

Postprint: Research on Adaptive Sidelobe Cancellation Method for Radio Interference Suppression with Precise Time Delay Compensation

Authors: Huang Da, Wang Zhuang, Cheng Zhu, Dong Liang, Su Yao

Date: 2017-10-11T00:00:00+00:00

Abstract

When navigation signals affect L-band radio observations as radio frequency interference, unlike interference in radar and communication domains, their power is typically below the noise floor, rendering traditional anti-jamming methods that exploit interference signal correlation ineffective, and resulting in a lack of effective evaluation metrics. To address these issues, a radio anti-interference system framework is constructed based on the radio signal processing pipeline, and from the perspective of radio observation data applications, two metrics—interference suppression degree and signal loss degree—are proposed. Additionally, an adaptive sidelobe cancellation method that suppresses the noise component in the interference subspace after precise delay compensation is proposed to mitigate the effects of navigation signals; simulation results demonstrate that this method can effectively suppress the impact of navigation signals on radio observations, outperforming traditional eigen-subspace based adaptive sidelobe cancellation methods.

Full Text

Preamble

Astronomical Research & Technology, Vol. 13, No. 3, July 2016

Research on Adaptive Sidelobe Cancellation Radio Interference Mitigation Method with Accurate Delay Compensation

Authors: Da Yi¹, Wang Zhuang¹, Cheng Zhu², Dong Liang³, Su Yao

¹ School of Electronic Science and Engineering, National University of Defense Technology, Changsha, Hunan

² Research Institution of Electronic Engineering, School of Electronic Science and Engineering, National University of Defense Technology, Changsha, Hunan

³ Yunnan Observatories, Chinese Academy of Sciences, Kunming, Yunnan
School of Electronic Engineering, Xidian University, Xi' an, Shaanxi

Abstract

When navigation signals affect L-band radio observations as radio frequency interference, they differ from interference in radar and communication systems in that their power is typically below the noise floor. This makes traditional anti-interference methods that rely on interference signal correlation ineffective and lacking in effective evaluation metrics. To address these issues, this paper constructs a radio anti-interference system framework based on radio signal processing workflows and proposes two metrics—interference suppression degree and signal loss degree—from the perspective of radio observation data applications. Additionally, an adaptive sidelobe cancellation method is proposed that suppresses the noise component of the interference subspace after precise delay compensation to eliminate navigation signal effects. Simulation results demonstrate that this method can effectively suppress the impact of navigation signals on radio observations and outperforms traditional adaptive sidelobe cancellation methods based on eigenspace.

Keywords: Radio astronomy interference mitigation; Adaptive sidelobe cancellation; Navigation signal; Variable fractional delay filter

Introduction

With the development of radio astronomy, the frequency bands allocated by the International Telecommunication Union for radio observations can no longer meet research demands. Radio telescopes frequently operate outside protected bands, making them susceptible to interference signals that severely limit observation quality. Navigation signals represent a common source of interference in L-band radio observations. According to documentation from the Global Positioning System and Beidou navigation satellites, the primary frequencies of navigation signals overlap with observation bands for radio sources at redshifts of 0.1–0.3. The main frequencies are: GPS L1: 1575.42 ± 1.023 MHz, L2: 1227.6 ± 10.23 MHz; Beidou B1: 1556.098 ± 2.046 MHz, B3: 1268.52 ± 10.23 MHz.

The minimum signal level specified in navigation system documentation corresponds to a power flux density of -196 to -201 dBw/(m²/Hz). In contrast, a 1 mJy radio signal has a power flux density of -290 dBw/(m²/Hz). Consequently, navigation signals are 89–91 dB stronger than radio signals at the receiver. Since navigation signals typically enter radio receivers through antenna sidelobes, the antenna receiving system significantly affects signal reception. After filtering and other processing stages, navigation signal power usually falls below the noise floor but remains above the radio signal power level.

Suppressing interference signals weaker than noise in radio observations presents the primary challenge addressed in this paper. For such weak navigation signals,

obtaining complete prior information is difficult, though signal characteristics like spatial properties and correlation can be exploited for interference mitigation. However, anti-interference processing inevitably impacts radio signal processing. Therefore, an effective anti-interference system must both utilize interference signal characteristics and minimize effects on radio signal processing.

Utilizing spatial characteristics requires multi-channel reception. Large single-dish radio telescopes and phased array antennas inherently possess multi-channel capabilities that can extract interference signal subspaces for elimination through orthogonal projection. However, when signal and interference subspaces are not orthogonal, observations suffer significant degradation. Auxiliary antennas are commonly employed to leverage interference correlation, enabling more accurate interference subspace estimation through methods such as orthogonal subspace projection and multi-array sidelobe cancellation.

Traditional eigenspace-based adaptive sidelobe cancellation methods from radar signal processing utilize the orthogonality between strong interference signal subspaces and noise subspaces to eliminate interference. For suppressing navigation signals weaker than noise in radio observations, the system framework must be reconstructed according to radio signal processing workflows, and the adaptive sidelobe cancellation method must be improved. Additionally, new evaluation metrics are needed to assess interference suppression and signal loss from the perspective of radio observation data applications.

Given the large apertures of radio telescopes, auxiliary antenna arrays must be deployed far from the main antenna, causing signal delays due to spatial separation that reduce navigation signal correlation. Therefore, precise delay compensation is essential. This paper first constructs an auxiliary antenna-based radio anti-interference system framework according to radio signal processing workflows. From the standpoint of radio observation data applications, it proposes interference suppression degree and signal loss degree as evaluation metrics. An improved adaptive sidelobe cancellation method suppresses the noise component of the interference subspace after precise delay compensation. Finally, Monte Carlo simulations analyze the effects of different parameters.

System Framework Construction

In large single-dish radio telescopes, suppressing navigation signals requires multi-channel auxiliary antenna arrays to exploit both spatial characteristics and correlation. Adaptive sidelobe cancellation, a common anti-interference technique, obtains optimal weight vectors for auxiliary arrays using interference correlation and spatial properties, synthesizing antenna patterns that produce nulls in interference directions.

To minimize impact on radio signal processing, the anti-interference system should operate independently. [Figure 1: see original paper] illustrates the framework of the radio anti-interference system based on auxiliary antennas. Typically, radio receivers have much wider bandwidth than interference sig-

nals (e.g., 300-800 MHz). The original radio receiver signal y enters the anti-interference system, where a bandpass filter selects the band containing navigation signals. For instance, the Shanghai Astronomical Observatory's 25 m telescope has an intermediate frequency of 442-2400 MHz, requiring selection of the appropriate IF signal.

After mixing and low-pass filtering, signal y enters a multi-channel data acquisition system. Delay compensation is critical: integer delays I are compensated through zero-padding, while fractional delays p are compensated using a variable fractional delay filter, yielding delay-compensated main antenna signal y' . The compensated y' and auxiliary array signals x_1, \dots, x_k undergo adaptive sidelobe cancellation processing. The processed signal is then added to y that has passed through a bandstop filter, producing the final interference-mitigated signal y'' through subsequent digital-to-analog conversion and upconversion.

Key challenges include: (1) Radio astronomy interference is typically below noise power, requiring specialized evaluation metrics; (2) Large telescope apertures necessitate distant auxiliary array placement, requiring precise delay compensation; (3) Complete prior information about navigation satellites is unavailable, though their relatively fixed orbits enable exploitation of spatial characteristics; (4) Eigenspace-based methods require improvement for sub-noise interference power levels.

Precise Delay Compensation Adaptive Sidelobe Cancellation Method

Performance Metrics

Traditional metrics like cancellation ratio cannot effectively characterize interference and signal component variations when interference power is below noise power. This paper proposes interference suppression degree $G_{\text{interference}}$ and signal loss degree G_{signal} , defined as:

$$G_{\text{interference}} = \max \left[\frac{R_{x\tilde{y}}(\tau)}{R_{x\tilde{y}}(\tau)} - 1 \right]$$

$$G_{\text{signal}} = \max \left[\frac{R_{S\tilde{y}}(\tau)}{R_{S\tilde{y}}(\tau)} - 1 \right]$$

where $R_{x\tilde{y}}$ represents the cross-correlation between auxiliary antenna signal x and main antenna signal \tilde{y} before/after interference mitigation, $R_{S\tilde{y}}$ represents the cross-correlation between reference radio signal S and main antenna signal \tilde{y} , and \max denotes the maximum value. The “ \sim ” symbol indicates post-mitigation quantities. These metrics directly reflect pattern changes in interference and signal directions.

Variable Fractional Delay Filter

To achieve precise delay compensation, this paper employs a non-iterative weighted least squares (WLS) variable fractional delay all-pass filter based on the Farrow structure. This approach approximates ideal filter coefficients using high-order polynomial approximations of fractional delays, simplifying the transfer function to a weighted sum of sub-filters and significantly reducing computational complexity.

The WLS method minimizes the error between the variable fractional delay filter's frequency response and the ideal fractional delay frequency response function across a specified passband and delay range:

$$J = \int_0^{\omega_p} W(\omega, p) |e^H(\omega, p)|^2 d\omega$$

where $e^H(\omega, p)$ is the error function, $W(\omega, p)$ is a non-negative weighting function, and p is the fractional delay factor. Taylor series expansion simplifies the integral. [Figure 2: see original paper] shows the phase delay error results for the WLS-VFD filter with p ranging from -0.5 to 0.5 and normalized frequency ω from 0 to 0.9 , demonstrating accurate fractional delay implementation across wide bandwidths.

Adaptive Sidelobe Cancellation Algorithm

The core problem is solving for the optimal weight vector. Traditional eigenspace-based methods project the weight vector onto the interference subspace using orthogonality between interference and noise subspaces. Accurate interference subspace estimation is crucial.

For p uncorrelated narrowband interferences received by k auxiliary elements with N snapshots, the estimated covariance matrix \hat{R}_x undergoes eigen-decomposition:

$$\hat{R}_x = \hat{U}_I \Lambda_I \hat{U}_I^H + \hat{U}_N \Lambda_N \hat{U}_N^H$$

where \hat{U}_I and \hat{U}_N span the interference and noise subspaces, respectively. When navigation signal power is below noise power, the largest p eigenvalues and remaining $k-p$ eigenvalues show small differences, making accurate interference subspace estimation difficult.

This paper improves traditional eigenspace-based adaptive sidelobe cancellation by exploiting noise stationarity to estimate and remove noise components from the interference subspace. The algorithm proceeds as follows:

1. Estimate signal delay τ based on navigation signal direction and spatial geometry between main and reference auxiliary antennas.

2. Calculate delay factor p from τ and sampling frequency; compensate integer delay I through zero-padding and fractional delay p via variable fractional delay filter.
3. Estimate auxiliary array covariance matrix \hat{R}_x and cross-correlation vector \hat{R}_{xy} using finite snapshots.
4. Perform eigen-decomposition of \hat{R}_x ; compute the average λ_{avg} of the $k-p$ smallest eigenvalues.
5. Subtract the diagonal matrix formed by λ_{avg} from \hat{R}_x to obtain noise-reduced R_x :

$$R_x = \hat{R}_x - \lambda_{\text{avg}}I$$

6. Re-decompose R_x to obtain improved U_I and compute the optimal weight vector:

$$w_{\text{opt}} = U_I U_I^H \hat{R}_{xy}$$

This approach removes noise components from the interference subspace, enhancing orthogonality and improving performance.

Simulation Results and Analysis

Simulation Setup

The main antenna model is based on the FAST 30 m demonstrator pulsar antenna. Since radio signal forms vary significantly across sources, a random signal with 1 mJy power spectral flux density represents the radio signal. The auxiliary array is a uniform linear array of omnidirectional elements with 0.09 m spacing. Beidou navigation signal C/A code at 1268.52 MHz serves as interference.

Monte Carlo simulations compare the proposed method with and without delay compensation against traditional eigenspace-based adaptive sidelobe cancellation. Parameters include main-to-auxiliary array distance, interference arrival angle, auxiliary element aperture, and element count. summarizes simulation parameters. To ensure statistical reliability, the Monte Carlo iteration count is determined using the law of large numbers with confidence level $\alpha = 0.0158$ and error $\epsilon = 0.03$, requiring 743 iterations.

Effect of Main-to-Auxiliary Array Distance

Increased separation causes greater signal delay, reducing navigation signal correlation. [Figure 3: see original paper] shows that interference suppression performance degrades with distance for both methods, but the delay-compensated method maintains 15 dB higher suppression than the uncompensated method. Signal loss G_{signal} remains similar regardless of delay compensation, with both

methods showing approximately 1 dB loss. The delay-compensated method consistently outperforms traditional eigenspace-based cancellation by 7-20 dB in interference suppression.

Effect of Arrival Angle and Element Aperture

Navigation signal power varies with arrival angle due to antenna pattern effects. [Figure 4: see original paper] demonstrates that as the arrival angle moves away from the main lobe, interference suppression decreases for all methods. The delay-compensated method maintains 7-20 dB better suppression than traditional methods across angles, while the uncompensated method only exceeds traditional performance within 1.5° of the main lobe. Signal loss is greater near the main lobe (within 2.5°) due to deeper nulling, with the proposed method showing approximately 3 dB higher loss than traditional methods.

Increasing auxiliary element aperture effectively raises interference-to-noise ratio. Both methods improve suppression with larger apertures, but the delay-compensated method maintains a 7-10 dB advantage over traditional methods when aperture exceeds 1.4 m. Signal loss differences between methods remain around 1 dB.

Effect of Observation Time and Element Count

Observation time (number of snapshots N) affects covariance matrix estimation accuracy, while element count influences null depth and interference cancellation capability. [Figure 5: see original paper] shows that interference suppression improves with longer observation times, with the delay-compensated method achieving 10-18 dB better suppression than traditional methods and 10-12 dB better than the uncompensated method. Signal loss G_{signal} stays within 1 dB.

As element count increases, both methods improve, but the delay-compensated method maintains a 14 dB advantage over traditional methods and outperforms the uncompensated method by a similar margin. Signal loss for the proposed method is approximately 1 dB higher than traditional methods across all element counts.

Conclusion

This paper addresses navigation signal interference in L-band radio astronomy by constructing an auxiliary array-based anti-interference system framework and proposing interference suppression degree and signal loss degree as evaluation metrics. An improved adaptive sidelobe cancellation method suppresses noise components within the interference subspace. Considering reduced navigation signal correlation due to spatial delays between the main antenna and auxiliary array, a non-iterative WLS variable fractional delay all-pass filter achieves precise delay compensation.

Monte Carlo simulations demonstrate that the proposed method improves interference suppression by 10-20 dB compared to traditional eigenspace-based adaptive sidelobe cancellation, with only 1 dB additional signal loss. Performance advantages are maintained across varying distances, arrival angles, element apertures, observation times, and element counts. The method effectively mitigates navigation signal interference while preserving radio astronomical data quality.

References

- [1] Hellbourg G, Trainini T, Weber R, et al. RFI subspace estimation techniques for new generation radio telescopes. Proceedings of the 20th European Signal Processing Conference (EUSIPCO 2012), 2012: 200-204.
- [2] Sardarabadi A M, van der Veen A J. Subspace estimation using factor analysis. IEEE 7th Sensor Array and Multichannel Signal Processing Workshop, 2012: 477-480.
- [3] Hellbourg G, Chippendale A P, Kesteven M J, et al. Reference antenna-based subspace tracking for RFI mitigation in radio astronomy. 2014 IEEE Global Conference on Signal and Information Processing (GlobalSIP), 2014: 1286-1290.
- [4] Warnick K F. Auxiliary antenna-assisted interference mitigation for radio astronomy arrays. IEEE Transactions on Signal Processing, 2011: 439-451.
- [5] Zhao Yongbo, Wang Zhihui, Zhang Shouhong. An eigenspace-based algorithm for adaptive antenna sidelobe cancellation. Aeronautical Computer Technique, 2004: 187-191.
- [6] Qin Shunyou, Li Guang, Zhang Lijun, et al. Measurement technology for 40 m radio telescope antennas. 2009 National Antenna Annual Conference: 1-61.
- [7] Zhang Hongbo, Mao Peifeng, Wang Min, et al. The 40 m radio telescope. Publications of National Astronomical Observatories of China, 2009: 187-191.
- [8] Deng Tianbo. Non-iterative WLS design of all-pass variable fractional-delay digital filters. IEEE Transactions on Circuits and Systems I: Regular Papers, 2012: 358-371.
- [9] Farrow C W. A continuously variable digital delay element. IEEE International Symposium on Circuits and Systems, 1988: 2641-2645.
- [10] Gao Jianjian, Cao Yang, Gan Hengqian, et al. Design, manufacture and test of the L-band feed for the FAST 30 m demonstrator. Astronomical Research & Technology—Publications of National Astronomical Observatories of China, 2015: 48-52.

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

Source: ChinaXiv—Machine translation. Verify with original.