ABCP 2026 Annual Conference: *Artificial Intelligence and Cyber Security Track*

GNSS Interference Detection and Mitigation Technologies

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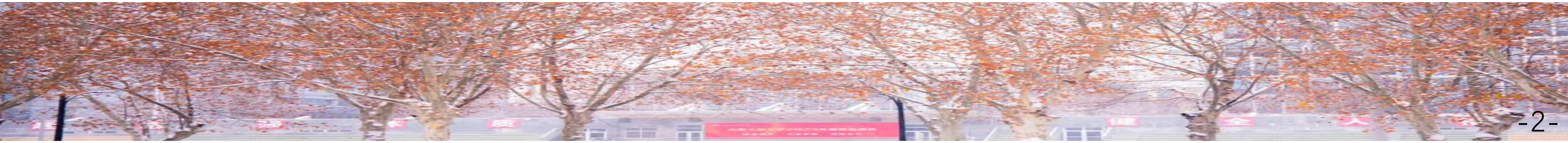
Outline

- Satellite Navigation Countermeasures
- GNSS Interference Detection based on TF Analyses
- GNSS Interference Detection based on Hough Transform
- GNSS Anti-Interference based on FrFT
- GNSS Anti-Interference based on FrFT & Notch Filtering



Satellite Navigation Countermeasures

Cornerstone of Space Technology

Economic Pillar

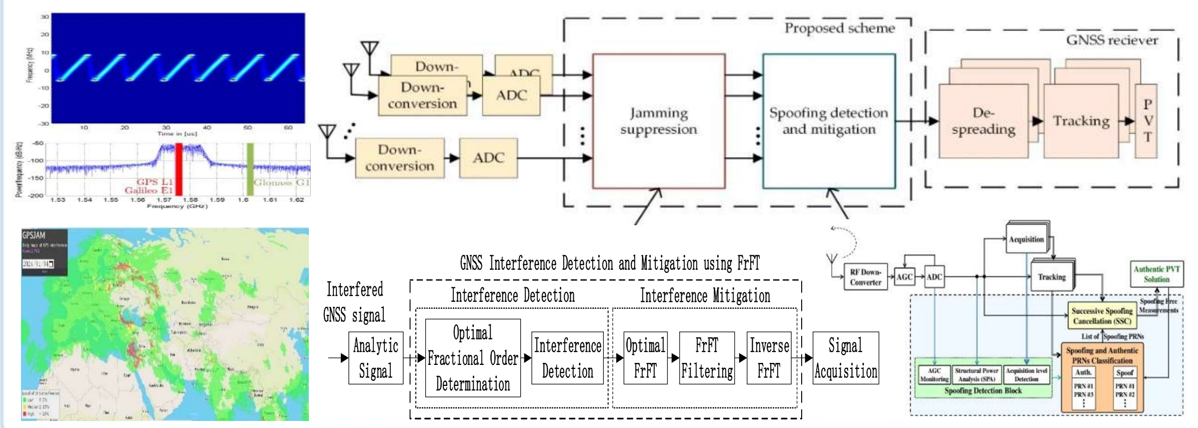
Scientific Battlefield

Industry Empowerment

- Satellite navigation has been widely used in intelligent transportation, autonomous driving, smart cities, search and rescue, satellite orbit determination, aircraft flight.
- Satellite navigation is particularly important for the development of space technology.
- GNSS signal processing and anti-interference have become the core technologies.

Support systems and multipliers for space technology

GNSS anti-interference - the main battlefield of modern scientific and technological development



GNSS empowers all industries

Satellite navigation research is crucial to the rapid rise of space technology and the leap-forward development of social economy.

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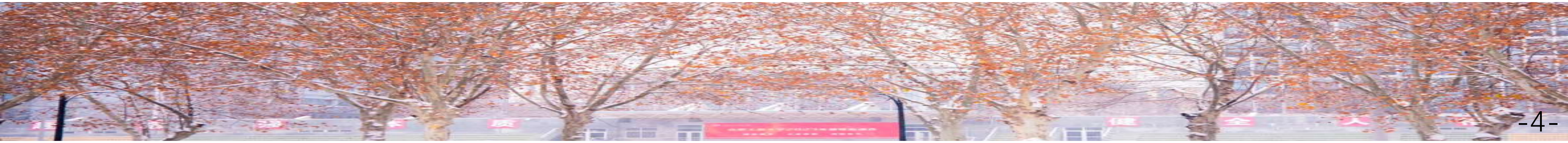


GNSS Interference Detection using Choi-Williams Transform

Choi-Williams Transform (CWT)

Spectrogram

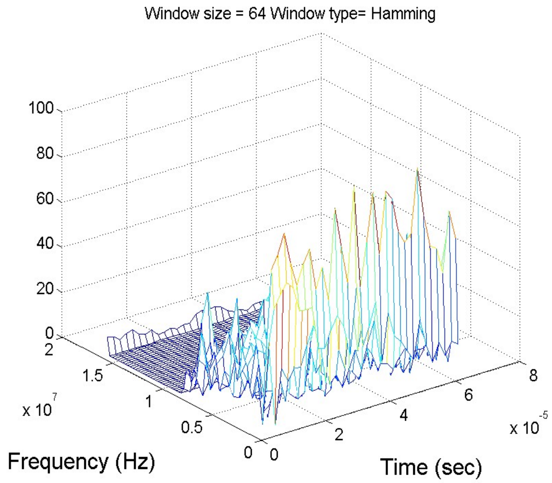
- The spectrogram is a visual representation of the spectrum of frequencies of a signal as it varies with time, which is computed using the Short-Time Fourier Transform (STFT).

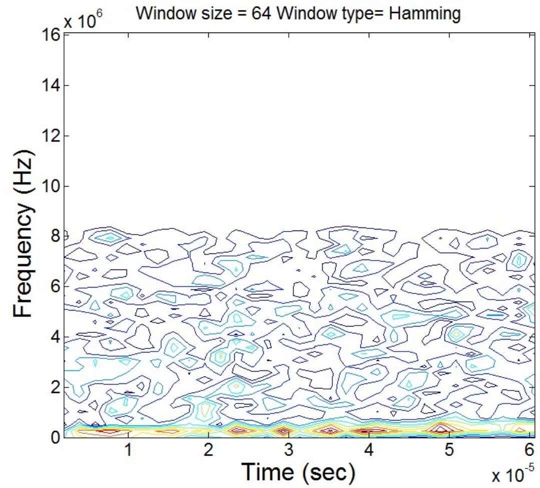
$$\mathrm{Spectrogram}(t,\omega)=\left|\int_{-\infty}^{\infty} y(\tau)\gamma(\tau-t)\mathrm{e}^{-\mathrm{j}\omega\tau}\mathrm{d}\tau\right|^2$$

- For a signal y(t), define its temporal standard deviation as Δt and its spectral standard deviation as Δf. The uncertainty principle can be expressed as the uncertainty principle states: $\Delta t \cdot \Delta f \geq \frac{1}{4\pi}$

- The spectrogram presents the time-frequency (TF) resolution trade off problem, providing poor localization properties in the TF plane.

The spectrogram of Galileo E1 OS signal with sweep interference by using a Hamming window of length L = 64 samples. C/No = 38 dB-Hz, JNR = -10 dB.



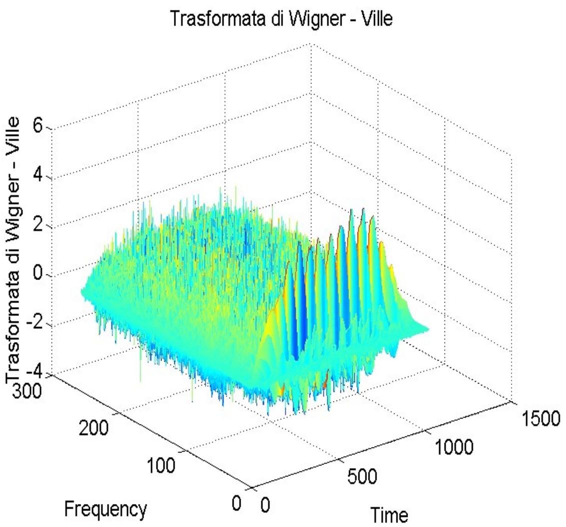


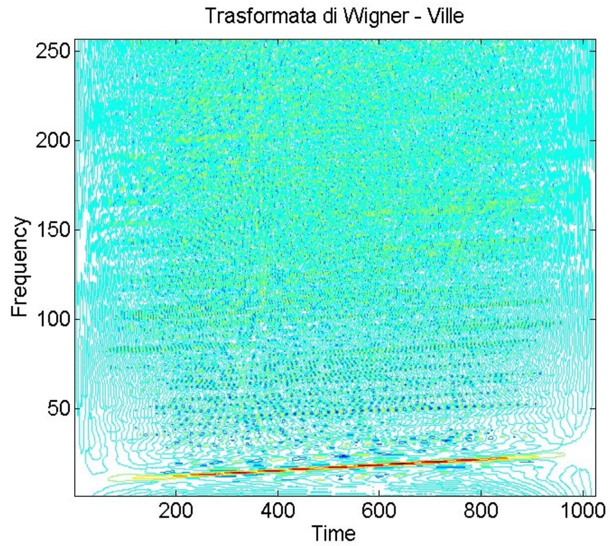
GNSS Interference Detection using Choi-Williams Transform

Wigner-Ville Distribution (WVD)

The **Wigner-Ville Distribution (WVD)** is a powerful tool in time-frequency (TF) analysis that provides a joint representation of a signal in both time and frequency domains, but it can introduce **cross-term interference** due to its quadratic nature.

$$WVD_y(t,f) = \int_{-\infty}^{\infty} y\left(t+\frac{\tau}{2}\right) y^*\left(t-\frac{\tau}{2}\right) \mathrm{e}^{-\mathrm{j}2\pi f\tau}\,\mathrm{d}\tau$$





The Wigner-Ville distribution of Galileo E1 OS signal with sweep interference. C/N0 = 38 dB-Hz, JNR = -10 dB-Hz.

The WVD shows improved TF localization properties but **presents very severe cross interfering terms problems** due to interaction of different frequency components.

GNSS Interference Detection using Choi-Williams Transform

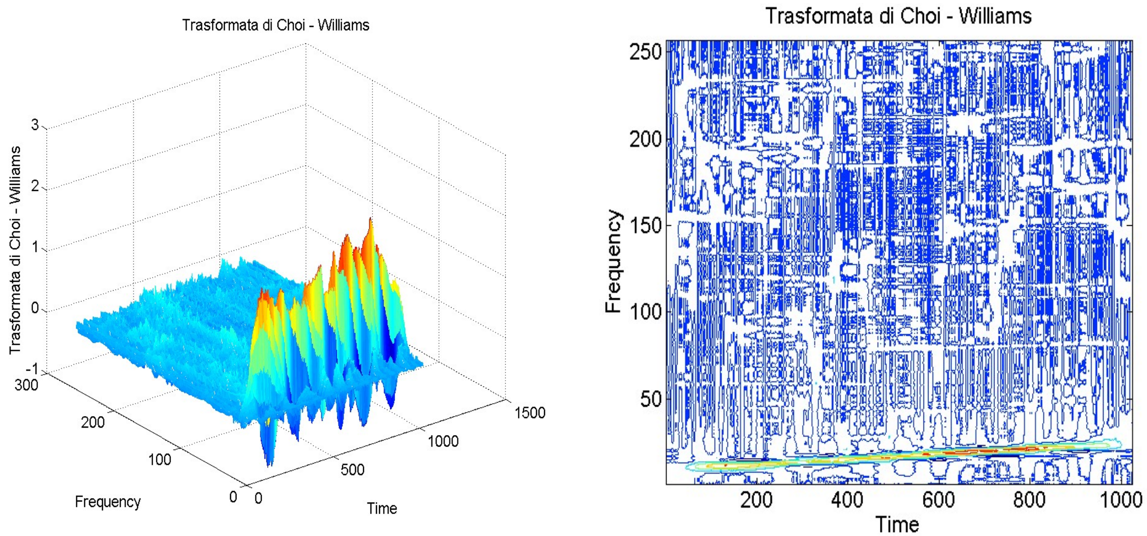
Choi-Williams Transform (CWT)

- To mitigate cross-term interference in the Wigner-Ville Distribution (WVD), **the Choi-Williams kernel function** can be incorporated into Cohen's class of time-frequency distributions, yielding the Choi-Williams Transform (CWT).

$$CWT_y(t,f) = \iint_{-\infty}^{\infty} \varphi(\theta,\tau)\, AF_y(\theta,\tau)\, \mathrm{e}^{-\mathrm{j}2\pi(f\tau-\theta t)}\, \mathrm{d}\theta\, \mathrm{d}\tau$$

where: $\phi(\theta,\tau)$ is the Choi-Williams kernel: $\varphi(\theta,\tau) = \mathrm{e}^{-\frac{(\theta\tau)^2}{\sigma}}$

$AF_y(\theta,\tau)$ is the ambiguity function of $y(t)$: $AF_y(\theta,\tau) = \int_{-\infty}^{\infty} y\left(t+\frac{\tau}{2}\right) y^*\left(t-\frac{\tau}{2}\right) \mathrm{e}^{\mathrm{j}2\pi\theta t}\, \mathrm{d}t$



The CWT of Galileo E1 OS signal with sweep interference. C/N0 = 38 dB-Hz, JNR = -10 dB-Hz.

The CWT partially mitigates the cross terms in the TF plane by using an effective attenuating Choi-Williams kernel function.

- Kewen Sun*, Wei Liu, HuaminXu, Yang Dongkai, Interference Detection based on Time-Frequency Analysis for GNSS Receivers, *ION GNSS+ 2013 Conference*, Nashville, Tennessee, USA, September 16-20, 2013

GNSS Interference Detection using Joint Hybrid TF Analysis

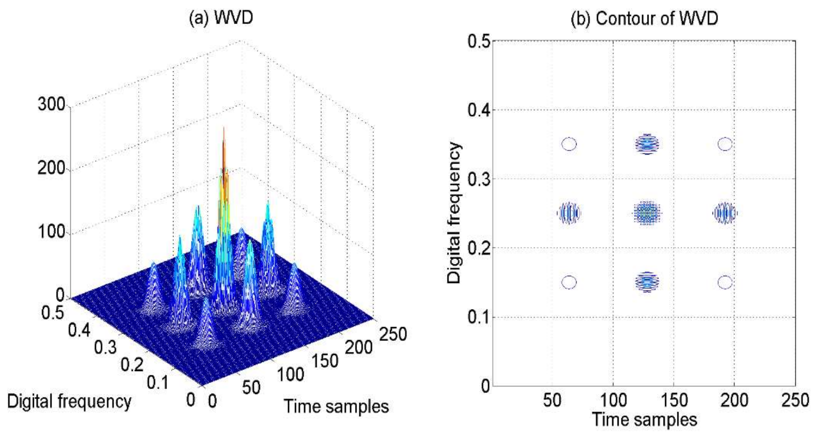
Joint Hybrid TF Analysis based on SPWVD and CWT

Pseudo Wigner-Ville Distribution (PWVD)

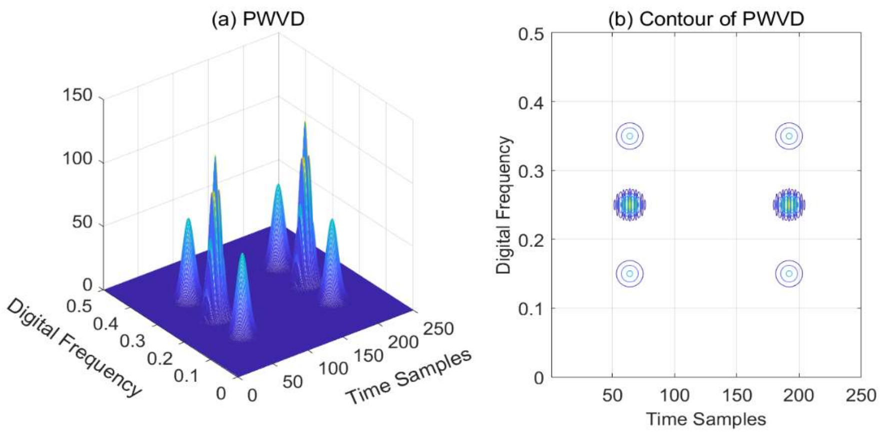
- The Pseudo Wigner-Ville Distribution (PWVD) is a modified version of the standard Wigner-Ville Distribution (WVD) that applies **a smoothing window in the frequency domain** to reduce interference terms while maintaining reasonable time-frequency resolution.

$$PW_y(t,f)=\int_{-\infty}^{\infty} h(\tau)y\left(t+\frac{\tau}{2}\right)y^*\left(t-\frac{\tau}{2}\right)\mathrm{e}^{-\mathrm{j}2\pi f\tau}\mathrm{d}\tau$$

- The PWVD introduces a symmetric window $h(\tau)$ to limit the integration range, reducing cross-terms, but may still exhibit some residual interference.



The WVD of four Gaussian components' signal.



The PWVD of four Gaussian components' signal.

GNSS Interference Detection using Joint Hybrid TF Analysis

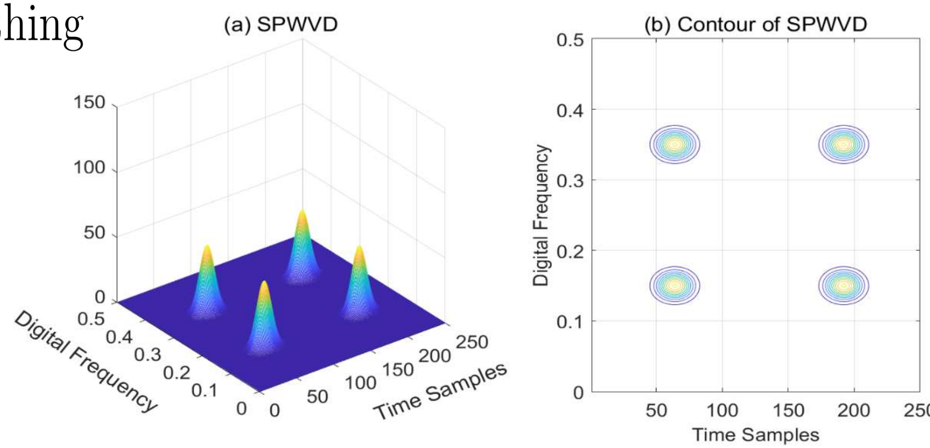
Smoothed Pseudo Wigner-Ville Distribution (SPWVD)

- Since the cross-terms with the WVD are strongly oscillating, the most effective way of removing such cross-term interference is to apply **two-dimensional low-pass filtering** in the ambiguity function domain, developing the smoothed version of pseudo WVD, that is Smoothed Pseudo Wigner-Ville Distribution (SPWVD).
- The SPWVD is a time-frequency analysis tool designed to reduce the interference terms present in the standard WVD while maintaining good resolution. **It applies smoothing windows separately to the time and frequency domains.**

$$\mathrm{SPWVD}_y(t,f)=\int_{-\infty}^{\infty}h(\tau)\Big[\int_{-\infty}^{\infty}g(u-t)y\big(u+\tau/2\big)y^*\big(u-\tau/2\big)\mathrm{d}u\Big]\mathrm{e}^{-\mathrm{j}2\pi f\tau}\mathrm{d}\tau$$

$$\mathrm{SPWVD}=\mathrm{Time\ Windowing\ (PWVD)}+\mathrm{Frequency\ Smoothing}$$

- Although the adoption of the smoothing window in SPWVD is beneficial to suppress the cross-terms in the TF plane, **it smears localized components, leading to less accurate TF localization of the auto-terms of the signal, as compared to the WVD approach.**



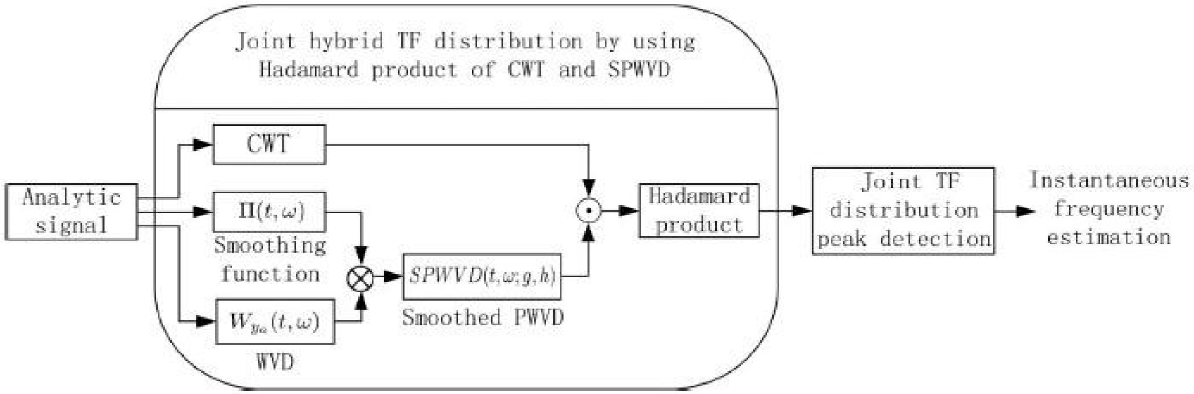
The SPWVD of four Gaussian components' signal.

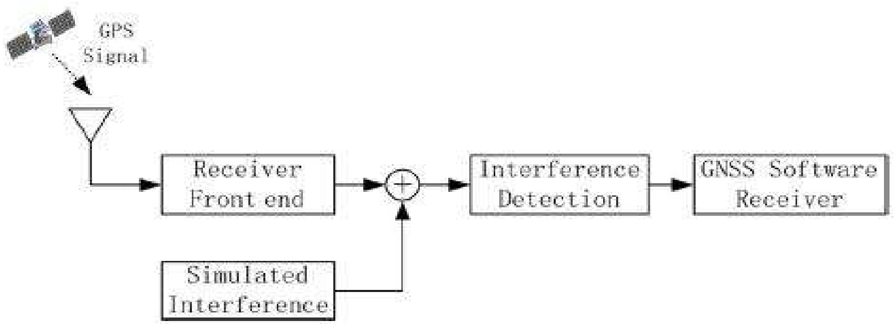
GNSS Interference Detection using Joint Hybrid TF Analysis

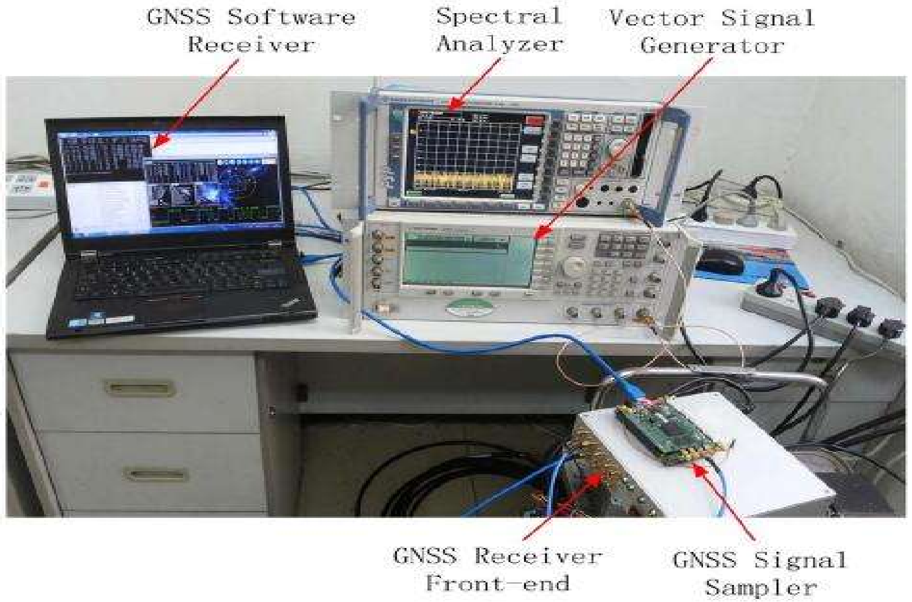
■ Hadamard Product of CWT and SPWVD

- To eliminate the cross-terms present in the quadratic TF distribution and to preserve good time and frequency resolutions at the same time, **a novel joint hybrid TF distribution based on the Hadamard product of CWT and SPWVD** has been proposed in interference detection for GNSS receivers.

$$M(t,\omega) = CWT(t,\omega) \odot SPWVD(t,\omega)$$

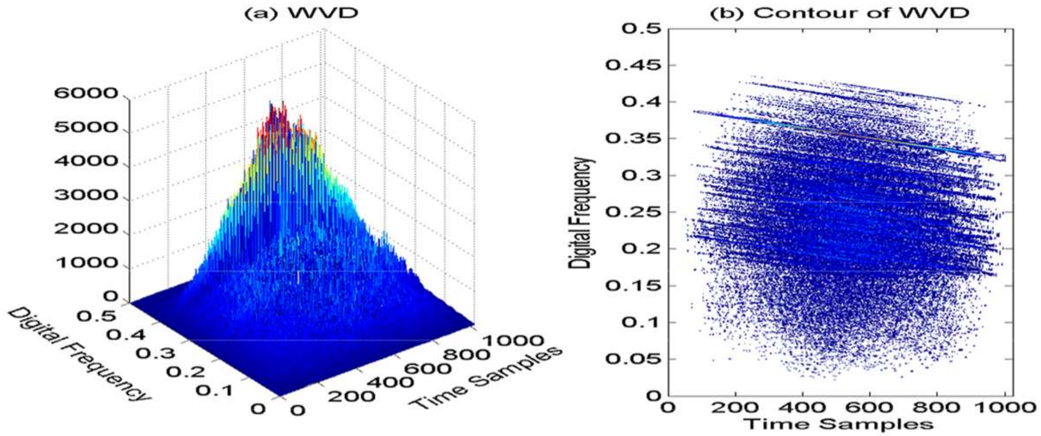




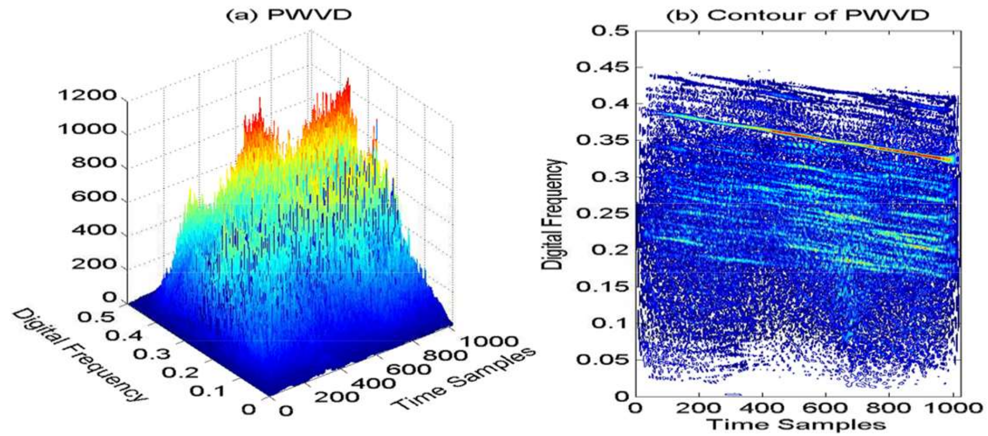


GNSS Interference Detection using Joint Hybrid TF Analysis

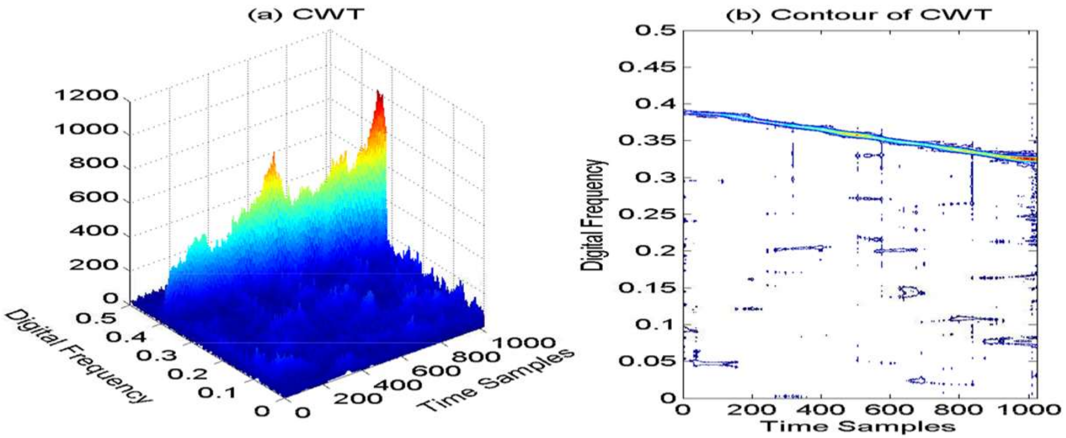
■ Sweep Interference Detection Results



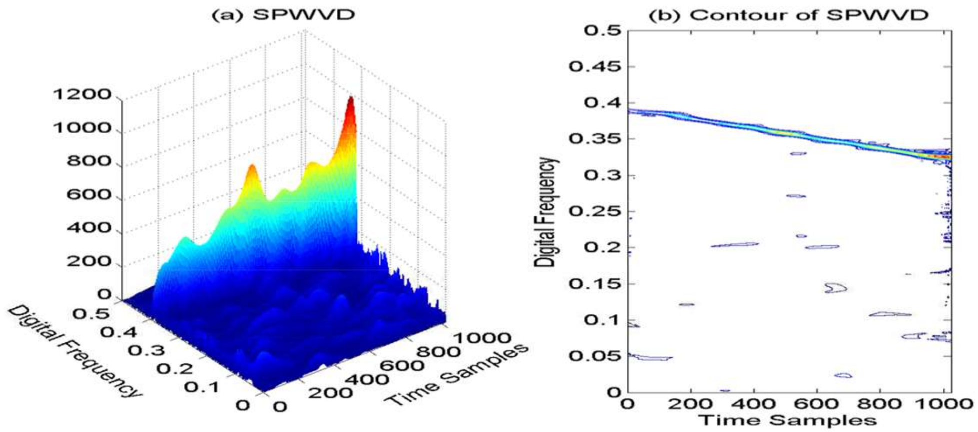
WVD of GPS L1-C/A signal with sweep interference. C/No = 46 dB-Hz, JNR = -8 dB.



PWVD of GPS L1-C/A signal with sweep interference.



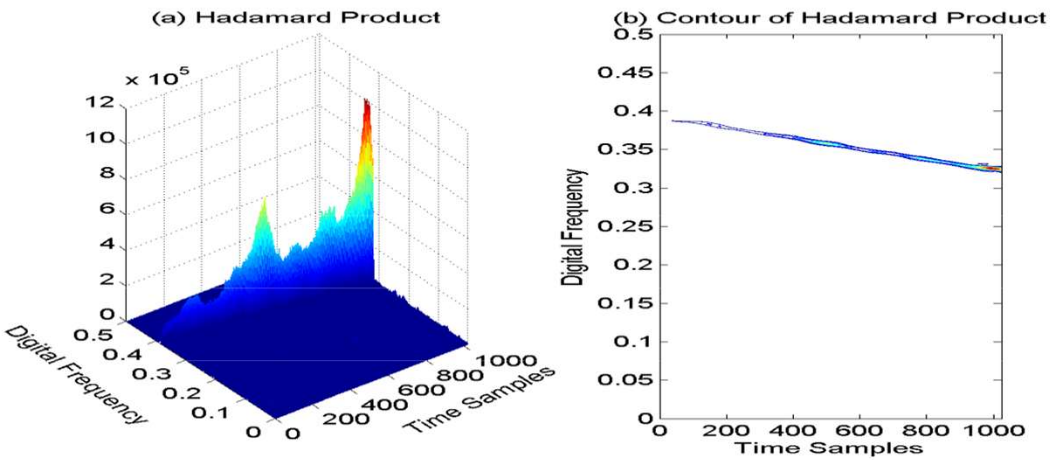
CWT of GPS L1-C/A signal with sweep interference.



SPWVD of GPS L1-C/A signal with sweep interference.

GNSS Interference Detection using Joint Hybrid TF Analysis

- The cross-terms are partially mitigated by the Choi-Williams kernel function, and the peaks of the CWT are clearly observed denoting the GNSS interference contribution.
- The adoption of the smoothing window in SPWVD effectively suppress the cross-terms in the TF plane, but it smears out localized components, leading to less accurate TF localization of the auto-terms of the signal compared to the original WVD.
- **The peaks of the joint hybrid TF distribution emerge as a line representing the contribution of the sweep interference while its values remain zero in the other area of the TF plane.**

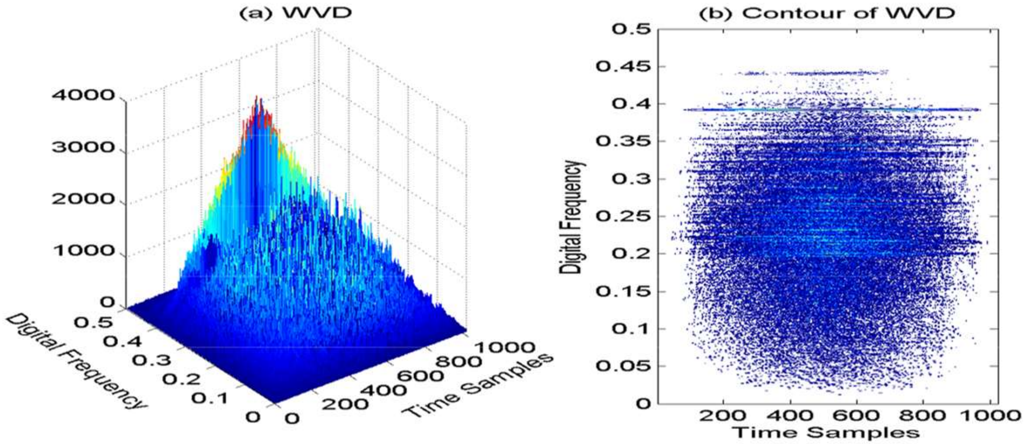


Hadamard Product of CWT and SPWVD for GPS L1-C/A signal with sweep interference. C/N0 = 46 dB-Hz, JNR = -8 dB.

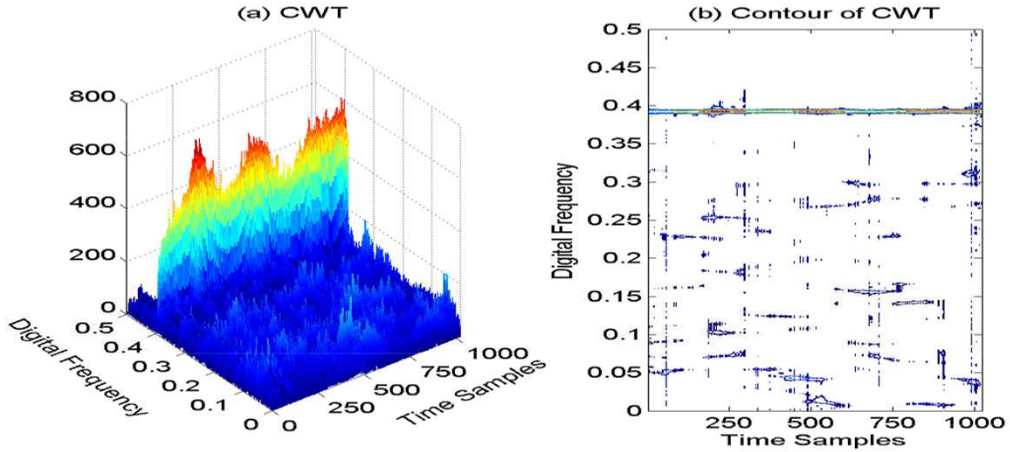
- Kewen Sun*, Min Zhang, Dongkai Yang, A New Interference Detection Method based on Hybrid Time-Frequency Distribution for GNSS Receivers, *IEEE Transactions on Vehicular Technology*, 2016, 65(11): 9057-9071

GNSS Interference Detection using Joint Hybrid TF Analysis

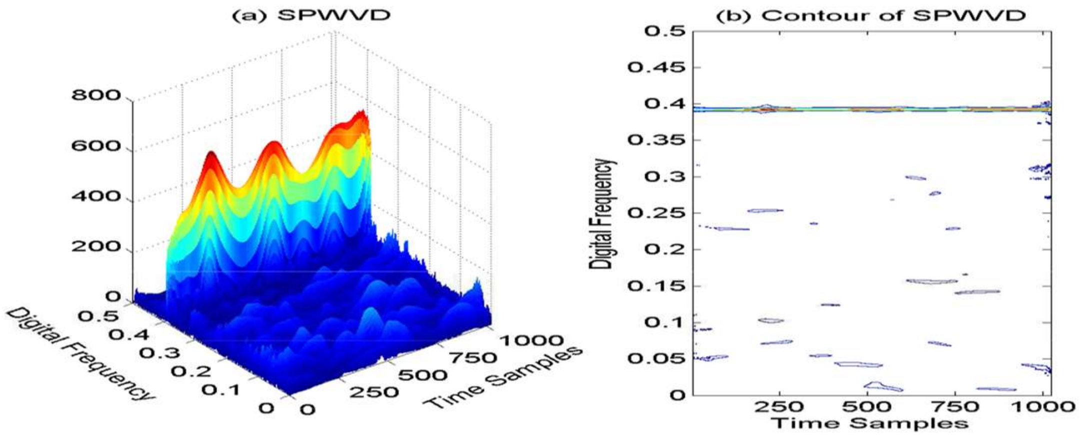
■ Continuous Wave Interference Detection Results



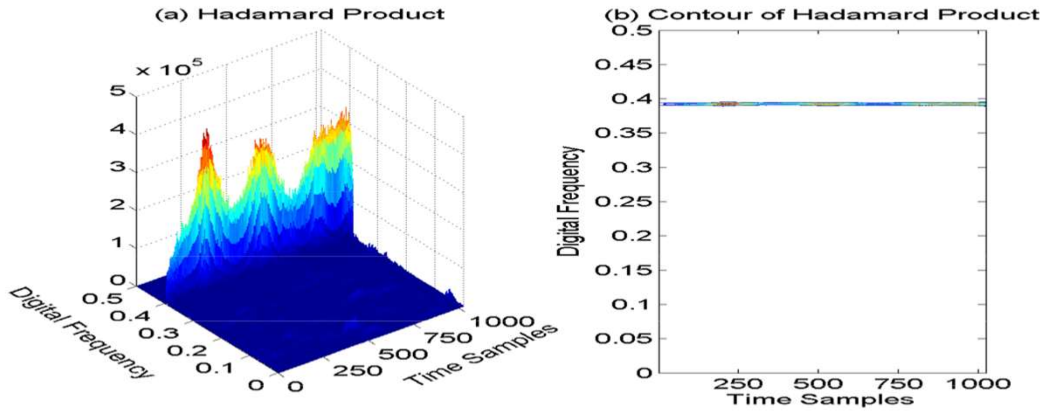
WVD of GPS L1-C/A signal in the presence of the CWI. C/N0 = 46 dB-Hz, JNR = -8 dB.



CWT of GPS L1-C/A signal in the presence of the CWI. C/N0 = 46 dB-Hz, JNR = -8 dB.



SPWVD of GPS L1-C/A signal in the presence of the CWI. C/N0 = 46 dB-Hz, JNR = -8 dB.

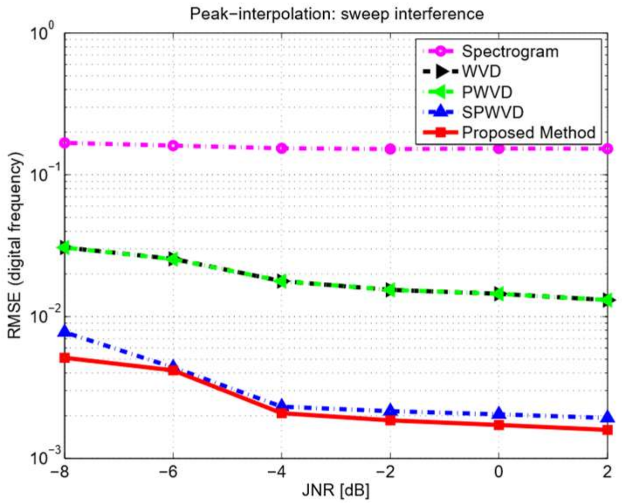


Hadamard Product of CWT and SPWVD for GPS L1-C/A signal with the CWI. C/N0 = 46 dB-Hz, JNR = -8 dB.

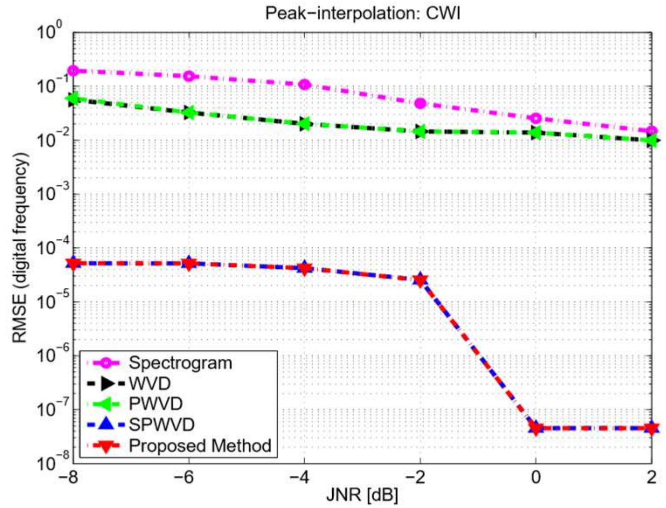
GNSS Interference Detection using Joint Hybrid TF Analysis

- The cross-interfering terms are effectively suppressed by using the SPWVD, but deteriorated TF localization properties are obtained.
- **The proposed joint hybrid TF analysis method completely eliminates the cross-terms present in the TF distributions, presenting good readability in the TF plane and preserving satisfactory TF resolutions.**

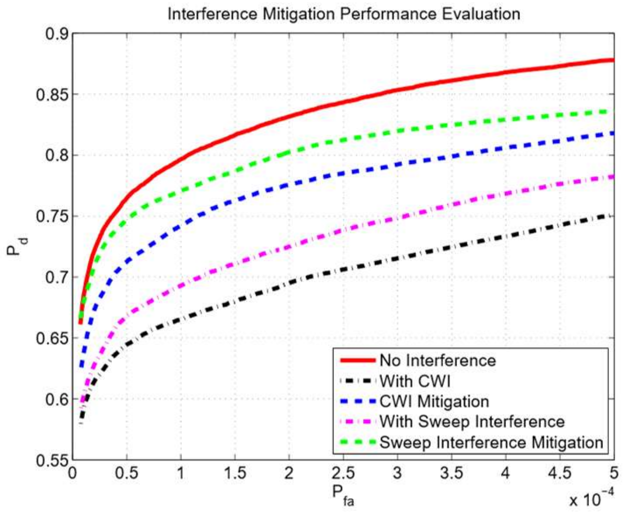
■ Statistical Performance Analysis



RMSE of the frequency estimation for the ***sweep interference*** *present in the received GPS L1-C/A signal .*



RMSE of the frequency estimation for the ***CWI*** *present in the received GPS L1-C/A signal.*



ROC curves in different signal scenarios. The coherent integration time is 2 ms, C/N0 = 37 dB-Hz, JNR = 15 dB.

- **GNSS interference estimation precision is nearly improved by 3 orders of magnitude; interference detection performance is improved by more than 15% with the proposed method.**

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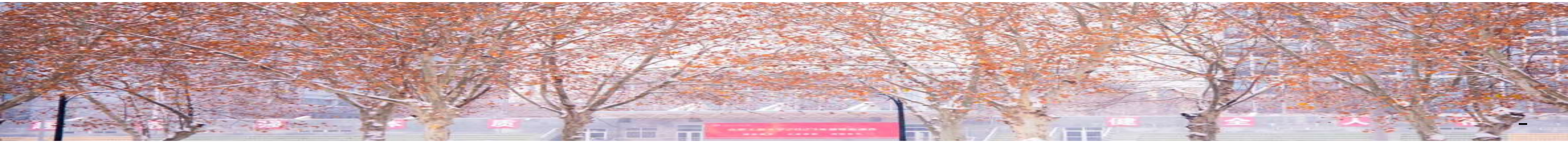
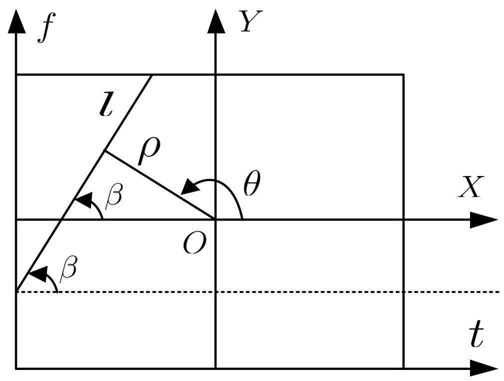


Rearranged Wavelet–Hough Transform Method

Wigner-Hough Transform (WHT)

- Hough transform can be used to detect the line of frequency modulation law for a given signal in the TF image space.

$$\mathcal{WHT}_y(\rho,\theta) = \iint_{-\infty}^{\infty} W_y(t,f)\,\delta\big(\rho - t\cos\theta - f\sin\theta\big)\,\mathrm{d}t\,\mathrm{d}f$$



Scheme of Hough transform

Hough Transform on Reassigned Scalogram

Step 1 - Continuous Wavelet Transform (CWT)

$$W_y(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} y(t)\,\psi^*\!\left(\frac{t-b}{a}\right)\mathrm{d}t, \quad a>0,\ b\in\mathbb{R}.$$

Step 2 - Reassignment to Time-Frequency Plane

The reassigned time t'(a, b) and frequency f'(a, b) are computed using gradients of the squared CWT modulus.

$$t'(a,b) = b + \frac{\partial \ln |W(a,b)|^2}{\partial b}\cdot\frac{a^2}{2},\quad f'(a,b) = \frac{f_0}{a} - \frac{\partial \ln |W(a,b)|^2}{\partial (1/a)}\cdot\frac{f_0}{a^2}$$

Rearranged Wavelet–Hough Transform Method

Step 3 - Reassigned Wavelet Transform (RWT):

The RWT redistributes the energy of W(a, b) to the reassigned points (t', f’).

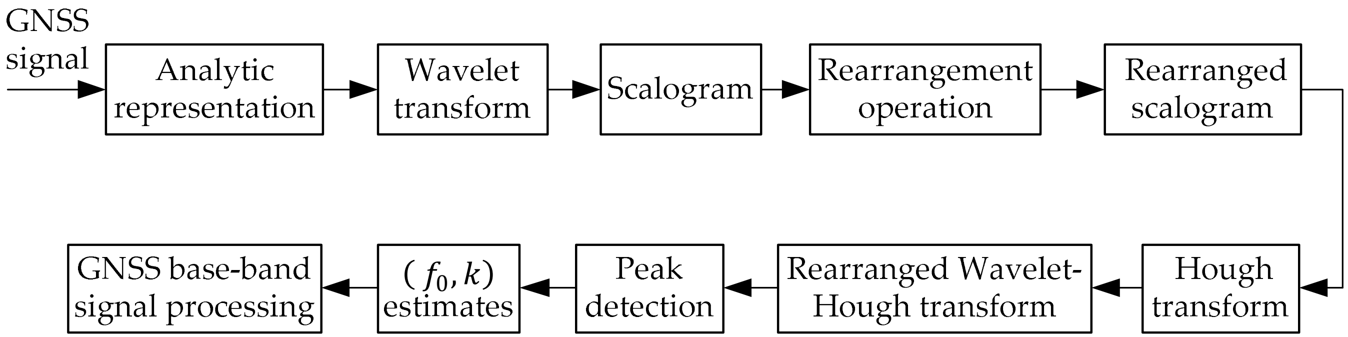
$$RWT(t,f) = \int_0^{\infty}\int_{-\infty}^{\infty} \frac{1}{a^2}|W(a,b)|^2 \cdot \delta\left(t - t'(a,b)\right)\delta\left(f - f'(a,b)\right)\mathrm{d}b\,\mathrm{d}a$$

Step 4 - Hough Transform Applied to RWT

The Hough Transform accumulates energy along curves (e.g., lines) in the time-frequency plane. For detecting lines parameterized by angle (theta) and distance (rho),

$$\rho = t\cos\theta + f\sin\theta$$

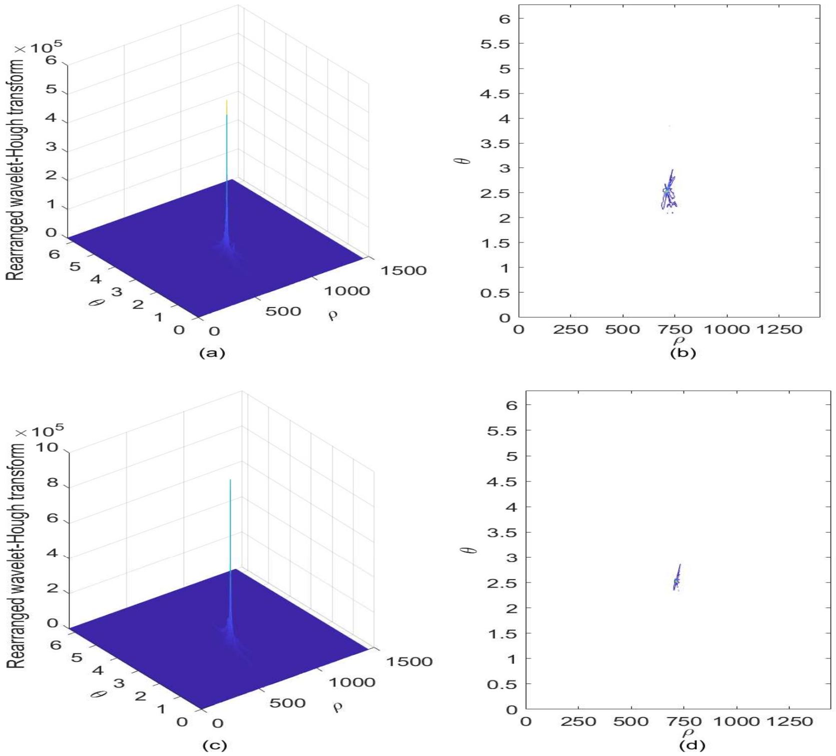
$$RWHT(\theta,\rho) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} RWT(t,f)\cdot\delta\left(\rho - t\cos\theta - f\sin\theta\right)\mathrm{d}t\,\mathrm{d}f$$



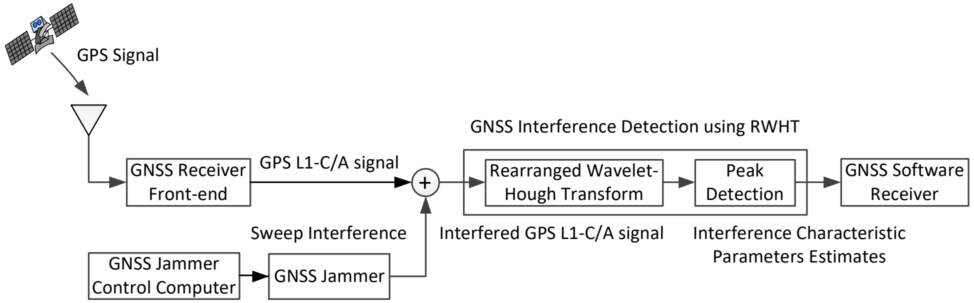
GNSS Interference detection by using the rearranged wavelet-Hough transform for GNSS receivers.

Rearranged Wavelet–Hough Transform Method

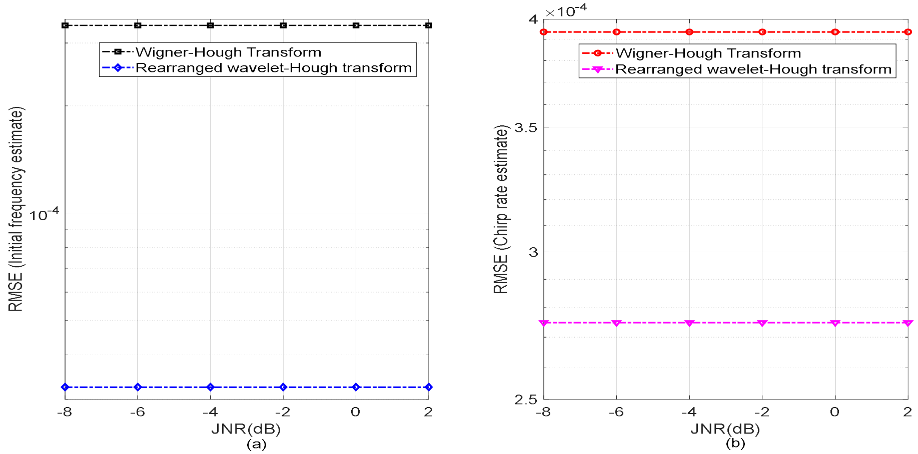
Performance Evaluation



The rearranged Wavelet-Hough transform of the GPS L1-C/A signal in the presence of sweep interference. C/N0 = 40 dB-Hz. (a) Rearranged Wavelet-Hough transform, JNR=-8 dB; (b) Contour of rearranged Wavelet-Hough transform; (c) Rearranged Wavelet-Hough transform, JNR=-2 dB; (d) Contour of rearranged Wavelet-Hough transform.



The scheme of the GNSS interference detection test in the lab.



The RMSE of the estimated chirp rate and initial frequency of the sweep interference present in the received GPS L1-C/A signal by using Wigner-Hough transform and rearranged Wavelet-Hough transform, respectively. C/N0=40 dB-Hz. (a) RMSE of the estimated initial frequency of the sweep interference; (b) RMSE of the estimated chirp rate of the sweep interference.

- Kewen Sun*, Tengteng Zhang, A New GNSS Interference Detection Method Based on Rearranged Wavelet–Hough Transform, *Sensors*, 2021, 21(5):1714

Smoothed Pseudo WVD–Hough Transform Method

Smoothed Pseudo Wigner-Hough Transform (SPWHT)

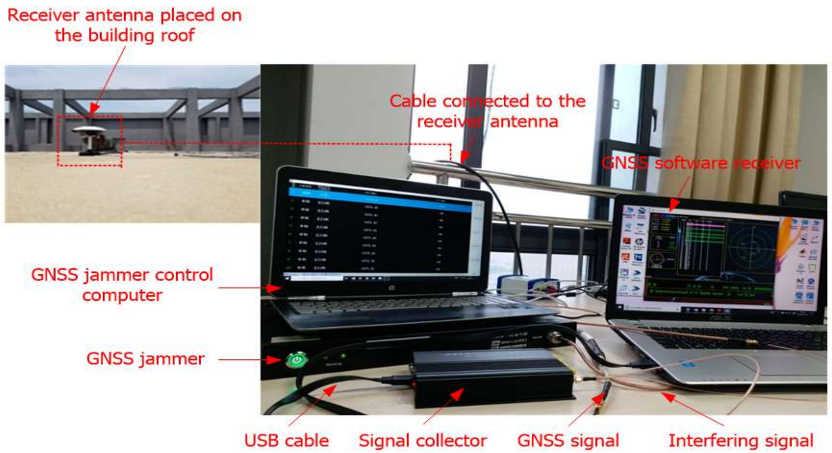
✓ **We first define the smoothed pseudo–Wigner distribution via a 2D kernel, and then having its Hough transform.**

$$W_y^{\Phi}(t,f) = \iint_{-\infty}^{\infty} \Phi(\tau,\nu)\, y\Big(t+\frac{\tau}{2}\Big)\, y^*\Big(t-\frac{\tau}{2}\Big)\, \mathrm{e}^{-\mathrm{j}2\pi(f-\nu)\tau}\, \mathrm{d}\tau\, \mathrm{d}\nu$$

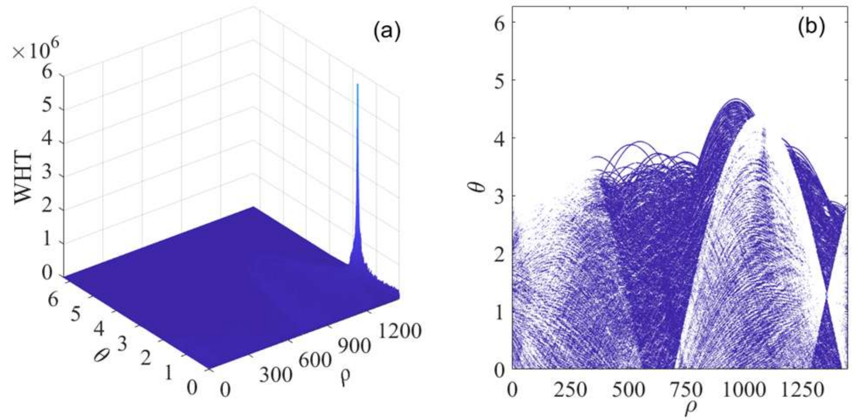
$$\mathcal{SPWHT}_y(\rho,\theta) = \iint_{-\infty}^{\infty} W_y^{\Phi}(t,f)\, \delta\big(\rho - t\cos\theta - f\sin\theta\big)\, \mathrm{d}t\, \mathrm{d}f$$

$$\theta \in [0,\pi),\ \ \rho \in \mathbb{R}$$

Performance Evaluation

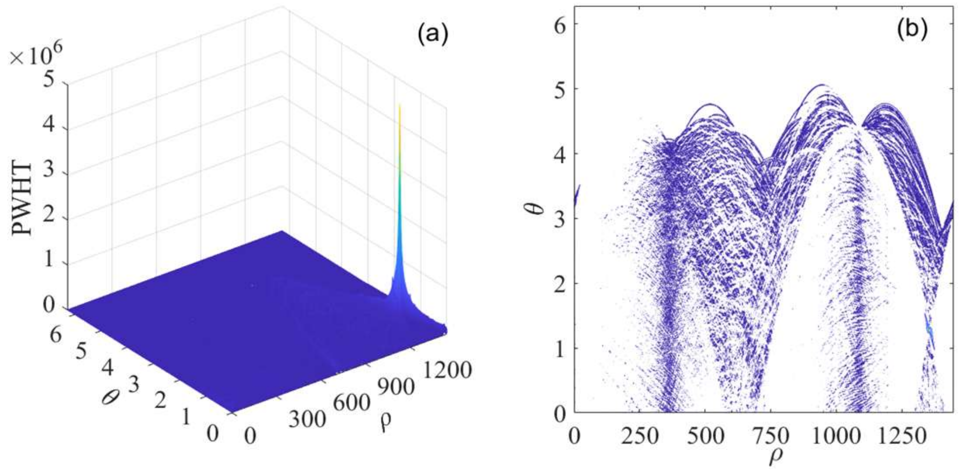


The experimental platform of the GNSS interference detection test.

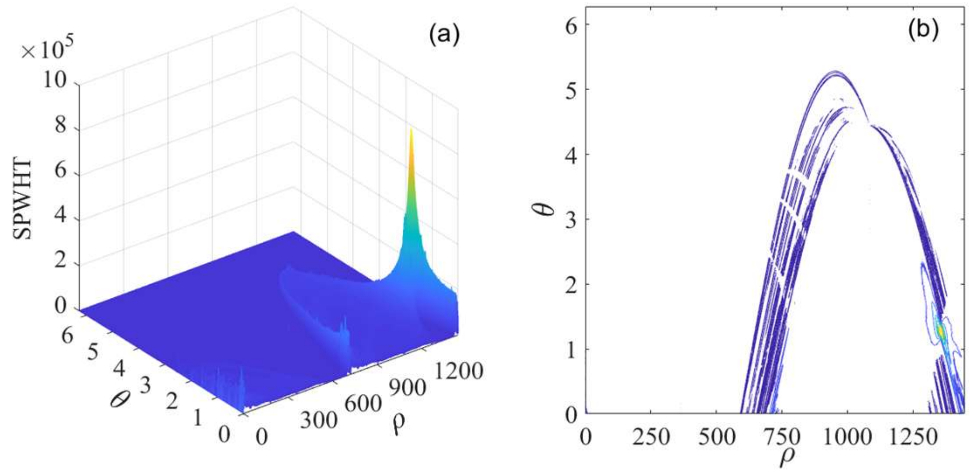


The WHT of GPS L1-C/A signal disturbed by sweep interference.

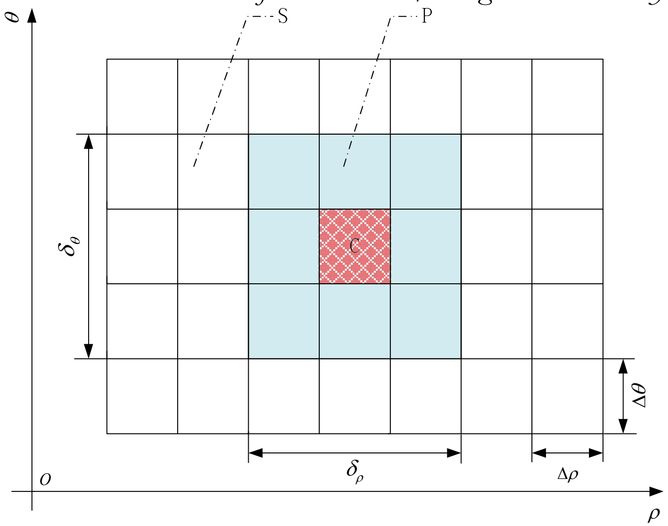
Smoothed Pseudo WVD–Hough Transform Method

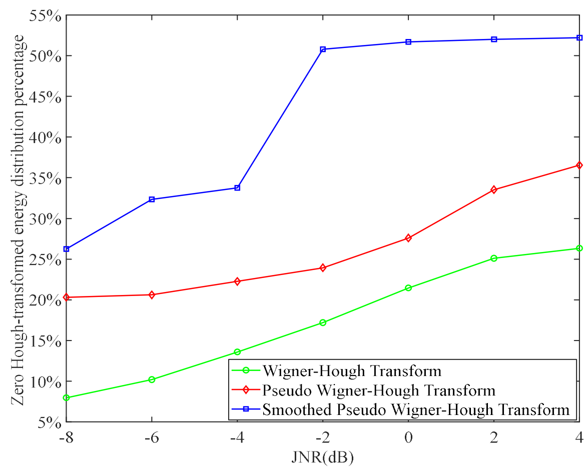


The PWHT of GPS L1-C/A signal disturbed by the sweep interference.



The SPWHT of GPS L1-C/A signal disturbed by the sweep interference.





The zero Hough-transformed energy percentage metrics of the Hough transform techniques.

- **Kewen Sun***, Baoguo Yu, Mireille Elhajj, Washington Yotto Ochieng, etc, A Novel GNSS Interference Detection Method based on Smoothed PseudoWigner-Hough Transform, *Sensors*, 2021, 21(13):4306
- **Kewen Sun***, Jiang Guo, A Novel Interference Detection based on Wigner-Hough Transform for GNSS Receivers, *ION GNSS+ 2019*, Miami, Florida, USA, September 16-20, 2019
- **Kewen Sun**, A GNSS Receiver Interference Detection Method based on Smooth Pseudo Wigner-Hough Transform, **Patent Application Number: 202411122405.2**

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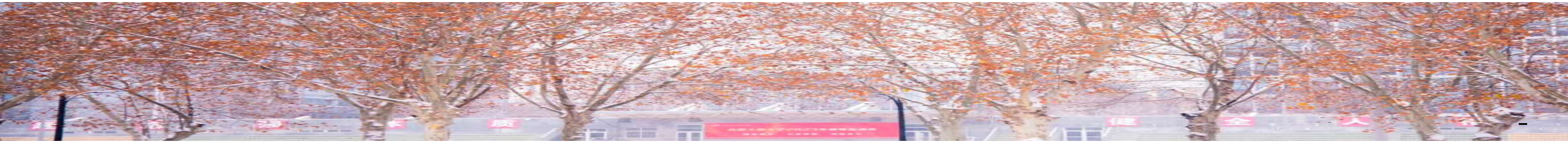
- GNSS Interference Detection based on TF Analyses
- GNSS Interference Detection based on Hough Transform
- GNSS Anti-Interference based on FrFT
- GNSS Anti-Interference based on FrFT & Notch Filtering

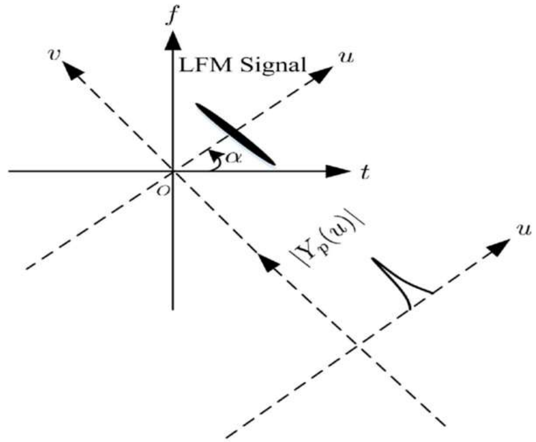


GNSS Anti-Interference using FrFT Filtering

Fractional Fourier Transform (FrFT)

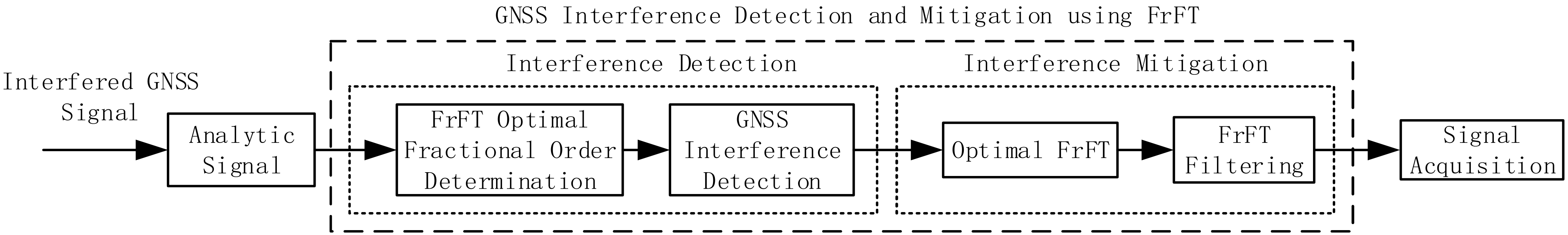
$$Y_p(u) = F_p(u) = \int_{-\infty}^{+\infty} y_a(t) K_p(u,t)\mathrm{d}t$$

$$K_p(u,t) = \begin{cases} A_\alpha e^{j\pi[(t^2+u^2)\cdot\cot\alpha - 2tu\cdot cs \quad]}, & \alpha \neq k\pi \\ \delta(t-u), & \alpha = 2k\pi \\ \delta(t+u), & \alpha = (2k+1)\pi \end{cases}$$



TF distribution of LFM signal and its FrFT projection to the fractional domain.

GNSS Anti-Interference by using FrFT

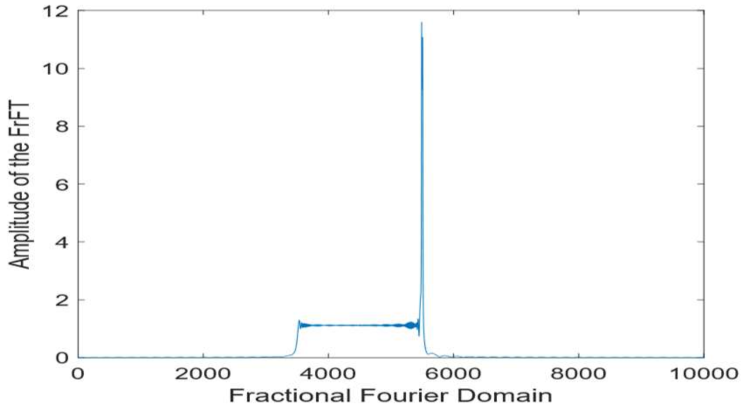


- Kewen Sun*, Mireille Elhajj, Washington Yotto Ochieng, A GNSS Anti-interference Method based on Fractional Fourier Transform, *IEEE Transactions on Aerospace and Electronic Systems*, 2024, 60(5): 5636 - 5650
- Kewen Sun, A GNSS Receiver Anti-interference Method based on FrFT Filtering, Patent Application Number: 2024111168052

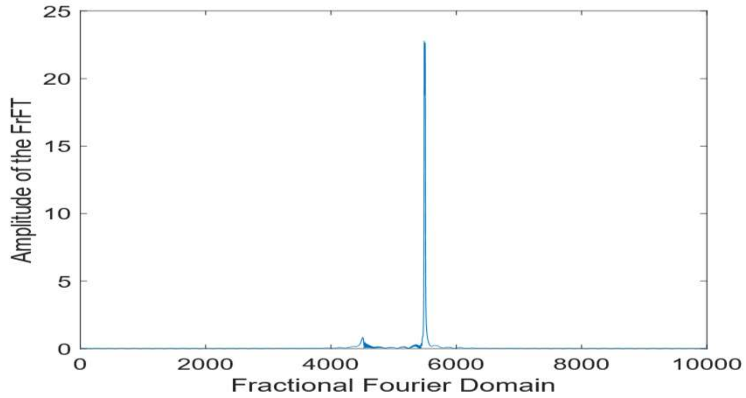
GNSS Anti-Interference using FrFT Filtering

Signal Preprocessing by using Hilbert Transform

- ✓ A real LFM interfering signal can be decomposed into the sum of two complex signals, which makes the FrFT of the GNSS interfering signal have a different optimal fractional order. When the FrFT of the interfering signal is observed in the fractional Fourier domain using the optimal fractional order, only the energy of one complex signal is strengthened, the energy of the other complex signal is scattered.



The FrFT of a real LFM signal in the fractional order Fourier domain.



The FrFT of a real LFM signal after Hilbert transform in the fractional order Fourier domain.

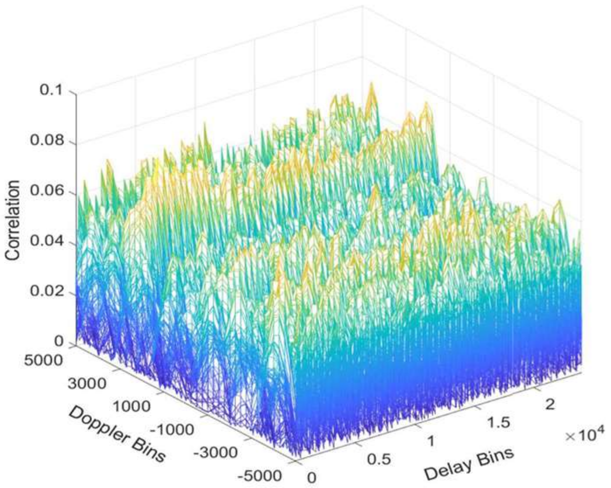
- ✓ When the real LFM signal is preprocessed by the Hilbert transform, **the analytic form of the real LFM signal presents a good property of energy concentration in the fractional domain,** which is beneficial to the filtering or removal of the GNSS interfering signal.

GNSS Anti-Interference using FrFT Filtering

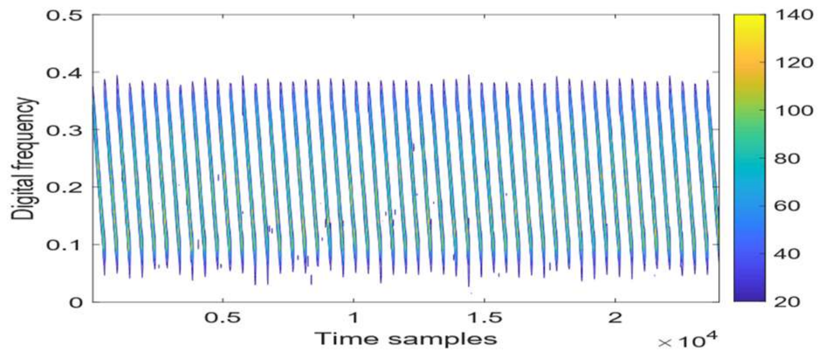
GNSS Anti-Interference Experimental Parameters Setting

■ Parameters in GNSS Anti-interference Experiment

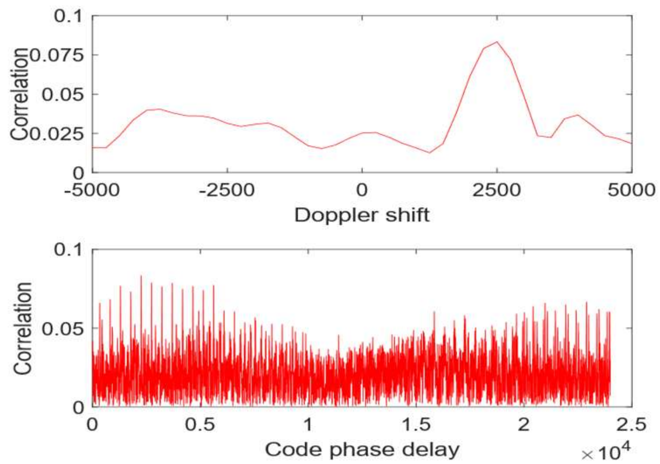
Parameter	Value
Carrier-to-Noise Ratio, C/N_0	46 dB-Hz
Jamming-to-Noise Ratio, JNR	2 dB
Doppler shift, f_d	3 kHz
Coherent integration time	1 ms
Left sweep frequency deviation, Δf_0	4.5 MHz
Right sweep frequency deviation, Δf_1	-2.5 MHz
Sweep period	0.02 ms



The cross ambiguity function evaluated using the interfered GPS L1-C/A signal



Time frequency evolution of the received original interfered GPS L1-C/A signal

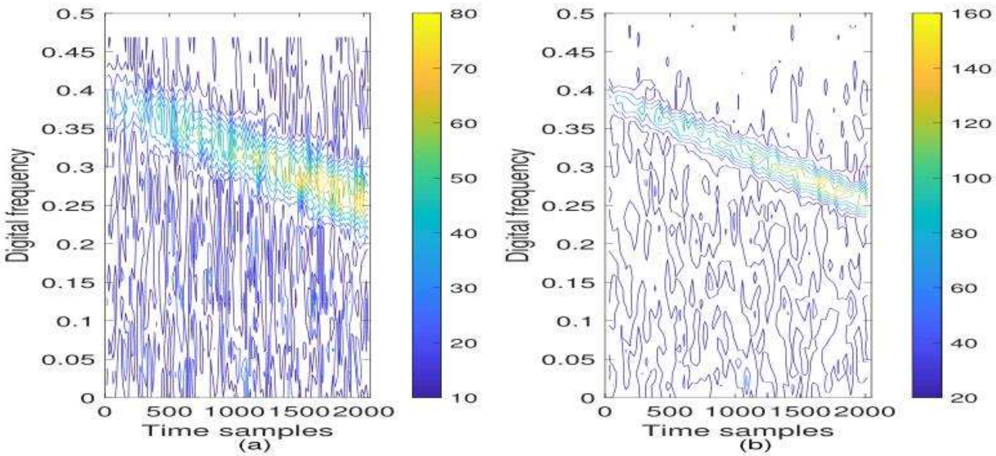


The Doppler shift and code phase delay estimated using the original interfered GPS L1-C/A signal

GNSS Anti-Interference using FrFT Filtering

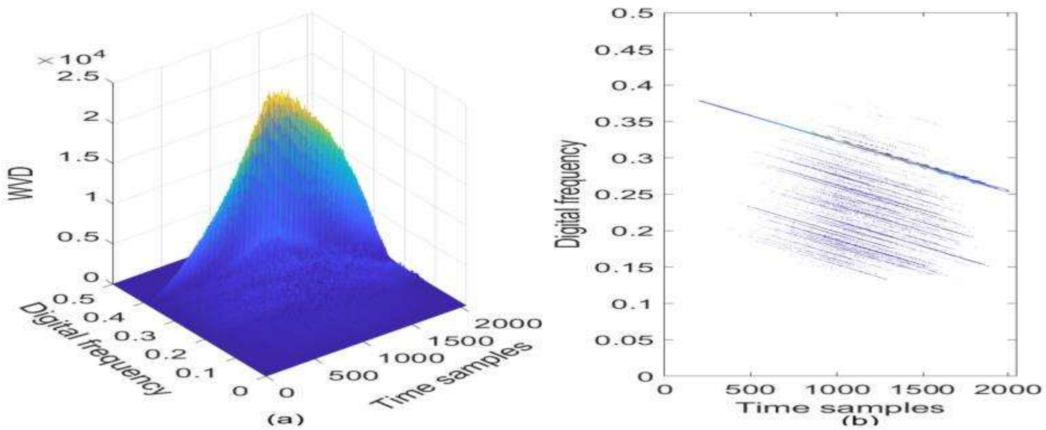
State of the Art TF Analysis Techniques

✓ TF resolution trade-off problem of the spectrogram



The spectrogram of the interfered GPS L1-C/A signal, adopting a Hamming window function. C/N0 = 46 dB-Hz, JNR = -4 dB. (a) window size = 31; (b) window size = 63.

✓ The cross-term problem existed in the Wigner-Ville distribution



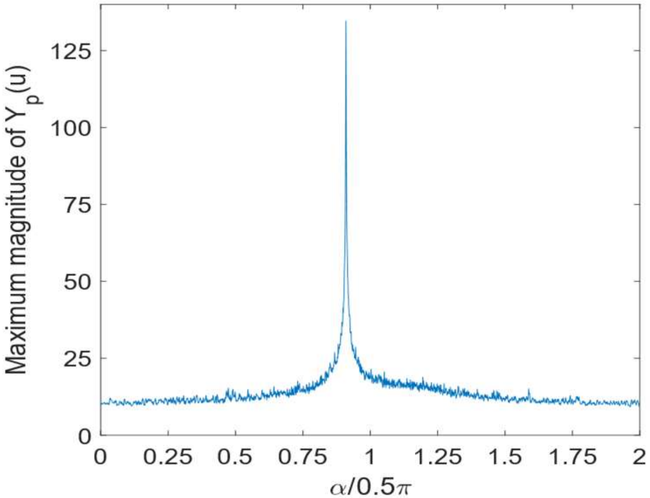
The WVD of the interfered GPS L1-C/A signal. C/N0 = 46 dB-Hz, JNR = -4 dB. (a) WVD; (b) contour of WVD.

GNSS Anti-Interference using FrFT Filtering

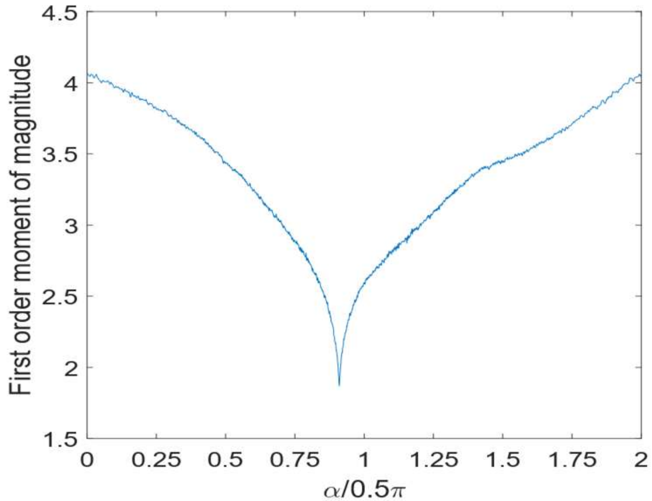
Optimal Fractional Order Determination

✓ In order to address the problem of inefficient search methods and unreliable interference detection and mitigation of the current techniques. An efficient optimal fractional order determination model **First Order Moment of Magnitude (FOMM) of the FrFT** has been developed to reduce the computational complexity, expressed as:

$$\overline{Y_p(u)} = \frac{1}{N}\sum_{u=1}^{N} |Y_p(u)| \Rightarrow p_{opt,FOMM} = \arg\min_p \overline{Y_p(u)}$$



The maximum magnitude (MM) of the FrFT of the interfered GPS L1-C/A signal.

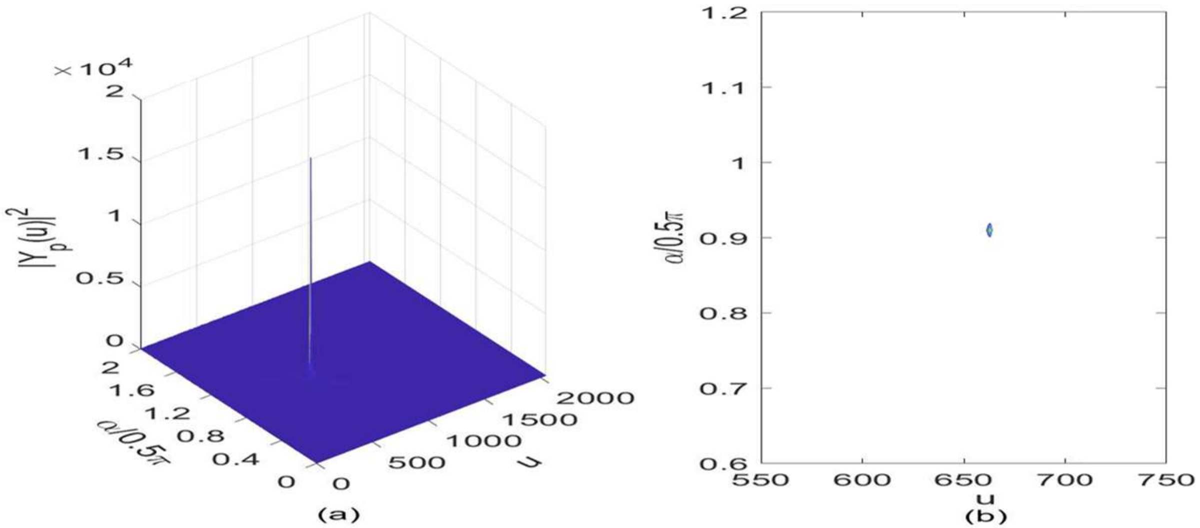


The first order moment of magnitude (FOMM) of the interfered GPS L1-C/A signal.

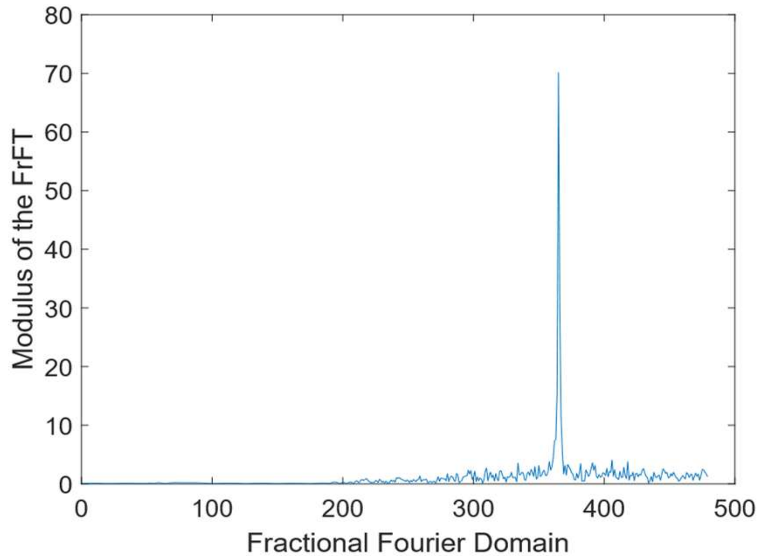
GNSS Anti-Interference using FrFT Filtering

FrFT based GNSS Interference Detection

✓ When the FrFT is used in interference detection, **the problem of detecting the sweep interference in the TF plane is converted to the problem of determining the FrFT energy peak location in the u-p plane.**



The FrFT based interference detection for the interfered GPS L1-C/A signal.

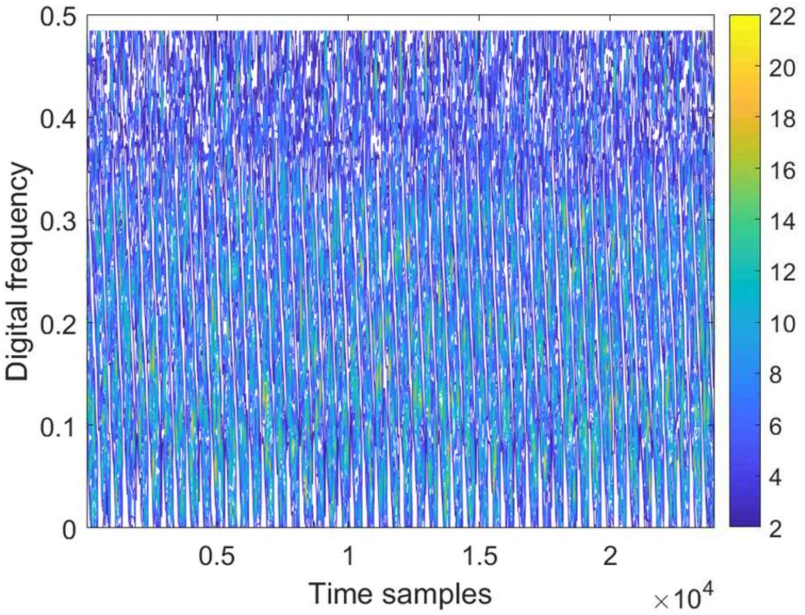


The modulus of the FrFT of the received original interfered GPS L1-C/A signal in a sweep period.

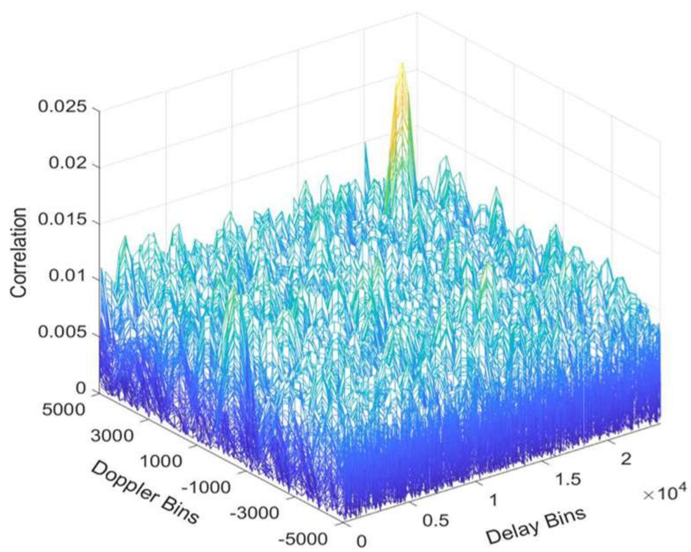
GNSS Anti-Interference using FrFT Filtering

FrFT Filtering

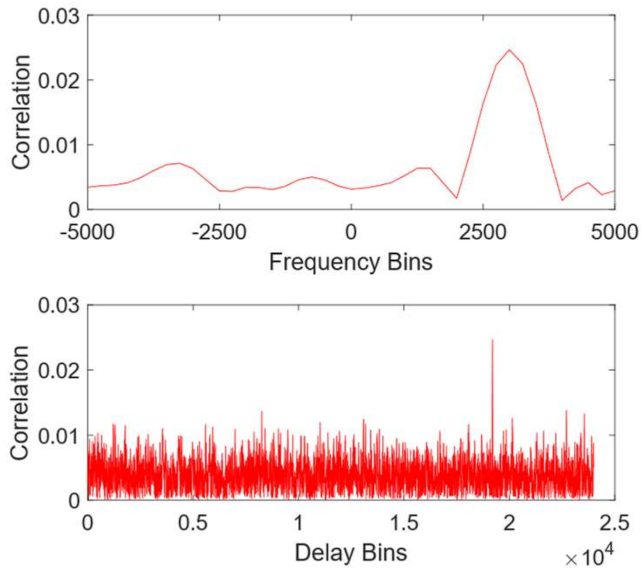
✓ When the FrFT filtering is used in GNSS interference, the sweep interfering components can be effectively removed.



The time-frequency evolution of the FrFT-filtered GPS L1-C/A signal.



The cross ambiguity function evaluated using the interfered GPS L1-C/A signal processed adopting the FrFT filtering method. The sweep period of the sweep interference is 0.02 ms, and the coherent integration time is 1 ms in the signal acquisition process.

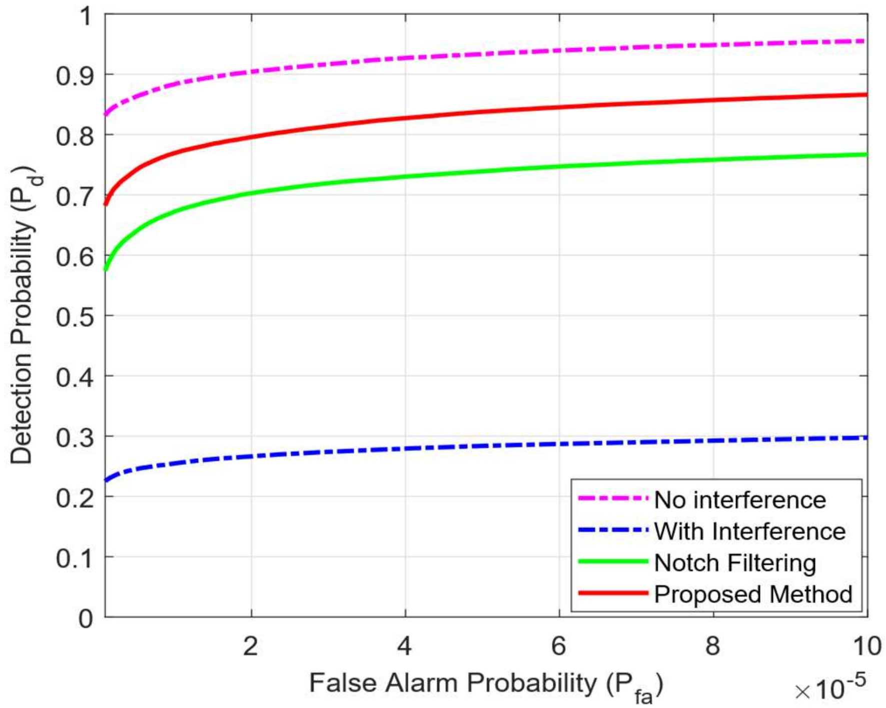


The Doppler shift and code phase delay estimated using the interfered GPS L1-C/A signal processed adopting the FrFT filtering method.

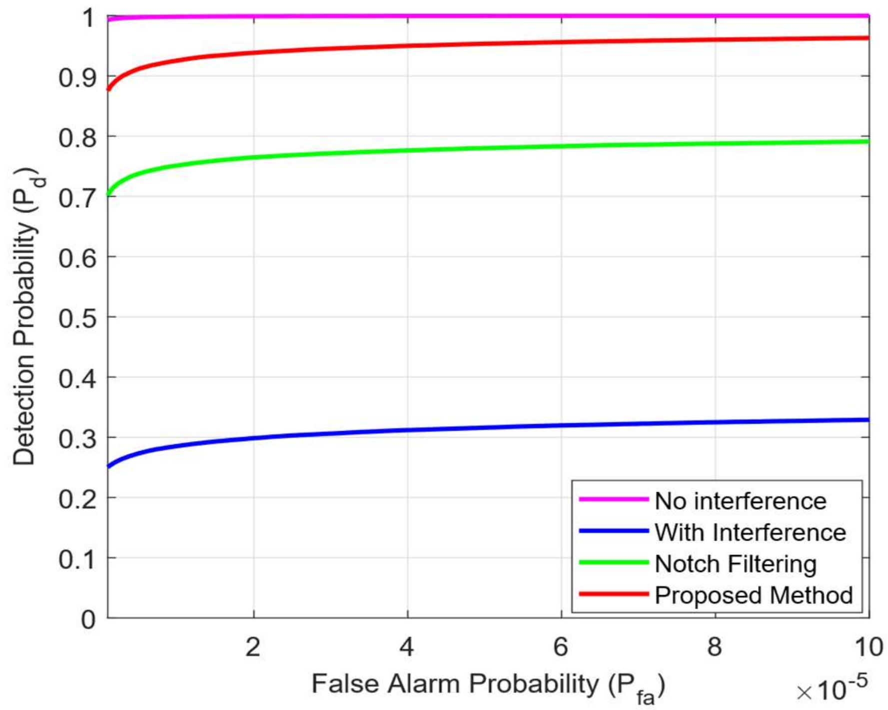
GNSS Anti-Interference using FrFT Filtering

GNSS Anti-Interference Performance Evaluation

- **Receiver Operating Characteristic (ROC) Comparison**



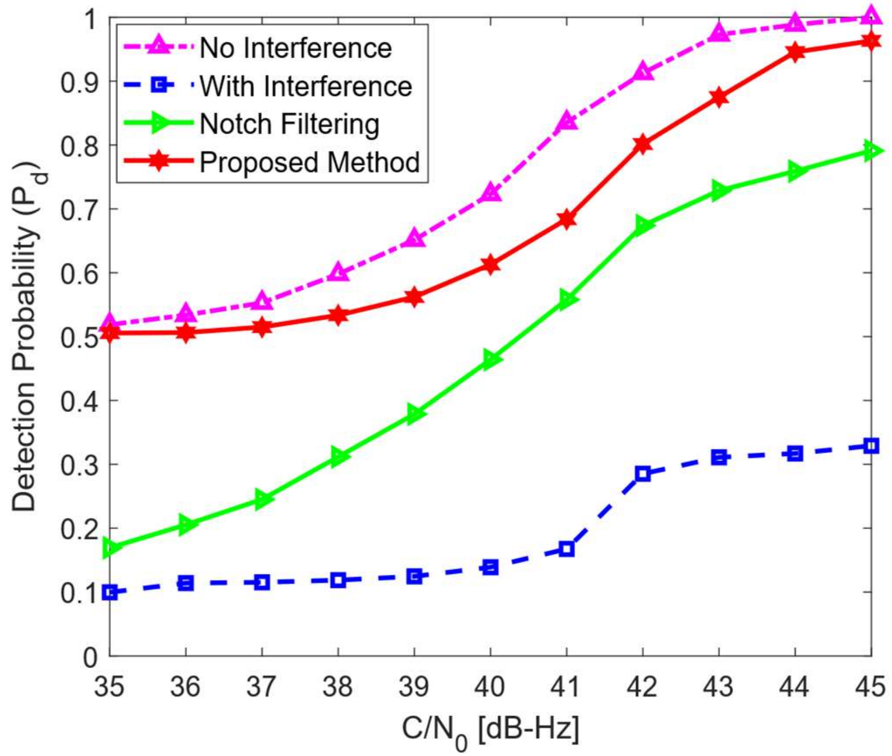
The ROC curves of the GPS L1-C/A signal in different signal scenarios. The coherent integration time is 2 ms, C/N0 = 40 dB-Hz, JNR = 20 dB.



The ROC curves of the GPS L1-C/A signal in different signal scenarios. The coherent integration time is 1 ms, C/N0 = 45 dB-Hz, JNR = 10 dB.

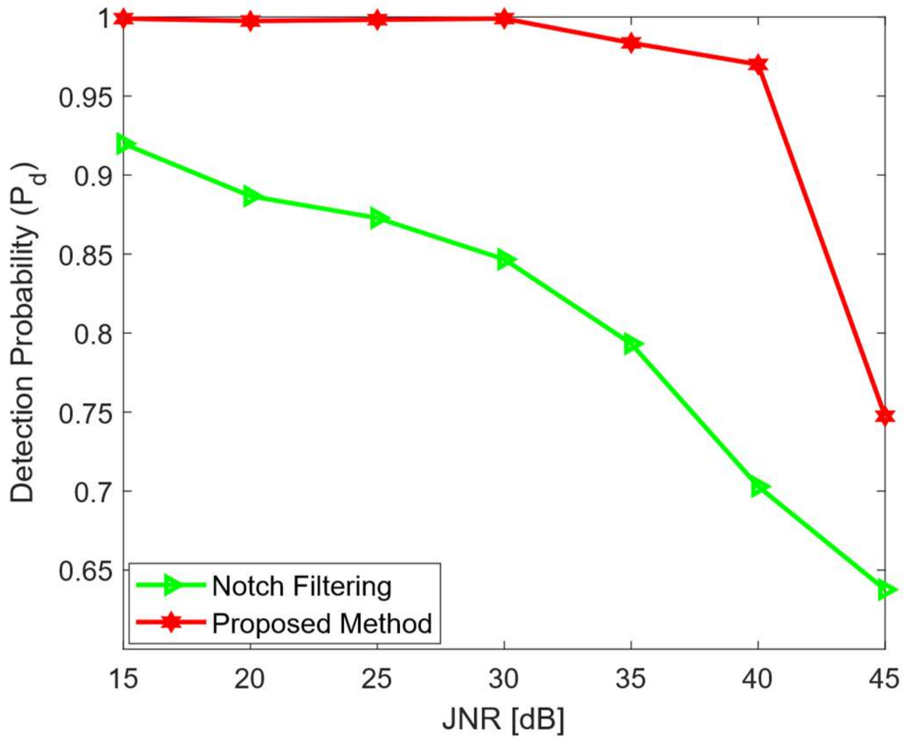
GNSS Anti-Interference using FrFT Filtering

■ SNR Curve Comparison



The SNR curves of the GPS L1-C/A signal in different signal scenarios. The coherent integration time is 1 ms in the signal acquisition.

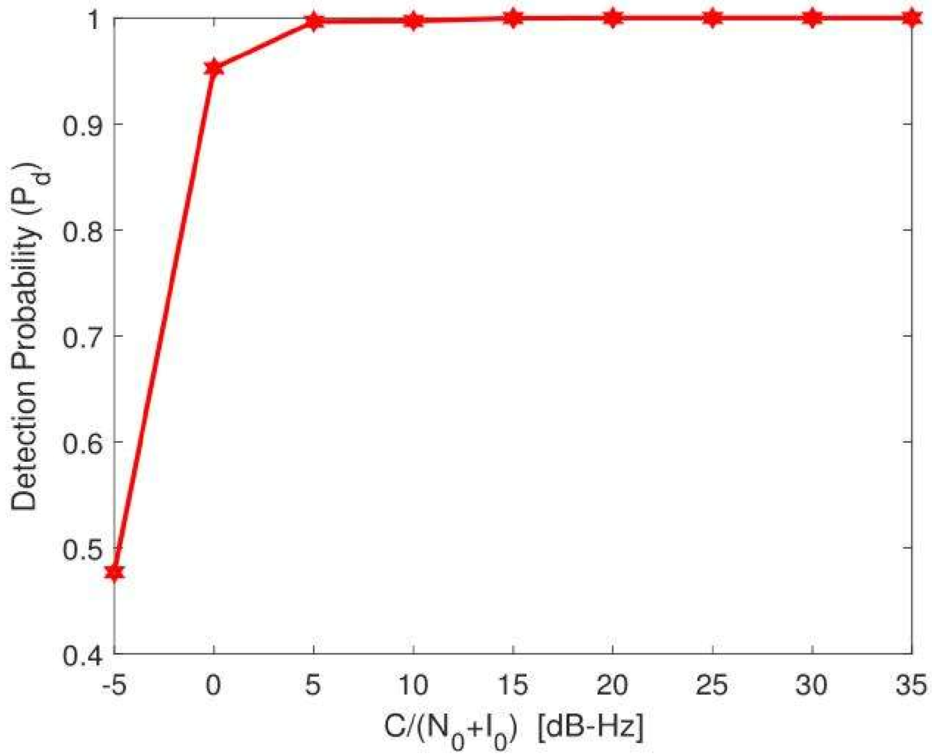
■ Jamming Tolerance Analysis



The detection probabilities in the acquisition of GPS L1-C/A signal with C/N0 equal to 45 dB-Hz by using two-pole notch filter and FrFT techniques respectively in different interfering scenarios. The coherent integration time is 2 ms.

GNSS Anti-Interference using FrFT Filtering

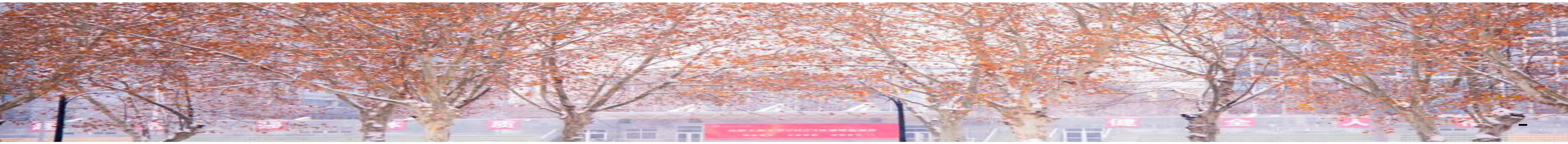
■ C/(N0+I0) Curve Analysis



The C/(N0+I0) curve of the FrFT based anti-interference method using GPS L1-C/A signal in different interfering scenarios. The coherent integration time is 2 ms in the signal acquisition.

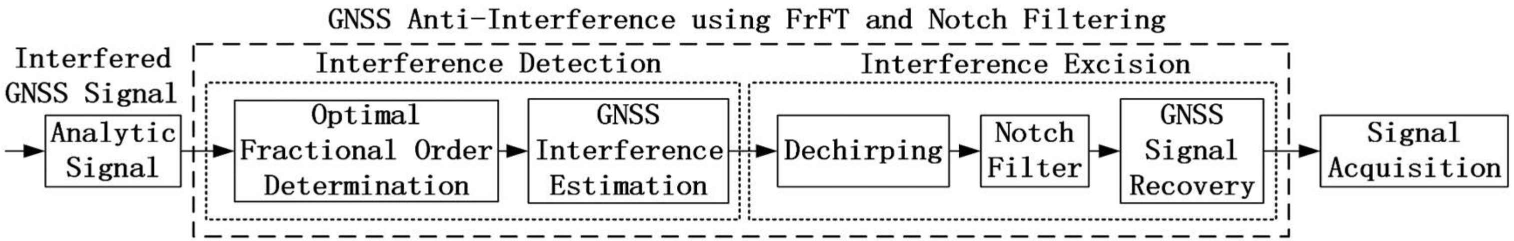
Outline

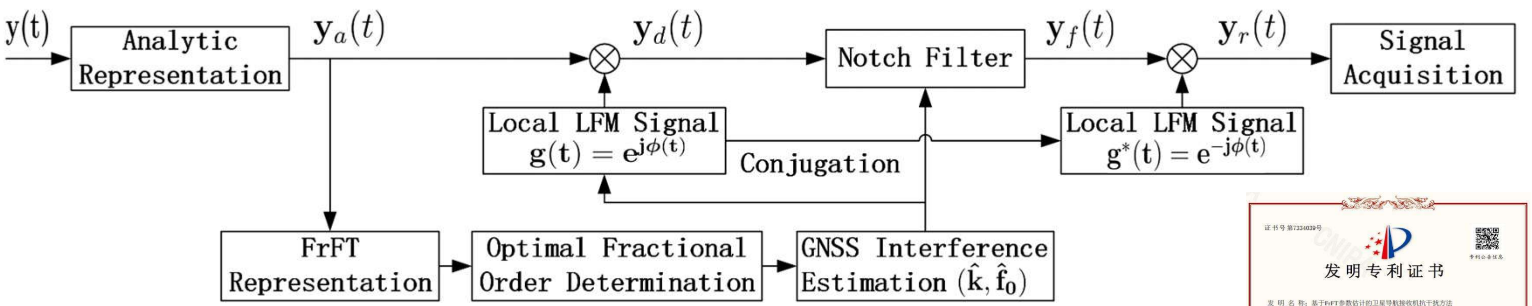
- Satellite Navigation Countermeasures
- GNSS Interference Detection based on TF Analyses
- GNSS Interference Detection based on Hough Transform
- GNSS Anti-Interference based on FrFT
- GNSS Anti-Interference based on FrFT & Notch Filtering

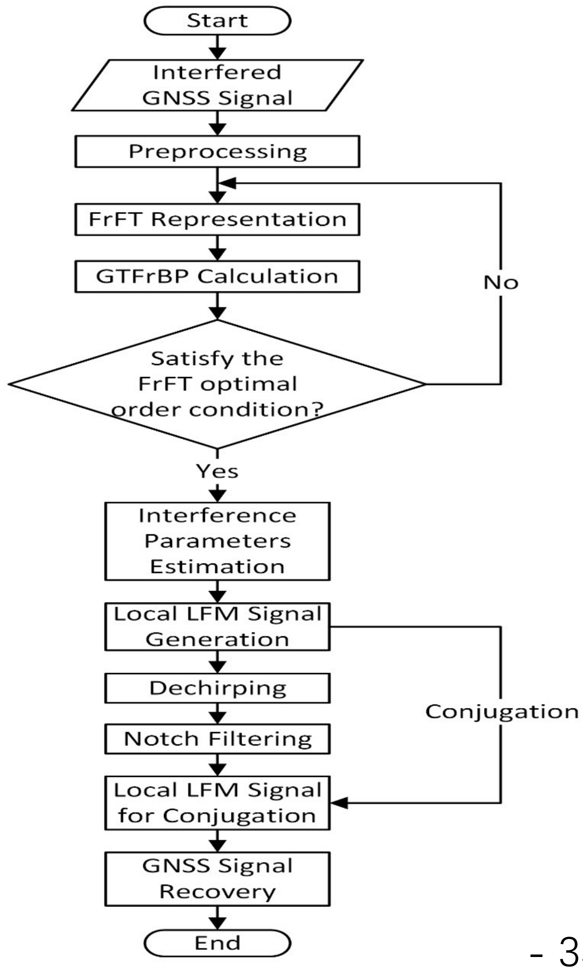


GNSS Anti-Interference using FrFT and Notch Filtering

FrFT & Notch Filtering based Anti-Interference Scheme







- Kewen Sun*, Baoguo Yu, Liangfeng Xu, Mireille Elhajj, Washington Yotto Ochieng, A Novel GNSS Anti-Interference Method using Fractional Fourier Transform and Notch Filtering, *IEEE Transactions on Instrumentation & Measurement*, DOI: 10.1109/TIM.2024.3451600, 2024
- Kewen Sun, Haijun Huang, Yin Wang, Cheng Wu, Cong Wang, Jun Wang, A GNSS Receiver Anti-interference Method based on FrFT Parameters Estimation, Patent Number: ZL 2022 1 0248955.3


发明专利证书

Patent Certificate

GNSS Anti-Interference using FrFT and Notch Filtering

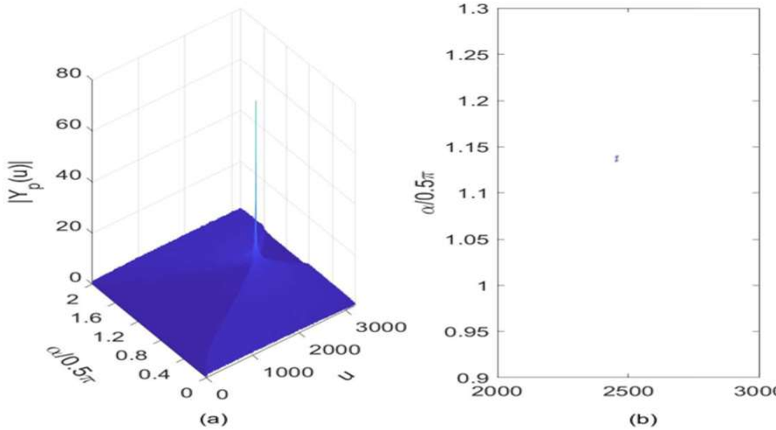
Determination of the Optimal Fractional Order of FrFT

TFrBP Model

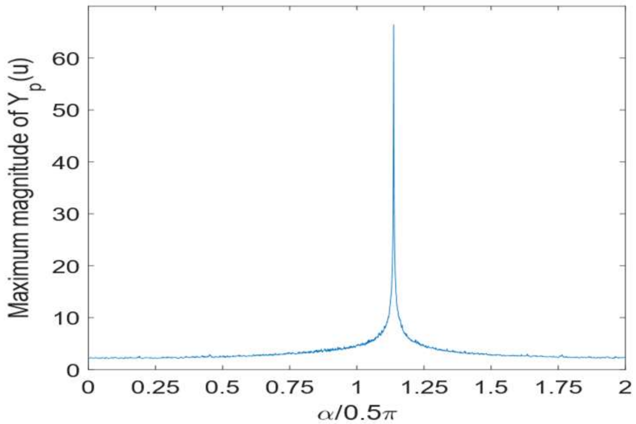
✓ The criterion of **time fractional bandwidth product (TFrBP)** has been developed, given as:

$$\boxed{TFrBP\{y(t), F_p[y(t)]\} = T_y \cdot FrB_y \Rightarrow p_{opt,GTFrBP} = \arg\min_p \; TFrBP\{y(t), F_p[y(t)]\}}$$

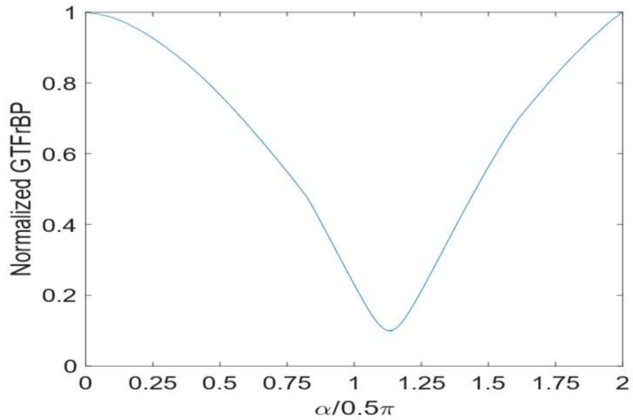
where $T_y = \frac{\left[\int (t-\eta_t)^2 |y(t)|^2 \mathrm{d}t\right]^{1/2}}{\|y(t)\|}$ $FrB_y = \frac{\left[\int (u-\eta_u)^2 |Y_p(u)|^2 \mathrm{d}u\right]^{1/2}}{\|Y_p(u)\|}$ $\eta_t = \frac{\left[\int t|y(t)|^2 \mathrm{d}t\right]^{1/2}}{\|y(t)\|}$ $\eta_u = \frac{\left[\int u|Y_p(u)|^2 \mathrm{d}u\right]^{1/2}}{\|Y_p(u)\|}$



The FrFT based interference detection for the GPS L1-C/A signal in the presence of sweep interference. C/N0 = 45 dB-Hz, JNR = 3 dB.



The maximum magnitude of the FrFT of the GPS L1-C/A signal in the presence of sweep interference.

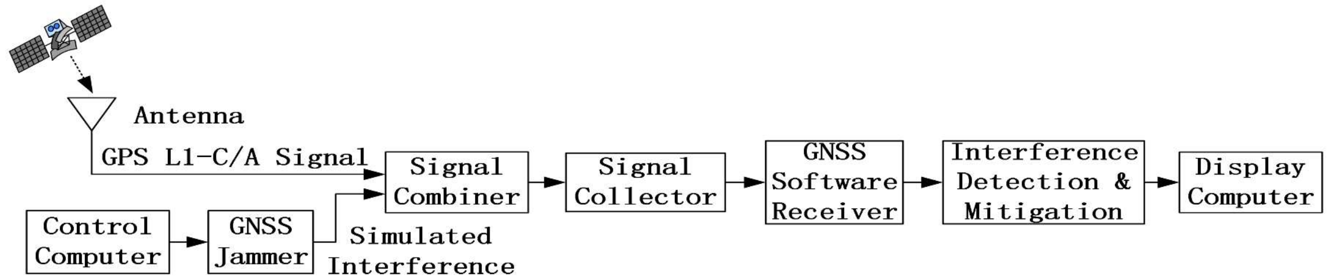


The normalized GTFrBP of the GPS L1-C/A signal in the presence of sweep interference.

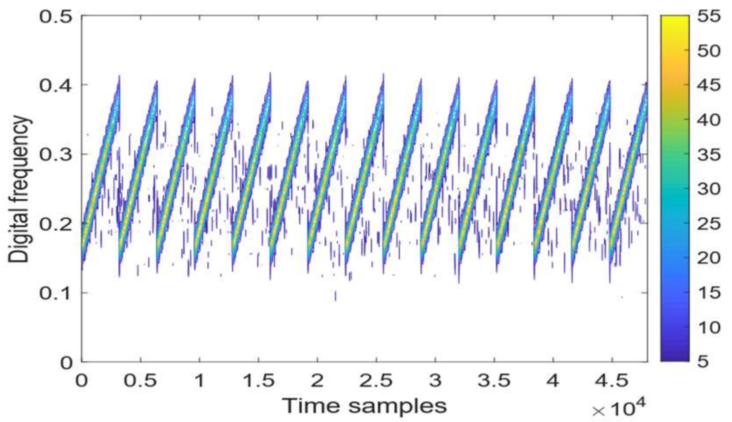
GNSS Anti-Interference using FrFT and Notch Filtering

GNSS Anti-interference Experimental Tests

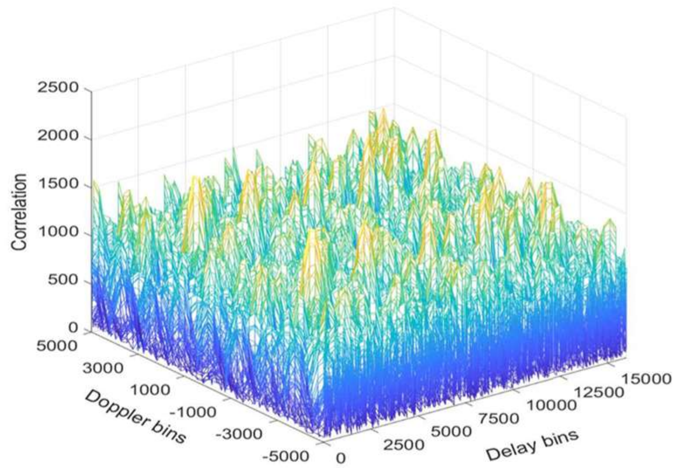
✓ When no anti-interference countermeasure is activated, failed result of acquiring the GPS L1-C/A signal (PRN 3) is shown, with no emerging CAF peak found in the search space.



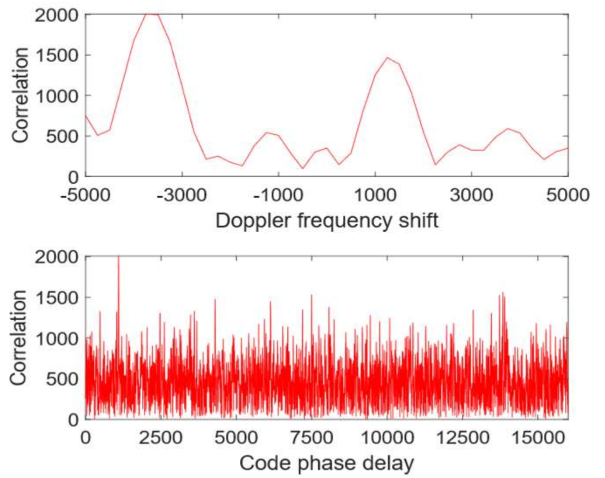
The experimental scheme of the proposed GNSS anti-interference method.



The spectrogram of the interfered GPS L1-C/A signal with the duration of 3 ms.



The cross-ambiguity function of the interfered GPS L1-C/A signal (PRN 3): 1 ms coherent integration time and no GNSS interference mitigation.

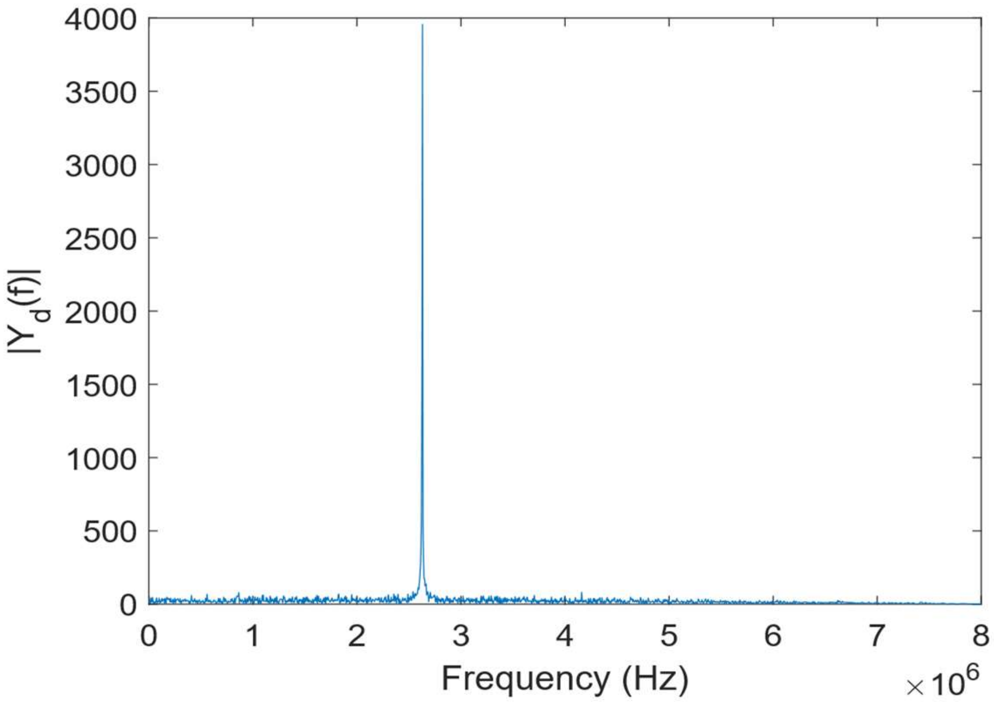


The estimated Doppler shift and code phase delay of the original interfered GPS L1-C/A signal (PRN 3) when anti-interference is not activated.

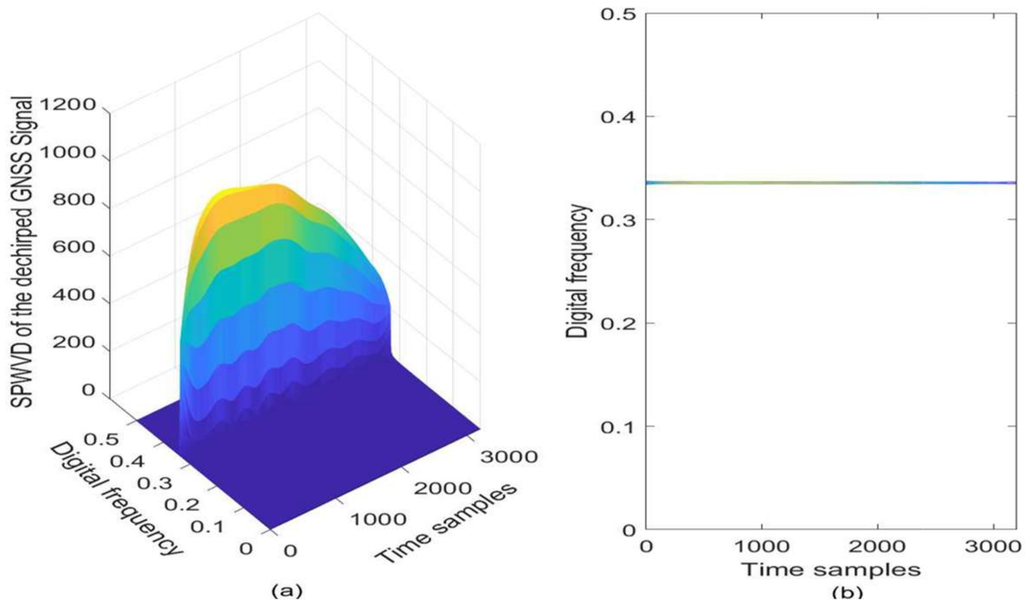
GNSS Anti-Interference using FrFT and Notch Filtering

Dechirping

✓ By using the estimated sweep rate of the sweep interfering signal, a local LFM signal can be constructed to dechirp the originally received GNSS signal.



The amplitude spectrum of the interfered GPS L1-C/A signal after dechirping.

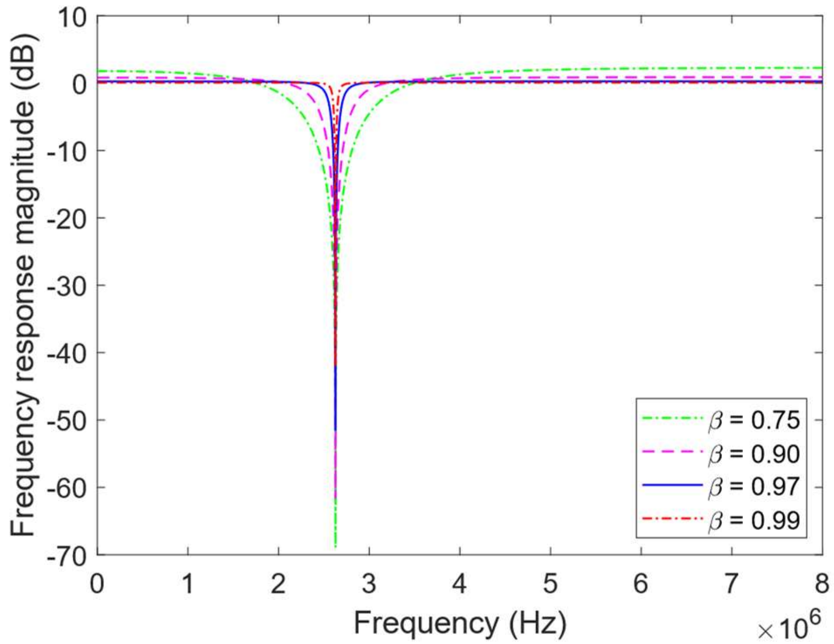


The SPWVD of the interfered GPS L1-C/A signal after dechirping: (a) the SPWVD; (b) the SPWVD's contour.

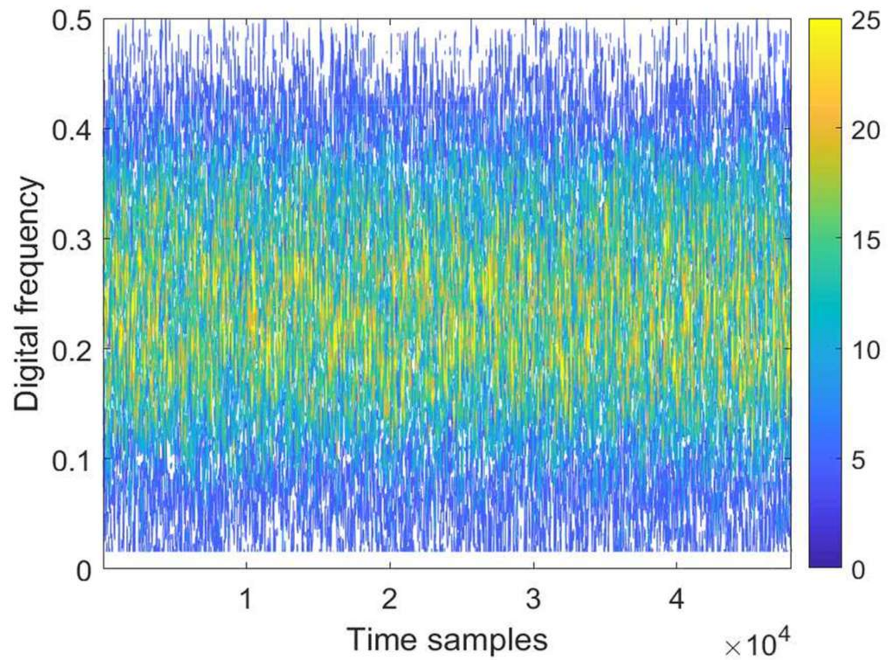
GNSS Anti-Interference using FrFT and Notch Filtering

■ Notch Filtering

✓ Based on the starting frequency estimate of the GNSS sweep interfering signal obtained by adopting the proposed method, **a single frequency notch filter is designed to achieve clean filtering of the interference.**



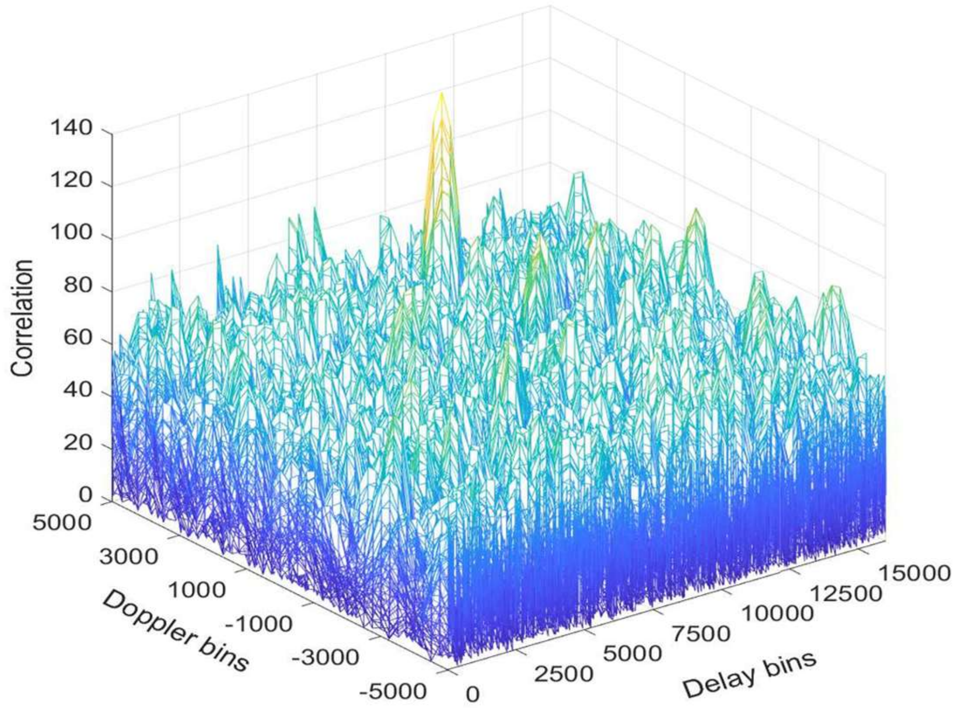
The magnitude frequency response curves of the transfer function of the notch filter using different filter pole radius values.



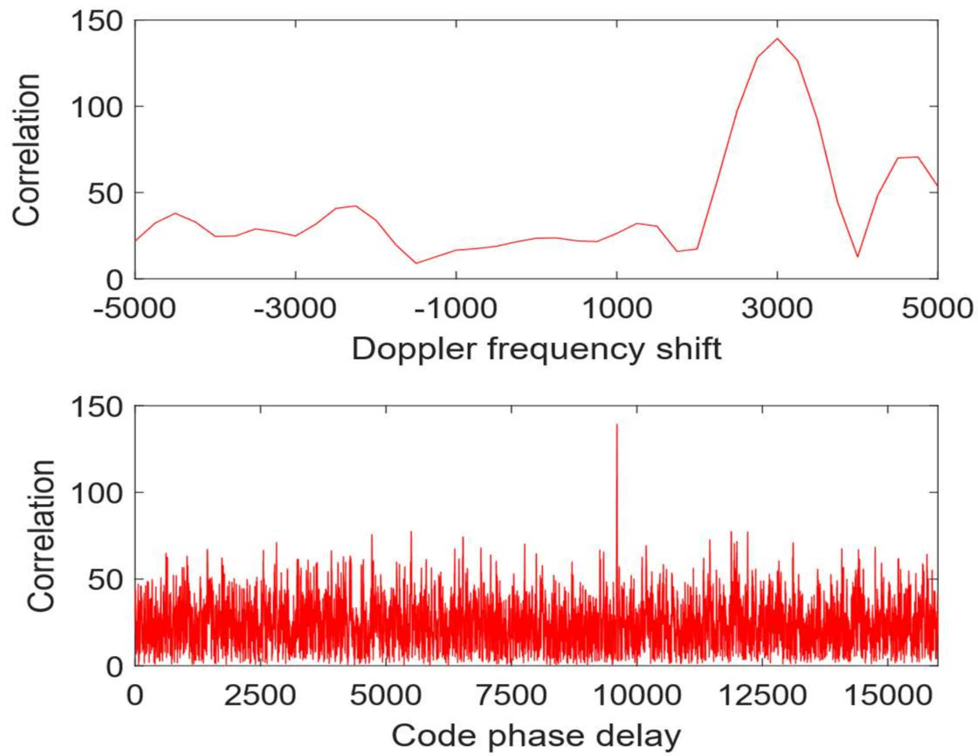
The spectrogram of the recovered GPS L1-C/A signal with the duration of 3 ms after interference suppression.

GNSS Anti-Interference using FrFT and Notch Filtering

■ Acquisition Results after Interference Suppression



The cross ambiguity function of the interfered GPS L1-C/A signal using the proposed FrFT and notch filtering based GNSS interference detection and mitigation method: 1 ms coherent integration time.

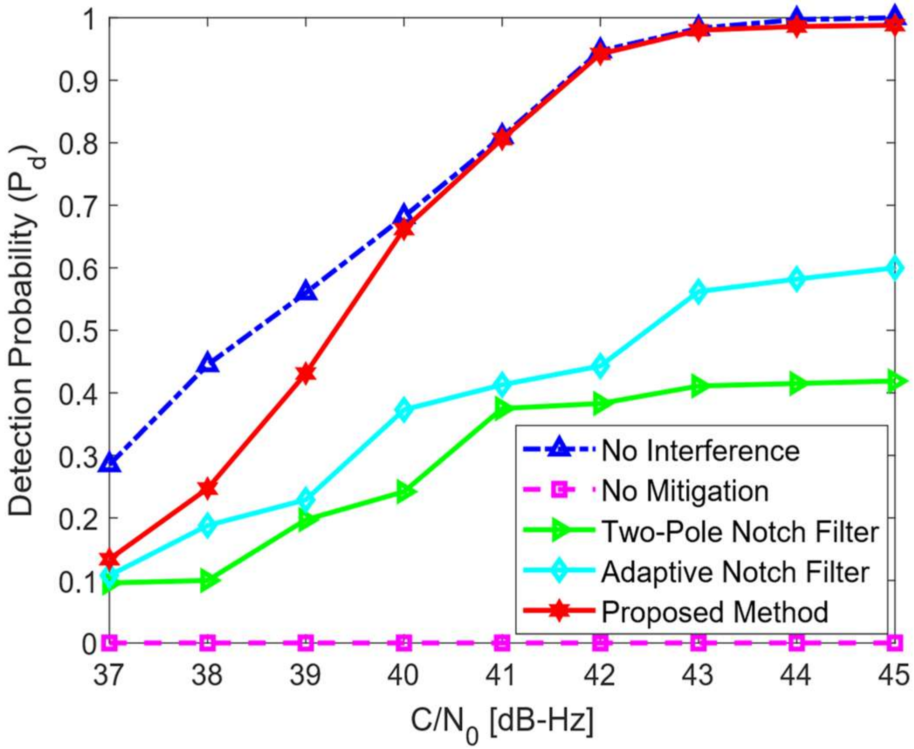


The Doppler shift and code phase delay estimates of the GPS L1-C/A signal with the sweep interference by adopting the proposed GNSS anti-interference method.

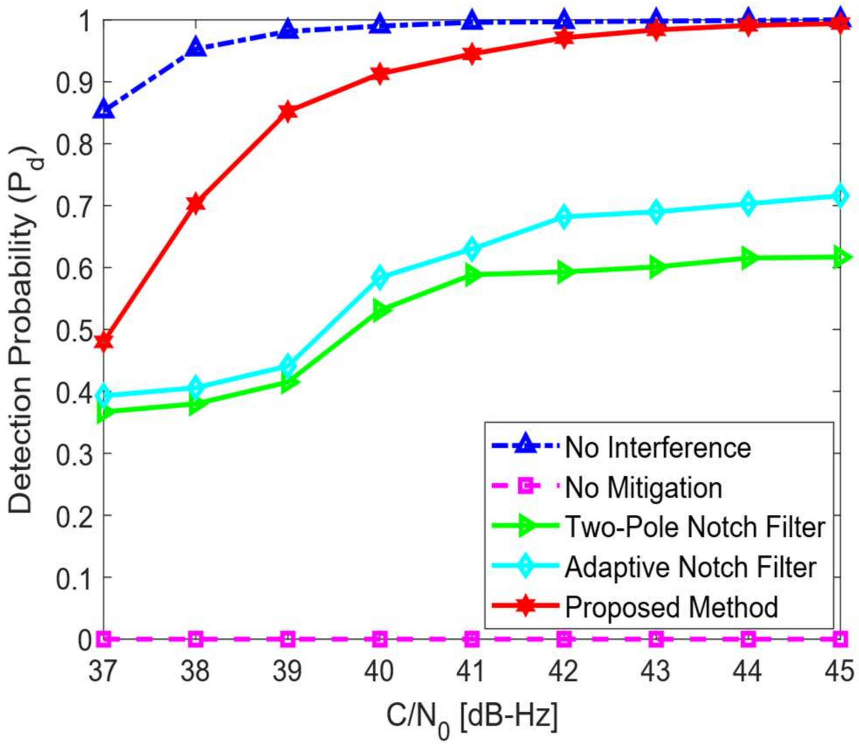
GNSS Anti-Interference using FrFT and Notch Filtering

Performance Evaluation

■ C/N0 Curve Comparison



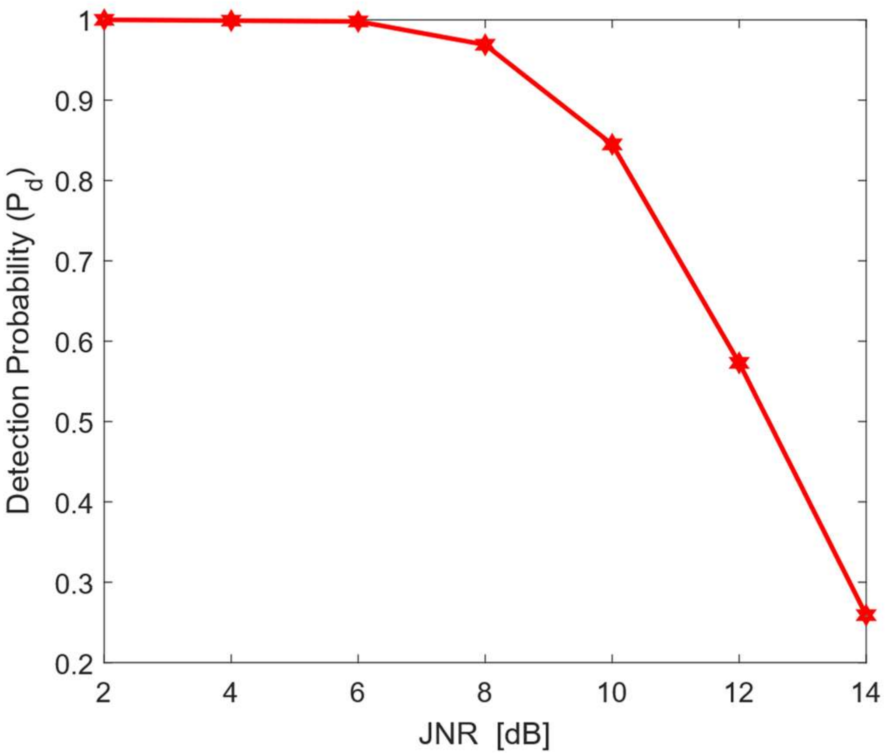
The C/N0 curves of the GPS L1-C/A signal acquisition procedure, with the coherent integration time being 2 ms. The JNR value is set to 2 dB when the sweep interference is present in the received GPS L1-C/A signal.



The C/N0 curves of the GPS L1-C/A signal acquisition procedure, with the coherent integration time being 4 ms. The JNR value is set to 5 dB when the sweep interference is present in the received GPS L1-C/A signal.

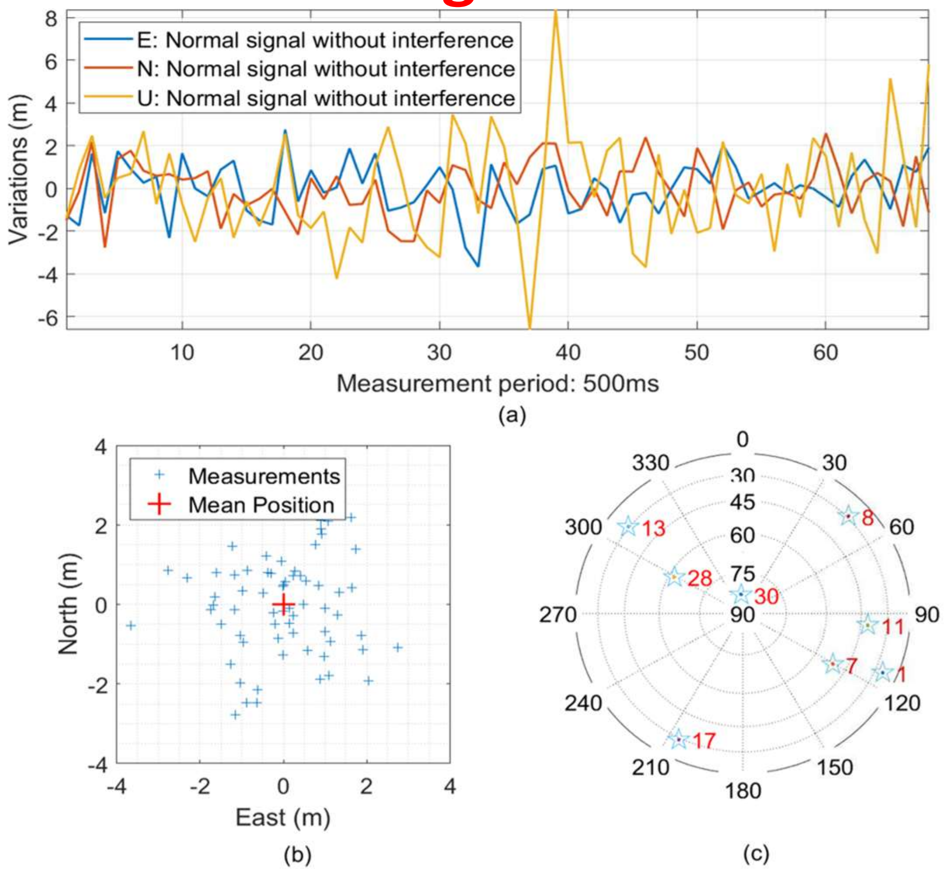
GNSS Anti-Interference using FrFT and Notch Filtering

■ Jamming Tolerance Analysis



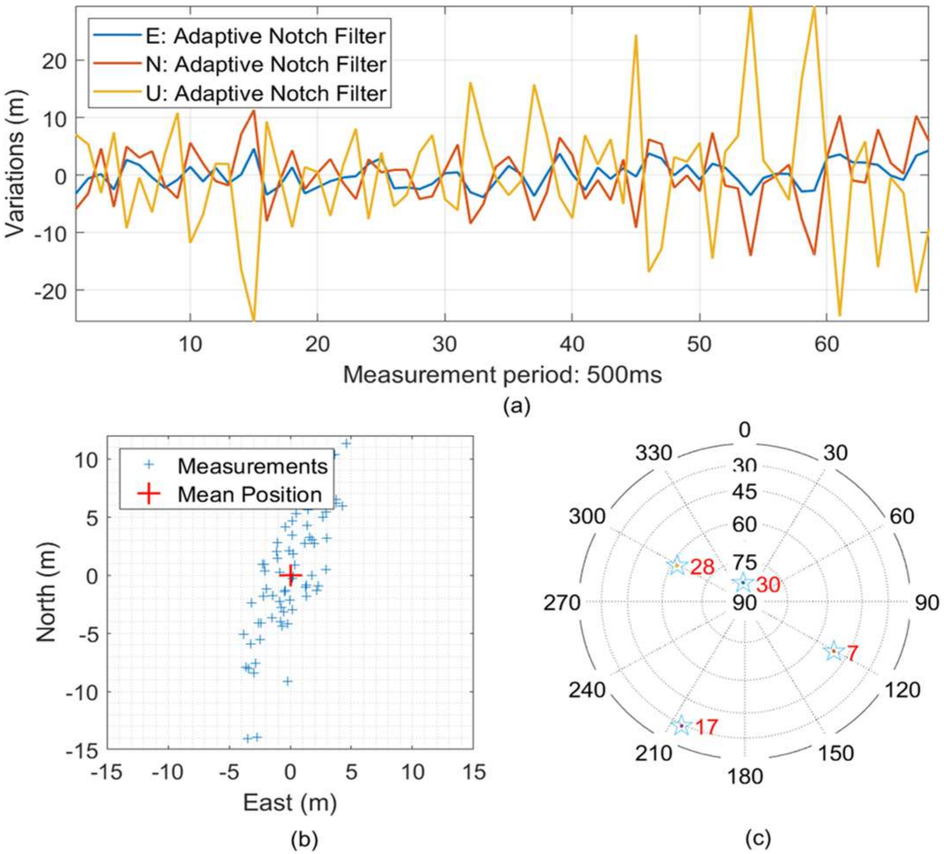
The detection probabilities in the acquisition of GPS L1-C/A signal with the C/N0 value being 45 dB-Hz by using the proposed method in different interfering scenarios. The coherent integration time is 2 ms.

■ Positioning Results

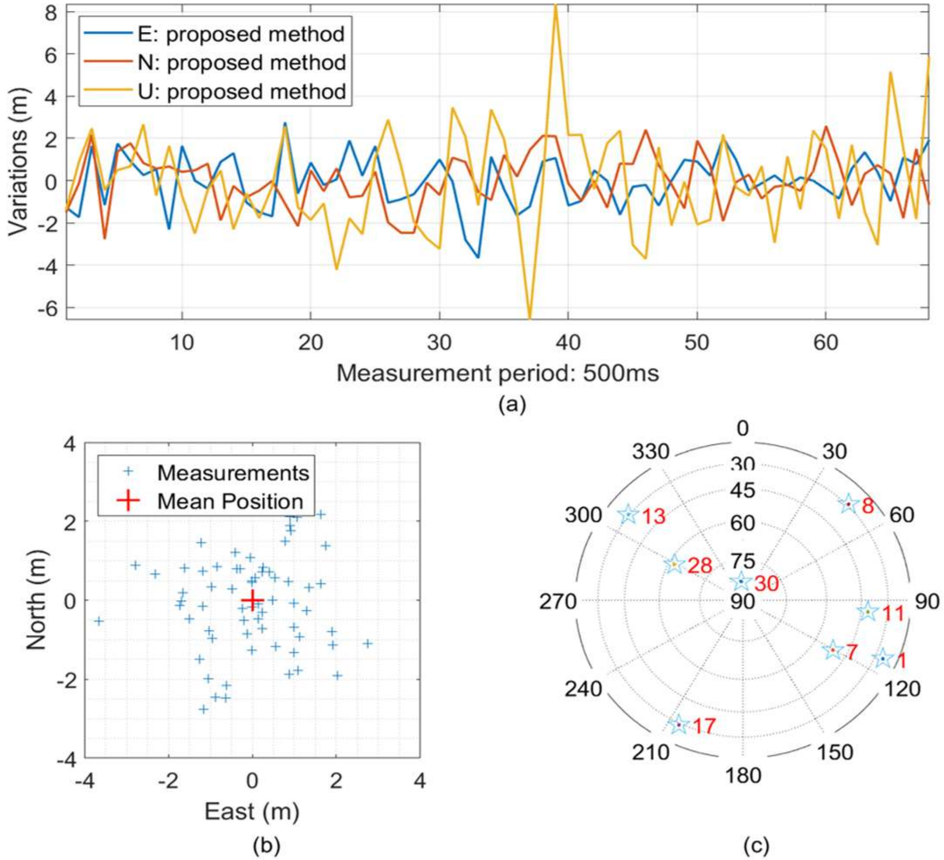


The positioning results ***for the normal situation without interference in the real GPS L1-C/A signal.*** *(a) The variations in coordinates within the UTM system; (b) The positioning errors in the UTM system; (c) The sky plot displaying the satellite constellation.*

GNSS Anti-Interference using FrFT and Notch Filtering



The positioning results obtained using ***the adaptive notch filter technique*** *in the presence of sweep interference in the real GPS L1-C/A signal, with a sweep period of 0.2 ms and a jammer-to-noise ratio (JNR) value of 3 dB. (a) The variations in coordinates within the UTM system; (b) The positioning errors in the UTM system; (c) The sky plot displaying the satellite constellation.*



The positioning results by using ***the proposed method****: the sweep interference is within the real GPS L1-C/A signal, with the sweep period being 0.2 ms and JNR value equal to 3 dB. (a) The variations in coordinates within the UTM system; (b) The positioning errors in the UTM system; (c) The sky plot displaying the satellite constellation.*


Thank you for your attention!