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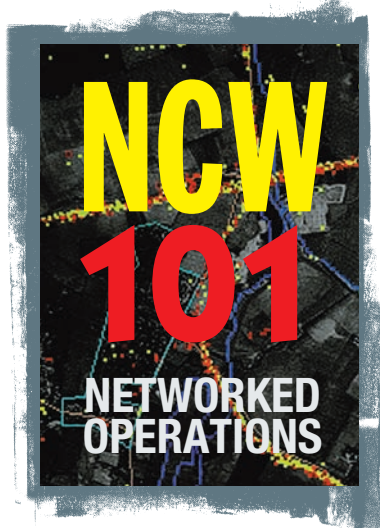
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GPS in networked systems .. part 2

NCW 101 PART 13

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THIS SECOND PART OF NCW 101 – GPS DISCUSSES NCW BENEFITS derived from GPS and also explores differential GPS in its various forms, and its long-term impact.

As noted earlier, the first benefit derived from GPS is that it provides a completely unified coordinate system and thus positional frame of reference for all users. The second benefit is that GPS provides an accurate shared timebase across all user systems. The third benefit is a byproduct of the previous two, in that, location information on friendly systems is consistent in relative terms, with known errors, facilitating deconfliction and friendly fire avoidance. The fourth benefit is the least obvious, which is Location Aided Routing, in ad hoc or self-forming network protocols. Knowing where a friendly platform is located permits a smart networking protocol to make clever choices about where and how it routes network traffic. In practical terms, GPS is now becoming ubiquitous in the battlespace, from handheld equipment through to platform and weapon embedded systems.

Some existing and proposed examples of GPS applications are:

- Handheld or portable optical and laser targeting when equipped with a GPS receiver can generate automatically GPS coordinates of a target, removing the potential for operator error in relaying the data to the fire control system used to attack the target.
- Shoot-and-scoot capability for a wide range of ground mobile systems, be they conventional or rocket artillery, armoured vehicles, air defence weapons or ISR systems.
- Midcourse and terminal flightpath guidance for a wide range of smart munitions, as well as 'casualty mode' flightpath control for electro-optical weapons when target lock is broken.
- Time synchronisation of multiple weapons fusing to increase instantaneous overpressure effects.
- Improved target deconfliction and acquisition in autonomous smart submunitions used for anti-armour attack.
- Navigational reference for a wide range of UAVs including low cost micro-UAVs, which cannot carry bulky inertial references.
- Positioning reference for air delivered acoustic,

seismic, infrared and other unattended sensor devices.

- Tracking aid for ground based high gain antenna systems; a UAV or manned aircraft will broadcast its GPS coordinates to facilitate aiming and tracking of its position.

- Portable satellite terminals, which use GPS to orient and automatically acquire and track satellites, especially in MEO or LEO orbits. This is an 'enabling' technology for 'microsatellites'.

- GPS navigation equipment for steerable parachute systems used in airdrops, allowing the payload to be precisely delivered to the intended recipient.

- Automated aerial refuelling for UAVs.

- Positioning and timing reference to increase the resolution of Synthetic Aperture Radars.

- Positioning and timing reference to increase the accuracy of Displaced Phase Centre moving target indicator radars.

It is difficult to say exactly where the greatest benefit will eventually lie in GPS, given there are so many benefits provided across such a broad range of capabilities.

In smart munitions applications, GPS has largely fulfilled most of its potential at this time. There are few guided munitions today that do not use GPS either as a primary or backup navigational reference.

Deconfliction will clearly be very high on the list, as friendly fire has been a costly and painful headache since the advent of weapons, which by range challenge the limits of human eyesight. The more dynamic the battlespace, the bigger a headache deconfliction becomes, since maintaining track of friendly and hostile movements becomes more difficult, moreso when effort is being put into

not being seen. Location aided routing and GPS aided antenna tracking, be it of airborne or orbital vehicles, is another area where the full impact of GPS is yet to be seen.

In smart munitions applications, GPS has largely fulfilled most of its potential at this time. There are few guided munitions today that do not use GPS either as a primary or backup navigational reference. As the cost of GPS receivers declines, fewer and fewer munitions will exist without GPS capability. Much the same applies for platform embedded navigation systems, and handheld GPS equipment is often used to plug that gap.

The principal limitation of baseline GPS lies in its accuracy, which is best case for good GDOP conditions and good radio propagation, of the order of metres.

Over the past decade, however, much intellectual effort has been invested into the development of a wide range of differential GPS schemes to improve upon this. The best accuracy achieved in differential systems is now of the order of centimetres.

DIFFERENTIAL GPS

The basic idea underpinning all differential GPS (DGPS) schemes is that of producing via separate means a measurement of the GPS error arising at a given point in time and space, and using that error to correct the measurement produced by a GPS receiver. A wide range of differential systems now exist and a wide range of distribution channels can be used to carry the correction messages.

In a GPS based system the navigation error is produced primarily by three mechanisms, which are: uncompensated atmospheric transmission delays in the satellite signals, errors in the satellite's onboard atomic clock and orbital ephemeris data transmissions, and GPS receiver errors caused by noise and multipath radio propagation. These errors appear in the pseudo-range measurement to each of the satellites in view and carry through to the navigation coordinates produced.

Commercial DGPS schemes in use provide a 'band-aid' fix to compensate for atmospheric



The Joint Precision Airdrop System (JPADS) uses GPS and steerable parachutes to provide extremely high accuracy compared to traditional airdrop deliveries.



The US Air Force EDGE High Gear program trialled an extremely accurate Wide Area Differential GPS scheme for weapons guidance. Depicted images from drops of modified GBU-15 glidebombs, using only differential GPS guidance.



delays and satellite orbital and clock errors by measuring pseudo-ranges to satellites from a precisely surveyed location, and using these to calculate a correction which is broadcast to aircraft by a radio beacon.

Devised initially to defeat Selective Availability clock dithering (Part 1), the updates must be as frequent as one per second, to preserve satellite visibility relationships between the ground station and GPS user, the coverage is typically limited to about 300 NMI. A number of commercial DGPS schemes exist, which use dedicated radio datalinks and one that 'piggybacks' the DGPS signal on to commercial FM radio transmissions. The latter was accurate to one metre at 75 NMI. The US LAAS system is typical of this style of DGPS.

A more advanced but similar approach is used in the US civilian WAAS system created by the FAA to support airline operations. Typically, an INMARSAT or other satellite radio channel is used to distribute the DGPS correction message to user receivers. WAAS provides wide area coverage by dividing the surface of the earth into smaller footprints and producing differential corrections for each.

The limitation of all such DGPS systems is the relatively high update rate to the receiver, which in turn occupies bandwidth and also makes the receiver more vulnerable to dropouts in the channel carrying the correction message.

During the 1990s the US Air Force sought to address this problem with two development programs, both intended to increase GPS accuracy for aircraft and munitions.

The starting point for both lay in identifying and quantifying the behaviour of all sources of error in GPS position measurement. Mostly, these errors manifest in the time it takes for the signal to propagate from the satellite to the GPS receiver. In context, a radio signal covers around one foot of distance per nanosecond (10^{-6} seconds) of time. Even a few nanoseconds of unmeasured time error amounts to metres of unwanted location error.

Orbital drift. While the almanac specifies the parameters of the orbit of each satellite, the actual path followed by the satellite is not quite the same due to variations in the earth's gravitational field, and the gravitational attraction of the sun and the moon. Typically, a polynomial correction with multiple terms is used to correct the shape of the orbital path.

Satellite clock drift. Despite the use of precision atomic clocks in the satellites, some drift will occur and must be corrected at the receiver end.

Carrier phase slips. While the oscillators in the GPS satellites are highly stable, they will from time to time slip a cycle, which introduces a timing shift

and position error of the order of 0.25 metres.

Ionospheric delays. Varying ionospheric conditions will impact the time it takes for the GPS signal to propagate through the ionosphere, this depending on local conditions but also the elevation angle of the satellite relative to the receiver.

Dry tropospheric delays. Varying low altitude or tropospheric conditions will impact the time it takes for the GPS signal to propagate through the troposphere. This depends upon local conditions but also the elevation angle of the satellite relative to the receiver.

Wet tropospheric delays. Varying cloud, rain and fog conditions in the troposphere will also impact the time it takes for the GPS signal to propagate through the troposphere. This depends upon local conditions but also the elevation angle of the satellite relative to the receiver.

Radio frequency multipath propagation. A well known plague in mobile telephony, multipath, arises when a receiver sees both a direct signal from a satellite and one or more reflected signals bounced off local terrain features. Where the reflected signal is more powerful, it can seduce the receiver and introduces an error proportional to additional distance the signal has travelled.

Receiver noise. Electrical noise in the GPS receiver will occasionally corrupt the signal, producing a degradation and unwanted slip in the correlator, introducing an error.

Solid earth tide error. This error results from the earth bulging due to gravitational tidal forces, and can be as large as 30 cm in altitude twice daily.

Measuring these errors accurately can present interesting technical challenges, but the plus is



The now operational WAGE system was used for trials of the enhanced AGM-86C Block II cruise missile.

that they are mostly errors that change very slowly. In practice, a differential system using such error corrections need only update itself at 30 to 45 minute intervals.

During the mid 1990s the US Air Force launched the EDGE (Exploitation of DGPS for Guidance Enhancement) High Gear program to demonstrate the military potential of wide area differential GPS techniques for weapon guidance, by achieving accuracies better than three metres. The USAF EDGE Program resulted from a series of Concept Exploration Studies sponsored by the JDAM program office. The purpose of these studies was to determine alternatives for providing the JDAM with a three-metre CEP under adverse weather conditions.

Four studies were contracted, and these focused primarily on precision seekers for the JDAM. Requirements were that the techniques were cheap, autonomous, allow for retargeting in flight, and all weather capable.

One of these studies, conducted by SRI International of Menlo Park, California (formerly Stanford Research Institute), identified the potential of Wide Area DGPS (WADGPS) techniques to fulfill this requirement. The USAF subsequently contracted SRI to conduct a proof of concept experiment. This experiment involved the testing of DGPS over a long (ie 2000 NMI) baseline (ie Florida to California), and this led to the construction of a four-station WADGPS network termed the EDGE Reference Receiver Network (RRN). Following the testing of the network, a number of GBU-15 glidebombs were modified for DGPS/inertial guidance and successfully tested at Eglin AFB in Florida.

The EDGE RRN evolved from the long baseline WADGPS experiment, and included further design enhancements by SRI to enhance its accuracy. The network employed four ground stations, each no less than 1000 NM from the intended test range at Eglin in Florida. The stations were placed at Kirtland AFB in New Mexico, Ellsworth AFB in South Dakota, Hanscom AFB in Massachusetts and Roosevelt Roads NS in Puerto-Rico, at precisely surveyed locations.

Each ground station comprised a high quality military 12-channel GPS receiver and choke ring antenna designed for very low multipath reception, a desktop computer and a modem. Software running on the computer would gather GPS measurements, calculate errors for the site, and via a modem communicate these to a central site. A computer at the central site would then calculate the proper correction values to be broadcast via radio modem for aircraft operating in the test area.

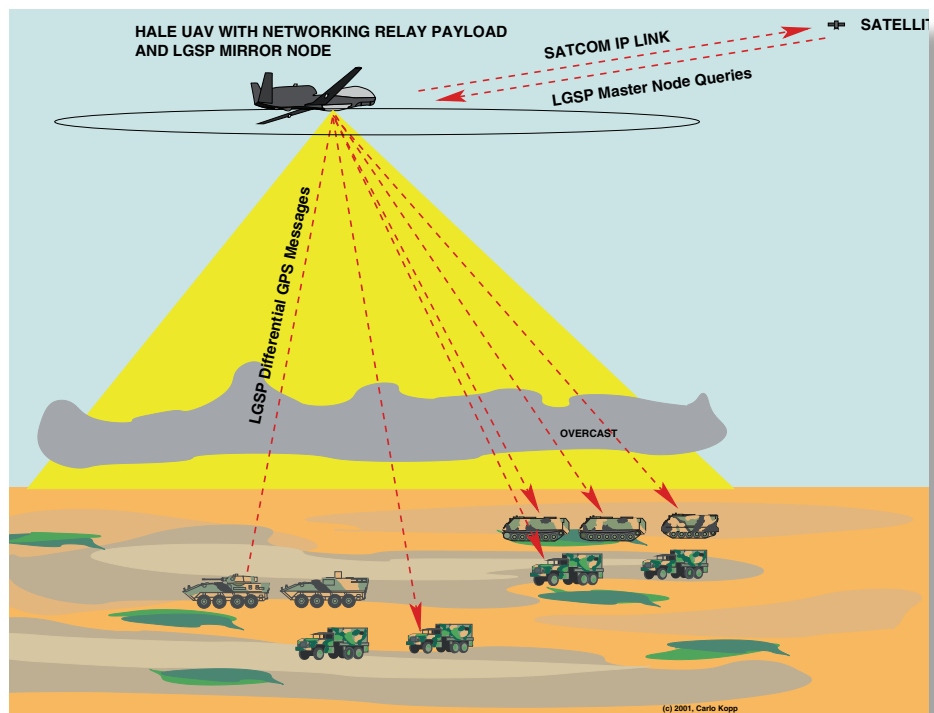
While the hardware requirements for the EDGE RRN were clearly trivial, the SRI developed software that calculated the corrections was certainly not. A number of rather clever techniques were used, requiring no less than 40,000 lines of code to minimise the resulting DGPS error. The result of these corrections was a position error which during the EDGE trials varied between 5cm and 1.57m, with an RMS value of 40cm (15.7 in). On average, the position error was less than 18 inches, in a network with reference stations of the order of 2000 NM apart, with WADGPS updates produced every six seconds and each deemed valid for 30-45 minutes. Accuracy in WADGPS schemes improves with geographical coverage, as more widely spaced reference stations can keep satellites in view longer and therefore determine their orbits more accurately. A continental network would do better than the existing EDGE, and a global network even better.

The EDGE program culminated in several test drops of modified GBU-15 munitions at Eglin. Subsequently, hardware and software developed for these bombs was incorporated into the EGBU-15 block upgrade of the US warstock of GBU-15s. While EDGE demonstrated the potential of differential GPS, the parallel WAGE (Wide Area GPS Enhancement) program demonstrated the insertion of encrypted DGPS corrections into Page 4 of the GPS broadcast almanac message. It was used at the time for trials of the AGM-86C Block II CALCM and a modified AGM-130 powered glidebomb and has since become an operational system. WAGE corrects for orbital drift and clock drift.

DISTRIBUTING DGPS CORRECTIONS

The problem of transmitting differential GPS corrections to a suitably equipped receiver is not entirely trivial. A number of schemes have been used over the years, and more recently, alternatives have developed.

The WAGE system is arguably the cleanest technically, as the correction messages are embedded in the navigation message itself. The drawback is that this is sent at 50 bits/sec and the update rate is very slow – a problem in applications where a receiver must start up and initialise very quickly. Examples are smart munitions or receivers



The Lightweight GNSS Support Protocol distributes differential GPS corrections via existing network channels.

emerging from the footprint of a jammer and needing to rapidly update themselves.

The mostly commonly used method is however that of dedicating a separate radio channel to carry the differential correction messages. Whether this channel is from a ground station or a satellite is only an implementation issue. The EDGE, LAAS and WAAS systems, many proprietary systems, and Australian VHF beacon trials all used this method. While it works well its principal drawback is cost – fiscal, volumetric, weight, cooling and power – especially in military applications where channel jamming is a major issue.

An alternative approach is to use a general purpose datalink or network to carry the corrections. While numerous schemes have emerged in recent years, the most sophisticated and fastest is the Lightweight GNSS Support Protocol, devised at Monash University, to carry GPS messages and differential corrections over Internet Protocol

capable datalinks and networks.

LGSP is currently being submitted as an IETF draft standard in the US.

The advantages of using in situ networking or datalink channels in military applications are manifold, as such channels are jam resistant, usually much faster than dedicated radio links, and are usually already installed across a wide range of platforms.

In conclusion, GPS has become an indispensable part of the networked battlespace, and a key enabler in synchronisation, deconfliction and achieving high precision.

Further Reading:

<http://www.ausairpower.net/TE-GPS-Guided-Weps.html>

<https://gps.losangeles.af.mil/>

<http://www.colorado.edu/geography/gcraft/notes/gps/gps.html>

