A Narrowband Interference Excision Algorithm in the Frequency Domain for GNSS Receivers

*Mi Young Shin[1], Chansik Park[2], Ho-Keun Lee[3], Dae-Yearl Lee[3],
Dong-Hwan Hwang[4], Sang Jeong Lee[4]

[1]Department of Electronics Engineering, Chungnam Nat'l Univ (E-mail: snyh@cslab.cnu.ac.kr)
[2] School of Electrical and Computer Engineering, Chungbuk Nat'l Univ (E-mail: chansp@chungbuk.ac.kr)
[3] Agency for Defense Development (E-mail: ldy0310@yahoo.co.kr)
[4] Department of Electrical and Computer Engineering, Chungnam Nat'l Univ (E-mail: eesjl@cnu.ac.kr)

Abstract

Interference can seriously degrade the performance of GPS receiver because GPS signal has extremely low power at earth surface. This paper presents a Narrowband Interference Excision Filter (NIEF) in frequency domain that removes narrowband interferences with small signal loss. A NIEF transforms the received GPS signals with interferences into the frequency domain with FFT and then compute statistics such as mean and standard deviation to determine an excision threshold. All spectrums exceeding the threshold are removed and the remaining spectrums are restored by IFFT. A NIEF effectively can remove various and strong interferences with a simple structure. However, the signal power loss is unavoidable during FFT and IFFT. Besides the hamming window and overlap technique, a threshold-whitening technique and an adaptive detection threshold are adopted to effectively reduce the signal power loss. The performance of implemented NIEF is evaluated using real signals obtained by 12 bit GPS signal acquisition board. The output of NIEF is fed into the Software Defined Receiver to evaluate the acquisition and tracking performance. Experimental results shows that many types of interference such as single-tone CWI, AM, FM, swept CWI and multi-tones CWI are effectively mitigated with small signal power loss.

Keywords: Anti-jamming, Interference suppression, Narrowband - interference, Frequency domain suppression

1. Introduction

Over the years, frequency domain GPS RFI (Radio Frequency Interference) mitigation methods have already been extensively researched. However, many implementation issues, such as the determination of the detection threshold for different kinds and levels of interference and the minimization of the signal power loss during frequency domain transformation, have not been fully addressed. Also the effectiveness of these algorithms in signal acquisition, tracking and navigation performance has not been fully validated using real GPS signals.

This paper designs the NIEF considering implementation issues, especially small signal loss. The NIEF adopts the hamming window and 50% overlap in order to reduce the signal power loss which is unavoidable during FFT and IFFT. Also a whitening technique method is used for efficient interferences suppression. To test the performance of the proposed filter for various situations, experiments using real GPS signals are done for single-tone CWI (Continuous Wave Interference), AM (Amplitude Modulation), FM (Frequency Modulation), swept CWI and multi-tones CWI of the JSR (Jamming to Signal Power Ratio) values from 25dB to 40dB.

The paper is organized as follows. Section 2 provides an overview of the interference suppressor technology and the structure of the NIEF. Section 3 describes experimental results. Concluding remarks are given in section 4.

2. Structure of NIEF

The interference mitigation process in the frequency domain transforms the received GPS signal containing interferences into the signals in the frequency domain and determines an interference excision threshold. All spectrums exceeding the threshold are removed and the remaining signals are transformed into time domain signals. Fig.1 shows a typical structure of the interference mitigation filter in the frequency domain, overlapped FFT filter.

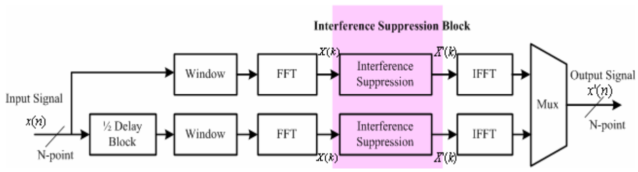


Figure 1. The Structure of Overlapped FFT Filter

2.1 FFT and IFFT

The received GPS signal, $x(n)$ is composed of the transmitted GPS signal, the AWGN (Additive White Gaussian Noise) and the interferences (see Eq.(1)). In Eq.(1), $s(n)$ is the transmitted GPS signal, $a(n)$ is AWGN, and $j(n)$ is the interference signal.

$$x(n) = s(n) + a(n) + j(n) \tag{1}$$

The received GPS signal is transformed to the frequency domain one by the FFT. The FFT output of N -samples, $X(k)$, is given in Eq.(2) [2, 3].

$$X(k)=\sum_{n=0}^{N-1}x(n)e^{-j2\pi kn/N},\quad k=0,1,\ldots,N-1 \qquad (2)$$

If the magnitude of spectrum of each frequency bin is larger than the magnitude of the thermal noise level, it can be regarded as the interference and will be weighted to reject by the weighting factor, ω .(see Eq.(3)). Because the power of GPS signal is much smaller than that of thermal noise, the GPS signal is not likely to be rejected [1]. The remaining signal is restored in the time domain through IFFT (see Eq.(4)) [2, 3].

$$X'(k)=\omega X(k),\ \ k=0,1,\cdots,N-1 \qquad (3)$$

$$x'(n)=\frac{1}{N}\sum_{k=0}^{N-1}X'(k)e^{j2\pi kn/N},\ \ n=0,1,\cdots,N-1 \qquad (4)$$

The Sampling frequency, f_s , and the block size, N , are parameters to determine the frequency resolution as in Eq.(5). The higher frequency resolution leads to increase the number of the rejectable interference and to minimize the signal loss when the interference is rejected. However, the larger block size brings the increment of computation amount. In this paper, the frequency resolution is 22.32kHz because the block size, N , is 256-sample and the sampling frequency is 5.714MHz.

$$Frequency\ resolution=f_s/N \qquad (5)$$

2.2 Window Function

The FFT processing without window brings the spectral leakage [2, 3]. Windowing smoothes the discontinuities at the block boundary and lessens the effect of spectral leakage. The signal energy will be spread across the spectrum directly proportional to the width of the main-lobe and inversely proportional to the height of the side-lobes of the window. In the GPS application, the objective is to minimize the frequency spreading of each CW tone in order to minimize the number of frequency bins that will be excised [4]. At the same time, it is also required to minimize the degradation of the GPS signal when the interference is not present. The window selection requires a tradeoff between the minimization of spectral leakage, the reduction in SNR due to the signal attenuation incurred by multiplying the data sequence by a window and the effectiveness of the spectral containment for a CW tone.

In Table 1, the characteristics of Rectangular window, Blackman-Harris window and Hamming window are compared [2, 3].

Table 1. Window Weighting Characteristics in FFT Analysis

Window	Side-lobe Height	Worst Case Processing Loss	Frequency Containment
Rectangular	-13dB	3.92dB	25 bins
Blackman-Harris	-92dB	3.47dB	6 bins
Hamming	-43dB	3.10dB	4 bins

Most filters with OFFT (Overlapped Fast Fourier Transform) structure use Blackman-Harris window because of the lower side-lobe height [4, 5]. This paper uses the Hamming window since it has the smallest the frequency containment and the least processing loss as shown in Table 1. The Hamming window can be expressed as Eq.(6) [2].

$$w(n)=0.54-0.46[\cos(2\pi n/(N-1))](0\le n<N) \qquad (6)$$

2.3 Overlap Processing

In this paper, 50% overlap technique is adopted to reduce the signal power loss by the window. The 50% overlap processing is of a complex structure, but it reduces the effect of the signal attenuation from windowing on the output SNR [6, 7]. The reduction of the SNR loss by the overlap processing is shown in Table 2 when the interference is not present and Hamming window is used. Each path in the processing chain produces one-half of the usable output sequence as shown in Fig.2. This figure shows the contribution of each data path to the overall result. The overlap function unfortunately doubles the processing since it requires a second processing path that includes Window block, FFT/IFFT block and Interference Suppression block, as shown in Fig.1.

Table 2. Reduction of the Signal Loss by the Overlap Processing

	Without the overlap processing	With the overlap processing
SNR Loss	2.4dB	0.1dB

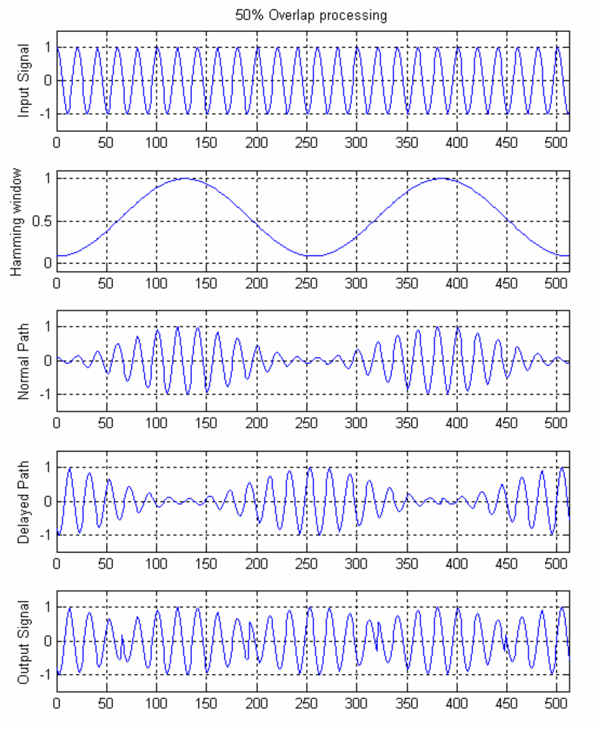


Figure 2. 50% Overlap Processing

2.4 Interference Suppression Technique

CW interferences occupy relatively few frequency bins, and their amplitudes are above the noise floor [4]. The interference suppression block determines the interference excision threshold and then removes all spectrums exceeding the threshold every 256 samples. The functional description of the interference suppression block is shown in Fig.3.

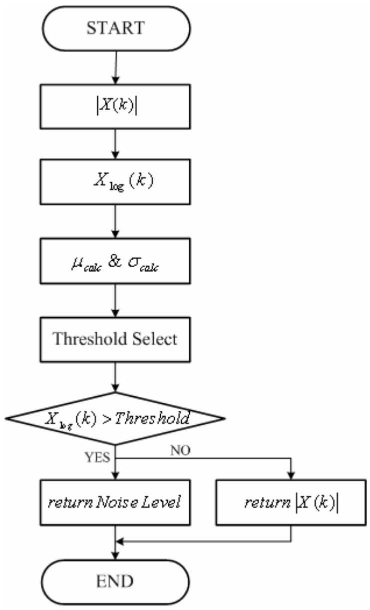


Figure 3. Flow chart of the Interference Suppression Block

Table 3. Scale Factor for the Threshold

σ_{calc}	Scale Factor (α)
$\sigma_{calc} < 4$	2.2
$4 \le \sigma_{calc} < 5$	2.0
$5 \le \sigma_{calc} < 8$	1.3
$8 \le \sigma_{calc} < 12$	1.0
$12 \le \sigma_{calc} < 16$	0.8
$16 \le \sigma_{calc}$	0.5

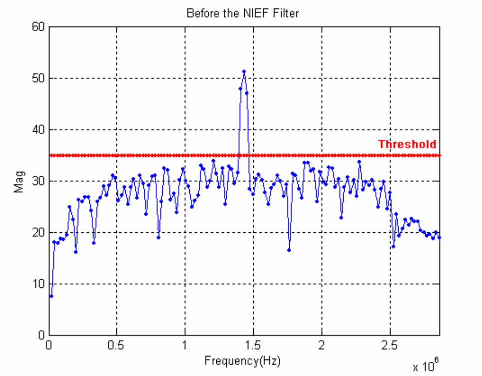
The interference suppression block firstly transforms the magnitude of the FFT output($X(k)$) into the magnitude in decibels($X_{\log}(k)$) for each frequency bin to determine the threshold which is the boundary between the interference and the thermal noise. Then, it calculates the standard deviation (σ_{calc}) and mean (μ_{calc}) of the magnitudes of 256 samples. The standard deviation and the mean are parameters that determine the threshold. The threshold can be calculated as in Eq.(7) [4]. The scale factor, α , is chosen as in Table 3 for six reference points considering the standard deviation. The larger standard deviation indicates the presence of interferers and results in a smaller scale factor to maintain the threshold at the level of the noise floor.

$$Threshold = \mu_{calc} + \alpha \cdot \sigma_{calc} \quad (7)$$

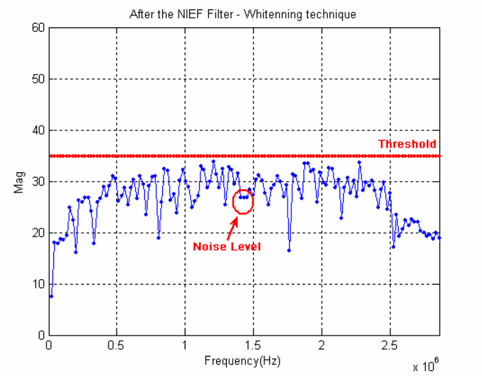
Table 4 compares the SNR loss of 'threshold-excision' algorithm and 'threshold-whitening' algorithm. The 'threshold-excision' algorithm removes the magnitude of a sample exceeding the threshold [7, 8]. Accordingly, this algorithm excises not only the interference power but also the signal power. The 'threshold-whitening' algorithm sets the magnitude of a sample exceeding the threshold to the noise level [7, 8]. The one drawback with this approach is that an estimate of the background noise level must be made, complicating the algorithm.

Table 4. Filter Insertion Loss according to the Interference Suppression Technique

CW Interference	SNR Loss	
	Excision	Whitening
0	0.09dB	0.08dB
1	0.88dB	0.70dB
3	2.76dB	1.77dB



(a) Before the NIEF



(b) After the NIEF

Figure 4. Interference Suppression Processing

In this paper, if the magnitude of a sample is larger than the threshold, then the magnitudes is set to noise level as shown in Fig.4. The noise level can be expressed as in Eq.(8) where M is the number of bins above the threshold.

$$Noise\ Level = \frac{\sum_{k=0}^{N-1} X_{\log}(k)}{N-M},\ if\ \ X_{\log}(k) > Threshold,\ X_{\log}(k) = 0 \quad (8)$$

The structure of NIEF is shown in Fig.5.

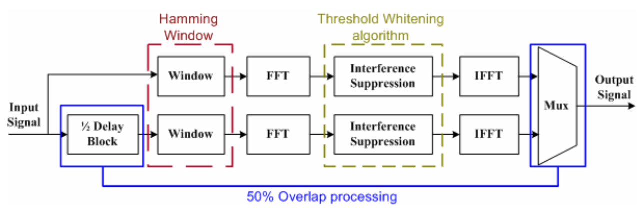


Figure 5. The Structure of NIEF with the Whitening Algorithm

3. Performance Evaluation

3.1 Test Environment Setup

This section shows performance test results of NIEF using the test environment shown in Fig.6. GPS L1 Simulator and a signal generator were used to generate the GPS signal and interferences, respectively. These two signals were combined in a combiner unit, and the output was fed to the 12bit GPS signal acquisition board. The output of the 12bit GPS signal acquisition board is IF signal of 1.134MHz center frequency sampled with 5.714MHz sampling frequency and fed into the NIEF. The output of NIEF will be fed into the SDR (Software Defined Receiver) designed to evaluate the navigation performance. During the experiment, the GPS simulator was set to have 10 visible satellites with DOP 1.6. The narrowband interferences considered in the test are single-tone CWI, multi-tones CWI, swept CWI, AM and FM as shown in Table 5. 3 minute data samples have been collected for testing the NIEF against maximum 40dB J/S interference.

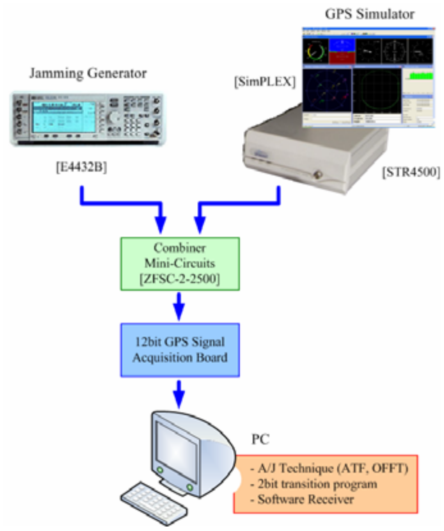


Figure 6. Test Environment Setup

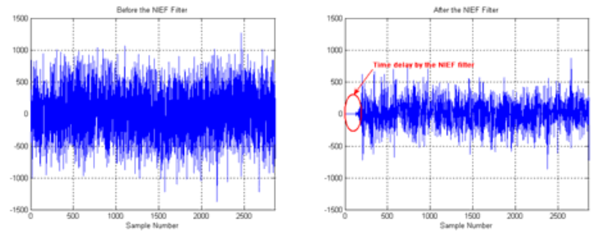
Table 5. Interference Scenario

Interference Type	Frequency	Characteristics
CW	1575.47 MHz	
MCW	1575.32 MHz 1575.47 MHz 1575.62 MHz	
Swept CW	1575.47 MHz ~ 1576.47 MHz	− Rate : 10Hz − Point count : 50
FM	1575.47 MHz	− Wave form: square − Deviation : 50kHz − Rate : 1kHz
AM	1575.47 MHz	− Wave form : square − Depth : 0.5 − Rate : 1kHz

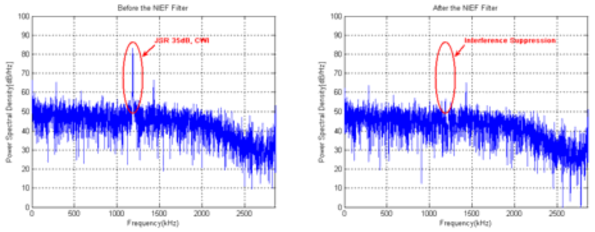
3.2 Test Results

3.2.1 Interference Suppression Performance

Fig.7 shows one of the test results where it can be seen that the NIEF rejects CW interference effectively. Similar results have been obtained for other types of interferences.



(a) Time domain-Before filter (b) Time domain-After filter

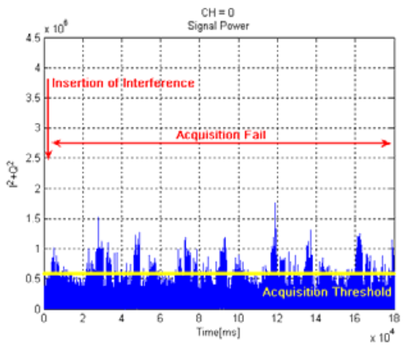


(c) Frequency domain-Before filter (d) Frequency domain-After filter

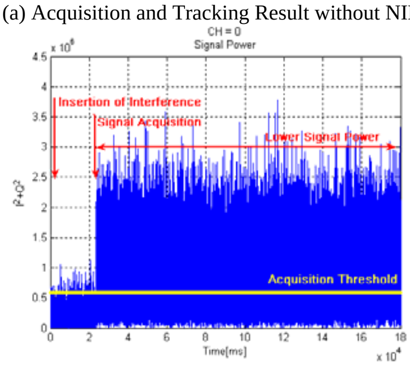
Figure 7. Interference Suppression Performance

3.2.2 Acquisition and Tracking Performance

The test has been executed when the interference was applied both from the beginning and during the state of signal tracking in order to analyze the effect of interference on the signal acquisition and tracking. Fig.8 shows the performance of signal acquisition and tracking in case that the interference is inserted from the beginning. The signal was not acquired without NIEF, but it could be acquired and tracked using the NIEF. Fig. 9 shows the performance of signal acquisition and tracking in case that the interference applied during the state of signal tracking. In case that the NIEF was not used, SNR was degraded and both the bit lock and the frame lock was lost. In case that the NIEF was used, however, the signal tracking was maintained with 8.0dB SNR.

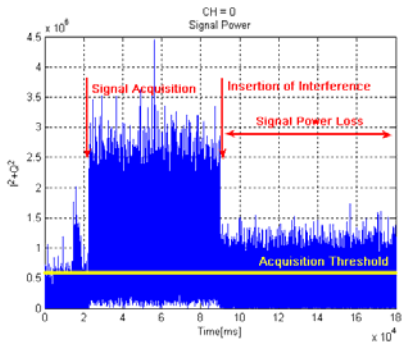


(a) Acquisition and Tracking Result without NIEF

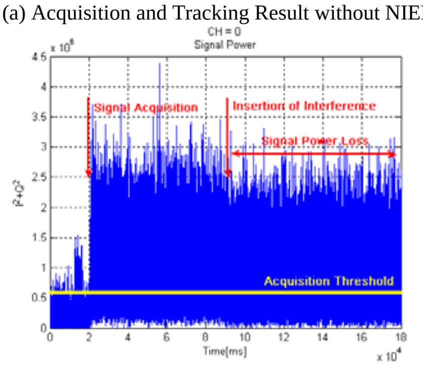


(b) Acquisition and Tracking Result with NIEF

Figure 8. Acquisition and Tracking Performance
- Insertion of Interference from the beginning



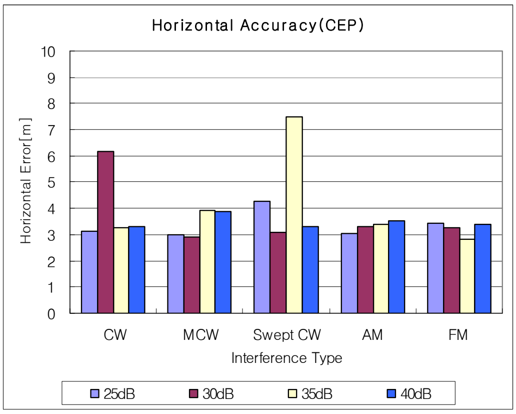
(a) Acquisition and Tracking Result without NIEF



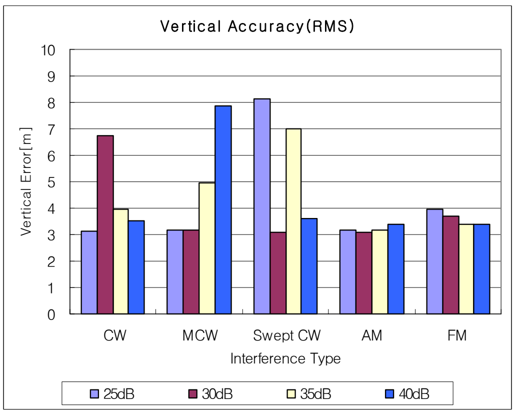
(b) Acquisition and Tracking Result with NIEF

Figure 9. Acquisition and Tracking Performance - Insertion of Interference when Tracking

3.2.3 Navigation Performance

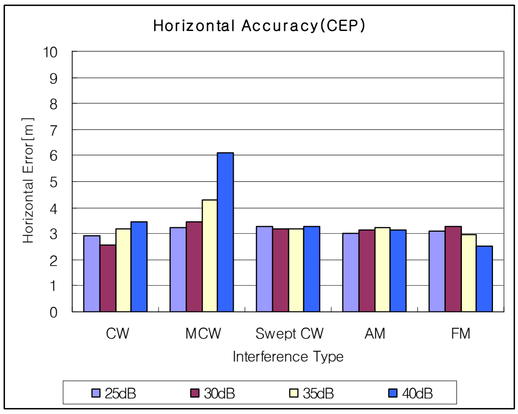


(a) Horizontal Accuracy (CEP)

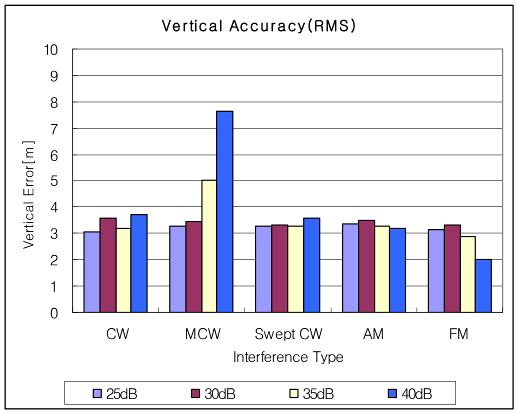


(b) Vertical Accuracy (RMS)

Figure 10. Navigation Performance - Insertion of Interference from the beginning



(a) Horizontal Accuracy (CEP)



(b) Vertical Accuracy (RMS)

Figure 11. Navigation Performance - Insertion of Interference when Tracking

As the navigation performance, horizontal and vertical error have been analyzed for CW, MCW, Swept CW, AM, FM interferences. As the Fig.10 and Fig.11, the position error has been within 10m(CEP) horizontally and 10m(RMS) vertically although the interference was inserted with 40dB JSR. It can be seen that the error for MCW interference is largest because the signal loss is largest.

4. Conclusions

The NIEF with small signal power loss was designed and tested in this paper. The experiments with real data show that the filter insertion loss is less than 0.1dB when interference is not present. The experiments show that the NIEF is effective to mitigate CW, MCW, Swept CW, AM and FM type interference. The receiver with NIEF can acquire and track the satellite when more than 40dB JSR interferences are added regardless of receiver channel tracking status. The horizontal accuracy is better than 10m for all types of interference with 40dB JSR.

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