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Analyzing the capability of a radio telescope in a bistatic space debris observation system *

Zhe Zhao[1,2], You Zhao[1] and Peng-Qi Gao[1]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China; *zhaozhe@bao.ac.cn*

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Abstract A bistatic space debris observation system using a radio telescope as the receiving part is introduced. The detection capability of the system at different working frequencies is analyzed based on real instruments. The detection range of targets with a fixed radar cross section and the detection ability of small space debris at a fixed range are discussed. The simulations of this particular observation system at different transmitting powers are also implemented and the detection capability is discussed. The simulated results approximately match the actual experiments. The analysis in this paper provides a theoretical basis for developing a space debris observation system that can be built in China.

Key words: instrumentation: detectors — large radio telescope techniques: radar astronomy

1 INTRODUCTION

Space debris is a result of space exploration activities. Since the first satellite, Sputnik-1, was sent into outer space more than 50 years ago, space debris has become a huge problem. Before long, it will be a formidable obstacle hindering human beings from space exploration and development. The International Space Station was forced to execute four collision avoidance maneuvers from April 2011 to April 2012 and two additional maneuvers more recently (NASA-ODPO 2012). The United States Space Surveillance Network published on its website that there were about 16 400 objects cataloged as of May 2012. Only a few satellites are included in this catalog and all the other entries are so-called space debris. Most of the objects in this catalog are larger than 10 cm. The population of very dangerous debris whose diameter is limited in the range from 1 cm to 10 cm is extremely large. Space debris is distributed in low Earth orbit (LEO) and geostationary Earth orbit (GEO) which are also two major areas used for human activities in space. The main methods of observation include optical telescopes and radar. According to previous research, radar is mainly applied to LEO observations and optical telescopes are mainly used for GEO observations. Since there are many satellites that observe natural resources, survey satellites, weather satellites, space stations, astronomical observation platforms and some new communication satellites orbiting in LEO, we need to precisely predict the trajectories of space debris in LEO to avoid collisions and therefore protect space vehicles. A special observation system using a radio telescope together with radar

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could enhance the ability to observe small space debris with full considerations of cost control and the use of existing facilities.

When we use radar and a radio telescope to compose a space debris observation system, one of the main aims is to use the radio telescope to receive the signals reflected from small debris which could not be observed by radar. It is necessary to utilize space surveillance radar as a transmitter. The system will use the wave signals that could not be detected by the radar. Because of the slow movement of a large aperture antenna, it is necessary to employ the beam-park mode during operation. In this mode, the transmitter antenna stares at a certain zone which means the angles for azimuth and elevation are fixed. At the same time, the antenna of the radio telescope is directed to the same zone. These two beams form a cross region in the sky. The transmitter keeps transmitting pulse signals to the fixed direction. The radio telescope will then detect the reflected signals from the space debris passing through the cross region after it is synchronized with the transmitter. The pulse signals could be monochromatic signals or noisy signals. By irradiation of the space debris with a monochromatic signal, highly accurate measurements of Doppler shifts in the frequency and radial velocities can be made. A noisy signal, such as a linear frequency modulation signal, is generally used to measure the angular coordinates and angular velocities. For a bistatic system whose first goal is to detect small space debris with a radio telescope, a monochromatic signal is enough. For the data processing, the amount of data that would be gathered in the detection experiments could be many gigabytes. It will not be plausible to deal with the raw data in real-time. Consequently, the most appropriate method is to adopt a post-processing algorithm which has the advantage that the parameters could be adaptively changed or the original data could even be reprocessed with new, improved algorithms.

According to existing literature, observation systems that participate in collaborative space-debris monitoring programs include the Effelsberg Radio Telescope, the Arecibo Radio Telescope (di Martino et al. 2004; Thompson et al. 1992), the Goldstone Bistatic Radar (Matney et al. 1999), etc. The Effelsberg Radio Telescope was used for the first time for detection of small space debris in a collaboration with Track and Imaging Radar (TIRA) in 1996. The Effelsberg Radio Telescope is administered by the Max Planck Institute for Radio Astronomy in Germany. It has a 100-meter dish antenna which enables its powerful detection ability. In the first collaboration, the Effelsberg Radio Telescope detected 371 objects, and detected pieces of debris as small as 9 mm at an altitude of 1000 km. The American Goldstone Bistatic Radar was also used for detection of space debris. The Goldstone facility is located in the California desert. The size of the transmitting antenna is 70 m and the aperture of the receiving antenna is 35 m. In 2004, NASA used this radar for detecting small space debris. The result was that the radar could be used for measuring small objects whose diameters range from 2 mm to 1 cm at altitudes from 600 km to 1000 km. By using a large radio telescope, in view of its huge detection power, the radio astronomy community can control investment and use existing equipment to build a small space debris observation system in China. This is one way to quickly enhance detection ability of small near-Earth debris. This paper focuses on analyzing the effect of using various radio wavelengths on the ability to observe space debris using a radio telescope. The simulation studying the ability of an existing bistatic space debris observation system provides a reference for the development of a similar space debris observation system that would be constructed in China.

In this paper, Section 2 will discuss the relationship between working wavelength and detection range of the radio telescope, while Section 3 will give analysis about the relationship between working wavelength and the size of space debris which could be detected by the radio telescope. The effect of the transmission parameters on the bistatic system will be discussed in Section 4. At the end in Section 5, we summarize the whole article and discuss the next step of the work.

2 THE RELATIONSHIP BETWEEN WAVELENGTH AND DETECTION RANGE

The observation system is composed of a radar system and a radio telescope. The radio telescope is implemented as the receiver of a bistatic radar system, and the radar becomes the source of radio emission. As a passive receiving cell, the equation describing the radio telescope (Skolnik 2008) is

$$R_{\mathrm{R}}^2 R_{\mathrm{T}}^2 = \frac{P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{R}} \lambda^2 \sigma_B F_{\mathrm{T}}^2 F_{\mathrm{R}}^2}{(4\pi)^3 K T_s B_n (\mathrm{S/N})_{\mathrm{min}} L_{\mathrm{T}} L_{\mathrm{R}}}, \tag{1}$$

where R_{T} denotes range from the emission source to the target; R_{R} denotes the range from the radio telescope to the target; P_{T} is the transmitting power; G_{R} is the antenna gain of the receiver; G_{T} is the antenna gain of the transmitter; λ is wavelength; σ_{B} is the target radar cross section (RCS); T_{S} is the noise temperature of the system; F_{T} and F_{R} are propagation factors for the transmitter and receiver respectively; K is the Boltzmann constant; B_n is the filter bandwidth of the receiver; $(\mathrm{S/N})_{\mathrm{min}}$ means minimum signal to noise ratio; L_{T} and L_{R} are system losses in the transmitter and receiver respectively.

According to antenna theory, the relationship between the parabolic antenna gain and its effective reception area A_{e} is

$$G = \frac{4\pi A_{\mathrm{e}}}{\lambda^2}. \tag{2}$$

If we make

$$\kappa = \frac{P_{\mathrm{T}} A_{\mathrm{T}} A_{\mathrm{R}} F_{\mathrm{T}}^2 F_{\mathrm{R}}^2}{4\pi K T_s B_n (\mathrm{S/N})_{\mathrm{min}} L_{\mathrm{T}} L_{\mathrm{R}}}, \tag{3}$$

then, Equation (1) could be reduced to

$$R_{\mathrm{R}} R_{\mathrm{T}} = \sqrt{\kappa \cdot \sigma_B} \cdot \frac{1}{\lambda}. \tag{4}$$

According to the relative positions of the target and the terminal stations, the bistatic system can be divided into three different forms (Skolnik 2008): transmitter centered; receiver centered; transmitter and receiver centered. The transmitter and receiver centered form means that the target is no closer to either the transmitter or the receiver. If the distance between the receiver and the transmitter and the distance between the target to the receiver have the same order of magnitude, there are three positional relations of the receiver and transmitter which are illustrated from left to right in Figure 1, and the relations between their angles are as follows: $\beta_B = \theta_R - \theta_{\mathrm{T}}$, $\beta_B = \theta_{\mathrm{T}} + \theta_R$ and $\beta_B = \theta_{\mathrm{T}} - \theta_R$.

The triangle defined by the bistatic system is

$$R_{\mathrm{T}} \cdot \cos\theta_{\mathrm{T}} = R_{\mathrm{R}} \cdot \cos\theta_{\mathrm{R}}, \tag{5}$$

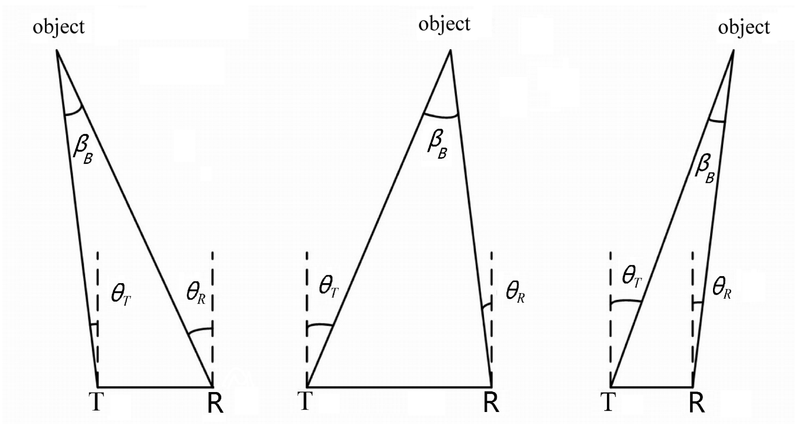

Fig. 1 Spatial relations between positions of the components in a bistatic system.

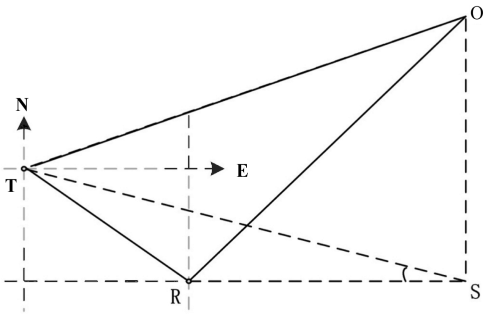

Fig. 2 Geographic coordinates and spatial relationship for TIRA and the Effelsberg Radio Telescope.

Table 1 Major parameters of the Effelsberg Radio Telescope and TIRA

Facilities	TIRA	Effelsberg
Antenna	32 m	100 m
Trans Power	2 MW	–
Polarization	RCP	–
Beam Angle	0.45°	0.165°
Elevation	76.12°	75°
Azimuth	93°	90°
Range	600–1200 km	700–1100 km
Longitude	7.1296°E	6.882778°E
Latitude	50.6166°N	50.524722°N

Notes: RCP means right circular polarization.

so, Equation (3) could be transformed to

$$R_{\mathrm{R}}^2 \cdot \frac{\cos\theta_{\mathrm{R}}}{\cos\theta_{\mathrm{T}}} = \sqrt{\kappa \cdot \sigma_B} \cdot \frac{1}{\lambda}. \tag{6}$$

According to Equation (6), when the target's RCS σ_B is fixed, the square of the range from the radio telescope to the target is inversely proportional to the wavelength and is related to the orientations of the antenna.

As mentioned in the Introduction, the Effelsberg Radio Telescope and TIRA have been effectively used for space debris observation. The major parameters that have been used for space debris detection (Shi 2011) are shown in Table 1.

A simulation of the ability of this bistatic system to detect space debris in LEO was developed according to Equation (6). In the simulation, the noise temperature of the system was assumed to be 290 K; the antenna efficiency was assumed to be 0.45; system losses were set to be 0.1; and the $(\mathrm{S/N})_{\min}$ was assumed to be 0.01. The geographic coordinates and spatial relationship of TIRA and the Effelsberg Radio Telescope are shown in Figure 2, and the relation between angles could be calculated as follows:

$$\cos\angle SRT = -0.933\,; \qquad \cos\angle STR = 0.9505\,;$$

and

$$\cos\angle OTS = 0.2399\,; \qquad \cos\angle ORS = 0.2588\,;$$

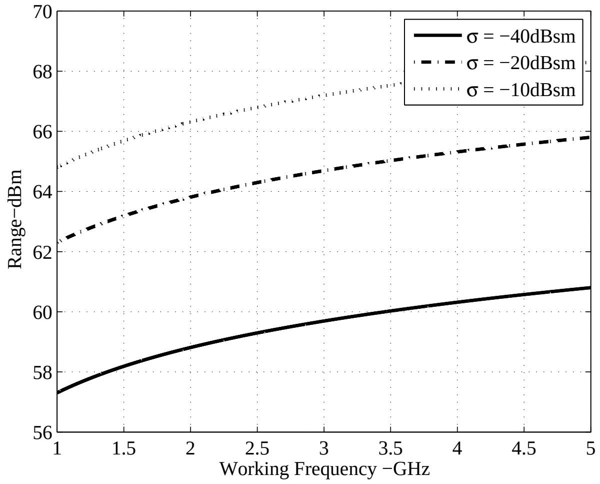

Fig. 3 Simulation results of the detection range.

so finally

$$\begin{aligned}\cos\theta_{\rm T} &= \cos(90^\circ - \angle OTR) = \sqrt{1-(\cos\angle OTR)^2}\\ &= \sqrt{1-(\cos\angle OTS\cos\angle STR)^2} = 0.9737\,;\end{aligned}$$

$$\begin{aligned}\cos\theta_{\rm R} &= \cos(\angle ORT - 90^\circ) = \sqrt{1-(\cos\angle ORT)^2}\\ &= \sqrt{1-(\cos\angle ORS\cos\angle SRT)^2} = 0.9704\,.\end{aligned}$$

The relationship between frequency and the detection range was calculated according to the parameters listed above. The simulation results are shown in Figure 3.

As can be seen from this graph, when the working frequency was equal to 1.5 GHz, that is the radar was operating in the L-band, the small pieces whose RCS was –40 dBsm could be detected at a distance of about 800 km, where 800 km is equal to 59 dBm. The simulation result approximates the actual ability of the Effelsberg Radio Telescope to detect small space debris. The following rules can be summed up from Figure 3: with the increase of the working frequency, the detection distance of the system for fixed sized fragments will increase, which means that with the operating wavelength decreasing, its detection ability can be improved. However, the enhancement in detection ability is disproportionate. If the detection range needs to be increased 10 times, the corresponding working frequency should be increased 100 times while all other system factors are unchanged. The increase in detection range has a limited extent. If we increase the working frequency, atmospheric loss, the influence of water vapor absorption, etc, may actually reduce the intensity of the scattering signal. Again the ability of the system to detect space debris declines.

3 RELATIONSHIP BETWEEN WORKING WAVELENGTH AND THE SIZE OF THE SPACE DEBRIS

As shown in the radar relation of Equation (1), in the case when the basic performances of the radio telescope and the radar are fixed, the relationship between the working wavelength and the RCS of space debris at a fixed orbital height can be described as follows

$$\sigma_B = R_{\rm R}^2 R_{\rm T}^2 \cdot \frac{\lambda^2}{\kappa}. \tag{7}$$

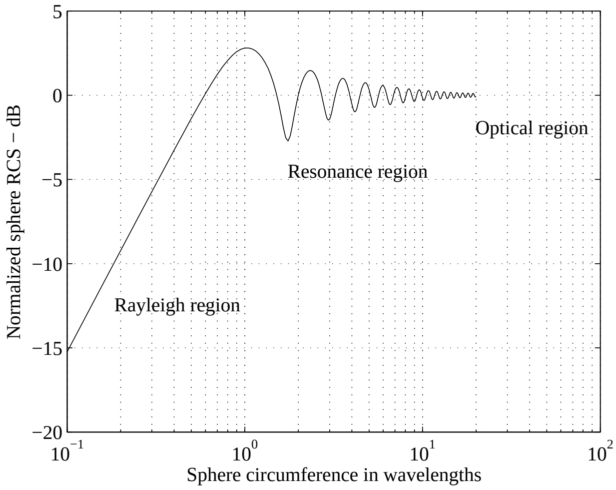

Fig. 4 Relationship of RCS and wavelength.

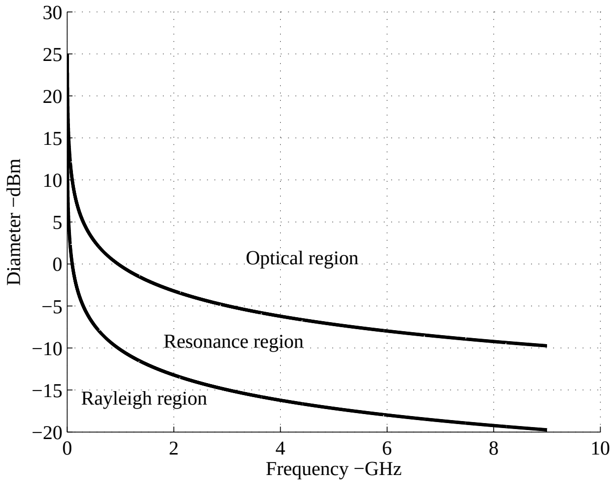

Fig. 5 Space debris RCS regional division.

For different sizes and different working wavelengths, the target RCS can be in different areas including the Rayleigh region, the resonance region and the optical region. An ideal piece of small space debris is assumed to be a metal ball, which has circumference L, and if $L > 10\lambda$, that is the target RCS and working wavelength show an optical property, then it is in the optical region; when $L < \lambda$, it is in the Rayleigh region; the resonance region is between the Rayleigh region and the optical region. The relationship is shown in Figure 4.

According to Figure 4, RCS in the resonance region changes in complicated ways, so radar systems are not normally designed to operate in this region (Skolnik 2008). We can also find the relationship between working wavelength and target equivalent sphere diameter as shown in Figure 5.

From the curve in Figure 5, space debris whose diameter is 10 cm is in an optical region when the working frequency is greater than 9.6 GHz, and is in the Rayleigh region when working frequency

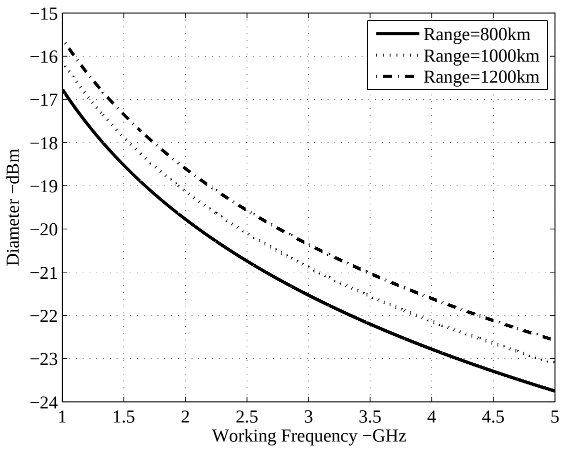

Fig. 6 The relationship between diameter of detectable debris and the working frequency.

is less than 0.95 GHz. When the diameter of space debris drops below 1 cm, it is all in the Rayleigh region when the working frequency is less than 9.6 GHz. Plus, because of water absorption and the influence of the atmosphere, a radar system that detects debris well has already determined that the working frequency is lower than the 5 GHz band (Yang & Shi 2008). So, for small pieces of space debris, especially those whose diameters are less than 1 cm, we can assume that normal radio telescopes used for detecting them operate in the Rayleigh region.

Experience has shown that in the Rayleigh region, the relationship between small target RCS and working wavelength can be described by the formula (Mahafza & Elsherbeni 2004) given in Equation (8)

$$\sigma_B = \frac{144 \cdot \pi^5 D^6}{\lambda^4}. \tag{8}$$

By combining with Equation (1), we can find the following formula

$$D = \sqrt[6]{\frac{R_{\rm R}^2 R_{\rm T}^2 \lambda^6}{144\kappa \cdot \pi^5}}. \tag{9}$$

A similar simulation to the one mentioned above was done and the parameters of TIRA and the Effelsberg Radio Telescope were used once again. Figure 6 shows the curves describing the diameter of the debris and working frequency at different heights. The basic rule is when the range from the target to the radio telescope is fixed, along with the increase in the working frequency, the size of the detected debris correspondingly reduces, so that the detection ability is enhanced. However, when the working frequency is fixed, if the range is enlarged and the size of debris that is detectable is reduced, then the trend is that the larger the range becomes, the detection ability that is available becomes weaker.

4 THE EFFECT OF TRANSMITTING PARAMETERS ON THE BISTATIC SYSTEM

As a complex system that transmits and receives, the parameters of the transmitter, such as transmitting power, antenna gain and beam angle, could be crucial to the overall performance of a bistatic system. The beam angle is calculated relative to the aperture of the antenna and affects the angular resolution. The related physical property is that if the beam angle of the radar is wide, the angular resolution will decay but the detection efficiency will increase. The antenna gain is related to the antenna aperture, antenna efficiency and the working frequency. These parameters partly rely on

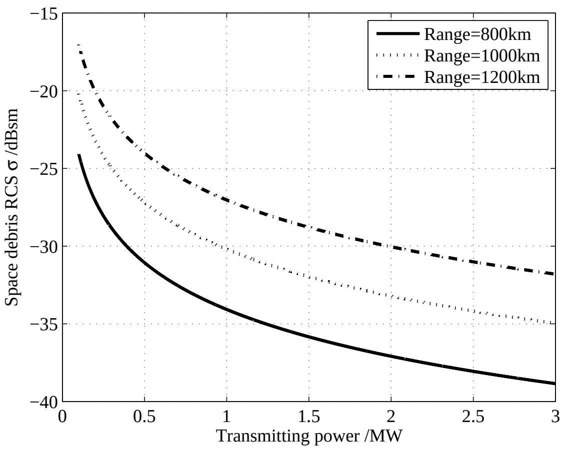

Fig. 7 Detectable RCS under different transmitting powers.

the radar antenna. Once the radar station is chosen, these parameters will be fixed. The transmitting power is calculated relative to the radar transmitter. A space surveillance radar could be equipped with more than one transmitter. In this section, we would like to discuss the relationship between transmitting power and the detection capability of the system.

The formula for a bistatic space debris observation system could be rewritten as

$$\sigma_B = \frac{(4\pi)^3 K T_s B_n (\mathrm{S/N})_{\min} L_{\mathrm{T}} L_{\mathrm{R}} R_{\mathrm{R}}^2 R_{\mathrm{T}}^2}{P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{R}} \lambda^2}. \tag{10}$$

This equation describes the relationship between the received RCS and the transmitting power. This equation seems to be complex. We could simplify it by defining a new parameter

$$\psi = \frac{(4\pi)^3 K T_s B_n (\mathrm{S/N})_{\min} L_{\mathrm{T}} L_{\mathrm{R}} R_{\mathrm{R}}^2 R_{\mathrm{T}}^2}{G_{\mathrm{T}} G_{\mathrm{R}} \lambda^2}. \tag{11}$$

It is easy to identify that the detectable RCS expresses a reciprocal relationship with transmitting power.

$$\sigma_B = \frac{\psi}{P_{\mathrm{T}}}. \tag{12}$$

If we set the size of space debris and the detectable RCS to be fixed, we can deduce that the forth root of observation range of the radio telescope is proportional to the transmitting power. The equation can be rewritten as follows

$$R_{\mathrm{R}}^4 \frac{\cos^2\theta_{\mathrm{R}}}{\cos^2\theta_{\mathrm{T}}} = \frac{P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{R}} \lambda^2 \sigma_B}{(4\pi)^3 K T_s B_n (\mathrm{S/N})_{\min} L_{\mathrm{T}} L_{\mathrm{R}}}. \tag{13}$$

Using the previous parameters of the simulated system ($f = 1.5$ GHz), the relationship between the power of radar output and the system performance was tested. The simulation results are shown in Figure 7 and Figure 8.

The two figures show the detectable size of space debris RCS for the radio telescope at distances in the range we are interested in and the detectable range for the fixed size targets under different transmitting powers. The results show that the transmitting power affects the detection capability of the radio telescope. It is clear that when the transmitting power increases, the smallest RCS value decreases and the farthest detection range increases.

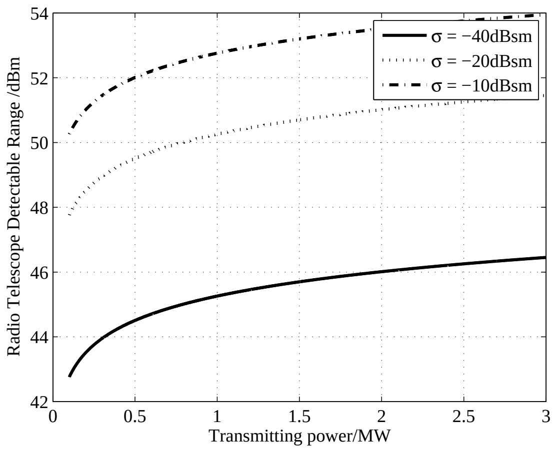

Fig. 8 Detectable range under different transmitting powers.

5 CONCLUSIONS

We analyzed the effect of detection ability on space debris observation using a radio telescope with different working wavelengths. The simulation results demonstrated that in a certain range of wavelength, as the wavelength decreased, the ability for space debris detection correspondingly improved, especially for small pieces. The work shown in this paper is useful for understanding bistatic space debris detection systems that have already been established and for the further construction of a space debris detection system that is based in China, which can improve the ability of space debris observation, especially for small pieces. The following work will address the problem of selecting a station for a bistatic detection system with a radio telescope in order to accelerate the process of constructing a small space debris detection system in China.

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References

di Martino, M., Montebugnoli, S., Cevolani, G., et al. 2004, Planet. Space Sci., 52, 325

Mahafza, B. R., & Elsherbeni, A. Z. 2004, MATLAB Simulations for Radar Systems Design (CRC Press), 529

Matney, M., Goldstein, R., Kessler, D., & Stansbery, E. 1999, Advances in Space Research, 23, 5

NASA-ODPO 2012, Increase in ISS Debris Avoidance Maneuvers, in NASA Orbital Debris Quarterly News, 16, 1

Shi, R. 2011, Space Debris Radar Detection Technology Assembly (in Chinese), 1, 7

Skolnik, M. I. 2008, Radar Handbook (McGraw-Hill), 3rd edn.

Thompson, T. W., Goldstein, R. M., Campbell, D. B., Stansbery, E. G., & Potter, A. E., Jr. 1992, Geophys. Res. Lett., 19, 257

Yang, P., & Shi, H. 2008, Modern Radar (in Chinese), 30, 36