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A Software for RFI Analysis of Radio Environment around Radio Telescope

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Abstract: Radio astronomy uses radio telescopes to detect very faint emissions from celestial objects. However, human-made radio frequency interference (RFI) is currently a common problem faced by most terrestrial radio telescopes, and it is getting worse with the development of the economy and technology. Therefore, it is essential to monitor and evaluate interference during the planning, construction, and operation stages of the radio telescope and protect the quiet radio environment around the radio astronomical site. In this paper, we present a software for an RFI analysis of the radio environment around the telescope. In this software, information has been collected, including the location of the site; the technical specifications, such as aperture and the frequency range of the radio telescopes; and the terrain around the site. The software and its modules are composed of telescope, geographic, and meteorological databases, and analysis modules of terrestrial and space-based RFI. Combined with the propagation characteristics of radio waves, we can analyze and evaluate RFI on the ground and in space around the radio telescope. The feasibility of the software has been proved by the experimental implementation of the propagation properties and RFI source estimation. With this software, efficient technical support can be expected for protecting the radio environment around the telescope, as well as improving site selection for planned radio astronomical facilities.

Keywords: radio telescopes; radio frequency interference; RFI analysis software

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1. Introduction

Radio astronomers study the Universe by detecting and analyzing radio waves emitted by celestial objects, such as stars, galaxies, and black holes. These signals are transmitted over long distances and require sensitive instruments to detect them. However, RFI from human-made sources, such as mobile phones, TV broadcasts, satellites, and other communication systems, can cause unwanted noise and signal interference, making it difficult to distinguish between the cosmic signals and the RFI. This can seriously degrade the quality of astronomical data, limit the sensitivity of observations, and even render some observations useless.

Therefore, radio astronomers take special care to position their telescopes in remote locations away from human-made RFI sources and use various RFI mitigation techniques to filter out or correct for interference. Setting up the Radio Quiet Zone (RQZ) is the most effective way to protect the electromagnetic environment from the terrestrial RFI [1]. Meanwhile, some large radio telescope facilities have established monitoring systems for terrestrial RFI and developed the satellite RFI databases and prediction systems to prevent interference from satellites [2–4].

In addition, astronomers also need to use some statistical algorithms or manual editing to further mitigate and flag the RFI-contaminated data [5–7]. With new technologies such as multi-beam and phased array feed receivers, the amount of astronomical data is increasing dramatically, and avoiding RFI or providing efficient flagging will be necessary for next-generation radio facilities. Some machine-learning-based RFI recognition methods have been applied and developed to reduce human intervention and increase accuracy [8–10]. This type of supervised learning method requires a large amount of training data to obtain accurate results and is mostly in the experimental stage.

In the field of RFI monitoring and estimation, Ref. [11] provided a scientific basis for the scientific site selection and radio astronomy protection operations through relevant electromagnetic environment tests. Ref. [12] validated the applicability of the ITU-R model in the Karst Region of Guizhou to support the analysis and assessment of the RFI around FAST. Ref. [13] focused on an intelligent monitoring and positioning system to reduce radio frequency interference (RFI) based on monitoring, identifying, and positioning RFI sources. Ref. [14] conducted electromagnetic compatibility studies on FAST, evaluated the RFI impact on mobile communication stations by conducting RFI tests, and proposed a permanent communication station to reduce RFI. Ref. [15] analyzed the radiation characteristics of the public communication stations around FAST and proposed interference avoidance and frequency coordination strategies based on cognitive theory.

In recent years, radio astronomical facilities in China have been rapidly developed. The Five-hundred-meter Aperture Spherical radio Telescope (FAST) has commenced astronomical observation since 2020, the 65-m radio telescope of Shanghai Astronomical Observatory (TM65) has obtained several extraordinary outcomes, and the Qitai 110m Radio Telescope (QTT) in Xinjiang is under construction [16–19]. Meanwhile, the development of the economy and electronic infrastructure near the telescope site has made the electromagnetic environment complex. Wang et al. studied the radio signal's fading characteristics in the Karst landscape environment and analyzed the radiation characteristics of the public communication stations around FAST RQZ [15,20]. In order to manage the surrounding electromagnetic environment more efficiently and balance the requirements of science and economics during the site selection and in the construction and operation phases of the radio telescope, we need to analyze and estimate RFI sources and protect the radio environment around the site.

In this paper, we describe an RFI analysis software that can estimate single or multiple RFI sources on the ground or in space around the radio telescope. Section 2 introduces the software and its modules, including the telescope, geographic, and meteorological database, and the analysis modules of terrestrial RFI and RFI in space. Section 3 presents the experimental implementation of the propagation properties and RFI source estimation. Section 4 gives a conclusion.

2. The RFI Analysis Software of Radio Environment around the Radio Telescope

This section introduces the RFI analysis software of the radio environment around the telescope. It is able to calculate the propagation loss based on the location of the RFI source and receiver, and it can further calculate the field strength and power at the receiver by combining the parameters of the RFI source and receiver. With this information, we can better manage the radio equipment or select the frequency range for observation in the site selection and operation phases of the telescope.

The schematic diagram is shown in Figure 1. It contains the database part and the functional part. The observatory database maintains the location of the site and the technical parameters of each telescope. The geographic and meteorological database gives the Digital Elevation Model (DEM) and radio meteorological environmental data. The RFI sources database offers information on the location of stationary RFI sources, the orbits of sources in space, and their operating parameters. The RFI analysis module provides terrestrial and space-based RFI analysis functions and radio wave propagation characteristics analysis for single or multiple RFI sources.

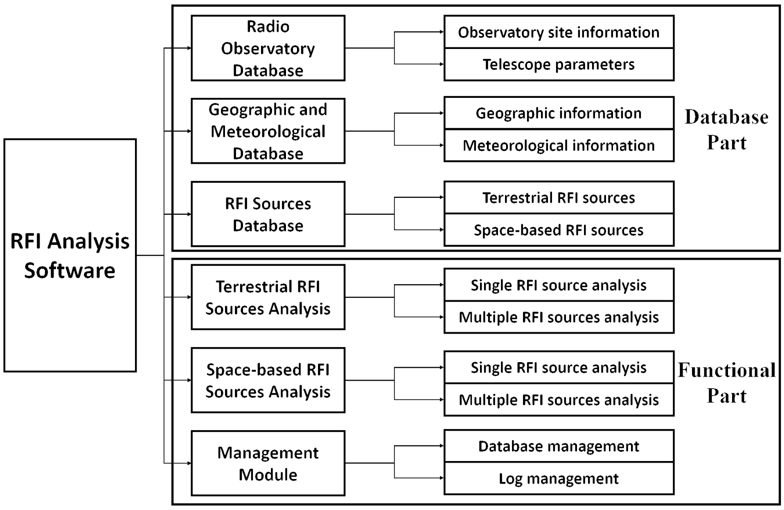

Figure 1. The schematic diagram of the RFI analysis software.

The software is developed on the Visual Studio platform using the C++ development language. It provides a friendly human–machine interface, keeping the interface simple and highlighting the system's main functions. The user interface is divided into two main parts: the menu bar and the map area, where the menu bar provides shortcut buttons for all functions of the software, and the map area carries out station marking and effective display. The software interface is designed in a simple style and can be operated in a guided manner according to the user's functional requirements.

Figure 2 shows the specific architecture of the software, which is designed in a layered approach, with four layers, including the application layer, the core layer, the support layer, and the physical layer.

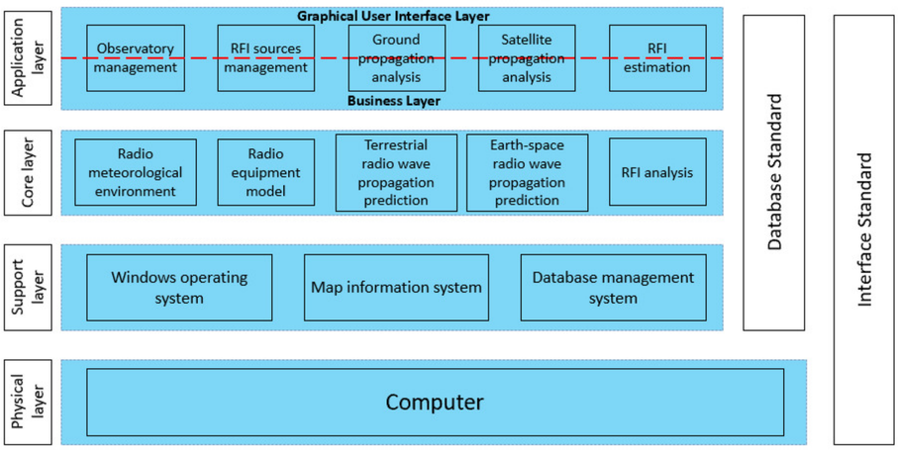

Figure 2. The specific architecture of the RFI analysis software.

The application layer is at the top of the architecture and consists of the graphical user interface layer and the business layer. The graphical user interface layer is responsible for receiving various parameter configuration commands from users and providing a consistent access interface for users, as shown in Figure 3. The business layer provides reusable business function modules, and the implementation of this layer and the graphical user interface layer results in a message-driven mechanism to communicate through a custom set of messages and exchange data information through memory. The functional modules of the application layer mainly include astronomical observatory management, RFI source management, terrestrial point-to-point/area propagation characteristics analysis, satellite point-to-point/area propagation characteristics analysis, etc.

The core layer mainly provides the underlying methods for each functional module of the business layer, including radio meteorological environment modeling, radio equipment modeling, terrestrial radio wave propagation prediction, Earth–Space radio wave propagation prediction, and RFI analysis. This layer provides various kinds of data and analysis results for each functional module. The interaction with the business layer adopts the API interface method, which provides a unified access interface for users and communicates with the upper layer through the interface function.

The support layer provides the required basic service environment for the upper layer, including the Windows operating system, map information system, and database management system. The operating system provides process services, thread services, interface units, etc. The map information system provides the geographic information required by the software. The database management system realizes the storage and management of antenna, equipment data, and radio wave propagation environment data.

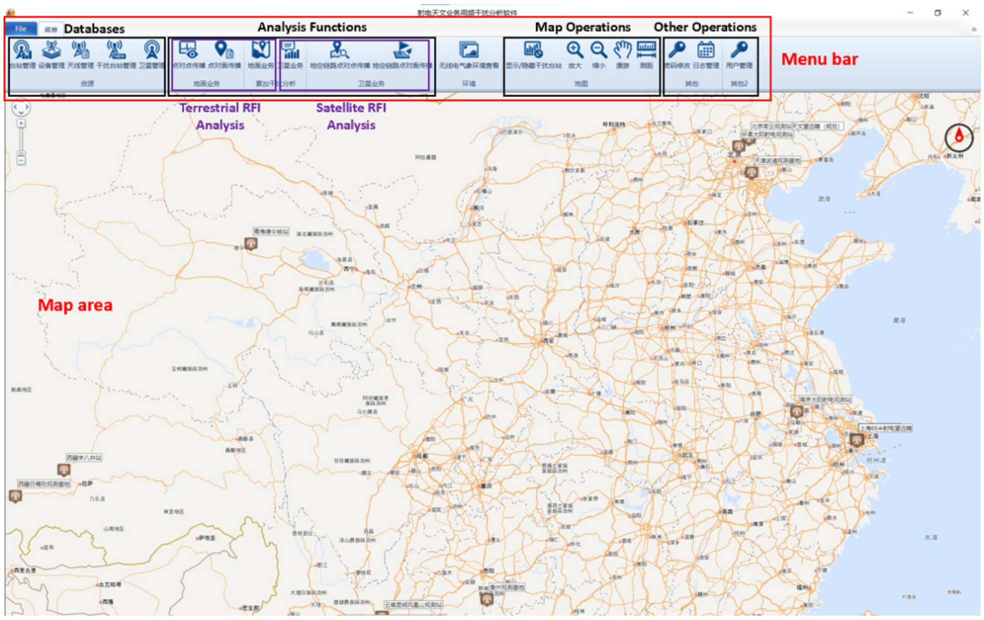

Figure 3. The graphical user interface of the RFI analysis software.

2.1. Databases

The radio observatory database has a hierarchical design, where one observatory may have multiple telescope systems, and one telescope system may also have multiple antennas. It contains the name, the longitude and latitude of the observatory site, and the equipment parameters, including receiving frequency range, aperture, gain, beam pattern, and polarization. Users can add, delete, modify, and query observatory sites, telescope systems, and antenna equipment.

The geographic database provides the 3 arc-sec accuracy DEM with a longitude range from 70° E to 135° E and a latitude range from 10° N to 55° N. A DEM is a 3D computer graphics representation of elevation data to represent terrain or overlaying objects, commonly of a planet, moon, or asteroid. DEMs are used often in geographic information systems and are the most common basis for digitally produced relief maps. The geographic data will be loaded and used to construct the transmission loss model between the RFI transmitter and the receiver.

The meteorological database consists of a ground dielectric constant, conductivity, atmospheric refractive index and gradient, atmospheric temperature, atmospheric humidity, atmospheric pressure, etc. The ground electrical parameters include ground conductivity and dielectric constant, which are determined by measuring the ground wave propagation field strength and time delay from the transmitting source, and then using the ground wave propagation characteristics for inversion. The atmosphere parameters, such as pressure and temperature, are obtained by analyzing meteorological data from 752 terrestrial meteorological stations in China, 120 space-based stations, and more than 600 terrestrial stations in the neighboring areas of China for the past 20 years. The meteorological data required for calculation are mainly selected from the annual statistical data of the ITU, and the parameters are shown in Table 1. Combined with parameters such as the location of the proposed link, antenna height, and percentage time, our software predicts the basic transmission loss not exceeded for a given percentage of an average year based on the radio meteorological data.

Table 1. The parameters in the meteorological database.

No.	Parameter Name	Unit
1	Vertical reflectivity gradient [21]	N-units/km
2	Average sea level value of surface reflectivity [21]	N-units
3	Average annual difference in the values of the reflectivity at the surface and 1000 m above the surface [21]	N-units/km
4	Wet term of the surface reflectivity [21]	ppm
5	Surface water vapor density [22]	g/m^3
6	Mean annual rainfall amount [23]	mm
7	Ratio of convective to total rainfall amount [23]	-
8	Probability of rainy 6-hours periods [23]	%
9	0 degree isotherm height [24]	km
10	Mean rain height [24]	km

The RFI sources database records the terrestrial and space-based RFI sources. Terrestrial RFI data offer the location, frequency range, power, and main lobe angle. Satellite RFI data offer the orbit calculated by the Two-Line Elements (TLE), the antenna beam pattern, the frequency range, and the power. When performing RFI analysis, users can manually add new RFI sources or select RFI sources from the database.

2.2. RFI Analysis Module

We construct the RFI analysis module with these databases to analyze the propagation characteristics and interference situations for different RFI sources. The RFI analysis module supports the analysis of a single RFI source for a single receiver or an area, which can be used to evaluate additional electronics around the telescopes and provide a basis for site selection, respectively. Moreover, the analysis of RFI sources can be terrestrially fixed or satellite services, as shown in Table 2.

Table 2. Scope of application of different types of wave propagation calculation models.

No.	Model Name	Supported Frequency Range	Services
1	Terrestrial radio wave propagation prediction model [25]	30 MHz∼50 GHz	radio, mobile communication, television, radar
2	Earth–Space radio wave propagation prediction model [26–30]	1 GHz∼55 GHz	communication, navigation, radio, television

The terrestrial model facilitates the prediction of propagation characteristics within the troposphere, spanning a frequency range from 30 MHz to 50 GHz. This model considers the main transmission mechanisms within the troposphere, including propagation close to the surface of the Earth, anomalous propagation due to stratified atmosphere, troposcatter propagation, and propagation via sporadic-E reflection. Utilizing numerical analysis techniques for synthesis, the model enables the prediction of transmission loss [25,31]. A practical propagation prediction model will then be derived by further combining domestic experimental data and analysis results.

Compared to free-space propagation, several propagation effects may require consideration when calculating the propagation loss for Earth–space paths: tropospheric effects (including gaseous absorption, and attenuation and depolarization by rain and other hydrometeors), ionospheric effects (such as scintillation and Faraday rotation), and local environmental effects (including attenuation by buildings and vegetation). Moreover, the prediction methods for Earth–space telecommunication systems vary depending on the specific service involved, including broadcasting-satellite systems [27], maritime mobile systems [28], land mobile systems [29], and aeronautical mobile systems [30]. In the case of space-to-Earth paths for broadcasting systems, the propagation attenuation factor $A(f)$ is calculated by the formula, and the unit is dB [26]:

$$A = A_{\rm bs}(f) + A_{\rm sc}\,(p,f) + A_{\rm gas}\,(f) + \sqrt{A_{\rm st}^2\,(p,f) + [A_{\rm rain}\,(p,f) + A_{\rm cloud}\,(p,f)]^2} \quad (1)$$

$A_{\rm bs}$ is the antenna attenuation factor, $A_{\rm sc}$ is the ionospheric atmospheric attenuation, $A_{\rm gas}$ is the atmospheric gases attenuation, $A_{\rm st}$ is the troposphere scintillation attenuation, $A_{\rm rain}$ and $A_{\rm cloud}$ are the attenuation factors of rain and cloud, respectively, f is the frequency, and p stands for the time percentage of each parameter.

In practice, the software will combine models based on the service type and frequency range, RFI source location, and electromagnetic wave propagation mode to calculate the propagation loss and field intensity. The next section gives some experimental RFI analysis for terrestrial and satellite RFI sources.

3. Experimental Implementation of the RFI Analysis Software

In this section, we present the experimental implementation of the software for propagation analysis and RFI estimation. Both the terrestrial and satellite RFI parts include the point-to-point and point-to-area functions. The point-to-point analysis is used to guide the installation and application of radio transmitters. The emission power of the equipment is derived from the measurement in the microwave darkroom, then the measurement results are loaded into the software to obtain the interference level in different locations. The point-to-area analysis is used for radio telescope site selection. It is able to calculate the distribution of the interference level of an existing RFI source to an area. Thus, the part with the lowest interference intensity is selected as the alternative site.

3.1. Terrestrial RFI Analysis

The characteristics analysis of the point-to-point radio wave propagation needs to set the transmitting and receiving point information: the user can choose from the database or add new sites, equipment, and antennas. The input information includes the site location, transmitting equipment operating frequency, power, antenna main lobe azimuth and elevation angle, receiving equipment name, sensitivity, and antenna main lobe azimuth and elevation angle. The radio meteorological environment around the transmitting and receiving points is also obtained from the database, and the results are calculated using the algorithm model.

For multiple-RFI-sources analysis, we integrate the received power over a time period of T. The power received from an interferer during observation can be expressed as follows:

$$I = \frac{1}{N}\sum_{i=1}^{N}\frac{P_t(i)\cdot G_t(i)\cdot G_r(i)}{L_p(i)} \quad (2)$$

where I is the interference power in the reference bandwidth at the receiver input averaged over the observation period T, N is the number of samples in the integration time T, $P_t(i)$ is the transmitting power level in the radio astronomy service bandwidth at the input to the antenna, $G_t(i)$ is the gain of the transmitting antenna in the direction of the radio astronomy antenna, $G_r(i)$ is the gain of the radio astronomy antenna in the direction of the transmitter, and $L_p(i)$ is the propagation loss at instant i.

Table 3 and Figure 4 show the computing results of the point-to-point propagation characteristics analysis. The example uses a communication station as the RFI source, which operates at 870 MHz and is located at (106°37′4.0005″ E, 25°37′45.010″ N). The left part shows the plot of the analytical results: the variation in field strength and topography versus distance from the transmitter. The right table gives the corresponding computing results. Compared with the free-space propagation loss, our algorithm further takes into account the terrain and atmosphere, and the calculated field strength is lower and more in line with the actual situation.

Table 3. The point-to-point analytical results for terrestrial RFI source.

Distance (km)	Altitude (m)	Field Strength (dB μV/m)	Free-Space Propagation (dB μV/m)
0	1206	87.78	107.77
3.79	1104.3	33.03	76.21
7.57	1154.2	31.19	70.18
11.36	1091.7	18.79	66.66
15.15	1198.3	25.4	64.16
18.93	1103.4	20.8	62.23
22.72	1017	21.43	60.64
26.51	823.9	13.64	59.3
30.29	837.9	−13.46	58.14
34.08	903	0.05	57.12

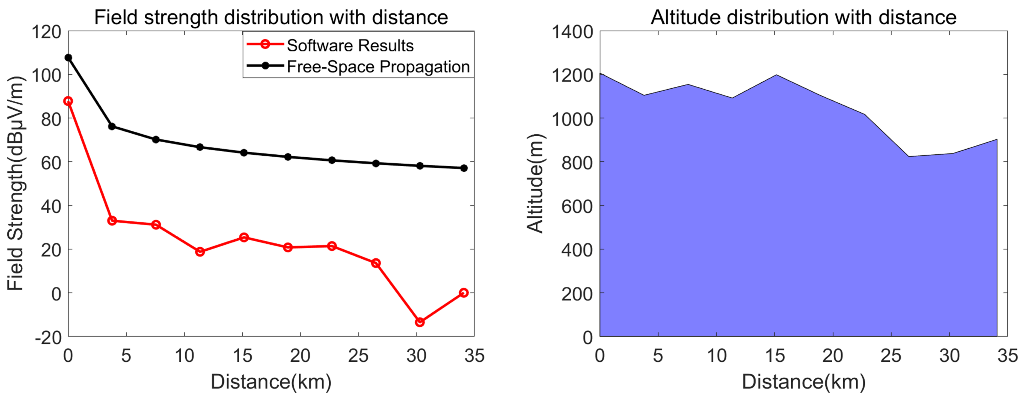

Figure 4. The point-to-point analysis for terrestrial RFI source.

The characteristics analysis of point-to-area radio wave propagation requires setting the transmitting point and receiving area information, where the transmitting point can also be loaded from the database, or added by the user. The receiving area can be obtained by manually entering the latitude and longitude range, or by selecting an area on the map.

Table 4 and Figure 5 show the results of the point-to-area propagation characteristics analysis. The left part gives the distribution of the RFI source field intensity in the selected area. The table on the right gives the corresponding latitude, longitude, altitude, distance from the RFI source, field strength, and propagation loss of the different sampling points in the selected area.

Table 4. The point-to-point analytical results for terrestrial RFI source.

Longitude (°E)	Latitude (°N)	Distance (km)	Altitude (m)	Field Strength (dB μV/m)	Propagation Loss (dB)
106.14119	26.20192	69.885	1744	4.477	169.987
106.14119	26.24359	67.256	1751	5.465	168.97
106.14119	26.28526	64.878	1760	6.457	167.978
106.14119	26.32692	62.739	1771	7.42	167.015
106.14119	26.36859	60.878	1784	8.304	166.13
106.14119	26.41026	59.321	1796	9.129	165.306
106.14119	26.45192	58.092	1804	9.712	164.722
106.14119	26.49359	57.213	1803	9.949	164.486
106.14119	26.53526	56.701	1783	9.718	164.717
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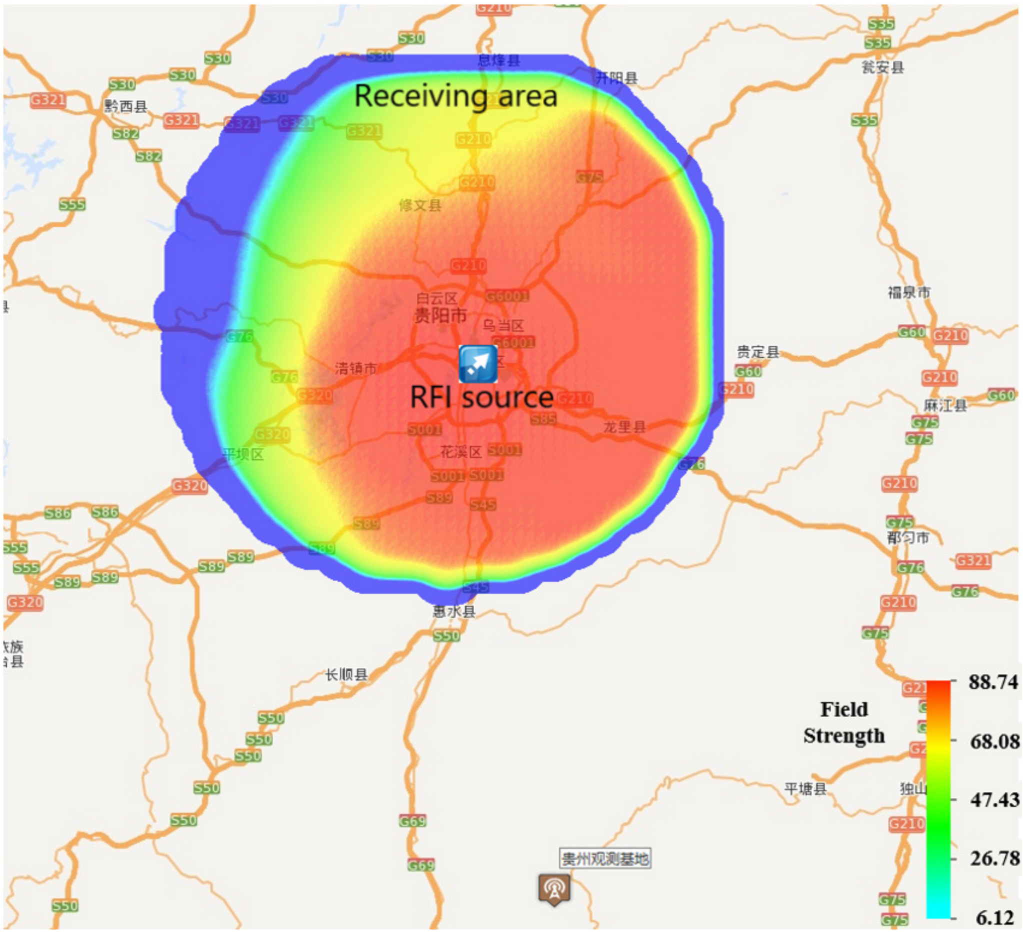

Figure 5. The point-to-area analysis for terrestrial RFI source.

Figure 6 shows the compared results of the software analysis and the practical test. The transmitting site is in Hanglong Town, Guizhou Province, and the receiving site is at the FAST site. The practical test results (black line) cover 0.1–1.7 GHz. It can be seen that there is a high agreement between the analytical results of our model (red line) and the actual measurements, showing that our model is more practical than the free-space propagation model (blue line).

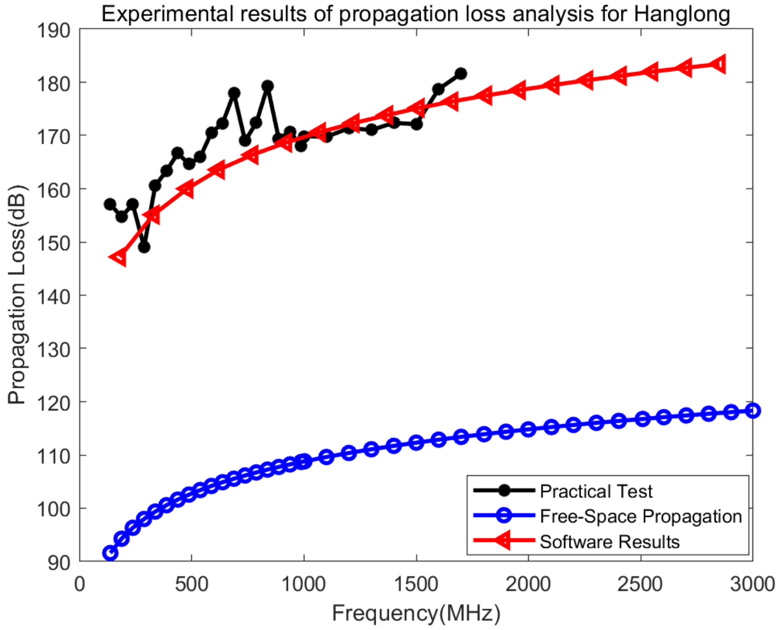

Figure 6. The analytical results of propagation loss from Hanglong to FAST.

3.2. Satellite RFI Analysis

The operation of the satellite RFI analysis function is similar to that of the terrestrial analysis function. Satellite point-to-point radio wave propagation characteristic analysis requires the input of transmitting and receiving equipment information, which can be selected from the database or added manually. The input includes satellite information: name, operating frequency, power, main lobe shape and pointing angle[1] [2], and receiver information: name, location, sensitivity, main lobe azimuth and elevation angle. The corresponding radio meteorological parameters are also retrieved from the database, and the results are calculated using the appropriate algorithm model.

Figure 7 shows the analytical results of the satellite RFI point-to-point propagation characteristics. It gives the variations in the transmission losses of GPS_BIIF_4, GPS_BIIF_9, and GPS_BIII_2 to the receiving device with time. Furthermore, the computing results also can be output as a table.

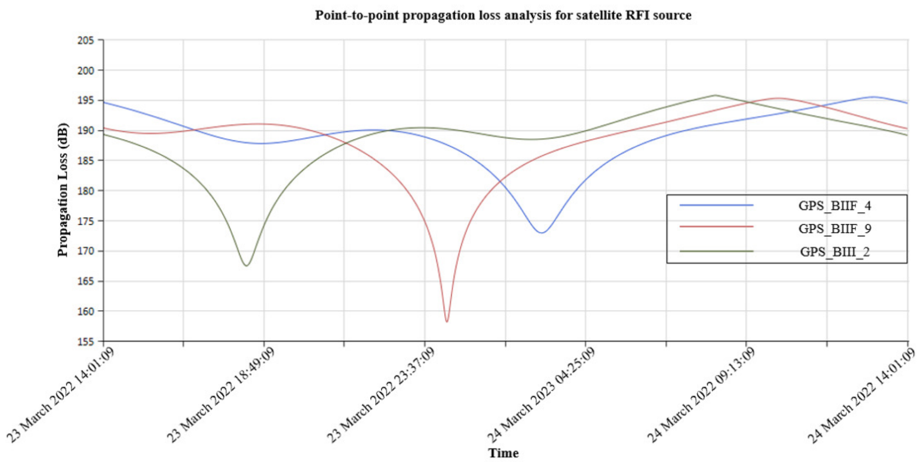

Figure 7. The point-to-point analysis for satellite RFI source.

In reality, interference of the satellite received by radio telescopes is usually the result of multiple satellites acting simultaneously. ITU-R M.1583-1 gives a method for calculating radio telescope interference from non-geostationary orbiting satellites [32]. However, it does not take into account the propagation loss between the satellite and the telescope. Our software combines the estimation method and propagation loss model to give a more realistic estimation.

Figure 8 shows the RFI estimation for multiple satellites including individual satellites and synthetic results. The corresponding time, satellite position, and interference power information can be saved as a table.

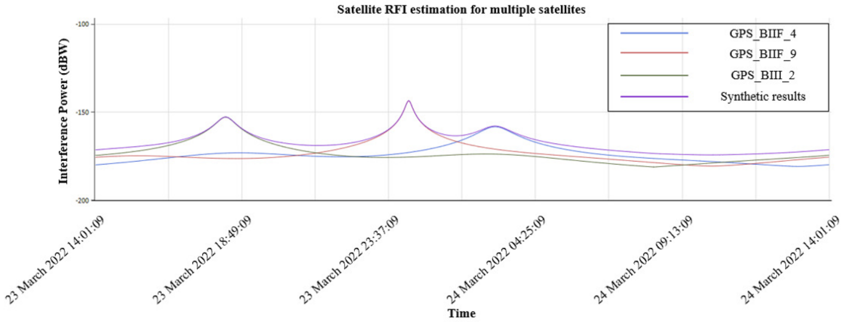

Figure 8. The results of satellite RFI estimation.

In this section, we present the main function of the software, including the propagation loss field strength computing for both terrestrial and satellite RFI sources. Furthermore, we compare the estimated results with actual tests for point-to-point terrestrial RFI sources. The experiments show that our models give identical results to the actual test and are more accurate compared with the free-space model.

4. Conclusions

In conclusion, we have constructed RFI analysis software for the radio environment around the radio telescope, combining complex information from celestial and satellite sources into a database. The database provides RFI sources, radio telescopes, and meteorological and geographic information, and users can add, delete, and modify the database for maintenance operations. The functional module provides the algorithms and interface to calculate the propagation loss for different kinds of RFI sources and environments. We further verified its accuracy by comparing the results of software analysis and practical tests.

With the software, we can use point-to-point analysis to evaluate the new transmitter and guide the subsequent installation and application of the transmitter. On the other hand, the software also provides point-to-area analysis to calculate the interference intensity distribution over an area, which can be useful for the selection of radio astronomical sites. The software is expected to be an efficient tool for protecting the radio environment around the radio telescope. In addition, interference analysis of satellites can guide us in choosing the observation time with minimum impact and support the division of spectrum resources in the future.

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Abbreviations

The following abbreviations are used in this manuscript:

RFI	Radio frequency interference
RQZ	Radio Quiet Zone
API	Application Programming Interface
DEM	Digital Elevation Model
FAST	Five-hundred-meter Aperture Spherical radio Telescope
TLE	Two-Line Elements

Notes

[1] https://celestrak.org/, accessed on 22 March 2022.

[2] https://www.space-track.org/, accessed on 22 March 2022.

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