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High Accuracy Time Space Position (TSPI) Field Test Results

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Abstract:
Flight test applications require accurate data to verify and validate the test article's performance. This data is most useful when it is properly correlated with other contemporaneous test data. This includes ensuring that all collected data can be cross-referenced with the aircraft's position and orientation in space. This enhances one's knowledge of what is happening during different maneuvers, allowing engineers to better determine the limits of an airborne platform.

Time Space Position Information (TSPI) systems deliver this positional data. TSPI systems are able to provide very accurate data by combining highly accurate and precise internal sensor components with careful installation and calibration. This paper discusses Curtiss-Wright's new MiTSPI nTTU-2600 Miniature TSPI device and presents some real-world test data that demonstrates its performance.

Key words: TSPI, GPS, INS, IMU, GNSS

Introduction

Time Space Position Information (TSPI) systems provide extremely accurate position, orientation, velocity, and acceleration data about test articles. This data can be combined with other conventional flight test data from analog sensors and digital buses to greatly improve the overall situational awareness for the flight test engineers who are tasked with monitoring and analyzing the results of a flight test. This information is also very useful in determining the overall capabilities and limitation of a test article, since the TSPI data allows the measurements taken by the conventional flight test data acquisition system to be correlated with specific maneuvers.

In this paper, we will introduce the technologies that are used to generate TSPI data. We will then introduce Curtiss-Wright's new miniature TSPI product, the MiTSPI nTTU-2600. Finally, we will present the results of a series of real-world tests that Curtiss-Wright has performed to measure the accuracy and precision of the TSPI data generated by the nTTU-2600.

How Do TSPI Devices Work?

The best way to determine the position of a test article today is through the use of an Inertial Navigation System (INS) that is comprised of two components. These components are a Global Navigation Satellite System (GNSS) and an Inertial Measurement Unit (IMU). The original and most widely used GNSS system is the US government's Global Positioning System (GPS). Some other commonly used GNSS systems include the Galileo system operated by the European Union, the GLONASS system operated by Russia, and the BeiDou system operated by China.

Commercial GNSS receivers have a positional accuracy that varies between meters to sub-meter due to several factors including the number of simultaneous satellite systems that are being tracked and if the receiver has single or multiple (differential) receivers. In addition, the GNSS data is typically updated at lower rates (5 to 20 Hz), which can be too slow to catch some course change information. For example, a missile traveling at Mach 2 traverses about 780 m/s, equating to a significant possible gap in position information when relying solely on GNSS with updates at 5 Hz.

There are many potential sources of error with GNSS systems, including:

- The location of the GNSS antenna, and multi-path effects on the test article.
- The type of GNSS receiver used, e.g., multi-constellation and/or differential GPS (DGPS).
- Atmospheric uncertainty due to charged particles can introduce errors up to a few dozen meters.

- Clock errors – even a few nanoseconds could mean a one-meter error.
- Ephemeris error, i.e., the difference between theoretical and actual satellite position.

An unlucky combination of these errors could result in location data that is too inaccurate to be useful for some test scenarios.

Additionally, GNSS receivers do not provide orientation information, such as the roll, pitch, and yaw of a platform, although some models compute a trajectory/velocity, albeit at low data update rates. The orientation information, along with the trajectory information, form the six degrees of freedom (6DOF) data that is critical to help correlate aircraft sensor data with maneuvers to assess an aircraft's performance and operation limits accurately. In contrast, INS units typically provide the 6DOF information to help achieve a better correlation of measured platform flight test dynamics with the stresses experienced by the platform during these maneuvers.

An INS generally consists of a GNSS and an Inertial Measurement Unit (IMU) which uses accelerometers, gyros, and inclinometers to detect changes, at high sample/update rates, in the forces impacting the test platform and thereby accelerations relative to an inertial frame of reference. Modern IMUs have high updates rates up to 800Hz and can be used to derive velocities and spatial positions in 6DOF without any additional external inputs.

Since the IMU units essentially calculate position and orientation information by calculating differences from a starting reference point, errors accumulate and propagate over time, and in-flight recalibrations may be necessary for continued accurate readings.

TSPI units rely on fusing data from the GNSS and the IMU to provide higher accuracy and higher update rates by using the lower update and relatively more accurate GPS receivers to provide the “truth” data on the platform position and the higher update rate IMU data to estimate the platform position and 6DOF data through data fusion/filtering techniques such as Kalman filters.

Flight Test Requirements For TSPI

Since modern aerospace platforms are typically space-constrained, it is important for the TSPI unit to be optimized to reduce its size, weight, and power (SWaP). It is also important that the TSPI unit integrates well with the rest of the flight test data acquisition system and how data is telemetered to the ground and/or stored for post-flight access. Both real-time and post-test data are required, so the TSPI unit must be able to provide both. In real-time, the TSPI and trajectory information needs to be formatted for efficient transmission while still being easily decoded by the onboard/ground station software for flight test point clearance and safety reasons. The limited RF downlink bandwidth and real-time processing of data in the ground station, during the flight test, place a premium on ensuring that the critical data is quickly transmitted to the ground for decisions on safety and/or to repeat a test point.

In contrast, post-test data analysis can provide higher fidelity by using the full INS dataset, including all acceleration and rate sensor measurements, captured by the TSPI unit at higher update rates. Due to the need for transmitting a quick summary of the data along with the need to record all of the data for post-flight analysis, it is important for the TSPI unit to have the ability to locally record all of the GNSS and IMU/INS data.

Introducing The MiTSPI nTTU-2600

Curtiss-Wright has developed a compact and accurate TSPI solution called the MiTSPI nTTU-2600. The nTTU-2600 is a network tactical TSPI unit with an integrated recorder. The unit provides user-selectable TSPI information for real-time telemetering via Ethernet and/or IRIG-106 Chapter 4 PCM (Clock and Data) and for simultaneous data recording as IRIG-106 Chapter 10 for post-flight retrieval and analysis.

The nTTU-2600 contains sub-systems / functional blocks for both acquisition and recording, as shown in Figure 1 and Figure 2.

Figure 1. MiTSPI nTTU-2600

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• **MINS-600-1**: The Miniature INS (MINS) module interfaces with an external GPS antenna to receive the GPS signals and to process them for the “truth” data. In addition, the MINS includes a miniature IMU that computes the 6DOF data. The MINS combines both the GPS and IMU data to estimate, using Kalman filters and with appropriate translations of the leverage arms data, the test platform’s TSPI and 6DOF data relative to its preferred datum which is often the platform’s Center of Gravity (CoG).

• **MREC-601-1**: The miniature recorder module is used for recording the TSPI data provided from the MINS-600-1. An industrial-temperature rated CompactFlash Express (CFexpress) memory card, available in 512GB capacity, is accessible through a sealed, hinged door on the front of the MREC.

• **MPPC-600-3**: The processor module for the data acquisition system performs the necessary overhead functions and processes the TSPI data for real-time telemetry and for recording locally.

• **MACQ-600-1**: The overhead acquisition module for the data acquisition system provides the functionality to create IRIG-106 Chapter 4 PCM (Clock / Data) for real-time telemetry output as an RF telemetry stream. In addition, the MACQ outputs real-time multicast TSPI output on its Ethernet port.

• **MPFM-461/MPSM-2005-3**: Power filtering and power supply module for the TSPI unit, accepting a MIL-STD-704F 28VDC prime power.

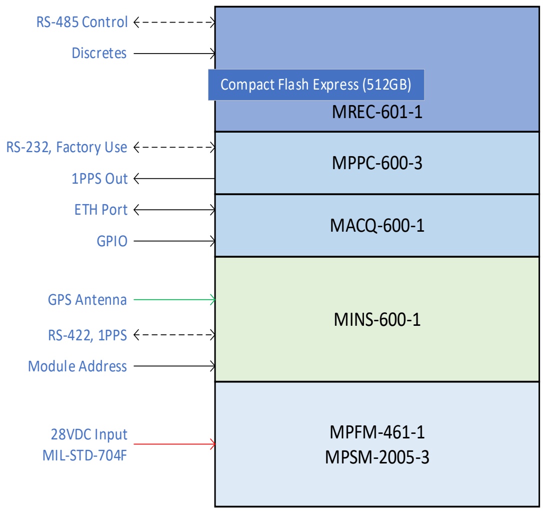

Figure 2. nTTU-2600 Block Diagram

The nTTU-2600 can transmit real-time serial and Ethernet TSPI data at up to 20 Mbps. However, in almost all cases, the nominal rate is less than 2 Mbps based on the TSPI sensor data rates. The real-time serial and Ethernet multicast outputs can be configured to send user-selected navigation (fused) parameters, position/position error in Earth-Centered-Earth-Fixed (ECEF) or North-East-Down (NED) formats, 6DOF data in ECEF or NED formats, accelerations, and angular rates in body-frame references, and GNSS statistics. Additional IMU data, such as delta velocity and delta angles for coning and sculling, Quaternions, Rotation Matrix, and health status, can be locally recorded for post-test analysis.

A well-calibrated and well-installed nTTU-2600 unit provides the following performance during GNSS lock conditions:

Table 1: nTTU-2600 Specifications

Parameter	**Accuracy / Specification**
Heading (magnetometer only)	2.0° rms
Heading (above 5.0 m/s, with GPS lock)	< 0.1° rms
Pitch (static)	< 0.08° rms
Pitch (dynamic)	< 0.03° rms
Roll (static)	< 0.08° rms
Roll (dynamic)	< 0.03° rms
Horizontal Position	< 1.0 m, rms (0.01 m with RTK)
Vertical Position	< 1.5 m, rms (0.01 m with RTK)
Velocity accuracy	< 0.02 m/s
TSPI update rate	Up to 400 Hz

Configuring The nTTU-2600

The nTTU-2600 is configured using Curtiss-Wright’s TTCWare setup software. Several items need to be properly configured to get high quality data from the TSPI unit.

First, the location of the GNSS antenna relative to the nTTU-2600 mounting reference must be entered. After that, the lever arm and boresight measurements need to be entered to establish the distance and angles of the nTTU-2600 mounting, to the desired datum and reference planes of the test article. This has the effect of offsetting the GPS data which is received at the antenna and the local IMU measurements and shifting the position and orientation to match the test article’s datum and desired refence planes.

Next, the content of the actual data packets needs to be defined. The nTTU-2600 allows the engineer who is configuring it, to define up to three packets. Each packet can be recorded locally, multicasted on the Ethernet, or both. The idea is that one packet which is intended for

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telemetry purposes would have a low update rate and only contain essential information. The next packet could have different information at a higher update rate but be intended for recording. Finally, the third packet might have all information enabled for recording at a low update rate. In this manner, the engineer can satisfy multiple use cases with the same TSPI unit.

For each packet, the available parameters are categorized into five main groups: Time, IMU, GNSS, Attitude, and INS. The engineer can select the parameters that are required for their test.

Packets are multicast on the Ethernet using Curtiss-Wright's DARv3 format. The local recording onboard the nTTU-2600 uses the IRIG-106 Chapter 10/11 recording standard. For the multicast data, the Curtiss-Wright nGWY-2000 network to PCM gateway can be used to receive the Ethernet packets from the nTTU-2600 and other network sources. The nGWY-2000 selects the parameters of interest and inserts them into the IRIG-106 Chapter 4 PCM stream for transmission to the ground via the telemetry link.

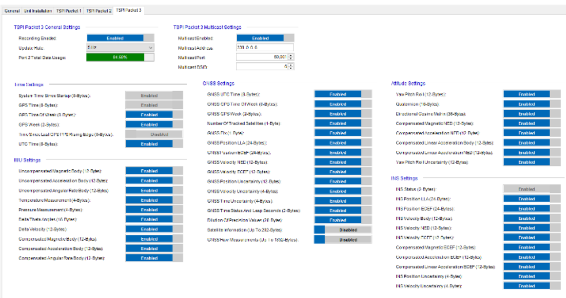

Figure 3. nTTU-2600 Packet Setup

Real-World Testing

As part of the nTTU-2600 development and verification, Curtiss-Wright conducted road tests, using a cargo van as the test platform, to demonstrate the accuracy and precision of the data generated by the nTTU-2600. This could not be demonstrated with laboratory testing alone because the IMU sensors require actual motion in order to be fully exercised. A precisely defined route (shown in Figure) comprised of multiple turns and straight-line stretches was used to test the capabilities of the nTTU-2600. Each drive lasted about fifteen (15) minutes and generated approximately 400,000 data points at a 400 Hz update rate.

The nTTU-2600 requires the platform to be travelling at more than five (5) meters per second for the GNSS receiver to generate accurate heading estimates. Similarly, the IMU requires multiple changes in direction to exercise the rate sensors before accurate data can be measured. Each test drive commenced from a stationary "rest" position in the Curtiss-Wright parking lot. Roughly the first 30 seconds of each drive was done at low speeds within the parking lot. Due to these factors, the data collected during the first 35 seconds of each test was excluded from the analysis. Also, all data below five (5) meters per second was excluded as the test platform does not travel an adequate distance for accurate GNSS heading estimates.

Figure 4. Test Drive Route For TSPI Data Analytics

For the test, two nTTU-2600 units, mounted in different orientations approximately one (1) meter apart (as shown in Figure 5), were used to validate the leverage arms and boresight calculations, unit performance, and to compare measurements. One nTTU-2600 unit was mounted with a roll of 45 degrees and a yaw of 135 degrees, while the other was mounted with a roll of 30 degrees and a yaw of -30 degrees. The orientations were such that the two units experienced forces in different directions and magnitudes, as the test platform (cargo van) was driven around the prescribed test route. The two nTTU-2600 units were provided identical GPS RF signals from a GNSS antenna, using a GNSS splitter. In an ideal scenario, both nTTU-2600 units should provide nearly identical values for all TSPI parameters, after accounting for the leverage arms, boresight, and orientations corrections. The nTTU-2600 units were also provided with a synchronized IEEE-1588 time using an Ethernet switch. The same switch was used to route data from the nTTU-2600 devices to a laptop computer.

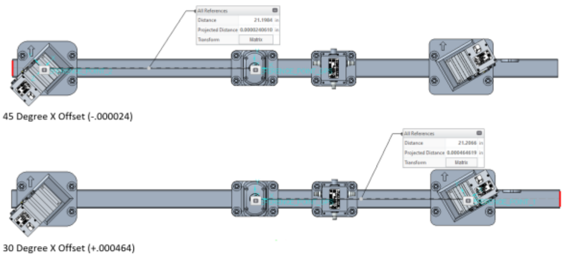

Figure 5. nTTU-2600 Test Fixture Design

Establishing Test Criteria And Limits

Multiple road test runs were conducted, and various TSPI parameter data were collected for analysis. The parameters included physical locations (latitude, longitude, and altitude) and orientation (heading/yaw). The physical locations measured and estimated by the two nTTU-2600 units were compared to Google maps, and with one another. In order to verify the precision and accuracy of the data, much of the data analysis was done by comparing the results from the two nTTU-2600 units.

The nTTU-2600 design accuracy is provided in Table 1. Each parameter's accuracy is specified as a root-mean-square (rms) value, given the stochastic (random) nature of the errors from the GNSS and IMU sensors. Additionally, the processed results of the two nTTU-2600 units would have a larger rms values, by a factor √2, given that they are linear combinations of stochastic variables[1]. A good example of this is the relative location errors calculated by subtracting identical parameters like latitude or longitude.

In this paper, we present the (i) Distance and (ii) Heading/Yaw results of two separate drives, Drive 1 and Drive 2 as described below.

- Drive 1: GPS Antenna offset to each nTTU-2600 unit was set to zero (0) meters, requiring each nTTU-2600 to provide identical location estimates and similar heading values after the boresight, leverage arms, and orientation corrections are applied. This assumes that the relative physical mounting of the two units is within the heading parameter's accuracy.
- Drive 2: GPS Antenna offset to each nTTU-2600 unit was half of the 1.076878 meter distance between the units. This requires each nTTU-2600 to provide location estimates that are at a distance of 1.076878 meters and similar heading values after the boresight, leverage arms, and orientation corrections are applied. Again, we assume that the relative physical mounting of the two units is within the heading parameter's accuracy.

Horizontal Position / Distance Results

The horizontal position/distance between the two nTTU-2600 units were calculated using the Haversine formula[2] for both Drive 1 and Drive 2.

As Drive 1 used a zero (0) offset for the GPS Antenna location, the relative distance between the two nTTU-2600 estimates is expected to have a mean value of zero (0) meters and be within the unit's rms (standard deviation) value of 1 meter increased by a factor of √2, thus imposing a limit of 1.414 meters for the calculated values rms (standard deviation).

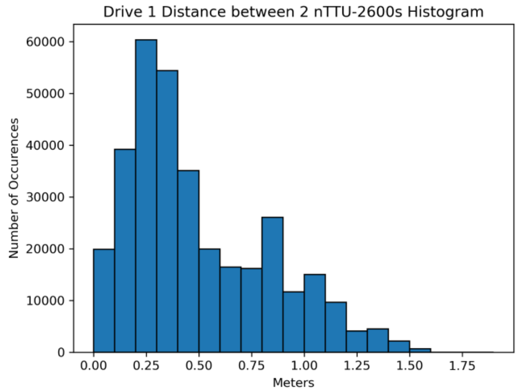

Figure 6. Drive 1 Distance Histogram

Likewise, as Drive 2 used a GPS Antenna offset of 1.076878 meters, the relative distance between the two nTTU-2600 estimates is expected to have a mean value around 1.076867 meters and be within the unit's rms (standard deviation) value of 1 meter increased by a factor of √2, thus imposing a limit of 1.414 meters for the calculated values rms (standard deviation) about the 1.076878 meters mean value.

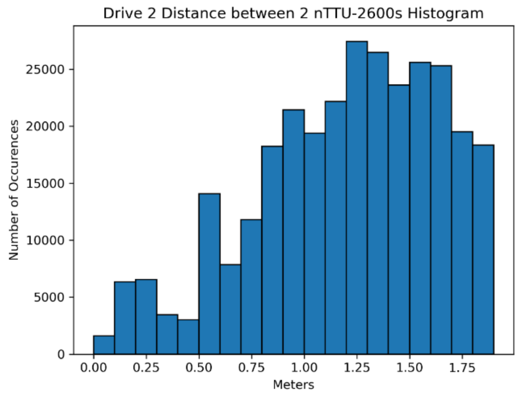

Figure 7. Drive 2 Distance Histogram

For Drives 1 and 2, the calculated distance between the two nTTU-2600 units is shown as histograms in Figure 6 and Figure 7 respectively.

Figure 6, for Drive 1, shows a peak around 0.25 meters instead of the expected zero (0) meter mean value, but almost all of the 400,000 data points are within the 1.414 meters limit for the calculated rms (standard deviation) for the location. In fact, a significant number of the data points are within 1 meter, implying that the native nTTU-2600 location accuracy is much better than the stated 1 meter rms accuracy.

Figure 7, for Drive 2, shows a peak around 1.25 meters instead of the expected 1.076878 meter mean value, but almost all of the 400,000 data points are within the 1.414 meters limit for the calculated rms (standard deviation) about that mean value. In fact, a significant number of the values are between 0.75 meters and 1.75 meters, implying that the native nTTU-2600 location accuracy is much better than the stated 1 meter rms accuracy.

The distance between the two units, as a function of time, are provided in Figure 8 and Figure 9 for Drive 1 and Drive 2 respectively.

Figure 8, for Drive 1, shows the expected zero (0) mean value as a green line and expected rms (standard deviation) of 1.414 meters as a red line. The calculated relative distance between the two nTTU-2600 units is almost always within the expected rms value of 1.414 meter. The dotted blue line shows the calculated standard deviation value of 0.335 meters for all the Drive 1 relative distance measurements, as compared to the 1.414 meter limit, a difference of 0.675 meters better performance than the limit.

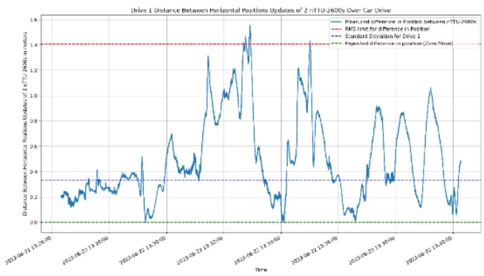

Figure 8. Distance Between The Two TSPI Units – Plotted For Drive 1

Figure 9, for Drive 2, shows the expected 1.076878 meter mean value as a green line and expected rms (standard deviation) limit of 2.491 meters (1.414 meters rms + 1.076868 meter mean) as a red line. The calculated relative distance between the two nTTU-2600 units is almost always within the expected rms value of 2.491 meter. The dotted blue line shows the calculated standard deviation value of 1.752 meters for all the Drive 2 relative distance measurements, as compared to the 2.491 meter limit, a difference of 0.738 meters better performance than the limit.

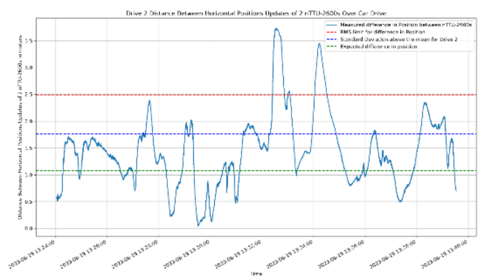

Figure 9. Distance Between The Two TSPI Units – Plotted For Drive 2

Heading / Yaw Results

The heading/yaw results from the two nTTU-2600 units, are compared for Drive 1 and Drive 2. In contrast to the location calculations, the yaw results for both units and for both drives are expected to be identical as the nTTU-2600 boresight, leverage arms, and orientation corrections would remove the mounting dependencies. Our carefully designed experiment used 3-D printed mounting blocks to achieve the roll of 45 degrees and a yaw of 135 degrees for one unit, while the other was mounted with a roll of 30 degrees and a yaw of -30 degrees. However, both units were mounted to the cargo van's roof rail using U-bolts and there might be slight mismatches in relative orientation leading to a bias in the measured/calculated yaw results, as described below.

The heading/yaw results from each nTTU-2600 were converted to a range between -180 degrees and +180 degrees relative to true north, and then subtracted from one another. Ideally, the subtracted values should provide a zero (0) mean and be within the specified nTTU-2600 rms values increased by a factor of √2 for the linear processing of two stochastic variables.

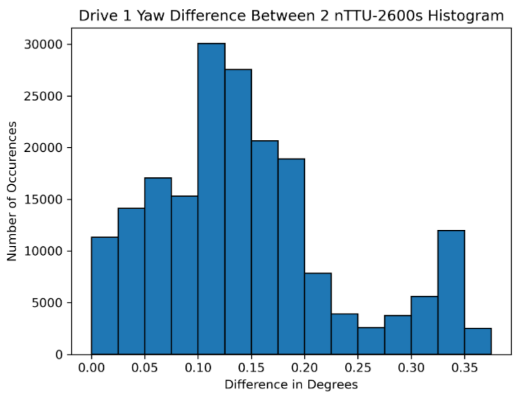

Figure 10. Yaw Difference For Drive 1

Figure 10 shows the histogram of calculated heading/yaw differences between the two nTTU-2600 units for Drive 1. The peak value is about 0.11 degrees and shows a possible bias in the relative mounting between the two units. However, the maximum difference in yaw estimates between the two units is less than 0.35 degrees thereby highlighting the highly accurate estimates from the nTTU-2600 units.

Figure 11 shows the histogram of calculated heading/yaw differences between the two nTTU-2600 units for Drive 2. The peak value is about 0.19 degrees and shows a possible bias in the relative mounting between the two units. Also note that for Drive 2, the nTTU-2600 is also using the relative distance of 1.076878 meters in its calculations as it arrives at a yaw solution, thus possibly accounting for the difference between the Drive 1 and Drive 2 end results. However, the difference in yaw estimates between the two units is still less than 0.35 degrees thereby highlighting the highly accurate estimates from the nTTU-2600 units.

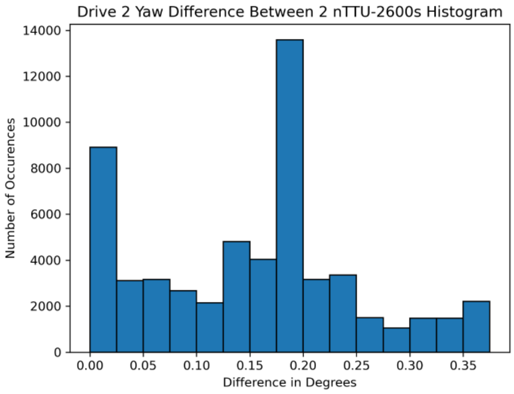

Figure 11. Yaw Difference Drive 2

Conclusion

This paper presents details of a miniature TSPI unit, model nTTU-2600 from Curtiss-Wright that provides high accuracy TSPI data within 1 meter rms horizontal and 1.5 meter rms altitude and less than 0.1 degrees rms for pitch, roll, and yaw. The nTTU-2600 includes a GNSS receiver that also supports Satellite-Based-Augmentation-System (SBAS) and a miniature IMU, for navigation solutions calculated by a Kalman filter at updates rates up to 400 Hz. The field tests carried out by Curtiss-Wright demonstrate and validate the specifications of the nTTU-2600. Additional results from current field tests and from airborne tests, if available, will be provided at our presentation during the International Telemetry Conference 2023.

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