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White Paper

Overcoming Issues in Precise Navigational Methods

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Contents

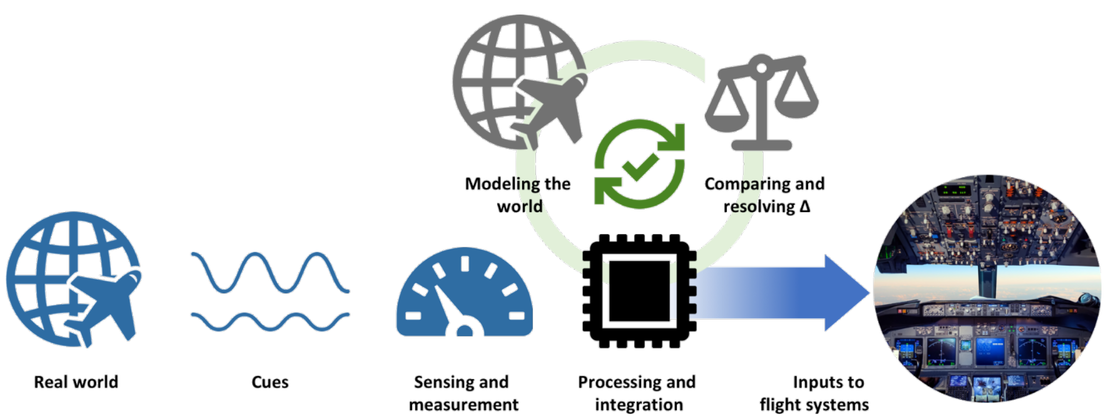
Abstract

Measurement of position to within a few centimeters is readily available today, allowing unprecedented precision in navigation. This has been made possible through numerous improvements in methods and technology. The tools we employ and the way we use them have inherent errors and vulnerabilities, which jeopardize surety. The variety of methods can be understood in a framework which suggests a multi-element approach to safeguard precision.

Introduction: A simple model of navigation

Consider an aircraft flying from origin to destination. To maintain course, it has a generic navigation system. The orientation and correction methodology is depicted in Figure 1.[1] At appropriate times, the Real World provides cues, which are sensed and measured. These feed into a processing and integration loop in which the predictions from a world model are compared with the direct results from the Real World. Once resolution is complete, inputs to the flight systems (e.g., automated flight controls or displays for human pilots) and revisions to the world model are made. The next set of cues and measurements reinitiates the cycle.*

Figure 1: The navigation process for an aircraft



This simple framework applies to any navigation method. For example, an ancient Phoenician pilot directing a ship from port to port would rely on visual cues from landmarks and then compare those with prior experience and memory. Discrepancies would be resolved and, if necessary, new headings and directions provided to the helmsman. A more modern instance would be a commercial aircraft, say a Boeing 787. One of the first steps in the cold and dark checklist after ensuring power is being supplied to the aircraft is to

* Insight from author John Steinbeck is applicable here. He describes how we gain knowledge in *The Log from the Sea of Cortez* (1951): "So we draw worlds and fit them like tracings against the world about us, and crumple them when they do not fit and draw new ones."

turn on both Inertial Reference System (IRS)[†] switches. The IRS does not require manual input of its location, rather GPS provides this information. During flight, positioning satellites provide cues and GPS is the primary navigation system, with IRS backup, for the Flight Management System (FMS).[2] The FMS contains the programmed route and is linked to automated flight control systems for adjustments.

The broadest class of cues involves the reception of some signal, typically electro-magnetic (including visible light) or sound waves, which provide orientation to a fixed source or one that is in motion with a predictable track. This requires knowledge of time to ascertain source position. These sources generating the cues are external. The cues fall into two categories:

- **Natural:** Including visual landmarks, magnetic field lines, celestial objects, and gravity.
- **Artificial:** Including signals from GPS satellites and pseudolites (ground-based GPS alternative), signals from navigation beacons (dedicated systems), as well as signals of opportunity (telephone, television, radio—in short, anything not dedicated to navigation).[3]

One approach to navigation utilizes a computer and two sets of three unaligned (typically orthogonal) instruments. Gyroscopes (for rotation) and accelerometers (for translational motion) provide position, velocity, and orientation. An inertial navigation system (INS) utilizes dead reckoning, extrapolating a future position from its current position, time, and velocity.[4] This too, surprisingly, depends on external cues. The gyroscopes are affected by the external gravitational field and the initial position has to come from an external source.

An INS is a self-contained system. Other self-contained systems generate signals internally (e.g., sonar, radar, LIDAR). Although the origin of these signals is internal, these methods require the capture of a reflection from an external source, which is then input from a programmer or another system, such as GPS.

Exploiting cues for navigation

There are a plethora of navigation methods and systems. The diversity of approaches, cues collected, type of primary sensor, and the advantages and disadvantages of each is shown in Table 1.

Some methods are not available unless conditions are right. For example, piloting and celestial navigation require visibility of the intended targets. Interference from competing sources can confound the use of magnetic compasses or radio beacons.

Navigational techniques

All of the approaches in Table 1 are susceptible to inherent and extrinsic errors. For example, terrain matching is prone to errors ranging from camera resolution, altered terrain features, map errors, and optical

[†] For our purposes, an IRS is similar to an INS. The former is a term common to commercial airlines. IRSs, typically, are solid state and rely on optical gyroscopes.

aberrations.[5] Besides drift, inertial navigations systems (INS) suffer from thermal-mechanical noise, calibration errors, and periodic effects such as Schuler oscillations.[6]

Piloting[7]	**Description:** Use of landmarks for orientation and geolocation. Requires experience and familiarity or a map. **Cue:** Light reflected from natural features **Sensor:** Optical system (e.g., eyes) **Pros:** Very few tools needed **Cons:** References must be visible
Terrain matching[8]	**Description:** Positioning by correlating track altitude against predictions from a terrain map. Requires terrain database and ability to measure height above surface. Used in cruise missiles and underwater UAVs. **Cue:** Altitude readings from radar or sonar **Sensor:** Radar or sonar antennae **Pros:** Can maintain a safe altitude above the surface. **Cons:** Requires high degree of processing, depending on "square area" of terrain being correlated.
Celestial navigation[9]	**Description:** The use of bodies in the sky (sun, moon, stars) to fix position. Requires maps, clock, tables, instruments (e.g., compass, astrolabe, sextant). **Cue:** Light from celestial object **Sensor:** Optical system (e.g., eyes) **Pros:** Ephemerides (tracks) of celestial objects well documented and understood. **Cons:** Must be able to see targets. Computationally complex.
Magnetic compass navigation[10]	**Description:** Using the angle offset from a magnetic compass to hold course. **Cue:** Compass reading **Sensor:** Magnetic compass **Pros:** Magnetic field lines and variations well plotted and mapped **Cons:** Strong magnetic fields from current carriers can compete with the natural field. Other errors include deviation, dip error, and offsets when accelerating or rotating.
Beaconing and radio navigation[11]	**Description:** Obtaining relative bearing or position from fixed transmitters designed to emit pulsed or continuous signals (e.g., lighthouses, radio transmitters, radar, navigational aids, Loran-C, Omega). Radio nav requires special equipment. **Cue:** E-M signals **Sensor:** Antennae **Pros:** Ephemerides (tracks) of celestial objects well documented and understood. **Cons:** Does not provide 3-D positioning. Some omnidirectional beaconing (e.g., NDB and VOR) only provide bearing, not distance. Solving for position can be complicated. Ground-based beacons can be blocked by other objects.

Signals of opportunity[12]	**Description:** Obtaining relative bearing or position from sources not intended specifically for navigation (e.g., commercial radio and television signals, Wi-Fi, cell towers). **Cue:** E-M signals **Sensor:** Antennae **Pros:** Readily available at no cost, ample number of sources, particularly near population centers, proximity yields high signal strength **Cons:** Signals are not designed with navigation in mind. May require special equipment or receivers. No control over broadcast
Inertial Navigation System[13]	**Description:** Employs self-contained gyroscopes and accelerometers. Integrating acceleration yields velocity; a second integration generates position. Uses dead reckoning to track position. Three main varieties: Mechanical, optical (ring lasers or fiber optics), and MEMs. Dead reckoning requires knowledge of initial position. **Cue:** Forces acting on internal sensors **Sensor:** Gyroscopes and accelerometers **Pros:** Cannot be jammed, well-understood performance, most errors can be corrected with updates, very inexpensive for applications requiring low performance (good for short term). **Cons:** Integration and double integration generates increasing drift in velocity (linear) and position (quadratic). High performance systems (navigation grade) are expensive.

Figure 2: Grade, cost, and performance parameters for IMUs [14, 15, 16, 17]

GRADE	COST	GYROSCOPE BIAS STABILITY	ACCELERATOR BIAS STABILITY
Navigation/Strategic	$1,000,000	0.001°/hr	< 0.01 mg
	$100,000	0.01°/hr	0.1 mg
Tactical	$10,000	0.1°/hr	0.1 mg
Industrial/Commercial	$1,000	1.0°/hr	1.0 mg
	< $100s	> 100°/hr	> 10.0 mg

Inertial navigational systems constitute an important class. The earliest systems were developed in the 1950s using simple accelerometers and mechanical gyroscopes in a sensor package called an Inertial Measurement Unit (IMU). Improvements range from increased precision and accuracy (largely due to fine resolution of optical signals in ring lasers or fiber optics) to decreased cost (using micro electromechanical systems, MEMs). IMUs are available in several grades, differentiated by the degree of precision required to perform the primary function of the unit. The number and terminology for the grades vary from source to source, but generally fall into three categories:

- **Navigation (also Strategic or Maritime):** Provides attitude, heading, and platform stabilization over long periods of time without the need of additional sensors.

- **Tactical:** Suitable for short-term navigation and stabilization, often integrated with GPS and other navigation systems to improve performance.
- **Commercial (also Automotive or Industrial):** Lower grade units, often mass-produced, which provide basic orientation and stabilization.

Key figures of merit for IMUs are the in-run bias stability for the internal gyroscopes and accelerometers, measured in degrees/hr and g. As shown in Figure 2 (above), the higher the grade of IMU, the greater the precision and, usually, cost.

Errors and uncertainty in GPS navigation

It is instructive to conduct a deeper dive into a ubiquitous navigation approach: GPS. This system consists of a constellation of 24 or more satellites in Mid-Earth Orbit (MEO) at altitudes of approximately 12,500 miles.[18] Each satellite broadcasts a message (50 bits/second) containing a variety of navigation information (satellite position, time, status, ionospheric modeling, and satellite clock corrections). This message must travel through space, the atmosphere, and may be reflected from the ground as well as natural or man-made surfaces before reaching the GPS system receiver.

Complicating this picture is the need for simultaneous signals from a minimum of 4 satellites to obtain full 3-D position information and time. Each of these signals is subject to a variety of effects and issues listed in Table 2 (below). Satellites and receivers can fail or suffer from noise and timing instabilities; the satellite might deviate from predicted orbital path; relativistic effects need to be considered; space or terrestrial weather-caused variations in the atmosphere are unpredictable and can alter signal propagation; line of sight can be blocked or limited by obstacles; and intentional and unintentional denial or degradation of signal can occur.

Table 2: GPS errors, causes, effects, and remedies

ERRORS AND ISSUES	DESCRIPTION	EFFECT MAGNITUDE	REMEDIATION
Satellite issues			
Satellite clock stability	GPS atomic clocks stable to within 2 ns/day	1.35 m[19]	Correction from Navigation Broadcast Signal
Satellite clock bias	Difference between on-board clock time and GPS time. Includes clock and rate drift.	10 m[20]	Correction from Navigation Broadcast Signal
Hard failure	**Two types:** Long-term (LT)-irreparable signal loss Short-term (ST)-temporary loss of signal	LT: 15 years mean time between failure (MTBF) ST: 0.5 years MTBF[21]	LT: replace satellite; ST: switch to redundant sub-system

ERRORS AND ISSUES	DESCRIPTION	EFFECT MAGNITUDE	REMEDIATION
Orbital Mechanics and Relativity			
Eccentricity	Deviation from pure circular orbit (affects velocity and position of satellite).	45 ns max for eccentricity of 0.02 = 1.35 m[22]	Can be predicted and compensated for
Sagnac effect	Variance in signal propagation time due to rotation of Earth.	30 m[23]	Can be predicted and compensated for
Ephemerides	Deviation from calculated orbital trajectory.	2 m[24]	Correction from Navigation Broadcast Signal
Relativistic effects	**Two types:** **Special relativity (SR):** because of its motion, satellite clock seems to run slower than receiver clock. **General relativity (GR):** gravity is weaker for satellite and its clock runs faster.	Combined effect: 38 μs/day = 11.4 m[25]	Can be predicted and compensated for
Signal propagation			
Ionospheric effects	Occurs during transit of ionosphere (50-1000 km altitude). Interaction with ionized gases results in refraction, dispersion, and attenuation.	Delay can be as high as 300 ns (100 m) for long slant paths.	Partial compensated for from ionospheric information in Navigation Broadcast Signal
Tropospheric effects	Occurs during transit of troposphere (surface - 20 km altitude). Interaction with non-ionized gases results in refraction and attenuation. Two components: wet (accounts for 10% of total effect, difficult to model) and dry (accounts for remainder, straightforward to model).	2.5 – 25 m[26]	Can be partially predicted and compensated for
Multipath	Increased path length and interference, caused by signals reflected from surfaces prior to reception.	Up to 100 m[27]	Clutter free receiver environment, choke ring antenna
Positional Dilution of Precision	Baseline vectors from 3 or more satellites fix the position of the receiver. Uncertainties in the length of these vectors generates an error "volume" around the true position.	Dependent upon vector uncertainty and desired confidence level [28]	Can be calculated
Receiver issues			
Receiver clock error	The accuracy of receiver clocks (often quartz-based) is very low compared to atomic clocks in GPS satellites.	Highly dependent on quality of clock	Clock steering, error estimation, differencing[29]
Receiver noise	Noise due to various factors: temperature, shock, vibration, interference from receiver components (e.g., antenna).	3 cm[30]	Adaptive filters

ERRORS AND ISSUES	DESCRIPTION	EFFECT MAGNITUDE	REMEDIATION
Intentional issues (human-caused)			
Selective availability	Deliberate signal degradation to decrease precision for non-military use.	100 m	Discontinued in 2000.
GPS scheduled maintenance	Routine servicing or upgrades of satellite or ground systems.	0.5 years MTBF[31]	
Jamming	Intentional overwhelming of and drop GPS signal strength.[32]	Can be continuous or intermittent while in range of transmitter	Switch to other navigation system during jamming exposure.
Spoofing	Transmission of false or inaccurate GPS signals to deceive or divert.[33]	Can be continuous or intermittent while in range of transmitter	Authentication of signal allows operator not to act on spurious signal.
Unintentional issues			
Space weather	Sun-produced radio bursts degrade signal to noise ratio of GPS broadcasts. Geomagnetic storms can distort upper atmospheric layers and double the total electron content of ionosphere, impacting signal transmission.[34]	Variable	Modeling and monitoring of space weather.
Spectrum interference	Transmission in spectrum bands adjacent to GPS can interfere with or degrade GPS signals.	Variable	Regulation of spectrum and power limit criteria.[35]

Historical example: Trends in precise targeting

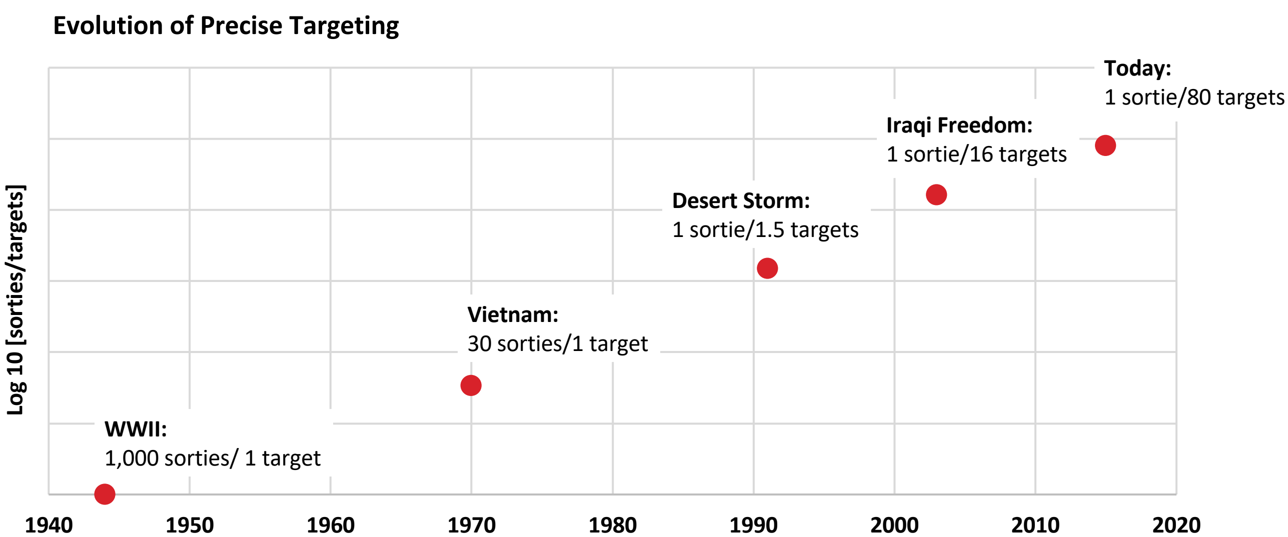
Advances in PNT have revolutionized the military. The impact been particularly significant in the ability to defeat targets from the air. A key metric is the number of sorties required to defeat a target. Over the course of 70 years, the improvement has been staggering, an increase of five orders of magnitude.[36]

Targeting from the air has two elements, the delivery platform and the munition. In the Second World War, emphasis was on upgrading aircraft navigation and target sighting techniques. The bombs themselves were initially unguided and, once released, followed paths sculpted by gravity and winds. The American B-17 and B-24 bombers were able to achieve a little over 30% of their payloads within 1,000 feet of the target. At the beginning of the conflict taking out a single objective required hundreds of sorties.[37] By the war's end, new developments, such as gliding bombs, allowed greater stand-off distance. The munitions would travel on roughly a 1:5 glidepath and land within 1/2 mile of target. Weapons with maneuverable, radio-controlled fins were also created.[38]

The next few decades saw increased use of radio signals to improve navigation (e.g., Loran and Omega) as well as initial trials with inertial navigation. A great leap forward in targeting came with the application of lasers, reducing the 90% CEP (Circular Error Probable) in the Vietnamese Conflict by almost a factor of 10 from WWII statistics.[39]

Inertial systems were widely available for aircraft in the 1990s, which improved airstrikes further during **Operation Desert Storm**. In that decade, Global Positioning System (GPS) technology matured not only for aircraft but also for smart, guided munitions. One result was the Joint Direct Attack Munition (JDAM), widely used in the subsequent Gulf War. **Iraqi Freedom** saw another decadal advance in precision. Currently, GPS is integrated with IMUs in a variety of precision guided munitions.[40]

Figure 3: Exponential reduction in sorties/target due to PNT advances



As impressive as "tightening the CEP" over several decades has been, problems with precise navigation loom. We can become victims of our own success. Over-reliance on technology, such as GPS, can manifest itself in significant ways. One challenge is that operators who depend on technology to navigate or control can become "out of the loop." This impedes recognition of problems and slows diagnosis and mitigation. In short, passive processing of information can have disastrous effects.[41] A 2008 study at Cornell University examined how drivers disengage from their environments when using GPS navigation, including hindering the construction of cognitive maps.[42] A second pitfall is overconfidence in the degree and availability of precision. This is particularly important when relying on a single approach for positioning and navigation. Consider a potential "box canyon" in the design of the precision guided munitions described above: Assumption of the anticipated CEP drives the size and design of weapons for a desired target kill; this defines the required size and nature for delivery aircraft compartments (e.g., bomb bay) and systems; in turn, this determines the number of aircraft and weapons necessary to complete a mission. If the precision is not there, for example in anti-access, area denial (A2/AD) regions, then the original calculations must be modified and likely inflated. It is important to understand and pre-empt inherent errors, degradation, and singular reliance in navigation systems.

Conclusion: Integrated solutions using complementary navigation approaches

The goal of precise navigation is confidence knowledge of one's location and heading. When novelist John Steinbeck initiated his famous journey through America with his dog, Charley, he got hopelessly lost in a small town in upper New York state. He tried referring to map after map to reorient himself, "but, to find where you are going, you must know where you are . . . and I didn't."[43] His lament highlights the deep connection between positioning and navigation. Another key dimension is time, because so many technologies devoted to these two activities rely on an explicit knowledge of "when."

Navigating the sea, land, and air relies on tools, methods, and systems. A single system may not be appropriate or may not be reliable in a specific situation. One remedy is to have redundant systems—if your compass is stuck, use another compass. However, singular dependence on a navigation method can leave one abandoned if cues or references are lost or unreliable. Another approach is to employ multiple systems. A modern airliner like the Boeing 787 has inertial reference systems, dual GPS receivers, radio navigation aids, and, if all else fails, a magnetic compass and maps on the Electronic Flight Bag.[44] However, the pinnacle approach to achieve precision navigation is to fuse data from complementary sources in an integrated system. One can achieve precision in position to with a centimeter using a combination of GPS, INS, and signal processing (carrier-phase tracking).[45]

The Advanced Navigation Technology (ANT) Center, located at Wright-Patterson Air Force Base, has proposed an adaptive methodology that combines inputs from a variety of sensors such that the loss of one or two does not critically impact navigation performance.[46] One method that is often underutilized is Vision-Aided Navigation. Such systems are impervious to intrusion like jamming or spoofing (although decoying is a possibility), are becoming more affordable, and can provide useful situational awareness.

A visual system which is instructive to consider is LIDAR. LIDAR is the IR and visible light analog of radar. Radar wavelengths are in the cm range while LIDAR is in the micron range. Hence, the resolution of LIDAR is thousands of times improved. New sources such as solid state and fiber optic lasers have brought the cost of LIDAR systems down dramatically in recent years. It is doubtful that LIDAR will replace a radar, however it may earn a position in a sensor suite to achieve the integrated precision navigation vision. A well-designed assembly of navigation systems, some of which can sense farther or be more reliable or are better able to penetrate murk in certain conditions, will corroborate our position and heading and continue our advances in PNT.

About Dr. Donald R. Erbschloe, Erbschloe Technical Consulting

Dr. Donald R. Erbschloe applies more than 30 years of experience focused on academia, operations, and science and technology to very challenging problems, taking concepts from the laboratory to the hands of those who need solutions.

Dr. Erbschloe's career is balanced among three primary thrusts: Aviation, academia, and science. He is a command pilot in the Air Force with more than 4,000 flying hours. In 2006 Dr. Erbschloe became the first Chief Scientist at the Air Mobility Command (AMC), the organization responsible for Air Force rapid global mobility. In prior positions, he served three tours on the faculty at the Air Force Academy in the Department of Physics and as the Director of Research on the Dean of the Faculty staff and was the Military Assistant to three Air Force Chief Scientists at the Pentagon. He was the Commander and Deputy Director of the Air Force Office of Scientific Research, the Air Force's basic research manager. Following this assignment, he moved to the Office of Science at the Department of Energy as the Deputy and Chief Operations Officer, where he helped oversee 10 world-class laboratories. Dr. Erbschloe earned his Doctor of Philosophy Degree at the University of Oxford.

About Psionic

Psionic delivers leap-ahead capabilities for a broad range of Defense applications, including navigation in all environments and under all threat conditions. Products that utilize the company's proprietary SurePath™ technology provide reliable, long-distance navigation in GPS-challenged environments. More information about the company's Defense solutions is at www.Psionic.ai/defense.

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