Use of Global Positioning System (GPS) Receivers Under Power-Line Conductors

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Abstract—The use of global positioning system (GPS) technology continues to grow and recent accuracy augmentations will generate ever more innovative applications. The issue of GPS use under or near electric power lines has been raised since some GPS documents have vague warnings about such use. First, GPS and the satellite microwave signals used to determine position, velocity, and time are described. Then, the potential effects of electromagnetic interference and/or signal scattering from overhead conductors are evaluated analytically and with some practical measurements under transmission lines. This work demonstrates that it is unlikely that power line conductors will interfere with use of the GPS satellite signals.

Index Terms—Conductors, electromagnetic interference, electromagnetic reflection, global positioning system, GPS, interference, noise, power transmission lines, scattering.

I. INTRODUCTION

The global positioning system (GPS) enables unique capabilities, and the benefits are substantial. This satellite-based radionavigation system has many new civilian applications for the position, velocity, and time information it can provide. As GPS use expands, it becomes more important to evaluate any potential sources of interference. One issue that is sometimes raised is the potential for degraded performance of GPS receivers when they are used near electric power facilities. Of specific interest is the use of the GPS satellite-based microwave signals under or near power line conductors. At the surface of the earth the satellite microwave signals are weak and any reduction of signal intensity due to scattering by conductors or noise due to corona and/or gap discharges could degrade receiver performance or cause loss of signal lock.

II. GPS

The GPS is a satellite-based radionavigation system developed by the U.S. Department of Defense to provide worldwide coverage and year-round navigation and positioning data primarily for the U.S. military [1]. Since the only equipment required by the user is a receiver/processor, the cost to the user of the system can be relatively small. For this reason, the personal and commercial market for GPS-based equipment, applications, and services has grown exponentially and has moved ahead of military use. GPS use is expanding internationally and there is discussion of a competing GPS constellation of satellites and infrastructure funded and operated by the European Community [2].

At present, 28 GPS satellites are in place [3], consisting of six orbital planes of four satellites each and four active on-orbit spares. On any given day, the number of operating satellites is variable and could drop to 24 before additional replacements are added. Each satellite, at an altitude of about 20,000 km, is moving at about 4 km/s and completes an orbit of the earth in approximately 12 h.

GPS satellites are equipped with highly accurate atomic clocks that keep time to within 3 ns. This precision in time measurement is at the heart of the GPS system function. Precise determination of the transit time for a radio wave to travel from a GPS satellite with a known position in space to the user’s receiver on earth is the basis for all GPS applications. The distance, or range, is obtained by multiplying the apparent transit time by the speed of light. The phrase “apparent transit time” is used because this time and the ranges derived from it will include propagation errors and other potential errors, including dilution of position errors related to satellite constellation geometry at time of use. In general, position and velocity information are determined by trilateration, which uses the ranges or distances to compute a three-dimensional (3-D) position (a process called ranging). For 3-D navigation, the GPS receiver requires range information from at least four satellites; the fourth satellite is needed to adjust for receiver clock errors. The position is given as latitude, longitude, and elevation, usually with respect to a reference ellipsoid model of the earth, such as the World Geodetic System [4], [5].

III. GPS SATELLITE SIGNAL DESCRIPTION

Each GPS satellite broadcasts very weak, uniquely identifiable signals, using spread spectrum technology [1], [2]. At present, each satellite transmits its carrier signals on two different radio frequencies in the L-Band of the frequency spectrum: Link 1 (L1) at 1575.42 MHz and Link 2 (L2) at 1227.60 MHz; each has a bandwidth of 20.46 MHz [1]. The carrier waves are modulated with pseudo-random noise (PRN) codes for each satellite [6]. GPS transmits two types of PRN codes with significantly different structures: Coarse Acquisition (C/A code) and Precise or Protected (P-code). The C/A code is a sequence of 1,023 bi-phase modulations of the carrier signal. Each period for a possible binary phase reversal is called a chip. Since the C/A code is repeated 1000 times/s, the chip rate is 1.023 MHz. The P-code has a very large sequence of chips so that a complete sequence takes 267 days to complete [1]. The chip rate of the P-code is 10.23 MHz, significantly higher than that of the C/A code.
The GPS carrier signal power density at the surface of the earth is far below the received noise density as shown in Fig. 1. In fact, the signal normally cannot be detected by a spectrum analyzer. The noise spectral density at a matched receiver \( (N_{\text{receiver}}) \) is computed as the product of Boltzman’s constant \( (k) \) and the “equivalent noise temperature” \( (T_{eq}) \) in °K. This temperature is apportioned to various sources of noise such as circuit and transmission line thermal noise. Thus

\[
T_{eq} = \sum_{i} T_i
\]

where \( T_i \) is the equivalent temperature of the \( i \)th noise source. Above 300 MHz, most noise is generated by sources internal to the receiving system [7]. However, some noise is generated external to the receiver and is accounted for by a portion of the equivalent noise temperature called the “antenna noise temperature.” Of special interest in this paper is the contribution to the antenna noise temperature from power line corona electromagnetic interference (EMI).

The C/A and P-codes are to used to determine the transit time of the radio wave as it travels from the satellite to the receiver. The user’s GPS receiver does this by internally generating an exact replica of the satellite’s PRN code at the same instant the satellite generates and transmits its code sequence and uses this code to extract the signal from background noise in a process called correlation. In this process, the receiver essentially offsets the internal replica code in time with respect to the (propagation delayed) code received from the satellite and integrates over the signal’s duration until the signal is extracted from the noise. The amount of offset needed to do this is used to determine the time lag or transit time of the signal.

Another signal, the navigation message, is also modulated onto the L-band carriers. This message contains data on satellite ephemerides (orbital location), system time, on-board clock behavior, status messages, and C/A to P-code handover information. In the future, GPS modernization may include more satellites, additional frequencies, a more robust civilian code, a new military code, and stronger signals—depending on government funding and policy decisions.

IV. GPS RECEIVER PERFORMANCE CRITERIA

The GPS signal must have sufficient strength to be detected by a correlation receiver. One measure used to quantify this strength is the carrier to noise ratio \( (C/N_0) \) defined as the signal power of the unmodulated GPS carrier available to a matched receiver divided by the noise power spectral density in the same receiver [8]. It is useful to relate \( C/N_0 \) to the measure of signal quality for the receiver used in this study. For this receiver, an “amplitude measurement unit” (AMU) is used to estimate relative signal strength of the satellite and is related to \( C/N_0 \) by [9]

\[
\frac{C}{N_0} = 20\log_{10}(AMU) + 27 \text{ dB-Hz}
\]

Since an AMU is a measure of signal strength, this relationship holds only if the noise is a constant. This is reasonable if the dominant source of noise is internal to the receiver. If however, external noise is important, AMU cannot be directly related to \( C/N_0 \). It has been reported by the manufacturer that minimum acceptable carrier signal strength for the receiver used in this study may range from 2 – 6 AMU [10]. Assuming that the dominant source of noise is internal, this corresponds to carrier to noise ratios per unit bandwidth of from 33 to 43 dB-Hz.

It is possible that a power line can interfere with the performance of a GPS receiver in one of two ways. First, if the receiver noise due to EMI from the power line is comparable to or greater than the equivalent thermal noise, then the performance may be degraded. Second, if the electromagnetic scattering of the signal from overhead conductors is significant, then the received signal may be reduced and receiver performance degraded.

Each of these possibilities will be considered in turn. Following this, the results of experiments to study the performance of a GPS receiver near a power line will be reported.

V. POWER LINE EMI

This section is to evaluate the possibility that EMI from power transmission lines will interfere with the operation of GPS receivers. Two mechanisms by which this might occur are 1) corona along the length of the transmission line conductors and 2) spark discharges on the transmission line hardware [11], [12].

A. Corona Noise

EMI from power line conductors is important only on transmission lines for which the 50/60-Hz conductor surface electric fields are large enough to cause corona (i.e., local ionization of the air) [11]. The corona caused by these large electric fields at the conductor surface induces impulsive currents on the transmission line. These induced currents, in turn, cause wide band electric and magnetic “noise” fields that fill the entire frequency spectrum from below 100 kHz to approximately 1000 MHz, although they are usually too small to be measured above 10 – 20 MHz [12], [13]. Weather has a large influence on corona noise. In fact, the noise level can be 15–25 dB higher during foul weather. Another factor that affects corona is altitude. The usual rule of thumb is that corona noise increases approximately 1 dB/300 m of altitude above sea level [14].

It is commonly stated that electromagnetic interference from transmission line corona is only a problem when the following three conditions are satisfied:

1) The transmission line voltage is above 230 kV.
2) The frequency of interest is less than 30 MHz.
3) The distance between the transmission line and the receiver is small (i.e., less than a few hundred feet).
Since the second condition is not satisfied for microwave frequency GPS receivers, it could be expected that there will not be a problem. However, the signal strength from a GPS satellite is so small that a more complete investigation is warranted. Here, a noise calculation using a typical 500-kV transmission line will be made to evaluate the possibility for degraded performance. The computer program used for the calculation will be WBNOISE that was developed for the EPRI and described in [15].

The following (worst case) assumptions will be made for this calculation.

1) The receiving antenna will be assumed to be directly under the power line.
2) The polarization of the “noise” field will be assumed to be matched to that of the receiving antenna. Thus, no polarization loss of the noise will occur.
3) Average stable foul weather conditions (i.e., practical worst case) will be assumed.

Since WBNOISE calculates noise only up to 30 MHz, the noise cannot be directly calculated at this frequency. Rather, the calculation will be made at 10 MHz and then scaled to 1575 MHz using a conservative model for the corona noise spectrum [16].

The 500-kV transmission line geometry of [15] was studied, and it was assumed that the receiving antenna was 1 m above the ground. The average stable foul weather (i.e., practical worst case) noise in a 9-kHz bandwidth receiver with a CISPR Quasi-Peak detector in dB relative to 1 μV/m was obtained and is shown in Fig. 4 of [15]. The largest value of “average stable foul weather” noise in a CISPR standard quasipeak receiver at 10 MHz was 40 dB (μV/m). To apply these data to the problem considered here, it is necessary to do the following.

1) Convert from a CISPR receiver to one with an RMS detector and bandwidth appropriate for calculation of the carrier to noise ratio.
2) Convert the noise frequency from 10 to 1575 MHz.
3) Calculate the incident noise power density in a 1-Hz bandwidth at the antenna.
4) Calculate the incident power density at the receiver from the GPS satellite carrier.
5) Calculate C\text{}/N_0 to determine if it is acceptable.

For frequencies below 30 MHz, the noise in a receiver with 9-kHz bandwidth and RMS detector can be obtained by subtracting 8 dB from the noise in a CISPR receiver [13].

The noise in a 1-Hz bandwidth (since C\text{}/N_0 is reported per unit bandwidth in decibel-Hertz) can be obtained by adding $10 \log_{10}(1/9000) = -29.5$ dB (i.e., the received noise power is proportional to bandwidth) [16]. The noise at a frequency of 1575 MHz can be computed by adding $10 \log_{10}(10/1575) = -22.0$ dB (i.e., using Fig. 4 of [16], it is conservatively assumed that the spectrum drops off as $1/(f)^{1/2}$ in the frequency range from 10 to 2000 MHz). Finally, the effective electric field noise level at 1575 MHz (assuming a receiver with an RMS detector and after correcting to a bandwidth of 1 Hz) is

$$E_{\text{effective}} = -29.5 \, \text{dB-Hz} \, \mu\text{V/m}.$$  

This is read as “the effective (i.e., RMS) electric field in decibels with respect to 1 μV/m within a 1-Hz bandwidth (BW).”

Since the power density of a plane wave in free space is

$$P = E^2/\eta_0 \quad \text{(where} \quad \eta_0 = 120\pi \, \Omega \quad \text{is the impedance of free space)},$$

the effective electric field can be converted into an incident noise power density dB-Hz (μW/m²) by subtracting $60 + 10 \log(\eta_0)$ dB to yield

$$N_{\text{incident}} = - 115.3 \, \text{dB-Hz} \, \mu\text{W/m}^2.$$  

Again, this is read as “the effective (i.e., RMS) incident noise power density at 1575 MHz in decibels with respect to 1 μW/m² within a 1-Hz bandwidth.”

GPS transmitters are located in satellites approximately 20,000 km above the earth’s surface. The transmitter output for the civilian signal is about 25 W and the antenna gain is 13 dB, yielding an effective radiated power of approximately 500 W [1]. Since the gain of the receiving antenna is not known and the noise is assumed to be from a source external to the receiver, the carrier-to-noise ratio will be determined from a comparison of incident fields. It will thus be (conservatively) estimated here that the receiving antenna responds identically to the GPS signal and to the noise.

The incident power density at the earth’s surface of a carrier signal from a transmitter that feeds a directional antenna is

$$C_{\text{incident}} = [P_t(\text{dB}) + G_t(\text{dB}) - 10 \log_{10}(4\pi d^2) + 60] \, \text{dB} \, \mu\text{W/m}^2$$  

where $P_t$ is the transmitter power delivered to the antenna, $G_t$ is the antenna gain relative to an isotropic antenna, and $d$ is the distance between the satellite and the receiver in meters. For this case

$$C_{\text{incident}} = -70.0 \, \text{dB} \, \mu\text{W/m}^2 \quad \text{or about} \quad 6 \mu\text{V/m}$$  

Thus, the carrier-to-noise ratio $C/N_0$, for the incident field is 45.3 dB-Hz. This is above the minimum specified by the manufacturer of the receiver used in this study (i.e., 43 dB). Given the number of conservative assumptions used in this calculation (e.g., 500-kV transmission line, spectral decay of $1/(f)^{1/2}$, noise polarization matched to the GPS antenna, etc.), it is unlikely that the transmission line corona noise could degrade operation of the GPS receiver. Nevertheless, since the $C/N_0$ ratio is close to the minimum, it was decided that an experiment was necessary to determine whether there was any interference of a transmission line with the operation of the GPS receiver. This experiment will be reported later.

B. Spark or Gap Discharge Noise

Spark discharges generally occur between parts of hardware on a power line that are physically close but at different voltages [11], [12]. If the voltage becomes high enough, a spark occurs across the gap. Due to the nature of this discharge, the electric and magnetic noise fields from these sparks tend to dominate those from corona at frequencies above 10 – 20 MHz [12] and can be detected at frequencies above 1000 MHz. As with corona, weather has a large influence on gap discharges. However, the effect is opposite. In fact, gap discharges generally occur only during dry weather; wet conditions tend to equalize voltages between different parts of the hardware and hence suppress them.
Spark discharge fields are generally not calculated because the discharges tend to be intermittent, models are crude and only limited measured data are available [16]. Rather, if there is a problem, the source of the discharge is located and repaired [17]. GPS receivers are typically operated near ground level at some distance from spark gap sources. As a final comment, it can be said that gap sources often occur on low voltage distribution lines. Thus, they are more likely to be found on the distribution lines than on transmission lines because the former are more numerous [12]. Later, results of GPS measurements near spark discharges will be reported.

VI. GPS MICROWAVE SIGNAL SCATTERING

A possible concern for use of GPS equipment under or very close to power lines is whether an incident GPS satellite signal can be significantly scattered by a power line with a resulting adverse effect on the received signal. This possibility is considered next.

A number of simplifying assumptions will be made in the calculations presented here. First, it will be assumed that there are no towers either near the receiver or on a direct line between the satellite and receiver. Although towers are expected to be strong scatterers, they are too complex to be included in the simple model considered here. It is more appropriate that they be examined experimentally in a separate study. Given this, towers have been eliminated from the model. Second, the transmission line conductors are assumed to be horizontal, and each phase is assumed to consist of only a single conductor. Third, phase conductors are far enough apart that they can be analyzed separately. Finally, reflection from the earth will be neglected. While this effect can be important, its inclusion would not change the conclusions of this report and the additional mathematics may obscure the argument. Despite these assumptions, the simple model analyzed here leads to reasonable conclusions about whether power line conductors can interfere with GPS signals.

Consider the single conductor shown in Fig. 2. Here, a GPS signal is assumed incident upon a single power line conductor at an angle $\theta_i$, as shown. Since the signal is circularly polarized, it can be decomposed into two plane waves: one polarized parallel to and the other perpendicular to the conductor. It is shown in [18] that for a parallel polarized incident wave, the ratio of scattered to incident field (component along the direction of the conductor) for scattering from a cylindrical conductor model of a power line conductor is

$$\frac{E^s}{E^i} = \frac{\sqrt{\pi}}{k a \ln (0.2885 k a \sin(\theta_i)) \sqrt{kr \sin(\theta_i)}}$$

where $k = (2\pi f)/3.0 \times 10^8$, $f$ is the frequency in Hertz, $a$ is the radius of the cylindrical conductor, and $r$ is the distance between the conductor and the receiver in meters. It is also shown in [18] that the perpendicular polarized incident wave is scattered much less than the parallel one. Thus, if scattering of the parallel polarized wave is small enough, it is not necessary to consider the perpendicular polarized component.

For an assumed 1.27-cm conductor radius, $r = 10$ m, $\theta_i = \pi/2$ and $\lambda = 19$ cm (at 1575.42 MHz), (7) yields a ratio of scattered field/incident field of 0.032 or about a 3.2% reduction in the field for normal orientation. Only for grazing angles of incidence (i.e., values of $\theta_i$ near zero) does the scattered field increase markedly from this result. In this case, however, the calculation becomes much more complex [19]. Given the very small scattered field from a single conductor, it is clear that a three-phase line with single conductors will also not significantly affect the GPS signal. It appears then that power line conductors have little effect on the signal and that a GPS receiver/antenna can be used under power lines without bundled conductors. Based on measurements to be reported later, it is believed that this conclusion can also be applied to transmission lines with bundled conductors. It should be noted that even if there were significant attenuation due to scattering for one satellite signal it is unclear if this would cause a problem for a GPS user. This is because a GPS receiver relies on a dispersed constellation of satellites (at least four and often more). However, loss of lock on just one satellite could cause a poorer (less accurate) position solution due to an increase in dilution of position caused by poor satellite constellation geometry. Bundled conductors in heavy corona may merit further analysis to confirm that receiver performance is not degraded by reducing the number of satellites available to the receiver.

VII. GPS SIGNAL MEASUREMENTS UNDER 345-KV LINES

A series of measurements to evaluate GPS signal reception quality under power lines was performed in both fair and foul weather across the easements of two different double circuit, twin-subconductor, 345-kv transmission lines. These measurements were performed with a Trimble GPS receiver and a circularly polarized cross-dipole antenna system. The purpose of the measurements was to evaluate whether the GPS satellite signal incident on metallic conductors can be significantly scattered and adversely affect the signal received and/or whether power line EMI can degrade receiver performance.

At one location (Site #1 in Fig. 3), measurements were performed along a traverse under a double circuit 345 kV transmission line. The satellite constellation geometry that existed during the fair weather measurements at the site is shown in Fig. 4. Measurements along a traverse were also made at another...
Fig. 5. Sketch of transmission line configurations at site # 2.

Fig. 3. Sketch of 345-kV transmission line at site # 1.

Fig. 4. GPS satellite constellation geometry at site # 1 during measurements.

location (Site #2 in Fig. 5) within an easement that included two double-circuit 345-kV lines and a double-circuit 120-kV line.

For all of these measurements, several satellites were visible to evaluate reception quality but not all are included in the presentation of results. More specifically, data from satellites with an elevation above the horizon of less than about 20° is not given because it is more subject to multipath errors and shielding by nearby objects such as trees. The impact of these factors changes as orientation to the receiver changes when the easement was traversed during measurements. This situation could result in a change in reception quality that is not associated with conductor scattering of the GPS carrier wave.

According to the results of Section V, the only condition under which corona noise might cause a problem is during foul weather since in this case corona noise is 15–25 dB higher than in fair weather. In order, then, to isolate the possible effect of scattering from power line conductors, the first measurements were conducted in fair weather along the traverses described above. The signal amplitude in AMU for GPS carrier L1 was logged for each satellite in view at one-second intervals while driving across the 345-kV easements and directly under the transmission lines. This quantity was output by the GPS receiver in the standard NMEA format and then converted to $C/N_0$ using (2) and the assumption that the noise is constant and entirely internal to the receiving system [9], [20]. The measured value of $C/N_0$ was then used to evaluate changes in reception quality as the easement was traversed. The results reveal no practical change in each satellite’s $C/N_0$ even when directly under the 345-kV transmission lines (see Figs. 6 and 7). Thus, it does not appear that scattering from power line conductors leads to any significant change in signal strength. This result is consistent with the earlier discussion of this subject: the conductors are small compared to a carrier signal wavelength and the receiver antenna is generally located at ground level some tens of wavelengths away.

Note that no satellite signal measurements were made inside a steel lattice tower within the area enclosed by the steel structure members and legs. However, it is anticipated that this could cause a shielding problem because of the large metallic members near a line between the satellite and the user.

The possible effect of corona noise was evaluated by repeating the measurements described above in foul weather conditions. Since the signal amplitude available from the receiver is not a measurement of noise, it cannot be used to evaluate noise level. Instead, noise was indirectly measured by noting the number of satellites on which the receiver was locked as a function of position along the traverse. It was hypothesized that excessive corona noise would cause loss of lock on at least some satellite signals. For Sites #1 and #2, the receiver maintained lock on eight and nine satellites, respectively, over the entire traverse. Thus, no degradation in receiver performance can be attributed to EMI from corona.

VIII. OTHER SOURCES OF ELECTRICAL INTERFERENCE

There are many nonpower system sources of potential interference that can create noise within the GPS satellite signal bandwidth. Out-of-band emissions by radio, TV, communications, and radar transmitters can cause an electromagnetic interference problem. Other potential EMI sources include gasoline engine ignition systems, TV and computer monitors, electric motors, fluorescent lights, ac–dc converters, alternators, and generators and switching power supplies. The broadband noise of a gap discharge source can extend above 1 GHz and is cited by GPS receiver manufacturers as a potential interference

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source (e.g., proximity to spark plugs on an all-terrain vehicle). During the course of the measurements reported in this paper, the GPS receiver was operated close to a number of gap discharge sources on distribution lines with no effect on receiver performance. The distance to the source is most likely the main factor in the lack of an observed influence on GPS receivers. Of course, the design characteristics of the GPS receiver/antenna system is always important in overall performance.

IX. GPS SATELLITE ANOMALIES

There is another type of GPS receiver problem not caused by scattering of incoming signals or noise in the GPS carrier bandwidth. GPS receivers may experience problems when a GPS satellite exhibits operational anomalies, such as low power, PRN code generation error, or outages. These events are rare but do happen. It is important to be aware of these events because the resulting loss of signal lock could erroneously be attributed to any nearby power lines. In one 3-mo period in 1998, a total of 107 anomalies, an average of 1.2 per day, were observed for satellites that could be seen over the continental United States [21]. The satellite anomalies included brief generation and transmission of nonstandard C/A or P-codes, maintenance problems, and short-term disruptions in the navigation message. The average duration of outages was about 6 s, ranging from a few seconds to 93 s. These satellite anomalies can cause positioning errors outside of specified accuracy and loss of lock. The period of time affecting the user includes the outage duration plus the time to reacquire the satellite signal and is receiver dependent. For example, on November 26, 1998, a triple outage sequence occurred on the L1 signal of satellite PRN# 15. These outages occurred in succession, separated by variable lengths of time and spread over a period of about 3–4 min (44 s for the first signal outage, 8 s for the second, and 16 s for the third). Receivers of different designs took from several seconds to over 2 min to reacquire the satellite signal after the outages [21]. Research has been done on algorithms for GPS receivers to perform on-board interference detection and monitoring to improve performance [22]. The design and performance of GPS receivers can be variable, but changes in hardware and software continue to improve receiver performance.

X. CONCLUSIONS

This paper reports on an evaluation of the possibility for power line conductors to affect GPS receivers used near power lines. The following conclusions were reached.

- A simple model has been used to show that electromagnetic scattering of GPS signals by power line conductors is unlikely to cause significant signal degradation. Carrier-to-noise ratio measurements under transmission lines in foul weather support this conclusion for practical situations. Even if there were significant attenuation due
to scattering for one satellite signal, it is unclear if this would cause a problem. This is because a GPS receiver relies on a dispersed constellation of satellites (at least four and often more). However, loss of lock on just one satellite could potentially affect accuracy due to an increase in dilution of position error caused by poor satellite constellation geometry.

- A theoretical evaluation of transmission line corona noise at the GPS carrier frequency did not indicate that corona noise could affect GPS receiver performance. Measurements made in foul weather confirm this conclusion. Specifically, it was noted that there was no loss of lock of satellite signals as a GPS receiver was moved across a power line easement.

- The GPS receiver was operated close to a number of gap discharge sources on distribution lines with no effect on receiver performance. GPS receivers may experience problems when a GPS satellite exhibits operational anomalies, such as low power, PRN code generation error, or outages. These events are rare but do happen. It is important to be aware of these events because the resulting loss of signal lock could erroneously be attributed to any nearby power lines.

- Further work might include an analysis of degraded performance due to steel lattice towers and signal scattering from bundled conductors in corona.

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REFERENCES


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