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ROBUST NAVIGATION ISSUES IN THE EVENT OF GNSS FAILURES*

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Civil society currently has ubiquitous availability of both timing and navigation data from various Global Navigation Satellite Systems (GNSS). This availability is not assured in future times and places due to both extremes in natural environments and adverse human efforts to create extreme unnatural environments. The potential span of variability of the natural environment can include repetition of the 1859 super flare with attendant effects on the ionosphere and sustained degradation of the satellite assets due to enhanced radiation environments. Application of unnatural environments can include drastic and destructive effects such as High Altitude Nuclear Detonations (HAND) and the more mundane GPS jamming as done by North Korea. Given that future GNSS availability cannot be assured, suitable and robust navigation backup means beyond GNSS are necessary for aviation and other users. One aspect of assured navigation in the absence of other sources requires quality ephemeris information to the celestial reference that has no particular *a priori* information as to when GNSS will be lost.

INTRODUCTION

Society today is awash with time and navigation support at astounding levels. Do users ponder the inordinate infrastructure behind our '911-enabled' cellphones; are we aware of the technical aspects behind 'smart phones' with mapping apps guiding our walks, the GPS route tools in our cars and the normal means that clocks use to re-synch time without our input? If we stop to think, this ubiquitous support extends to the safety critical functions such as the navigation support and air-traffic control needed by civil aviation.

The 'Global' term of Global Navigation Satellite Systems discusses the intent and actuality of coverage spanning most of the earth. The 'Navigation' term talks to the technical characteristics being sufficient to address navigation with respect to some level of world model such as the World Geodetic Survey (WGS). Where all of the system elements converge is the application of the controlled reference broadcasts from the platforms—artificial satellites. Navigation and timing are available at receivers that receive multiple satellite reference broadcasts, apply the satellite ephemeris and solve for both apparent range to the satellite positions and GNSS time with compensation estimates for the effects of propagation. The end results, with software filtering of the reception by commercially available chip-sets that permeate mobile devices, have errors from WGS 'truth' of order 10's of meters position. This performance implies compensated time delay

* This material does not present an official view or position of the US Government.
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estimates in the neighborhood of 50-100 nanoseconds. We have come out of a period of astounding successes in space efforts such that several GNSS systems are on orbit (some not fully populated) with additional systems / augmentation efforts planned.

GNSS is so successful that it has largely driven out competing radio navigation means as shown by the fact of the US, Canada and Russia stopping LORAN broadcast in 2010.[*] GNSS is so prevalent that proficiency in celestial navigation is no longer required for US naval officers.[1] Similarities between the various GNSS systems dependency on propagation conditions have created a condition where the majority of navigation and timing applications have a singular weakness: the systems require benign environments at the satellite, in the ionosphere and at the receiver to reliably function. Since GNSS systems require benign environments to provide those ubiquitous functions that we have grown to expect, can we expect reliable, uninterrupted function into the future? If not, what scope of environmentally induced failures might be experienced, with what effects and what duration? When we establish the scope of potential GNSS failures, we can sensibly talk to the strategy of appropriate backup techniques for risk mitigation against GNSS failures.

ANOMALOUS SATELLITE ENVIRONMENTS

GNSS orbits were chosen to provide reasonable coverage for moderate numbers of vehicles; the various primary systems, GPS, GLONASS and Galileo, are intended to cover the earth via roughly ½ geosynchronous orbit operations with ~50° inclination. GPS applies a 12 hour orbit at ~22600 km radius with 24 active satellites as threshold capabilities (currently 32). The GNSS orbit set spans a relatively 'quiet' zone at high inclinations and sweeps through the outer Van Allen radiation belt as it crosses the magnetic equator. The various GNSS systems anticipate the radiation environment in terms of Betas, protons (emphasized in the trapped region of the belt) and other ionizing sources when the expected life is determined. The radiation environment chosen may be a conservative extrapolation of benign solar conditions, such that a design expectation would be some number of years at a specific flux level and quoted for some fraction of that expectation based on a number of radiation enhancements due to less benign solar events.

Satellite environments under anomalous conditions are expected to include modification of both the density and energy of the trapped particles. Further expansion of the belts (to include transient trapped structures) can be expected for both Coronal Mass Ejections (CME) associated with large X-class flares and local injection of charged particles from High Altitude Nuclear Detonations (HAND). Note for the long term radiation environment that impacts satellite useful lifespan, no difference exists as to the mechanism of damage; damage is due the flux and energy of trapped particles that the vehicle must traverse. The transient environment that a satellite must survive if within line of sight of a nuclear explosion includes X-ray, Gamma energy photons as well as Neutron fluences, and the effects of those ionizing radiation types on active circuits and cables. As GPS had its origin as a purely military system, we expect the prompt nuclear survival topic was addressed competently and will not further discuss it here.

Persistent radiation degradation has several effects; the HAND events in 1962 caused multiple satellite failures within months from loss of power where the enhanced radiation environment accelerated defect damage in the solar arrays. Various satellites losses have been attributed to Flare/CME events shortening their lifetimes. Further issues will occur with penetrating radiation causing defect damage in active circuitry, changing gains, increasing noise figures and causing

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[*] Special Notice Regarding LORAN Closure: http://www.navcen.uscg.gov/?pageName=loranMain

the systems to lose their highly tuned characteristics necessary for providing the GPS compliant signals. Severe environmental conditions can cause prompt losses in satellite assets, but the inevitable result of increased radiation environments will be the shortened lifetimes of existing satellites on orbit (necessitating replacement via new launches).

ANOMALOUS IONOSPHERIC PROPAGATION ENVIRONMENTS

Civil users of GNSS services operate receiver systems either in the air (airborne applications), on the ground (mobile or survey) or afloat. Each of these applications have to address the effects of the path that satellite signals take to the receiver; e.g. the path through the normally weakly ionized, spatially and temporally non-uniform media that is the ionosphere. The propagation issue is sufficiently important for airborne GNSS results that 4 satellites are applied to have the four constraints for the four unknowns. Total Electron Count (TEC) based total time delay is unknown *a priori*. The four-satellite approach solves for an average delay applied to the three range estimates. Maritime and mobile land based GNSS solutions apply the vertical constraints of the vehicles to permit fewer satellites in a strong solution as the systems escape the basic need to have fully determined estimates. Given lengthy tracking solutions and relatively slow vehicles constrained on the vertical dimension, tracking filters can apply the satellite motion over the time of the 'fix' to allow two satellites to act like four satellites with relatively poor geometry due to the height of the receiver being usefully fixed.

The assumed behaviors of GNSS signal propagation 'go out the window' when the underlying assumptions of 'weakly ionized' and semi-uniform TEC are violated. In particular, if paths from the satellites to the receiver have distinctly different delays due to localized TEC effects, solution accuracy will be significantly degraded or precluded. Some aspect of this localized TEC patch can be noted by the 'Morningside ionosphere effect' where satellite paths from the dark into the sunlit atmosphere have lower delays than satellites more nearly overhead or ones that are through a more zenith sun angle. Strongly localized enhanced TEC areas are difficult to distinguish except when they interact with the atmosphere as aurora. Large CME events (and HAND events) cause aurora at rather low latitudes; the 1859 "Carrington event" super flare caused reported aurora as far as south 20 degrees magnetic (Hawaii, Cuba), and the 1962 Starfish HAND produced bright aurora both north of the detonation point and at the magnetic conjugant point.

Aurora and localized ionized particle traps (L-shell reflections) are part of severe natural events as they interact with the earth's magnetic field and present problematic conditions for GNSS systems. HAND events add localized debris / 'Beta patches' and large striated plasma concentrations to the trapped particles, creating rather adverse conditions for signals to get from the satellite to the receiver at all and the specifics of delay estimation / compensation may simply be insoluble for civil GNSS systems.

ANOMALOUS RECIEVER ENVIRONMENTS

Civil users do not expect an opponent actively attempting to interfere with uses of utilities necessary for safe and agreed civil applications such as time and navigation. Despite this reasonable expectation, both unintended sources (such as the LightSquared GPS interference case) and deliberately malicious GNSS jamming efforts have been noted.[2] According to a paper by Seo and Kim reported by InsideGNSS, over 250 ships and over 1000 aircraft within line of sight of North Korea noted GPS disruptions during a 16 day period of jamming in 2012.[3]

Civil GNSS sets also have attributes of design such that they are low cost but not hardened, such that they cannot be expected to operate in either severe natural environment due to nearby lightning strikes or from artificial events such as Electromagnetic Pulse (EMP) from a HAND event. GNSS receivers are not sufficiently reliable systems to operate without backups.

MITIGATION STRATEGY

The loss of GNSS utilities have certain constraining aspects where some losses are annoying and other losses are threatening as they impact safety critical tasks. While many might consider impacts on personal telephone use as 'critical', we restrict ourselves to brief mention of the impacts of the GNSS time utility to the synchronization of communications and networks. Modern systems that depend on a GNSS common network time do include timeslot shared digital telephony, so loss of GNSS time may disrupt cell communications.

Where this paper offers a specific mitigation means, it is in the area of backup navigation means in clear skies for something better than 'Dead Reckoning', e.g. forward propagation and integration of estimated accelerations and courses to place aircraft or ships at appropriate points in the event of loss of GNSS services. Given the starting issue of the vulnerability of civil GNSS to interruption by extreme natural or unnatural events, compounded by the systematic elimination of the primary backup (LORAN) and the cessation of competence in the secondary backup means of celestial navigation, robust backup navigation means must be made available that do not depend on external sources no longer provided or tools with expertise that is no longer taught.

The recommended future mitigation strategy against GNSS loss is a return to practical means of celestial navigation, integrated as an augmentation source to the current generation of gyros and accelerometers with GPS augmentation that form the core of Inertial Navigation Systems. The inexact nature of historic celestial navigation is assessed to have been due to limits of the tools and the limitations of human observations. Modern automated telescope systems, when combined with modern portable time standards and computational engines, are fully capable of managing the measurements and calculations necessary for robust navigation at useful error levels.

To retain safe operations, a backup to GNSS should be no worse than the roughly 100 m class location errors that are expected from LORAN. The specifics of the problem (location of a point near the earth in the inertial coordinate frame in a manner useful to navigation) can be examined to discern minimum system characteristics e.g. requirements. The rotation rate of the earth fixed frame against the distant stars corresponds to the sidereal day, or ~86,164.09 SI seconds. At the equator this angle rate of $\sim 7.292\times10^{-5}$ rad/s corresponds to a rate of ~ 465 m/s, so to first order we must attain 0.1 second or better quality angle measurements to support an overall error budget under 100 m. This places our objective angle measures at < 7.3 μrad, our measurement integration budget at 0.1 s and determination of the local vertical (gravity vector) in the same error size of approximately 5-7 μrad. In a similar manner, the specific star RA/DEC estimation must not violate the capability of the telescope resolving power and the refraction effects should be minimized by high elevation sightings coupled with appropriate compensation from wavelength and measured atmospheric data. For daylight sighting needs, the system should have appropriate filters and estimation strategies to use the edge of the Sun as a celestial reference. Suitable slow telescope optics and good baffling permit daytime sightings of bright navigation stars when well away from the sun-center vector.

The sizing of the telescope is determined by the ordinary diffraction spot size (2.44 λ/d) and an expectation of centroid estimation of roughly $1/10^{th}$ of a symmetric spot via 3× oversampling by the camera pixels while using, say, 0.6 μm visible light. The calculation indicates that 4-5 μrad uncertainty reporting should be achieved at any telescope aperture over ~2.5 cm when combined with an appropriate detector array. Angle reporting for the telescope boresight relative to the local reference is a function of the resolvers and gimbal repeatability; a system with 24 bits provides estimation at ~0.37 μrad (robust accuracy).

The determination of local vertical (e.g. the zenith reference) will need to be supported by some form of inclinometer/tilt-meter appropriate to the host platform dynamics (high bandwidth for aircraft, lower bandwidth on shipping). These are commercially available in the form of 'digital artificial horizons' for aircraft and 'roll compensation gimbals' for ships. 5 μrad (~1 arcsecond) measurement quality is not trivial but available via integration and smoothing of system output from commercial products.

The time reference necessary to support such automated celestial navigation is a stable local reference that traces back to UT1 via widely known, accessible and internationally accepted means (such as UTC with current leap-second corrections). While GNSS time distribution can support the coordination of the local reference, the local system must be stable and capable of maintaining time in the event of GNSS loss. Commercial systems with extended battery backup based on Rubidium secondary systems or chip scale atomic clocks are in application today.

The computational engine behind such capabilities needs to interface to the various sensors making the celestial sightings and carry a suitable ephemeris of navigation stars with hosting update functions with periodic reception of IERS Bulletin A for UT1 calculation. As of the time of this paper, any contemporary personal computer carries vastly more computation capability than is needed for any of the specific tasks and the mundane issues of providing slots for cards to carry some of the functions together with robust casing / cabling drives the selection process.

A summary of the technical requirements to provide an automated collection of 'the solution of intercepts' sightings can be satisfied by a standard 'hobbyist' computerized telescope smaller than 10 cm aperture feeding a filtered silicon CCD detector system with centroid estimation software. Notably such systems normally operate on stable land platforms. One vendor of such systems advertises pointing knowledge consonant with the known ephemeris position after automated alignment processes with better than 0.7 μrad mechanical tolerances and with encoder and calculation accuracy better than 0.4 μrad. Integrating such computerized automated telescopes into aircraft or ships will not be a trivial undertaking (with the need for artificial horizons / gravity vector reporting). Local time standards with known error magnitudes to UT1 can be obtained and maintained close to true UT1 without GNSS support for extended outages. Computer capabilities necessary to support automated celestial navigation are commonly available. Early perusal of the GNSS backup problem indicates that all the elements of this solution for clear skies, or above the clouds operations are well in hand and do not involve exotic or expensive items.

The approach defined was verified during the alignment and calibration development of the flying Infrared data collection platform (the HALO II)[*] where the historic use of pressure altitude instead of geodetic altitude was noted when the celestial sightings failed to properly converge using the pressure height from the cockpit air data computer.

CONCLUSION

This paper examines the current situation where GNSS is a ubiquitous timing and navigation reference without robust backup capabilities in the event of failure. The paper next considers the natural and unnatural environments where GNSS can be expected to fail for civil users. The paper declares that given the critical safety functions provided by GNSS, a robust backup to aviation /

[*] Gulfstream II-B / Tail No. N178B; URL: http://www.airliners.net/photo/Grumman-American-G-1159B/0853662/L/

marine users should be available for use without *a priori* information on when GNSS might fail. The paper proposes an automated celestial navigation capability, performs preliminary scoping to determine what requirements might be for such a system and then identifies commercial sources for those specific functions that could meet requirements.

The current situation is stunning; we have critical dependence on GNSS without meaningful backups in the event of loss and we are discussing elimination of the necessary standards behind any solutions to that problem.

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