Combining GPS based Precise Timing and Accurate Navigation requirements, benefits

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1 Astract

It has been a continuous trend that all aerospace and payload programs require more and more parameters to be measured during flight tests, at increasing sampling rates. Contextual data, associated with measurements – like timestamp, geolocation, attitude - are instrumental to performing a relevant analysis of measured data. Therefore flight test teams, in charge of engineering high speed measurement systems, need to ensure proper time alignment amongst all on-board systems, facing two challenges:

- Distribute precise time (better than 1 µs), even in case of GPS loss, over the whole test mission duration
- Distribute precise position and attitude, which are time-stamped consistently with the distributed time

In this paper, we demonstrate how a combined position & attitude measurement sensor and precise time server can meet all "Positioning, Navigation and Timing (PNT)" needs for a complex observation payload like an on-board test system and a SAR imagery radar, with benefits in terms of architecture simplification, and overall performance increase in terms of time and attitude accuracy.

We also review the benefits of associating a high stability clock with a GPS receiver, in terms of improvement of some GPS reception performances.

Keywords: Position Navigation and Timing, GPS performance improvement, Interference Detection and Mitigation.

2 Introduction

Position / attitude measurement instruments on one hand, time and frequency generation instruments on the other hand, have been traditionally very distinctive products or solutions, handled by different teams and specialists within companies or research institutions.

As a "time based" positioning system, Global Navigation Satellite System (GNSS) in essence provides simultaneously a clock reference and the means to elaborate a position solution.

GNSS generalized usage therefore introduces a dramatic opportunity for gathering together positioning and timing techniques. Thanks to the on-going miniaturization of all associated components (GNSS receiver, high performance frequency oscillator, inertial measurement unit), it is possible to integrate both position / attitude measurement and time / frequency generation functions in a single instrument, using GNSS signal as the common reference.

On the timing side, the use of a high performance oscillator disciplined by GNSS combines the high short term frequency stability from the oscillator with the high long term stability from GNSS. It allows also to deliver low phase noise frequency signals which are important in many radio communications and radar applications. The implementation of network timing protocols, like NTP or PTP (IEEE-1588) provides an elegant way to transfer precise time through an IP network, thus avoiding the need for dedicated media (like IRIG). In addition, the timing distribution is immune to temporary GNSS loss, as the frequency oscillator, in holdover mode, is used to maintain the local timescale, with some long term drift - which is actually a key performance feature for the oscillator.

On the position and attitude side, tight coupling between GNSS (in standalone or in differential correction mode) and IMU, also combines the short term "stability" from the IMU with the absolute accuracy from the GNSS reception, in order to provide navigation solutions that include all the parameters of interest: position, orientation, speed, rotation rate, acceleration, etc.. Temporary loss of GNSS is handled by the IMU, which maintains navigation solutions in dead reckoning mode – with a drift depending on the IMU performance. High dynamics can be captured by using a high sampling rate from the IMU.

Such a combined approach provides benefits in terms of Size, Weight and Power (SWAP) as applications requiring both position/attitude and timing can access them through a single instrument, single antenna solution avoiding discrepancy resulting from separate sources.

3 Examples of applications requiring PNT

In order to illustrate how a single instrument can efficiently provide all critical Position, Attitude and Timing information, we chose two applications, one in the Intelligence Surveillance Reconnaissance (ISR) area, the other one in the flying test bench area.

3.1 On-board test bench

New aircraft or modernization programs require more and more data to be recorded and analyzed in view of qualification and certification. Distributed sensors are operating at increasing sample rates in order to capture transient phenomena or high frequency vibrations. Those data must be acquired and recorded in real time, with IP network topology being well adapted to cope with such large streams of data.

Along with measurement data, contextual data are needed in order to perform relevant analysis. Timestamps provide time alignment of samples and allow to correlate measurements made by different sensors at the exact same time. Position, attitude (relative to the body frame), speed, and acceleration measurements can be used to directly determine relationships between the measured data and some of the flight envelop parameters.

3.1.1 Typical architecture

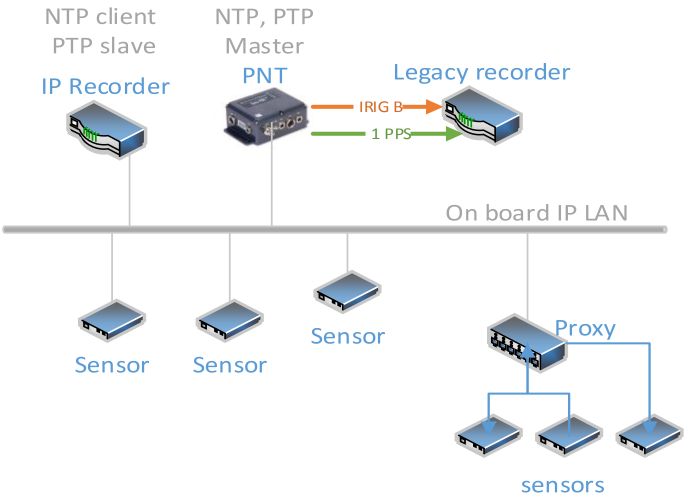

Fig 1: Typical timing architecture for an on-board timing system

In a typical on-board flight test system, the measurement data are time-stamped by the recorder. The recorder timescale and clock is itself disciplined thanks to 1 pps and / or IRIG B signals for legacy recorders, and thanks to a Network Timing Protocol (NTP) client or Precise Timing Protocol (PTP - IEEE1588 v1 & v2) slave for recent recorders.

The iNET standard recommends the use of PTP protocol, as the way to transfer precise time on an Ethernet network from a master clock to a slave clock, thanks to the exchange of PTP messages that contains ingress and egress message timestamps, allowing the PTP slave to adjust its clock to synchronize with the PTP master clock.

Required Position and Navigation (PN) data are stored within the recorder along other sensor data, but at a lower rate (typically 1 to 100 Hz).

3.1.2 Timing and positioning requirement

The time accuracy required for data time-stamping depends on the sampling frequency, but typically ranges from 100 ns to 10 ms. The appropriate techniques for time transfer can be summarized as below:

Required time transfer accuracy	Appropriate time transfer method
1 – 10 ms	NTP (network) IRIG B AM (dedicated media)
10 µs - 1 ms	PTP (network) IRIG B DCLS (dedicated media)
100 ns – 10 µs	1 pps (dedicated media)

Fig 2 : time transfer methods according to required time-transfer accuracy

Position and Navigation data are strongly application dependent. However, attitude measurement is a common requirement with heading accuracy ranging between 0.1° and 1°.

3.2 Synthetic Aperture Radar for imagery

All recent analysis confirm the need for ISR capabilities, whether it's on land, air, sea, and space. Synthetic Aperture Radar (SAR) is now a mature technology that provides imagery of vast ground or maritime zones along the trajectory of the vehicle. It's an interesting complement to optical observation, thanks to its capability to see camouflaged objects through any weather.

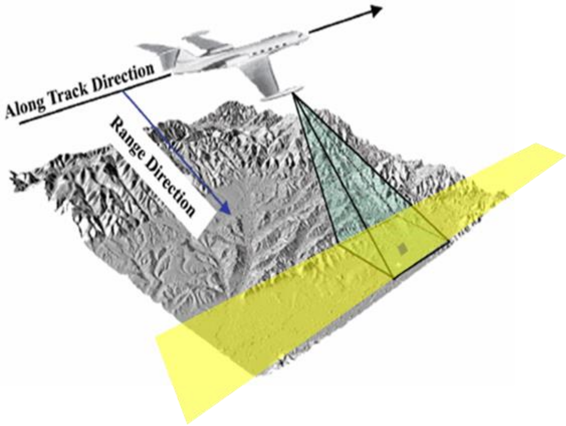

Fig 3: SAR imagery radar principle and SAR image

3.2.1 Key stakes

In a SAR radar, a synthetic antenna is created thanks to the straight movement of the vehicle. The antenna's virtual length is roughly equal to the traveled distance during the signal integration period. This synthetic antenna is therefore very long, resulting in very good resolution along the movement axis.

Like for optical observation, the important criteria for SAR performance are related to:

- Resolution: ability to resolve an object of interest within several pixels, to allow reconnaissance (and identification)
- Geometric conformity: a square on the ground must be reported as a square on the SAR image (without echo migration)
- Contrast: ability to distinguish between objects that have small reflectivity difference

It has been shown that these key features are adversely impacted by many PNT aspects:

On the time & frequency side:

- Slow frequency emitter instability: generates echo migration and decreases image conformity
- Phase noise increases the post-correlation spurious level and tends to decrease the contrast

On the navigation measurement side, if not properly measured and compensated for:

- Longitudinal position variations impact geometric conformity
- Longitudinal, transverse and vertical velocity components variations affect both geometric conformity as well as resolution
- Transverse and vertical accelerations impact resolution

The following example from [5] provides a numerical calculation of the constraints applicable on standard deviation for position, velocity and acceleration, in order to maintain:

- Geometric conformity criteria: echo shifts by less than half a resolution cell
- Resolution criteria: size of resolution cell increases by less than 10 %

For a X band lateral SAR radar (λ = 3 cm), 1 m resolution, -10° elevation, 0.5 s integration time:

	Geometric conformity criteria	Resolution criteria
Longitudinal move	STD on longitudinal position < 0,5 m	STD on longitudinal velocity < 2 ms^{-1}
Transverse move	STD on transverse velocity < $1,6.10^{-2}$ ms^{-1}	STD on transverse acceleration < $1,2.10^{-1}$ ms^{-2}
Vertical move	STD on vertical velocity < 8.10^{-2} ms^{-1}	STD on vertical acceleration < 8.10^{-1} ms^{-2}

STD: standard deviation

Fig 4: Requirements on navigation data accuracy for a SAR radar

In addition, for vehicles (helicopters, drones) which have significant parasitic yaw and roll movements, it is necessary to adjust the antenna steering direction, based on attitude measurements.

Following radar processing, the available SAR images (strip map, or focalized map) must be properly geo-referenced. Such referencing – a classical operation in surveying – requires to know both the position and attitude of the observation vehicle with the appropriate accuracy.

3.2.2 Typical architecture

The below diagram shows the typical (simplified) architecture of a SAR radar, and the PNT information needed by each subsystem of the radar.

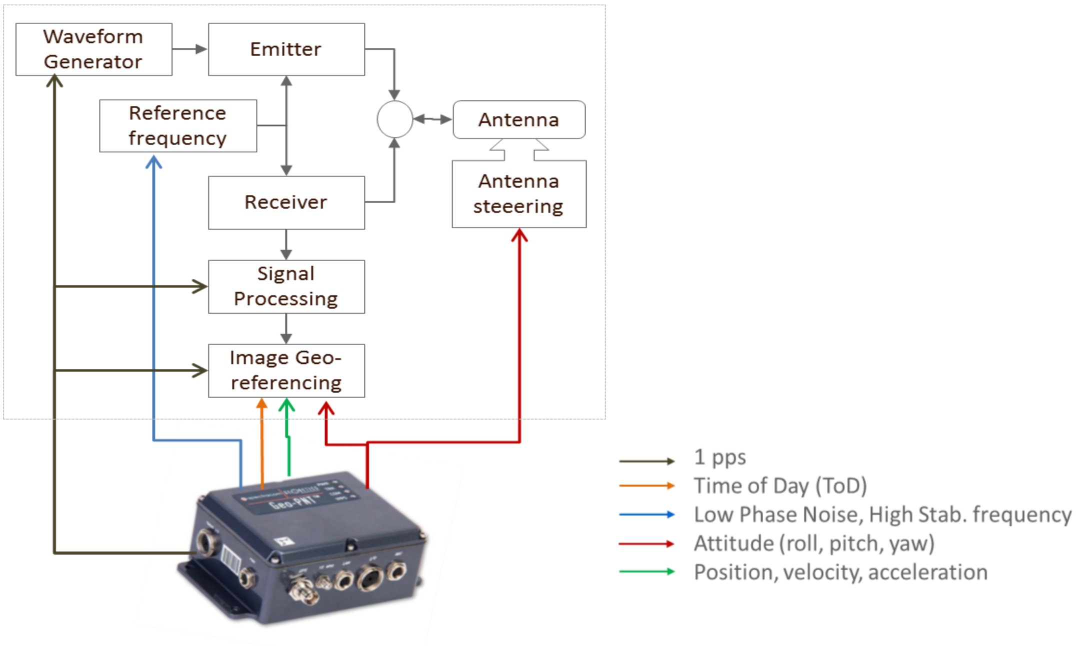

Fig 5: PNT requirements for a SAR radar subsystems

4 State of the art PNT instrument

Geo-PNT is an all-in-one box PNT instrument that provides:

1. Time & Frequency reference
- Low phase noise, high stability frequency signal, based on either Oven Compensated Quartz Oscillator (OCXO) or Chip Scale Atomic Clock (CSAC)
- Configurable pulsed signals, including 1 pps and IRIG B, referenced to UTC
2. Navigation solutions (serial or LAN interface)
- Position, velocity, accelerations, yaw, pitch, roll, rotation rates

The Geo-PNT, with internal MEMS Inertial Measurement Unit (IMU) can be configured to work in standalone mode or in RTK mode. Accuracies are provided in Fig. 6.

	Horizontal / vertical position	Velocity	Acceleration	Attitude Roll, pitch / Heading
Standalone	1.5 m / 2.5 m	0.1 ms^{-1}	0.15 ms^{-2}	0.2 ° / 0.5°
RTK	0.05 m / 0.1 m	0.02 ms^{-1}	0.1 ms^{-2}	0.1 ° / 0.3°

Fig 6: Geo-PNT position & navigation performances

5 Improving GNSS receiver operation thanks to a high performance oscillator

Having a good oscillator obviously contributes to good timing performances (short term stability, phase noise) which are required by applications like flying test bench applications, as well as radar and other ISR applications.

But it also contributes to the improvement of the GPS receiver performances.

GPS reception requires that the receiver's clock aligns on the transmitted satellite clock. This alignment needs to be initialized at receiver startup, but needs also to be maintained all along receiver operation. As most GPS receiver use a poor short term stability oscillator (typically a TCXO), clock adjustment of the receiver oscillator needs to be done for each, as clock error is one of the four variables to be calculated along with the three position components (of course, if the receiver is fixed at a well-qualified position - which is often the case for timing receivers - then a single satellite allows to discipline the receiver clock).

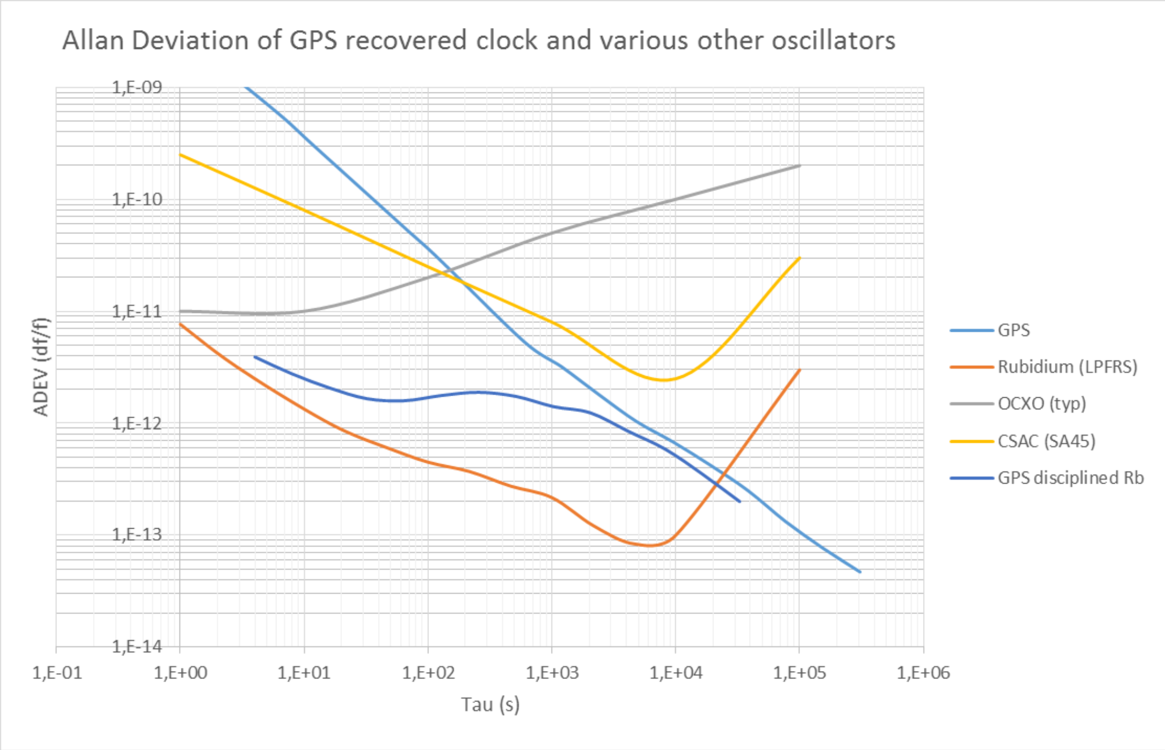

Fig 7: compared ADEV for GPS, and various types of oscillators

Allan Deviation (ADEV) [1] is the widely used metric for clock stability characterization over different periods of observation (Tau). The lower the ADEV, the more stable the oscillator is. Fig 8 shows the typical ADEV as communicated by various oscillator providers (Rubidium : LPFRS from Spectratime, CSAC : SA45 from Microsemi, OCXO from Rakon). In addition, it shows ADEV of GPS recovered clock, as well as GPS disciplined rubidium clock (SecureSync from Spectracom); the latter illustrates the effect of disciplining, which combines the short term stability of the rubidium, with long term stability of GPS.

It can be seen that, below a Tau of 100 s, GPS recovered clock is less stable than all oscillators. For Tau higher than 100 s, GPS becomes better than an OCXO; and slightly better than CSAC. It becomes better than rubidium only for Tau higher than 20 000 s.

The use of a good quality oscillator, e.g. featuring good long term stability, provides interesting options for improving some receiver features, depending on the application.

5.1 Improvement of vertical position and velocity measurement accuracy

Krawinkel et al, [2] from Erdmessung Leibniz Universität Hannover, created a receiver clock model, using real ADEV measurements of a few oscillators, which was then input to an Extended Kalman Filtering, as a way to determine the influence of clock process noise in code-based GPS single point positioning. This work concluded that vertical position and vertical velocity accuracies could be improved respectively by 58 % and 66 % respectively when using a rubidium oscillator.

5.2 Integrity monitoring

Bednarz et al [3] from MIT, made some laboratory measurements and observed accuracy improvement of vertical position accuracy ranging from 34 to 44% using also an atomic reference. Going further, Bednarz proposes to use the good external clock reference (instead of processing received signal to extract clock error) in order to determine the three position parameters. Then extract the clock error from pseudo-range measurement, which is a good predictor of the vertical position error.

By setting a range of acceptable clock errors, it is possible to establish a Vertical Protection Level (VPL), as the main input of a clock-aided integrity monitoring mechanism. Such integrity monitoring adapts to changing atmospheric conditions or multipath or other clock sources.

5.3 Multipath mitigation

In a similar approach, Preston et al [4] developed a CSAC clock model, allowing to solve the three geometric coordinates parameters equation, relying on the atomic clock, thanks to only three satellites in view (which is appreciable in urban canyons for example). A suddenly growing GPS recovered clock error, extracted from pseudorange measurements, probably reflects the presence of multipath. The satellite affected by multipath can then be excluded from 3D position calculation, as a multipath-mitigation mechanism. It provides an Interference Detection and Mitigation (IDM) reliable timing source to improve confidence in estimated PNT solution that are computed within autonomous computation.

5.4 Three satellites operation

We have seen earlier that clocking the GPS receiver with a high stability oscillator allows to perform GPS processing limited to solving the three position parameters, with only three satellites in view. This in itself is an interesting feature for applications where only a small portion of the sky is accessible, either momentarily (aircraft manoeuvers) or permanently (masked GPS antenna, canyons).

6 Conclusion

In this paper, we have illustrated how applications like airborne radar surveillance, and test benches require accurate time and frequency as well as navigation data to be provided to their various sub-systems. System performances depend (amongst others) on the accuracy of PNT data.

With Geo-PNT, Spectracom offers a solution which combines both timing & navigation within a single enclosure, easing the integration of this function as well as optimizing its Size Weight and Power.

In addition, combining a GPS receiver with a high stability oscillator can contribute to the improvement of GPS reception and IDM mechanism. Depending on application requirements, a high performance external clock – OCXO, Rubidium or CSAC - can be used to either increase vertical position and velocity accuracy, to implement clock based integrity monitoring mechanism – including multipath mitigation, or simply to increase GPS reception reliability when a limited number of satellites can be viewed.

7 Acknowledgment

The present study has been solely possible thanks to great material provided by Geodetics Inc. and warm advice of Dr. Jeffrey A. Fayman, Vice President of Geodetics Inc.

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