Spoofing GPS Receiver Clock Offset of Phasor Measurement Units

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Abstract

We demonstrate the feasibility of a spoofing attack on the GPS receiver of a phasor measurement unit (PMU). We formulate the attack as an optimization problem where the objective is to maximize the difference between the time offset of the PMU's receiver clock before and after the attack. Since the PMU uses this clock offset to compute a time stamp for its measurements, an error in the receiver clock offset introduces a proportional phase error in the voltage or current phase measurements provided by the PMU, with a phase-wrap of 2π (in practice, the computed maximum receiver clock offset error is never large enough to induce a phase error that requires a phase-wrap of 2π) . The decision variables in the optimization problem are the satellites' ephemerides, pseudoranges, and the receiver coordinates. The constraints are cast such that the receiver and satellite positions computed from the solution of the optimization problem will be close to their pre-attack values to avoid detection. We show that the spoofing attack is feasible for any number of visible satellites. Simulation results, in which four and seven satellites are spoofed, are presented to illustrate the effect of the attack on the phase measurement provided by a PMU.

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I. INTRODUCTION

The motivation behind this work stems from the current trend of increasing deployment of phasor measurement units (PMUs) across the power grid. Under the US-DOE Smart Grid vision and its European counterpart, electric power systems are undergoing radical transformations in structure and functionality. As such, these transformations are enabled by the integration of new technologies. One such technology that has received considerable attention is the PMU, which provides synchronized positive sequence voltage and phase measurements of a power system in real-time [1]. These devices enable power system engineers to directly measure the power system state, allowing for real-time control and monitoring of power flows in the power grid. While the many applications of PMUs are still under research, some of them include [2]: i) verification of voltage transformers in a substation, ii) verification of transformer current polarity and phase, iii) verification of state estimator results, iv) verification of system models [3], and v) synchronization of fault and disturbance records. Therefore, incorporation of PMUs into the power grid results in more efficient distribution of power and better fault detection in transmission lines. While the integration of this new technology may bring about significant advances in power system real-time monitoring and control, it may also be a source of security concern. Specifically, as these PMUs depend on GPS signals to synchronize their measurements, they are also susceptible to spoofing attacks. A method for spoofing PMU receivers that results in maximal phase error while evading detection is formulated and simulated.

PMUs use a GPS receiver front-end to derive a time stamp in Coordinated Universal Time (UTC) for their phase measurements. As such, they are vulnerable to spoofing attacks. The GPS receiver acquires signals transmitted by satellites, decodes each satellite's navigation data, and estimates the receiver position and the current time. A spoofing attack on the GPS receiver can cause a faulty time stamp, which introduces errors in the PMU's phase measurements. This report focuses on one particular method of data-level spoofing that introduces the maximal phase error in the PMUs' measurements.

The first comprehensive assessment of the vulnerabilities in the civilian GPS infrastructure was published a decade ago in a report prepared by the Volpe National Transportation Systems Center [4]. This report concluded that among the different types of attacks, GPS spoofing is the most pernicious and difficult to detect. Generally speaking, spoofing attacks fall under two categories: signal-level and data-level. Signal-level spoofing focuses on causing the receiver to lose lock to the real GPS signal by overpowering it with the spoofed signal. One method is to use a GPS simulator to generate a rogue GPS signal matching the genuine signal's phase, code delay, and encoded data. The spoofer gradually increases its transmission power until the GPS receiver locks onto the malicious signal, at which point the victim receiver is fully under the spoofer's control [5]. It was shown that such an attack causes significant errors in the phase measurements provided by the PMUs. In data-level GPS spoofing, the data of the GPS signals, namely the ephemerides, are altered in such a way that the receiver using the spoofed data computes the incorrect location, velocity, or clock offset. The problem is to determine how to manipulate these data in order to cause interference while evading detection. This type of spoofing

is the focus of this report.

The absence of effective countermeasures against civilian GPS receiver spoofing has been made known to major manufacturers, but little has been done to address such deficiencies in security [5]. Only recently, research into GPS spoofing have resulted in several recommendations to counteract such attacks [6], [7]:

1) Amplitude discrimination
2) Time-of-arrival discrimination
3) Polarization discrimination
4) Angle-of-arrival discrimination
5) Cryptographic authentication
6) Signal strength discrimination

The first two methods can be implemented in software but only provide a rudimentary defense against spoofing attacks. Polarization and angle-of-arrival discrimination require multiple antennas to implement and are ineffective against sophisticated coordinated attacks involving multiple rogue GPS transmitters. An extensive review of cryptographic techniques is made in [8]; owever, cryptographic methods require significant changes to the current GPS signal coding scheme, which is unlikely to happen in the short term [5]. Recent developments in cryptographic methods that allow for minimal modifications to the current system include navigation message authentication (NMA) and signal authentication sequences (SAS) [9], [10], [11]. These schemes are robust against signal spoofing but provide no security for unauthorized signal access. Furthermore, to the authors' best knowledge, civilian GPS receivers have not implemented these techniques at the time this report was written.

In [12], the authors demonstrated a spoofing attack on a PMU and reported constraints on the velocity and acceleration with which the GPS clock can be manipulated. The attack hijacks the receiver's tracking loops and steers them to modify the receiver's clock offset as desired. They found that if the tracking loops are steered too aggressively, the receiver loses lock and the spoof is readily detected. While the work in [12] employed an attack based on time shifting each satellite's signal with a delay, we propose an attack based on modifying the encoded data without modifying the underlying signal characteristics. As such, we do not expect to be bound by the bandwidth of the receiver tracking loops, only by the rate at which the GPS receiver incorporates new ephemerides and the rate at which the PMU updates its time stamp based on the GPS receiver. The impact of GPS receiver spoofing on the frequency monitoring network of the power grid is demonstrated in [13]. The authors showed that alterations to the PMUs' receiver clock offset can hamper determination of fault locations and introduce erroneous oscillation modes in a power system. However, methods to introduce errors in the receiver clock offsets of the PMUs were not discussed.

We investigate the feasibility of an attack on the GPS receiver of a PMU using a GPS simulator. Most of the civilian GPS receivers on the market today do not have the capability of detecting such an attack. In addition, the price of a GPS simulator has dropped significantly from as high as $400,000

ten years ago to around $20,000 today, greatly reducing the barrier to GPS spoofing [5]. These GPS simulators have also seen significant miniaturization during this period, which makes a spoofer difficult to physically locate.

To demonstrate the feasibility of a GPS spoofing attack, we formulate the attack as an optimization problem where the objective is to maximize the difference between time offsets of the PMU's receiver clock before and after the attack while maintaining the computed receiver location close to its pre-attack value. We perform the optimization for a given instant in time, which is the time when the spoof is to be implemented. The decision variables in the problem are the satellite ephemerides, pseudoranges, and receiver position. The ephemerides are a set of values broadcast by the GPS satellite that allow the receiver to compute the satellite position at a particular time. The pseudorange is the measured distance from the satellite to the receiver and is computed by multiplying the signal propagation velocity, which is assumed to be the speed of light ($c = 299792458$ m/s), by the signal transit time, which is derived from the nonsynchronized satellite clock and receiver clock. Because of the receiver clock offset (which is responsible for the nonsynchronization), the pseudoranges measured by the receiver all deviate from the true range by a common amount. In the optimization problem, the constraints are placed on the decision variables as required in order to avoid spoofing detection. Methods of attack are presented for four-satellite and seven-satellite cases. For the specific spoofing attack simulation presented in this report, it is shown that the error introduced in the receiver clock offset can be as high as 2.3 ms, which corresponds to 14% of a cycle in a 60-Hz signal.

The remainder of this report is organized as follows. In Section II, we describe the algorithm that a GPS receiver uses to compute its position and time offset. In Section III, we formulate the attack as an optimization problem for finding the maximum receiver clock offset for an arbitrary number of visible satellites. Section IV presents the results of two simulated spoofing attacks for the four-satellite and seven-satellite cases. Section V describes ideas for designing systems to detect and hinder such attacks. Finally, concluding remarks are made in Section VI.

II. Calculation of Receiver Position

In this section, we explain how a GPS receiver computes its position and clock offset given the satellite ephemerides and pseudoranges. The relation between the satellite ephemerides and satellite position is also explained. In subsequent developments, an overline above a symbol denotes vectors and a superscript star denotes the pre-attack value of some real-valued variable; i.e., $\overline{\delta}$ is a vector and x^* is the pre-attack value of x.

A. GPS Receiver Position and Time Synchronization Error Calculation

A GPS receiver determines its distance from a satellite by measuring the time of signal transmission from the satellite to the receiver and multiplying that by the speed of the signal propagation, which is assumed to be the speed of light. Given the satellites' positions and their ranges from the receiver, the

receiver location could be computed through a process known as trilateration [14]. In three dimensions, three satellites are needed to determine the receiver's exact location, provided that there is no noise in the measurements and the time between the satellites' clocks and the receiver clock are perfectly synchronized. However, in reality the receiver clock has an offset t_u (with respect to GPS time t_E) that arise from internal hardware bias in the local clock oscillator (note that we use t_E to denote the GPS system time at *any particular time*). For solvability, it is safe to assume that the receiver clock offset is constant across all receiver channels [15]. Therefore, we can express the GPS time as:

$$t_E = t_r - t_u, \tag{1}$$

where t_r denotes the receiver clock time. The coordinated universal time (UTC), t_{UTC}, is offset from the GPS time t_E by an integer number of leap seconds Δt_{UTC}, which is 15 s as of January 1, 2010 [14]. Therefore, t_{UTC}, which is used for PMU time synchronization [16], is computed as follows:

$$t_{UTC} = t_E - \Delta t_{UTC}. \tag{2}$$

Figure 1 shows a general three bus system with PMUs dispatched at each bus. A voltage phasor is measured at each bus and time-stamped using the reference time signal t^*_{UTC}. This time-stamp is common to all three buses and provides the synchronization of the PMUs' phasor measurements.

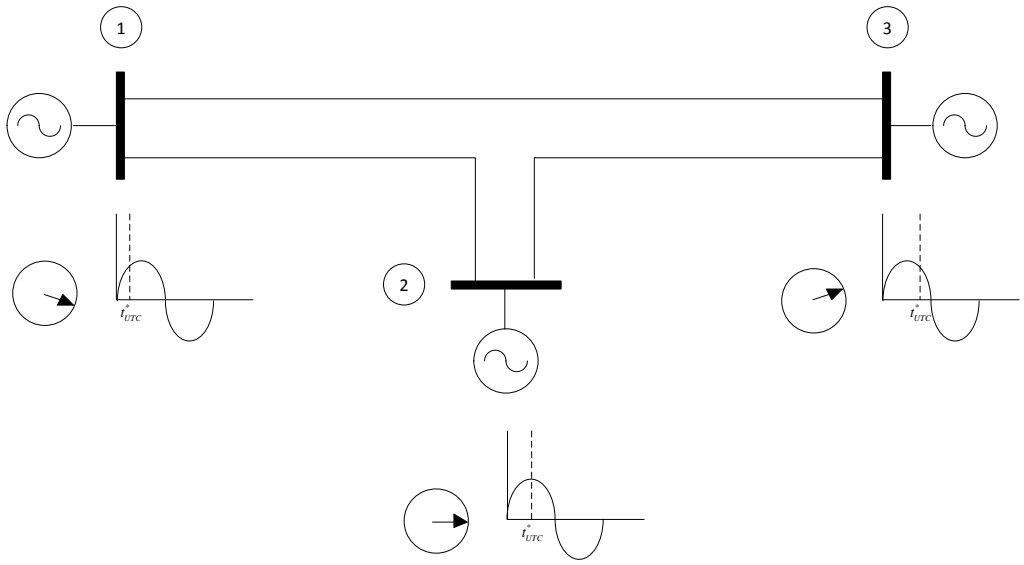


Fig. 1: PMU and Associated Phasor Measurements.

With the addition of the receiver clock offset as a variable, at least four satellites are needed in order to determine the receiver's position as given by its Earth-Centered Earth-Fixed (ECEF) coordinates and the clock offset. The satellite-to-receiver distance, which is computed by taking the time difference between the satellite clock providing the GPS time t_E and the receiver clock t_r and multiplying by the

propagation speed, does not yield the true range between the satellite and the receiver because of the receiver clock offset. Instead, this measurement is called the *pseudorange*, which can be expressed as a linear function of the true range and the receiver clock offset.

B. Four Visible Satellites

For a given time, let ρ_i and r_i be the i^{th} satellite's pseudorange and true range, respectively, x_i, y_i, and z_i be the i^{th} satellite's ECEF coordinates, x_u, y_u, and z_u be the receiver's ECEF coordinates, $c = 299792458$ m/s, and t_u be the receiver clock offset. Then,

$$\rho_i = r_i - ct_u, \quad i = 1, 2, 3, 4, \tag{3}$$

$$r_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2}. \tag{4}$$

The satellite coordinates x_i, y_i, and z_i are computed by the receiver through a set of parameters, known as the ephemerides (described in detail below), contained in the GPS signal. In the four-satellite case and assuming no noise in the measurements, the receiver location and the clock offset can be obtained by solving (3)-(4) directly, as the number of unknowns is equal to the number of equations. This system of nonlinear equations is solved by the GPS receiver through a nonlinear solution method, e.g., Newton-Raphson.

C. More Than Four Visible Satellites

It is almost always the case that more than four satellites are visible at a particular instant of time. Then in (3)-(4), $i > 4$, which results in an overdetermined system. In this scenario, the solution x_u, y_u, z_u, and t_u is obtained by solving a Least Squares Errors (LSE) problem of the form:

$$\min \quad f_0 = \sum_{i=1}^{n} (\rho_i - r_i + ct_u)^2, \quad n > 4, \tag{5}$$

where n denotes the number of visible satellites. The GPS receiver solves the LSE problem in (5), which can be solved numerically using, e.g., the Gauss-Newton method.

D. GPS Ephemerides

The ephemerides are a set of parameters that allow the receiver to compute a satellite's position at any time. Up-to-date ephemerides are uploaded from the GPS control segment to the satellites once per day and then broadcast to the receiver as part of the navigation data signal. A detailed description of the ephemerides and their role in calculating a satellite's position is presented next.

The accurate characterization of the GPS satellites' orbits is essential for determining the receiver's position. In the absence of external perturbations, the trajectory of a satellite is solely governed by the

TABLE I: Keplerian Elements

a	semimajor axis of ellipse
e	eccentricity of ellipse
τ	time of perigee passage
i	inclination of orbit
Ω	longitude of ascending node
ω	argument of perigee

TABLE II: Forces on GPS Satellites and Resultant Accelerations [14].

Force	Acceleration (m/s^2)
Earth Gravity	0.56
Equatorial bulge	5×10^{-5}
Lunar/Solar Gravity	5×10^{-6}
Solar radiation	1×10^{-7}

gravitational force of Earth and can be described by

$$\frac{d^2\overline{s}_i}{dt^2} + \frac{G}{s_i^3}\overline{s}_i = 0, \tag{6}$$

where $\overline{s}_i = [x_i,\ y_i,\ z_i]^T$ is the position vector of the i^{th} satellite, $s_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$, $G = 3986005 \times 10^8$ m^3/s^2 is the product of the universal gravitation constant and the mass of the Earth [14]. The solution of (6) is characterized by six constants of integration, which are a subset of the ephemerides, and are known as *Keplerian elements* (listed in Table I), which result from solving (6) with the initial conditions $\overline{s}(0)$ and $\frac{d\overline{s}(0)}{dt}$. Consequently, given these six parameters and the initial time, the receiver can compute the position and velocity vectors of the satellite at any point in time. In order to describe a satellite's orbit even more accurately, the additional forces acting on the satellite must be considered. These forces include the so-called third-body gravitation from the Sun and the Moon, solar radiation pressure, and the Earth's tidal variations, among others. Table II lists some of the major perturbing forces and their effects on the satellites' orbits. Although the accelerations from the other perturbing forces are small compared to the gravitational acceleration of the Earth, their effects do add up to significant changes over an extended period of time.

It is still possible to completely characterize the satellite's motion under full perturbation with the Keplerian elements; however, these parameters will no longer be constant. A reference time known as the *epoch* (denoted by t_{0e} in Table III) is established to characterize the time-dependent integrals of motion. At the exact reference time, t_{0e}, the six Keplerian elements in Table I describe the position and velocity vectors of the satellite exactly, but as time progresses the true position and velocity vectors of the satellite will deviate from the position and velocity vectors computed by the six integrals. In order to account for these deviations, parameters that characterize how the Keplerian elements change

over time are added to the satellite's navigation signal. This expanded parameter set which contains the Keplerian elements is known as the satellite's ephemerides and is updated by the satellite every two hours. The information contained in the ephemerides is summarized in Table III. A full specification of the ephemerides can be found in [17], which describes the interface between the GPS space segment and the GPS user segment.

TABLE III: GPS Ephemeris Data Definitions [15].

t_{0e}	Reference time of ephemeris
$\sqrt{a}$	Square root of semimajor axis
e	Eccentricity
i_0	Inclination angle
Ω_0	Longitude of ascending node
ω	Argument of perigee
M_0	Mean anomaly
$\frac{di}{dt}$	Rate of change of inclination angle
$\dot{\Omega}$	Rate of change of longitude of ascending node
Δn	Mean motion correction
C_{uc}	Amplitude of cosine correction to argument of latitude
C_{us}	Amplitude of sine correction to argument of latitude
C_{rc}	Amplitude of cosine correction to orbital radius
C_{rs}	Amplitude of sine correction to orbital radius
C_{ic}	Amplitude of cosine correction to inclination angle
C_{is}	Amplitude of sine correction to inclination angle

For completeness, Table IV provides the algorithm by which a GPS receiver computes the position of a satellite in ECEF coordinates from the GPS ephemerides. The parameter t used in step (3) of Table IV is the time at which the GPS signal was transmitted from the satellite. The subscript k appearing in the computations signifies that the variable is measured at time t_k, the time (in seconds) from epoch t_{0e} to time of transmission t.

To ease notation in subsequent developments, we denote by $\delta_i(j)$ the j^{th} ephemeride of satellite i and define $\overline{\delta}_i = [\delta_i(1),\ \delta_i(2),\ \ldots,\ \delta_i(m)]^T$ as the vector that contains the ephemerides broadcasted by the i^{th} satellite. Using this notation, we can express the ECEF position of the satellite as a function $\overline{\delta}_i$ such that

$$\begin{aligned} x_i &= f(\overline{\delta}_i, t), \\ y_i &= g(\overline{\delta}_i, t), \\ z_i &= h(\overline{\delta}_i, t), \end{aligned} \tag{7}$$

where the functions $f(\cdot)$, $g(\cdot)$, and $h(\cdot)$ can be defined using Table IV.

TABLE IV: Computation of Satellite's ECEF Coordinates [15].

(1)	$a = (\sqrt{a})^2$	Semimajor axis
(2)	$n = \sqrt{\frac{\mu}{a^3}} + \Delta n$	Corrected mean motion
(3)	$t_k = t - t_{0e}$	Time from ephemeris epoch
(4)	$M_k = M_0 + nt_k$	Mean anomaly
(5)	$M_k = E_k - e \sin E_k$	Eccentric anomaly
(6)	$\sin \nu_k = \frac{\sqrt{1-e^2}\sin E_k}{1-e\cos E_k}$ $\cos \nu_k = \frac{\cos E_k - e}{1-e\cos E_k}$	True anomaly
(7)	$\phi_k = \nu_k + \omega$	Argument of latitude
(8)	$\Delta\phi_k = C_{us}\sin(2\phi_k) + C_{uc}\cos(2\phi_k)$	Argument of latitude correction
(9)	$\Delta r_k = C_{rs}\sin(2\phi_k) + C_{rc}\cos(2\phi_k)$	Radius correction
(10)	$\Delta i_k = C_{is}\sin(2\phi_k) + C_{ic}\cos(2\phi_k)$	Inclination correction
(11)	$u_k = \phi_k + \Delta\phi_k$	Corrected argument of latitude
(12)	$r_k = a(1 - e\cos E_k) + \Delta r_k$	Corrected radius
(13)	$i_k = i_0 + (di/dt)t_k + \Delta i_k$	Corrected inclination
(14)	$\Omega_k = \Omega_0 + (\Omega - \dot{\Omega}_e)t_k - \dot{\Omega}_e t_{0e}$	Corrected longitude of node
(15)	$x_p = r_k \cos \mu_k$	In-plane x position
(16)	$y_p = r_k \sin \mu_k$	In-plane y position
(17)	$x_s = x_p \cos\Omega_k - y_p \cos i_k \sin\Omega_k$	ECEF x-coordinate
(18)	$y_s = x_p \sin\Omega_k + y_p \cos i_k \cos\Omega_k$	ECEF y-coordinate
(19)	$z_s = y_p \sin i_k$	ECEF z-coordinate

III. Mathematical Formulation of Attack

In this section, we provide the mathematical formulation of the spoofing attack such that the receiver clock bias offset is maximized. The problem is cast as an optimization problem where the objective function is the phase error of the PMU measurements.

A. GPS Receiver Spoofing and Impact on the Phase Information Provided by PMUs

Time synchronization across PMUs is crucial for maintaining an accurate measurement of phase angles. In the following developments, we assume that the maximum receiver clock offset from its pre-attack value is not large enough to cause a phase-wrap in the phase measurement provided by the PMU. Therefore, for demonstrating the feasibility of an attack on PMU time synchronization (and phase measurements), we simply seek to maximize the absolute difference of the receiver clock offset t_u (post-attack) with respect to its pre-attack value t_u^*. A GPS simulator can simulate a rogue GPS navigation data signal and cause simple receivers to latch onto the new signal by gradually overpowering the true GPS signal, thus forcing the receiver to compute an incorrect receiver clock offset. For a 60-Hz signal, the PMU's phase measurement error ε_θ is related to the receiver clock offset error through the linear relationship

$$\varepsilon_\theta = [60 \times (t_u - t_u^*) \times 360^\circ] \bmod 360. \tag{8}$$

Figure 2 shows the result of a GPS spoofing attack on bus 2 (red) of the general three bus system. The receiver clock offset t_u is shifted from its pre-attack value of t_u^*, causing a proportional error in the estimate of t_{UTC}. Consequently, the erroneous time-stamp $\tilde{t}_{UTC}$ used by the PMU of bus 2 results in an incorrect phase estimate, which causes the PMU to lose synchronization from the rest of the system.

We are interested in determining the maximum phase shift error that can be introduced in a PMU's phase measurement by spoofing the GPS signal. Though many commercial GPS receivers are not secured against spoofing, we nevertheless employ the following constraints to demonstrate the feasibility of an attack under simple spoofing detection schemes: i) The difference between the true receiver location and the location calculated by the spoofed receiver should be small, and ii) The difference between the true ephemerides and the spoofed ephemerides should be small. The difference between the pre-attack clock offset and the spoofed clock offset is maximized. In the optimization problem, the decision variables are the satellites' ephemerides.

In order for the attack to successfully evade detection, the perturbation of the original data must be such that after the GPS receiver computes its new location and clock offset with the spoofed data signal, the location is still close to the pre-attack location while the difference between the new clock offset and the pre-attack clock offset is maximized. In the optimization problem, the decision variables are the satellites' ephemerides.

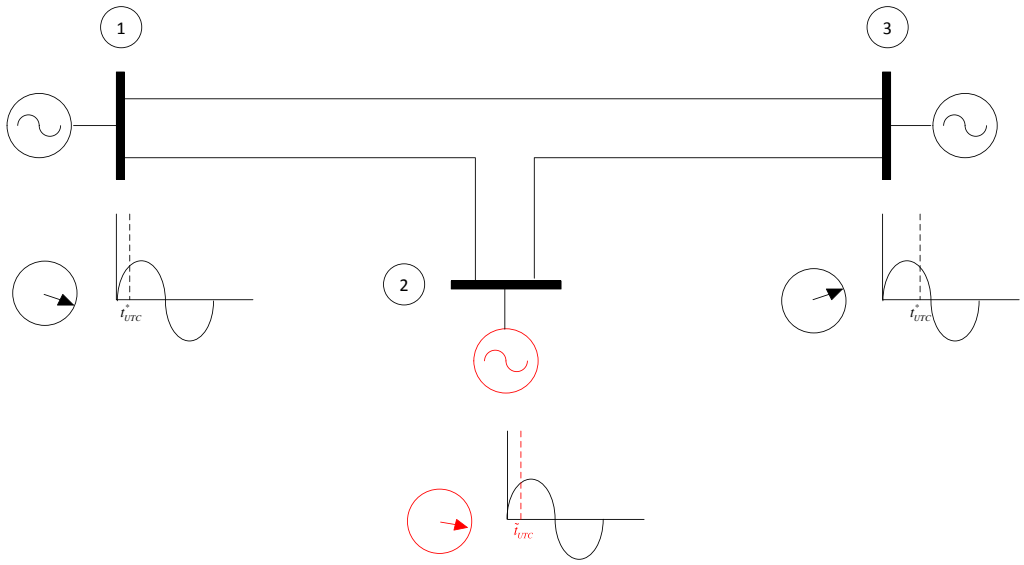


Fig. 2: PMU and Associated Phasor Measurements Post-Attack.

B. Four Visible Satellites

In this case, the problem can be formulated as a maximization of the clock offset error as follows:

$$\begin{aligned}
\text{max} \quad & (t_u - t_u^*)^2 \\
\text{subject to} \quad & \rho_i = r_i - ct_u, \quad \forall i = 1,2,3,4 \\
& |x_u - x_u^*| \leq \varepsilon_{x_u} \\
& |y_u - y_u^*| \leq \varepsilon_{y_u} \\
& |z_u - z_u^*| \leq \varepsilon_{z_u} \\
& |\delta_i(j) - \delta_i^*(j)| \leq \varepsilon_{\delta_i}(j), \quad j = 1,2,\ldots,m \\
& x_i = f(\overline{\delta}_i, t) \\
& y_i = g(\overline{\delta}_i, t) \\
& z_i = h(\overline{\delta}_i, t)
\end{aligned} \tag{9}$$

where x_u, y_u, z_u are the receiver's ECEF coordinates, $\overline{\delta}_i$ are the i^{th} satellite's ephemerides. The differences between the decision variables and their pre-attack values (denoted by *) are bounded by ε_{x_u}, ε_{y_u}, ε_{z_u} and $\varepsilon_{\delta_i}(j)$. As discussed above, these bounds are specified to demonstrate that the spoofing can still succeed even if the receiver checks for abrupt changes to these parameters from their pre-attack values as a possible countermeasure to detect spoofing (to the authors' best knowledge, there are currently no commercial products that implement these countermeasures). If the receiver does not check for abrupt changes in the receiver and satellite positions and the ephemerides as a way to detect data spoofing, then these bounds can be relaxed to positive infinity. In addition, (3) must also be satisfied as constraints to the optimization problem so that the solutions found are valid. The expression for t_u in the objective function is obtained by summing the expressions in (3) and solving for t_u, which results in

$$t_u = \frac{-1}{4c} \sum_{i=1}^{4} (\rho_i - r_i). \tag{10}$$

C. More Than Four Visible Satellites

In this case, the system is overdetermined and, assuming noise in measurements, an exact solution to (3) no longer exists. Therefore, the constraints arising from (3) are replaced by the LSE condition in (5). Since (5) itself is an optimization problem, it cannot be readily stated as a regular constraint. However, we can exploit the fact that the LSE problem is itself an optimization problem; thus, in the spoofing attack formulation, we impose as constraints the first-order optimality conditions of the LSE problem, i.e.,

$$\frac{\partial f_0}{\partial x_u} = \frac{\partial f_0}{\partial y_u} = \frac{\partial f_0}{\partial z_u} = \frac{\partial f_0}{\partial t_u} = 0, \tag{11}$$

where

$$\begin{aligned}
\frac{\partial f_0}{\partial x_u} &= 2\sum_{i=1}^{n}\left[\frac{(\rho_i - r_i + ct_u)(x_i - x_u)}{r_i}\right],\\
\frac{\partial f_0}{\partial y_u} &= 2\sum_{i=1}^{n}\left[\frac{(\rho_i - r_i + ct_u)(y_i - y_u)}{r_i}\right],\\
\frac{\partial f_0}{\partial z_u} &= 2\sum_{i=1}^{n}\left[\frac{(\rho_i - r_i + ct_u)(z_i - z_u)}{r_i}\right],\\
\frac{\partial f_0}{\partial t_u} &= 2c\sum_{i=1}^{n}(\rho_i - r_i + ct_u).
\end{aligned} \tag{12}$$

The problem of maximizing the receiver clock offset when more than four satellites are visible is described by

$$\begin{aligned}
\text{max} \quad & (t_u - t_u^*)^2\\
\text{subject to} \quad & \frac{\partial f_0}{\partial x_u} = \frac{\partial f_0}{\partial y_u} = \frac{\partial f_0}{\partial z_u} = \frac{\partial f_0}{\partial t_u} = 0\\
& |x_u - x_u^*| \le \varepsilon_{x_u}\\
& |y_u - y_u^*| \le \varepsilon_{y_u}\\
& |z_u - z_u^*| \le \varepsilon_{z_u}\\
& |\delta_i(j) - \delta_i^*(j)| \le \varepsilon_{\delta_i}(j), \quad j = 1, 2, \ldots, m\\
& x_i = f(\overline{\delta}_i)\\
& y_i = g(\overline{\delta}_i)\\
& z_i = h(\overline{\delta}_i).
\end{aligned} \tag{13}$$

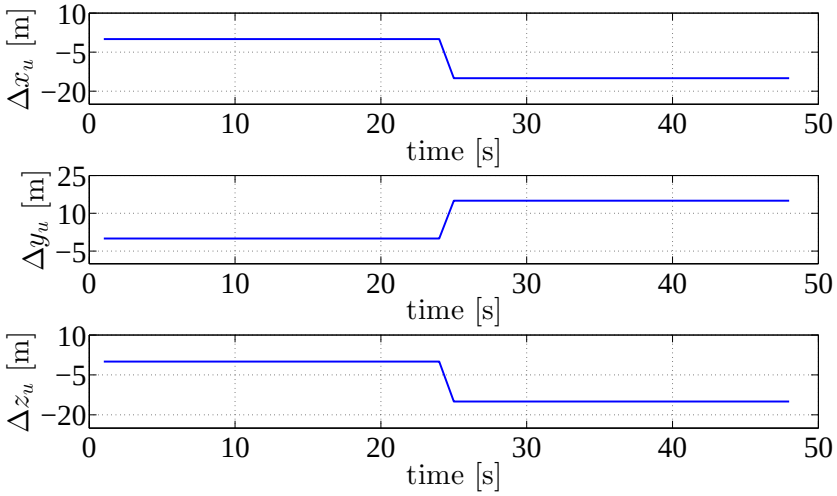
The variable t_u in the objective function can be solved from any of the expressions in equation (12); e.g., by using $\frac{\partial f_0}{\partial t_u} = 0$, we obtain

$$t_u = \frac{-1}{nc}\sum_{i=1}^{n}(\rho_i - r_i). \tag{14}$$

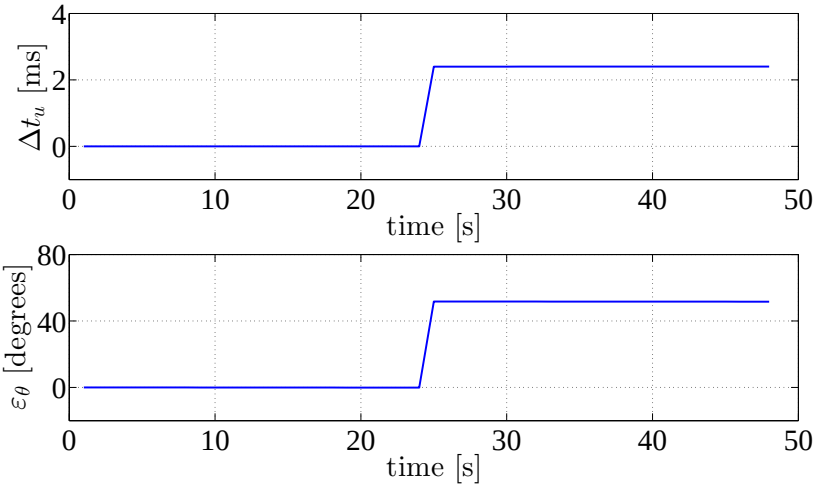
IV. Case Studies

In this section, we illustrate the concepts developed in Section III by presenting the results of spoofing a simulated GPS receiver that is receiving signals from four and seven satellites. The optimization problem described in Section III has been implemented in the MATLAB environment with the perturbation of each of the satellites' ephemerides limited to $\pm 2\%$ of their pre-attack values.

For the four-satellite case, the optimization problem in (9) is computed for 24 time instances. The solutions for position and clock offset of the spoofed receiver are plotted along with the corresponding pre-attack solutions in Fig. 3. The attack occurs 24 seconds into the simulation. In Fig. 3(a), it is observed that the jumps in the ECEF coordinates of the receiver due to the spoofed ephemerides are indeed within the 15 m bounds specified by the constraints. Therefore, if the threshold for detecting an



(a) Receiver ECEF Coordinates.



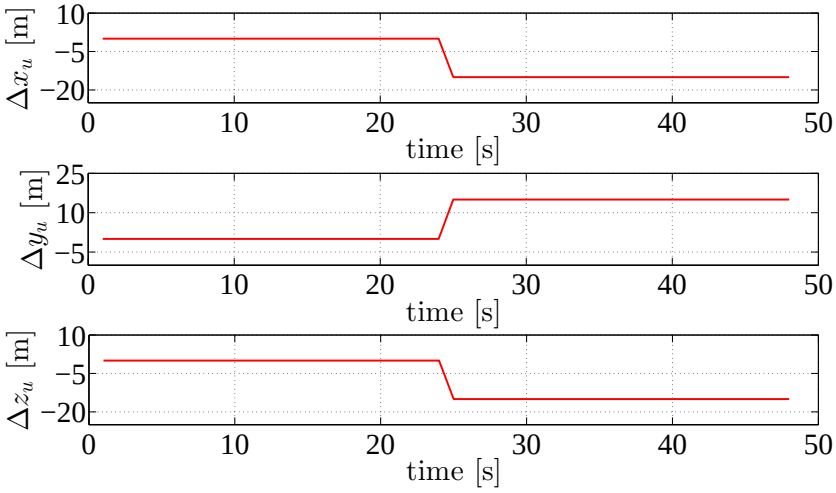
(b) Receiver clock offset and phase angle.

Fig. 3: Receiver Position, Clock Offset, and PMU Phase Error for Spoofing Four Satellites.

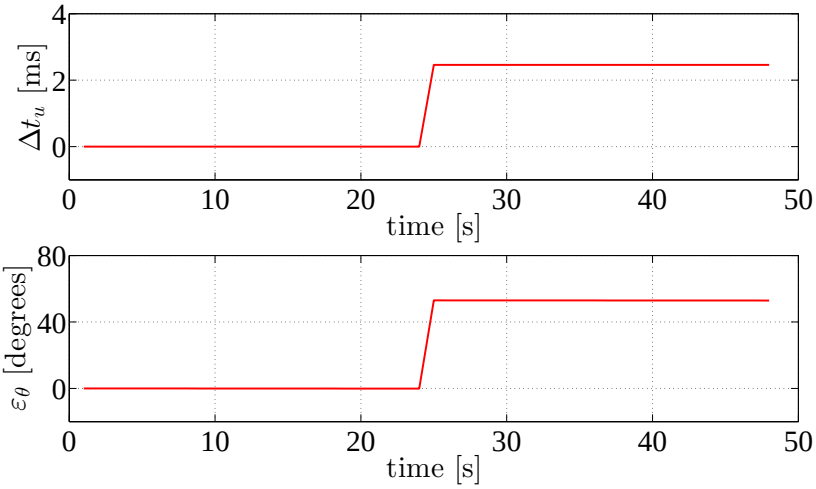
attack is greater than 15 m, then such spoofing would not be noticed. Figure 3(b) shows the change in the receiver clock offset from the spoofing attack and the resulting PMU phase angle error corresponding to the attack.

The optimization problem in (13) is computed for the seven-satellite case using the same bounds on the ephemerides, pseudoranges, and receiver locations as the four-satellite case. The results from the simulation are shown in Fig. 4. The phase angle error resulting from these attacks can be as high as 52°, which corresponds to 14 percent of a full cycle for a 60-Hz system.

Figure 5 shows the receiver clock offset and the resulting PMU phase error for both the four-satellite and seven-satellite spoofing on the same plot. Comparing the two plots, it can be seen that the maximum phase errors that can be introduced under the same constraints for each satellite are nearly the same.



(a) Receiver ECEF Coordinates.



(b) Receiver clock offset and phase angle.

Fig. 4: Receiver Position, Clock Offset, and PMU Phase Error for Spoofing Seven Satellites.

V. Countermeasures

In this section, some possible countermeasures for GPS receiver spoofing are described. The methods presented here are by no means comprehensive and as the receiver technology evolves, more sophisticated attacks and countermeasures are expected to be developed. The effectiveness of the attack demonstrated in this report suggest that spoofing detection needs to be employed by PMUs in the power grid, and in general any high-reliability system using a GPS time stamp. As described in the Introduction, such detection schemes include [6], [7]:

1) Amplitude discrimination
2) Time-of-arrival discrimination
3) Polarization discrimination

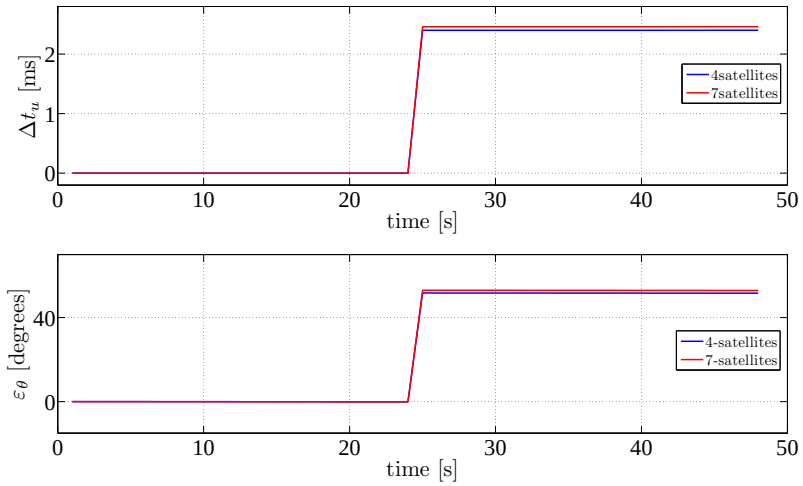


Fig. 5: Clock Offset and PMU Phase Error for Spoofing Four and Seven Satellites.

4) Angle-of-arrival discrimination
5) Cryptographic authentication
6) Signal strength discrimination

The attack proposed in this report would be easily detected by 4 or 5, but 4 requires multiple networked antennas, and 5 requires changes to the GPS signal architecture.

Several other simple spoofing detection schemes would readily detect the attack proposed in this paper. If a receiver is connected to the Internet, it could download the most recent ephemerides from the GPS control segment to validate the received navigation data. Since the proposed attack relies on spoofing the ephemerides, a cross-check would reveal tampering. Of course, the spoof would not be revealed until the online ephemeris data were updated, creating a window of opportunity for the spoofer to cause damage.

Instead of checking against published ephemeris data, the receiver could compare the received navigation data with the almanac, a reduced-resolution but multi-satellite version of the ephemerides that is continually broadcast by every satellite along with its own navigation data. Receivers typically use stored almanac data upon startup to obtain a quicker fix on all visible satellites. By comparing a computed satellite position with the position expected from the almanac, an aggressive spoof could be detected. However, conservative spoofers could stay below any particular threshold by tightening the constraints on the optimization problem.

Most GPS clocks do not use the receiver clock offset measurement directly, but rather use it to guide an independent crystal-controlled oscillator. Monitoring the discrepancy between the oscillator and the computed GPS time could reveal tampering.

Another spoofing detection scheme takes advantage of the fact that the genuine satellite signals, while less powerful than the spoofed signals, are still present. Exact cancellation of the genuine signals

would require a complicated spoofer. This technique is known as vestigial signal defense (VSD) and is described in detail in [18]. VSD is software-based, requiring no extra hardware. A spoof is detected if additional GPS signals are present in addition to the most powerful ones. The drawback of VSD is that the buried signals are hard to distinguish from multipath interference, but if the GPS receiver is in a static environment (as is the case for PMUs), then multipath effects could be measured and accounted for.

Finally, the proposed spoof would be easily detected in real time if the victim receiver were networked to a trusted GPS receiver at another location, assuming that the trusted receiver is not being spoofed. The victim receiver need only validate the navigation data, the current GPS time estimate, or other signal characteristics such as the P(Y) code. The work in [19] shows that spoofing could be revealed by comparing the P(Y) code on the trusted and victim receivers. The P(Y) code is an encrypted military code that is transmitted in quadrature with the civilian GPS code. A spoofed signal could not contain the genuine P(Y) code.

VI. Conclusions

PMUs provide synchronized real-time measurements of voltage and current phasors across the power system. They rely on GPS signals to time stamp their measurements. As such, these devices are vulnerable to spoofing attacks. One method of spoofing is to introduce an error in the receiver clock offset, which introduces a proportional phase estimation error from the PMU.

This report demonstrates the feasibility of an attack on PMU phase measurements through spoofing the ephemerides' data on the GPS signal. An optimization algorithm that maximizes the error in the receiver clock offset while maintaining the receiver position close to its pre-attack value is proposed. The bounds placed on the maximum receiver position change due to the attack are to ensure that the spoofing avoids detection. When four satellites are visible and no noise is in the measurements, an exact solution to the optimization problem can be found. In the case of more than four satellites, a LSE solution to the optimization problem is formulated with the least squares condition recast into a first order optimality constraint. The feasibility and effectiveness of the proposed spoofing method is demonstrated through simulations of four- and seven- satellite cases.

Future plans involve extending the domain of optimization from an instant in time to a duration over which the PMU can be potentially spoofed. Subsequent experimental work includes a demonstration of this attack on a PMU by building a GPS spoofer (hardware demonstration). The optimization algorithm will be used to compute the optimal spoofing method for a particular time well in advance of the spoofing attack. The solution of the optimization problem will then be downloaded onto the GPS simulator for execution at a later time. Given the feasibility of such an attack, the effects of erroneous phase measurements on state estimation and stability analysis must be assessed and countermeasures developed.

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