Compensating for Latency Variations in Air-to-Air Missile T&E Using Live Aircraft Linked to a Missile HWIL Simulation

A Technical Paper from the Joint Advanced Distributed Simulation Joint Test Force

Dr. Larry McKee, Science Applications International Corporation

Presented at the Simulation Interoperability Workshop
March 1998, Orlando, FL

JADS JTF
http://www.jads.abq.com
11104 Menaul NE
Albuquerque, NM 87112-2454
(505) 846-1291
FAX (505) 846-0603

Compensating for Latency Variations in Air-to-Air Missile T&E Using Live Aircraft Linked to a Missile HWIL Simulation

Dr. Larry McKee
Science Applications International Corporation
Joint Advanced Distributed Simulation Joint Test Force
11104 Menaul Blvd NE
Albuquerque NM 87112
(505) 846-0559
FAX: (505) 846-0603
mckee@jads.kirtland.af.mil

Keywords:
Latency, ADS, T&E, Synchronization

ABSTRACT: *The Live Fly Phase (LFP) of the Systems Integration Test (SIT) was executed by the Joint Advanced Distributed Simulation (JADS) Joint Test Force (JTF) and the 46th Test Wing at Eglin AFB, FL during 1997. The purpose of the SIT was to evaluate the utility of using advanced distributed simulation (ADS) to support cost-effective testing of an integrated missile weapon/launch aircraft system in an operationally realistic scenario. The SIT missions simulated a single shooter aircraft launching an air-to-air missile against a single target aircraft.*

In the LFP, the shooter and target were represented by live aircraft and the missile by a simulator. ADS techniques were used to link two live F-16 fighter aircraft flying over the Eglin Gulf Test Range to the AMRAAM AIM-120 hardware-in-the-loop (HWIL) simulation facility at Eglin. In order for this linking to have utility for the T&E of the AMRAAM missile under test, the latency variations between the live aircraft and the missile HWIL simulation facility had to be removed so that the aircraft entity state and missile launch data could be properly synchronized to the missile simulation. This paper presents the techniques used to synchronize inputs to the missile HWIL simulation and their effectiveness at achieving the required degree of synchronization. Also, the resulting latency is characterized, and conclusions on T&E applications of the LFP ADS configuration are given.

1. Overview

The Live Fly Phase (LFP) of the Systems Integration Test (SIT) was executed by the Joint Advanced Distributed Simulation (JADS) Joint Test Force (JTF) and the 46th Test Wing at Eglin AFB, FL during 1997. The purpose of the SIT is to evaluate the utility of using advanced distributed simulation (ADS) to support cost-effective testing of an integrated missile weapon/launch aircraft system in an operationally realistic scenario. The SIT missions simulated a single shooter aircraft launching an air-to-air missile against a single target aircraft. The scenarios utilized in the LFP missions were based on previous AMRAAM testing and are shown in Figure 1-1. These scenarios were modified somewhat to accommodate testing limitations and were replicated during LFP testing.

In the LFP, the shooter and target were represented by live aircraft and the missile by a simulator. ADS techniques were used to link two live F-16 fighter aircraft flying over the Eglin Gulf Test Range to the AMRAAM AIM-120 HWIL simulation facility at Eglin. The LFP test configuration is shown in Figure 1-2. Global Positioning System (GPS) and telemetry data were downlinked from the aircraft and passed to the Central Control Facility (CCF) at Eglin. GPS, inertial navigation system (INS), and tracking radar data for each aircraft were combined by the TSPI Data Processor (TDP) in the CCF to produce optimal entity state solutions. The aircraft entity state data were transformed into Distributed Interactive Simulation entity state protocol data units (DIS ES PDUs) and transferred to the AMRAAM HWIL laboratory at the MISILAB over a T-3 link. The shooter aircraft "fired" the AMRAAM in the MISILAB at the target and provided rear data link (RDL) updates of the target position and velocity to the missile during its flyout. The AMRAAM seeker was mounted on a flight table and responded to radio frequency (RF) sources in the MISILAB which simulated the seeker return from the target, the relative motions of the target and the missile, and electronic countermeasures (ECM).

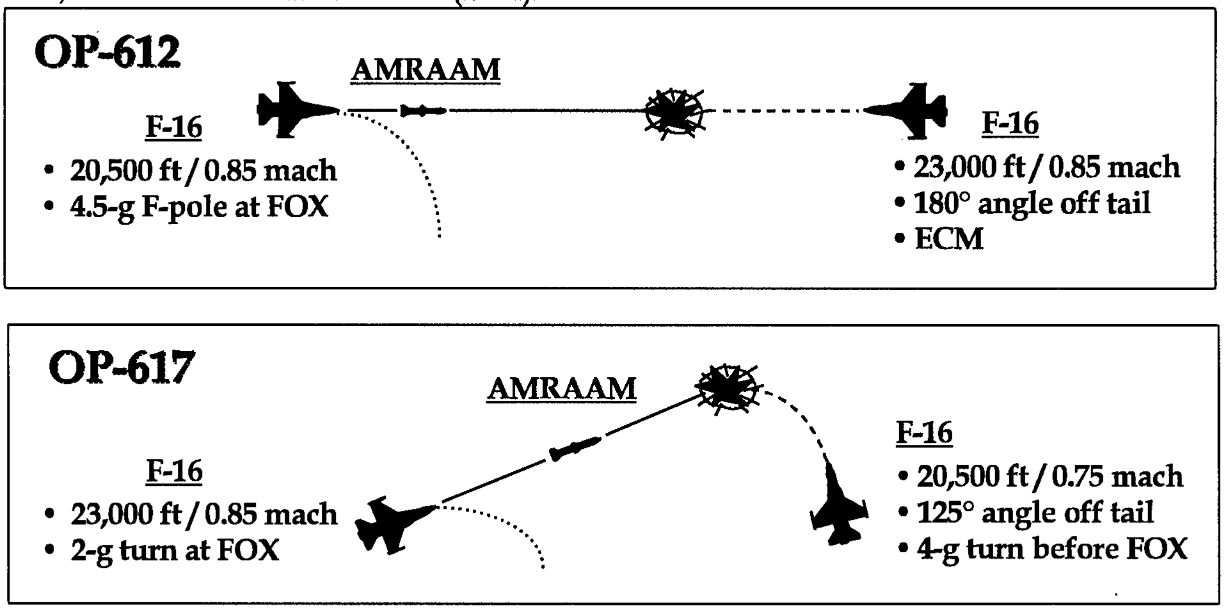

Figure 1-1. AMRAAM Live Fire Profiles (FOT&E(2), 14 September 93 and 9 July 93)

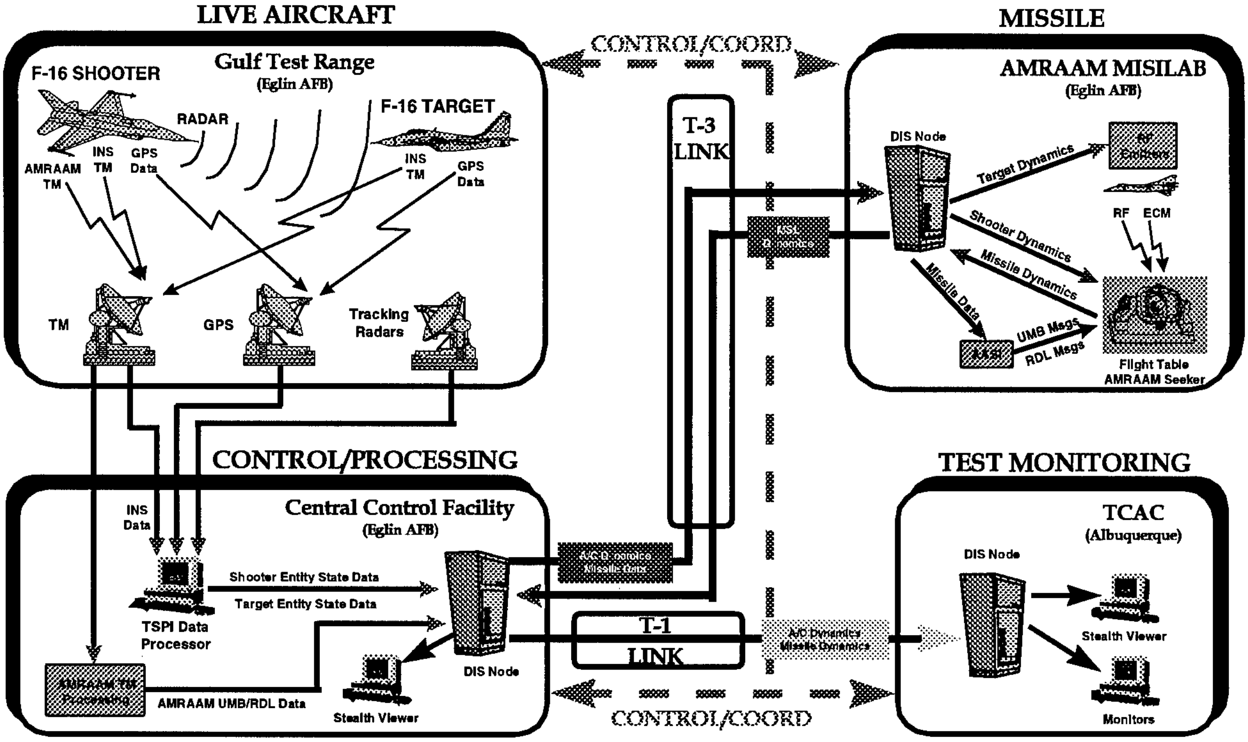

Figure 1-2. Live Fly Phase Test Configuration

A T-1 link between the CCF and the JADS Test Control and Monitoring Center (TCAC) allowed JADS personnel to monitor the simulated intercepts.

The actual umbilical and RDL messages from the shooter aircraft were used to initialize, launch, and update the missile in the MISILAB during each simulated engagement. The shooter carried an Integration Test Vehicle (ITV) pod which emulated the AMRAAM missile in its pre-launch configuration, and AMRAAM telemetry from the pod was downlinked and processed by the CCF. The telemetry was converted into DIS Data PDUs and transferred to the MISILAB over the T-3 link. The messages were then reconstructed and synchronized to the aircraft TSPI data by the Advanced Aircraft Simulation Interface (AASI) in the MISILAB.

The test runs were controlled from the CCF. The control center ensured that all players were ready for each run and issued the commands to start and stop the passes. PDUs were processed at the TCAC to provide JADS personnel with real-time stealth node viewing of the simulated engagement.

In order for this linking to have utility for the T&E of the AMRAAM missile under test, the latency variations between the live aircraft and the missile HWIL simulation facility had to be removed so that the aircraft entity state and missile telemetry data could be properly synchronized to the missile simulation.

2. Synchronization Assessment

During periods of linked testing, the live aircraft executed the scenarios depicted in Figure 1-1, and the data input into the MISILAB simulation were analyzed to determine the degree of data synchronization achieved.

2.1 Synchronization Method

Analysis of data synchronization relied on matching the data time stamps at the point at which synchronization was required: input to the MISILAB HWIL simulation. Three streams of data had to be synchronized for input:

- Shooter entity state data
- Target entity state data
- Missile umbilical and RDL data

Note that the time stamps necessary for synchronization must define when the data were valid (i.e., when the entity state data were valid as an entity description and when the missile telemetry data were created). These "time of validity" time stamps were created as part of the TDP solution (using time stamps of the individual data input to the TDP) and were inserted into the missile telemetry data downlinked from the ITV pod. The time stamps were preserved when the TDP output was converted into ES PDUs and when the ES PDUs were converted into MISILAB input. Likewise, the time stamps were preserved when the missile data from the ITV were converted into Data PDUs and then used by the AASI for synchronizing the umbilical and RDL data to the shooter and target entity state data.

The shooter and target entity state data were synchronized for MISILAB input during an interpolation process at the MISILAB. The data were buffered at the MISILAB before interpolation so that differences in the arrival time of the shooter and target data could be accommodated. The buffered data were interpolated at the 600 Hz frame rate of the MISILAB simulation using the time stamps on the shooter and target entity state data, and the two entities were treated separately. This process was designed to result in synchronization of the shooter and target entity state data to within the accuracy of the entity state data time stamps (±2 ms).

The umbilical and RDL messages were synchronized to the entity state data by the AASI. The AASI determined the time of validity of the umbilical message and held it until the time stamp on the entity state data being input into the simulation matched. When the matching entity state time stamp was detected, the AASI input the umbilical message into the simulation. Then the RDL data was input into the simulation by the AASI at the correct time relative to the umbilical message. In other words, the RDL messages had the same degree of synchronization relative to the entity state data as the umbilical messages.

2.2 Synchronization Results

The degree to which the shooter and target PDUs were unsynchronized to each other when received at the MISILAB was evaluated from the differences in the latencies of the PDUs and found to be about 30-70 ms. The process of interpolation resulted in the shooter and target entity state data being synchronized to each other and effectively eliminating the latency differences. Detailed analysis showed that the shooter and target entity state data were indeed synchronized to each other to within the accuracy of the entity state data time stamp, ±2 ms, and shared a common degree of synchronization to the MISILAB simulation frame rate.

An illustration of the improvement in the synchronization of the target entity state data is shown in Figure 2.2-1. This figure first shows the target north position versus the PDU time (i.e., the "time of validity") as curve (1), which reflects the smoothness of the TDP solution. Next, this figure shows the same data plotted versus PDU log time (curve (2)). This curve shows how the smooth data was distorted upon receipt in real-time at the MISILAB PDU logger due to sample-to-sample latency variations. However, the data were interpolated to the 600 Hz rate for input to the MISILAB simulation based on the PDU time, so that the resulting 600 Hz data were smooth versus the interpolated "time of validity," the ccf_time, as shown in the figure by curve (3) overlaying the position versus PDU time curve (curve (1)). That the interpolated data were also input into the MISILAB simulation as smooth data is illustrated by the fourth curve in the figure (curve (4)). This curve shows the interpolated data versus input time into the MISILAB simulation, as measured by the IRIG time of each input frame logged by DTCS, the simulation input logger.

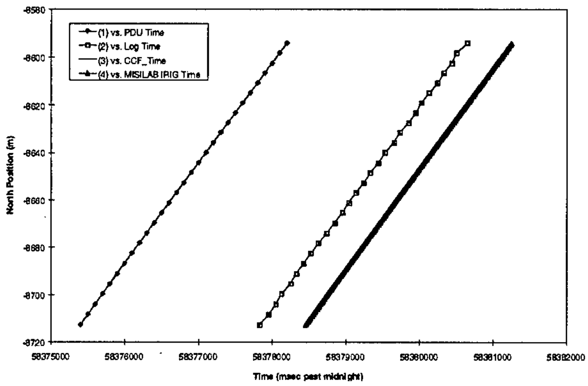

Figure 2.2-1. Target North Position Versus Time (Run #5 - 9/11/97)

A better way of illustrating the lack of synchronization in the logged PDU data and the improved synchronization of the MISILAB input is by plotting the latencies of the respective data. Figure 2.2-2 shows the latency of the target data plotted in Figure 2.2-1 versus the respective log times (time data were actually received). The PDU latency is plotted versus PDU log time (time of logging by the PDU logger in the MISILAB). Notice the significant sample-to-sample latency variations of the 10 Hz PDU data; the standard deviation of these latency values was about 12 ms on this run. The second curve in Figure 2.2-2 shows the latency of the interpolated 600 Hz data versus the DTCS log time. Notice that the latency of the interpolated data was constant over this time, showing that the MISILAB input was very well synchronized. Also, notice that the latency of the DTCS data was about 600 ms larger than that of the PDU data. This significant increase in latency was caused by the interpolation process, which required that a sufficient sample of PDU data (500 ms worth) be buffered for interpolation. The buffer was also sized to compensate for anticipated relative latency differences between the shooter and target ES PDUs.

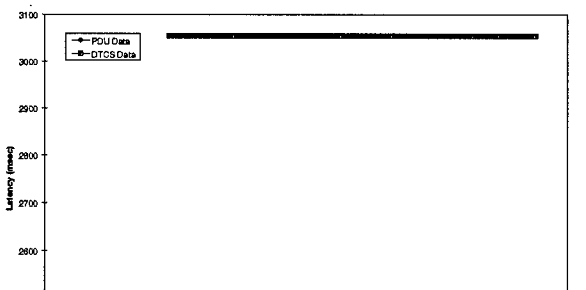

Figure 2.2-2. Latency of Target Entity State Data Versus Time (Run #5 - 9/11/97)

As Figure 2.2-2 shows, a measure of good synchronization of the MISILAB entity state inputs was a constant value of latency for the data logged by DTCS. However, when the latency of the shooter and target entity state data logged by DTCS was examined, the latency values for a given run were found to not be constant. Rather, the latency during a run was found to increase slightly with time. In general, there was found to be a regular increase rate of about 0.2 ms/s during every run. Also, the latency would occasionally "jump" by up to about 20 ms. These features are illustrated in Figure 2.2-3.

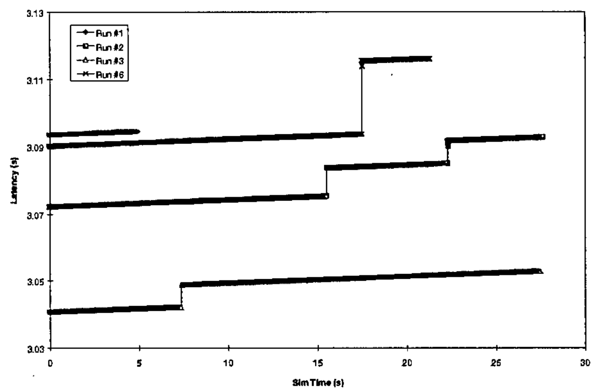

Figure 2.2-3. Latency of Entity State Data Versus Sim Time (Mission #1 - 9/11/97)

Figure 2.2-3 shows a sampling of the runs from Mission #1. Note that every curve in the figure has the same general slope of 0.2 ms/s and that there are occasional relatively large "jumps" in the latency.

The cause of the general latency increase was found to be that the interpolation of the PDU data was not occurring at precisely 600 Hz, as assumed for the assignment of the "time of validity" time tags. Rather, the interpolation rate was actually 599.88 Hz, as was the entity state data input rate.

In addition to the latency growth caused by this frequency mismatch, there were also occasional latency "jumps," as Figure 2.2-3 shows. The latency "jumps" had the following features:

- The latency "jumps" did not occur at specific times relative to the simulation. Rather, the times of occurrence appeared to be random.
- The amount of each latency "jump" was always an integral number of 600 Hz frame times (i.e., multiples of 1.7 ms), within the precision of the time stamps (0.1 ms). The number of frames that the latency jumped by varied from one to thirteen, with no systematic behavior.
- Each latency "jump" resulted in a discontinuous change in the degree of synchronization equivalent to the number of simulations frames represented by the "jump."

The combined result of the systematic increase in the DTCS log interval and the latency "jumps" was a progressive loss of synchronization of the entity state data input to the MISILAB during each run. The interpolation frequency error, by itself, caused a synchronization loss of one frame each 8.33 seconds of sim time, which amounted to the synchronization loss of 2-3 frames during the Mission #1 runs. The latency "jumps" resulted in additional discontinuous synchronization losses of the MISILAB inputs of up to 13 frames at one time.

The synchronization of the entity state data actually input into the MISILAB simulation was determined by the actual simulation frame rate, 599.47 Hz, resulting in a synchronization loss of 0.88 ms/s between elapsed simulation time and real elapsed time. Because of the frame rate of the MISILAB simulation was less than the entity state data input rate, the latency "jumps" in the input reduced the loss of synchronization. This happened because the simulation had been running further and further behind real elapsed time, and the latency "jumps" effectively resulted in the entity state data being passed into the simulation at a sim time closer to the correct real elapsed time. Hence, the loss of synchronization of the entity state input to the MISILAB simulation was less than 0.2 ms/s, or one simulation frame each 8.33 seconds. This resulted in a loss of synchronization of only 5 msec, or 3 frames, by the end of the longest runs. This represented a position offset of about 1.4 m (using the largest velocity value of 270 m/s) and had negligible effect on the overall simulation fidelity.

The degree of synchronization of the umbilical message to the aircraft entity state data was reported by the AASI after each run. The value reported was the difference between the time tag of the umbilical message and the time tag of the entity state data at the time the umbilical message was input into the MISILAB simulation. The AASI was able to synchronize the umbilical message input to within about 20 ms of the entity state data. For the largest target velocity of 270 m/s, this could result in a difference between the target position indicated in the umbilical message and the target position from the entity state data of about 5 m. This difference is much less than the accuracy of the target position in the umbilical message and would have no significant effect on the simulation fidelity.

3. Latency Results

Latency values were calculated throughout a run from the differences in the time stamps for the same set of entity state data logged at various locations. The latencies for Mission #1 at various logging locations are summarized in Table 3-1. The entries in the table are the averages of the means and standard deviations for all runs during the mission with complete missile flyouts.

The major components to the latencies given in Table 3-1 are presented in Table 3-2. These include the transmission latency between the CCF and MISILAB PDU loggers, the latency between the MISILAB PDU logger and the DTCS logger, and the transmission latency between the CCF and TCAC PDU loggers.

Note from Table 3-1 that the total latency of the LFP ADS configuration was given by the latency of the MISILAB simulation output (Missile ES PDUs) and had a value of about 3.08 seconds

Table 3-1. Latencies (in msec) at Various Logging Locations (Mission #1 - 9/11/97)

	At CCF Logger		At MISILAB[1]		At TCAC Logger	
Entity	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Shooter	2430.0	12.8	3075.9	4.4	2458.7	14.1
Target	2432.1	11.8	3075.9	4.4	2460.7	12.9
Missile	3090.3	6.2	3082.1	4.6	3118.8	8.1

[1]Note: Latency at MISILAB determined from data logged by DTCS for aircraft and from data logged by MISILAB PDU logger for missile.

Table 3-2. Latency Components (in msec) (Mission #1 - 9/11/97)

	CCF Logger to MISILAB Logger[1]		MISILAB Logger to DTCS Logger	CCF Logger to TCAC Logger	
Entity	Mean	Std Dev	Mean	Mean	Std Dev
Shooter	1.2	0.8	644.6	28.6	5.3
Target	1.2	0.9	642.5	28.6	5.1
Missile	8.2	4.2	---	28.6	4.5

[1]Note: Latency for missile ES PDU data is from MISILAB logger to CCF logger.

The following is also noted from Tables 3-1 and 3-2:

- The single largest contribution to the total latency was from the processing of aircraft entity state data by the TDP and smoother. This processing resulted in over 2.4 seconds of latency at the CCF logger.

- The next largest latency contribution was caused by the buffering of the aircraft entity state data at the MISILAB before input into the simulation. The buffering was needed for interpolation and synchronization of the entity state data and added over 640 msec of latency to the total.
- Transmission of the aircraft ES PDUs from the CCF to the MISILAB resulted in an insignificant contribution to the total latency (1.2 msec).
- The relatively small standard deviations in Tables 3-1 and 3-2 show that the latencies were fairly stable and reproducible.
- The latency of the aircraft ES PDUs at the TCAC was nearly 2.5 seconds. This latency was deemed to be too large to allow safe and effective control of the live aircraft from the TCAC. Note that the aircraft traveled almost 700 m in 2.5 seconds, so that the TCAC position display could be in error by this amount relative to the real-time aircraft locations.
- The average difference between the target and shooter ES PDU latencies at the CCF PDU logger was 2.1 msec.
- The latency of the missile ES PDUs at both the CCF and the TCAC was about 658 msec larger than the latency of the aircraft ES PDUs. The cause of this significant latency difference was the delay in running the MISILAB simulation due to the buffering of aircraft entity state data for synchronization purposes (i.e., the MISILAB simulation was internally synchronized, but the aircraft inputs were not externally synchronized to the missile output). This meant that the direct visualization of the engagement at these nodes resulted in a scene in which the missile was significantly out of synchronization with the aircraft. Without correcting for this latency difference, the missile would appear to be trailing the shooter before launch and would appear to miss the target by passing behind it. This lack of synchronization in the engagement display was corrected for the CCF stealth viewer by delaying the aircraft ES PDUs in order to synchronize them with the missile ES PDUs. Without such real-time corrections, the analysts at nodes remote from the MISILAB were not presented with a time-coherent view of the engagement during the live missions. (This was not a problem for the display at the MISILAB, since the simulation was internally synchronized.)
- The transmission latency from the CCF PDU logger to the TCAC PDU logger was the same for all three entities, 28.6 msec. This value is comparable to the logger-to-logger latencies observed during the previous Linked Simulators Phase of testing (Reference [1]).

The time dependence of latency at various logging locations was also examined. An example for the missile ES PDU latency is given in Figure 3-1. This plot shows that the missile PDU latency exhibited discrete "jumps" and a regular increase of latency between "jumps." The regular increase rate is most noticeable in Figure 3-1 after the "jump" and has a value of about 0.2 ms/s. The values of the regular increase rate and the "jumps" match the time dependence of the latency of the aircraft entity state data input into the MISILAB simulation.

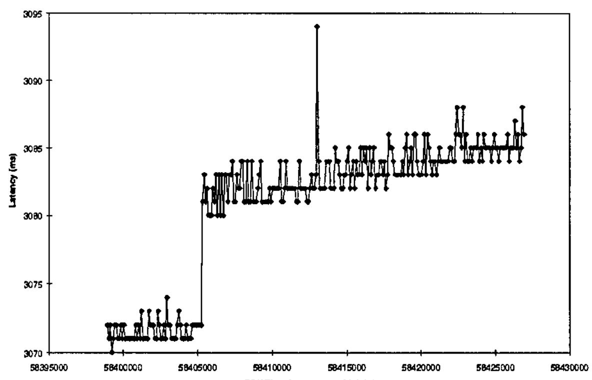

Figure 3-1. Latency of Missile Entity State Data at MISILAB PDU Logger (Run #5 - 9/11/97)

The conclusion is that the time variation in the MISILAB simulation input (i.e., the aircraft entity state data) resulted in the same time variation in the MISILAB simulation output (i.e., the missile ES PDUs): a regular latency increase rate of 0.2 ms/s and occasional latency "jumps" which were multiples of the simulation frame time (1.7 msec). As previously concluded from the synchronization assessment, these latency variations did not affect the validity of the MISILAB simulation results.

4. Summary and Conclusion

The technique used during the LFP trials for synchronizing the MISILAB inputs worked quite well. The shooter and target entity state data were synchronized to each other within ±2 ms, and the synchronization of these inputs to the MISILAB simulation frame rate was only limited by the accuracy and stability of the input rate. The umbilical and RDL messages were synchronized to the entity state data to within about 20 ms. The degree of synchronization achieved was within requirements for the MISILAB simulation and had no significant effect on the simulation fidelity.

Processing required to obtain accurate aircraft TSPI data and for synchronization of the MISILAB inputs resulted in relatively large total latencies, over 3 seconds. However, this latency value had no impact on the simulation fidelity, because there was no closed-loop interaction between the missile and the target (the missile reacted to the target, but the target did not react to the missile).

The latencies were too large to allow applications of the LFP ADS architecture to closed-loop engagements between the missile and target. If the latency were to be dramatically reduced in the future, a method for uplinking information on the missile to the live target aircraft and pilot would also have to be developed before closed-loop applications would be possible.

On the other hand, the LFP architecture does have utility for evaluation of an open-loop engagement between the missile and target (in which the missile reacts to the target, but the target does not react to the missile). This does not significantly restrict the utility of the LFP architecture, since nearly all current missile testing uses open-loop scenarios in which the target flies scripted profiles.

5. References

[1] "System Integration Test Link Simulators Phase Final Report," JADS JT&E, July 1997.

Author Biography

DR. LARRY MCKEE has 25 years experience directing and performing R&D programs in DT&E, nuclear weapon effects, system survivability, neutral particle beam interactive discrimination, and high energy laser effects. This experience includes 20 years as an Air Force officer with duties in management of advanced R&D programs in directed energy weapon technology, R&D leadership at the Air Force Branch and Division levels, development and instruction of advanced graduate courses, and technical direction of underground nuclear tests. He joined SAIC in 1989 and currently supports the JADS JT&E as the technical lead for the System Integration Test, designed to evaluate the utility of ADS for the T&E of integrated launch aircraft/missile systems.

INTERNET DOCUMENT INFORMATION FORM

A . Report Title: Compensating for Latency Variations in Air-to_Air Missile T&E Using Live Aircraft Linked to a Missile HWIL Simulation

B. DATE Report Downloaded From the Internet 1/28/99

C. Report's Point of Contact: (Name, Organization, Address, Office Symbol, & Ph #): Joint Advanced Distributed Simulation
Joint Test Force
ATTN: Ann Krause (505) 846-1291
11104 Menaul NE
Albuquerque, NM 87112-2454

D. Currently Applicable Classification Level: Unclassified

E. Distribution Statement A: Approved for Public Release

F. The foregoing information was compiled and provided by:
DTIC-OCA, Initials: VM_ **Preparation Date**: 1/28/99__

The foregoing information should exactly correspond to the Title, Report Number, and the Date on the accompanying report document. If there are mismatches, or other questions, contact the above OCA Representative for resolution.