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Data Synchronization Discrepancies in a Formation Flight Control System

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DATA SYNCHRONIZATION DISCREPANCIES IN A FORMATION FLIGHT CONTROL SYSTEM*

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ABSTRACT

Aircraft hardware-in-the-loop simulation is an invaluable tool to flight test engineers; it reveals design and implementation flaws while operating in a controlled environment. Engineers, however, must always be skeptical of the results and analyze them within their proper context. Engineers must carefully ascertain whether an anomaly that occurs in the simulation will also occur in flight. This report presents a chronology illustrating how misleading simulation timing problems led to the implementation of an overly complex position data synchronization guidance algorithm in place of a simpler one. The report illustrates problems caused by the complex algorithm and how the simpler algorithm was chosen in the end. Brief descriptions of the project objectives, approach, and simulation are presented. The misleading simulation results and the conclusions then drawn are presented. The complex and simple guidance algorithms are presented with flight data illustrating their relative success.

NOMENCLATURE

AFF	Autonomous Formation Flight
ARTS	Airborne Research Test System
e	error signal
G	low-pass filter
GPS	global positioning system
i	frame number
INS	inertial navigation system
n_1	GPS relative position error (high frequency)
n_2	INS relative position error (low frequency)
PCM	pulse code modulation

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PSFCC	production support flight control computer
s	Laplace operator
SRA	Systems Research Aircraft
t	time
UTC	coordinated universal time
v	velocity
x	position
x_1	GPS relative position measurement
x_2	INS relative position measurement
z	true relative position
Δt	time difference

INTRODUCTION

Flight testing often is an iterative process of testing, modifying, and retesting. Even with the use of high-fidelity simulations, the iterative nature persists. In most cases, simulation testing reduces the number of iterations; however, misleading simulation results can have the opposite effect. This report presents a chronology illustrating the effects of such a problem experienced by the Autonomous Formation Flight (AFF) project.

The AFF project is attempting to realize fuel savings by autonomously flying an aircraft in the induced vortex of a leading aircraft, which necessitates accurate relative position estimates. The AFF project reaches these estimates by combining global positioning system (GPS) and inertial navigation system (INS) information using a complementary filter. Time delays, inherent in the combined system, require the use of a position synchronization algorithm. The project initially used a simple algorithm; however, complexity was added to the synchronization algorithms in response to erroneous simulation test results. The modified algorithm failed in flight as a direct result of the added complexity. The simulation error then was discovered and the original algorithm was reimplemented.

This report provides brief descriptions of the AFF experimental platform, simulation, and relative position estimation method. The initial position synchronization algorithm is presented with the erroneous simulation results that indicate an algorithm deficiency. The second, more complex algorithm is presented with flight data and discussion illustrating its deficiency. The erroneous simulation results and successful flight tests results of the reimplemented initial algorithm are discussed.

AIRCRAFT SYSTEMS

The AFF experiments are flown onboard the NASA Systems Research Aircraft (SRA).[1] The SRA is an F/A-18 airplane that has special research computers known as production support flight control computers (PSFCCs). The PSFCCs consist of a research processor, containing

research control laws, interconnected through dual-port random access memory to a production processor containing production control laws. The PSFCCs allow the pilot to select the research processor and automatically revert to the production processor when any flight limits are exceeded.[2]

For formation flight experiments, a second NASA F/A-18 acts as the leading aircraft and transmits its state and navigational information through a pulse code modulation (PCM) telemetry system to the SRA. The guidance algorithms then compute and pass the relative positions to a controller using 20-Hz proportional-plus-integral-plus-derivative with state feedback to maintain the desired relative position. The controller inputs are relative position error, relative velocity error, trailing aircraft roll angle, and trailing aircraft normal acceleration. The outputs are roll stick and pitch stick commands; they are used in place of pilot stick commands.

The formation flight guidance and control algorithms are hosted on the Airborne Research Test System (ARTS) computer. A real-time embedded system, the ARTS gathers the aircraft sensor data used in the guidance and control functions and sends computed pitch and roll stick commands to the inner-loop controller contained in the PSFCCs. The PSFCCs, in turn, command aircraft actuator deflections. Figure 1 shows a basic system interconnection.

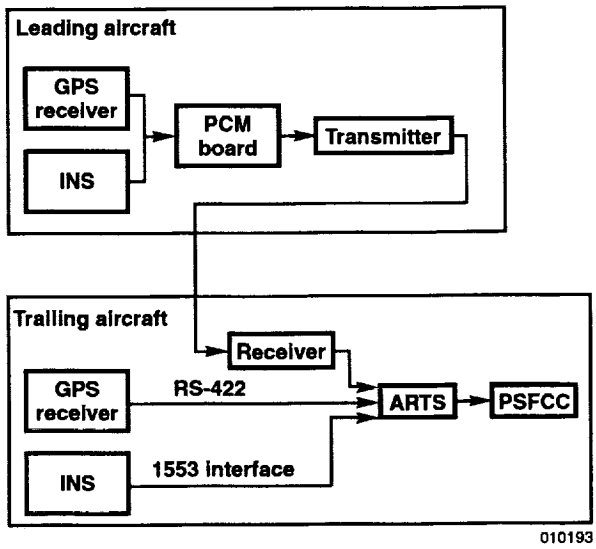


Figure 1. Basic AFF system interconnection.

Ground station–corrected, carrier phase, differential GPS position data are also provided by the SRA. These data are used as a "truth source" with which to compare the algorithm-calculated relative positions. Ground station–corrected data are not used as inputs to the AFF guidance algorithms to avoid reliance upon ground station availability.

THE FORMATION FLIGHT SIMULATION

The NASA Dryden Flight Research Center (Edwards, California) F/A-18 simulator provides a full six-degree-of-freedom, hardware-in-the-loop, nonlinear, real-time simulation. The simulation models the aerodynamics, actuators, sensors, engines, and aircraft telemetry and all pertinent

aircraft systems.[3] The simulation interfaces with a fixed-base cockpit, mission computers, PSFCCs, and an ARTS computer. In addition, telemetry, an IEEE 1553 bus, and computational delays are included in the simulation with estimated noise in the aerodynamic surface commands and movements.

The simulation was expanded to a two-ship formation flight simulation by adding the capability to record and replay an aircraft trajectory. Using a telemetry model, trajectory data are broadcast to the simulated trailing aircraft, simulating air-to-air telemetry. The simulator passes the data to the ARTS computer containing the guidance and control algorithms that compute the roll and pitch stick commands required to maintain formation flight. These commands are passed to the PSFCCs that return computed surface commands to the simulator.

The simulation telemetry model emulates the leading aircraft instrumentation telemetry stream. A PCM simulator board is used for output of a serial PCM-encoded bit stream using data from the simulation computer current value table. The bit stream is passed to the ARTS computer that contains the formation flight guidance and control algorithms. The ARTS functions in concert with the PSFCC computers identically to how it functions onboard the SRA. Figures 1 and 2 show the aircraft and simulation system interconnections, respectively.

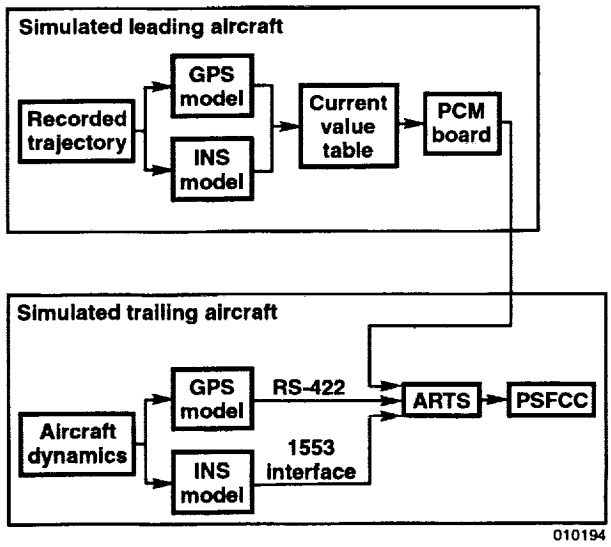


Figure 2. Basic AFF simulation system interconnection.

RELATIVE POSITION ESTIMATES

Close formation flight of aircraft can achieve substantial fuel savings by flying each aircraft in the upwash field generated by all other aircraft in the formation.[4] Requiring a pilot to maintain the required precise relative position during long-distance flights, however, is unreasonable. In such circumstances, an automatic controller is necessary to maintain the formation. To allow good performance of the controller, accurate relative position measurements are needed.

The AFF project estimates relative aircraft position by combining two independent relative position measurements with a complementary filter. The resulting estimate and aircraft state information are input to an automatic relative position controller. The controller then computes

roll and pitch stick commands. These commands are sent to inner-loop flight controls that were developed for previous programs.[2]

The first relative position measurement is obtained by differencing the 2-samples/sec GPS position measurements for both aircraft. With common satellites and close aircraft proximity, ephemeris data errors, satellite clock errors, and atmospheric distortion errors are practically eliminated. Reference 5 provides descriptions of each of these errors. The remaining dominant error is caused by the 2-samples/sec data being processed by the 20-Hz algorithm. The resulting GPS relative position measurement can therefore be represented as:

$$x_1(t) = z(t) + n_1(t) \tag{1}$$

where $x_1(t)$ is the GPS-measured position, $z(t)$ is the true position, and $n_1(t)$ is the measurement error.

A second relative position measurement is obtained using the onboard INS. The primary INS measurement errors are caused by its low-frequency drift and biases. The INS relative position measurement can therefore be represented as:

$$x_2(t) = z(t) + n_2(t) \tag{2}$$

where $x_2(t)$ is the INS-measured position, $z(t)$ is the true position, and $n_2(t)$ is the low-frequency INS errors.

A complementary filter combines the two independent relative position measurements to provide an accurate relative position estimate. Figure 3 shows the filter. By subtracting one measurement from the other, $x_2 - x_1$, the error $e = n_2 - n_1$ is obtained. A low-pass filter,

$$G(s) = \frac{\pi/4}{s + \pi/4} \tag{3}$$

tuned to remove n_1 from e, provides n_2. Subtracting this result from the original measurement $z + n_2$ leaves an accurate position estimate that is used as an input to the formation flight controller. Reference 6 provides a more detailed explanation of complementary filters.

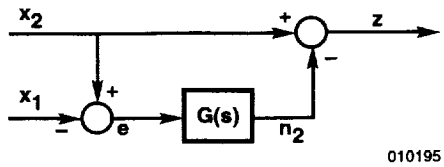


Figure 3. Complementary filter.

POSITION SYNCHRONIZATION LOGIC

Inherent time delays associated with transmitting GPS data from one aircraft to another cause the AFF guidance routines to asynchronously receive positional data. Without time correlation, this asynchronous data leads to large jumps in the relative longitudinal GPS position that the complementary filter is unable to remove. Relative position jumps in the lateral and vertical axis also exist, but these are much smaller than in the longitudinal axis. This characteristic is no surprise; the longitudinal axis has the largest velocity component. The complementary filter is

much more successful in eliminating position jumps in the lateral and vertical axes than in the longitudinal axis.

Figure 4 shows the results of a simulated time delay. In this example, the formation was flying at approximately 600 ft/sec and had a 0.1-sec transport delay between the trailing and leading aircraft GPS updates. The time delay, in combination with the 2-samples/sec GPS signal, caused the trailing aircraft to appear to move ahead of the leading aircraft. The relative position appears to jump more than 300 ft. These jumps are too large for the complementary filter to satisfactorily correct.

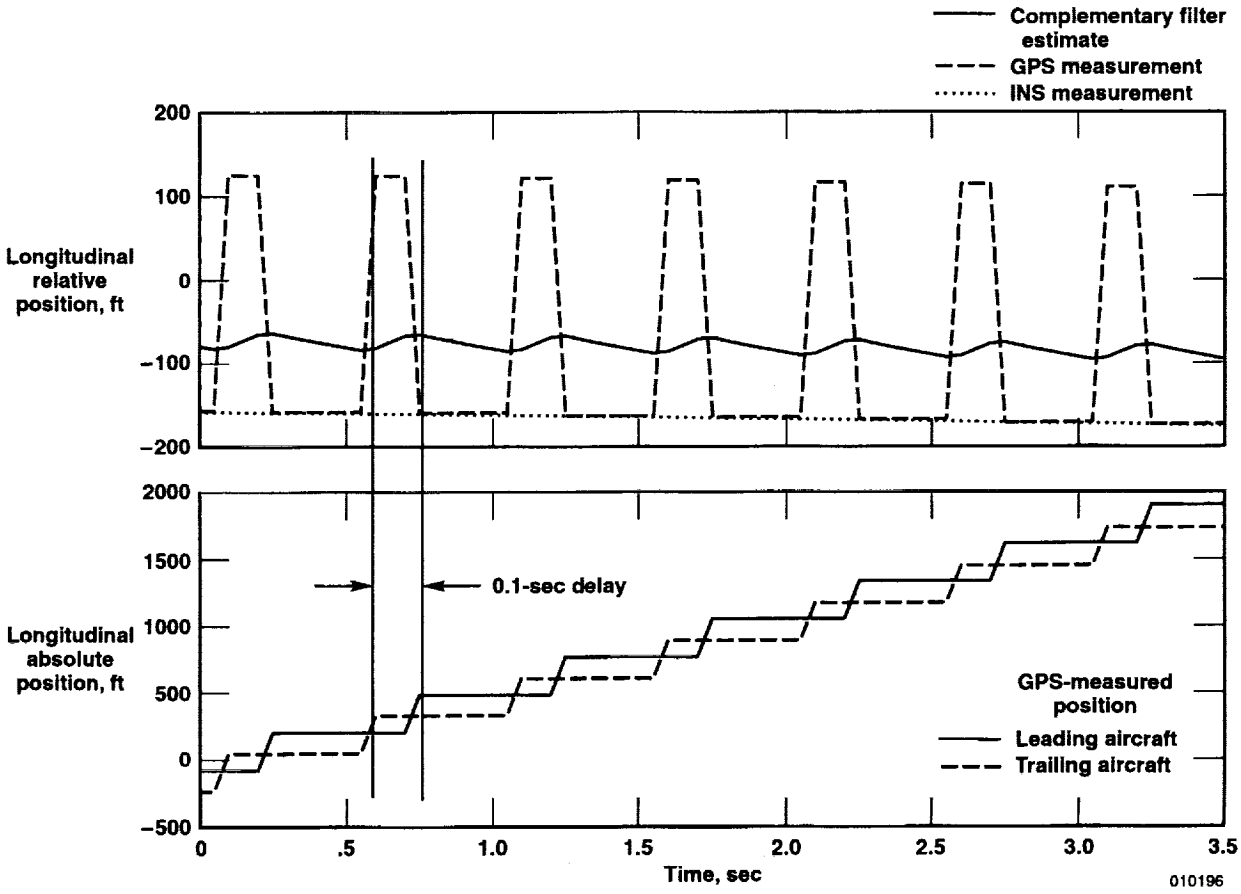


Figure 4. Uncorrected relative position estimates.

Data synchronization logic has been developed to make the combined system robust to such asynchronous GPS data and temporary signal loss. The logic uses the GPS coordinated universal time (UTC) to align the two aircraft position measurements. The logic assumes the UTC and positional measurements are taken at the same time, contained in the same telemetry message, and concurrently received by the algorithm. If the trailing aircraft UTC is larger than the leading aircraft UTC, the leading aircraft position is extrapolated as:

$$x_1 = x_{i-1} + v_i \Delta t \tag{4}$$

where x is the position, v is the velocity as reported by the INS, i is the frame number, and Δt is the time difference between the trailing and leading aircraft updates. Figure 5 shows the UTC-based synchronization algorithm, which compares the leading and trailing aircraft UTC values and extrapolates the position estimate if one is lagging behind the other.

REVISED POSITION SYNCHRONIZATION LOGIC

Implementation of the guidance and control algorithms into the simulation revealed an apparent flaw in the guidance logic. The GPS relative position measurements spiked, causing poor complementary filter estimates. The cause indicated by the simulation was that the assumption of concurrent positional and UTC information was invalid. The guidance logic therefore had calculated the relative positions with asynchronous GPS positional information, which caused the spikes.

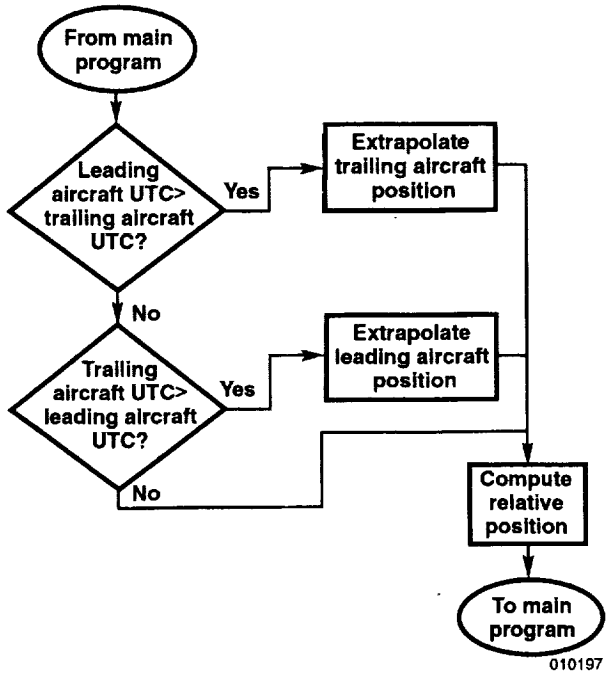


Figure 5. UTC-based synchronization logic.

A general algorithm, based directly on the position information, was then designed to be independent of the UTC. More complex than the UTC-based logic, this position-based algorithm works directly with the GPS positional data. The new logic, as with the old, extrapolates missing positions using velocity information until both trailing and leading aircraft updates are acquired.

Figure 6 shows the logic. For example, upon receiving a GPS position update for the leading aircraft, the position-based logic checks whether a GPS position update for the trailing aircraft has also been received. If not, the logic determines if it has received the trailing aircraft GPS position update in a previous frame by checking whether a logical flag, the trailing aircraft bit, has previously been set high. If the bit is not high, a second logical flag, the leading aircraft bit, is set high to indicate that a leading aircraft update has been received. The trailing aircraft position then is extrapolated using velocity information and the known GPS sampling rate. If a trailing aircraft update is received in a subsequent frame without a leading aircraft update, the logic checks whether the leading aircraft bit is high. If the bit is high, as it is in this example, both the leading and trailing aircraft bits are reset to low and the relative position calculation continues without extrapolation.

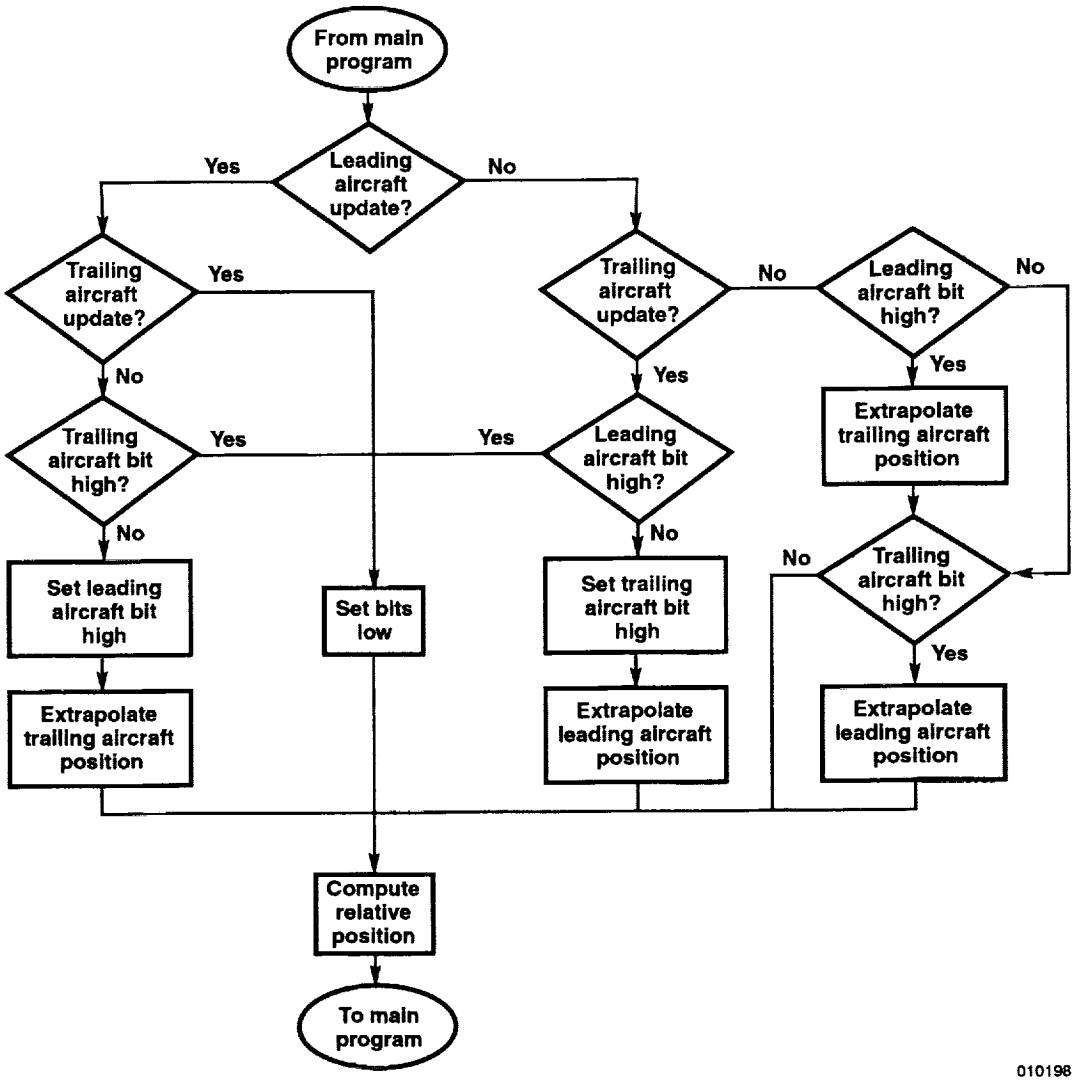


Figure 6. Position-based synchronization logic.

The new logic was tested in the simulation and appeared to work flawlessly. No relative position spikes existed, and the complementary filter successfully combined the INS and GPS measurements. The software then was promoted to the aircraft and used in flight.

POSITION-BASED ALGORITHM FLIGHT TEST RESULTS

Upon execution of the new software in flight, large, unexplained, relative position biases became apparent. Figure 7 shows a 300-ft relative position bias reported by the complementary filter that disappeared when the guidance algorithm was reset.

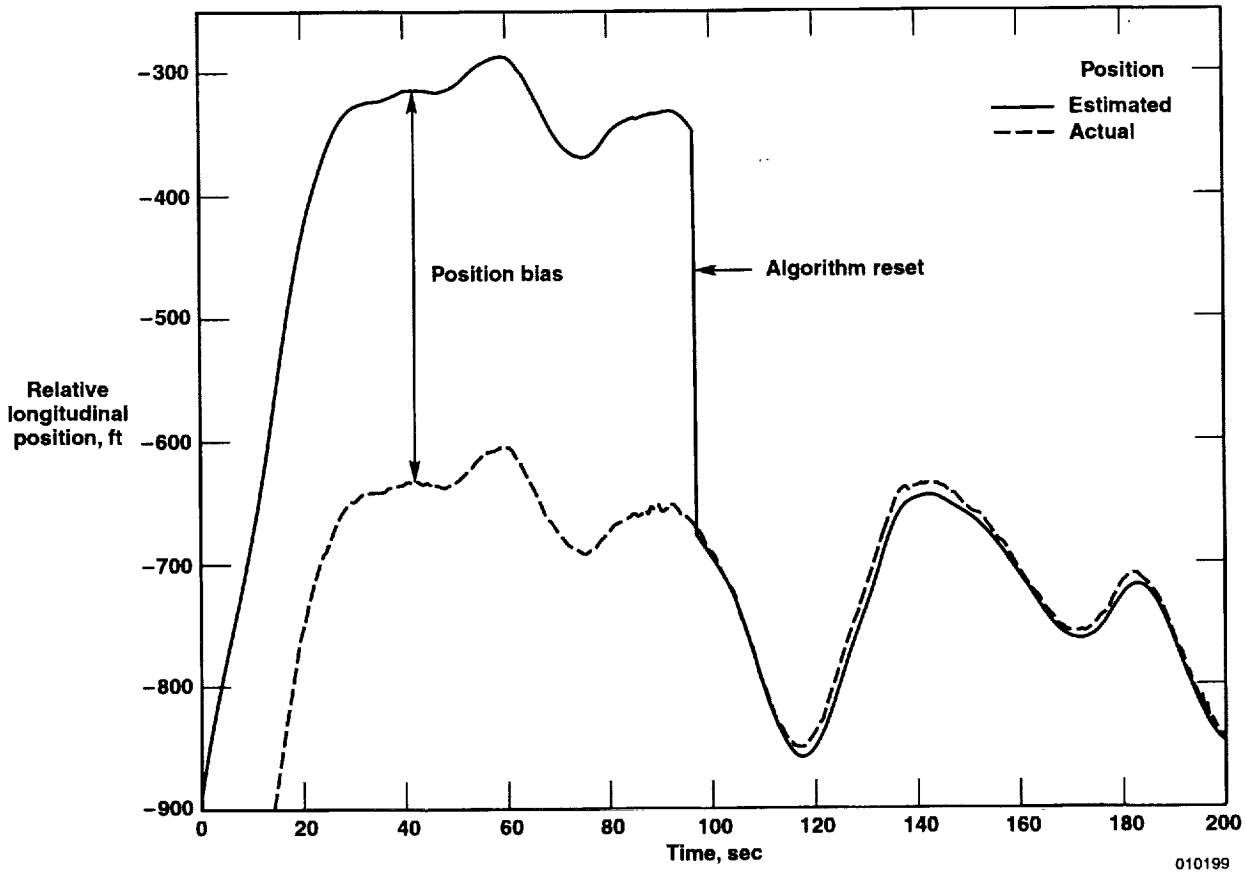


Figure 7. Position bias in flight data.

Close analysis of the data revealed a flaw in the position-based synchronization logic initialization routine. The logic assumes that the system will initialize only when both aircraft are waiting for GPS updates; it does not account for the situation in which one aircraft already has received a GPS update and the other has not. Therefore, the bits upon which the logic relies are initialized into incorrect states. When the algorithm begins in this asynchronous state, unneeded position extrapolations are completed, resulting in a relative position bias. The only way to eliminate the bias is to reset the algorithm until it initializes in a synchronous state.

To correct the algorithm, adding more complex logic to account for the asynchronous initialization state would have been necessary. The same flight, however, revealed that the air-to-air telemetry simulator did not correctly model the PCM message structure. The air-to-air telemetry system puts the positional information in the same message as the UTC, which indicates that the original simulation results are invalid. Not only is the UTC-based algorithm not flawed, it is immune from initialization issues found in the position-based algorithm.

The simulation has been corrected to provide concurrent information from the current value table, and the algorithm has been retested. No relative position spikes were observed, and the algorithm performed well. The complex algorithm therefore has been abandoned and the simpler UTC-based algorithm has been promoted to the aircraft.

TIME-BASED ALGORITHM FLIGHT TEST RESULTS

The guidance algorithm with the UTC-based synchronization algorithm also has been tested onboard the SRA. Throughout the flights, no relative position spikes were observed. The complementary filter successfully combined the GPS and INS relative position measurements returning position estimates with less than a 7-ft error. Figure 8 shows postflight, carrier phase, ground station–corrected differential GPS relative positions compared with the complementary filter outputs.

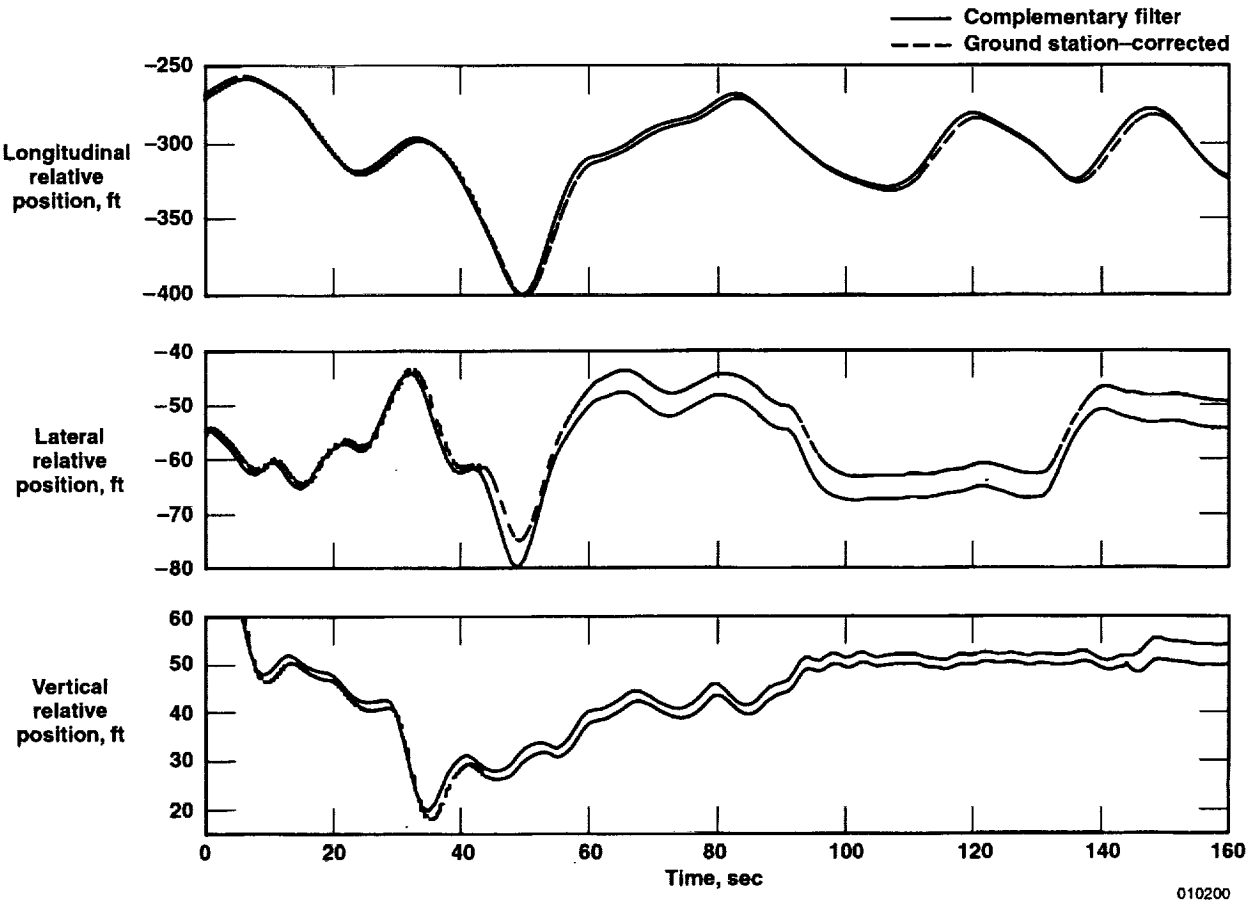


Figure 8. Filter output and ground station–corrected position.

Figure 9 shows the complementary filter inputs and output; figure 10 shows an expanded scale plot with more detail. The plots clearly demonstrate the need for the complementary filter. The GPS measurements are updated only at 2 samples/sec, and the INS-derived measurements slowly drift over time. Alone, each measurement is insufficient. The complementary filter, however, maintains the low-frequency component of the GPS signal and the high-frequency component of the INS signal, producing accurate position estimates.

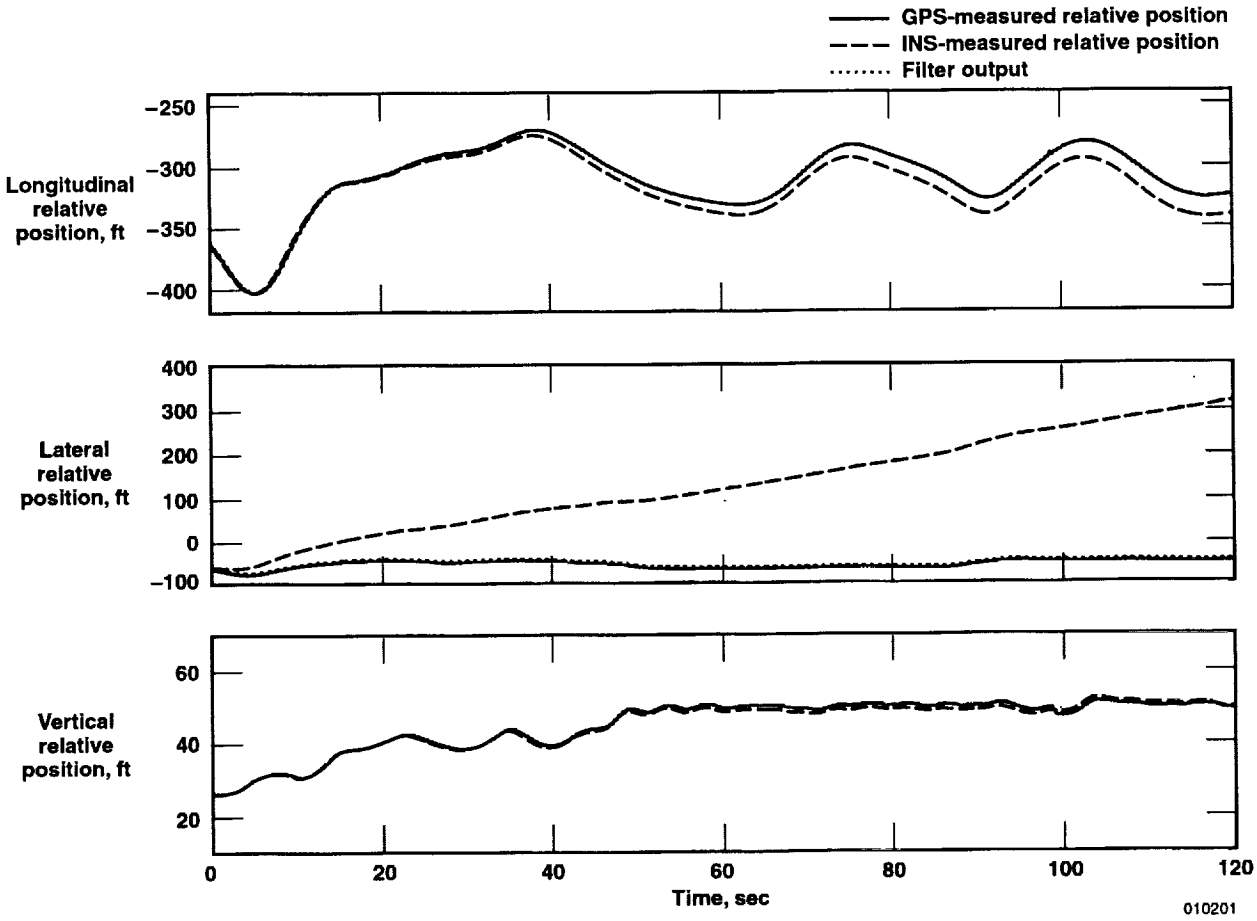


Figure 9. Complementary filter inputs and output.

The effects of the synchronization algorithm are apparent in figure 10. The GPS position estimates are dominated by the nature of the 2 samples/sec, but small changes in relative position estimates are also apparent. These changes are the result of imperfect position extrapolations. When the algorithm is waiting for an aircraft GPS position update, it imperfectly extrapolates the position. When the position update is provided, a small step occurs as the algorithm switches from the estimated to the true position.

The INS-derived relative position drift is caused by small differences in the INS-reported velocities of each aircraft. The velocity difference is integrated to obtain relative position estimates, which exacerbates the velocity differences. A ramping bias is the net result. The drift is especially clear in the lateral axis; a 300-ft drift occurs over a period of 2 min.

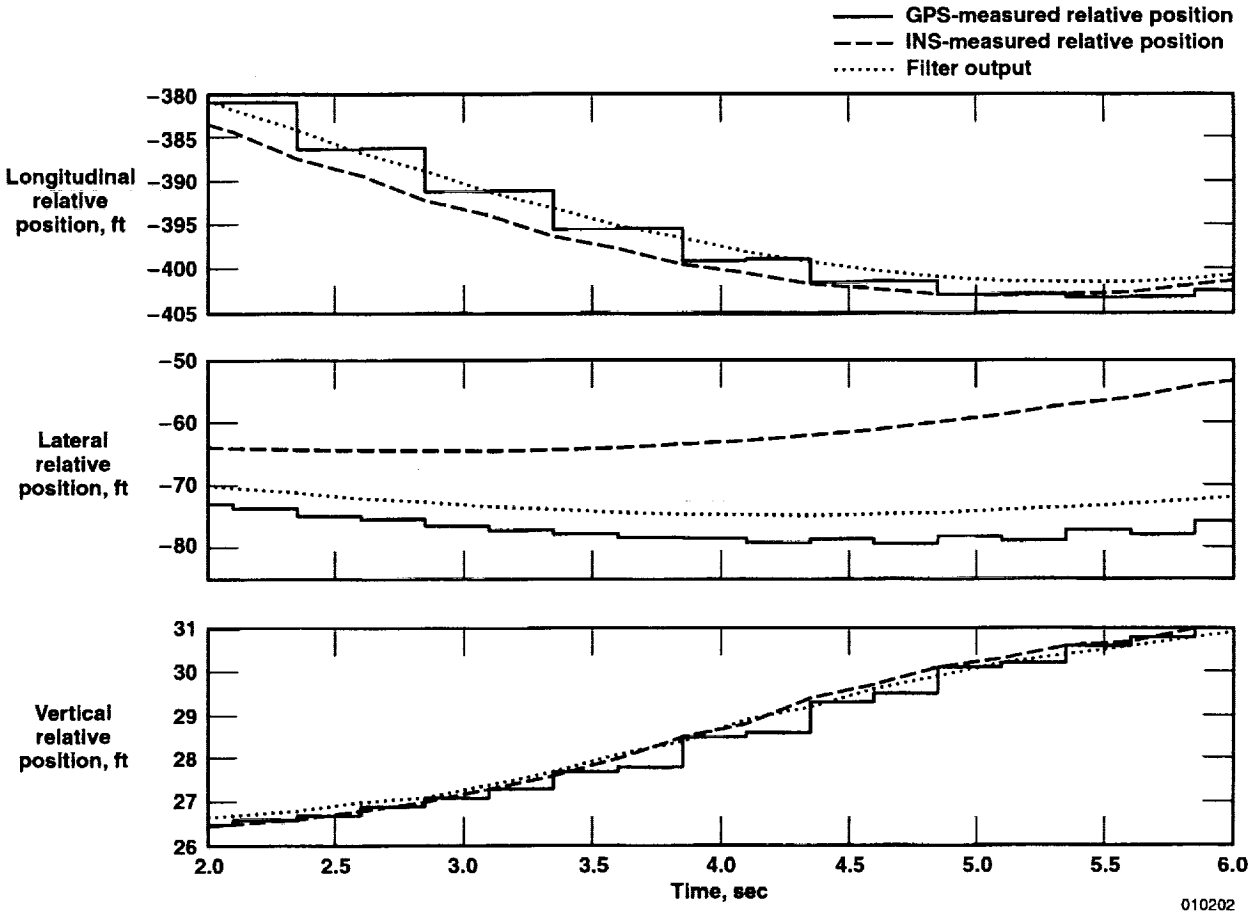


Figure 10. Complementary filter inputs and output (expanded scale)

CONCLUDING REMARKS

This report presented an overview of the Autonomous Formation Flight (AFF) program and its objectives, approach, and use of a complementary filter to obtain relative position estimates. The effects of misinterpreted simulation data on the flight test program were demonstrated.

When the AFF simulation indicated a flaw in a position synchronization algorithm based on coordinated universal time (UTC), the project switched to a position-based algorithm. Tested in the AFF simulation, the position-based algorithm showed potential to work well in flight. The simulation testing, however, did not consider variations in initial states of global positioning system (GPS) updates. Relative position biases caused by initializing in asynchronous states therefore were not detected until flight.

To correct the position-based algorithm, additional complexity would have had to been added. The same flight, however, indicated that the UTC-based synchronization flaw was nonexistent; it was caused by a simulation error. The air-to-air telemetry simulation used a current value table that did not provide concurrent positional and UTC information. The UTC-based algorithm, which was immune from the initialization problem, therefore was reimplemented, tested, and taken to flight. The system was successful in obtaining relative position estimates with less than a 7-ft error.

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