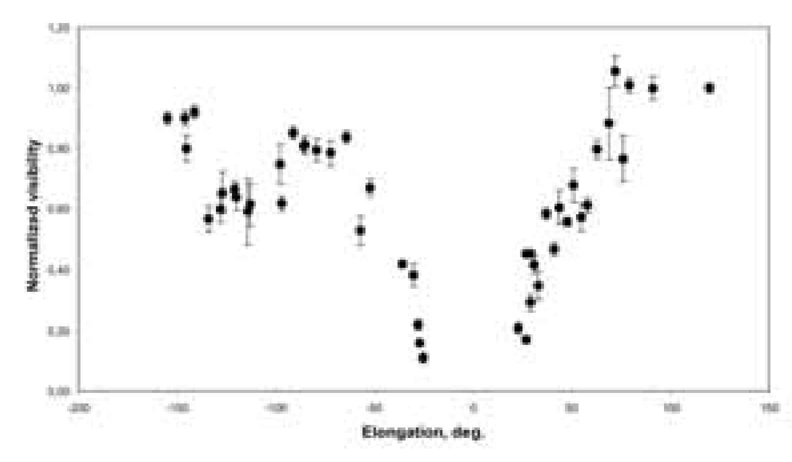

Figure 4: The dependence of visibility function amplitude versus elongation measured by UTR-2 – URAN-1 interferometer.

sources at various elongations, ecliptic coordinates, and frequencies are interesting for high resolution imaging with LOFAR and LWA.

3.3 Possibilities of the interplanetary medium studies with low frequency radio recombination lines

Radio recombination lines (RRLs) at decametric wavelengths were detected nearly 25 years ago with UTR-2 radio telescope. They corresponded to the principal quantum numbers bigger than 600 and became a very effective means of the rarefied interstellar plasma diagnostics [Konovalenko, 1990].
The line integral intensity is determined by the following relation

$$I_L \approx 2 \cdot 10^6 N_e N_i S b_n \beta_n / T_e^{2.5} \qquad (1)$$

where N_e and N_i are the electron and ion densities (cm^{-3}), S is the path length (pc), T_e is the electron temperature (K), b_n and β_n are the departure coefficients.
The dielectronic-like recombination mechanism is valid for carbon atoms under the typical interstellar medium conditions ($N_e \sim N_i \sim 0.1\ cm^{-3}$, $T_e \sim 50 - 100$ K, $S \sim 1$ pc), $b_{n(max)} \sim 2$, $\beta_{n(max)} \sim 10 - 100$. In this case $I_L \sim 10$ s^{-1} (relative intensity is $\Delta T_L/T_C \sim 10^{-3}$).
For the interplanetary medium as well as for the adjacent local interstellar medium the following parameters are probable: $N_e \sim 1$ cm^{-3}, $T_e \sim 10^4 - 10^5$ K. Under these conditions the mechanism of high temperature dielectronic recombination has been predicted for Mg, Ca, K, and other elements [Shaver, 1975] but still not detected. This mechanism can considerably amplify the absorption RRLs intensities at low frequencies ($b_{n(max)} \sim 10^2 - 10^3$, $\beta_{n(max)} \sim 10^3 - 10^4$). This leads to the detectable values of intensity ($I_L \sim 1\ s^{-1}$, $\Delta T_L/T_C \sim 10^{-4}$).
It is interesting to search for similar interplanetary lines firstly near the ecliptic plane. A set of experiments has been carried out with UTR-2 in the direction of the radio source Virgo A. The preliminary results show that it is reasonable to continue this work.
At the present time interstellar RRLs have been detected with UTR-2 and 4096 channels

DAC in many galactic directions [Konovalenko et al., 2001b]. Probably, some of these lines arise in regions which are close to the Solar system. Generally speaking, the recombination line investigations with the future large low frequency instruments are very interesting and promising.

4 Solar system radar investigations

The solar corona and CME radar studies are important parts of LOFAR scientific concept [Rodriguez, 2004]. Project LOIS is one of the approaches to these studies [Thide, 2002]. Using the SURA transmitting system and UTR-2 receiving antenna several attempts of the Sun and Moon radio location have been carried out at frequencies about 9 MHz. The reliable data have been obtained only for the Moon. During these experiments the East-West antenna as well as the 8-beam mode of the North-South antenna have been used. The main restriction to the Sun radar studies is too low frequency of SURA transmitter (the maximal value is 9 MHz) and, thus, predominant influence of the ionosphere and interference. In order to probe the radar experiments further it is reasonable to use at frequencies of 5–30 MHz an antenna situated in Horby (Sweden) which has the low directivity but high output power (up to 500 kWt). Let us point out that every of URAN receiving antennas can be equipped with a transmitter spending only moderate financial investments. If the power per element is up to 1 kWt then the full power is $0.2 - 1$ MWt and PG-factor is 50 MWt — 1.5 GWt. Such upgrade will allows us to carry out the unique radar multi-static experiments using existing low frequency radio telescopes and, especially, with the LOFAR future co-operation.

5 Conclusion

The work by the past and current generations of low frequency telescopes and investigators has pioneered many of the scientific and technical areas that will be exploited by the emerging new instruments such as LOFAR and LWA. Many of the lessons gained from the past experiences remain valid today, and this paper has reviewed many of these areas of science and technology. Also, there is the possibility that some of the old generation of instruments, often with formidable existing collecting area, can be used to benefit and compliment the new instruments. For example, if re-fitted as a transmitting array the URAN antennas might be very suitable for use for bi-static radar studies with the new generation of receiving arrays such as LOFAR and LWA. This would provide a useful compliment to the LOIS transmitting capability, for example.

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