Automated Implementation of Pointing Calibration for the Jiamusi 66-meter Deep Space Antenna Postprint

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Abstract

Antenna pointing accuracy constitutes a critical system parameter that directly influences mission execution quality. Pointing correction and calibration represent fundamental methodologies for precision enhancement. The existing pointing calibration procedures for the Jiamusi 66-meter deep space exploration system necessitate manual schedule formulation and manual execution of tracking scans across numerous celestial targets, requiring continuous repetition of target configuration and antenna manipulation throughout operations. A comprehensive pointing calibration automation software suite has been designed and implemented, enabling automatic planning of calibration schedules and autonomous execution of calibration observation plans, which enhances scanning efficiency, substantially reduces manual operation and intervention requirements, and liberates human resources. This system facilitates more uniform distribution of observation azimuth and elevation for calibration targets, thereby enabling the resultant data to more effectively improve pointing accuracy when utilized in pointing correction model solution computations.

Full Text

Automated Implementation of Pointing Calibration for a 66m Deep Space Antenna in Jiamusi

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Abstract

Antenna pointing accuracy is a key system parameter that affects mission execution quality. Pointing correction and calibration are fundamental approaches to improving accuracy. The existing pointing calibration process for the Jiamusi 66m deep space exploration system requires manual planning and manual tracking scans of numerous celestial objects, with repeated target setting and antenna operations throughout the process. This paper designs and implements a complete automated pointing calibration software system capable of automatic planning of calibration schedules and automatic execution of calibration observation plans, which improves scanning efficiency, greatly reduces manual operation and intervention, and frees up human resources. The system enables more uniform distribution of calibration targets in azimuth and elevation, allowing the results to better improve pointing accuracy when applied to pointing correction model calculations.

Keywords: Pointing calibration; Dynamic programming; Automation
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Introduction

Due to the extreme distance of deep space targets, antennas must have high pointing accuracy [1] to ensure accurate target acquisition and tracking [2]. When pointing accuracy is insufficient and the antenna cannot properly align with the target, mission execution can be seriously affected. As the Jiamusi 66m deep space antenna is the largest fully steerable antenna in China and represents a first-of-its-kind design and construction, improvement of pointing accuracy remains in an exploratory stage.

Current methods for improving antenna pointing accuracy address the problem from both hardware and model correction perspectives. To meet the antenna system's requirements for ultra-large hollow inner diameter and high precision in azimuth angle measurement components, photoelectric encoders are employed as the system' s angle measurement elements. The selected azimuth grating encoder achieves an encoding precision of [value], while the elevation photoelectric encoder achieves [value]. On the software side, an antenna calibration subsystem is established to perform angle calibration through radio source observations [3]. Using numerous precisely measured radio sources as references, a series of differential data between the antenna' s actual pointing azimuth/elevation and the radio source positions is measured. Through data processing, an error correction model is obtained.

The original calibration system for the 66m antenna used very few radio sources for establishing its correction model and employed a cross-scan observation mode for these sources to correct antenna pointing accuracy. This approach demanded high operational correctness rates, yielded unsatisfactory calibration results, and led to low work efficiency. Consequently, the pointing accuracy of the 66m antenna has not been well improved for an extended period.

During radio source observations, the entire calibration process requires manual planning, manual tracking according to the plan, radio source judgment, file record checking, and other operations. The observation cycle is long and demands extended operator attention. Additionally, due to non-uniform distribution of radio sources across the sky during manual task planning, there is a clear need for calibration software with good scanning effects and a high degree of automation.

The automated pointing calibration software designed in this paper primarily consists of two components: automatic planning and automatic scanning. The automatic planning component mainly implements automatic generation of calibration plans. Through the software interface, users can set the sky area to be scanned, visually observe the coverage of scanning points within the sky area, compare scanning point dispersion, and formulate plans using different scanning strategies. Users can select appropriate plans for actual observation while optimizing antenna switching time to improve operational efficiency. The scanning component primarily implements automatic execution of calibration plans. The software reads pre-formulated scanning plans and, following the principle of time compliance, executes the plans sequentially to automatically complete radio source tracking, scanning, and scanning file generation.

Pointing Calibration Principle

Antenna pointing error is defined as the deviation between two reference coordinate systems: the commanded position coordinate system and the antenna' s actual response position coordinate system. The purpose of antenna pointing calibration is to measure azimuth and elevation deviation values across the entire sky region and add these deviation values to the antenna' s azimuth and elevation commands [5].

The deviation between the two reference coordinate systems, E, is defined as follows: [equation description]

Where A_observed and E_observed are the observed azimuth and elevation angles when the antenna is actually pointing at the radio source, and A_command and E_command are the theoretical azimuth and elevation values calculated from ephemeris data for a given moment.

Assuming the selection of radio sources as shown in Fig. 1, each radio source is scanned and observed using the method illustrated in Fig. 2 to obtain the azimuth deviation ΔA and elevation deviation ΔE between the theoretical and actual positions of the radio source. These values are then substituted into the mathematical model of antenna pointing error [6]:

$$\Delta A = C + C\sin(A)\tan(E) + C\cos(A)\tan(E) + C/\cos(E) + C\sin(A)\tan(E) + C\cos(A)\tan(E) + C\sin(2A) + C\cos(2A) + C\sin(4A) + C\cos(4A)$$

$$\Delta E = C + C\cos(E) + C\sin(E) + C\cos(2E) + C\sin(2E) + C\cos(A)\tan(E) + C\sin(A)\tan(E) + C\cos(2A) + C\sin(2A) + C\cos(4A) + C\sin(4A)$$

Where A is the measured azimuth, E is the measured elevation, C is azimuth encoder zero-point error, C is azimuth tilt error, C is electrical axis deviation, and other C terms represent various systematic errors. Using least squares fitting on a batch of radio source pointing error measurement data, the coefficients C through C are solved and loaded into the antenna control unit software, thereby minimizing systematic antenna pointing errors.

During pointing calibration, the antenna performs azimuth and elevation scanning of radio sources as shown in Fig. 1. Signal intensity varies with position during scanning, indicating antenna pointing deviation as shown in Fig. 2.

Implementation of Automatic Planning Software

Based on stratified sampling principles, the pointing calibration planning process must satisfy the following principles to obtain more accurate and universally applicable pointing error parameters:

1. For pointing accuracy calibration, the entire sky region must first be scanned extensively to achieve comprehensive coverage.
2. During pointing accuracy calibration, scanning points should be as uniformly distributed across the sky region as possible.

Through collaboration with the National Astronomical Observatories, the number of available radio sources for observation increased from [original number] to [current number], solving the problem of insufficient calibration sources.

To improve antenna operational efficiency during calibration, switching time should be optimized to track and scan as many radio sources as possible in the shortest time.

Planning Algorithm Design

According to these planning principles, a sky-region-based scanning planning algorithm was designed. The sky region measured by antenna azimuth and elevation values is divided into several equally sized sky units, with the goal of performing one cross-scan on a calibration radio source in each unit whenever possible. The algorithm flow is shown in Fig. 3.

Users can set planning parameters including azimuth lower limit (az_start), elevation lower limit (el_start), azimuth upper limit (az_end), elevation upper limit (el_end), azimuth interval (az_diff), elevation interval (el_diff), scan start time (t_start), and scan end time (t_end). The software divides the sky region into azimuth_count × elevation_count units based on user parameters, where azimuth_count = az_diff / az_interval and elevation_count = el_diff / el_interval, with each unit size being az_diff × el_diff.

When a radio source completes scanning within a unit, that unit is considered scanned and will not be scanned again.

The algorithm proceeds as follows: First, the sky unit initialization algorithm resets the evaluation value for all unscanned units. Then, from the source catalog, it selects a radio source, calculates the source' s azimuth/elevation angles and pointing time when the antenna moves from its current position to the source, and calculates the corresponding sky unit based on the azimuth/elevation angles. If the unit has not yet been planned, the algorithm calculates an evaluation value (grade) and fills the source' s name and azimuth/elevation angles into the sky unit.

The evaluation value is calculated as: $grade = symbol \times \sqrt{((A\_source - A\_current)^2 + (E\_source - E\_current)^2)}$ where $symbol = 1$ if $(A\_source - A\_current)$ 0, otherwise -1.

After initialization, the software preprocesses the evaluation values of each unit according to user-selected star selection rules [7]. The star selection module then selects the next radio source to track and scan based on the processed evaluation values, repeating this process until planning is completed.

The software provides three built-in star selection rules for users to choose from based on actual needs.

Fig. 7 shows the interface of the automated pointing calibration program. Fig. 8 compares the star selection effects, demonstrating that in the same observation period, the new planning algorithm achieves a much more uniform distribution of calibration sources across the entire sky region compared to manual planning.

Implementation of Automatic Scanning Software

Based on the scanning plan file and following the principle of time compliance [8], the software automatically tracks radio sources in the plan sequentially. The algorithm flow is shown in Fig. 9.

The software can parse plan files generated by the automatic planning module or third-party plan files in agreed formats. It reads the radio source table in the plan, finds the first observation target later than the current moment, predicts the motion trajectory, and automatically completes a series of scanning and recording tasks. Upon reaching the predetermined time, it automatically completes radio source tracking, scanning, and scanning file generation, then seeks the next observation target, repeating this process until observation ends. The system automatically skips expired observation targets to ensure other targets can be completed according to plan.

Results and Conclusion

We have designed and completed a complete automated pointing calibration system that enables automatic planning of calibration schedules and automatic execution of calibration observation plans. This enriches and improves the functionality of the calibration subsystem for the Jiamusi 66m deep space exploration system, enhancing calibration work efficiency and antenna pointing accuracy.

Pointing accuracy, as a key parameter of deep space exploration systems, plays a crucial role in mission execution quality. After two months of actual tracking verification, the automated pointing calibration software designed in this paper meets all design requirements.

The system improves calibration work efficiency in several ways: the work cycle has been reduced, scanning efficiency has increased by [percentage] compared to the original system, and manual operations have been reduced from hundreds of times to just 2-3 times. The calibration process reduces the knowledge requirements for operators—personnel no longer need to understand radio astronomy or even master antenna pointing calibration principles, but only need to learn simple software operations, significantly reducing operational difficulty.

Through the new planning algorithm, calibration sources are distributed more uniformly across the sky region, enabling better improvement of pointing accuracy when results are applied to pointing correction model calculations. After calibration using this system, both azimuth and elevation pointing accuracy of the antenna have reached [value], representing more than a twofold improvement over the original accuracy.

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Abstract: As the key parameter of the antenna system, pointing accuracy affects the quality of task implementation. A basic way of improving accuracy is to do pointing correction and calibration, which needs plenty of work that must be done manually for the 66m deep space antenna in Jiamusi, including task planning and tracking scan of a large number of celestial objects. The operation of setting various targets and controlling the antenna have to be repeated hundreds of times. To increase the efficiency of target scanning, and to reduce manual operations, a complete set of automation software for pointing calibration has been designed and developed, which makes it possible for automatic programming and execution of calibration observation planning. The practical results show that the distribution of scanning sources can be more uniform, which helps to improve the accuracy of pointing corrections when applied in pointing correction model.

Keywords: Pointing calibration; Dynamic programming; Automation

Note: Figure translations are in progress. See original paper for figures.