Data and Sensitivity Assistance for Mobile Users of GPS from the @Road Reference Network

Per Enge (per@relgyro.stanford.edu), Stanford University
Rod Fan (rfan@road-inc.com) and
Anil Tiwari (atiwari@road-inc.com), At Road, Inc.

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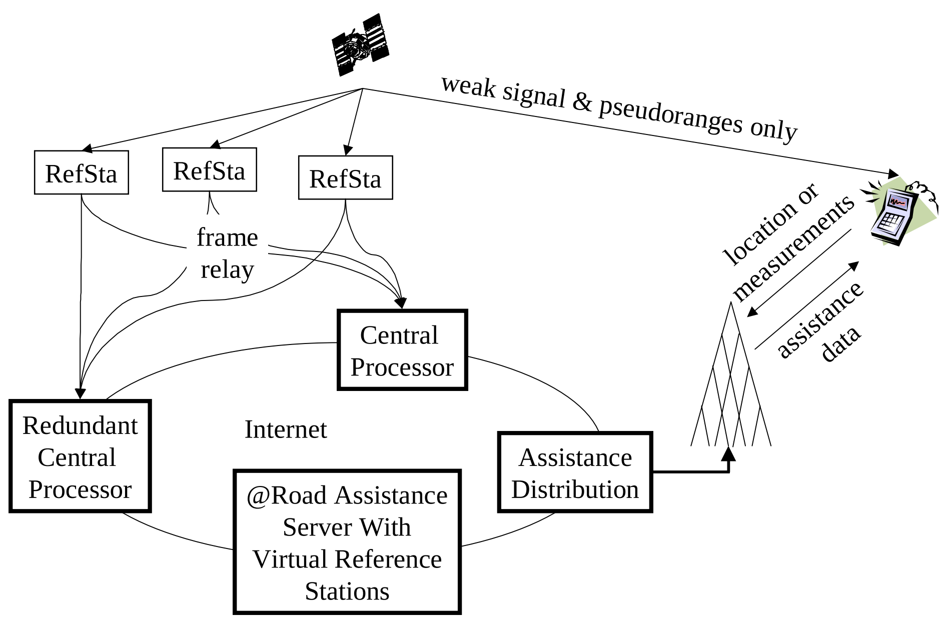
1 Introduction

With the help of researchers from Stanford University, @Road is expanding the utility of their present GPS networks to better serve mobile users in urban or obstructed environments with data and time assistance. To date, our networks have provided differential corrections, and they have been used solely to improve the *accuracy* of GPS. In the near future, they will also provide data and time assistance for GPS signal acquisition. This data will be made available on an Internet server so that subscribers can export the information to their mobile users of GPS. Our overall architecture is shown in Figure 1.

Figure 1: @Road Network



To provide accuracy assistance, our reference receivers are already distributed over the Continental United States, and technology licenses have been extended to smaller networks in Sweden, Australia, Denmark, Europe and Australia. These receivers use a frame relay network to send GPS measurements to our redundant hubs. The hubs develop corrections for the largest GPS errors, and these corrections are made available to subscribers. Mobile users apply the corrections and typically enjoy accuracies of 1 meter or better (2drms in the horizontal). In the past, the Radio Data Service has been used to send the corrections over sub-carriers of FM broadcast stations.

Our service is being enhanced to broadcast additional data and time assistance for signal acquisition. The first improvement is directed at reducing the *time-to-fix* of the receiver, and the second will reduce the *signal-to-noise ratio threshold* required for signal acquisition. These improvements will assist the coverage and availability of position fixing for GPS receivers used in difficult environments. Needless to say, accuracy assistance will still be a part of the overall system.

Data and time assistance is important when the GPS signal is weak or obstructed. In urban areas, buildings frequently obstruct the GPS satellites and a given satellite may only be in clear view for a few seconds at a time. If the receiver is used indoors, then the GPS signal may be much weaker than normal and acquisition aiding is critical.

To enhance signal acquisition, critical information broadcast in the *navigation message* from each GPS satellite will be collected by the geographically distributed receiver network and made available on an Internet server. This information will include the ephemeris information that describes the satellite location and the time information needed to unpack the ephemeris parameters. The GPS satellite only updates this information every *30* seconds. Such a lengthy observation period may not be available when users suffer from obstructions and momentary satellite outages. Consequently, we will make the ephemeris and almanac information available on the server for subscribers to deliver over alternate links to their users. With such assistance, the user can use satellites even if they are only intermittently observed.

In time, the following information will also be made available on the server

- actual bit sequences from the GPS navigation message
- Doppler shifts for all GPS satellites
- more accurate time information

This information can be used to improve receiver sensitivity, because it can be used to extend the averaging time used by the mobile receiver during signal acquisition.

Section 2 of this paper describes the architecture of the existing system, and includes data that describes the accuracy of the @Road DGPS service. We describe the existing architecture in some detail, because it is well suited for the development and delivery of the new information to assist signal acquisition and receiver sensitivity. Section 3 describes the planned enhancements.

2 Current Differential GPS Network to Improve Accuracy

At present, @Road GPS networks span the lower 48 states, and there are smaller networks in Sweden, Australia, Denmark, Europe and Australia. These systems backhaul

GPS measurements from a sparse network of GPS reference receivers to redundant network hubs. A processor at the hub uses these measurements to create *vector corrections* to the GPS measurements (U.S. patent no. 5,621,646). These vector corrections can be customized to any given location by a virtual reference station. The virtual reference station is specific to a customer chosen locale, and translates the vector correction into localized correction information suitable for wireless devices in that area.

2.1 System Architecture and Information Flow

Our current reference nodes for the United States are spatially distributed over the service area. These nodes are located in Seattle, Eugene, Fremont, and San Diego on the west coast; and Bangor, Virginia Beach, Duluth and Miami for the east coast. Nodes at Salt Lake City, El Paso, Kansas City, and New Orleans cover the center of the United States. These locations were chosen to provide reasonable uniform geographic coverage and because they have ready access to the frame relay communications network.

The reference nodes use a frame relay communications network to send their data to a pair of redundant network hubs located in Fremont, California and Raleigh, North Carolina. The frame relay network is used because it does not suffer excessive latency, and it is low cost and reliable. Physically, it consists of terrestrial links including fiber optic cable, microwave and copper land lines. It alleviates the timing limitations of other terrestrial wide area by using short, sequentially transmitted and recovered packets.

The network hubs process the data to generate separate corrections for the position and clock errors of each satellite and a grid of ionospheric corrections. For each satellite, these estimates comprise three correction components for the location of the satellite and a clock correction for each satellite. The hub processor also generates a grid of corrections for the ionospheric delay. These latter corrections are not satellite specific. An ionospheric correction is generated for each vertex of a 5^o by 5^o grid in longitude and latitude. Taken together, the grid of ionospheric corrections covers the service area.

The @Road/Stanford correction strategy contrasts local area DGPS techniques that are designed to serve rather small areas. Local area DGPS utilizes a single correction station that aggregates the effect of the satellite location errors, the satellite clock error and the ionospheric delay. Such a system sends a *scalar* correction for each local area to service the field receivers that receive the same GPS satellites as that of the correction station, whereas the system described here sends a *vector* correction. A sparsely distributed receiver network covers a large geographical area. The algorithms that generate these corrections were developed at Stanford University and are covered by U.S. Patent No. 5,621,646. The Federal Aviation Administration funded the original development of the algorithms, and so the U.S. government retains certain rights to the invention. In addition, @Road purchased a license for their use that is within the company's field of interest. @Road utilizes its complementary patent No. 5,959,577 to cover the GPS, wireless and internet space for commercial usage.

The vector corrections are sent to localized virtual station servers where they are converted to conventional scalar data for distribution to the local wireless receiver users. These servers do not have to be located within their respective service areas. These scalar corrections for accurate position, plus ephemeris information to facilitate the GPS signal acquisition are transmitted to the mobile wireless devices over customer links.

2.2 Processing Summary

The processing tasks are distributed according to the processor power available and the point in the system where the relevant data becomes available. This processing architecture is summarized in Table 1.

Table 1: Summary of Processing Tasks for Each Network Element

Network Component	Processing Tasks
GPS Reference Receiver	For each satellite in view • Measure code and carrier on two GPS frequencies • Collect navigation message • Collect signal to noise ratio and cycle slip indicators
Reference Node	• Collect measurements from reference receivers • Collect meteorological inputs • Remove tropospheric delays • Separate ionospheric delays using dual frequency measurements • Send data to network hub
Network Hub	• Process inputs from all nodes • Process iono-free pseudorange measurements to estimate clock and ephemeris corrections • Process iono delays to form ionospheric correction grid • Construct vector corrections • Manage communications • Monitor correction integrity • Manage network hub selection • Send vector corrections to virtual correction stations
Virtual Reference Station	• Reconstitute local area corrections • Measure and add local meteorological corrections • Send data to mobile wireless devices to assist the acquisition and to provide accurate location solution
Mobile User	• Perform fast and enhanced GPS signal acquisition using assisted ephemeris information • Reconstruct DGPS corrections in RTCM format • Deliver data to associated GPS receiver

2.3 Performance Advantages

The current @Road/Stanford architecture enjoys a number of virtues that are relevant to the planned enhancements. These are: high reliability, high integrity and low cost. This subsection describes the source of those strengths.

Reliability: The multiplicity of reference nodes makes the system robust, because several node failures would be required to noticeably degrade the quality of the service. The @Road/Stanford network has operated successfully for the last seven years.

Integrity: The network derives integrity from two sources: independent position domain monitoring and reasonability checks for the underlying estimates of satellite clock, ephemeris and the ionosphere.

Applying the corrections to the data received from the reference receivers monitors the end-to-end performance of the system. After all, the reference receivers are at precisely known locations and so this check would detect any faults in the system. Importantly, any service customer could also implement such an end-to-end check by simply surveying the site of a fixed receiver.

The @Road/Stanford system has particularly high integrity because it estimates the underlying system states. These states include the clock and ephemeris errors in the navigation message from each GPS satellite. They also include the underlying state of the ionosphere and the offsets between the clocks located at the reference nodes. This approach enables powerful integrity checks on the underlying states. For example, we have a-priori information that bounds the size and rate of change of the ionospheric delay. If our estimate of any vertical ionospheric delay is larger than 50 meters, then a system fault is likely. If the delay rate is greater than mother nature allows, we also suspect a system fault. Similar checks can be enacted on the other underlying states.

Cost: The use of wide area DGPS networks reduces the cost of the service. Such sparse networks are less expensive than networks that would place a reference receiver at every service site. The virtual reference station and pre-processor are all housed in a single inexpensive package. This computer is industrial quality, but much less expensive than a high quality DGPS reference station, which is no longer required at each local delivery node.

This wide area system makes use of the Internet infrastructure facilities to minimize the number of GPS reference receivers. This element is the most expensive component in the system. Similar savings exist when we modify our system to provide assistance data.

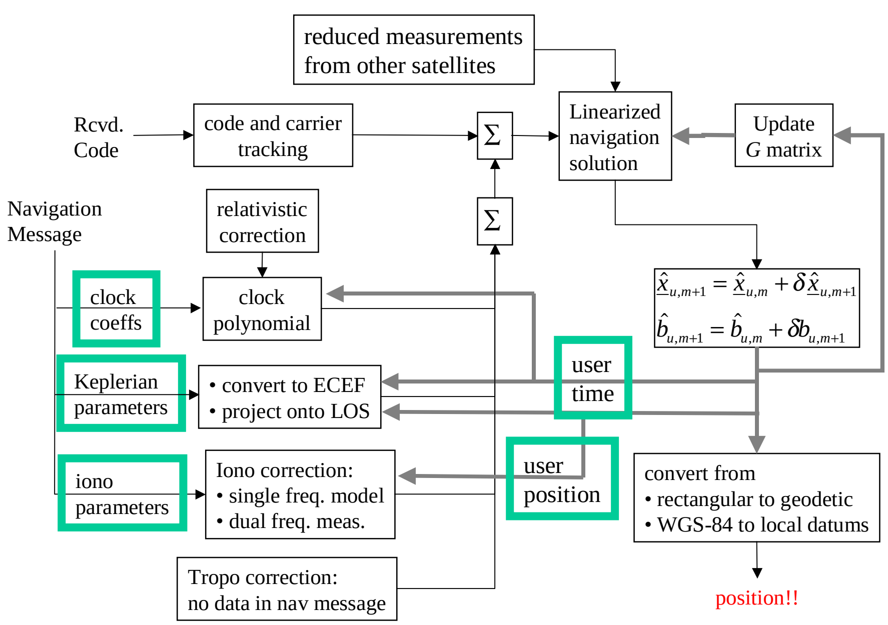
3 Updated Network to Provide Data and Time Assistance Data

As described in the Introduction, the role of our GPS reference network is expanding. Originally, our network was directed entirely at accuracy assistance. With Selective Availability (SA) turned on, differential GPS improved performance from around 70 meters to better than 5 meters. However, SA was turned off on May 2, 2000, and the accuracy of un-aided GPS users improved to around 10 meters without any differential aiding. This dramatic turn of events diminished the importance of accuracy assistance. However, the increased use of GPS in urban environments and even indoors has greatly increased the need for assistance to signal acquisition and receiver sensitivity.

This need is addressed by the TIA/EIA/IS-801 standard prepared by the Telecommunications Industry Association Subcommittee TR45.5 *Spread Spectrum Digital Technology – Mobile and Personal Communications Standards*. IS-801 is entitled *Position Determination Service Standard for Dual-Mode Spread Spectrum Systems*, and builds on TIA/EIA-95-B, *Mobile Station-Base Station Compatibility Standard for Dual-Mode Spread Spectrum Systems* or TIA/EIA/IS-2000-5, *Upper Layer (Layer 3) Signaling Standard for cdma2000 Spread Spectrum System*.

IS-801 defines a set of messages between the mobile station and base station to provide a position determination service. It defines the transport protocols used between the mobile and base. It also defines the procedures used by the base to process messages from the mobile and to send messages to the mobile. Similarly, IS-801 defines the procedures to be used by the mobile. Finally, it defines the message formats to be used in both directions. The standard is written to accommodate a variety of architectures ranging from thin clients to thick clients. Thin clients send pseudorange data to the base for the final position computation. In contrast, thick clients send position estimates to the base.

Figure 2: GPS Receiver With Data & Time Assistance



The IS-801 standard provides for the transmission of the data indicated in Figure 2. As shown, the navigation message can be virtually reconstructed by the receiver if the clock coefficients, Keplerian parameters, and ionospheric parameters are received. The receiver also requires a rough estimate of time to solve for satellite position and clock offset from the received parameters. This information will be made available on our server, and will allow the receiver to reconstruct the GPS navigation message.

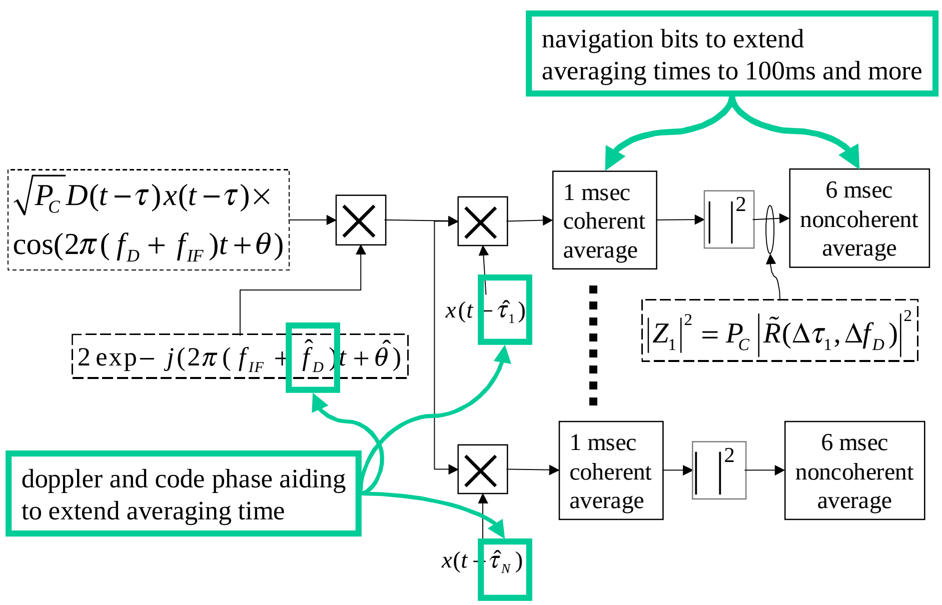
This alternate broadcast is welcome. The navigation message, when delivered by the GPS satellite, is more fragile than code tracking. It must be received without interruptions for 18 to 30 seconds before the elements required for position fixing have been accumulated by the receiver. Such a lengthy observation period may not be available when users suffer from obstructions and momentary satellite outages. Fortunately, code tracking can be performed on much shorter data sets. In addition, the navigation message is more fragile with respect to signal-to-noise ratio (SNR). It becomes prone to word and subframe errors when the signal to noise ratio drops to 27 dB-Hz. In contrast, code tracking can hang on down to 20 dB-Hz – albeit with poor accuracy. With this assistance, the user can use satellites even if they are only intermittently observed.

To further assist signal acquisition, the following information will eventually be made available on the server:

- actual bit sequences from the GPS navigation message
- Doppler shifts for all GPS satellites
- estimate of the code phase

This information is shown in Figure 3, and is used to extend the averaging time used for signal acquisition. Such an extension is particularly helpful when trying to acquire weak signals. Without such information, the averaging time used during signal acquisition is limited by the unknown bits being sent in the navigation message from the GPS satellites and the unknown Doppler shift contained in the measurement.

Figure 3: Signal Acquisition Showing Data & Time Aiding



Knowledge of the navigation bits allows the acquisition averaging time to be extended beyond a few milliseconds. Each bit lasts for 20 milliseconds, because the data rate is 50 bits/second. If these bits are not known, then a coherent average cannot span a bit boundary. Otherwise, the average accumulated before the bit boundary may have a different sign then the average accumulated after the bit boundary. This difference may attenuate the signal component in the overall average. In fact, coherent averaging times are typically a few milliseconds – simply to minimize the probability that they span a bit boundary.

The navigation bits do not need to be provided instantaneously. This information may have latencies greater than a bit duration, because the mobile can predict current bits from past bits. Such prediction is effective, because many of the fields in the GPS navigation message change infrequently or vary predictably.

Knowledge of the satellite Doppler shift also enables the averaging time to be extended. If this frequency offset is not known, then the average accumulated by the acquisition algorithm will change signs and prevent long averaging times. This limitation can be mitigated by using smaller frequency bins in the receiver, but it can also be mitigated by providing information from our reference network.

The Doppler offsets contained in the mobile pseudorange measurements are the sum of three components. These are: the satellite Doppler relative to a fixed user, the frequency offset in the user clock relative to GPS time, and the user dynamics. Of these, the satellite Doppler may be as large as 5 kHz and is usually the largest term. The frequency offset in the user clock depends on the clock quality and whether or not the phone is synchronized to GPS time by other means. CDMA systems are the subject of the IS-801 standard, and these phones are synchronized to GPS through the CDMA system itself. If not synchronized externally, typical Doppler offsets of 1.5 kHz can be due to the user clock. Finally, the Doppler shift due to user dynamics varies with the speed of the mobile platform. Most cell phones move slowly, so the corresponding Doppler shifts may be a few Hertz.

As the Doppler uncertainty is reduced, either the mobile performance improves or complexity decreases. To this end, the @Road GPS server will provide satellite Doppler information to support IS-801 applications. In addition, time/frequency information will be available to assist algorithms that also try to estimate or control the frequency offset of the user clock. This information will be made available in steps of increasing accuracy.

A hierarchy of capability is made possible by increasing the accuracy of the time estimates provided by any assistance network. Table 2 shows this hierarchy. For example, if the network can provide 100 milliseconds of time accuracy, then the navigation data provided by the network can be used. The ephemeris and clock polynomials simply do not need a very accuracy notion time to be useable. At the other extreme, time accuracies of 100 nanoseconds are required if they are to be used along with the GPS pseudorange measurements in the navigation solution. Time accuracies of better than 1 millisecond require the network to account for the propagation time from the base station to the user. The @Road network will provide time in increasing accuracies.

Table 2: Hierarchy of Time Errors and Corresponding Capabilities					
	Time Error	Distance traveled by SV	Fraction of a navigation bit	# of C/A code chips	Ranging precision
Simply need a reference bit	100 ms	*270 m*	5 bits	100,000 chips	20,000 miles
	10 ms	*27 m*	0.5 bits	10,000 chips	2000 miles
	1 ms	*2.7 m*	*0.05 bits*	1000 chips	200 miles
Need to account for propagation time across cell	100 us	*27 cm*	*0.005*	*100 chips*	20 miles
	10 us	*2.7 cm*	*0.0005*	*10 chips*	2 miles
	1 us	*0.27 cm*	*0.00005*	*1 chip*	1000 ft
	100 ns	*0.027 cm*	*0.000005*	*0.1 chip*	*100 ft*

4 Summary

The @Road reference network is capable of providing aiding information that can be used in a variety of mobile applications to enhance the GPS performance. As more and more GPS capable handsets and PDA's become available, the need for a reliable service such as the @Road solution that is based on a robust architecture becomes more and more important. The differential correction data provided by this service would allow a handset to meet and exceed the accuracy required by E911 phase II mandate. In addition, the assistance data provided by @Road could be used to enhance traditional GPS performance in urban canyons and under dense foliage, resulting in improved acquisition time, sensitivity and accuracy.