

Innovation

A Growing Concern Radiofrequency Interference and GPS

Felix Butsch Deutsche Flugsicherung GmbH (DFS)

Over the past couple of years, there has been extensive discussion of the potential interference that ultra-wideband (UWB) radio signals might cause to GPS once UWB devices proliferate across the planet. But GPS is also susceptible to interference from more conventional transmissions both accidental and intentional (jamming). For example, a particular directional television receiving antenna widely available in the consumer market contains an amplifier which can emit spurious radiation in the GPS L1 frequency band with sufficient power to interfere with GPS reception at distances of 200 meters or more. Harmonic emissions from high-power television transmitters might also be a threat to GPS. Furthermore, the GPS L2 frequency is susceptible to interference from out-of-band signals from transmitters operating in the lower part of the 1240 to 1300 MHz band which is shared by terrestrial radiolocation services and amateur radio operators. As for intentional interference, the weak GPS signals can be readily jammed either by hostile forces during conflicts or by hackers who could easily construct a GPS jammer from a surplus home-satellite television receiver.

So, just how susceptible are GPS signals to interference and how can such interference be monitored? **Dr.-Ing. Felix Butsch** answers these questions in this month's column. Dr. Butsch graduated in electrical engineering at the University of Karlsruhe in 1990. Subsequently, he worked as a research associate at the Institute of Navigation of the University of Stuttgart, first in the area of remote sensing radar and, since 1995, in researching electromagnetic interference to GPS and GLONASS. He obtained the Doktor-Ingenieurs degree for his interference work in 2001. In 2000, he joined Deutsche Flugsicherung (DFS), where he is involved in the field of interference monitoring and in several projects dealing with the definition of the Galileo satellite navigation system.



Whenever a GPS receiver suddenly loses track of satellites or displays an unexpectedly low signal-to-noise ratio, S/N , or signal-to-noise density ratio, S/N_0 , at a certain location, one should suspect radio frequency interference (RFI). This is especially true when a dual frequency receiver indicates a reasonable S/N_0 on one frequency and a low value or no value on the other frequency.

In this article, I attempt to shed some light on the subject of RFI as a source of GPS error on the basis of my experience with this phenomenon in Germany and some neighboring countries since 1995. Since I have learned from experience that the S/N and S/N_0 are very useful for analyzing the impact of RFI, I will explain what these variables mean and how a GPS receiver estimates them. Moreover, I will describe how to determine and use the spectrum of interfering signals to

assess their impact. In addition, I will present recent experience with RFI on GPS in Germany.

Signal-to-Noise Ratio

The S/N of a signal is the ratio of received signal power, S , to the noise power, N , accompanying the signal. It is a unitless quantity and is typically expressed in decibels (dB). The noise may be caused by the receiver itself due to the random motion of electrons in its circuitry (thermal noise), by natural emissions such as ground and atmospheric radiation picked up by the antenna, or by interfering transmitters. The S/N is a measure of the quality of signals. In general, the higher the S/N the more accurate a GPS range measurement will be.

Usually, the higher the elevation angle of the received satellite, the higher the signal power (with the exception that when

a satellite is near the zenith, the received power decreases slightly due to the shape of the satellite's transmitting antenna beam).

A GPS receiver correlates received signals with a self-generated replica of the pseudorandom noise (PRN) code of the satellite to be received; that is, it multiplies the signals together and integrates the product. This can be described mathematically (with some simplifications) as follows:

$$U_{rec}(t) \cdot U_{replica}(t) = \left\{ \sqrt{S} \cdot c(t + \Delta\tau) \cdot \sin\left[2\pi \cdot (f_{RF} + \Delta f) \cdot t + \Delta\phi\right] \right\} \cdot \left\{ 1 \cdot c(t) \cdot \sin(2\pi f_{RF} t) \right\} \quad (1)$$

where:

$U_{rec}(t)$ Received signal

$$U_{rec}(t) = \sqrt{S} \cdot c(t + \Delta\tau) \cdot \sin\left[2\pi \cdot (f_{RF} + \Delta f) \cdot t + \Delta\phi\right]$$

$U_{replica}(t)$ Replica signal

$$U_{replica}(t) = 1 \cdot c(t) \cdot \sin(2\pi f_{RF} t)$$

(with an amplitude of 1 for simplicity)

\sqrt{S} Amplitude of received signal, square root of the signal power

f_{RF} Carrier frequency, e.g. L1

t Time

$c(t)$ Code, e.g. C/A code

$\Delta\tau$ Delay of the received code

Δf Velocity-induced Doppler shift of the carrier frequency

$\Delta\phi$ Phase shift of the carrier

Synchronizing the code replica with the received signal by means of the receiver's code-tracking loop maximizes the correlation integral:

$$\text{Max} \left\{ \frac{1}{2T} \int_{-T}^{+T} U_{rec}(t) \cdot U_{replica}(t) dt \right\} \quad (2)$$

$$\Rightarrow \Delta\tau, \Delta f; \Phi(t) = \int_0^t \Delta f(t) dt$$

where:

T Integration time, typically 1 to 20 milliseconds

Φ Measured carrier phase = integrated Doppler shift.

The faster the tracking loop synchronizes the code replica with the received signal, the higher its bandwidth is. Unfortunately, a fast tracking loop comes at a price: the noise power, which is proportional to the bandwidth of the loop, is higher than it

Innovation

would be for a slow loop. The noise power, N is the product of noise power density, N_0 , and loop bandwidth, B_L :

$$N = N_0 B_L \quad (3)$$

The receiver's software commonly adjusts B_L during acquisition of the signal (that is, during the initial attempt to synchronize the signals) and sometimes also afterwards, to adjust the receiver to accommodate the actual receiver-satellite line-of-sight dynamics. The S/N in turn changes as the loop bandwidth changes. For this reason, it is useful to normalize the S/N to the loop bandwidth and indicate the signal-to-noise density ratio, S/N_0 (in dB-Hz) in-lieu-of the S/N .

Estimating S/N_0

As already mentioned, GPS receivers correlate received signals with a self-generated replica of the code. The correlation integral is proportional to the product of the amplitudes of the input signal and the replica signal. Since the amplitude of the replica signal is known (in Equation 1 I have set it to 1 for the sake of simplicity), the correlation integral can be used to estimate the power of the received signal S :

$$\frac{1}{2T} \int_{-T}^{+T} U_{rec}(t) \cdot U_{replica}(t) dt = \quad (4)$$

$$const \cdot \sqrt{S} \Rightarrow \hat{S}$$

where $const$ is a constant depending on the integration interval T (in many receivers, it is the duration of a GPS navigation message data bit of 20 milliseconds), and the amplitude of the replica signal, but also on the sampling frequency and the size of the receiver's analog-to-digital (A/D) converter steps. To determine a correct estimation of S in physical units, the receiver manufacturer must determine the constant $const$. An estimate for the noise power \hat{N} is determined from the mean squared deviation of the correlation integral I (according to Equation 4) from its average value \bar{I} over an interval of $\tau \gg T$, as follows:

$$\hat{N} = \frac{1}{\tau} \int_0^{\tau} (I(t) - \bar{I})^2 dt \quad (5)$$

From \hat{N} , one can determine an estimate for N_0 by division by the loop bandwidth B_L . Once the estimates for S and N or N_0 are known, estimates for S/N or S/N_0 can be easily calculated. (As defined here, S/N or S/N_0 are post-correlation

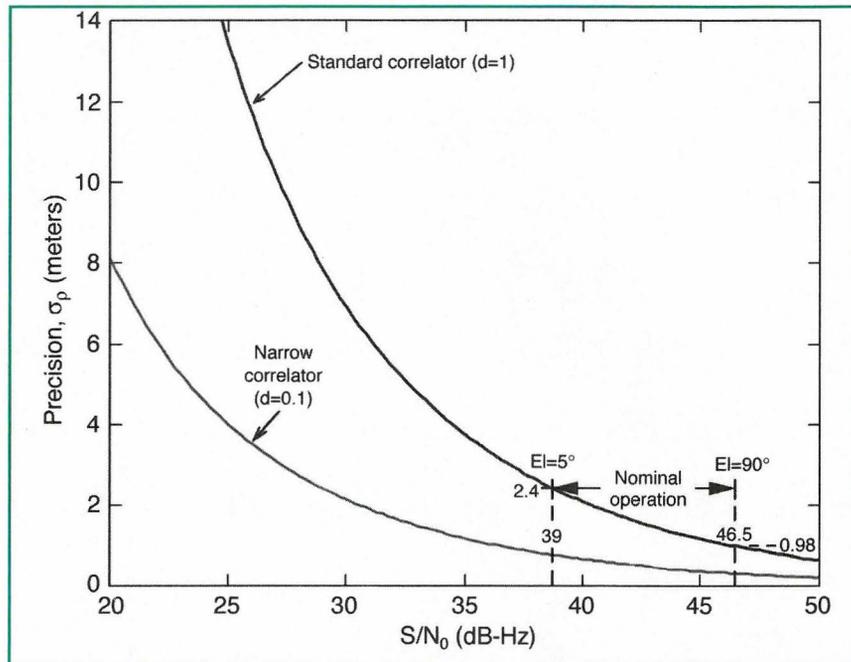


FIGURE 1 Typical variation of pseudorange precision as a function of S/N_0

quantities which can be related to the corresponding pre-correlation quantities, the carrier-to-noise power, C/N , and carrier-to-noise power density, C/N_0 .)

Most GPS receivers display and/or output an estimated value for the S/N or S/N_0 which we will call \hat{S}/\hat{N} . If \hat{S}/\hat{N} is determined correctly, one can use it to predict the precision (standard deviation) of the pseudorange and carrier-phase measurements derived from a satellite signal. This is especially helpful since, due to the large variation in the distance between satellite and receiver over time, it is difficult to calculate the standard deviation from the measured values themselves. Equations in the literature (see the "Further Reading" sidebar) describe the relationship between the precision of pseudorange and carrier-phase measurements on the S/N_0 for a variety of receiver types (actually for different types of code and carrier tracking loops). The common characteristic of all these relationships is that the receiver's precision is approximately inversely proportional to the square root of S/N or S/N_0 (in linear values, not in dB or dB-Hz).

Figure 1 shows a simulation of a plot of the typical variation of pseudorange precision, σ_p , as a function of S/N_0 for a standard correlator (correlator spacing of 1 code chip) and for a narrow correlator (correlator spacing of 0.1 chip).

Unfortunately, in practice most GPS users do not estimate measurement precision. They usually just watch whether

the \hat{S}/\hat{N} values are reasonably high or not. This often is because they do not know which type of tracking loop their receiver uses or how \hat{S}/\hat{N} is determined. Moreover, a lot of receiver types do not output a useful \hat{S}/\hat{N} for precision estimation, but rather display normalized values (for example, 0 to 30 or 0 to 100) to save effort and to make it easier for the user to assess whether or not a certain value is acceptable.

It would be very helpful, however, if GPS receivers used in the fields of science, geodesy and surveying, aviation, and marine positioning would display and/or output reasonable S/N estimates. This would allow user software to weight each pseudorange or carrier-phase measurement appropriately when calculating position. Furthermore it would enable the user to more easily assess the impact of multipath reception and RFI.

What \hat{S}/\hat{N} Says About RFI

If an interfering signal is received along with GPS signals, this signal is also modulated with the code replica during the correlation process. This way, the spectrum of the RFI signal is spread over the bandwidth of the GPS signals. Simultaneously, the spectrum of the GPS signal is de-spread. This is because the multiplication with the right PRN code removes the steps in the carrier phase, which were introduced by the binary phase shift keying modulation in the satellites. For this reason the product of

Innovation

received signals and the replica code can be filtered with a narrow filter (which is what the integration does, since it corresponds to a filtering with an "integrate and dump" filter).

Within the bandwidth of this narrow filter (for example, 100 Hz), the spectrum of the spread RFI signal (now occupying a bandwidth of 2.046 MHz, if a pure sinusoidal signal (continuous wave - c.w.) is spread with a C/A PRN code with

a code clock frequency of 1.023 MHz), the power density across the bandwidth is almost constant. For this reason, the spread RFI signal can be regarded as artificial noise and specifically white noise which has a constant power density for all frequencies. This artificial noise contributes to the total noise. Since artificial noise and thermal noise are uncorrelated, their power values (corresponding to the variance in the time domain) or

power density values can be summed. For this reason the \hat{S}/\hat{N} determined by the GPS receiver is no longer an estimation of the S/N_0 but of the $S/(N_0+N_{J,0})$, where N_0 is the power density of the thermal noise and $N_{J,0}$ (in watts per hertz) represents the power density of the artificial noise.

It can be shown that in general, the power spectral density (PSD) of the generated artificial noise can be assessed by the integral of the PSDs of the interfering signal and the replica signal:

$$N_{J,0} \approx \int_{-\infty}^{\infty} a(f) \cdot L_J(f) \cdot L_C(f) df \quad (6)$$

where:

$a(f)$ Pre-correlation transfer function which is the transfer function of the signal path between antenna and correlator, describing the attenuation of the interfering signal due to radio frequency and intermediate frequency filters as a function of frequency

L_J Power spectral density of the interfering signal in watts per hertz, which can be determined by normalizing the measured spectrum (in watts) to the resolution bandwidth of the spectrum analyzer (in hertz)

L_C Normalized power spectral density of the replica signal in inverse hertz.

Equation 4 clearly shows that the more both PSDs overlap, the higher the resulting $N_{J,0}$.

In the case of a sinusoidal interfering signal, the power density of the artificial noise can be simplified as follows:

$$N_{J,0} \approx \frac{J}{f_c} \quad (7)$$

where:

J (Jamming) power of the interfering signal, in watts

f_c Code clock frequency of the replica signal in hertz.

As long as the power of the artificial noise is lower than the power of the thermal noise, RFI does not have a significant impact. But if $N_{J,0} = N_0$, the \hat{S}/\hat{N} is degraded by 3 dB (a factor of 2), which means that the precision of pseudorange and carrier phase measurements are reduced by a factor of $\sqrt{2}$. If the power of the received RFI signal increases further beyond this point, the $S/(N_0+N_{J,0})$ or \hat{S}/\hat{N} is decreasing by 1 dB for every additional increase of the signal power by 1 dB (see **Figure 2**).

If the $S/(N_0+N_{J,0})$ or \hat{S}/\hat{N} falls below the so-called loss-of-lock threshold, the GPS receiver loses track of the sig-

GPS Problems?



PCI Time & Frequency Processor:
Fastest PCI cards on the market.
(1000 time tags per second)



ExacTime GPS Time & Frequency Generator:
Most Standard Features on the market.



TymServe Network Time Server
Handles more NTP requests than any other time server (> 800 per second).



StarLoc II Precision GPS Time & Frequency Reference:
Stratum 1 Accuracy supports all base station applications.

- ✓ LAN/WAN Timing
- ✓ Weather & Base Stations
- ✓ Embedded Timing Systems
- ✓ Range & Tracking Stations
- ✓ Metrology & Cal Labs
- ✓ Stratum I Standard



VME Time & Frequency Modules:
Most extensive VME Product Line.

GPS Solutions.

CONTACT US TODAY!

 **datum**
Timing, Test & Measurement

www.datum.com
US Toll Free: (800) 544-0233
34 Tozer Road, Beverly, MA 01915-5510
Tel: (+1) 978-927-8220 • (+1) 978-927-0233

nal; that is, it is no longer able to synchronize the code replica with the received signal and is therefore not able to per-

form a measurement. For strong signals which are received from satellites at high elevation angles, the loss-of-lock thresh-

old is reached at higher interference power levels compared with weak signals from satellites at low elevation angles. The actual value of this loss-of-lock threshold depends very much on the receiver type, especially the type of A/D converter, the type of the tracking loop, and whether the receiver applies special interference mitigation techniques. For a GPS receiver to resume tracking GPS signals, the power of the interference source has to be reduced below the so-called tracking threshold. This threshold is several dBs below the loss-of-lock threshold, because during the acquisition phase, when the receiver tries to synchronize the code replica with the received signal, the receiver is more susceptible to interference. To assess the impact of interfering signals on code and phase measurements, the actual \hat{S}/\hat{N} can be inserted into equations describing the dependency of standard deviations of pseudorange σ_p or carrier phase σ_ϕ on the S/N_0 as mentioned above.

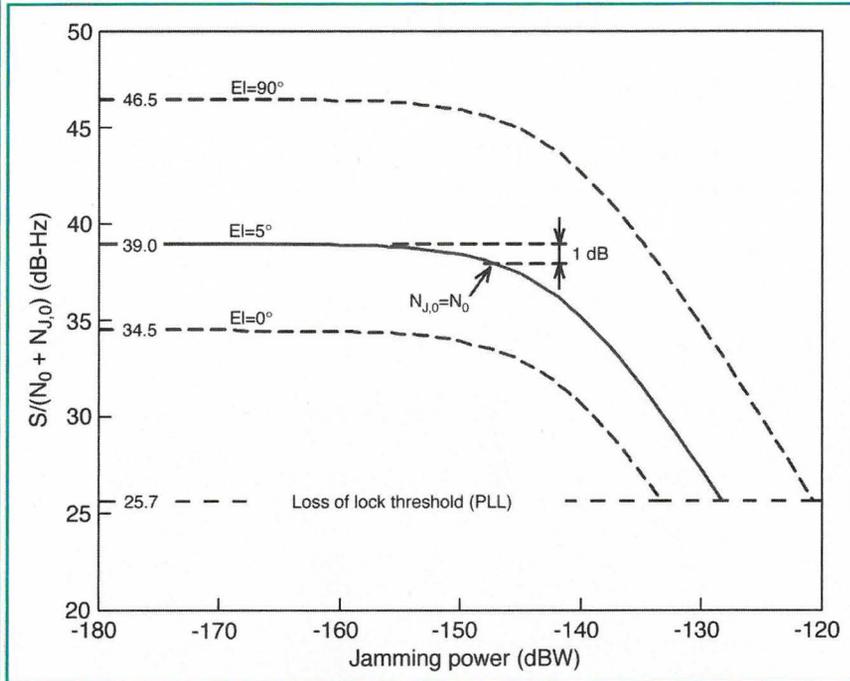


FIGURE 2 Degradation of the $S/(N_0+N_{j0})$ ratio by the interference power J

Analyzing RFI Impact

RFI usually prevents a GPS receiver from operating at all, causes it to lose lock on satellite signals, or causes it to display an unexpectedly low \hat{S}/\hat{N} at a certain location. If any of these symptoms occur, one should consider RFI as a possible cause. This is especially true if a dual frequency receiver is used and a reasonable S/N_0 is indicated on one frequency while a low value (or no value) is consistently indicated on the other frequency. It is usually difficult to recognize the impact directly on the pseudorange or carrier phase measurements, except if the RFI causes a loss-of-lock of the code- and/or carrier-tracking loops, which in turn prevents the receiver from outputting values.

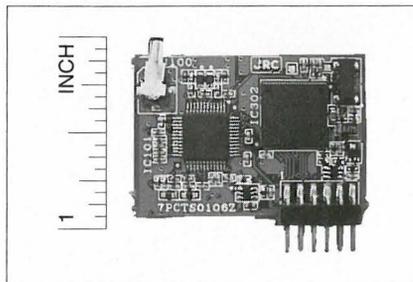
To analyze RFI impact on GPS measurements, it is necessary to obtain variables that are almost constant over time (that is, they vary only due to noise, multipath reception, or RFI). Such is not the case with raw pseudorange and carrier-phase measurements that vary significantly from epoch to epoch. However, such variables can be obtained by differencing raw observables that vary in the same way over time. This allows us to determine any unusual increase of the noise or the occurrence of unusual peaks due to RFI.

The following constructed observables are suitable for this purpose:

• Pseudorange minus carrier-phase measurements on L1 or L2: this observ-

Big Benefits In a Small Package

JRC introduces a remarkably compact 16-channel GPS receiver for all applications



The CCA-450 is only 1 inch in size, but offers big advantages:

- Built-in WAAS
- Light weight, low power consumption
- Extremely short TTFF
- 16-channel parallel all-in-view positioning

For further details, please contact:



Japan Radio Co., Ltd.

Since 1915

MAIN OFFICE: Akasaka Twin Tower, 17-22, Akasaka 2-chome, Minato-ku, Tokyo 107-8432, Japan Phone: 81-3-3584-8838 Fax: 81-3-3584-8879
SEATTLE BRANCH OFFICE: Phone: 206-654-5644 Fax: 206-654-7030
JRC AMSTERDAM OFFICE: Phone: 31-20-658-0750 Fax: 31-20-658-0755

able allows us to analyze primarily the impact of RFI on the pseudorange, since it is dominated by the noise of the pseudorange measurement.

⊕ L2 pseudorange minus L1 pseudorange and L2 carrier-phase minus L1 carrier-phase: It is almost always the case that a particular instance of RFI only affects one of the two GPS frequencies. In such a case, it is useful to analyze the difference between similar observables of both frequencies.

As the elevation angle of a satellite varies between 5 and 90 degrees, the S/N_0 of a satellite signal varies on the order of 7.5 dB. Simultaneously, the standard deviation of the pseudorange as well as the carrier phase vary by a factor of about 2.5 (see Figure 1). Therefore, an increase of the measurement uncertainty due to RFI can only be detected if the RFI causes an increase of the uncertainty by a factor sufficiently higher than 2.5. An increase of the uncertainty by a factor of $\sqrt{10} \approx 3.2$ could be determined, if the RFI is received over a sufficiently long time interval to determine the standard deviation of the measurements with a sufficient level of confidence (which is rarely the case). Such an increase of the uncertainty occurs if the $S/(N_0+N_{J,0}) = 1/10 \cdot S/N_0$, that is if the signal-to-noise ratio is degraded by 10 dB.

It is even harder to determine an increase of the bit error rate of the received navigation message or a decrease of the mean time between cycle slips due to RFI than an increase of the measurement uncertainty, since the former variables do not significantly deteriorate unless RFI is strong enough to cause complete loss of lock of the carrier-tracking loop. Therefore, \hat{S}/\hat{N} is the most sensitive variable for detecting RFI impact.

Directly Detecting RFI

It is possible to detect RFI directly by analyzing the spectrum of a received signal. This allows us to determine its frequency and modulation type. To monitor RFI, one can connect a spectrum analyzer or a digital signal processing (DSP) receiver to an off-the-shelf GPS antenna with a built-in pre-amplifier. The use of such an antenna has the following advantages:

- ⊕ such antennas are readily available
- ⊕ such antennas have almost isotropic characteristics in the upper hemisphere; therefore all potential interfering signals are received

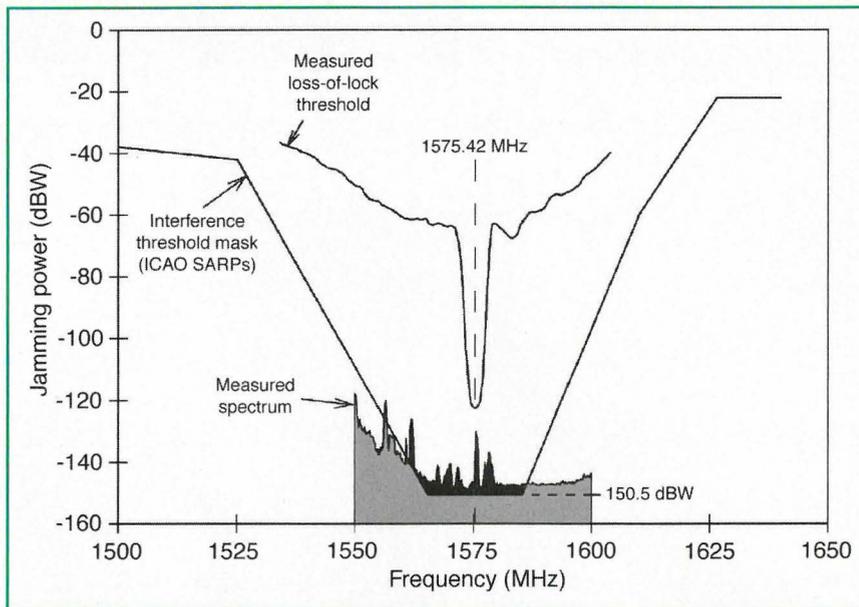


FIGURE 3 Comparison of measured spectrum with mask and loss-of-lock threshold curve

⊕ the patterns of almost all GPS antennas are comparable, since they all have to receive signals from all satellites above the horizon

⊕ interference thresholds for GPS receivers are referenced to the antenna port of a GPS receiver

⊕ the same signal spectrum is analyzed as that acquired by a GPS receiver.

It is useful to record spectrograms (illustrating received power as a function of frequency and time) of the interfering signals to get an idea of the spectrum's variation as a function of time.

For an assessment of the impact of a potential interfering signal, its spectrum can be compared with an interference threshold mask. For an interfering signal of a given frequency, such a mask specifies how much signal power a GPS receiver can tolerate without undue degradation of its measurement precision.

The "Standards and Recommended Practices for Airborne GNSS Receivers" published by the International Civil Aviation Organization (ICAO) has standardized an interference threshold mask for sinusoidal (c.w.) interfering signals. It would be difficult to develop such a mask for every imaginable kind of signal type (pulsed, amplitude modulated, frequency modulated, phase modulated, etc.). Nevertheless it is always possible to measure the spectrum of the interfering signal and to determine the power density of the artificial noise power it generates according to Equation 6, to compare it with a given threshold.

To analyze the impact on a particular

receiver type, it is useful to determine a receiver-specific susceptibility curve. Such a susceptibility curve can be obtained, for example, by feeding the receiver an artificially-generated interfering signal and determining the threshold for the interference power versus frequency. Useful criteria for determining susceptibility curves are:

- ⊕ the interference power required to prevent acquisition of a GPS signal
- ⊕ the interference power required to cause a \hat{S}/\hat{N} degradation of 10 dB
- ⊕ the interference power required to cause the loss-of-lock of the tracking loop.

Figure 3 shows the comparison of a measured spectrum of a potential interfering signal with the interference threshold mask as standardized by ICAO. It can be recognized that the spectrum exceeds the mask by approximately 10 dB. Therefore, the impact of this signal on the performance of a GPS receiver would likely be significant, degrading pseudorange and carrier-phase measurement precision. On the other hand, a comparison with the measured loss-of-lock threshold versus frequency curve shows that the signal is not strong enough to cause loss-of-lock.

Locating the Source of RFI

Once an interfering signal has been detected, it is desirable to localize its source. For this purpose, one must take bearing measurements from different locations and determine the intersection of the resulting lines-of-bearing.

Bearing measurements can be carried

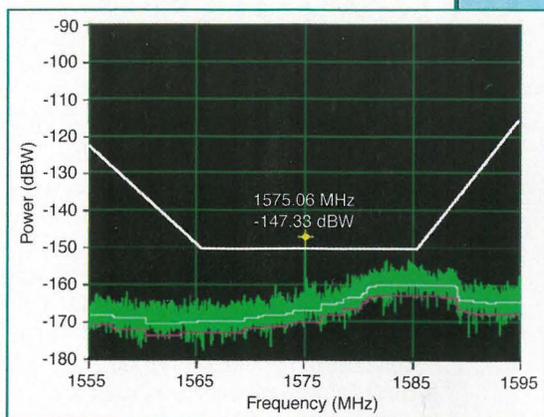


FIGURE 4 Interfering signal near the GPS L1 frequency

out, for example, by using a direction-finding antenna such as an Adcock phased antenna array and by evaluating the signals received by the various antenna elements with respect to their differences in phase and/or amplitude according to the Watson-Watt principle.

A third option is to use a network of synchronized receivers to determine the differences of time-of-arrival measurements. This has been done, for example, by cross-correlating the signals received by the individual antennas.

Typical RFI Sources

I have experienced the effects of RFI on GPS in Germany and some neighboring countries since 1995. During this time I only experienced RFI to the GPS L1 frequency twice:

- In 1997 near the Swiss airport of Lugano, signals emitted from a permanent transmitter operated by the Italian

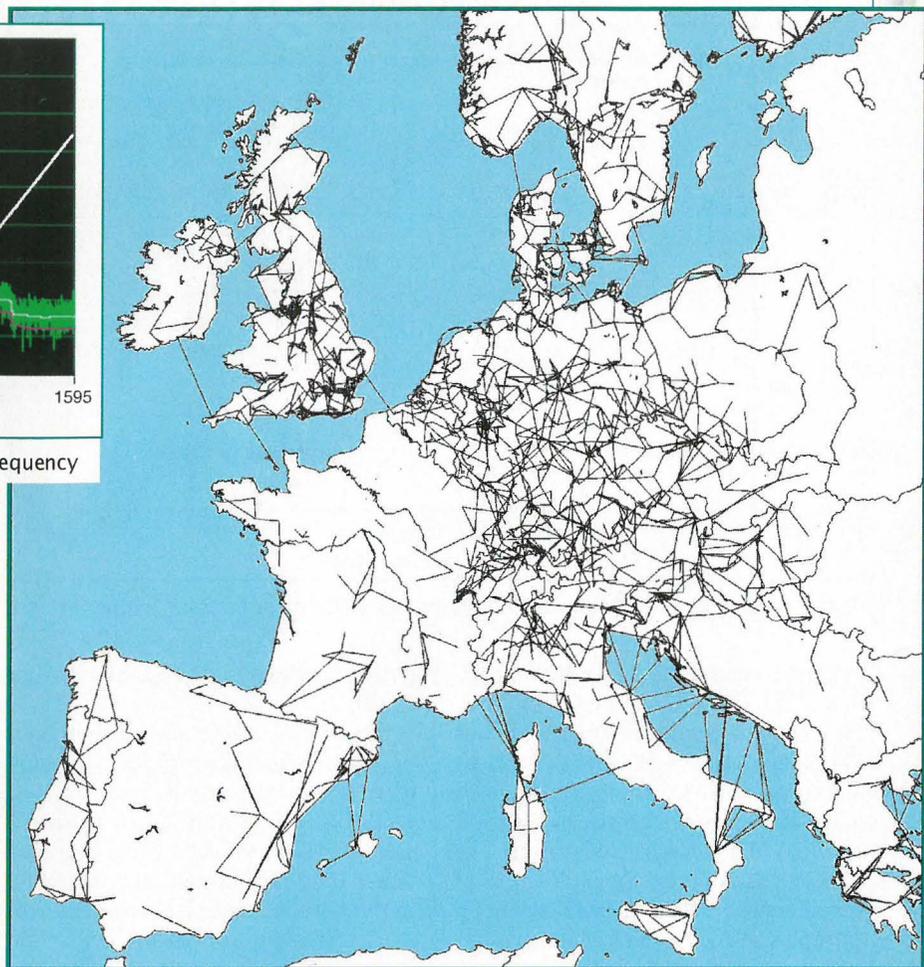


FIGURE 5 Map showing the links between European amateur radio digipeaters

military were detected (see Figure 3).

- In February 2002, for 20 to 30 seconds an unknown interfering signal with a frequency of 1575.06 MHz disturbed the reception of L1 at Frankfurt Airport

and surrounding areas up to a distance of 150 kilometers (see Figure 4). While geodetic GPS receivers exhibited a loss-of-lock, a certified aviation receiver merely experienced a degradation of the \hat{S}/\hat{N} .

Further Reading

For further details of the author's investigations of GPS interference, see

- *Untersuchungen zur elektromagnetischen Interferenz bei GPS* by F. Butsch, a Dr.-Ing. dissertation published as Report No. 2001.1 in the series *Technical Reports of the Department of Geodesy and Geoinformatics* by the Department of Geodesy and Geoinformatics, Stuttgart University, Germany, 2001. Copies can be requested from the author via e-mail: <Felix.Butsch@DFS.de>.

- "A Concept for GNSS Interference Monitoring" by F. Butsch published in the *Proceedings of ION GPS-99, the 12th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Nashville, Tennessee, September 14-17, 1999, pp. 125-135.

- "DFS Experience with GNSS Monitoring Systems" by W. Dunkel and F. Butsch published as Paper 003 in the *Proceedings of the European*

Navigation Conference GNSS 2002, Copenhagen, May 27-30, 2002.

For information on ICAO's recommended threshold mask for c.w. interference, see

- Section B.3.7 "Resistance to Interference" in Appendix B of "Standards and Recommended Practices for Airborne GNSS Receivers" contained in Annex X to the *Convention on International Civil Aviation* of the International Civil Aviation Organization, Amendment 76, Volume 1, Montreal, 2001.

For an introduction to the relationship between electromagnetic noise and GPS receiver performance, see

- "GPS Receiver System Noise" by R.B. Langley in *GPS World*, Vol. 8, No. 6, June 1997, pp. 40-45.

For a more in-depth discussion of the effect of noise on GPS receivers, see

- "GPS Signal Structure and Theoretical Performance" by J.J. Spilker, Jr. and "GPS Receivers" by A.J. Van Dierendonck in *Global Positioning*

System: Theory and Applications, Vol. 1, edited by B.W. Parkinson and J.J. Spilker, Jr. and published as Volume 163 of *Progress in Astronautics and Aeronautics* by the American Institute of Aeronautics and Astronautics, Washington, D.C., 1996.

For more information on GPS interference finding, see

- "Interference Direction Finding for Aviation Applications of GPS" by K. Gromov, D. Akos, S. Pullen, P. Enge, B. Parkinson, and B. Pervan published in the *Proceedings of ION GPS-99, the 12th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Nashville, Tennessee, September 14-17, 1999, pp. 115-123.

For an earlier *GPS World* article on GPS interference, see

- "Interference: Sources and Symptoms" by R. Johannessen in *GPS World*, Vol. 8, No. 11, November 1997, pp. 44-48.

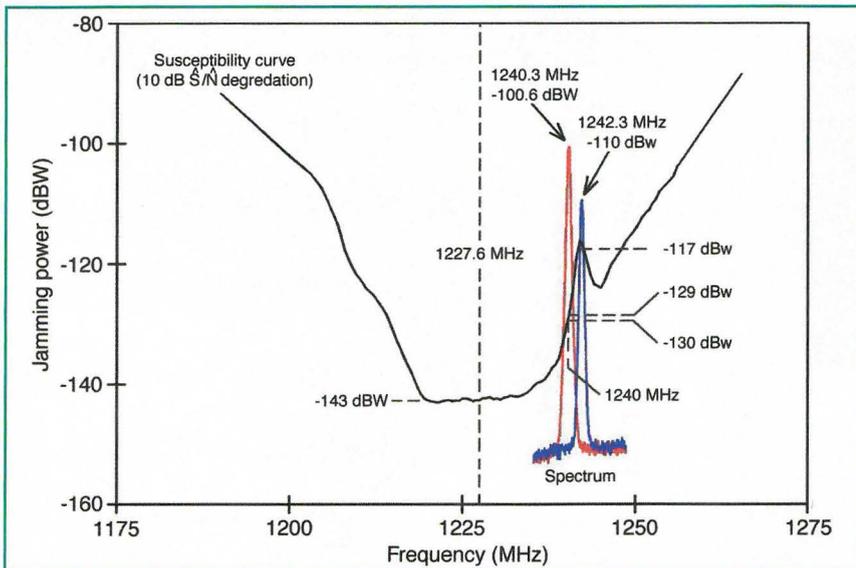


FIGURE 6 Spectrum of amateur radio digipeater signal near GPS L2 frequency

Dual-frequency GPS users routinely detect interference to the GPS L2 frequency in Germany, Switzerland, and The Netherlands. In all cases the sources are amateur packet radio transmitters in the frequency band between 1240 and 1243.25 MHz. Such transmitters are called “digipeater” (short for digital repeaters or relays). They are part of a Europe-wide network of a kind of wireless Internet operated by radio amateurs (see **Figure 5**). They cause interference to dual-frequency GPS receivers operated by researchers at several universities as well as by geodesists and surveyors. **Figure 6** shows a comparison of the spectra of such signals with a susceptibility curve representing the interference

power required to degrade the \hat{S}/\hat{N} by 10 dB.

Since digipeaters transmit short data packages which are separated by gaps of up to several seconds, receivers lose track of GPS signals for short intervals. The same is true for the degradation of the \hat{S}/\hat{N} or the occurrence of peaks in the pseudorange or phase measurement uncertainties. **Figure 7** depicts the impact of digipeater signals on the \hat{S}/\hat{N} of the L1 and L2 frequencies of dual-frequency receivers (unfortunately, the receiver used does not output the \hat{S}/\hat{N} in dB-Hz units). It can be recognized that the \hat{S}/\hat{N} of the L1 signal is undisturbed. For this measurement, investigators had set up one receiver to receive the P-code

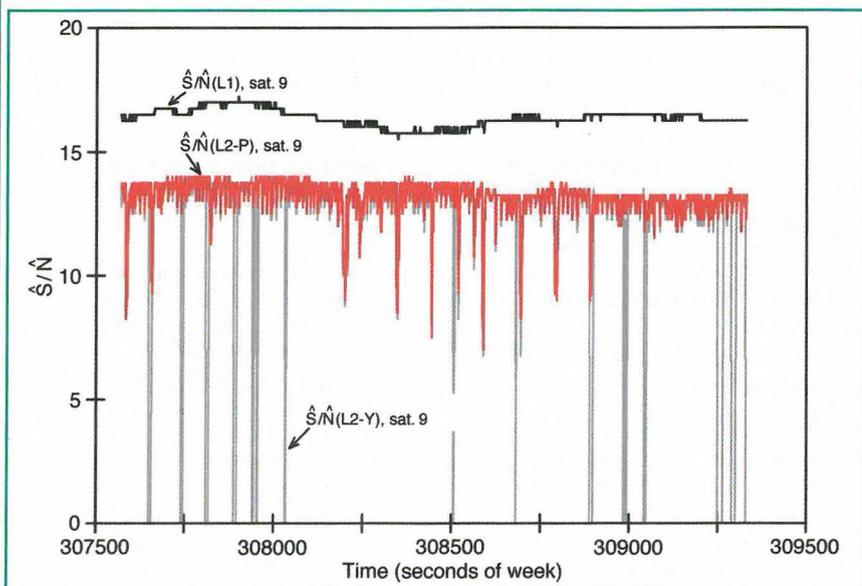


FIGURE 7 Impact of digipeater signals on \hat{S}/\hat{N} of the L1 and L2 frequencies

and another one (a semi-codeless receiver) to process the Y-code. The data packets transmitted by the digipeaters degraded the reception of the “P-code receiver” only slightly, whereas they affected the “Y-code receiver” significantly more.

After it became known that digipeaters caused interference to GPS signals, some manufacturers improved their GPS receivers either by using additional band-limiting filters or by adapting such a filter that had already been part of the design. Digipeater signals don’t pose a threat to L1-only receivers used in aviation, because of the large separation of the digipeater frequency band from the L1 frequency. But signals from digipeaters could interfere with the dual-frequency receivers used by the Ranging and Integrity Monitoring stations of the European Geostationary Navigation Overlay System (EGNOS).

Other transmitters operating near the L2 frequency, such as medium range air traffic control radars in the frequency band 1250 to 1260 MHz or Distance Measuring Equipment (DME) ground transponders operating in the band between 962 and 1215 MHz, turn out not to cause any interference due to the low duty cycle of their signals.

Conclusion

RFI should be considered as a possible cause whenever a GPS receiver suddenly loses track of satellites or displays an unexpectedly low signal-to-noise ratio. Experience has shown that S/N and S/N_0 are very useful for analyzing the impact of RFI. For this and also for other purposes, it would be desirable for GPS receivers to output a calibrated estimation of S/N or S/N_0 .

Moreover, it is useful to determine the spectrum of a potential interfering signal to assess its impact by comparison to standardized interference masks or measured interference susceptibility curves. In Germany and some of its neighboring countries, RFI to GPS is nearly always due to amateur radio transmitters that are part of a Europe-wide wireless network. ☺



“Innovation” is coordinated by Richard Langley of the University of New Brunswick. To contact him, see the “Columnists” section on page 2 of this issue.