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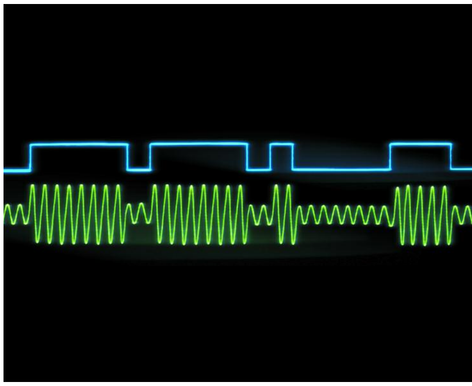
Dynamic Two-Way Time Transfer to Moving Platforms



WHITE PAPER

Dynamic Two-Way Time Transfer to Moving Platforms

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Abstract

Time based communications (TBC) involves the use of an active data channel for time transfer[1]. In 2002, testing was conducted with the Air Force Research Lab (AFRL) at Wright Patterson Air Force Base to demonstrate a TBC implementation from the ground to an airborne platform using standard communications channels and equipment. Algorithms to perform Dynamic Two-Way Time Transfer (DTWTT) have been developed to correct raw time transfer data for platform motion and measurement effects. Flight tests were conducted in November 2002 to demonstrate the algorithms and determine the level of performance that can be expected from dynamic two-way time transfer. Tests were conducted using Satellite Relay links and line-of-sight (LOS) links between the ground and the aircraft. The results from the Satellite Relay case were presented in a PTTI 2002 paper entitled "Two-Way Time Transfer to Airborne Platforms Using Commercial Satellite Modems". The LOS results are presented here.

This paper begins with a review of Dynamic Two-Way Time Transfer for the line-of-sight communications link case. The flight experiment is presented with a description of the data collection hardware as well as a detailed presentation of the flight data. Conclusions on the use of DTWTT are drawn based on the results of the flight tests.

1.0 Time Based Communications

Time-based communications is a technology where an active data communications channel is used as a vehicle for two-way time transfer. Precision timing is provided in the background of an active data transfer channel (one that is being used for data communication). This allows two ends of a communications link to be precisely synchronized without fielding an independent timing system.

Time-based communications (TBC) is a generic technology in which two-way time transfer is accomplished using a communications channel that meets a few basic requirements [1]. Implementation of these concepts has been accomplished over fiber [2] and satellite channels [1,3] with excellent results. TBC has a long history of successes including 20 ps time synchronization over fiber and subnanosecond time synchronization over satellite communications channels.

Dynamic time based communications involves exchanging time via a communications channel between two nodes where one or both of the nodes may be moving. The case considered in this paper is depicted in Figure 1 where time is being transferred from a fixed station on the ground to an aircraft. The standard two-way time transfer calculation [4, 6], assumes that the propagation delays in the send and receive paths (depicted by the green and red lines in Figure 1) are equal. In the dynamic case, this is obviously not true. The aircraft in Figure 1 transmits at one location and receives the signal from the ground transmitter at a different location (assuming that both sides transmit simultaneously, which is typically how two-way time transfer is done). The unequal path delays between the red and the green

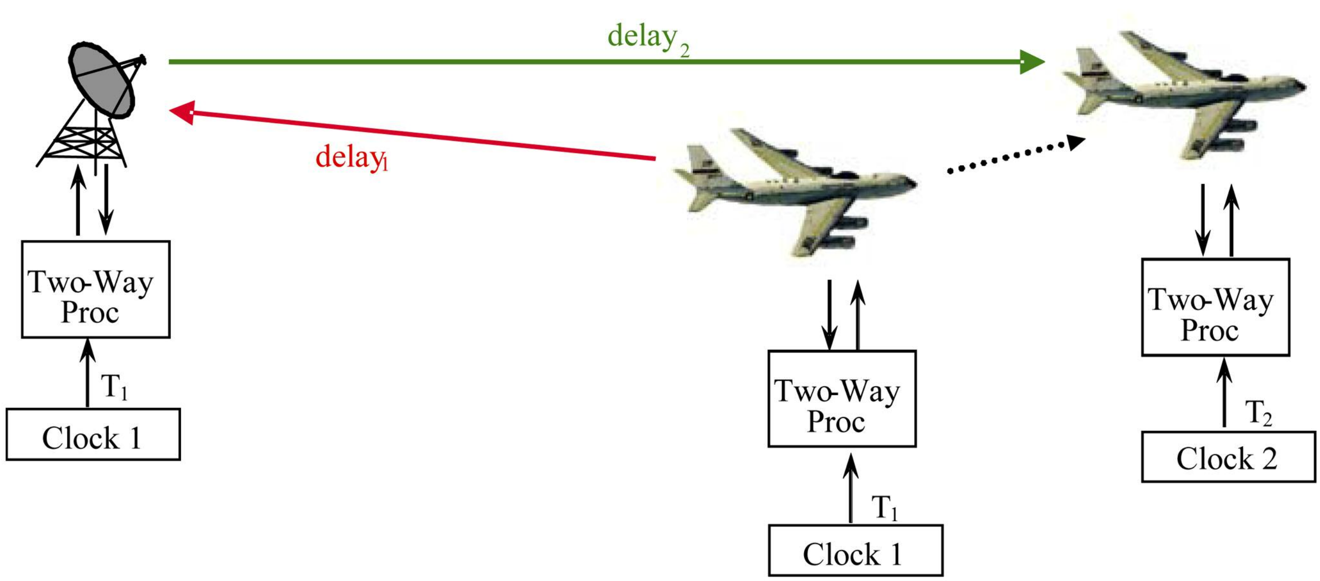

FIG.1 Dynamic Two-Way Time Transfer for LOS Case

paths bias the standard two way equation (where the propagation delays are assumed to be equal). In addition, the Sagnac term for the moving platform becomes time varying based on the change in location of the platform. The dynamic two way time transfer equation can be represented as,

$$T_2 - T_1 = .5*[(Meas_2 - Meas_1) + \Delta prop\_delay + \Delta Sagnac]. \quad (1)$$

where,
Δprop_delay = change in the propagation delay over the measurement interval and ΔSagnac = Sagnac time-of-flight correction between node 1 and node 2 [5, 6].

The Δprop_delay is a time varying value that depends solely on platform motion during the measurement interval. The ΔSagnac term is a time varying value that depends on the absolute position of the two platforms on the earth. The next section shows the magnitude of these effects for an airborne platform.

2.0 Flight Tests

Flight tests were conducted at Wright Patterson Air Force Base (WPAFB) in November 2002 using a RC-135 aircraft operated by the Air Force Research Lab (AFRL). The RC-135 (seen in Figure 2) is an airborne testbed that provides a laboratory environment supporting airborne terminal developments, on-orbit satellite evaluations, dynamic pointing and tracking algorithms, antenna and radome flight test, communications protocol validation, performance anomaly identification, and interoperability tests. For the dynamic two-way time transfer tests, equipment was installed in the aircraft and on the ground to make the timing measurements. The aircraft includes a Ku band satellite terminal in a radome on the top of the aircraft as well as other antennas for GPS collection, L-band links and other applications.

Nearly identical DTWTT equipment was installed on the aircraft and the ground (Figure 3). Each hardware suite included RF equipment (antenna, upconverter and downconverter) as well as two-way time transfer equipment (modem, measurement chassis and cesium). The modems were commercial satellite communications units that were modified to provide two-way measurements in the background of standard data transmission. The measurement chassis consisted of precision timing equipment including two-channel timers, amplifiers and a controlling computer. The computer was used to control the measurement collection and process the two-way measurements. The aircraft also includes multiple measurement devices (GPS and INS) to determine its location during flight.

The following sections detail the data collected during a flight test in which an L-band direct, line-of-sight communications channel was used between the ground and the aircraft. A point-to-point 1536 kbps QPSK channel with Viterbi 1/2 coding was used in both directions between the ground and the airplane. The ground antenna was a 13 dBi gain Yagi antenna with 30 degree horizontal beamwidth while the aircraft antenna was an omnidirectional blade antenna.

Multiple LOS flights were conducted during the demonstration. The first LOS flight resulted in data quality that was considerably worse than the data quality demonstrated in the satellite relay case [6]. The reduction in performance was determined to be multipath interference that occurred in the LOS case but not in the satellite relay case. As a result of the poor LOS data quality, a second LOS flight was conducted in which an attempt was made to maximize and minimize the effect of the multipath interference on the dynamic two-way calculation. The timing data for the second flight is detailed in the next section.

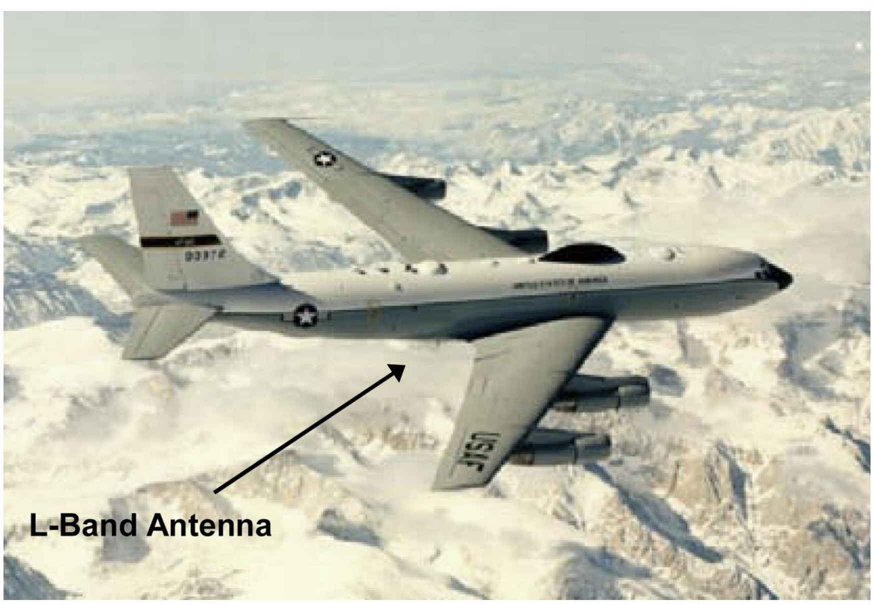

FIG.2 AFRL RC-135 Aircraft

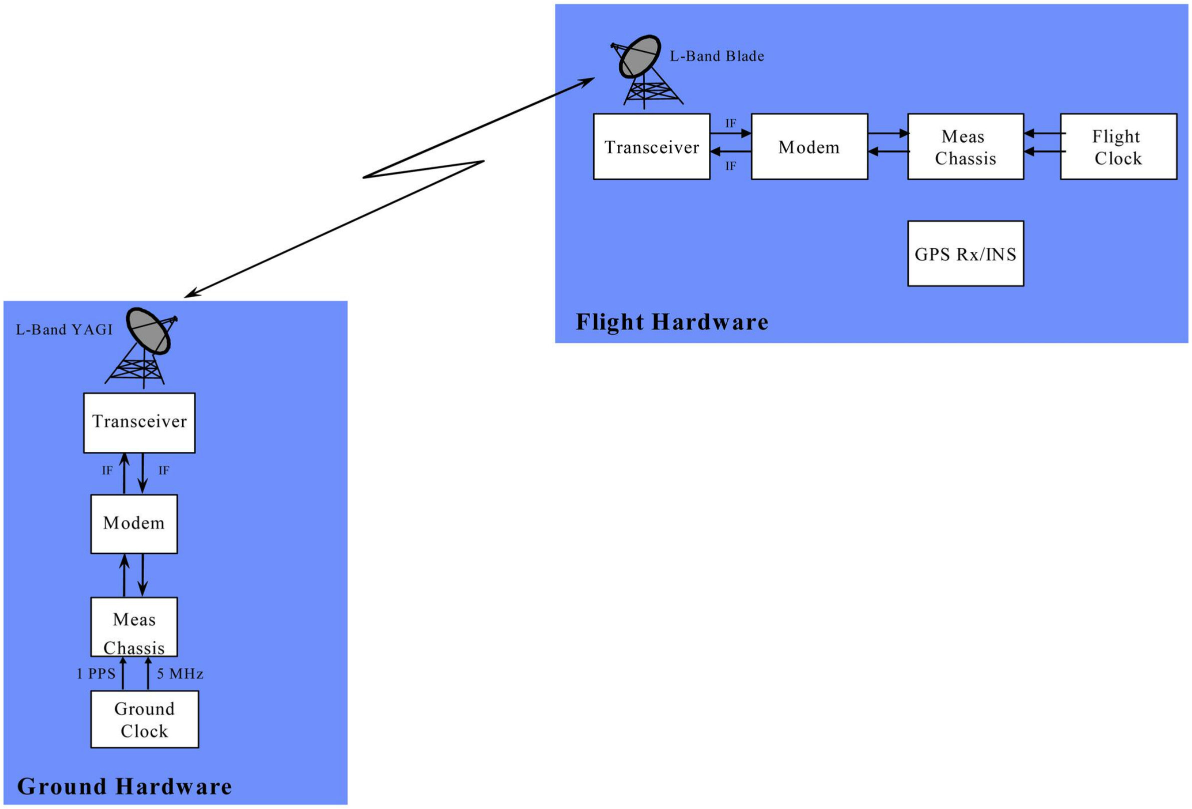

FIG.3 Hardware Configuration

2.1 Flight Data

The collection of clock measurement data provided the best method to verify the ability to create a record of the relative performance of two cesium clocks using DTWTT. The clock difference between the two cesiums was directly measured for at least 24 hours before the flight to establish the drift rate and phase relationship between the two clocks. One of the clocks was moved to the aircraft for each flight where it was measured during flight using DTWTT. After the flight, the clock was removed from the aircraft and returned to the ground measurement system where measurements against the ground clock were resumed. Power was maintained on the flight clock at all times (either AC or battery). The direct measurements between the clocks when they were colocated provided a ground truth for the flight data.

In addition to the ground truth measurements, the in-flight measurements were validated by computing the expected relativistic effects on the flight clock and comparing them with the actual measurement data. Relativistic effects act on the flight clock in a deterministic fashion that can be calculated based on the flight record. By computing the net effect from the gravitational, velocity and Sagnac contributions, a phase difference record between the ground clock and flight clock was computed. This phase record was used as a second method of validating the measurement data.

2.2 LOS Flight on 21 November 2002

A five hour flight was conducted on 21 November 2002 using the L-band line-of-sight configuration detailed above. The flight was divided into four segments where the look angle and/or antenna placement was varied in each segment in order to present the modem with different multipath environments and to determine the effect on the timing measurement. The goal was to present the aircraft with both bad and good environments to bound the timing performance that can be expected when no multipath mitigation is applied. The flight path showing the different segments is presented in Figure 4. The plane took off from Wright Patterson Air Force Base (WPAFB) and flew west to the edge of the ground antenna pattern where segment 1 began. The flight pattern for segment 1 was a trapezoidal pattern between 100 and 150 miles from WPAFB with the ground antenna between two hangars and in front of a chain link fence and the airborne (blade) antenna mounted on the bottom of the aircraft. This scenario was designed to provide the largest multipath contribution at the ground antenna as there were multiple sources for an indirect signal to the ground antenna (see Figure 5). Segment 2 was a repeat of the trapezoidal flight pattern used in segment 1 with the ground antenna moved from between the hangars to the front of one of the hangars as seen in Figure 5 and the aircraft antenna unchanged. Segment 3 used the same antenna locations as segment 2 with a change in the flight pattern from the trapezoidal pattern to a racetrack pattern to and from the hangar (to minimize the aircraft multipath). For segment 4, a blade antenna in the radome of the aircraft was used (instead of a blade antenna on the belly of the aircraft) and the aircraft flew a racetrack pattern that was tangential to the hangar location.

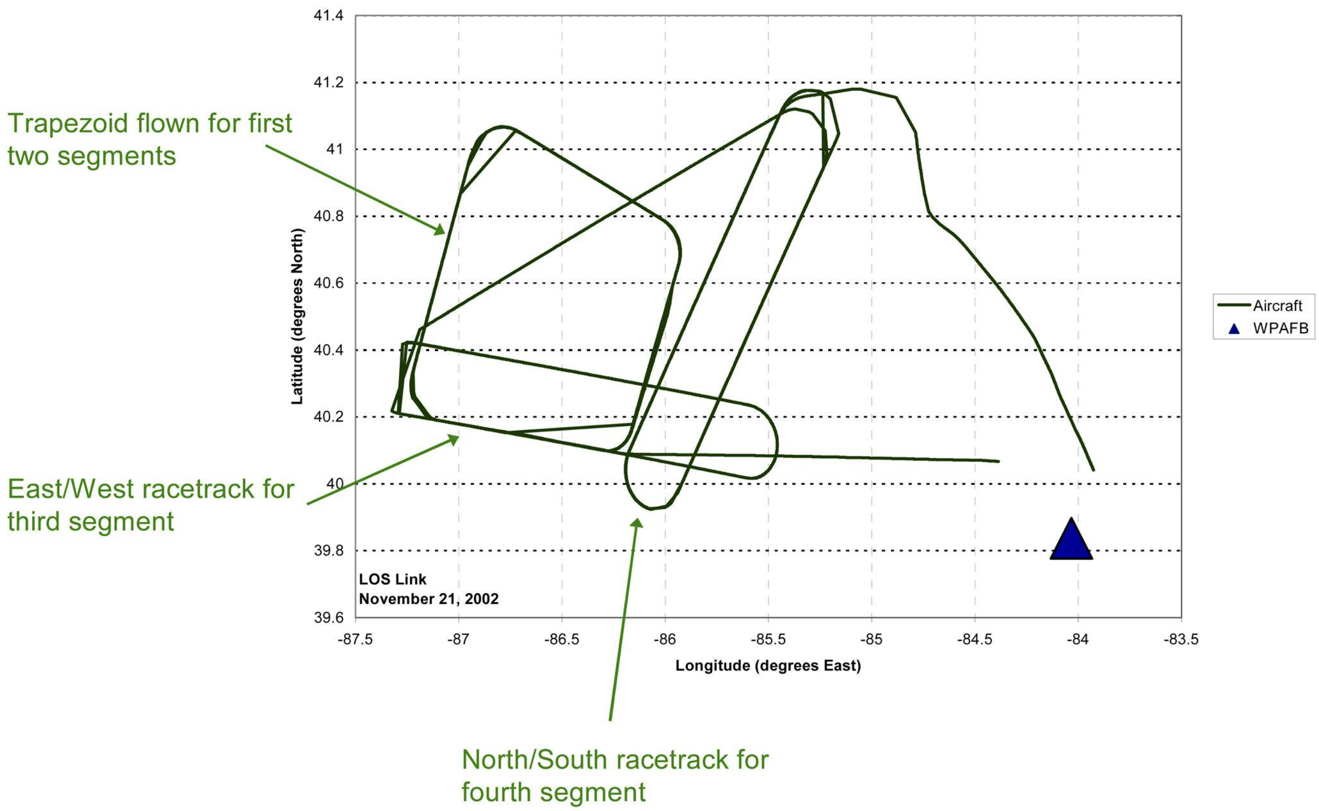

FIG.4 Flight Path

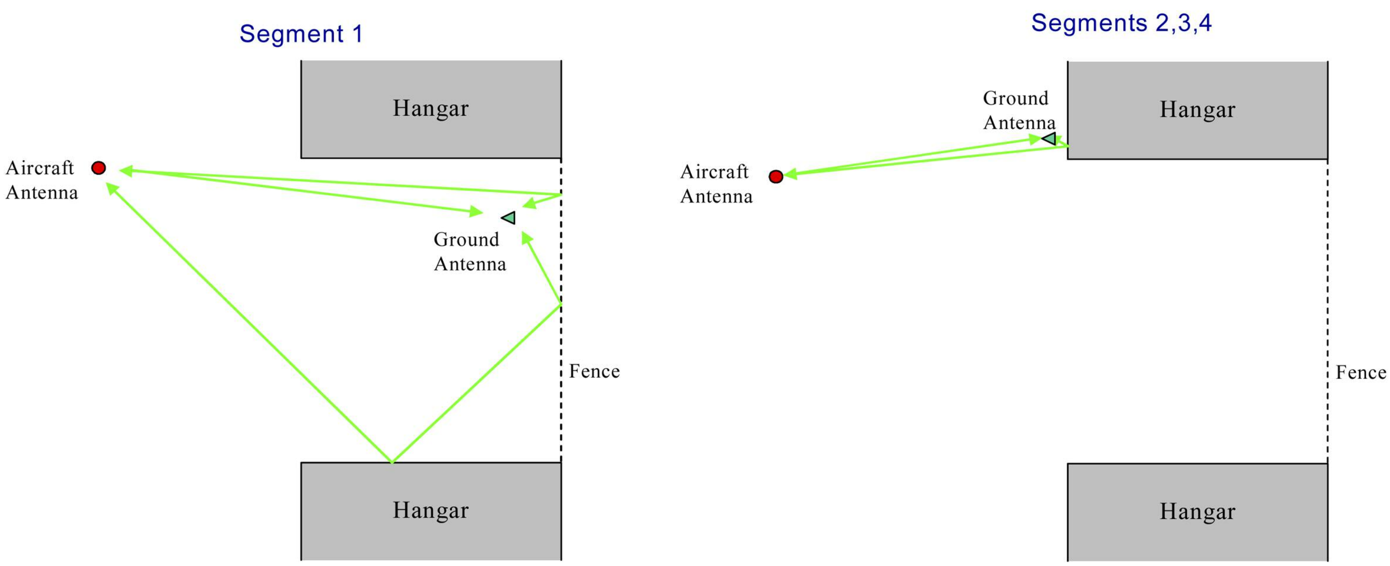

FIG.5 Multipath Geometries

The raw data in Figure 6 shows the performance during the different segments of the flight. This data was collected by taking a measurement once per second and applying the traditional two-way calculation with no corrections and no averaging. The data in segment 1 shows the worst degradation with a peak-to-peak noise of almost 40 ns. In segment 2 (where the aircraft was flown in the same pattern with a different ground antenna location), the multipath effects are greatly reduced and the data is more than a factor of two better. This is due to the elimination of the ground multipath sources that were present in the first segment. The data from segment 3 is similar to segment 2 but also shows the effect of flying the aircraft to and from the ground location while transmitting at fixed powers. The noise level increases as the plane flies away from the ground antenna and decreases as the plane gets closer. This correlation between SNR and jitter is a function of the modem electronics and has been experienced in prior tests. The data in segment 4 (tangential flight path with aircraft antenna in upper radome) shows good uniformity with a peak-to-peak noise level that is higher than segments 2 and 3. The higher noise level in segment 4 is due to lower SNR because of partial obscura in the radome.

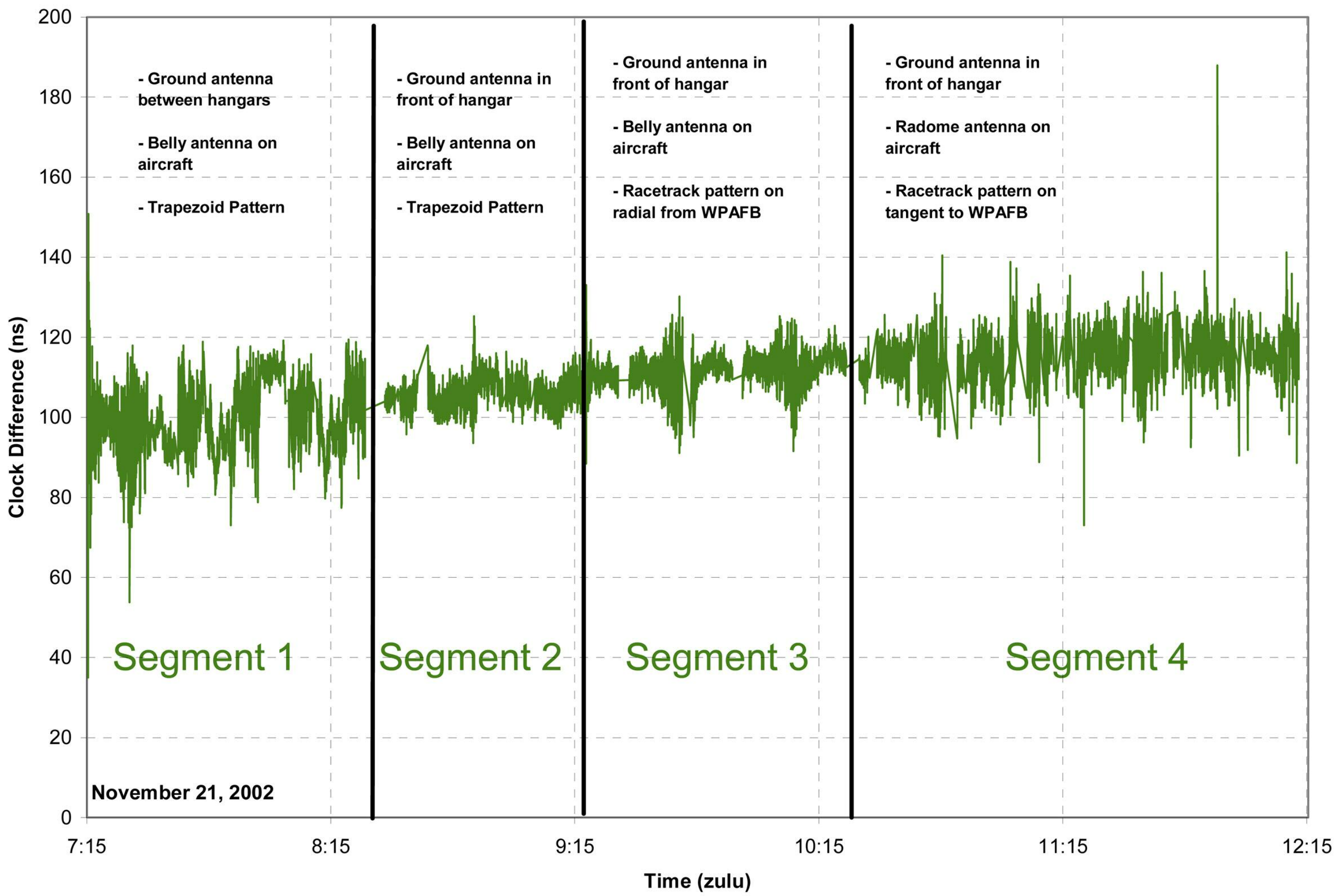

FIG.6 Raw Data

In order to correct the data in Figure 6, the Δprop_delay and ΔSagnac from (1) must be calculated and removed. Figure 7 shows the two corrections on the same plot. The Sagnac correction is the larger of the two effects in the line-of-sight case with a maximum value of 1.1 ns. In comparison, the platform motion corrections for the satellite relay case were greater than 150 ns [6]. The difference in correction magnitude between the two cases is due to the fact that in the line-of-sight case, the transmitted signal does not have to travel to a geosynchronous satellite and back. The transit time for the line-of-sight case is microseconds (vs 250 milliseconds for satellite case) and, as a result, the platform motion correction is much smaller. The Sagnac correction is also smaller due to the difference in propagation path between the two cases.

The flight record is used to calculate the relativistic effects that cause a frequency change on the flight clock. The phase record between the flight clock and the ground clock can then be determined over the flight period. Figure 8 contains the expected contributions from the dominant relativistic effects (gravity, velocity and sagnac) [5] as well as a net phase effect on the flight clock. The net effect on the flight clock is approximately 15 nanoseconds for the 5 hour flight and is dominated by the gravity effect.

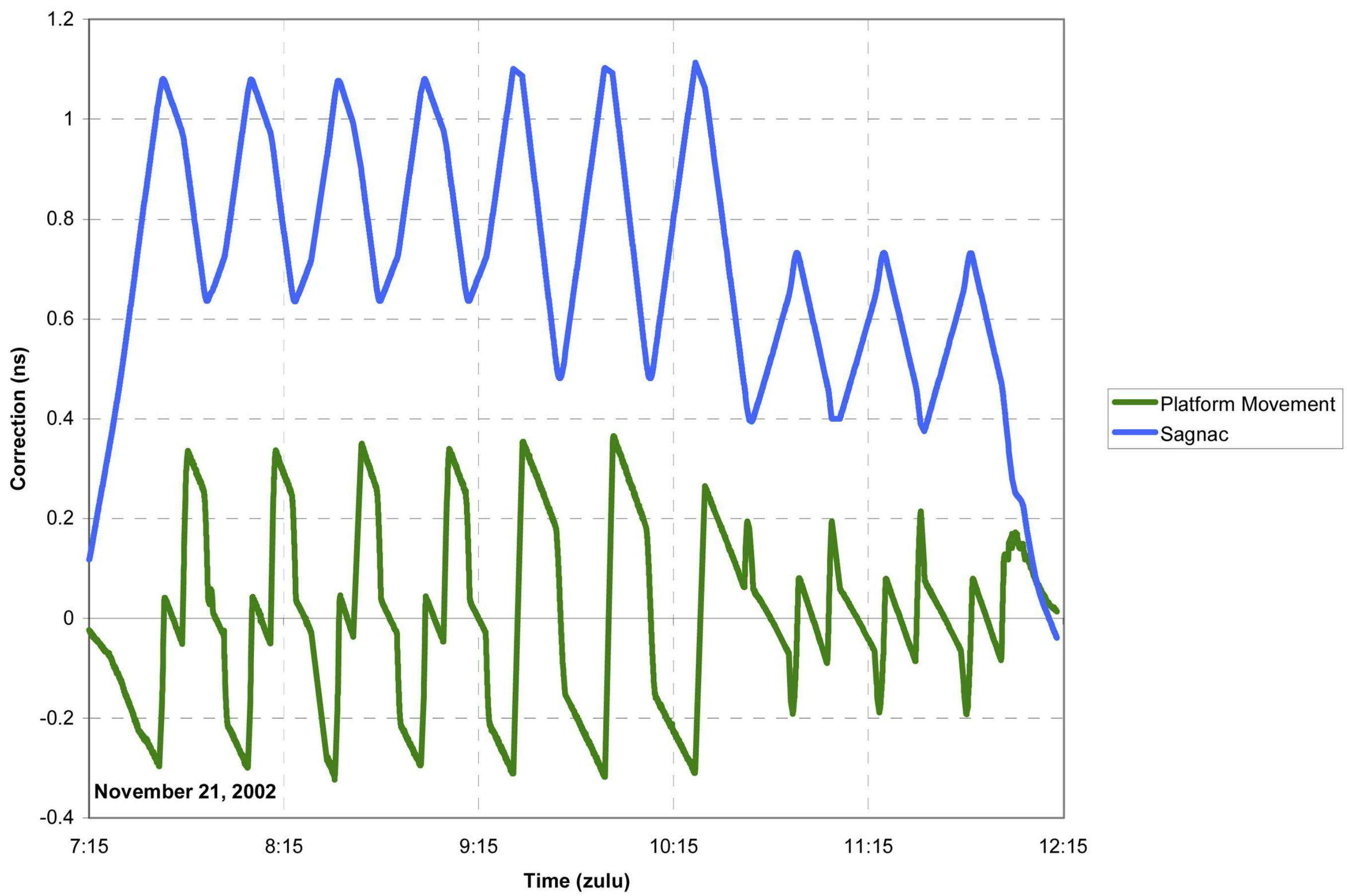

FIG.7 Corrections to Two-Way-Data

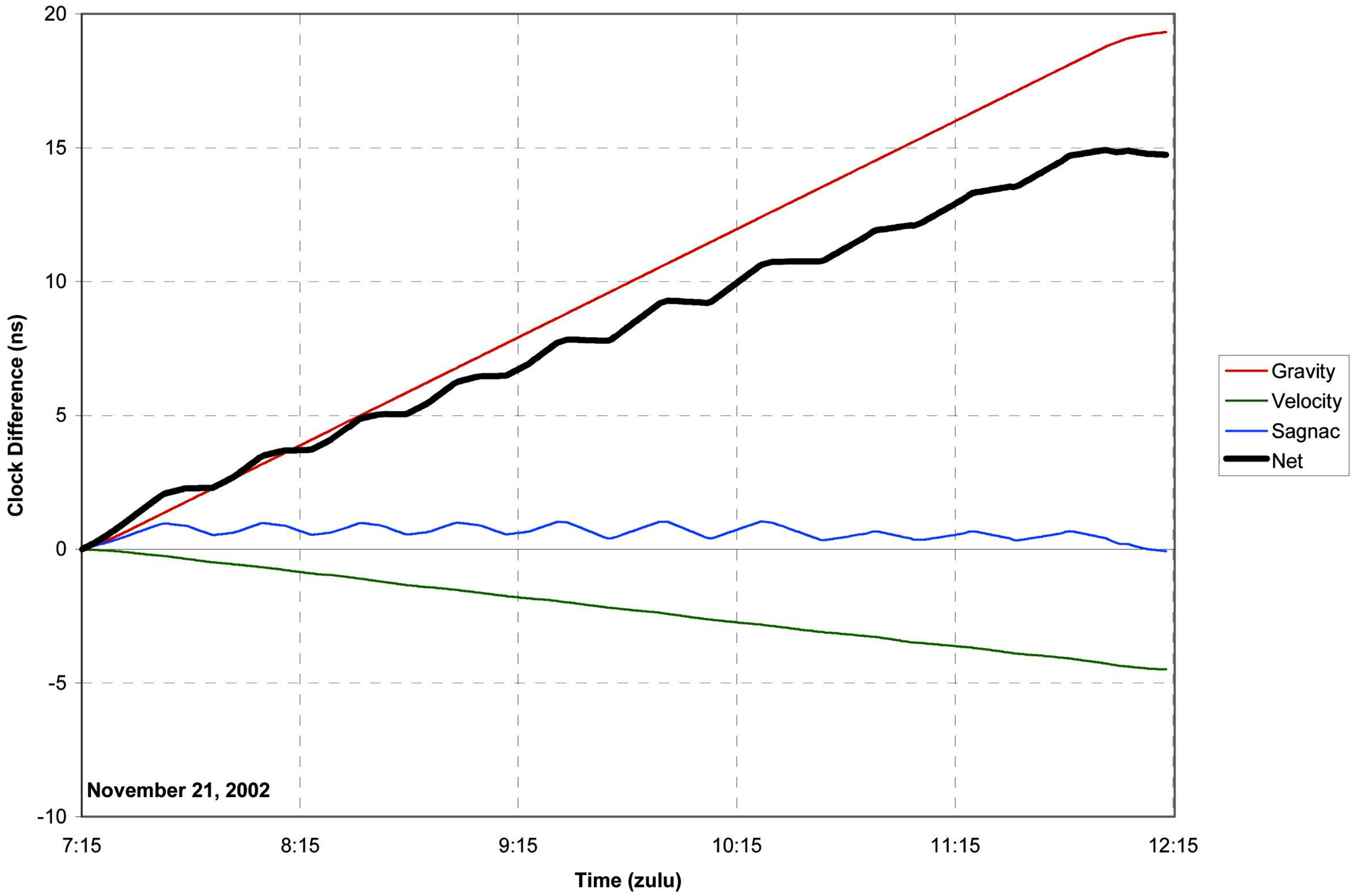

FIG.8 Relativity Effects

Once the corrections from Figure 7 are applied, the data is processed in a 60 second average in order to reduce the measurement noise. The corrected data is shown in Figure 9 with the net relativistic phase curve from Figure 8. The processed DTWTT data follows the predicted curve in the aggregate with good agreement in segments 2, 3 and 4. Segment 1 is significantly worse (as expected) due to the poor multipath environment. The data from segment 4 shows less structure than the data from the other segments but still has a higher peak to peak noise level. This data would benefit from further averaging since it is relatively white. The data from segments 1, 2 and 3 will not benefit from additional averaging without removal of the multipath effects.

The final evaluation of the data depends on how well the measured data connects the two clock difference sets that were collected on the ground both before and after the flight. This is shown in Figure 10 where the flight data is plotted on the same curve as the clock difference data collected on the ground before and after the flight. The flight data fills in the missing section well and provides a consistent relative clock offset record during flight.

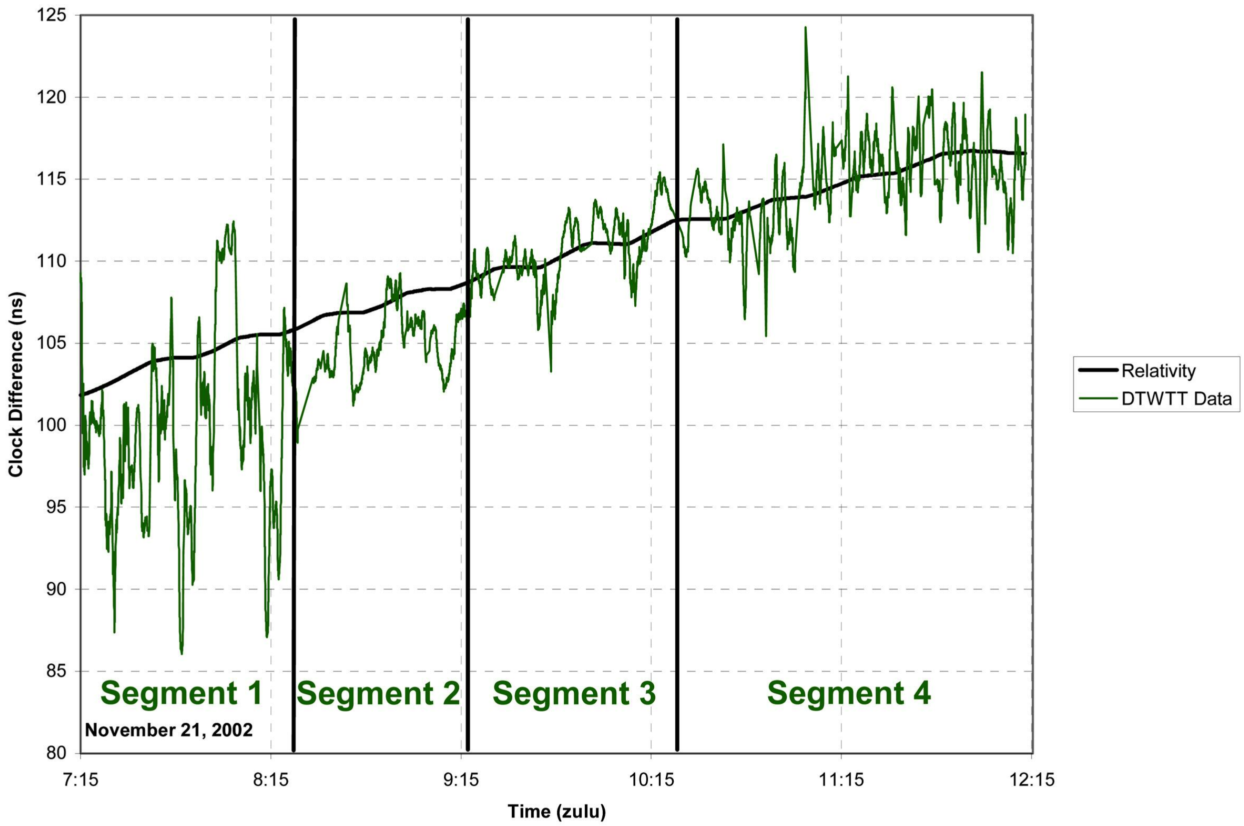

FIG.9 Corrected Two-Way Data (60 second average) vs Net Relativity

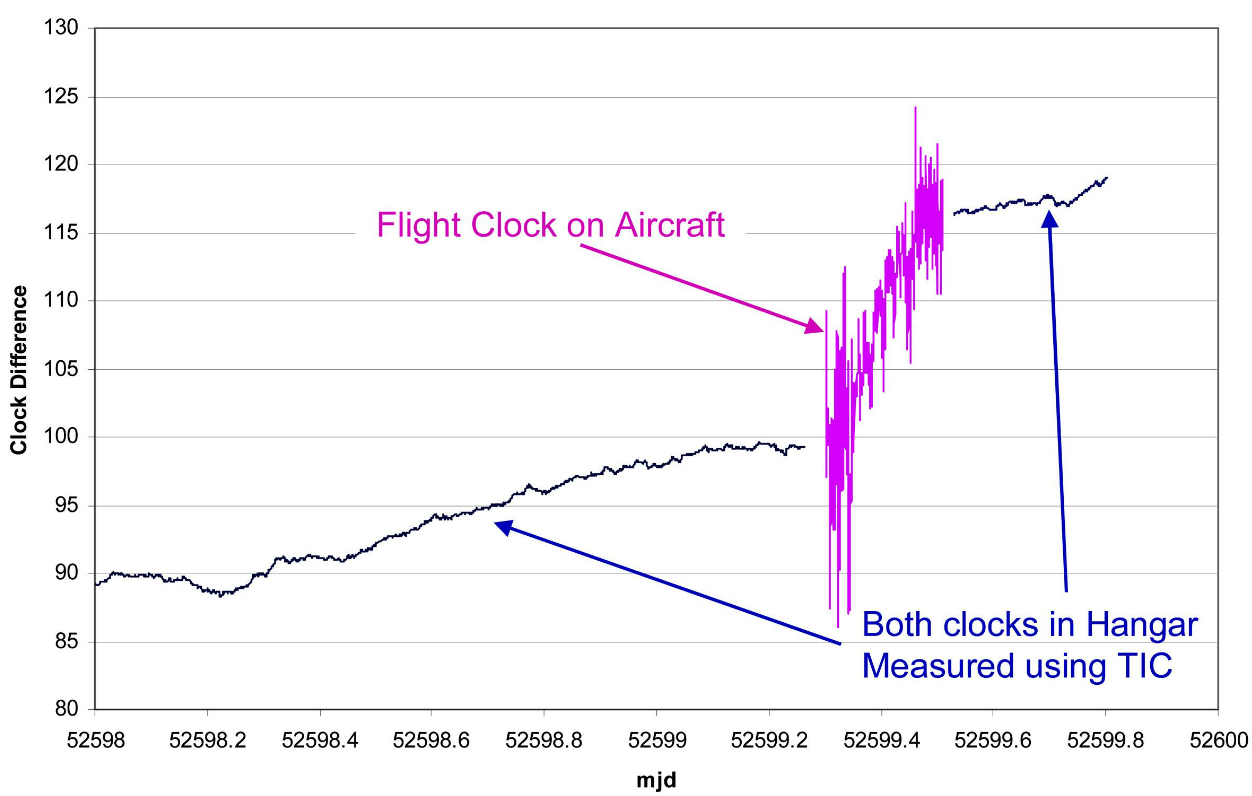

FIG.10 Clock Difference Data and Flight Data

3.0 Conclusions

Time based communications has been extended to the dynamic case to enable two-way time transfer between platforms in motion. The concepts of dynamic two-way time transfer have been introduced and demonstrated using an AFRL aircraft. Data was presented that shows that measurements can be made in flight to determine the clock difference between a ground clock and a flight clock to between 2-5 ns (RMS on a 60 second average) for a line of sight link. The variation in data fidelity is due to the effects of multipath on the signal both on the aircraft and the ground.

4.0 References

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