TIME SYNCHRONIZATION IN FLIGHT TEST DATA ANALYSIS

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ABSTRACT

A recurring problem in flight testing navigation systems is the need for an accurate, common time reference for the system under test and for the truth source to which it is compared. Lockheed Martin Aeronautics Company and Computer Sciences Corporation have developed software that utilizes all available timing information to reference the times of validity for each navigation measurement to Coordinated Universal Time. This permits accurate comparison and correlation of data necessary for statistical error analysis of the navigation system.

KEY WORDS

Time Synchronization, Flight Test Data Analysis, Navigation Accuracy, UTC, Navigation Systems

INTRODUCTION

The evaluation of an airborne navigation system's position and velocity accuracy requires that a common time reference be applied to measurements from each system under test and the truth source to which each system is compared. The requirement for a common time reference has become necessary as increasingly stringent accuracies currently specified for state-of-the-art navigation systems, typically containing a Global Positioning System (GPS) receiver and other navigation aids, may exceed the errors induced by a lack of time synchronization of the data measurements. For instance, at typical aircraft velocity and attitude rates, a 1 millisecond timing error may yield a position error of 1 foot and velocity errors exceeding 0.5 ft/sec. An accurate navigation aid on a highly dynamic platform must provide a time of validity for its navigation solution output; any error in this time of validity is effectively an error in its position or velocity solution, and counts against the system's measured performance. To verify performance in flight test, there are additional requirements on the flight test instrumentation and data reduction processes, stemming from the need to compare the system under test with an independent navigation truth source.

In order to facilitate accurate error analysis of advanced F-16 navigation systems, Lockheed Martin Aeronautics Company and Computer Sciences Corporation have developed software which applies a common time reference to measurements from each navigation source under comparison, interpolates the measurements to common points in time, and transforms the measurements into a common spatial coordinate system.

On F-16 flight data recordings, the time associated with the recorded navigation measurements is the time of transmission of the data digitally onto an asynchronous MIL-STD-1553 multiplexed ('mux') data bus, rather than the time that the data was actually valid, as measured by the navigation subsystem. This time of transmission is generally provided by a time code generator, installed as part of the flight test instrumentation equipment. However, the delay between the time of the navigation solution measurement, or time of validity, and the time of transmission to the mux bus varies, so that the data recorded from different subsystems is asynchronous. Additionally, the Time Space Position Information (TSPI) navigation solution, which is the flight test range's truth source against which onboard airborne navigation systems' accuracy is measured, is recorded separately and must then be synchronized in time with the mux recordings.

The "NAVTOOL" time conversion software was developed to provide a common time reference for analysis of navigation flight data, by defining the time associated with each recorded navigation data point as a Coordinated Universal Time equivalent to the time of measurement, rather than the time of transmission onto the mux bus. This software resolves the time asynchrony between data recorded from various navigation systems by making use of "time tag" values (embedded in time-critical avionic subsystem data blocks) and Coordinated Universal Time data (embedded in the GPS data block).

AVIONIC SYSTEM TIMING

An avionic subsystem's time tag is a key component in the time conversion process of replacing time of transmission with time of measurement. In order for some avionic subsystems to communicate time critical measurements to each other over the mux bus, a time stamp, or time tag, is provided by the subsystem along with the measurement data transmitted on the mux. These time tags indicate the time at which the measurement data was valid, and are generated by a 16 bit time tag counter internal to the subsystem. These time tag counters, having a least significant bit of 64 microseconds, will reach their maximum count, equal to 4,194,240 microseconds, and roll over to zero if not reset by an external source. It is one of the 1553 bus controller's tasks to keep all time tag counters in each avionic subsystem synchronized, and thereby minimize the accumulation of drift error. The bus controller does this by periodically resetting all the time tag counters for individual avionic subsystems to the value kept by its own avionic system clock; this value is referred to as avionic system time.

The counters are reset, one at a time, by use of a mode code reset command on the 1553 mux bus, with or without an associated data word. The first avionic subsystem to receive a reset command (generally the Inertial Navigation System (INS)) receives a reset command without a data word from the bus controller; thus the counter is reset to zero. The time tag counters for other subsystems are then reset sequentially, using a mode code reset command with a data word. The value in the data word is the avionic system time elapsed since reset, which the bus controller has read off of its own system clock just prior to sending a reset command to another time tag counter; that counter is then reset to the value of this data word. Thus, after all time tag counters have been reset, they report the same time, avionic system time. Note that once started, the reset commands are sent contiguously, so that minimal time elapses between the resetting of the INS time tag counter and resetting of the last time tag counter in the series.

After all time tag counters are reset, they are allowed to increment for a specified period of time. This interval is currently mechanized for 3.84 seconds on most F-16 production aircraft. The actual reset interval, or epoch, will vary slightly from cycle to cycle due to the asynchronous nature of the 1553 bus and varying bus duty cycle loading. After the interval has elapsed, the time tag reset sequence is repeated, starting with the INS time tag counter which is reset to zero, as described above. This interval of time from one reset sequence to the next, is referred to as a time tag epoch, and the value of the avionic system time at each system reset is transmitted as a parameter to the mux recording.

NAVTOOL SUBROUTINE: TIME CONVERT

At the heart of the time conversion routine lies the fact that the GPS navigation solution data block contains both an avionic subsystem time tag and a record of the Coordinated Universal Time for which the GPS measurement was valid. Since these parameters refer to the same point in time, they provide a means of converting avionic system time to Coordinated Universal Time, referred to as UTC, (Universal Time Coordinated).

The time conversion routine determines the times of validity of time-tagged data in terms of UTC during post flight data processing. UTC is obtained from the GPS recorded data blocks and represents seconds past midnight; therefore, it is a continuous, monotonically increasing time reference during each particular day, and is the ideal parameter for comparison and interpolation of flight test data. UTC time is desirable as a time base because long term accuracy of UTC as measured by the GPS receiver is greater than that of the mux recording source clock, and the resolution of UTC is 1 nanosecond versus a typical mux recorder clock’s resolution of 1 millisecond. Additionally, UTC is normally the time to which TSPI measurement data is referenced; therefore, conversion to UTC automatically provides a common time base for comparison with TSPI.

Since the onboard GPS receiver measures position by measuring time, accurate time is a normal byproduct of its navigation algorithm. This process may be viewed as a transfer of time from the atomic clocks on the satellites via radio frequency signals to the clock in the GPS receiver, which must perform highly accurate time measurements in order to meet GPS position accuracy requirements.

The time conversion process handles avionic subsystems of two categories:

- those subsystems whose measurement data are tagged with the value of the avionic system time. This time tag is then available for algorithm use to synchronize the measurement data from these subsystems.

- those subsystems without time tags, and thereby must be assumed to contain measurement data valid at the time of transmission on the mux recording.

Time Conversion for Time-tagged Avionic Subsystems

The method of converting the time of validity of time-tagged data on the 1553 mux bus from avionic system time to UTC is given below. It must be noted that the accuracy of the resulting UTC time is limited by the accuracy of the 1553 time tag counters (approximately 1 msec). The UTC time at avionic system clock reset, the beginning of a time tag epoch, can be computed as follows:

$UTC_{reset} = UTC_g – T_g$

where UTC_{reset} = UTC time at avionic system reset
UTC_g = UTC time of GPS measurement (embedded in GPS data block)
T_g = time tag value of GPS data block

The UTC time of validity (measurement) of a time-tagged avionic subsystem data block can then be computed as follows:

$UTC_i = UTC_{reset} + T_i$

where UTC_i = UTC time of measurement of time-tagged avionic subsystem (such as INS) data
UTC_{reset} = UTC time at avionic system clock reset
T_i = time tag value of this avionic subsystem data block

The UTC time of validity of a time-tagged data block in an epoch without valid GPS data can still be computed if GPS data is valid in the previous data block. First, calculate UTC at avionic system time reset for the previous epoch having valid GPS data, as follows:

$UTC_{reset}(previous) = UTC_g(previous) - T_g(previous)$

where $UTC_{reset}(previous)$ = UTC time at avionic system reset for the previous epoch
$UTC_g(previous)$ = UTC time of measurement of valid GPS data
$T_g(previous)$ = time tag value of valid GPS system data

Then compute UTC for a data block in the epoch without valid GPS data, by using a parameter available from the mux recording which contains the value of the avionic system time at system reset (epoch length), as follows:

$UTC_{reset} = UTC_{reset}(previous) + T_r$

where UTC_{reset} = UTC time at avionic system clock reset
$UTC_{reset}(previous)$ = UTC time at avionic system reset for the previous epoch
T_r = avionic system time at system reset (time elapsed between $UTC_{reset}(previous)$ and UTC_{reset})
Note that if more than one epoch has elapsed before finding a previous epoch with valid GPS data, then T_r represents a sum of each T_r for all intermediate epochs

Alternatively, the UTC time of validity of a time-tagged data block in an epoch without valid GPS data could be computed if GPS data is valid in a subsequent epoch having valid GPS data, as follows:

$UTC_{reset}(next) = UTC_g(next) - T_g(next)$

where $UTC_{reset}(next)$ = UTC time at avionic system reset for a following epoch having valid GPS data
$UTC_g(next)$ = UTC time of measurement of valid GPS data block
$T_g(next)$ = time tag value of valid GPS data block

Then compute UTC for the epoch without valid GPS data as follows:

$UTC_{reset} = UTC_{reset}(next) - T_r$

where UTC_{reset} = UTC time at avionic system clock reset
$UTC_{reset}(next)$ = UTC time at avionic system reset for the next valid GPS data block
T_r = avionic system time at system reset (time elapsed between UTC_{reset} and $UTC_{reset}(next)$
Note that if more than one epoch has elapsed before finding a subsequent epoch with valid GPS data, then T_r represents a sum of each T_r for all intermediate epochs

Then compute UTC for a data block in an epoch preceding valid GPS data as follows:

$UTC_i = UTC_{reset} + T_i$

where UTC_i, UTC_{reset} and T_i are as already defined

Time Conversion for Non-time-tagged Avionic Subsystems

We cannot determine the UTC equivalent of the time of data measurement by non-time-tagged avionic subsystems, due to the absence of the time tag itself. Without a time tag, there is no tie between UTC time at avionic system clock reset and the measurement time of a data point. Therefore, the best that can be done for non-time-tagged data is to identify their times of transmission onto the mux bus flight data recording and convert that time into UTC so that all data (time tagged or not) will have a common time base. Note that the delta between the time of measurement and the time of transmission onto the flight data recording will, in the case of non-time-tagged data, contribute to a timing error. This timing error can be minimized if non-time-tagged data blocks have a high rate of transmission relative to the rate of change in the data values.

Flight data recordings of mux data bus traffic stamp all transmissions on the mux bus from each avionic subsystem with a time provided by time-code generators onboard the flight test aircraft. This time stamp on each data block is encoded in IRIG (Inter-Range Instrumentation Group) format, and is therefore commonly referred to as IRIG time. To replace the IRIG time of data transmission for non-time-tagged avionic subsystem data with UTC, an offset delta is first computed between UTC and IRIG times at the instance of avionic system clock reset for each epoch, using data obtained from the GPS data block as described previously. This offset is then added to the IRIG time of transmission for each non-time-tagged data block in the epoch to obtain the corresponding UTC time of transmission. The replacement of IRIG time with UTC avoids errors or time zone differences induced by the IRIG time code generator. If the IRIG time code generator were disciplined by a GPS receiver or atomic clock, or otherwise synchronized to UTC, this step would not be necessary.

To compute this offset delta, UTC and IRIG times at avionic system clock reset must be obtained. Recall that the UTC value at avionic system clock reset is found by subtracting the value of the GPS measurement time tag from the corresponding UTC value at measurement. The IRIG time at avionic system clock reset is the time when the Bus Controller commands avionic subsystems via a mode code to reset their time tag counters in synchrony with the avionic system clock. The IRIG time at system clock reset may be obtained for each epoch directly from the mux recording of this mode code reset command. If IRIG/UTC time at system reset are not available then NAVTOOL obtains the necessary delta correction factor from the nearest epoch that had a IRIG/UTC time at system reset correlation.

Similarly, if a break in the mux flight data recording occurs, and GPS data is unavailable when recording resumes, the nearest available offset delta is utilized to resume converting IRIG times of transmission on the mux to UTC. Any time-tagged system data will be converted to UTC based on adding the time tag counter values to the UTC at reset approximated using the nearest available offset delta.

NAVTOOL SUBROUTINE: INTERPOLATE

Subroutine INTERPOLATE allows a user to linearly interpolate parameters within a time-converted flight data file triggered by the change in value of another parameter within the file. Since the interpolation occurs at the same time of the trigger parameter it is possible to have parameters from different flight sources at common points in time. This subroutine should be used only after the parameters to be interpolated have been time converted to UTC at time of measurement (for time-tagged subsystems), or UTC at time of transmission (the best that can be done for non-time-tagged subsystems), so they are provided a common time reference for the interpolation to operate on.

Alignment of the measurement data from various avionic subsystems to common points in time is required for accurate error calculations that compare avionic subsystem measurements to one another or to the TSPI truth source. Interpolation to common points in time is also required for any parameters employed in matrix arrays for transforming navigation data from one spatial coordinate system to another (such as inertial platform coordinates to local geodetic east, north, up coordinates).

The user of NAVTOOL software selects the avionic subsystems whose measurements shall be interpolated, and which avionic subsystem's measurements the others shall be interpolated to align with.

NAVTOOL SUBROUTINE: NAVIGATION COORDINATE TRANSFORM

The NAVTOOL software additionally provides for the transformation of velocity measurement data from one coordinate frame to another. For instance, the GPS subsystem parameters are in Earth-Centered Earth-Fixed (ECEF) coordinates, the INS provides velocities in inertial platform coordinates, and TSPI velocities are in a locally level geodetic coordinate frame using east, north, and up coordinates. Before accurate comparisons between parameters from multiple avionic subsystems and TSPI can ensue, the parameters must first be transformed into the same coordinate system. The NAVIGATION COORDINATE TRANSFORM subroutine therefore supports transformations to or from inertial platform, ECEF, and east, north, up coordinate systems.

All subsystem measurement data to be transformed as well as all parameters used in the transformation equations must have been time converted to a common UTC time base prior to the coordinate transformation process, and interpolated to common points in time.

RESULTS

Figure 1 illustrates the adverse effect of timing errors seen in a plot of GPS latitude error measured against TSPI. This figure plots the instantaneous latitude error as well as the root mean square (rms) error over time. The numeric value of the rms error is given at the top of the figure, as well.

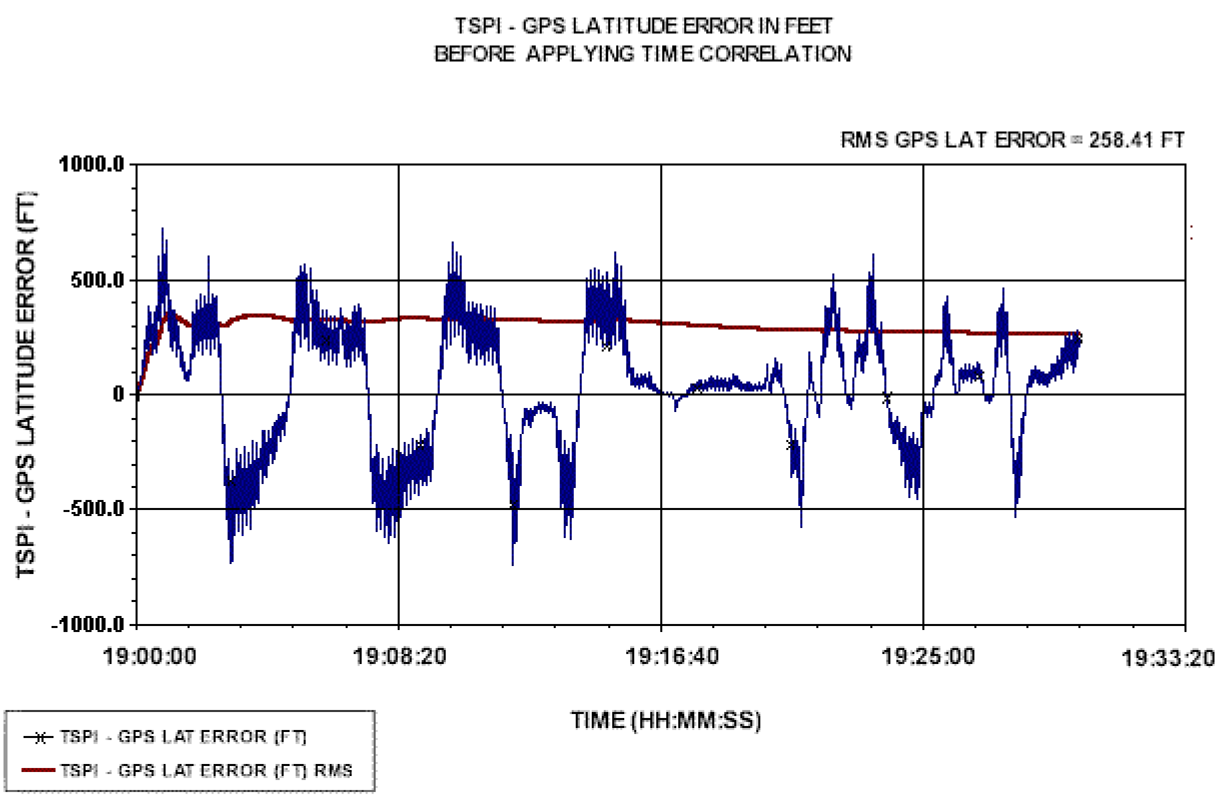

Figure 1. GPS Latitude Error prior to time alignment software

Figure 2 provides GPS latitude error measured against TSPI for the same data sample following the application of NAVTOOL software. Note that the rms error is markedly reduced.

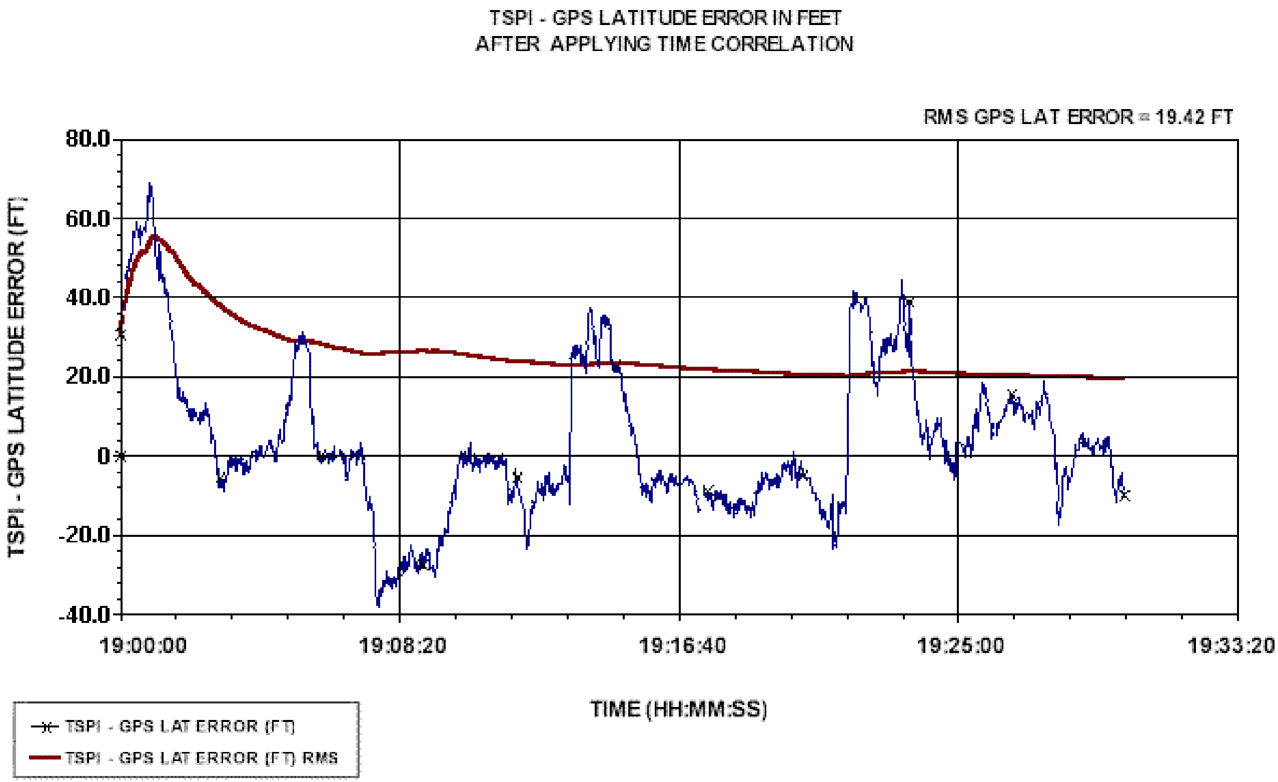

Figure 2. GPS Latitude Error following time alignment software

SUMMARY

In summary, in order to remove timing errors when post-processing flight data recordings of F-16 navigation systems, Lockheed Martin Aeronautics Company and Computer Sciences Corporation developed software which utilizes all available timing information from the aircraft avionic subsystems, including the avionic system time and the onboard GPS receiver's Coordinated Universal Time output. This method allows the times of validity of the measurements performed by each navigation system under evaluation to be accurately referenced to UTC. The truth source (TSPI) measurements also utilize UTC as a time reference, since the time code generator on the TSPI recording system is already calibrated to UTC. After all navigation measurement data are referenced to UTC, interpolation to common points in time and spatial coordinate transformations are performed. In this way, accurate error plots and statistical analyses may be obtained, making it possible to verify the navigation performance of onboard systems in the highly dynamic fighter aircraft environment.