CRIIS High Accuracy TSPI Architecture and Technical Maturity Demonstration Test Results

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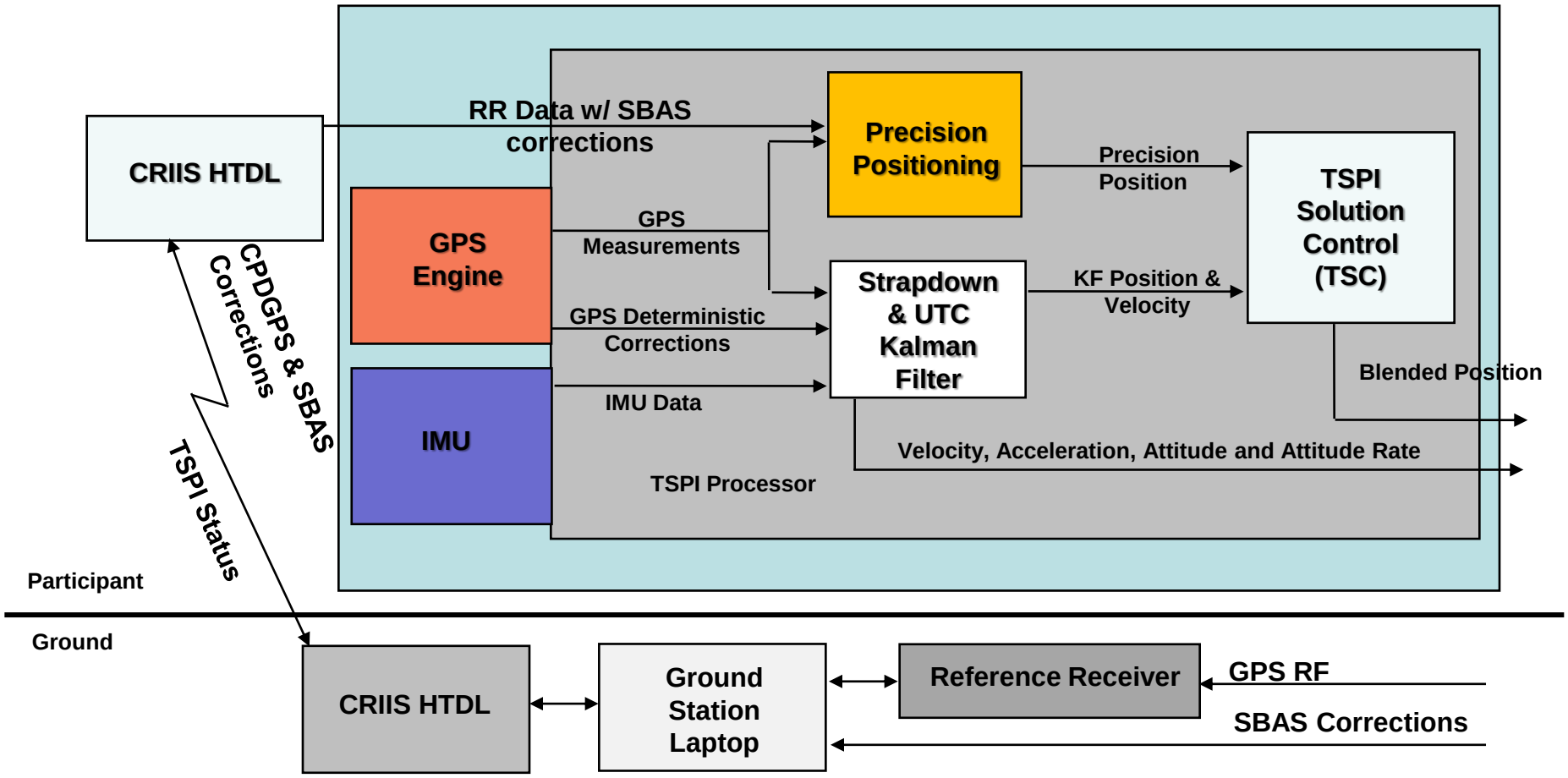
Outline

- CRIIS TSPI Architecture and Algorithms
  - RTK, UTC, SBAS, and RTK/UTC Blending
- TSPI Accuracy Validation Approach and Truth Source
  - M&S, HIL, Low Dynamic (Van, Roller-Coaster), High Dynamics
- HIL Simulation Results
- Roller Coaster Test Results – Lessons Learned
- Flight Test Results – TRL6 Discussion
- Conclusion

Overview

- TSPI Architecture and Algorithms
- TSPI Accuracy Validation Approach

CRIIS TSPI Architecture and Algorithms



SBAS= Precise Corrections for SV Position and Clock Errors (Sources: StarFire, JPL etc)

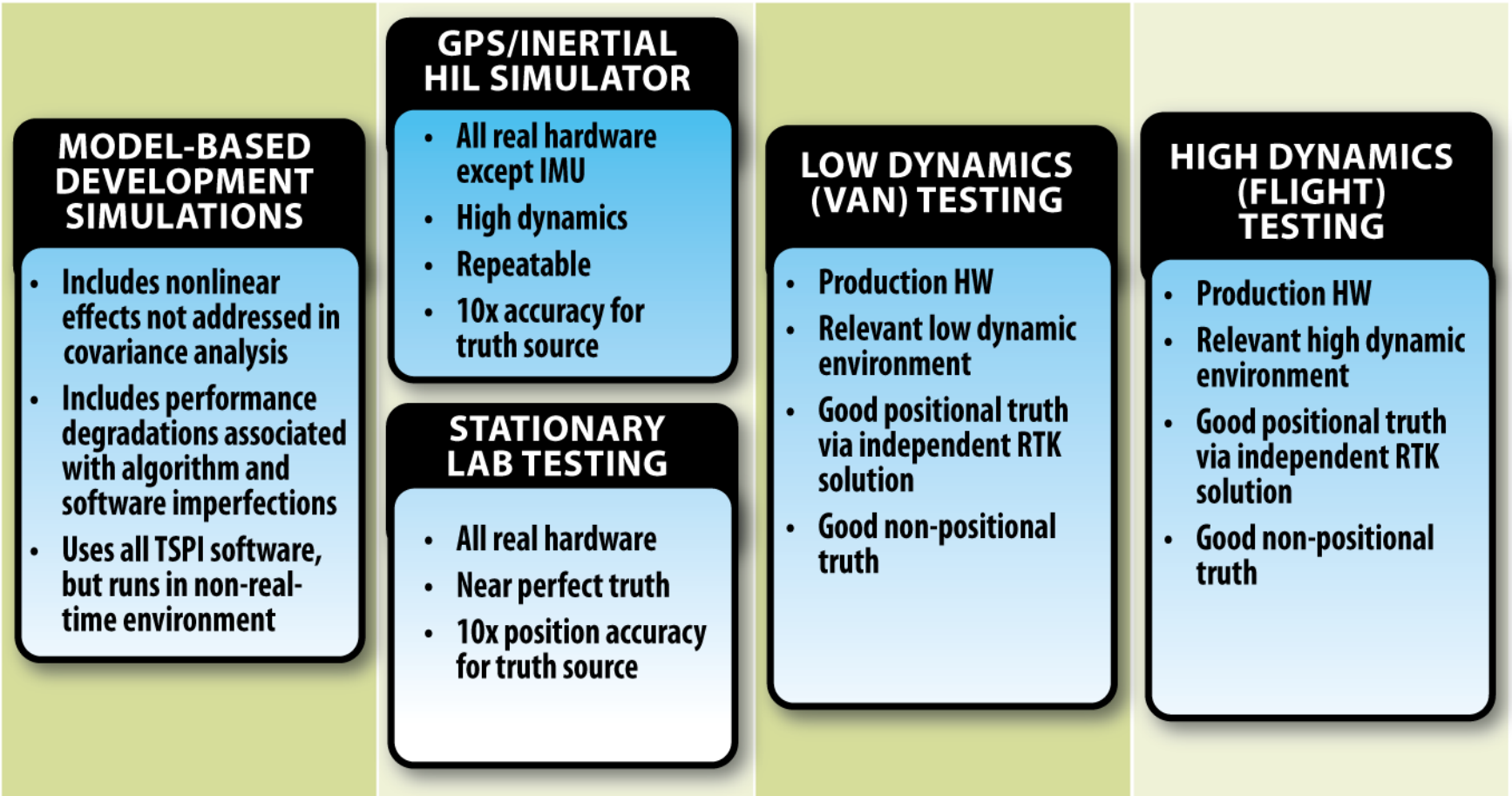
TSPI Level II
UTC GPS-Inertial Algorithm

- **UltraTight Coupling (UTC) is an Essential Part of High Accuracy Positioning in a High Dynamic Environment**
  - **Reduces TSPI Error Growth by Minimizing Duration of GPS Signal Loss**
  - **Signal Re-established Up to 30 Seconds After Signal Loss without the Need to Search**
- **Accurate Relative Timing between GPS, Kalman Filter, and IMU is Essential for Highest Accuracy TSPI Solution**
  - **TSPI Incorporates Synchronous Timing between GPS, Processor, and IMU**
  - **IMU Strobe is Required to Minimize Latency Error in IMU Measurements Used to Close GPS Signal Tracking Loops**
  - **Minimizes Error Growth Across GPS Outages**

TSPI Level II GPS-Inertial Design Built on Core UTC Approach Successfully Used in Phase I Demonstration

CRIIS TSPI Level II TSPI Verification and Truth Sources

Increasing Fidelity



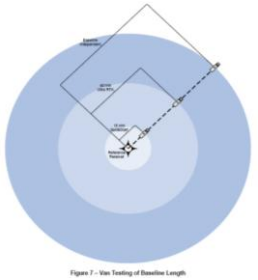
Continued Use of Crawl, Walk, Run Approach Used in Phase I is Proven and will Continue as the Verification Model

CRIIS TSPI Demo Approach

Incrementally Phased

Table 5 – TSPI Level II accuracy requirements

	Position Horizontal (m RMS)	Position Vertical (m RMS)	Velocity Horiz/Vert (m/s RMS)	Acceleration Horiz/Vert (m/s2 RMS)	Attitude (deg RMS)	Attitude Rate (deg/s RMS)
Level II Real Time	0.3		0.03	0.03	0.1	0.2
Level II Post Processed	0.1		0.01	0.01	0.05	0.1

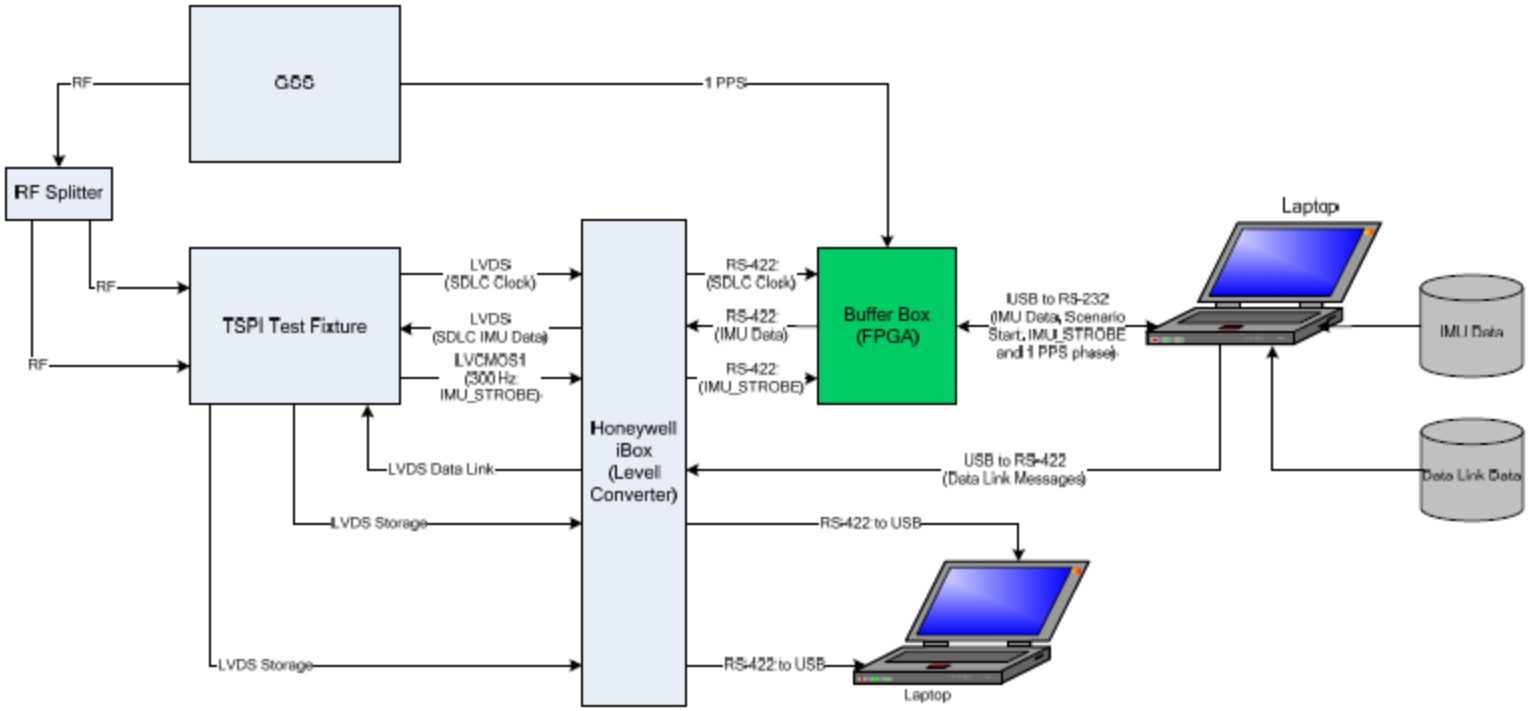


Test Phase	Test Objectives	Truth Source
Crawl: • Model-Based • Hardware-In-Loop • Stationary	Validate TSPI solution accuracy under • GPS simulation • Live Sky • RRs at Various Ranges	• GPS Simulator • Surveyed Antenna
Walk: Ground-Based Demonstrations • Van • Roller-Coaster	Validate TSPI solution accuracy under low and Moderate dynamics • RRs at Various Ranges	• SPAN (for Position) • Honeywell EGI (For Non-Positional TSPI Parameters)
Run: Flight Demos • T-38 Aircraft	Validate TSPI solution accuracy under high (flight) dynamics • RRs at Various Ranges	• SPAN • Honeywell EGI (For Non-Positional TSPI Parameters)

Figure 10 – AT-38B Talon

HIL Simulation Results

Hardware-In-The-Loop Tests



- NavStorm+ GPS Rx, TSPI Processor, RT Algorithms, and Simulated HG-1700 IMU
- Spirent Simulator for GPS RF
- Antenna Patterns, Error Models, and Simulated Datalink and GPS Outages
- Benefits:
  - Perfect Truth, Identifies Any Algorithmic Related Common Biases
  - Lends Credibility to Using SUT-o-SUT Comparison when 10X Truth Not Available

HIL Simulation of 50 nmi Flight Trajectory

- Used Actual TSPI Hardware and Software
- Atmosphere and IMU Modeled with AMPSAT
- Used T38 Antenna Gain Pattern
- Insensitive to Short Datalink Outages, Loss of All Reference Receiver Data, and SBAS Correction Data Outages
- Robust to Antenna Phase Effects

HIL – Nominal 50 nmi Jet Flight

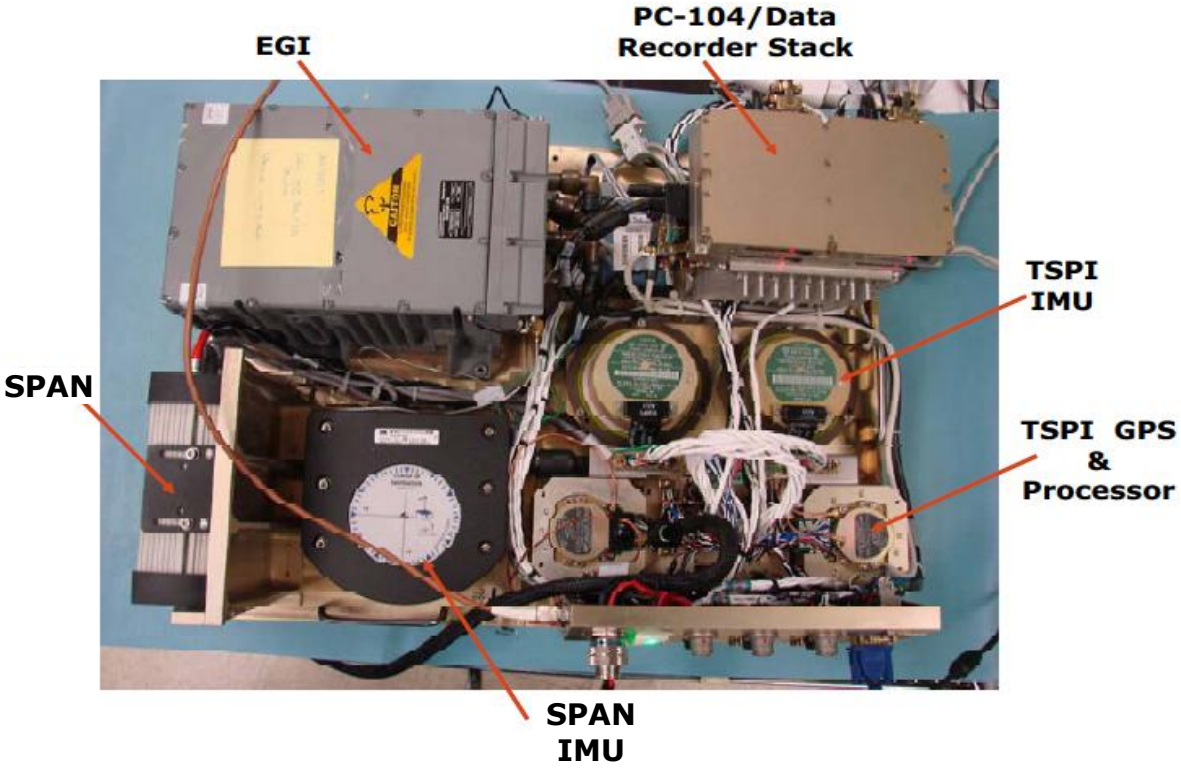
Segment #	1	2	3	4	5	6	7	Rqmt	Units
Acceleration H	0.031596	0.029654	0.030991	0.028738	0.031464	0.031421	0.035605	0.03	m/s/s
Acceleration V	0.017828	0.021379	0.018959	0.021449	0.018222	0.018126	0.023477	0.03	m/s/s
Velocity H	0.0062768	0.015176	0.01255	0.0079937	0.0057948	0.0061308	0.010889	0.03	m/s
Velocity V	0.0043504	0.0123	0.0065374	0.0054584	0.0050342	0.004428	0.0062275	0.03	m/s
Position H	0.044954	0.12879	0.10721	0.12939	0.24915	0.18462	0.055463	0.3	m
Position V	0.25932	0.25709	0.2305	0.18711	0.08161	0.13873	0.11449	0.3	m
Roll	0.0086153	0.0050646	0.011735	0.0057993	0.0061491	0.011675	0.013846	0.1	deg
Pitch	0.0072549	0.0071238	0.0066403	0.011235	0.0072613	0.019243	0.013018	0.1	deg
Heading	0.015395	0.010473	0.016771	0.017157	0.027976	0.027616	0.019956	0.1	deg
Roll Rate	0.01918	0.019233	0.018849	0.018982	0.019558	0.019212	0.024156	0.2	deg/s
Pitch Rate	0.019092	0.019313	0.019156	0.018596	0.018828	0.019171	0.019229	0.2	deg/s
Yaw Rate	0.018943	0.019033	0.01937	0.019036	0.019119	0.018952	0.019196	0.2	deg/s

- **HIL Test Predicts Good TSPI Performance Even with Maneuvers and Long Baseline**
- **Acceleration Errors Were Large Due to Lever Arm Amplification and IMU Inertial Sensor Assembly Relative Motion with Respect to Chassis**
  - **Resolved with Use of Filtered IMU Outputs for TSPI Acceleration**

Roller Coaster Live Test Results

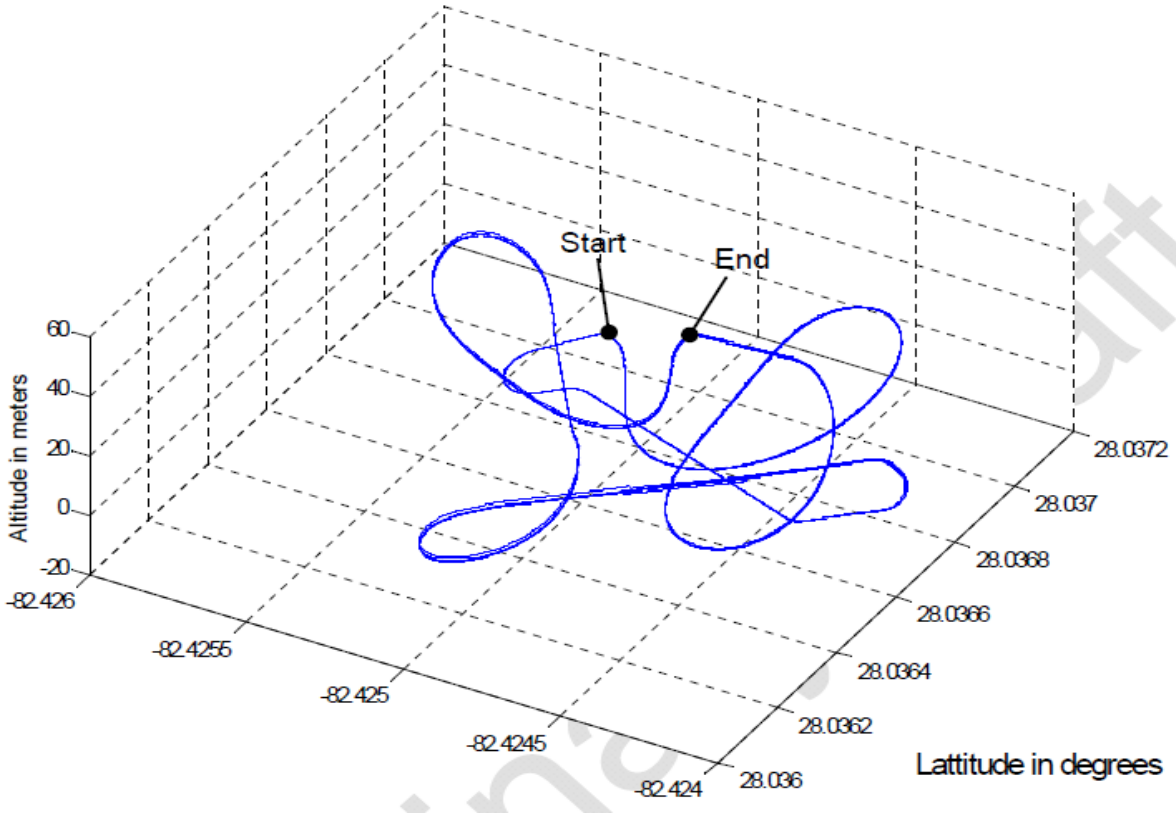
TSPI Plate Used for Demonstrations

Roller Coaster and Flight Tests



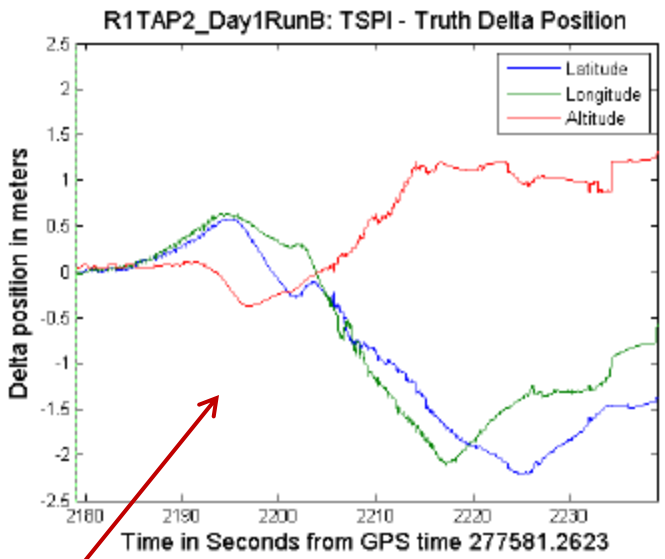
- Two CRIIS TSPI Prototype Systems Used for Comparison and Consistency Checking
  - CRIIS TSPI System Under Test (SUT): RCI NavStorm+ GPS Rx, HG-1700 IMU and TSPI Processor
- NovAtel SPAN Integrated with HG1700 for Post-Mission Reconstruction of Position Truth
- Honeywell HG-9900 Based Embedded GPS/INS (EGI) for Non-positional Truth
- GPS Antenna on T-38 Aircraft for GPS RF, HAFB L-Band Antenna for Reference Receiver Datalink

Roller-Coaster Maneuver Segment for Position Accuracy Analysis



- **Blended Position Truth: Fixed Integer SPAN Position Solution and Integrated EGI Velocity**
- **Position Scoring Segment is from 'Start (top of first hill)' to 'Stop (Plateau of Next Hill) Only**
  - **Time Duration = 25 sec**
  - **SPAN Solution Corrupted for Remainder Segment (Poor GPS Signals, Multipath etc.)**
- **Non-Positional TSPI Parameters Scored Over Entire Roller-Coaster Trajectory**

Roller-Coaster: Blended Truth Reference



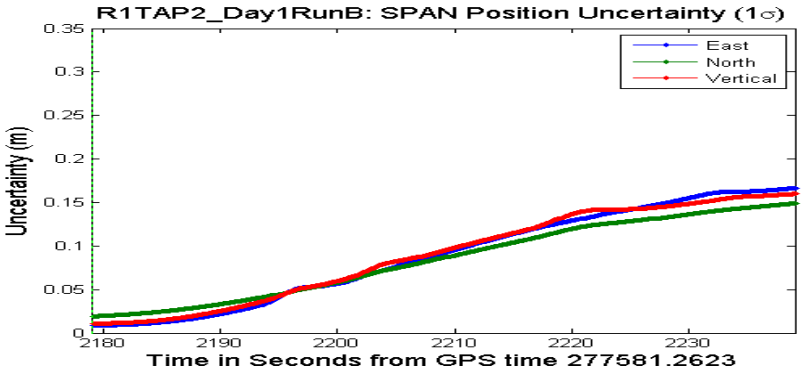
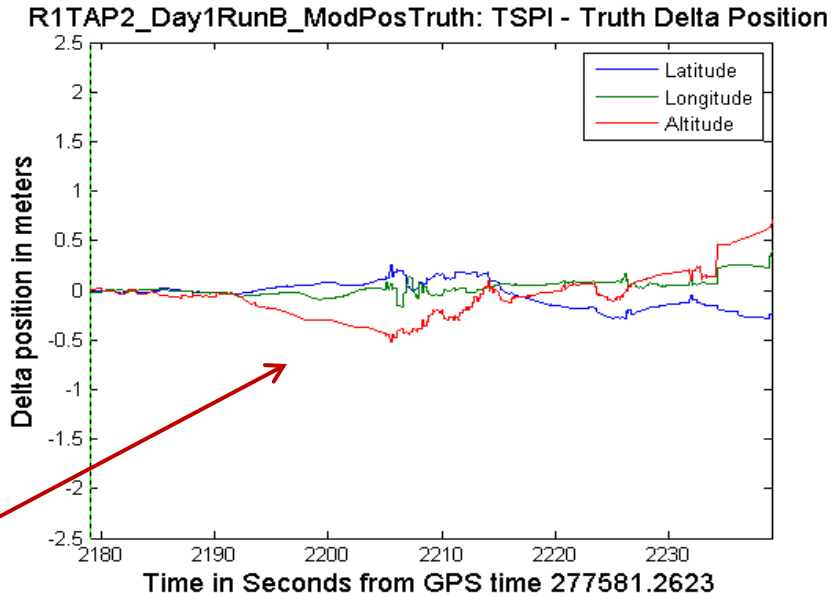


Figure 1: TSPI – SPAN



- **SPAN Truth Corrupted: Inconsistency Between SPAN Indicated Position Uncertainty and SPAN Position Solution During Non-RTK Mode**
- **Blended Position Truth: Used Initial Fixed Integer SPAN Solution Propagated by Integrated EGI Velocity**

Common Range Integrated Instrumentation System (CRIIS)

Rockwell Collins

Honeywell

Common Range Integrated Instrumentation System (CRIIS)

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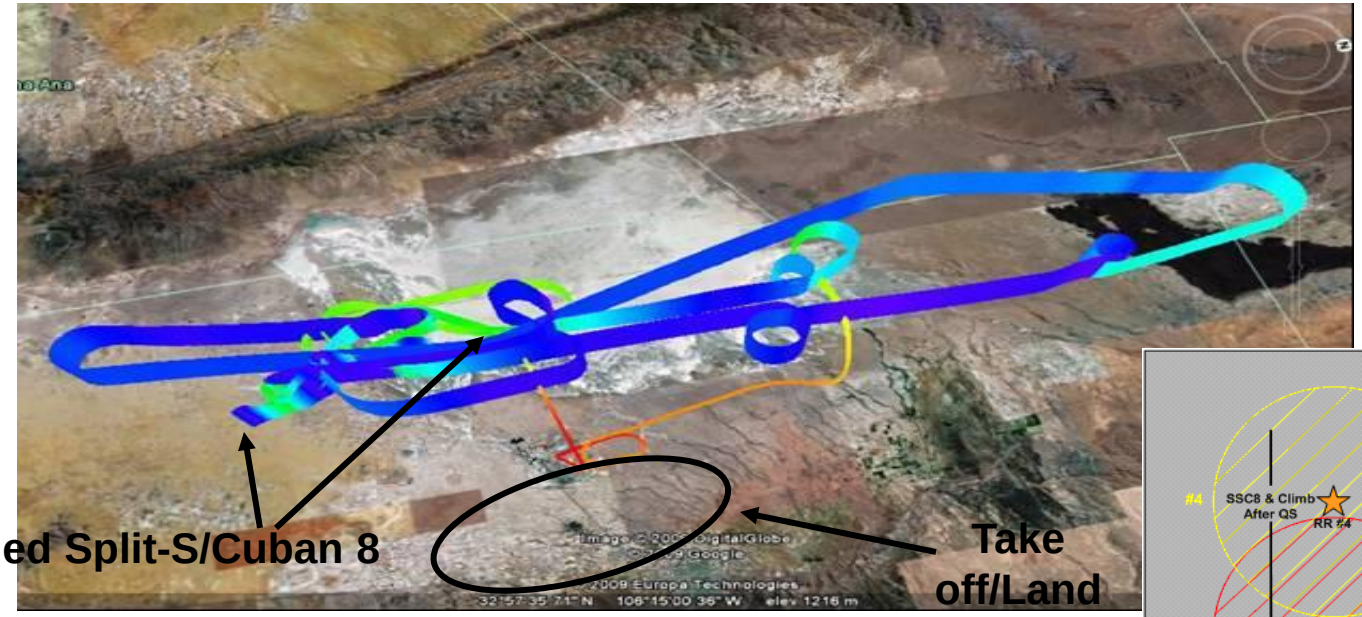
Dynamic Flight Test Results

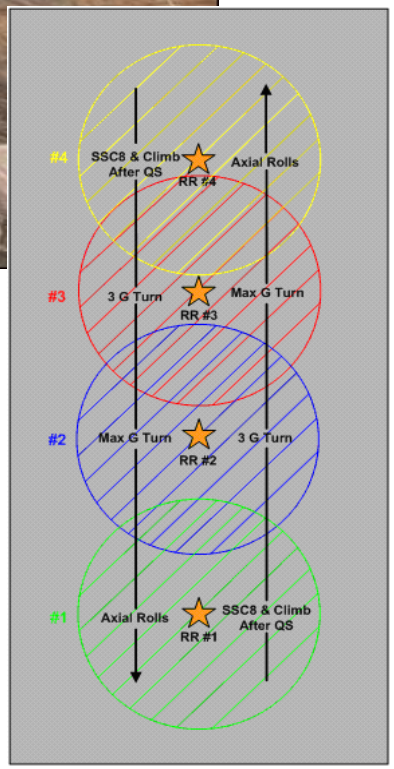
Reference Receivers and Datalink Set-Up

- Four Reference Receivers Spaced ~ 20 nmi Apart at Surveyed Locations (CORS Used)
- Datalinks Set Up at Each End of the Range
  - Used for Uplinking SBAS Corrections and DGPS Measurements from RR
- Data from All Four RRs Used for Producing Truth, Post-Mission, Using SPAN
- To Accommodate Short and Long Baseline Requirements Data from One Appropriate RR Used in CRIIS TSPI Computation

CRIIS TSPI High Dynamics

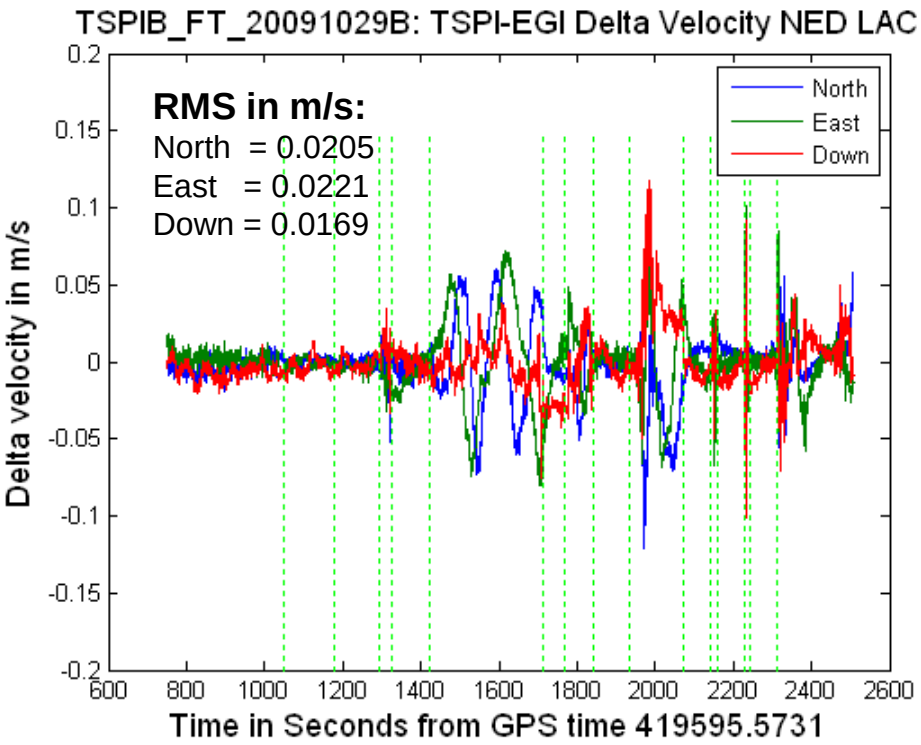
Flight Test 29 Oct 2009 – Holloman AFB

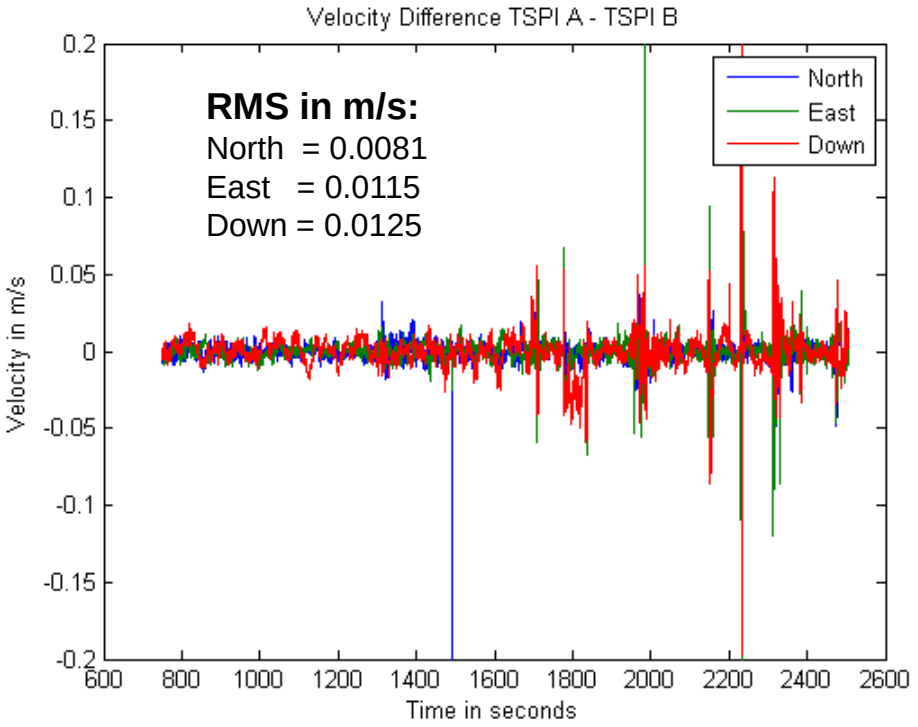




Flight Profile #1 Maneuvers		Flight Profile #1 Maneuvers
1 – Split S To Cuban 8		9 – Right Aileron Roll
2 – Orbit		10 – Straight And Level
3 – Climb		11 – Left Aileron Roll
4 – Straight And Level		12 – Straight And Level
5 – 3G Turn		13 – Max Accel
6 – Straight And Level		14 – Break Turns
7 – Max G Turn		15 – Straight And Level
8 – Straight And Level		16 - Orbit

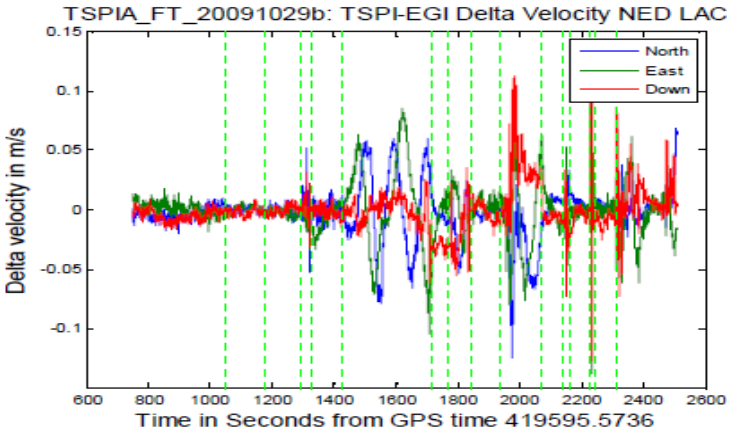
TSPI A to B Velocity Differences

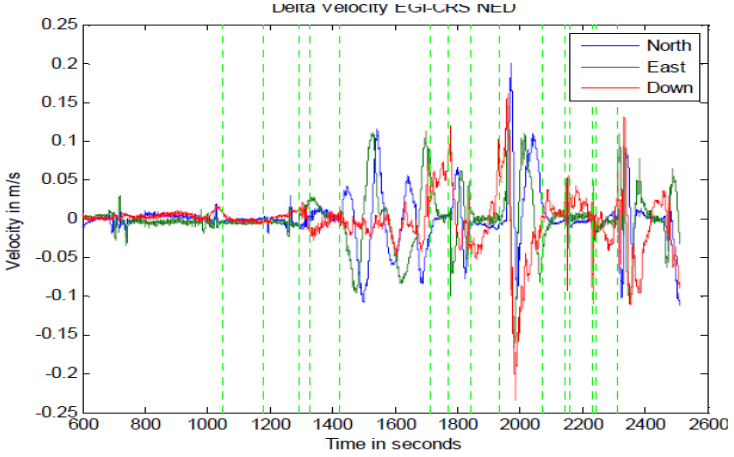




- **Horizontal Differences Between TSPI A & B are Less Than Half Those of TSPI B and EGI**
- **Lever Arm Errors in EGI IMU-to-GPS Antenna Are Suspected Cause**

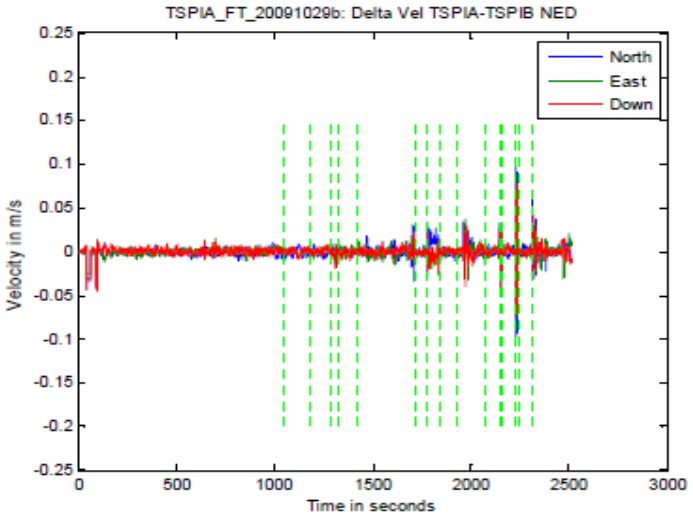
Velocity Accuracy
Using SUT-1 to SUT-2 Difference



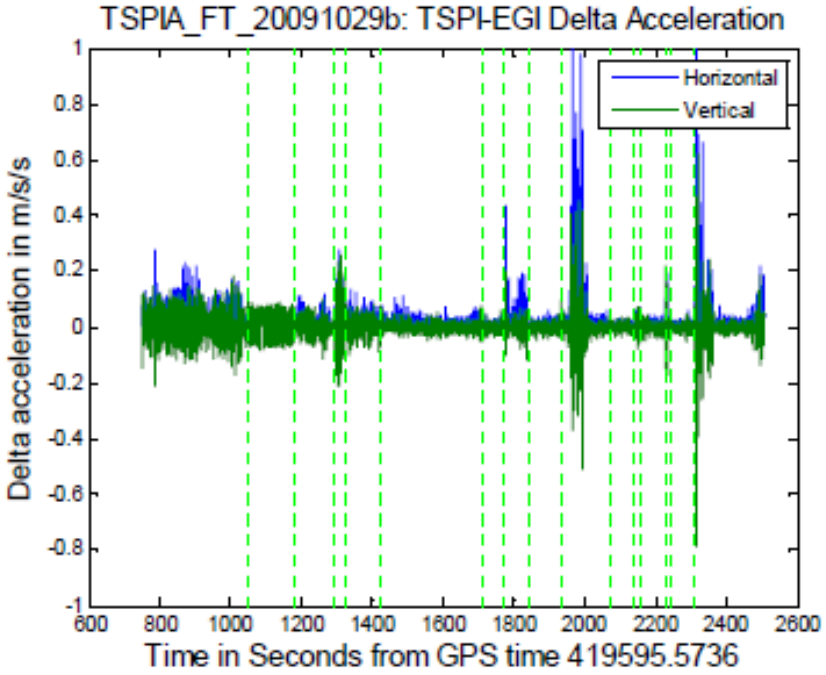


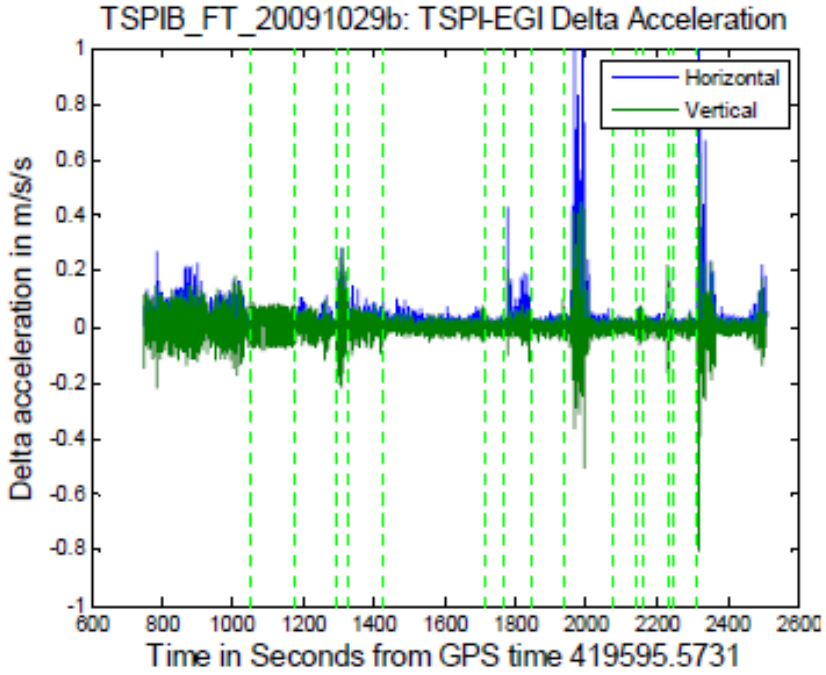
Key Observations:

- **Anomalies in CRIIS to EGI and CRS Velocity**
- **Differences During High Rotation Rate Maneuvers**
  - **Not Common Mode CRIIS Errors, Since Signatures for Each Truth Source is Different**
- **Anomalies in EGI to CRS Velocity Differences, Much Larger than SUTs Differences**
  - **Source of Anomalies is Lever Arm Errors**
- **CRIIS TSPI-A to TSPI-B Consistent**
  - **Method Can be Used for Accuracy Verification, Along With HIL (or Other Simulation to Verify Lack of Large Common-Mode Deterministic Errors)**



Acceleration Noise Issue





- **Vibrations During High G Maneuvers Added High Frequency Noise to Relative Acceleration Between EGI and TSPI**
- **Data Must Be Filtered to Below the Shock Roll-Off Frequency of Each Systems**
  - **High Frequency Noise and Shock mount Resonance Should be Above Filter BW**

Common Range Integrated Instrumentation System (CRIIS)

Rockwell Collins

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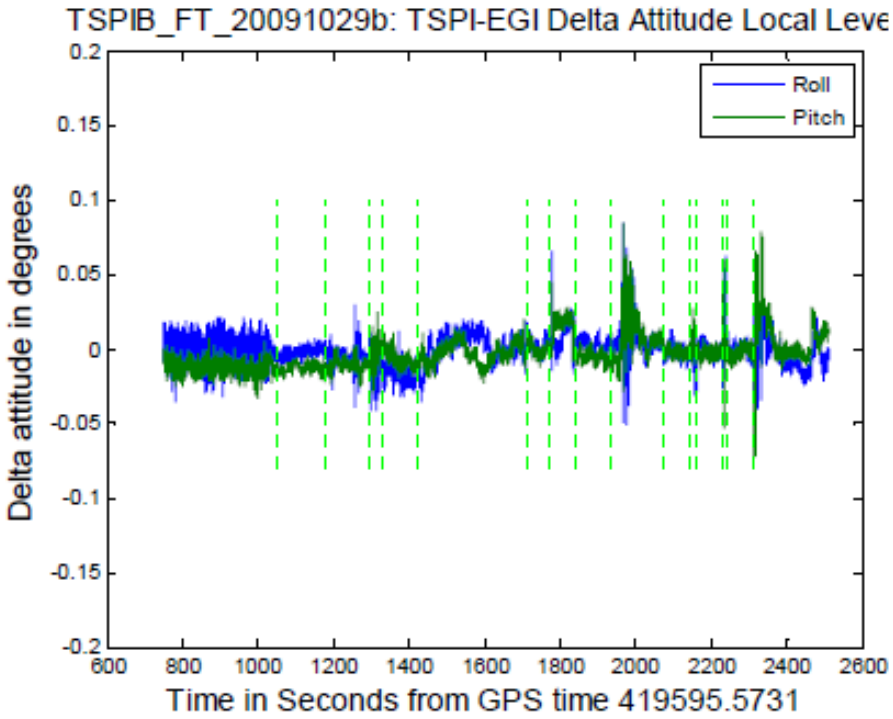
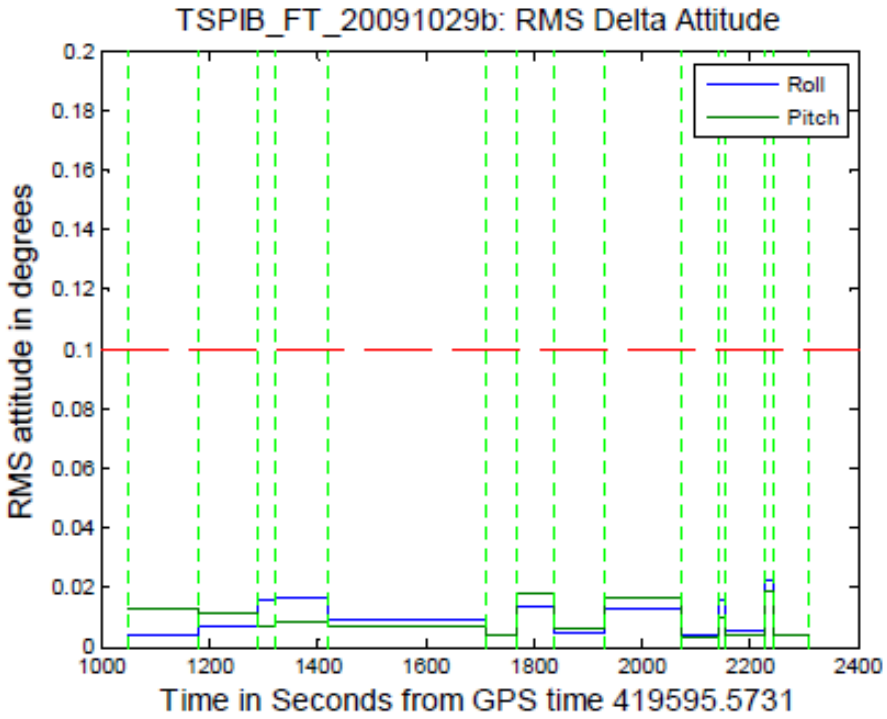
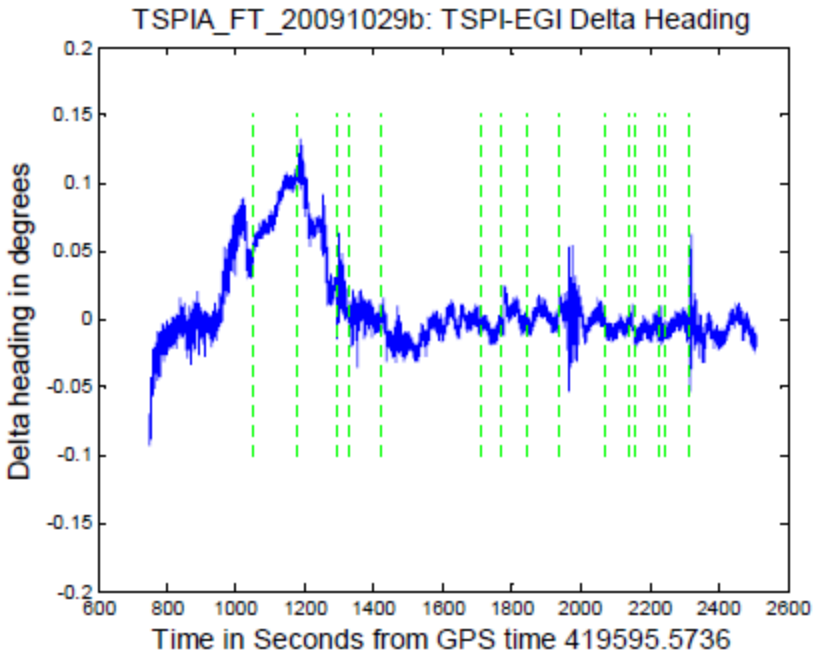
Attitude (Roll, Pitch) Accuracy

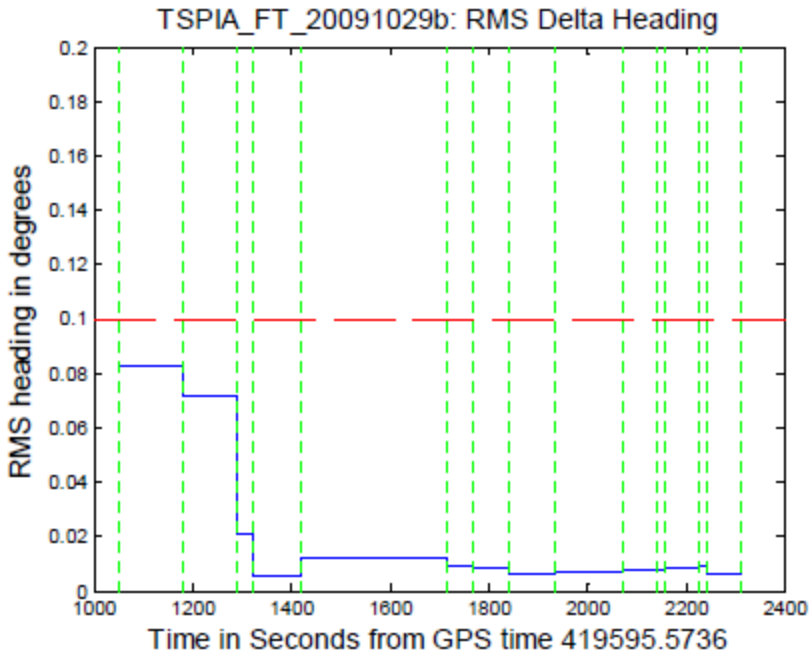




- **Attitude Accuracy Met Requirements with Margin Even Under High Dynamics**
  - **EGI Used as Truth**
  - **No Filtering Applied for Processing**
- **Segment by Segment RMS Values are Shown**

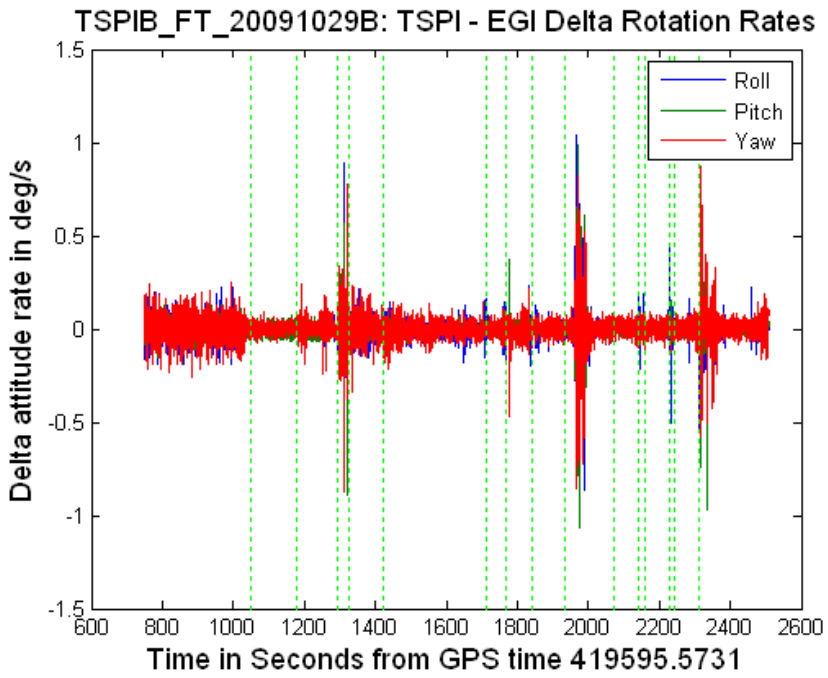
Attitude (Heading) Accuracy

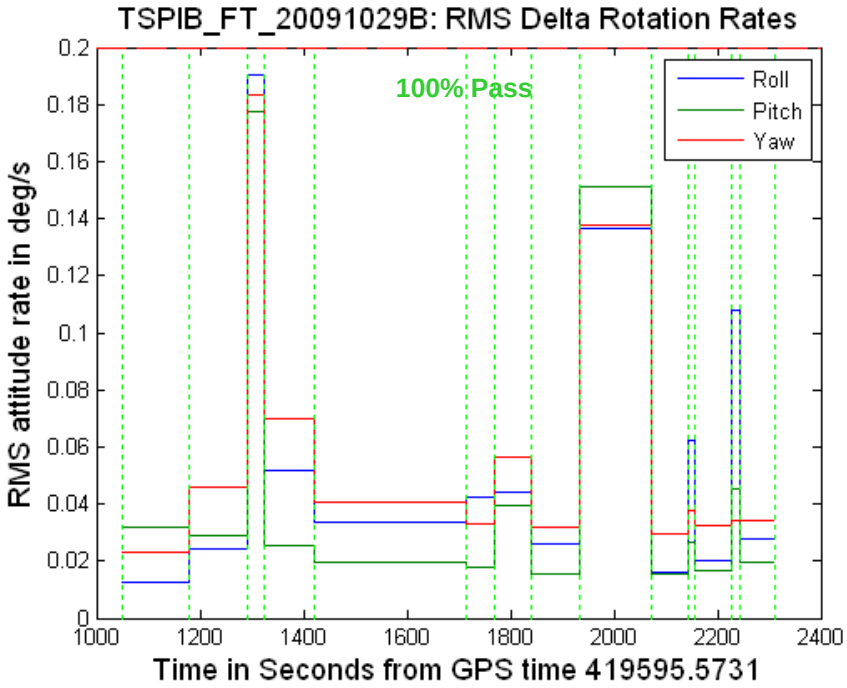




- **Heading was Well Aligned After Takeoff Roll**
- **Heading Accuracy Maintained During Maneuvers and Straight & Level Segments**
- **EGI Used as Truth (No Filtering Applied)**
  - **RMS Segment Errors Well within Spec**

Attitude Rates Performance





- **Attitude Rate Performance Good**
  - **Data Processed with 1 Hz Butterworth to Filter Out High Frequency Relative Motion between EGI and TSPI**

Flight Test Results
TSPI Level II Absolute Mode Summary

- **Absolute Mode Positioning Achieves Significant Margin**

Flight	27 Oct, Flight 1	27 Oct, Flight 1	27 Oct, Flight 1	27 Oct, Flight 1	27 Oct, Flight 1	Accuracy Rqmt
Maneuver Type	Cuban 8	180 2g Turn	360 3g Turn	360 5g Turn	360 Degree Aileron Roll	
Maneuver Segment (sec)	1926-2045	2292-2340	2350-2415	2540-2656	2725-2743	
Horizontal Position Accuracy (m)	0.3	0.7	0.6	0.7	0.7	3.0 m
Vertical Position Accuracy (m)	0.9	0.9	0.7	0.9	1.9	4.6 m
Horizontal Velocity Accuracy (m/s) (TSPI A-B)	0.02	0.01	0.01	0.04	0.02	0.05 m/s
Vertical Velocity Accuracy (m/s) (TSPI A-B)	0.01	0.01	0.01	0.01	0.01	0.05 m/s
Baseline (nmi)	NA	NA	NA	NA	NA	
RTK Mode	4,2,0	1	1	1,0	1,0	

Note: Velocity Accuracy Included in Absolute Mode as It is a Special Case Where No Datalink is Available

Flight Test Results
TSP Level II Position Accuracy

- **TSPI Level II Position Accuracy Met for Low and High Dynamic Maneuvers**
  - **Split-S Not Met in Post Processing but is Improved Over Real Time**

Flight	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flt 3	29 Oct, Flt 3	29 Oct, Flt 3	Rqmt (m)
Maneuver Type	Climb	360 degree 3g turn	360 degree 5g turn	360 degree aileron roll	Straight & Level	Split-S	Straight & Level	50 degree roll; 180 degree turn	
Maneuver Segment (sec)	1325-1422	1770-1840	1935-2072	2143-2158	1840-1935	1990-2084	3252-3393	3393-3490	
Real Time Horizontal Position Accuracy (m)	0.02	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.3
Real Time Vertical Position Accuracy (m)	0.1	0.2	0.1	0.2	0.1	0.3	0.1	0.1	0.3
Post Mission Horizontal Position Accuracy (m)	0.02	0.1	0.05	0.1	0.1	0.2	0.1	0.04	0.1
Post Mission Vertical Position Accuracy (m)	0.02	0.1	0.1	0.2	0.05	0.2	0.1	0.1	0.1
Max Baseline (nmi)	1	16	10	18	6	40	50	54	50
RTK Mode	8	8,5,4,2,0	8,7,4,2	8,4,0	8	4	4	4,1	

Flight Test Results
TSPI Level II Non-Position Solution

- **Attitude Accuracy Passes with Significant Margin in Most Cases**
  - **TSPI Level II Attitude Accuracy as Scored by Holloman CRS in this Case**

Flight	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	Requirement (deg)
Maneuver Type	Climb	360 degree 3g turn	360 degree 5g turn	360 degree aileron roll	Straight & Level	
Maneuver Segment (sec)	1325-1422	1770-1840	1935-2072	2143-2158	1840-1935	
Real Time Roll Accuracy (deg)	0.03	0.02	0.02	0.03	0.1	0.1
Real Time Pitch Accuracy (deg)	0.01	0.01	0.01	0.01	0.1	0.1
Real Time Heading Accuracy (deg)	0.01	0.01	0.02	0.02	0.1	0.1
Post Mission Roll Accuracy (deg)	0.005	0.01	0.01	0.01	0.005	0.05
Post Mission Pitch Accuracy (deg)	0.01	0.02	0.01	0.01	0.005	0.05
Post Mission Heading Accuracy (deg)	0.01	0.01	0.01	0.01	0.01	0.05

Flight Test Results
TSPI Level II Non-Position Solution

- **Attitude Rate Accuracy Passes with Significant Margin in Most Cases**
  - **TSPI Level II Attitude Accuracy as Scored by Holloman CRS in this Case**

Flight	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	Requirement (deg/sec)
Maneuver Type	Climb	360 degree 3g turn	360 degree 5g turn	360 degree aileron roll	Straight & Level	
Maneuver Segment (sec)	1325-1422	1770-1840	1935-2072	2143-2158	1840-1935	
Real Time Roll Accuracy (deg)	0.04	0.04	0.1	0.1	0.1	0.2
Real Time Pitch Accuracy (deg/sec)	0.03	0.04	0.2	0.02	0.1	0.2
Real Time Heading Accuracy (deg/sec)	0.1	0.1	0.1	0.04	0.2	0.2
Post Mission Roll Accuracy (deg/sec)	0.1	0.1	0.1	0.1	0.02	0.1
Post Mission Pitch Accuracy (deg/sec)	0.02	0.03	0.1	0.02	0.01	0.1
Post Mission Heading Accuracy (deg/sec)	0.05	0.02	0.1	0.02	0.01	0.1

Flight Test Results
TSPI Level II Non-Position Solution

- **Uncorrelated Mechanical Vibration Modes between TSPI and Truth Sources Caused Large Velocity Errors at Point of Navigation (GPS Antenna for This Test)**
  - **Hence, Truth Sources Were Not Capable of Scoring the TSPIs**

Flight	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	Requirement (m/s)
Maneuver Type	Climb	360 degree 3g turn	360 degree 5g turn	360 degree aileron roll	Straight & Level	
Maneuver Segment (sec)	1325-1422	1770-1840	1935-2072	2143-2158	1840-1935	
Real Time Horizontal Velocity Accuracy (m/s)	0.01	0.05	0.07	0.05	0.01	0.03
Real Time Vertical Velocity Accuracy (m/s)	0.01	0.04	0.07	0.06	0.04	0.03
Post Mission Horizontal Velocity Accuracy (m/s)	0.015	0.04	0.06	0.04	0.01	0.01
Post Mission Vertical Velocity Accuracy (m/s)	0.01	0.02	0.04	0.04	0.01	0.01

Flight Test Results
TSPI Level II Non-Position Solution

- **TSPI Level II Velocity Consistency between TSPI A & B was Investigated, Since Truth was Severely Impacted by Lever Arm Length**
- **Consistency between TSPI Units is Very Good as Seen Below**
  - **TSPI A/B Comparison is an Indicator that Level II Velocity Can be Met**

Flight	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	Requirement (m/s)
Maneuver Type	Climb	360 degree 3g turn	360 degree 5g turn	360 degree aileron roll	Straight & Level	
Maneuver Segment (sec)	1325-1422	1770-1840	1935-2072	2143-2158	1840-1935	
Real Time Horizontal Velocity Accuracy (m/s)	0.005	0.017	0.04	0.013	0.004	0.03
Real Time Vertical Velocity Accuracy (m/s)	0.004	0.009	0.03	0.008	0.002	0.03
Post Mission Horizontal Velocity Accuracy (m/s)	0.003	0.01	0.01	0.030	0.002	0.01
Post Mission Vertical Velocity Accuracy (m/s)	0.003	0.005	0.01	0.01	0.001	0.01

Flight Test Results
TSPI Level II Non-Position Solution

- High Frequency Motion components were Aliased to Near DC in 50 Hz TSPI Acceleration Outputs
  - Primary Driver Was Vibratory Motion of Isolated Inertial Sensor Assembly Relative to IMU Chassis
  - Problem will be Addressed in CRIIS Phase-II via Additional Filtering of IMU Outputs Used Only for Generation of the TSPI Acceleration outputs

Flight	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	Requirement (m/s/s)
Maneuver Type	Climb	360 degree 3g turn	360 degree 5g turn	360 degree aileron roll	Straight & Level	
Maneuver Segment (sec)	1325-1422	1770-1840	1935-2072	2143-2158	1840-1935	
Real Time Horizontal Acceleration Accuracy (m/s/s)	0.04	0.07	0.18	0.03	0.02	0.03
Real Time Vertical Acceleration Accuracy (m/s/s)	0.03	0.03	0.08	0.04	0.02	0.03
Post Mission Horizontal Acceleration Accuracy (m/s/s)						0.01
Post Mission Vertical Acceleration Accuracy (m/s/s)						0.01

PMP Acceleration Could Not be Scored Due to Measurement Aliasing

Flight Test Results
TSPI Level II Non-Position Solution

- **TSPI Level II Acceleration Accuracy was Evaluated for Consistency between TSPI A & B**
  - **Aliasing Found in 50 Hz Data and Not the Recorded 300 Hz Raw IMU Data**
  - **300 Hz IMU Data Used to Compare TSPI A & B**

Flight	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	29 Oct, Flight 2	Requirement (m/s/s)
Maneuver Type	Climb	360 degree 3g turn	360 degree 5g turn	360 degree aileron roll	Straight & Level	
Maneuver Segment (sec)	1325-1422	1770-1840	1935-2072	2143-2158	1840-1935	
Real Time Horizontal Acceleration Accuracy (m/s/s)	0.01	0.01	0.01	0.01	0.004	0.03
Real Time Vertical Acceleration Accuracy (m/s/s)	0.01	0.02	0.01	0.01	0.01	0.03
Post Mission Horizontal Acceleration Accuracy (m/s/s)						0.01
Post Mission Vertical Acceleration Accuracy (m/s/s)						0.01

300 Hz IMU Data Could Not be Used in PMP as it Operates Only on 50 Hz Data

Common Range Integrated Instrumentation System (CRIIS)

Rockwell Collins

Honeywell

Conclusions

- CRIIS High Dynamic Real-Time TSPI Developed and Implemented Using State-Of-The-Art Processing Algorithms
- CRIIS TSPI Level-II Accuracies Successfully Demonstrated thru a Phased Approach
  - M&S, HIL, Van, Roller-Coaster Used to Identify issues and Tune/Fix Algorithms
  - High Dynamics Flight Test Results Demonstrate TRL6 Maturity (Performance in Relevant Environment)
- System Development in EMD Phase