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# Scaling-laws of Radio Spike Bursts and Their Constraints on New Solar Radio Telescopes† ⋆

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**Abstract** Radio observation is one of important methods in solar physics and space science. Sometimes, it is almost the sole approach to observe the physical processes such as the acceleration, emission, and propagation of non-thermal energetic particles, etc. So far, more than 100 solar radio telescopes have been built in the world, including solar radiometers, dynamic spectrometers, and radioheliographs. Some of them have been closed after the fulfillment of their primary scientific objectives, or for their malfunctions, and thus replaced by other advanced instruments. At the same time, based on some new technologies and scientific ideas, various kinds of new and much more complicated solar radio telescopes are being constructed by solar radio astronomers and space scientists, such as the American E-OVSA and the solar radio observing system under the framework of Chinese Meridian Project II, etc. When we plan to develop a new solar radio telescope, it is crucial to design the most suitable technical parameters, e.g., the observing frequency range and bandwidth, temporal resolution, frequency resolution, spatial resolution, polarization degree, and dynamic range. Then, how do we select a rational set of these parameters? The long-term observation and study revealed that a large strong solar radio burst is frequently composed of a series of small bursts with different time scales. Among them, the radio spike burst is the smallest one with the shortest lifetime, the narrowest bandwidth, and the smallest source region. Solar radio spikes are considered to be related to a single magnetic energy release process, and can be regarded as

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an elementary burst in solar flares. It is a basic requirement for the new solar radio telescope to observe and discriminate these solar radio spike bursts, even though the temporal and spatial scales of radio spike bursts actually vary with the observing frequency. This paper presents the scaling laws of the lifetime and bandwidth of solar radio spike bursts with respect to the observing frequency, which provide some constraints for the new solar radio telescopes, and help us to select the rational telescope parameters. Besides, we propose a spectrum-image combination mode as the best observation mode for the next-generation solar radio telescopes with high temporal, spectral, and spatial resolutions, which may have an important significance for revealing the physical essence of the various non-thermal processes in violent solar eruptions.

**Key words** sun: activity—sun: corona—sun: radio radiation— radio telescope

## 1. INTRODUCTION

In the studies of solar physics and space science the phenomena of various eruptions in the solar atmosphere are important subjects, such as the solar flares and coronal mass ejections[1]. In these eruptive processes, a considerable part of energy is released in form of non-thermal particles. This kind of non-thermal energy may occupy 10%–50% of the total energy released in the eruptive process for various events[2]. These non-thermal particles originated from solar eruptions fly very fast with a sub-light speed, to cause a drastic disturbance in the solar-terrestrial space, which produces heavy influences on the space flight, space science exploration, satellite communication and navigation, even national security. The method of radio astronomy is one of the most important measures to detect the non-thermal processes mentioned above, for some phenomena in the solar eruptive processes, such as the acceleration, emission, and propagation processes of solar non-thermal particles, the radio observation is the most important measure of ground-based detection. Therefore, a lot of solar radio telescopes have been developed and constructed in various places of the world, and according to the complexity they can be divided into the following three kinds:

(1) Solar Radiometer

This is the simplest and earliest generation of solar radio telescopes, with the purpose of observing the total flux of radio emission from the whole solar disk at a single frequency band or several frequency points. This kind of radio telescopes have neither frequency resolution nor spatial resolution, but they are simple in structure and convenient in operation, they can realize a very high time resolution and accurate polarization measurement, and they can run stably in a long period, hence, they play always important roles in monitoring the long-term variation of solar radio emission, and in the predictions of the solar activity and space weather, etc. For instance, the 2800 MHz solar radiometers (sometimes called the 10.7 cm solar radiometers) are broadly distributed in the world, and the 2840 MHz solar radiometer in Beijing Huairou Station has been working since the 70s of the last century, and has made the long-term monitoring on the sun almost for four solar cycles.

(2) Solar Radio Dynamic Spectrometer

The radio flux measurement at a single frequency can not give the dynamic features of solar eruption sources, thus, the solar radio telescope that can measure the radio emission flux from the whole solar disk simultaneously at a large number of frequencies in a broad frequency band is designed and constructed, it is called the solar radio broadband dynamic spectrometer, which can make the spectral observation with the very high time and frequency resolutions in a definite frequency band, and obtain the dynamic information of spectral structure, polarization, bandwidth, lifetime, and frequency drift rate, etc. of solar radio burst sources.

The solar broadband radio spectrometer (SBRS) in China is composed of a group of five solar radio spectrometers respectively constructed in Beijing, Kunming, and Nanjing[3−6], in which the spectrometer located in Beijing is composed of three telescopes which work at the frequency bands of 1.0–2.0 GHz, 2.60–3.80 GHz, and 5.20–7.60 GHz, with the time resolutions of 5 ms, 8 ms, and 5 ms, and the frequency resolutions of 4 MHz, 10 MHz, and 20 MHz, respectively. The SBRS, as the most advanced solar radio telescope system in the world, has been fully constructed and put into operation since 1999, and has found successively many unique phenomena of solar radio bursts, such as the structures of microwave zebra-pattern, microwave broadband fast pulsation, microwave spike burst, and fish group, etc. Besides, the radio spectrometers have been built also by some universities and institutes[7].

There also exist some famous solar radio broadband spectrometers in the world, such as the Ondrejov spectrometer (with the working frequencies of 0.80–5.00 GHz, the time resolution of 10 ms, and the frequency resolution of 5 MHz in 0.80–2.00 GHz, and of 12 MHz in 2.0–5.0 GHz) in Czech Republic. Besides, there are also some solar radio dynamic spectrometers with various resolutions at different wavebands built in Switzerland, Japan, Russia, USA, and India.

(3) Solar Radioheliograph

Neither solar radiometer nor solar radio dynamic spectrometer can make an image of the observed target, thus to obtain the information of position and structure of radio emission sources, which is a fatal restriction for exploring the origin and rule of solar eruptions, as well as for revealing the relevant physical processes. Hence, people have developed and constructed the solar telescopes capable of imaging observations in radio bands since the 70s of the 20th century, these telescopes possess the spatial resolution, can acquire the radio images of the sun, so they are called solar radioheliographs.

The earlier solar radioheliographs can only realize the imaging observation at one single frequency or several frequency points. For example, the Nobeyama Radioheliograph (NoRH) in Japan is composed of 84 antennas to form an interferometric cross array, which can make imaging observations at 17 GHz and 34 GHz two frequencies on the Sun. The Nancy Solar Radioheliograph (NRH) of Meudon Observatory in France initially worked at 5 frequencies in the range of 150 MHz–450 MHz, and it has been upgraded to 10 frequencies through a renovation in recent years. Based on the original cross array, the SSRT (Siberia Solar Radio Telescope) in Irkutsk of Russia has been upgraded recently, and extended from a single observing frequency of 5.7 GHz to 32 frequencies in the range of 4.0 GHz–8.0 GHz with the frequency resolution of 125 MHz, it has become a new spectral heliograph, and obtained some preliminary results during the test observation[8,9].

In China, the radio spectral heliograph (MUSER) located at Minganto of the Baiqi area of Inner Mongolia was built and passed the examination in 2016, which is the newest generation of solar radio telescope in the world[10]. It is composed of 100 antenna units, to form an interferometer array arranged along three spiral arms, with the longest baseline greater than 3 km, working in an ultra-broad frequency band of 0.40–15.00 GHz in terms of the principle of aperture synthesis imaging, it can make the radio imaging on the Sun simultaneously at 584 frequencies, with the frequency resolution of 25 MHz, the time resolution of 25 ms at 0.4–2.0 GHz and of 200ms at 2.0-15.0 GHz, and the spatial resolution of 51" around 400 MHz and close to 1.4" around 15 GHz. This kind of solar radio telescope is also called the spectral radioheliograph, it can obtain the solar radio images simultaneously with higher spatial, temporal, and spectral resolutions, the frequency range basically covers all the source regions of solar eruptions, and the initially heating and propagating regions of non-thermal particles, so it is the important and fundamental facility for studying the initial energy release, particle acceleration and propagation of solar eruptions.

After a period of observations, a part of solar radio telescopes have realized their scientific objectives and retired gradually, some other telescopes have been gradually replaced by new telescopes because they are failed to achieve their initial scientific objectives. Meanwhile, on the basis of new scientific assumption and technical development, some new plans of solar radio telescopes are continuously proposed, such as the E-OVSA (Expanded Owens Valley Solar Array), the planning Frequency Agile Solar Radioheliograph (FASR) in USA, and the solar radio telescope system in the Chinese National Big Science Project – the second term of Meridian Project, etc. In the development of new solar radio telescopes, it is necessary to consider their design parameters, such as the observing frequency, bandwidth, temporal resolution, spectral resolution, spatial resolution, and polarization degree, etc. according to the requirement of scientific objectives. The too tough parameters will not only increase greatly the difficulty in the development of the telescope, but also sometimes make us unable to realize the expected scientific objectives. Then, how to select a reasonable group of design parameters of a solar radio telescope?

The statistical studies show that the occurrence rate of solar flares satisfies a power-law distribution, and at the different radio frequencies, the spectral index decreases a little with the increase of radio frequency, which means that most flares are triggered in the higher corona layer on the one hand, and the energy dissipation rate is also different in different corona heights[11,12]. It is found in the observations of broadband radio spectrometers with high temporal and spectral resolutions that the main body of a complex solar radio burst that continues for several ten minutes often contains several big pulses with a time scale of about several minutes, each big pulse is frequently composed of a group of pulses with a time scale of seconds, and each pulse is often composed of a group of several sub-pulses with a time scale of subsecond. It is frequently found in some violent eruptive processes that the radio spike bursts with an averaged lifetime from several to several ten milliseconds, which are often called the fast fine structure (FFS), generally appear as a group of several tens, several hundreds, even several ten thousands[13,14]. It is found by further studies that besides these spike bursts there are also some groups of tiny bursts, such as the dot bursts and narrow-band type Ⅲ bursts, for which the average lifetime, bandwidth, brightness temperature of individual bursts are quite similar to those of spike bursts, and they also appear in groups, the averaged bandwidth is commonly 1% of the central frequency, and the emission intensity is extremely high with the brightness temperature far greater than $10^{11}$ K. In fact, there are no evident boundaries between the spike bursts, dot bursts, and narrow-band type Ⅲ bursts, we may totally call them the small-scale microwave bursts (SMBs), and each SMB just represents one energy release process in the burst region[15]. In many spectral structures of solar radio bursts, such as the microwave zebra pattern, quasi-periodical pulsation (QPP), type Ⅱ and Ⅲ bursts, the interior of bright stripe is actually composed of a group of SMBs. For instance, Fig.1 gives an example of microwave QPP, we can expand it further, and find that its every pulse is actually composed of a group of microwave spike bursts or narrow-band type Ⅲ bursts[16]. Besides the bursts in the microwave band, in the other radio wavebands, for example in the type Ⅱ and Ⅲ bursts of the meter and ten-meter wavebands, there exist also some interior fine structures with an averaged lifetime of subsecond.

The common features of radio spike bursts, including the SMBs, radio dot bursts, and narrow-band type Ⅲ bursts mentioned above, are the shortest averaged lifetime, the narrowest averaged bandwidth, the highest brightness temperature among all the bursts in the same waveband, they frequently become a structural unit of other bursts, and probably represent the process of a kind of elementary burst (EB). They have a fast frequency drift, and a close correlation with the super heat particles emitted from the emission source region, thus they have attracted the wide attention of solar physicists, and proposed a series of challenges to the existing theories. For example, how these super heat particles are produced? What is the relationship of their occurrence with the flare eruption? How the super heat particles excite the emission of these EB processes? Why the bandwidth of these EBs is so narrow and the lifetime of these EBs is so short? Why they always appear as groups? If there is only one common source or there are different sources in one group of EBs? If they have a counterpart of optical, UV, or EUV emission? The answer for the above questions contains itself an important motivation for the fundamental plasma physics and the basic theory of astrophysics. Therefore, it becomes the basic requirement for the new generation of solar radio telescopes that whether we can realize the exact measurement for such kind of small bursts like spike bursts. This paper will analyze the basic restriction on the parameters of solar radio telescopes by studying the scaling laws of solar radio spike bursts.

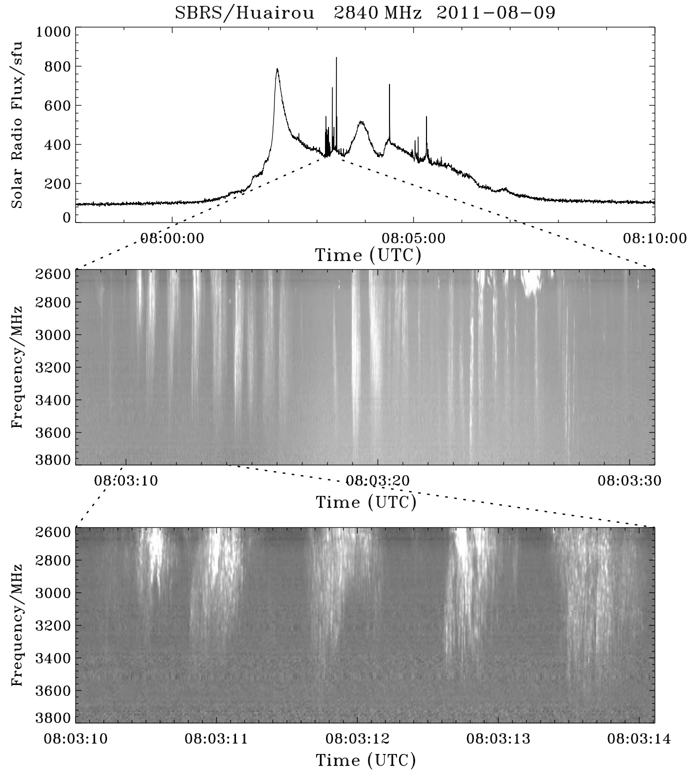


Fig. 1 The Chinese solar broadband radio spectrometer at Huairou (SBRS/Huairou) observed a microwave fast quasi-periodic pulsation (QPP) which contains several pulses, and each pulse is composed of a group of spike bursts. Here sfu is the abbreviation of solar flux unit.

## 2. SCALING LAWS OF SOLAR RADIO SPIKE BURSTS WITH RESPECT TO FREQUENCY

In the previous solar observations of over 70 years, including the ground-based solar radio telescopes and space radio detection devices (such as WIND-Waves, STEORO-Waves (Solar Terrestrial Relations Observatory-waves) etc., it was found that the frequency range of appearance of solar spike bursts was very broad, from several ten MHz (ten meter band) to about 10 GHz (centimeter band). At present, because of the relatively few detection measure, it is impossible to give a clear conclusion whether the similar spike bursts exist in the high-frequency band above 7.50 GHz and the lower frequency bands like hundred meter and thousand meter bands. However, the frequency range of the appeared radio spike bursts exceeds at least three orders of magnitude. Hence, it is necessary to find out the scaling laws of radio spike bursts with respect to frequency, i.e., the rules of the variations of the averaged lifetime and bandwidth etc. with the frequency, which can help us to understand better the physical mechanisms of solar radio eruption processes on the one hand, in the meanwhile it may also become the theoretical basis to select the parameters for designing the new generation of solar radio telescopes.

### 2.1 Scaling Law of Averaged Lifetime of Solar Radio Spike Bursts

A lot of solar radio observations show that the averaged lifetime of solar radio spike bursts seems to have a negative correlation with the frequency, i.e., the higher the frequency the shorter the averaged lifetime. Here, the previously published results[17,18] in addition to the results of several events[15,19] observed by the Chinese SBRS since 2006 are shown in Fig.2, in which the black pluses refer to the previous results, the diamonds are the observed results of SBRS in recent years. The observations of the whole sample cover the frequency range from 210 MHz to 7.0 GHz, in which the smallest lifetime of radio spike bursts is 5 ms, the longest lifetime is 91 ms, and the averaged lifetime is about 30 ms. It is ready to find from Fig.2 that the averaged lifetime of radio spike bursts actually has an obvious anti-correlation with the emission frequency, with a correlation coefficient of -0.58. Meanwhile, we have made the least square fitting on the above-mentioned scatter diagram, the fitting result is shown by the solid curve in Fig.2, which can be expressed by a power function:

$$\tau \approx 8.2 \times 10^3 f^{-0.84\pm0.15}, \quad (1)$$

here $\tau$ is the averaged lifetime of radio spike bursts in units of ms, $f$ is the frequency in units of MHz. It can be seen that the averaged lifetime of radio spike bursts really decreases obviously with the increase of frequency. It is estimated from Eq.(1) that the averaged lifetime of radio spike bursts is about 170 ms around 100 MHz, and the averaged lifetime is about 25 ms around 1.0 GHz, which is consistent with the practical observations. If there are radio spike bursts existed around 10 GHz, its averaged lifetime may be about 3.5 ms.

We have plotted also the fitting result of the previously observed events in Fig.2. The comparison of the two fitting results show that due to the increase of the observed results of SBRS since 2006, the averaged lifetime in high-frequency band has an evident raise as compared with the results obtained by Güdel et al.[17] in 1990 and Rozhansky et al.[18] in 2008 (the fitting function is $\tau \propto f^{-1.29}$). Moreover, the results observed by SBRS in the high-frequency band above 3.0 GHz are obviously scattered in Fig.2. Because only few spike bursts are observed in the high-frequency band, in addition, among the existing solar radio broadband spectrometers above 3.0 GHz, the Chinese SBRS has the highest time resolution, that is 8 ms in 2.60–3.80 GHz and 5 ms in 5.20–7.60 GHz, so, it is uncertain whether the radio spike bursts with the lifetime shorter than 5–8 ms exist in the above frequency bands. Sofar, there is no any solar radio broadband spectrometer with a time resolution higher than that of SBRS in operation. Hence, the present statistical results have a large uncertainty, and need to be verified by the events observed by new telescopes with a higher time resolution.

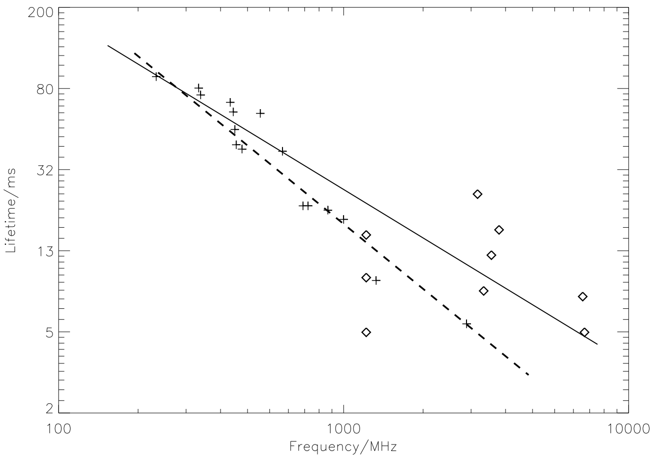


Fig. 2 The relationship between the averaged lifetime of solar radio spike bursts and the frequency. Here, the pluses represent the previous results[17,18], the dashed line is obtained by the least square fitting method. The diamonds represent the results observed by SBRS/Huairou since 2006[15,19], and the solid line is obtained by the least square fitting on the total sample. The correlation coefficient between lifetime and frequency is -0.58, which means a significant negative correlation with the confidence level of 99%.

### 2.2 Scaling Law of Bandwidth of Solar Radio Spike Bursts with Respect to Frequency

No matter whether we assume that the emission mechanism of solar radio spike bursts is the cyclotron maser[20] or plasma emission, the averaged emission bandwidth of spikes always represents the magnitude of spatial sizes of burst source regions indirectly.

A lot of observed events show that the frequency bandwidth of solar radio spike bursts is roughly in direct proportion to the emission frequency. Here, we have also collected the previously published results[21], and on this basis added in some events observed by SBRS since 2006[15,19], as shown in Fig.3. Similarly, the black pluses represent the previous results, and the diamonds refer to the results observed by SBRS in recent years. The observing frequencies of the total sample cover a range of 305 MHz–7.0 GHz, in which the smallest frequency bandwidth of radio spike bursts is 1.4 MHz (in respect to the central frequency of 710 MHz, the relative bandwidth is about 0.2%), while the largest frequency bandwidth is 115 MHz (in respect to the central frequency of 1250 MHz, the relative bandwidth is about 9.2%), and the averaged relative bandwidth is about 1%. The statistically calculated correlation coefficient between the bandwidth and the emission frequency of spike bursts is 0.47 for the 166 sample members, which obviously belongs to a positive correlation, i.e., the bandwidth of spike bursts increases with the increase of observing frequency.

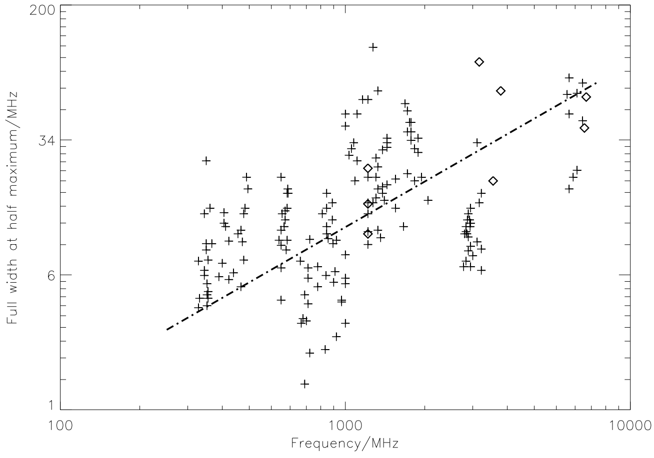


Fig. 3 The relationship between the averaged bandwidth of solar radio spike bursts and the frequency. Here, the pluses represent the previous results[17−18], the diamonds represent the results observed by S-BRS/Huairou since 2006[15,19], and the dot-dashed line is obtained by the least squared fitting on the total sample, the calculated correlation coefficient between bandwidth and frequency is 0.47, which means a significant positive correlation with the confidence level of 99%.

Similarly, we can make a function fitting for the scatter diagram in Fig.3 by using the least square method, the fitting result is shown by the dot-dashed line in Fig.3, which can be also expressed by a power function:

$$f_{\rm bw} \approx 0.011 \times f^{0.99\pm0.18}, \tag{2}$$

here, $f_{\rm bw}$ is the averaged bandwidth of radio spike bursts in units of MHz. It can be seen that the averaged bandwidth actually increases with the increasing frequency, and the index of the fitting function is equal to 0.99, very close to 1.0, in other words, the relation of variation between the averaged bandwidth and the frequency is very close to the linear rule. We can readily obtain the relative bandwidth of $\frac{f_{bw}}{f}$ ≈1.1%. It is evident that the dispersion of the averaged bandwidth of radio spike bursts in respect to the fitting function is very high in Fig.3. In fact, the relative bandwidths of most radio spike bursts are concentrated in the range of 0.5%–3.0%. But we can also find in Fig.3 that the events of radio spikes in the high-frequency band above 3.0 GHz are relatively rare, hence there is a larger uncertainty for the fitting function mentioned above.

## 3. CONSTRAINS OF THE SCALING LAWS OF SPIKE BURSTS FOR THE PARAMETERS OF THE NEW GENERATION OF SOLAR RADIO TELESCOPES

Because the spike bursts are the smallest eruptive units in solar radio bursts, the above scaling laws have provided the most important and fundamental theoretical basis for the design of the next generation of new-type solar radio telescopes.

In the design of new solar radio telescopes, the selected time resolution ($\Delta t$), i.e., the sampling time interval, should be smaller than the averaged lifetime of spike bursts. From the point of view of discrimination, at least two observing points are needed in one spike burst, that is to say the time resolution should be better than one half of the averaged lifetime, i.e., $\Delta t \leq \frac{1}{2}\tau$. For instance, the averaged lifetime of spike bursts is 170 ms around 100 MHz, which requires that the time resolution of radio spectrometers should be $\Delta t \leq 85$ ms around this frequency; the averaged lifetime of spikes is 25 ms around 1.0 GHz, which requires that the time resolution of radio spectrometers should be $\Delta t \leq 12.5$ ms around this frequency; the averaged lifetime of spike bursts is 3.5 ms around 10.0 GHz, which requires that the time resolution of radio spectrometers should be $\Delta t \leq 1.75$ ms around this frequency.

When we select the frequency resolution of solar radio telescopes, it is required that the sampling frequency interval is smaller than the averaged bandwidth of spike bursts. Similarly, for the sake of a reliable discrimination, the frequency resolution is required to be smaller than one half of the averaged bandwidth, i.e., $\Delta f \leq \frac{1}{2} f_{\rm bw}$. It is known from the above scaling law of bandwidth, the averaged bandwidth of spike bursts is about 1% of the central frequency, thus the frequency resolution should be smaller than 0.5% of the central frequency. For example, the frequency resolution of the telescope around 100 MHz should be $\Delta f \leq 0.5$ MHz; the frequency resolution of the telescope around 1.0 GHz should be $\Delta f \leq$ 5.0 MHz; and the frequency resolution of the telescope around 10.0 GHz should be $\Delta f \leq 50$ MHz. The parameters of main solar radio broadband dynamic spectrometers in the world are listed in Table 1, in which the values in the brackets are the proper parameters given by the synthetic consideration of this paper.

The above constrains on the time and frequency resolutions are proposed mainly for solar broadband spectrometers, but for solar radioheliographs, if we also select the design parameters according to the above theoretical constraints, then the telescope development, construction, and operation will face to a very rigorous challenge. For instance, if we select the time and frequency resolutions according to the above constrains, the low-frequency array of MUSER (MUSER-I) will design at least 200 frequency channels in 0.40–2.00 GHz, which is 2–3 times more than the present channels (the present channel number is 64); the time resolution will reach about 10 ms, which is 2–3 times higher than the present time resolution (25 ms). As we known, the daily observed data of MUSER-I is about 900 GB at present, if we select the parameters according to the above constrains, the daily observed data will exceed 10 TB. Similarly, if we select the parameters of high-frequency array of MUSER-II in 2.0–15.0 GHz according to the above principle, the frequency channels will be about 300, which is one half of the present one, but the time resolution will be higher than 5 ms, which is 40 times of the present one (200 ms). In this condition, the daily observed data will be about 80 TB, which is 20 times of the present one. Such a huge number of daily observed data will propose a very severe requirement and challenge for the data storage, retrieval, and extraction, as well as for the data processing and image analysis. Then, how to solve this problem?

**Table 1 The parameters of the main existing solar broadband dynamic spectrometers**

| Name \ Parameter | Frequency/MHz | $\Delta t$/ms | $\Delta f$/MHz |
|---|---|---|---|
| SBRS/Huairou | 1100–2060 | 5 (6–10)[a] | 4 (5–10) |
| | 2600–3800 | 8 (4–5) | 10 (10–20) |
| | 5200–7600 | 5 (3–4) | 20 (25–40) |
| SBRS/Nanjing | 4500–7500 | 5 (3–4) | 10 (20–40) |
| SBRS/Kunming | 625–1500 | 80 (3–4) | 0.2 (3–7) |
| | 70–700 | 80 (15–60) | 0.2 (0.4–3) |
| Ondrejov/Czech | 800–2000 | 10 (6–15) | 5 (4–10) |
| | 2000–5000 | 10 (3–6) | 12 (10–25) |
| Tremdorf-AIP/Germany | 40–170 | 100 (50–180) | 0.135 (0.2–0.85) |
| | 200–800 | 10 (15–45) | 1.0 (1–4) |
| AMATERAS/Japan | 150–500 | 10 (20–60) | 0.061 (0.8–2.5) |
| Phoenix/Swiss | 100–4000 | 100 (4–85) | 10 (0.5–20) |
| Blien/Swiss | 170–870 | 250 (13–50) | 3.5 (0.2–4.3) |
| Artemis/Greece | 20–650 | 100 (55–100) | 1.0 (0.1–3) |
| Culgoora/Australian | 18–1800 | 3000 (4–100) | 0.32 (0.1–9) |
| GB-SRBS/US | 10–30 | 1000 (235–500) | 0.03 (0.05–0.15) |
| | 25–350 | 1000 (25–270) | 0.03 (0.12–1.75) |
| | 300–3000 | 1000 (5–30) | 0.03 (1.5–15) |
| OoTY-Callisto/India | 45–870 | 250 (13–160) | 4.0 (0.2–4.3) |

[a] All the numbers in brackets of this table are the best selections according to the scaling-laws of radio spike bursts.

In fact, if too high time and frequency resolutions are selected for a radioheliograph to image the whole solar disk, its sensitivity will decline naturally, which is inevitable to cause the weak solar signals to be vague even submerged by noises, thus to lose the scientific objective of the telescope. More importantly, even for the radio spike bursts that commonly appear as groups of several tens even several ten thousands, the different groups are basically consistent in the physical formation process and source region, the total bandwidth occupied by them is over one order of magnitude broader than that of an individual spike (i.e., over 10% of the central frequency), and the duration time of a group of spikes is also over one order of magnitude longer than that of an individual spike, to reach the order of seconds even several ten seconds. For the imaging observations, if we can locate the source region and structure of a group of spikes, then we can realize the purpose to study them. Hereby, we propose an observing mode to combine both spectrum and image, i.e., by using the observation of single-antenna radio broadband spectrometer with high time and frequency resolutions, we can obtain the spectral features of solar radio emission in a broad band, the frequency resolution reaches 0.5% of the central frequency, and the time resolution reaches one half of the averaged lifetime of the spike bursts in the corresponding waveband, thus we can discriminate the spectral fine structures of eruptive processes; meanwhile, by using the imaging observation of radioheliograph composed of an array of multiple antennas in the corresponding band, the frequency resolution reaches about 5% of the central frequency, and the time resolution reaches 10 times of the averaged lifetime of spike bursts in the corresponding band, together with a high spatial resolution, thus we can obtain the spatial position of the burst source and the structural features of the source region. For example, we can select a proper time resolution of 1–2 s and the frequency resolution of 5 MHz for a radio heliograph around 100 MHz; while for a radio heliograph around 1.0 GHz, the time and frequency resolutions can be properly selected as about 250 ms and 50 MHz, respectively; and for a radio heliograph around 10.0 GHz, the time and frequency resolutions can be selected properly as about 35 ms and 500 MHz, respectively. The basic parameters of the present solar radioheliographs are listed in Table 2, in which the number in the brackets indicates the range of parameter values deduced from the synthetical consideration of this paper, and all the listed radio telescopes are the radio telescopes specified for observing the Sun. Besides, there are also some large radio telescopes in the world, such as the VLA in USA, LOFAR in Europe, ALMA in South America etc., which are mainly used to observe various cosmic radio sources. But there are also some times of about 5%–10% in each year assigned to solar imaging observations. Here, LOFAR was built in 2012 and composed of two arrays, respectively working in 10–80 MHz and 120–140 MHz, with an unprecedented high resolution and sensitivity. After LOFAR was established in 2012, it has performed multiple times of solar imaging observation, and obtained many important results[22,23].

For the solar violent eruption events, the advantage of the spectrum-image combination mode of solar radio observation is that it can acquire the spectrum and image information of eruptive processes simultaneously with the high temporal, spectral and spatial resolutions and high sensitivity, and can comprehensively reflect the full view and dynamic process of a solar radio eruption. However, it should be noticed that for the small-scale eruptive phenomena in the quiet sun or low solar atmosphere there are possibly multiple emission sources simultaneously existed in the solar disk, it is often difficult to confirm the relation between the spectral result and the eruption source in the imaging observation obtained by the above-mentioned spectrum-image observation mode.

**Table 2 The parameters of the main existing solar radioheliographs**

| Name \ Parameter | Frequency/MHz | $\Delta t$/ms | $\Delta f$/MHz | $\Delta\theta$[a] |
|---|---|---|---|---|
| MUSER/China | 400–2000 | 25 (70–260)[b] | 25 (40–200) | $10''$–$51''$ |
| | 2000–15000 | 206.25 (12–70) | 25 (200–1000) | $1.4''$–$10''$ |
| SSRT/Russia | 5700 | 35 | – | $22''$ |
| SRH/Russia | 4000–8000 | 300 (40–60) | 125 (400–800) | $16''$–$32''$ |
| NoRH/Japan | 17000 | 100 (10) | – | $10''$ |
| | 34000 | 100 (6) | – | $5''$ |
| Nancay/France | 150–450 | 100 (240–600) | 30 (8–20) | $1.3'$–$4.0'$ |
| E-OVSA/US | 1000–18000 | 680 (20–250) | 500 (50–900) | $3''$–$57''$ |
| URT-2/Ukraine | 8–33 | 1 ($\sim$1000) | 0.004 (0.8–3.3) | $20'$–$80'$ |

[a] $\Delta\theta$ is the angular resolution.

[b] All the numbers in brackets of this table are the best selections according to the scaling-law of radio spike bursts.

For radioheliographs, the spatial resolution depends on the length of the longest baseline: $\Delta\theta \approx \frac{\lambda}{D}$, $\lambda$ is the wavelength, $D$ is the length of the longest baseline of the telescope array. Because the wavelength in the radio band is over 4–7 orders of magnitude larger than that in the optical band, thus it is almost impossible to reach the spatial resolution as high as the optical, UV, and EUV telescopes. Moreover, most of radiation in the radio band is generated in the solar corona, and the radiation source is also much larger than the visible light source near the photosphere surface. Then, how to select the spatial resolution of radio telescopes? Previously, there were only some solar radio imaging observations at a few frequency points in the world, including the imaging of NoRH in Japan at 17 GHz and 34 GHz, the imaging of NRH in France at 5 frequency points in 150–450 MHz, and the imaging of SSRT in Russia at 5.70 GHz, etc., though the OVSA in USA has made the solar radio imaging observation at 1–18 GHz, it can not obtain the detailed information about the solar radio burst sources due to the limited number of telescope array units, as well as the limited resolution and sensitivity. Krucker et al.[24] combined the observation of VLA in USA and the observation of Phoenix spectrometer in Switzerland to study the source region of radio spike bursts, except a rough position of the source region, the source of an individual spike burst was still unable to be discriminated in practice. Therefore, based on the observed results mentioned above, at present we can not obtain the information about the spatial scales of emission sources of solar radio spike bursts and dot-like bursts etc., sometimes it is even difficult to determine the corresponding active region of burst sources.

However, according to the relative bandwidth of the solar radio spike burst spectrum with a high time-frequency resolution but without imaging observation, we can give an estimation for the upper limit of the size of radio spike emission source region. When we assume that the radiation mechanism of radio spike emission belongs to the plasma radiation, the spatial scale of emission source is directly proportional to the bandwidth and the characteristic length ($H_n$) of plasma density variation: $\Delta L \approx H_n \cdot \frac{f_{\rm bw}}{f}$. The characteristic length of plasma density is related to the height of emission source, according to the current density model[25] of the solar atmosphere, we can roughly estimate that the corresponding characteristic length of source region is $H_n \sim 2 \times 10^5$km at 100 MHz, $H_n \sim 5 \times 10^4$km at 1.0 GHz, and $H_n \sim 10^4$km at 10.0 GHz. It is known as mentioned before that the relative bandwidth of radio spike bursts is about 1%, which means that the upper limit of the spatial scale of spike burst source region corresponding to 100 MHz, 1.0 GHz, and 10.0 GHz is 2000 km, 500 km, and 100 km, namely about 3", 0.7", and 0.15", respectively. It is very obvious that for all the existing solar radioheliographs and planing solar radio telescopes, it is impossible to discriminate such a scale of radio burst sources, the hope can be laid on only the international super-telescope projects like SKA. Of course, with the aid of the imaging observations of existing radioheliographs, if we can determine the position of burst source in the solar active region and the spatial relation with the other magnetic structures, it also has an important significance for understanding the relevant physical processes of radio bursts, and for revealing the rules of the occurrence and evolution of relevant non-thermal processes. For example, in 2015, by using the imaging observation of VLA in USA and the spectral observation with high time and frequency resolutions, Chen et al.[26] found that the source region of a group of decimetric radio spikes was just located in the area where the shock wave was terminated at the flare loop top, providing a direct observation evidence that a flare terminates the acceleration of shock wave on electrons, which has been paid particular attention by international colleagues. This result also shows that the observation of spectrum-image combination mode has broad prospects for the relevant studies, which can be considered as a direction to develop the studies of solar radio astronomy in the future.

## 4. SUMMARY AND PROSPECTS

For the studies of solar radio astronomy, it is unquestionable that the higher the resolving power and sensitivity, the broader the frequency coverage of a telescope is better. But the design of high parameters always comes at a cost, when the channel number of a telescope increases, the frequency bandwidth of individual channel becomes narrower; and when the time resolution increases, the integration time becomes short, which will cause the sensitivity of the telescope to be declined, and make the relatively weak burst signals be vague so that be submerged by noises, thus the burst signals can not be discriminated. In the observed images, this appears as the blurred internal structure features of burst sources, unable to discriminate the structural details, and it is inevitable to sacrifice the scientific objective of the telescope. For the solar radio burst units of smallest scale, i.e., the radio spike bursts, dot-like bursts, and narrow-band type Ⅲ bursts, the scaling laws with respect to frequency show that the time scale of detail's feature variation in solar radio bursts decreases with the increase of frequency, and the bandwidth increases with the increase of frequency, on this basis, to determine the design parameters of the new generation of solar radio telescopes will give an economical and reasonable combination of parameters, so as to ensure the scientific output from the observed data of telescopes to the greatest extent. For the imaging observation, if we select too high time and frequency resolutions, it will not only face to a great challenge in techniques, but also inevitably reduce the observational sensitivity, and sacrifice the scientific objective of the relevant telescope. Therefore, we propose the spectrum-image combination mode to observe the solar radio eruptions on the basis of the scaling laws of radio spike emission, it can realize the observation simultaneously with high temporal, spatial, and spectral resolutions, as well as a high sensitivity, and can be taken as the principal mode for the future solar radio observations, it will have broad prospects for the relevant studies. However, the high parameters here are relative, they will be gradually upgraded with the development of radio and computer techniques.

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## References

1 Fang C., Ding M. D., Chen P. F., Physics of Solar Active Regions, Nanjing: Nanjing University Press, 2008

2 Lin R. P., Hudson H. S., SoPh, 1976, 50, 153

3 Fu Q. J., Qin Z. H., Ji H. R., et al., SoPh, 1995, 160, 97

4 Fu Q. J., Ji H. R., Qin Z. H., et al., SoPh, 2004, 222, 167

5 Lu L., Liu S. M., Song Q. W., et al., AcAsn, 2015, 56, 130

6 Lu L., Liu S. M., Song Q. W., et al., ChA&A, 2015, 39, 497

7 Wang L., Zhang P., Liu S. M., et al., AcAsn, 2017, 58, 48

8 Lesovoi S. V., Altyntsev A. T., Altyntsev E. F., et al., RAA, 2014, 14, 864

9 Lesovoi, S. V., Altyntsev, A. T., Kochanov, A. A., et al., STP, 2017, 3, 3

10 Yan Y., Zhang J., Wang W., et al., EM&P, 2009, 104, 97

11 Song Q. W., Huang G. L., Tan B. L., ApJ, 2012, 750, 160

12 Song Q. W., Huang G. L., Huang Y., Ap&SS, 2013, 347, 15

13 Fleishman G. D., Gary D. E., Nita G. M., ApJ, 2003, 593, 571

14 Chernov G. P., Fine Structure of Solar Radio Bursts. Berlin Heidelberg: Springer-Verlag, 2011, 375

15 Tan B. L., ApJ, 2013, 773, 165

16 Tan B. L., Tan, C. M., ApJ, 2012, 749, 28

17 Güdel M., Benz A. O., A&A, 1990, 231, 202

18 Rozhansky I. V., Fleishman G. D., Huang G. L., ApJ, 2008, 681, 1688

19 Wang S. J., Yan Y. H., Liu Y. Y., et al., SoPh, 2008, 253, 133

20 Tang J. F., Wu D. J., Zhao G. Q., et al., Progress of Astron., 2017, 35, 149

21 Csillaghy A., Benz A. O., A&A, 1993, 274, 487

22 Kontar E. P., Yu S., Kuznetsov A. A., et al., NatCo, 2017, 8, 1515

23 Chen X. Y., Kontar E. P., Yu S. J., et al., ApJ, 2018, 856, 73

24 Krucker S., Aschwanden M. J., Bastian T. S., et al., A&A, 1995, 302, 551

25 Tan C. M., Yan Y. H., Tan B. L., et al., ApJ, 2015, 808, 61

26 Chen B., Bastian T. S., Shen C. C., et al., Science, 2015, 350, 1238