

# The GPS Assimilator

## Upgrading Receivers via Benign Spoofing

Interference, jamming, and spoofing are increasing the GNSS user community's concerns about the security and reliability of their receivers. Although solutions are being proposed for future equipment designs that can process multiple signals from multiple GNSS systems, this article introduces a method for upgrading existing GPS user equipment to improve accuracy, robustness, and resistance to spoofing.

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**W**hat will GNSS receivers look like five years from now?

The answer, of course, depends on the application. Mass-market receivers used in applications that do not require precision positioning and timing (hand-held units for hikers, for example) will likely remain simple, single-frequency L1 C/A-code-based GPS devices.

On the other hand, a growing segment of military and civilian GNSS users will demand greater accuracy and reliability from their receivers than can be offered by single-frequency GPS. They will want multi-frequency GNSS devices to combat ranging errors due to ionospheric delay, and multi-system receivers

to improve satellite availability and robustness against signal interference.

Major commercial GNSS receiver manufacturers already have product roadmaps in place that anticipate these demands. Manufacturers realize that they will be at a competitive disadvantage relative to their peers if they only offer a subset of available GNSS signals to sophisticated users. "Why should I have to choose between signals?" their customers will complain, "I'd like all of them!"

Then there is the issue of GNSS security. At one time, perhaps 20 years ago or more, computer users were largely unconcerned with the security of their personal computers. That time has passed. As any victim of a computer virus knows, firewalls, anti-virus software, and protocols for secure data transfer are no longer optional, but required.

Likewise, the deepening dependence of the civil infrastructure on GNSS —

especially for timing synchronization — and the potential for financial gain or causing high-profile mischief make civil GNSS jamming and spoofing a gathering threat. Since the publication of the U.S. Department of Transportation's Volpe Report on GPS dependence nearly a decade ago, GNSS security researchers have repeatedly warned that civil GPS is not yet secure, and that users trust its signals at their peril.

As Professor David Last commented at a recent conference on GNSS security, "Navigation is no longer about how to measure where you are accurately. That's easy. Now it's how to do so reliably, safely, robustly."

Secure positioning, navigation, and timing (PNT) will require use of all available means: inertial navigation systems, stable frequency sources, multiple antennas, and cryptographic authentication. Product designers and system integrators will also want to exploit all radio frequency signals from which PNT

information can be extracted — including non-GNSS signals and signals never intended to be used for PNT.

In short, PNT devices in critical applications five years from now will likely be remarkably capable and secure devices that adhere to an all-signals-in-view, all-available-means philosophy.

Meanwhile, however, the overwhelming majority of GNSS receivers — even those in critical applications — are simple L1 C/A-based devices that fail when signals are blocked or jammed, complaining, “Need clear view of sky.” Moreover, no commercially available civil GNSS receiver, as far as we are aware, incorporates even rudimentary defenses against spoofing.

Will these receivers be considered obsolete in the near future as new equipment that incorporates multiple signals, GNSS systems, and security measures reaches the market? Perhaps. And perhaps the prudent course of action is to replace them with secure and reliable modern devices.

A decision to replace existing receivers, however, cannot be made lightly. The millions of deployed GNSS receivers in operation around the globe today represent an enormous investment in equipment and training. Moreover, in many cases the GNSS receiver is only an embedded subcomponent of a larger PNT-reliant system. It may be inconvenient, unsafe, or expensive to replace these embedded devices with modern counterparts. Nonetheless, the vulnerability of existing receivers, embedded and otherwise, to signal obstruction, jamming, and spoofing, and their inability to make use of modernized GNSS signals and other signals of opportunity, leaves much to be desired.

As an alternative to replacement of existing equipment, we propose augmentation. We have developed a technique for upgrading existing GNSS user equipment to address their shortcomings without requiring hardware or software modifications to the equipment.

This technique re-purposes a portable civil GPS spoofer to generate “friendly” spoofing signals whose implied navigation solution is derived from a fusion of

GPS and other observables. The spoofer is described in a paper by T. E. Humphreys et alia (2008) listed in Additional Resources near the end of this article.

Our benign spoofing technique is embodied in a device, called the GPS Assimilator, whose output is injected directly into the radio frequency (RF) input of existing GPS equipment to immediately “robustify” the equipment against GPS outages and interference. This article describes the GPS Assimilator’s design and operation and reports the preliminary performance results of a prototype model.

## Documenting the Need

Consider three examples of existing devices for which Assimilator augmentation is potentially preferable to replacement.

**Time Reference Receivers.** These devices, which typically cost several thousand dollars apiece, couple a GPS receiver to a stable oven-controlled crystal oscillator (OCXO) or atomic frequency reference. Timing receivers are used extensively in telecom networks; in particular, the IS-95 CDMA-based digital cellular standard and its progeny require each base station to be synchronized with a GPS receiver so that the timing of transmissions can be controlled to better than 10 microseconds.

Modern GNSS time reference receivers easily meet this requirement. They are also capable of extended (24–36 hours) “holdover mode” operation in case of signal blockage or jamming. Nonetheless, recent experiments with a popular time reference receiver model at the University of Texas Radionavigation Laboratory have revealed that these receivers are easily spoofed. Within the span of one hour, the pulse-per-second output of a receiver originally locked to authentic GPS signals can be driven to a larger than 10-microsecond error without raising any of the receiver’s internal alarms.

The obvious implication — that it would take a malefactor less than one hour to render a cell-phone base station inoperable via spoofing — is cause for concern. Unfortunately, due to the

tight coupling between the GPS receiver and the oscillator that it disciplines, the GPS receiver component cannot be easily swapped with a modern, secure version.

**Phasor Measurement Units (PMUs).** Also known as synchrophasors, these devices couple a GPS receiver to power measurement equipment in order to simultaneously obtain the phasor values of voltages and currents at particular instants of time. Although now used primarily for monitoring, these devices are expected to see widespread future application in closed-loop control systems designed to increase the carrying capacity of the power distribution grid.

The widespread installed base of PMUs (in Texas alone there are more than 8,000 installed today) represents a considerable investment. Unfortunately, like time reference receivers, the embedded GPS receivers in PMUs are easily spoofed. Timing errors lead to phasor angle errors, and, when these reach several degrees (~100 microseconds), they could destabilize closed-loop control of transient swings, ultimately damaging critical components of the power grid.

**Embedded Military GPS Receivers.** Unsurprisingly, GPS receivers find widespread use in armed forces worldwide. Several hundred thousand devices have been procured by the U.S. Department of Defense and foreign military sales customers over the last five years — a substantial collective investment. A large fraction of military-grade GPS receivers are used as embedded receivers, being coupled to targeting, tracking, and communications equipment via well-defined and field-tested interfaces.

Blockage or jamming of incoming GPS signals can render these critical downstream systems inoperable. Counterintuitive as it may seem that a vehicle-to-vehicle communications system would be disabled by GPS blockage, such is the nature of modern dependence on precision navigation and timing.

Each of these example devices would experience benefits in accuracy, robustness, or security from coupling to a solution such as the GPS Assimilator.

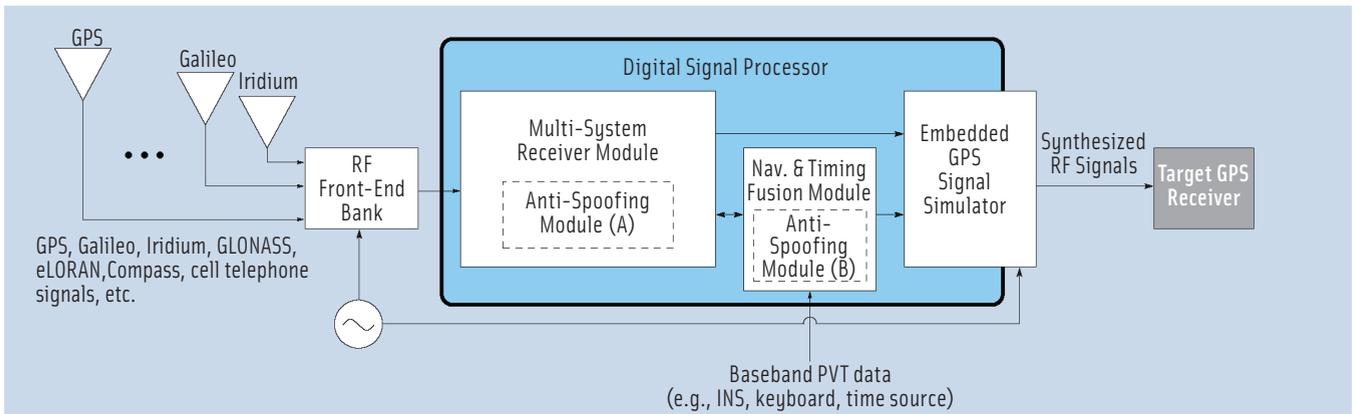


FIGURE 1 Block diagram of the conceptual Assimilator device.

## Conceptual Assimilator

The Assimilator concept is based on the principle that from virtually any modern environment one can extract a wealth of navigation and timing-related information. Thus, the Assimilator behaves opportunistically, scanning ambient radio waves for PNT information while also accepting baseband data from an inertial navigation system (INS), an external time source, or directly from the user.

All extracted PNT information is fused to yield an optimal navigation and timing solution. Up to this point, the Assimilator is no different from other proposed systems for robust navigation and timing that employ an “all available means” philosophy. For these proposed systems, as for the Assimilator, GPS is but one of several potential sources of PNT data.

Having obtained a fused PNT solution, however, the Assimilator then takes an unusual additional step: it embeds the PNT solution in a consistent set of synthesized GPS L1 C/A signals, the common denominator of all existing GNSS equipment. By casting its solution into this output format, the Assimilator can deliver the additional accuracy, robustness, and security of its solution to any GNSS device by simply injecting its output into the RF input of the target device. Thus, the Assimilator acts as a conduit for funneling ambient PNT information to existing GNSS equipment, without requiring hardware or software changes to the equipment.

Despite the inefficiency of re-generating GPS RF signals after already hav-

ing obtained a PNT solution, the assimilative approach is warranted in cases where, due to tight embedded coupling with expensive downstream equipment or due to user familiarity, augmenting existing equipment is more cost-effective or safer than replacing it.

## Assimilator Components

Figure 1 introduces the Assimilator concept in block diagram form. We will discuss each subcomponent in turn.

**Front-End Bank.** A bank of RF front ends digitizes segments of the RF spectrum containing signals that potentially bear PNT information. Naturally, GPS, Galileo, and other GNSS signals are among these, but so are terrestrial radionavigation signals such as LORAN/enhanced LORAN (now only outside the United States) as well as communication signals from cell phone towers or Iridium satellites — signals not originally designed for PNT.

**Multi-System Receiver Module.** The digitized data exiting the RF front-end bank are routed to a software-defined multi-system receiver module implemented on a digital signal processor (DSP). Here, each target signal is tracked, either independently or as part of a vector tracking loop.

Observables extracted from each signal may include pseudorange, carrier phase, carrier Doppler, signal strength, and navigation data. In the case of communication or other signals not originally intended for navigation and timing, the Assimilator must draw supplementary information such as ephemerides, clock offsets, or base station locations

from an internal or external database in order to make use of the observables.

### Navigation and Timing Fusion Module.

The observables are sent to a central navigation and timing fusion module, which also accepts baseband PNT inputs. For each input signal there exists in the fusion module an *a priori* noise and signal dynamics model, enabling the data to be optimally fused in a Bayesian estimation framework.

**Anti-Spoofing Module.** Both the multi-system receiver module and the navigation and timing fusion module are equipped with anti-spoofing software. Module A, which resides within the multi-system receiver module, continuously scans the RF data streams entering the Assimilator for spoofing signatures. Module B, which resides within the navigation and timing fusion module, watches for inconsistencies between observables in the centralized solution. Further details on these modules will be given later on.

**Embedded GPS Signal Simulator.** The output of the navigation and timing fusion module feeds an embedded GPS signal simulator. The embedded signal simulator is depicted in Figure 1 as residing partly outside the DSP because it includes an external RF upconversion component.

Several options are possible for signal simulation:

*Impaired GPS L1 C/A.* If reception of GPS L1 C/A signals is impaired, then the embedded simulator can generate signal replicas in two ways: a “matched” mode in which the simulator generates the same GPS L1 C/A signals that would

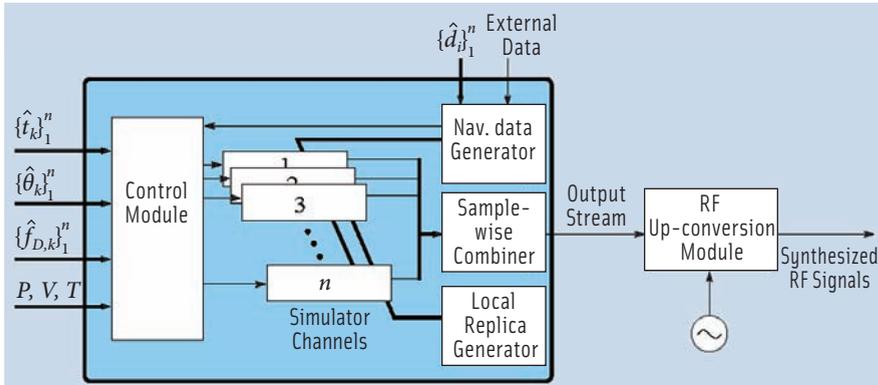


FIGURE 2 Expanded view of the embedded GPS signal simulator

be visible to the Assimilator in clear sky conditions, corrected to be consistent with the fusion module's PNT solution; and a "fictitious" mode in which the simulator generates a partially or entirely fictitious signal set the implied solution for which is consistent with the fusion module's PNT solution.

**Unimpaired GPS L1 C/A.** If several sufficiently strong GPS L1 C/A signals are available in the Assimilator's environment, then the embedded simulator can generate clean replicas of these, passing on to the target receiver the additional accuracy of the fused PNT solution by continually applying corrections to the code start times and carrier phases of the GPS L1 C/A signals.

Again, we have two options for generation: a "non-aligned" mode in which no attempt is made to align the code phase of the simulated and authentic signals, and a "code-aligned" mode where the simulator generates GPS signals that are approximately code-phase-aligned with the corresponding authentic GPS L1 C/A signals at the RF input to the target GNSS receiver.

In the second mode, the simulated signals are generally not in exact code-phase alignment due to corrections applied to match the simulated signals' implied solution with the fusion module's PNT solution. The advantage of code alignment is that the synthesized signals appear approximately as the authentic signals to the target receiver, which enables a user to "hot plug" the Assimilator into a target receiver with no interruption in the PNT.

### Inside the Signal Simulator

An expanded view of the embedded GPS signal simulator is shown in Figure 2. Its subcomponents will be treated in turn.

**Control Module.** The control module coordinates generation of the synthesized GPS signals by directing the carrier phase, carrier frequency, and code phase in each of  $n$  simulator channels.

The control module accepts the following inputs from the multi-system receiver module's L1 C/A tracking channels: the estimates  $\{\hat{t}_k\}_1^n$  of the start times of the  $k$ th ranging code interval on receiver channels 1- $n$ ; the estimates  $\{\hat{\theta}_k\}_1^n$  of the beat carrier phase on receiver channels 1- $n$  at times  $\{\hat{t}_k\}_1^n$ ; and the estimates  $\{\hat{f}_{D,k}\}_1^n$  of the Doppler frequency shift on receiver channels 1- $n$  at times  $\{\hat{t}_k\}_1^n$ .

Further, the control module accepts the following inputs from the fusion module: the estimated current time  $T$  and the estimated position  $P$  and velocity  $V$  of the Assimilator's antenna. The control module configures each simulator channel to generate a single GPS L1 C/A signal with a carrier frequency and code phase that are consistent with the fusion module's position  $P$ , velocity  $V$ , and time  $T$  solution.

**Simulator Channels.** Each of the  $n$  simulator channels can be configured to generate a unique GPS C/A signal, modeled as

$$x_n(\tau_i) = A_n(\tau_i) d_n(\tau_i) C_n(\tau_i - t_{n,k}) \quad (1)$$

$$\times Q \left\{ \sin \left[ 2\pi f_{IF} \tau_i + \theta_n(\tau_i) \right] \right\}$$

$$\dot{\theta}_n(\tau_i = t_{n,k}) = f_{D,n,k} \quad (2)$$

where

$x_n(\tau_i)$ , is the  $i$ th sample of the signal  $\tau_i$ , the time of the  $i$ th sample

$A_n(\tau_i)$ , the amplitude at  $\tau_i$

$d_n(\tau_i)$ , the navigation data bit value that applies at  $\tau_i$

$C_n(\tau_i - t_{n,k})$ , the ranging code chip value that applies at  $\tau_i$

$t_{n,k}$ , the start time of the  $k$ th ranging code interval

$Q\{\bullet\}$ , a quantization function

$f_{IF}$  is the intermediate frequency

$\theta_n(\tau_i)$ , the beat carrier phase at  $\tau_i$

$f_{D,n,k}$  the Doppler frequency shift at time  $t_{n,k}$

The ranging code function  $C_n(\tau)$  can be expressed as

$$C_n(\tau) = \sum_{j=-\infty}^{\infty} c_{n,j} \Pi_{T_c}(\tau - jT_c) \quad (3)$$

and the navigation data bit function  $d_n(\tau)$  as

$$d_n(\tau) = \sum_{j=-\infty}^{\infty} d_{n,j} \Pi_{T_d}(\tau - jT_d) \quad (4)$$

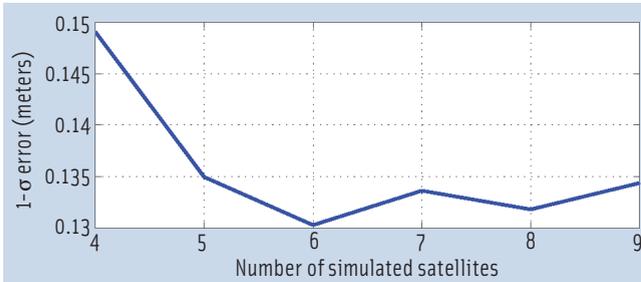
where  $\{c_{n,j}, c_{n,j+1}, \dots\}$  and  $\{d_{n,j}, d_{n,j+1}, \dots\}$  are, respectively, the unique ranging code chip sequence and navigation data bit sequence corresponding to the GPS satellite whose signal is being emulated on the  $n$ th simulator channel,  $T_c$  and  $T_d$  are the duration of one ranging code chip and one navigation data bit, and  $\Pi_T(\tau)$  is the usual rectangular support function equal to unity over  $0 \leq \tau < T$  and zero otherwise.

**Local Replica Generator.** The local replica generator generates the ranging code samples  $\{C_n(\tau_i - t_{n,k})\}_{i=1,2,\dots}$ , and the quantized carrier replica samples

$$Q \left\{ \sin \left[ 2\pi f_{IF} \tau_i + \theta_n(\tau_i) \right] \right\}, \quad i=1,2,3,\dots \quad (5)$$

The generation of carrier replicas is described in the article by B. Ledvina cited in Additional Resources. A command and data bus conveys phase and frequency information from the simulator channels to the local replica generator, and returns local carrier and code replicas from the local replica generator to the simulator channels.

**Navigation Data Generator.** The navigation data bit sequence,  $\{d_{n,j}, d_{n,j+1}, \dots\}$  required by the  $n$ th simulator channel,



**FIGURE 3** Minimum 1- $\sigma$  position and range-equivalent timing error deliverable to a target receiver by a one-bit quantized Assimilator output stream, as a function of the number of simulated signals. For the underlying ranging precision model, a code tracking-loop averaging time of 10 seconds and an early-minus-late correlator spacing of one chip are assumed.

is generated in one of two ways. When GPS L1 C/A signals are available, a steady stream of navigation data bits is taken from the GPS L1 C/A channels of the multi-system receiver module. Data bits extracted from the authentic signals are fed to the navigation data generator and compiled into a signal-specific data bit library.

If the receiver module loses lock on an authentic signal corresponding to one being simulated, then the navigation data generator continues to populate the simulated bitstream with navigation data from the data bit library, but the library no longer gets updated as before. This continues until the control module reconfigures the simulator channel to generate another signal.

If a simulator channel is configured to generate a signal for which there is no recent data bit library, then the navigation data generator produces data bits consistent with a standard ephemeris for the corresponding satellite. The navigation data generator can also accept user-supplied satellite data in the form of a databit library or a satellite ephemeris.

**Sample-wise Combiner.** Combination of the signals generated in each of the simulator channels is performed digitally sample-by-sample in the sample-wise combiner. For typical Assimilator operation, all output signals are weighted equally so that the target GNSS receiver sees a set of received signals with equal carrier-to-noise ( $C/N_0$ ) ratios.

However, the Assimilator is also capable of matching ambient  $C/N_0$  ratios in case this information is use-

ful for downstream systems. In this case, the  $i$ th sample from the  $n$ th simulator channel is weighted by the simulated amplitude  $A_n(\tau_i)$  and summed with the corresponding samples from the other simulator channels, each weighted appropriately. The combined signal is then re-quantized

to produce an output bitstream.

**RF Upconversion Module.** The output bitstream of the sample-wise combiner is routed to an RF upconversion module comprising a digital-to-analog converter, frequency mixers, filters, and a signal attenuator. The upconversion module converts the digital signal into a set of synthesized GPS signals at RF. The reference oscillator that drives the RF upconversion module must be the same oscillator that drives the Assimilator's RF front-end bank.

## Capabilities and Limitations

As with any system's functionality, the Assimilator has capabilities with finite limits. In this section, we describe these in terms of accuracy, robustness, and security.

**Accuracy.** For maximum compatibility with legacy GNSS receivers, the Assimilator outputs only GPS L1 C/A signals. The narrow bandwidth (~2 MHz) of the C/A ranging code limits the accuracy of the pseudorange-based position and time solution that the Assimilator can deliver to the target receiver. The Assimilator compensates for this limitation by generating synthetic signals with high  $C/N_0$  and by selecting a constellation geometry that minimizes the geometric dilution of precision (GDOP).

For purposes of illustration, let's suppose that the elevation mask angles of the target receiver are disabled so that for any number  $n$  of synthesized signals the Assimilator can employ optimal constellation geometry, which includes below-the-horizon satellites. The inverse

square-root relationship between minimum GDOP values implies that the minimum attainable GDOP for  $n$  satellites is

$$\text{GDOP}(n) = \text{GDOP}(4) \sqrt{\frac{4}{n}} \quad (6)$$

where  $\text{GDOP}(4) = \sqrt{5/2}$  is the minimum GDOP for 4 satellites.

Gains in precision due to increasing  $n$  are, unfortunately, vitiated by a decrease in  $C/N_0$  for all signals as a consequence of the interference contributed by each additional simulated signal. If we assume that signals are simulated with equal power and that the combined signal is quantized to one bit in the sample-wise combiner (one bit quantization being a practical choice for signal generation on a compact, low-power platform), then we can show empirically that the  $C/N_0$  value for each simulated signal drops from approximately 54 dB-Hz for  $n=4$  to 51 dB-Hz for  $n=9$ .

These  $C/N_0$  values can be incorporated into a ranging precision model and combined with the GDOP values from Equation (6) to bound the position and time precision the Assimilator can deliver to the target receiver. **Figure 3** shows this precision bound as a function of the number of simulated signals. The plot indicates that under the assumptions presented here a precision of approximately 13 cm is attainable. The plot further indicates that there is no advantage in simulating more than 6 signals.

Like the precision of code phase measurements derived from Assimilator-generated signals, carrier phase precision is determined by the  $C/N_0$  values of the simulated signals. For  $n=6$  simulated signals of equal power, the rms carrier phase errors are less than 0.4 degrees for each signal.

Another aspect of accuracy has to do with how well the Assimilator can eliminate the effects of ionospheric delay by exploiting multiple-frequency trans-ionospheric signals. The broadcast ionospheric model used in legacy single-frequency GPS receivers is known to eliminate only approximately half of the rms ranging error, leaving day-side

zenith delay errors up to 10 meters for a quiet ionosphere and much worse for an active ionosphere.

By contrast, standard dual-frequency L1 C/A and L2C GPS measurements at  $C/N_0=45$  dB-Hz can be used to reliably estimate the ionospheric delay to within 0.66 meters. Thus, the multi-frequency Assimilator can pass on to a single-frequency target receiver significant benefits in position and timing accuracy.

**Robustness.** The Assimilator's PNT solution is, by virtue of the diverse navigation and timing data that feed it, inherently robust against GNSS signal obstruction and jamming. Signals from cell phone base stations, Iridium satellites, and LORAN transmitters are 10s of decibels stronger than those from GNSS satellites. Thus, not only is the Assimilator robust to GNSS outages, it can also withstand substantial blockage, jamming, or other interference in the cell phone (1.9 GHz), Iridium (1.6 GHz), and LORAN (100 kHz) frequency bands.

Naturally, in a complete GNSS signal blackout, the PNT solution that the Assimilator feeds to the target receiver will be degraded, but by leveraging non-GNSS navigation and timing sources, the Assimilator limits this degradation substantially. Baseband aiding from an INS or stable frequency reference lowers the Assimilator's tracking threshold for GNSS signals and permits the Assimilator to "coast" through periods of complete RF blackout.

Ionospheric scintillation poses another challenge for GNSS receiver robustness. The deep power fades and accompanying fast phase transitions induced by equatorial ionospheric scintillation stress a receiver's carrier tracking loops. As the severity of scintillation increases, it can lead to navigation bit errors, cycle slipping, and complete loss of carrier lock.

The Assimilator makes best use of incoming GNSS signals by incorporating carrier phase tracking loops that are specially designed for scintillation robustness. (For maximum navigation accuracy, all carrier tracking loops within the Assimilator track carrier phase, not just frequency.)

One simple technique for extending the mean time between cycle slips (and decreasing the chances of frequency unlock) is to wipe off the navigation data bits from data-bearing channels so that a traditional full-cycle carrier tracking loop can be employed instead of a half-cycle Costas loop. This technique is discussed in the article by T. E. Humphreys et alia (2010) cited in Additional Resources.

The navigation data generator within the Assimilator's embedded signal simulator stores a signal-specific data bit library for each GPS L1 C/A signal. Because the C/A navigation message repeats every 12.5 minutes, this library can be used to predict the value of data bits that are received during scintillation-induced power fades. A network

multi-system receiver module. The module looks for outliers in pseudorange measurements in an extension of the popular receiver-autonomous integrity monitoring (RAIM) algorithm.

At a lower level in the processing chain, the Assimilator's anti-spoofing module A, which resides within the multi-system receiver module, monitors the individual incoming data streams for irregular behavior, employing, for example, the data bit latency and vestigial signal defenses introduced in the paper by T. E. Humphreys et alia (2008), the multi-antenna defense introduced in the article by P. Y. Montgomery et alia, or the signal quality monitoring technique introduced in the article by B. Ledvina et alia (see Additional Resources for full citations).

### The Assimilator's PNT solution is, by virtue of the diverse navigation and timing data that feed it, inherently robust against GNSS signal obstruction and jamming.

connection on the Assimilator permits data bit libraries to be downloaded from a remote server.

The Assimilator also benefits from access to modernized GNSS signals with pilot (data-free) channels that are by design more scintillation-robust than the legacy GPS C/A signal.

**Security.** As with robustness, the Assimilator is inherently more secure against signal spoofing than legacy civil GNSS receivers because of the diverse data from which its PNT solution is derived.

The paper by T. E. Humphreys et alia (2008) mentioned earlier demonstrated that developing a portable civil L1 GPS spoofer is relatively straightforward, but carrying out a successful spoofing attack becomes much more difficult when multiple signal types must be spoofed simultaneously. The Assimilator's anti-spoofing module B, which resides within the navigation and timing fusion module, exploits this inherent security by comparing the observables output by each of the independent signals tracked in the

Stronger civil spoofing defenses than these require cryptographic signal authentication. Over the last decade, GNSS security researchers have proposed techniques for navigation message and spreading code authentication, and authentication based on exploiting the known relationship between GPS C/A signals and the encrypted GPS Y-code on L1.

Of these, navigation message authentication (NMA) appears to be the most practical while still providing a strong defense against spoofing. The primary objection to civil NMA as applied to GPS is that it would require a change to the GPS signal-in-space specification, otherwise known as the GPS interface control document (ICD).

However, NMA could in fact be introduced in a way that is fully compatible with the current ICD by exploiting the flexible L2 or L5 navigation message structure. In this approach, one of the presently undefined navigation messages would be allocated for transmission of a digital signature. The GPS Operational

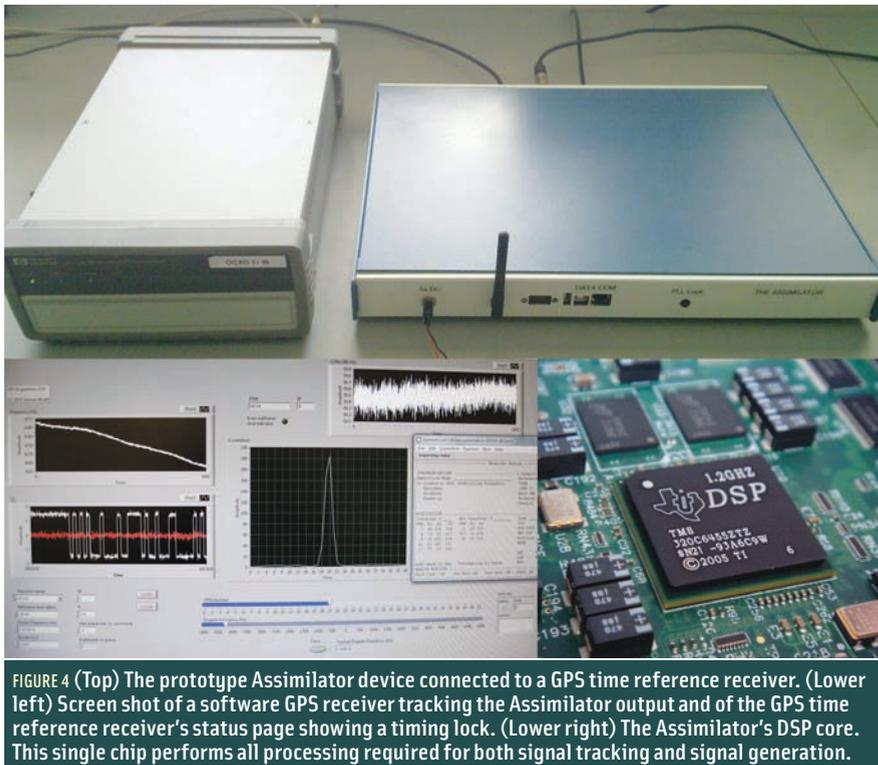


FIGURE 4 (Top) The prototype Assimilator device connected to a GPS time reference receiver. (Lower left) Screen shot of a software GPS receiver tracking the Assimilator output and of the GPS time reference receiver's status page showing a timing lock. (Lower right) The Assimilator's DSP core. This single chip performs all processing required for both signal tracking and signal generation.

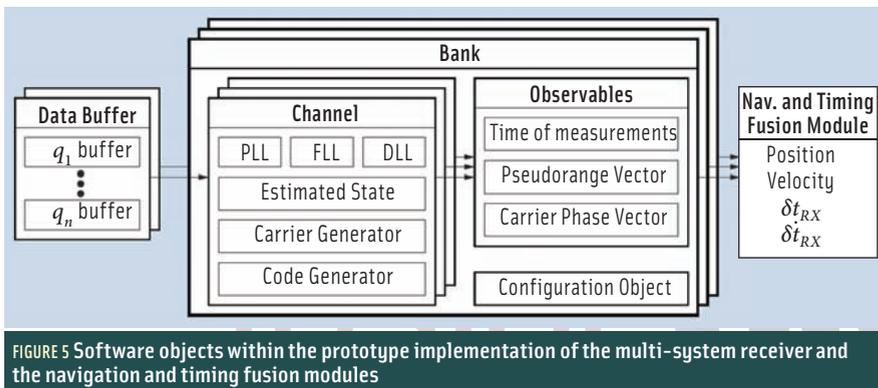


FIGURE 5 Software objects within the prototype implementation of the multi-system receiver and the navigation and timing fusion modules

Control Segment (OCS) would generate a public/private key pair, publishing the public key and keeping the private key secret. Users would download the public key from a trusted repository.

With the private key, the OCS would digitally sign all navigation data messages transmitted between the  $k$ th and  $(k+1)$ th digital signature message. The signature, at least 128 bits long for adequate security, would be transmitted to the user in the payload of the  $(k+1)$ th signature message.

With this scheme, users could periodically authenticate all navigation data bits modulated on a given signal. Only a slight extension to the GPS ICD would be required: an additional paragraph

defining the new digital-signature-bearing message

The Assimilator could be adapted to implement the algorithm that verifies the received digital signature. Thus, by combining the Assimilator with navigation message authentication on the GPS L2C or L5 signals, legacy GNSS receivers could be cryptographically secured against GPS spoofing attacks.

Whether by cryptographic means or otherwise, if the Assimilator detects a spoofing attack it alerts the user and excludes the spoofed signals from its internal PNT estimate. The synthesized GPS signals that the Assimilator continuously sends to the target receiver are accordingly spoof-free, and the target

receiver is protected from the spoofing attack.

## Prototype Assimilator

We have built a prototype Assimilator to prove the basic feasibility of the conceptual Assimilator introduced previously. The prototype is an extension of the GRID software-defined GNSS receiver introduced in the papers by T. E. Humphreys et alia (2006) and B. W. O'Hanlon and of the GPS spoofer discussed earlier.

The following sections will describe the prototype and offer initial experimental results.

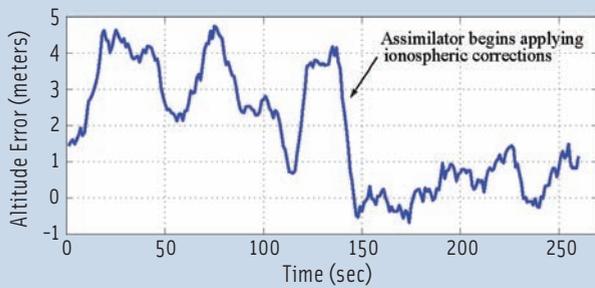
The prototype Assimilator is a dual-frequency device with a rudimentary spoofing defense. Its embedded signal simulator generates output signals in the code-aligned, unimpaired GPS L1 C/A simulation mode. The device receives L1 C/A and L2C GPS signals and outputs L1 C/A signals with code phases corrected for ionospheric delay.

Figure 4 shows a picture of the prototype assimilator coupled to a GPS time reference receiver. Also shown is a close-up of the DSP chip that simultaneously handles dual-frequency signal acquisition and tracking, and single-frequency signal simulation.

**Multi-System Receiver Module.** Though it currently only tracks GPS L1 C/A and L2C signals, the prototype Assimilator's multi-system receiver module is designed for expansion. Written in object-oriented C++, the module's principal feature is an extensible array of so-called Bank objects, each of which acts as an independent software receiver. Class polymorphism is exploited so that all Bank objects share a common structure.

Figure 5 illustrates the principal components of the Bank object. Data from each RF front end are stored in separate data buffers, with sub-buffers assigned to each of the front ends' quantization bits. The prototype uses two-bit quantization, but its processing algorithms can be adapted for  $N$ -bit quantization.

Each data buffer feeds a separate Bank object, of which the prototype Assimilator has two: one for GPS L1 C/A and one for GPS L2C. Each Bank object,



**FIGURE 6** Time history of altitude errors within an Assimilator-aided single-frequency receiver. Midway through the processing run the Assimilator activates ionospheric compensation, reducing the target receiver's altitude errors by approximately 2.5 meters.

in turn, houses an array of Channel objects, one for each independent signal to be tracked. Channel objects are made up of phase, frequency, and code tracking-loop objects and other supporting members.

All Channel objects within a Bank feed into a single Observables object that encapsulates the observables extracted from the signals to which the Bank is devoted. Each Bank object feeds a sequence of Observables objects to the navigation and timing fusion module to be fused into a single PNT solution.

#### Navigation and Timing Fusion Module.

The prototype Assimilator fuses dual-frequency GPS measurements into a single-frequency simulated GPS RF output by re-generating clean versions of the C/A signals that it tracks and by compensating for ionospheric delay on each of the simulated signals.

Only eight L2C-capable GPS satellite are currently in orbit, which implies that direct measurements of the L1 ionospheric delay are not available for all satellite-to-receiver paths. To compensate for ionospheric delay in all simulated signals, the prototype Assimilator uses whatever dual-frequency measurements are available to adjust the parameters of a simple single-layer ionospheric model. Delay estimates drawn from this model are then applied to adjust the code phase of simulated signals. No attempt is made at present to compensate for ionosphere-induced advances in the simulated signals' carrier phases.

**Anti-Spoofing.** For anti-spoofing, the prototype Assimilator implements a data bit latency defense. This simple defense is

premised on the difficulty of (1) predicting or synthesizing a consistent stream of navigation data bits for each signal, and (2) re-transmitting the broadcast GPS data bits with an undetectable latency.

In the prototype Assimilator's implementation of

the defense, Channel objects continuously monitor each navigation data bit stream and flag suspicious shifts in bit synchronization. The defense is far from foolproof, but it is simple to implement and substantially raises the bar for a successful spoofing attack.

**Embedded Signal Simulator.** The prototype Assimilator's embedded signal simulator functions just as described earlier for the conceptual Assimilator except that the prototype makes no attempt to choose the best possible combination of signals to simulate; it simply selects the strongest  $n$  tracked C/A signals (usually six) for simulation.

### Preliminary Performance Results

When tuned for efficiency, the prototype Assimilator meets real-time deadlines with computational resources to spare. The processing power of the prototype's DSP is such that it can run the equivalent of 135 parallel GPS C/A channels. Because their longer ranging codes cannot be stored in on-chip memory, L2C channels require the equivalent processing of four C/A channels.

More expensive still are the simulator channels, each of which requires an equivalent of 5.4 C/A channels. At full capability, the Assimilator can track 14 GPS L1 C/A signals and 14 GPS L2C signals while simultaneously generating 8 simulation signals, in addition to performing a one-hertz navigation solution and periodic background acquisition.

Of the prototype's hardware subsystems, the DSP and its peripherals, unsurprisingly, draw the most power,

requiring 6 watts. The dual-frequency RF front end draws 2 watts. A separate single-board computer used for network communications, remote reprogrammability, and housekeeping draws 1.3 watts. The RF upconversion module draws less than 700 milliwatts. Thus, the total power draw of the prototype Assimilator is less than 10 watts.

We conducted an experiment involving ionospheric delay modeling errors in order to illustrate the utility of the prototype Assimilator. The experiment was carried out in after-the-fact processing on a desktop PC running the Assimilator code.

A dual-frequency front end identical to that of the prototype Assimilator was used to digitize 300 seconds of dual-frequency data from a high-quality GPS signal simulator. The signal simulator's scenario profile was set to generate signals consistent with a Klobuchar ionospheric model with low electron content (~2 meters zenith delay at L1). We used data from the signal simulator to ensure a well-defined truth position. After-the-fact processing was required because the GPS signal simulator and the prototype Assimilator were not co-located.

The Assimilator ingested the dual-frequency digital data and generated a combined set of output single-frequency C/A signals. These were routed to a software-defined single-frequency GPS receiver (the target receiver) whose internal ionospheric model had been disabled. Midway through the run, the Assimilator began compensating for ionospheric delay by adjusting the code phase of its simulated signals. Prior to this moment, the target receiver showed positioning errors of approximately three meters, mostly in the altitude component.

To the target receiver it appeared as though a mismatch was occurring between the broadcast ionospheric model and the true ionosphere. However, when the Assimilator activated its dual-frequency-based ionospheric compensation, the target receiver's altitude errors were immediately reduced. **Figure 6** plots the altitude error time history. Clearly, even with this experiment's low-electron-content ionosphere, the target

receiver benefited from its coupling to the Assimilator.

## Conclusions

We have presented a technique for upgrading existing GNSS user equipment, without requiring hardware or software modifications to the equipment, to improve its accuracy, to increase its robustness in weak-signal or jammed environments, and to secure it against counterfeit GNSS signals. The technique is embodied in a device called the GPS Assimilator that acts opportunistically to extract navigation and timing information from its environment. The Assimilator encodes this information into a set of standard GPS L1 C/A signals with which all legacy GNSS receivers are natively compatible.

A dual-frequency prototype Assimilator with a rudimentary spoofing defense has been presented. Initial experimental results show the prototype successfully correcting ionospheric errors in a single-frequency target receiver.

Efforts are underway to develop the next-generation Assimilator prototype: a compact device equipped with a robust cryptographic defense against spoofing and capable of tracking dual-frequency GPS and CDMA cell telephone signals. Eventually, as board sizes are reduced, the Assimilator's processing core can be housed within its antenna enclosure, offering GNSS users the possibility of upgrading their current receivers with a simple change of antenna.

## End Notes

The assimilator concept and early hardware were developed at Coherent Navigation, Inc., a startup company of which Drs. Ledvina and Humphreys are co-founders, along with four others. Coherent Navigation Inc. has filed a patent covering the Assimilator concept and related technologies.

## Additional Resources

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