Precision Four-Dimensional Digital Mapping Teaches Humans and Machines to See In the Dark

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Abstract—**Safe and efficient aircraft navigation in challenging environments such as congested airports and metropolitan areas demands mapping solutions with the highest possible precision. Advances in imaging, onboard sensors, and always-connected aircraft provide the real time accuracy needed to operate in such conditions. This paper presents the results of over seven years of research, development, and commercial production of high precision digital mapping for piloted and autonomous aerospace systems and provides examples of the application of those systems to meet the navigation challenges of today and tomorrow.**

We review new developments using sub-centimeter survey techniques and proprietary tool chains to integrate data collected from in-flight and space-based sensors. These techniques have achieved sub 1-meter accuracy, producing mapping databases of airports and urban flying areas that are five to ten times more accurate than the aircraft mapping solutions flying today. We also discuss the essential role that temporal (4D) mapping will play as the industry strives to achieve not only greater accuracy, but greater responsiveness to aviation environments in which mapped artifacts and surrounding obstacles shift with time.

Representing ground transport vehicles in an airport, or the installation of a new building crane in an urban setting, not only requires dramatically more frequent mapping database updates than the current 28-day cycle, but also near real-time integration of dynamic environmental data. To support the 4D perspective, a cloud-based repository has been prototyped that stores digital maps that are continuously updated with data drawn from a wide universe of sources ranging from Notices to Airmen (NOTAMS) to sensor data "crowd sourced" from vehicles in flight.

Keywords—digital mapping, autonomous navigation, GPS, WAAS

I. INTRODUCTION

Digital maps that deliver enhanced situational awareness to pilots are becoming an increasingly prominent feature of the aviation toolset. These systems leverage the latest in sensor technology and computing horsepower to integrate terrain and obstacle databases for the pilot or autonomous aircraft system, providing situational awareness to understand where they are, and what is around them. The results are dramatic improvements in flight safety, particularly in night flying and bad weather when visibility is degraded. Synthetic Vision Systems (SVS) are an example of a technology that is enabled by digital maps. The FAA certified its first SVS in 2007 - the Gulfstream Synthetic Vision-Primary Flight Display (SV-PFD) system for the G350/G450 and G500/G550 business jet aircraft [1]. Historically, SVS has been deployed on business jets like the Gulfstream. However, as the technology rapidly matures, the application space is opening up to include virtually every aviation segment.

High precision mapping is a critical component of navigation systems. The methodologies discussed here achieve extremely accurate 4-dimensional digital map data. This paper explores the nature of today's mapping capabilities and how the new methodologies pave the way for the navigation systems of tomorrow.

Digital maps are typically understood to represent a specific 2 or 3-dimensional space. However, in the real-world aviation environment, mapped artifacts and surrounding obstacles shift with time. Representing ground transport vehicles in an airport, or the installation of a new building crane in an urban setting, requires a dynamic medium. To meet the needs of piloted and autonomous air traffic control, precision digital maps must be accurate both spatially (3D), and temporally (4D). In fact, the goals of 4D precision digital mapping for both piloted and autonomous systems converge. Both domains benefit from self-navigating aircraft, eliminating human error factors and the need for "last mile" remote or in-cockpit human piloting. This self-navigating capability maximizes passenger and crew safety and reduces delays. Precision digital mapping solutions can apply to forwardfit, new piloted and autonomous aircraft, and to retrofitting existing piloted fleets [2].

In the 3D precision mapping space, it is critical to apply highly accurate remotely sensed data collected from in-flight and space-based sensors to process and create digital maps. Autonomous navigation in airport and urban settings demands sub 1-meter accuracy – five to 10 times more accurate than the aircraft mapping solutions flying today [3]. Advanced data tool chains paired with sub-centimeter survey techniques are required to take the data from these sensors and create digital mapping databases of airports and urban flying areas with the required accuracy. This is achievable by surveyed data that is post-processed using known satellite positions, resulting in the correction of the data and sub-centimeter accuracy. This process can be used globally and does not require Global Positioning System (GPS) base stations. These surveyed points allow the databases to build spatial connections and can use independent points for verification.

To support the 4D temporal perspective, a cloud-based repository has been prototyped that houses digital maps updated in real time from various sources. These digital maps, coupled with today's aggressive push for always-connected aircraft through satellite, 5G, or WIFI, enable autonomous flight systems to learn about their immediate surroundings in real time. Today, aircraft mapping databases are updated on the 28-day Aeronautical Information Regulation and Control (AIRAC) cycle which is inadequate for autonomous navigation [4]. The cloud-based 4D solution is enabled by real time digital map updates based on all data available. Notices to Airmen (NOTAMS), for example, are analyzed using Artificial Intelligence (AI)-based difference detection algorithms to automatically determine changes to or additions of mapped locations and then automatically attribute the features of the digital map.

This paper is organized as follows: Firstly, the paper sheds light on the accuracy limitations of GPS, demonstrates the need to couple GPS with high precision digital maps, and highlights a new digital mapping production methodology that achieves the highest precision for navigation systems. Secondly, the paper presents case studies in which precision mapping contributed to the implementation of navigation systems that achieve noteworthy results in challenging scenarios. Lastly, a prototype system is introduced that stores precision mapping data and delivers that data electronically to support increasingly accurate and up-to-date on-aircraft mapping solutions.

II. WHY PRECISION MAPPING MATTERS

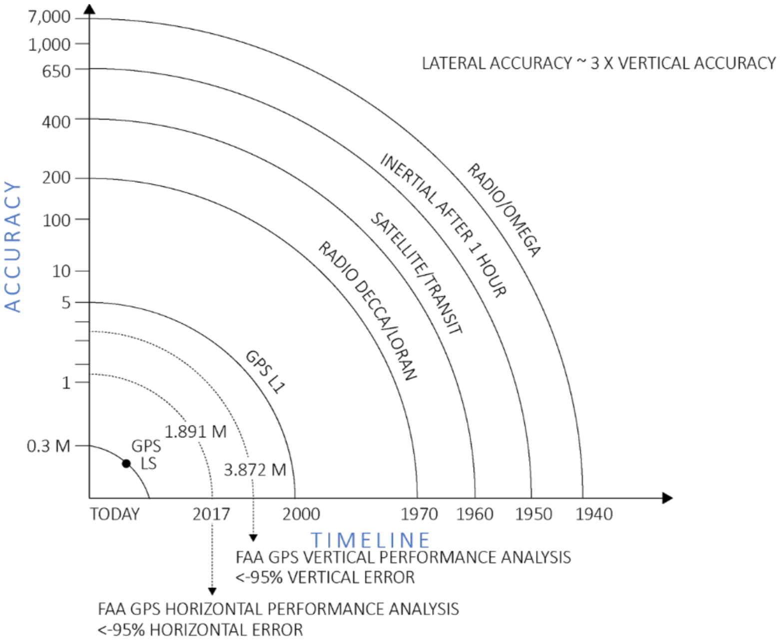
A. *GPS, The Foundation of Modern Navigation*

In a project that began in 1973 and became operational in 1993, the GPS was easily the most transformational navigation advancement since the invention of the sextant itself. Operated by the United States government, GPS is a satellite-based radio navigation system that provides geolocation and time information to a GPS receiver anywhere on or near the Earth [5].

As powerful as the system is, the accuracy and availability of GPS is limited and can be influenced by a range of factors which include satellite geometry, atmospheric conditions, signal blockage, and receiver design [6]. As a result, a great deal of research and development effort is focused on supplemental technologies that can improve resolution and provide continuous operation when GPS is unavailable.

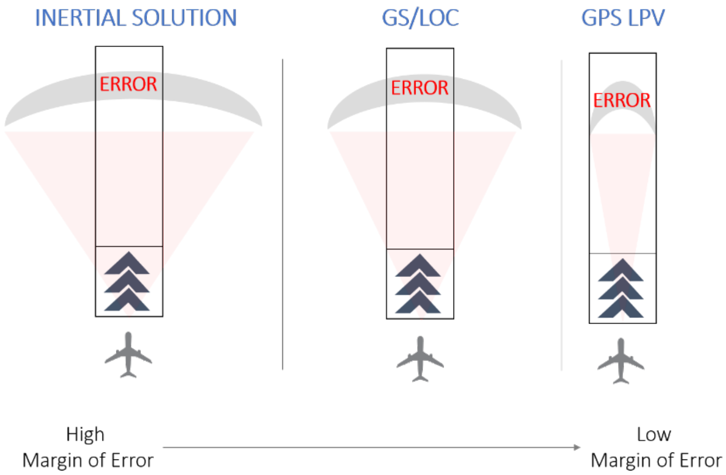
Wide Area Augmentation System (WAAS) is an air navigation system developed by the FAA to improve the accuracy of GPS navigation. It is made up of a network of satellites and ground stations that provide GPS signal corrections for a position accuracy better than three meters, about five times better than GPS alone. Among its many benefits, WAAS provides a low-cost solution to airport approach. No on-airport equipment is needed which means that any airport can publish a precision approach with only minor investment [7]. Figure 1 displays the evolution of location technology and the associated gains in accuracy.

Figure 1. Location Technology Evolution



However, GPS is only one component of a navigation solution. To use GPS effectively, navigation solutions must have correspondingly accurate maps for the pilots to not only know where they are located, but to know what is located around them [8]. Figure 2 demonstrates the need for sub-meter accurate mapping that keeps pace with advances in location technology.

Figure 2. Mapping Must Keep Up with Location Technology



B. *Navigation for Tomorrow*

The steady continuous improvements in navigation technology are providing direct and measurable benefits to military, commercial, and general aviation, as well as the traveling public. A better ability to operate in poor visibility situations has led to a dramatic reduction in cancelations and delays, along with the associated fuel costs [9]. Better situational awareness tools have reduced pilot workload when entering complex and unfamiliar airports. Above all, the commercial aviation system continues to enjoy ever increasing levels of safety, in no small part due to improved cockpit situational awareness and improved air traffic control. Commercial aviation fatalities in the U.S. have decreased by 95 percent over the last two decades [10].

At the same time, the movement toward unpiloted aircraft systems offers further savings in the form of reduced crew training and in-flight costs, along with reduced insurance liability. Unpiloted systems require redundant navigation systems for inflight and auto-land, integrating GPS, mapping, and on-board sensors. These navigation systems increase safety and confidence.

Advanced sensor systems, such as visual obstacle recognition, radar imaging, and heat mapping, offer a path to navigation systems that can be paired with GPS to provide desirable high accuracy redundancy without introducing new vulnerabilities [11]. A common thread through all non-GPS next generation sensor systems is the requirement for a high precision digital mapping solution which fixes an aircraft's location and its relationship to its surroundings. This is based on the identity of a local artifact and "looking up" the geo-referenced artifact in the on-board digital map to determine location.

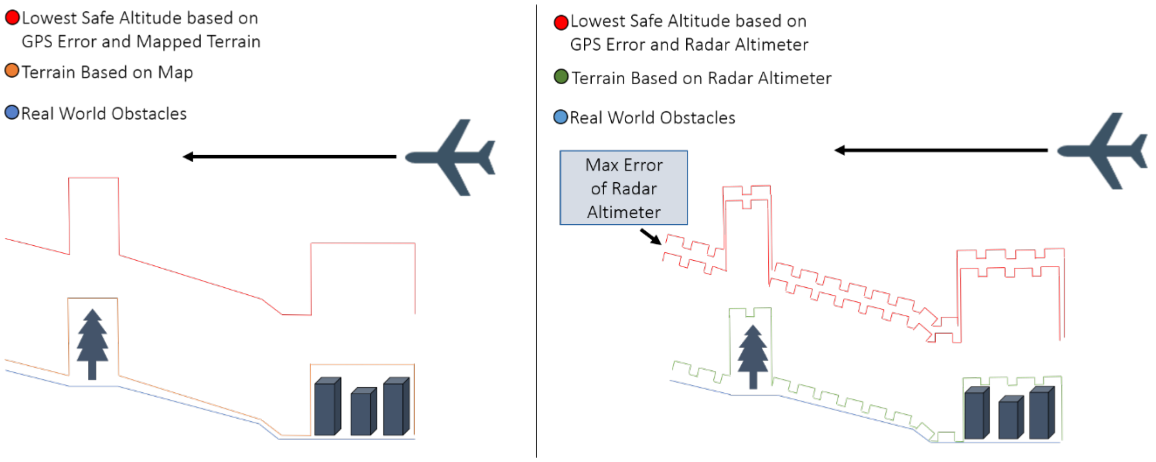
C. *Production of High Precision Spatial Maps*

A new approach to mapping, with a unique process and associated tool chains, has been developed to continue advancing the state-of-the-art for navigation technology and support the complementary technologies.

In addition to high resolution data, creating digital maps with sub-meter accuracies requires deep knowledge in projections and transformations. To appreciate the concept, consider peeling an orange and flattening the skin without ripping any of the edges. The terrains used in the new maps are made from the finest stereo imagery available in the commercial market, along with Light Detection and Ranging (LiDAR), depending on the location.

More precise aerodrome mapping databases (AMDBs) are built first by creating accurate elevation terrain models. One elevation terrain model is created of the surface which includes all obstacles within the Area of Interest (AOI), such as buildings and trees. The second terrain model that is created contains a bare earth model, capturing the terrain

Figure 3. Autonomous Systems Need Digital Maps



without obstacles. Subtracting these layers enables the creation of all obstacles quickly and automatically (See Figure 3).

Using the bare surface terrain, distortion-free features are extracted from the imagery. Distortion often occurs on the ends of runways because they are built up on berms to keep the elevation as flat as possible. All airport features are hand digitized based on bare earth models and raster data. A custom solution has been built to digitize these features in accordance with RTCA DO-272 and ARINC 816 formats. All data created is verified using an independent survey control which is typically accomplished by GPS and achieves a precision of 0.8 centimeters horizontal [12].

III. CASE STUDIES: MAPS ENABLING NAVIGATION IN LOW VISIBILITY CONDITIONS

A. Approach

Terrain data can have the accuracy required for aircraft to land in low visibility conditions. Currently GPS vertical accuracy is about four meters within 95% confidence [13]. However, GPS data does not identify where the ground is located, and by itself a GPS system cannot determine if the aircraft is in a safe location. When GPS is paired with a sub-meter vertical terrain map, pilots have increased confidence of where the runway is and how far away obstructions are, allowing the aircraft to land in low visibility conditions.

Using ground survey teams to independently verify bare earth models, sub-meter root mean square error (RMSE) can be achieved. This data precision allows for accurate digitization to occur. Determining the delta between the bare earth terrain and surface terrain, all obstacles can be viewed in 3D. All obstacles are then classified by mass and vector, and any that cross a specific threshold are flagged. Unique obstacles are then identified, enabling on-board navigation solutions to identify the objects and confirm own ship location. This capability is critical for un-piloted flights. The methodology achieves a resolution high enough to capture objects that are 40 centimeters tall or wide. This resolution is not currently required, but will be needed for un-piloted flight.

Because the terrain maps are generated by satellite imagery, the only obstacles in generating updated models are weather, current satellite orbits, and material cost. AOIs in humid and cloudy areas, for example, are harder to capture than locations in deserts. Additional satellites are launched regularly, increasing the overall availability of satellites in orbit over an AOI. While imagery remains expensive, with the number of enterprises entering the market it is possible to set up AOIs and have images delivered at a designated interval. Using imagery that has reduced resolution will allow for more satellites in orbit to capture the area and can dramatically reduce the material cost of purchasing image data. The effort needed after purchasing imagery for terrain creation and obstacle identification can be largely automated, further reducing costs.

Currently, radar altimetry, the classic solution to measure altitude above the terrain, has several issues. The technology is impacted by seasonal changes. Also, deciduous trees that have leaves tend to register higher altitudes than deciduous trees that have gone dormant. The same problems are seen in sparse trees, which may not be registered by radar altimetry [14].

To overcome the radar altimeter variability and limitations, terrain maps act as an ancillary data source providing height above ground information with only GPS error and a marginal error from the map.

B. On Ground

Bare earth terrains allow for the accurate digitization of airport features. The accuracy of the digitization determines the utility of the data. While less accurate data will provide a certain level of situational awareness, highly accurate airport maps have the potential to enable aircraft to taxi without any visual aid.

Low visibility is a significant issue for on ground operations, resulting in frequent delays. Current charts and 5-meter accurate airport maps alone are not sufficient for a pilot to taxi without visibility. With maps of suitable precision, rather than following a lighted truck, a pilot would steer the plane using the airport map. Future direct control of the aircraft nose wheel, by the avionics system powered by digital maps would enable gate to gate or pad to pad autonomous flight [15].

For taxiing, horizontal accuracy is critical. With GPS accuracy at two meters, the airport map needs to be sub-meter accurate [16]. With sub-meter accuracy, AMDBs will be able to provide autonomous taxi when combined with ADS-B for traffic awareness.

C. The Need for Temporal Precision – 4D Mapping

Today, aircraft mapping databases are updated on the 28-day AIRAC cycle. Established in 1964 and further refined over the years, the AIRAC cycle is premised on the need to have pilots, air traffic controllers, and air traffic flow managers working from identical charts and data; and collecting, validating, updating and redistributing this information. Although 28 days may seem like a painful-enough delay in receiving updates, in practice the cycle is even longer [17].

While it may serve its purpose in ensuring all of the data users are working from the same information base, the AIRAC refresh timeframe doesn't provide a context for bringing improved situational awareness to piloted cockpits and is categorically inadequate for autonomous navigation. The status of approaches, airport attributes and urban air obstacles can change rapidly. To meet the needs of next generation systems updated information must be delivered in real time, or as close to real time as can be practically achieved [4].

The NOTAMS process is the current, manual system for informing pilots of material changes between AIRAC updates. For example, the closure of a runway for surface repairs or the change in urban no-fly zones in Urban Air Mobility (UAM) applications. Those NOTAMS and air circulars need to be represented in airport maps. When the map is rendered, "closed" features could be displayed in the color red. Additionally, with the progress in the use of ADS-B in and out technology in both aircraft and ground transportation, the human and machine representation of traffic in 4 dimensions becomes a reality [18].

In the future, digital maps for approaches will incorporate dynamic obstacles that are reported by inflight instruments.

IV. THE DATA REPOSITORY & REAL TIME UPDATES

A comprehensive, normalized, and monolithic repository of data that realizes the full power of precision digital mapping is critical to the future success of navigation systems. The ability to cross-synchronize the location and state of navigation attributes would eliminate ambiguity across all of the imagery based systems that pilots and autonomous systems rely on: synthetic vision systems, flight management navigation databases, digital airport and heliport maps, and flight simulator virtual reality projections.

To support this synchronized perspective, a cloud-based repository has been prototyped, housing digital maps that are updated continuously from various sources. These digital maps, coupled with today's aggressive push for always-connected aircraft through satellite, 5G or WIFI, will enable autonomous flight systems to learn about their immediate surroundings in real time. NOTAMS, for example, are analyzed using AI-based difference detection algorithms to automatically determine changes or additions of mapped locations and then automatically attribute the features. Additionally, a machine learning feedback loop is proposed consisting of aircraft sensor data "crowd sourced" from vehicles in the air. Examples include AI-based image differential processing and obstacle identification such as a new crane on the skyline.

A monolithic Aviation Information Repository (AIR) has been architected and implemented to serve existing legacy operations while positioning for future autonomous flight. The AIR ingests Aeronautical Information Publications, Imagery, Surveyed Control Points, LiDAR, Elevation Models, AMDBs, & Navigation Database (ARINC-424). Having many data sources with built-in relationships allows data to be cross referenced and verified instantly. The original data can be stored in convenient formats, enhancing their confidence and allows for export of custom solutions.

Depicted in Figure 4 is the overall AIR architecture including support for legacy and future data delivery mechanisms. Phase 1 production and storage of data meets Type 1 Letter of Acceptance (LOA) levels of approval for consumption by avionics systems Original Equipment Manufacturers (OEM). Phase 2 storage of data enables avionics OEMs to provide on demand, real time updated data to airlines, fleet managers and pilots; end users can define the data they require and the data will deploy

Figure 4. The A.I.R

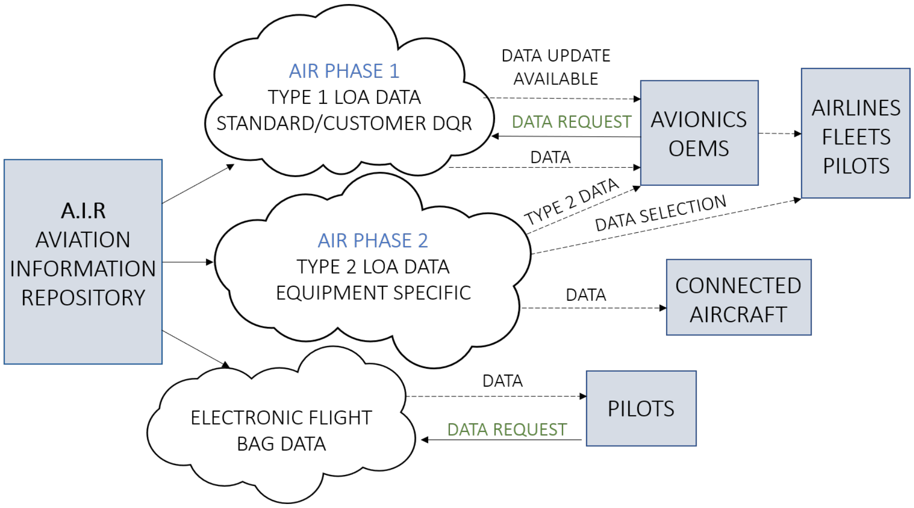
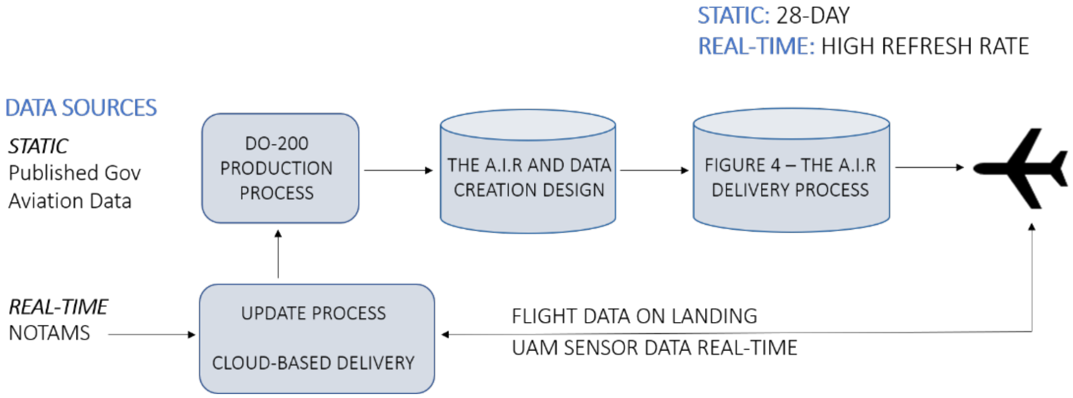


Figure 5. Static and Real-Time Data Delivery



directly into the connected aircraft over secure communications.

The AIR also supports emergency situations whereby a connected aircraft may be diverted to a region or airport that is not currently included in the on-board data. In situations like these, a real-time request can be made to download digital maps corresponding to the AOI. Figure 5 shows the design of the AIR Phase 1 and associated data production processes as implemented today.

The final feedback loop provides the ultimate real-time data updates. The system supports the cyclic production of data according to legacy 28-day periods, inter-cycle updates through automated analysis of NOTAMs, Flight Information Regions (FIR) and other data, and direct feedback from the aircraft based on their usage of data and their internal sensors. Thus, the ecosystem of data that brings applications to life is there to support the demands of future air traffic management.

V. CONCLUSION

High precision digital mapping is a critical enabling technology for the next generation of navigation systems. As aircraft location techniques become ever more precise to answer the fundamental question: Where am I?, digital maps must evolve in parallel to the same level of precision to accurately answer the related question: Where is everything else around me? Additionally, precise maps are required for autonomous sensor systems to build their picture of their surroundings.

Success in advancing the digital mapping state-of-the-art requires innovative approaches and advanced methodologies that integrate multiple technologies for augmented precision and enhanced reliability. The new methodologies presented here achieve sub-meter accuracies that are multiple times better than current fielded mapping products. The methodologies have the potential to fuel continued innovation, paving the way for new products to be brought to market that enhance flight safety and enable operations in increasingly challenging conditions.

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