USAFTPS-TIM-18B-02

A LIMITED EVALUATION OF LOW COST COMMERCIAL GPS NAVIGATION SYSTEMS

(Project Have FLEX)

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14. ABSTRACT
This report documents results of the limited evaluation of low cost commercial GPS navigation systems. Testing was requested by the USAF TPS, Edwards AFB, CA. The lead developmental test organization was the Air Force Test Center, Edwards AFB, California. The executing test organization was Class 18B of the USAF Test Pilot School, Edwards AFB. Testing was conducted from 1 to 18 March 2019 and comprised of 2 ground test hours and 17.6 flight test hours. The overall test objective was to investigate the accuracy and utility of low cost, commercial GPS navigation systems under a variety of flight conditions. All test objectives were met.

15. SUBJECT TERMS
Global Positioning System (GPS), low-cost, navigation devices, truth source, time, space, and position information (TSPI), commercial off the shelf (COTS), Stratus, Garmin, Pixel, iPhone, iPad, Sentry, Bad Elf

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EXECUTIVE SUMMARY

This report documents the results of Have Flight Experiment (FLEX), a limited evaluation of low cost, commercial GPS navigation systems. The executing test organization was the USAF Test Pilot School. The Lead Developmental Test Organization was the Air Force Test Center, Edwards AFB, California. Testing was conducted by class 18B as part of Test Pilot School's Test Management Program. Testing was conducted from 1 March to 18 March 2019 and consisted of approximately 2 ground test hours and 17.6 flight test hours. Nine sorties were conducted in T-38C, five sorties in the F-16D, and two sorties were conducted in C-12C. All sorties were conducted in the R-2508 complex with the exception of one C-12C sortie that utilized the national airspace over the Pacific Ocean near Santa Barbara, CA.

Flight test programs often required the use of an independent and highly accurate Time, Space, and Position Information (TSPI) reference while evaluating systems under test (SUTs). Typical TSPI systems included the Advanced Range Data System (ARDS) and GPS Aided Inertial Navigation Reference (GAINR) Lite (GLite) which record highly accurate aircraft position (1.5-10 feet), velocity (0.3-0.5 feet/second), and attitude (0.1-0.5º). These systems often required extensive aircraft down time for modification, and come at a significant cost to a flight test program's budget. Low cost (<$1000), commercial GPS devices, however, had become prevalent within the general and military aviation communities. Additionally, low cost, commercial GPS solutions are being used in multiple major commands for contingency flight operations.

The overall test objective was to investigate the accuracy and utility of low cost, commercial GPS navigation systems under a variety of flight conditions. The overall test objective was met. There were eight systems under test: Stratus 2, Status 3, iPhone XS, iPad mini 4, Google Pixel 3, Garmin D2 Charlie Watch, Sentry, and Bad Elf. Google Pixel 3 used the Global Navigation Satellite System (GNSS) Logger application to record position and velocity data, while the Garmin watch and Bad Elf used their native software. In all other cases, ForeFlight was used as the interface to and record data from the system under test.

SUTs were flown in a variety of flight conditions in the T-38C, C-12C, and F-16D aircraft modified with GLite C1, GLite C2B, and ARDS pod as truth data source respectively. Test points included stable cruise flight, low altitude navigation, high speed supersonic flight, and dynamic, high load factor aerobatic flight. Altitudes tested were from 500 feet AGL to 40,000 feet MSL; airspeeds ranged from 150 to 1000 knots groundspeed (KGS). In the national airspace, low altitude over-water flight was conducted to investigate multi-path effects. Testing was also conducted in mountainous terrain to determine the effects of that flight environment on the position accuracy. Data collected included time, latitude, longitude, altitude, and velocity from the SUT and TSPI.

Overall, the SUTs demonstrated much less accuracy than the TSPI systems, and may not be useful for test applications requiring high accuracy TSPI data. Some SUTs provided utility for general flight operations, especially at lower speeds, or test missions with less stringent navigational accuracy requirements. SUT 95% confidence radial position error from the TSPI truth source ranged from 50 to 900 feet. The velocity information, however, was typically within 1-2 knots of the TSPI truth source. The position accuracies of all devices during maneuvering were worse than during stable cruise flight. With the exception of the iPad and iPhone, Figures of merit (FOMs) as reported real-time by all the SUTs were generally found to be optimistic and not representative of their actual position accuracy. The SUTs that were able to interface with ForeFlight provided great overall situation awareness for general position in the airspace and for general point-to-point navigation. For the SUTs that provide an Attitude Heading Reference System (AHRS), testing showed these systems were inadequate to be used with military flight operations as a means of primary flight instruments during contingency operations.

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INTRODUCTION

This report documents the results of Have Flight Experiment (FLEX), a limited evaluation of low cost, commercial GPS navigation systems. The executing test organization was the USAF Test Pilot School. The Lead Developmental Test Organization was the Air Force Test Center, Edwards AFB, California. Testing was conducted by class 18B as part of Test Pilot School's Test Management Program. Testing was conducted from 1 March to 18 March 2019 and consisted of approximately 2 ground test hours and 17.6 flight test hours. Nine sorties were conducted in T-38C, five sorties in the F-16D, and two sorties were conducted in C-12C. All sorties were conducted in the R-2508 complex with the exception of one C-12C sortie that utilized the national airspace over the Pacific Ocean near Santa Barbara, CA.

BACKGROUND

Large flight test programs often included the requirement of a Time, Space, and Position Information (TSPI) reference or "truth" source in order to evaluate systems under test (SUTs). TSPI systems at Edwards AFB for the T-38, F-16, and C-12 were GPS Aided Inertial Navigation Reference (GAINR) Lite (GLite) Kinematic Global Positioning System (KGPS) Configuration C1 (without attitude reporting capability), Advanced Range Data System (ARDS), and GLite KGPS+Inertial Measurement Unit (IMU) Configuration C2B, respectively. All three require aircraft modifications and a Differential GPS (DGPS) ground station for post-flight data processing. These requirements led to extremely robust position and velocity accuracy (<10 feet for ARDS and <1.5 feet for GLite C1 and C2B) but may also added significant schedule constraints, including aircraft modification time, and monetary costs ($2,000 per flight hour) to test programs.

With the proliferation of GPS and Automatic Dependent Surveillance – Broadcast (ADS-B) transceiver technology in the civilian world, some lower budget, less complex flight test programs began utilizing low cost (<$1000), commercial GPS systems to provide position and/or velocity data for their SUT. While this approach allowed for rapidly fielded capability, there was no effort to demonstrate the accuracy of these SUTs under representative flight test conditions. Additionally, low cost, commercial GPS device solutions were being used in multiple USAF major commands (MAJCOMs) and military services for contingency flight operations.

The SUTs considered for this evaluation were common consumer devices with GPS capabilities such as the Apple iPhone XS, Apple iPad mini 4, Google Pixel 3, and Bad Elf, and others that were intentionally designed for use in general aviation such as the Garmin D2 Charlie watch. The remaining SUTs were ADS-B receivers with Attitude Heading Reference Systems (AHRS) that were capable of interfacing with commercial software, ForeFlight, to include aircraft attitude information as well as position information. These SUTs were the Stratus 2, Stratus 3, and Sentry.

Table 1: Edwards AFB (412 TW RANS/ENRT) TSPI Capabilities

TSPI Capability Name	Test Aircraft	TSPI System Type	Instrumentation	Certified Post-Mission Accuracy
Advanced Range Data System (ARDS)	F-16D	DGPS+IMU	Podded application for AIM-9 station on any operations aircraft; 3 plate configuration for larger, slow mover aircraft or vehicles	Pos=10.0 ft, Vel=0.3 ft/s, Acc=0.3 ft/s/s, Att=0.5 deg
GLITE KGPS Config C1	T-38C	KGPS, 12 channel, kinematic, single frequency. On board control and data recording. Post mission processing only.	PC-104 stack with CPU, GPS receiver, status display, recorder, optional data interface	Pos=1.5 ft, Vel=0.5 ft/s, Acc=0.5 ft/s/s Att=N/A
GLite KGPS+IMU Config C2B	C-12C	KGPS+IMU, onboard control and data recording. Post mission processing only. GPS: 12 channel, kinematic, single frequency. IMU: HG-1700	PC-104 stack with CPU, GPS receiver, IMU, status display, recorder, optional data interface	Pos=1.5 ft, Vel=0.5 ft/s, Acc=0.5 ft/s/s, Att=0.1 deg

* All abbreviations can be found in APPENDIX H – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

TEST ITEM DESCRIPTION

The project tested 8 low cost, commercial GPS navigational systems in different configurations for use on assigned C-12, T-38, and F-16 aircraft. Table 2 highlights each SUT's capabilities and how data were retrieved. More detailed information about each SUT can be found later in this section.

Table 2: Systems Under Test

System Under Test	AHRS Capable	AHRS Tested*	Additional Hardware (Communication method with SUT)	Data Recording Software	Satellite Constellations Used
Bad Elf	No	[redacted]	None	Bad Elf	GPS, GLONASS
Garmin D2 Charlie	No		None	Garmin Connect	GPS, GLONASS
iPad mini 4 (internal GPS)	Yes	No	None	ForeFlight	GPS, GLONASS
iPhone XS	Yes	No	None	ForeFlight	GPS, GLONASS, Galileo
Google Pixel	Yes	No	None	GNSS Logger	GPS, GLONASS, BDS, Galileo
Stratus 2	Yes	Yes	iPad (Wifi)	ForeFlight	GPS
Stratus 3	Yes	Yes	iPad (Wifi)	ForeFlight	GPS
Sentry	Yes	Yes	iPad (Wifi)	ForeFlight	GPS, GLONASS, BDS, Galileo

*SUTs capable of AHRS but who's interfacing software had not implemented AHRS functionality were not tested for AHRS

Low Cost Commercial Navigation Systems (SUTs)

Bad Elf GPS Pro+

The Bad Elf GPS Pro+ puck was a Bluetooth capable WAAS GPS & GLONASS receiver and barometric altimeter. The puck was capable of displaying latitude, longitude, altitude, track, speed, and universal time without connecting to a tablet device or phone. The device was designed to work with any Apple device and was capable of recording track data for download through a Bad Elf developed application or other flight applications such as ForeFlight. The puck had 16MB of flash memory and was capable of storing up to 200 hours of trip data if a sampling rate of 1Hz is selected. When enabled on the application, the Bad Elf GPS Pro+ began data logging when the power was turned on. The battery was capable of 24 hours of operation, when the Bluetooth radio and GPS were active. The puck was advertised as having an accuracy to 2.5m up to 60,000 feet and 1,000 knots. The puck dimensions were 3 inches x 2.42 inches x 0.69 inches and weighed 3.2 ounces. During flights, the device was stored in a flight suit pocket. Data were downloaded post flight from the Bad Elf developed application in a GPX format and was not connected to an external device. A picture of the Bad Elf can be found in Figure 1.

Figure 1: Bad Elf

Garmin D2 Charlie Watch

The D2 Charlie was an aviator smartwatch designed by Garmin. The watch was designed for general aviation and used to check weather via NEXRAD, navigate using GPS via a moving map on the watch face, and log flights. It contained a single high-sensitivity WAAS and GLONASS GPS receiver embedded in the watch. The watch size was 2 inch diameter, 0.69 inches thick. The watch had to be connected to a smartphone or tablet via Bluetooth using the Garmin Pilot application to log and download flight data for later use. The manufacturer claimed battery life with GPS operations as 12 hours, idle battery life was 12 days. For this test program, the watch was flown on the pilot's wrist. No accuracy was advertised by the manufacturer. Data were downloaded post-flight from Garmin Pilot application in a GPX format. A picture of the Garmin D2 Charlie was be seen in Figure 2.

Figure 2: Garmin D2 Charlie

iPad mini

The iPad mini 4 model A1538 was a consumer tablet computer designed by Apple. The tablet was 8 inches high, 5.3 inches wide, and weighed 0.67 lbs. The version of this iPad used for Have FLEX included an internal GPS receiver capable of Assisted-GPS (A-GPS) and GLONASS. The iPad served as a SUT when its internal GPS hardware was providing the solution and gathered data through the ForeFlight app.

The iPad was mounted on an aircrew's leg during the flight. Data were downloaded post-flight from the ForeFlight app in a KML format. A-GPS was not used during this evaluation because cellular connectivity was turned "off", and the AHRS capability when interfaced with ForeFlight was not evaluated. No accuracy was advertised by the manufacturer.

A total of four iPads were used on any Have FLEX test flight, three of these iPads were used to interface with the Stratus 2 and 3, and Sentry. The fourth was used as described here. A picture of the iPad mini can be found in Figure 3.

Figure 3: iPad mini

iPhone XS

The iPhone XS model MT6C2LL/A (A1921) was a smartphone designed by Apple. The phone was 3 inches wide, 6.2 inches high, and weighed 7.3 ounces. It contained several motion and location sensors including a magnetometer, barometer, and 6-axis gyro/accelerometer chip for sensing motion and orientation. Location sensors included A-GPS, GLONASS, and Galileo. The iPhone was mounted in the test aircraft using RAM mounts that allowed the aircrew to view the display and provide the smartphone a clear view of the sky. Data were recorded using the ForeFlight app similar to how data were collected from the iPad. Data were downloaded post-flight from the ForeFlight app in a KML format. A-GPS was not used during this evaluation because cellular connectivity was turned "off", and the AHRS capability when interfaced with ForeFlight was not evaluated. No accuracy was advertised by the manufacturer. A picture of the iPhone can be found in Figure 4.

Figure 4: iPhone

Google Pixel 3

The Pixel 3 was an Android operating system based smartphone designed by Google. The smartphone featured various accelerometers, barometer, compass, and gyroscope. It was able to receive Wide Area Augmentation System (WAAS) GPS, GLONASS, BeiDou Navigation Satellite System (BDS), and Galileo navigation sources. The Pixel 3 was 2.69 inches wide, 5.73 inches long, 0.31 inches thick and weighed 5.22 ounces. It was mounted in the aircraft using RAM mounts that allowed the aircrew to view the display and provide the smartphone a clear view of the sky. Navigation data recorded using a GNSS Logger application (https://github.com/google/gps-measurement-tools) since Android operations systems did not support ForeFlight. Data were downloaded post flight in an NMEA format. No accuracy was advertised by the manufacturer. A picture of the Pixel can be found in Figure 5.

Figure 5: Pixel

Stratus 2S

The Stratus 2S was a portable ADS-B receiver manufactured by Appareo. Stratus 2S was capable of WAAS GPS and contained AHRS sensors. The Stratus 2 was 2.6 inches wide, 6 inches long, 1.25 inches high and weighed 9.7 oz. If in range of an ADS-B broadcast tower, Stratus received real time weather and traffic information. Stratus 2 was designed to be paired with another device via WiFi which displayed and logged the data the Stratus 2 collects. The unit had to be rigidly attached to the aircraft in order to provide accurate AHRS data, and required a clear view of the sky for GPS reception. As installed in Have FLEX test aircraft, Stratus 2S was paired to an iPad secured to a crewmember's kneeboard operating ForeFlight to interface with the Stratus 2S. Data were downloaded post flight in a KML format. No accuracy was advertised by the manufacturer. A picture of the Stratus 2 can be found in Figure 6.

Stratus 3

The Stratus 3 was the next generation product in Appareo's Stratus line of portable ADS-B In receivers after the Stratus 2S. The Stratus 3 was identical in size, weight, and appearance to the Stratus 2. The Stratus 3 had all of the capability included in the Stratus 2S along with various software upgrades and additional features such the ability internally log data. As installed in Have FLEX test aircraft, Stratus 3 was paired to an iPad secured to a crewmember's kneeboard operating ForeFlight to interface with the Stratus 3. Data were downloaded post-flight from the ForeFlight app in a KML format. No accuracy was advertised by the manufacturer. A picture of the Stratus 3 can be found in Figure 6.

Sentry

The Sentry was a compact and portable ADS-B receiver manufactured by Avionix. Sentry supported four satellite navigation systems (WAAS GPS, Galileo, GLONASS, and BDS), and was able to track three constellations concurrently for redundant location tracking. Sentry included sensors to produce an AHRS solution. Sentry measured 2.25 inches wide, 3.25 inches long, 1.25 in tall, and 4.2 ounces. Sentry was paired with one of the iPads being worn on the kneeboard of aircrew. Data were downloaded post-flight from the ForeFlight app in a KML format. No accuracy was advertised by the manufacturer. A picture of the Sentry can be found in Figure 6.

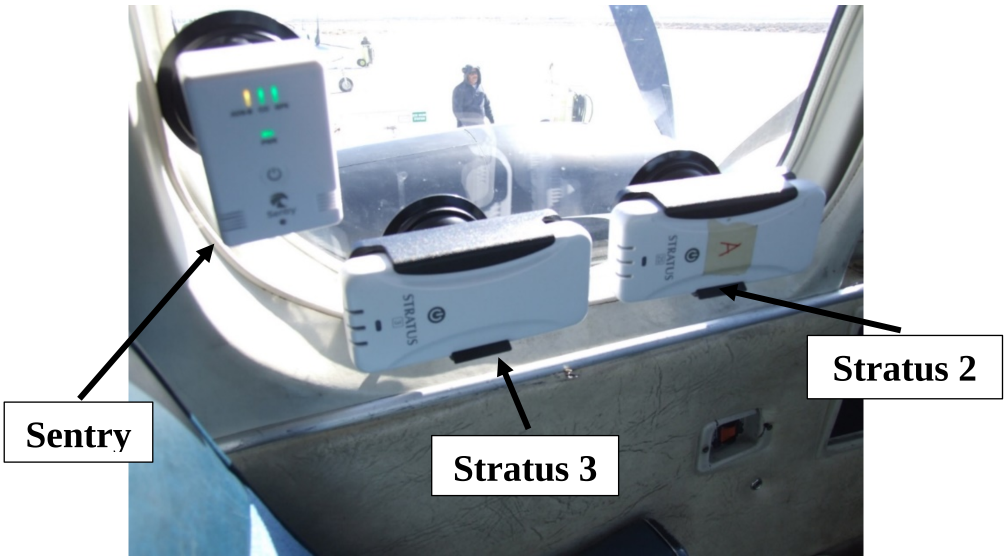

Figure 6: Stratus 2, Stratus 3, and Sentry

Global Positioning System (GPS)

GPS was a satellite-based radio navigation operated by US Air Force. In its most basic form, GPS receivers determined their position by using trilateration of at least three satellites. Since its inception, GPS augmentation techniques were generated to increase the accuracy of GPS, especially in areas of low coverage. Satellite-based augmentation systems (SBAS) were an air navigation aid created to increase availability, integrity, and accuracy of GPS by using ground-based reference stations to measure deviations in the satellite signals which were transmitted via the GPS satellites to receivers and used to improve accuracy. The regional SBAS for the US was called WAAS. Additionally, cell phones had the ability to utilize cell phone tower data to enhance the time-to-first-fix for receivers that are in areas of poor satellite signal quality. This technique was called A-GPS; however, the cellphones used in this test were operated in "airplane mode" which prevented the use of A-GPS. While the term “GPS” technically referred only to the American satellite-based radio navigation system, this report uses “GPS” to refer to general satellite-based radio navigation, sometimes referred to as GNSS, which includes satellites of other nations. Each SUTs capability to track satellite navigation constellations is described in its respective section.

Other Satellite Navigation Systems (GNSS)

Several SUTs were capable of utilizing GPS constellations other than American GPS. The other constellations included:

Global Navigation Satellite System (GLONASS) was a satellite navigation system alternative to GPS operated by Russian Federal Space Agency that consisted of 24 satellites that provided global coverage.

Galileo was a European Union EU developed satellite navigation system created to decrease dependence on US GPS or Russian GLONASS services. The public service of Galileo was used for this test.

BeiDou Navigation Satellite System (BDS) was a second generation Chinese military and commercial GPS navigation constellation created to compete with US and Russia. As of March 2019, 14 satellites were available for public service worldwide.

Automatic Dependent Surveillance – Broadcast (ADS-B)

Three of the SUTs: Sentry, Stratus 2, and Stratus 3, were ADS-B capable. While these systems still utilized on-board GPS systems to determine their position, they provided additional information that increased situation awareness. ADS-B systems with transmit-only capability were referred to as “ADS-B Out” and periodically broadcasted information such as current position, altitude, and velocity that were used by air traffic control receiver ground stations and other aircraft in the vicinity to track aircraft. Ground stations re-broadcasted received information to aircraft that were also equipped with “ADS-B In”. The three SUTs used in this testing were ADS-B In only. The ADS-B capability was used only for the contingency flight operations testing.

Test Aircraft

C-12C

The C-12C aircraft, shown in Figure 7, was a twin-engine turboprop transport built by Beechcraft. A single C-12C, USAF S/N 76-00161, was used to conduct testing in the relatively slower speed, and lower altitude portions of the flight envelope and was intended to represent performance more commonly associated with general aviation and small commercial aircraft. The C-12 housed a GLite (Config C2B) rack to collect TSPI data during the test flights. The Edwards AFB TSPI shop (412 RANS/ENRT) was the sole organization responsible for pre-flighting and post-flighting. A boresight was performed on the test aircraft by the TPS special instrumentation shop. This boresight was required to provide certified accuracy before the TSPI shop would release flight data. The TSPI shop created 8 different TSPI files for each SUT location to decrease the uncertainty of the position error calculations by putting the TSPI truth source “point” at the SUT location. The location of the SUTs and the TSPI source can be found in

Table 3. Further information about the C-12C aircraft and systems can be found in the flight manual (Reference 1).

Figure 7: C-12

Table 3: C-12 System Locations

System	Water Line (in)	Fuselage Line (in)	Butt Line (in)
TSPI IMU	97	186	11 R
iPad	114	136	14 L
Sentry	125	140	25 L
Stratus 3	122	136	25 L
Stratus 2	122	138	25 L
iPhone	120	107	20 L
Garmin	122	136	14 L
Bad Elf	122	140	14 L
Pixel	120	107	20 R

The C-12 carried AHRS capable SUTs through suction cups attached to the pilot's window. These SUTs were all aligned in accordance with manufacturer's specification and in a location to provide a high availability of GPS satellite reception. Cellphone SUTs were placed in already modified RAM mounts on the left and right sides of the cockpit. The iPad SUT was carried on the pilot's leg via a PIVOT kneeboard, and the Garmin watch was worn on the pilot's wrist. The Bad Elf was stored in the pilot's flight suit pocket. Additional iPads were located with the FTE in row 1 next to the TSPI. The SUT layout of the C-12 can be seen in pictures in Figure 8 and Figure 9. The GLite TSPI rack was located behind the left row 1 seat. Data were transferred by the TSPI team at Edwards AFB.

Figure 8: C-12 AHRS Capable SUT Installation

Figure 9: C-12 Cellphone SUT Installation

F-16C/D

The F-16C/D was a tandem two seat (D model variant), multi-role tactical fighter built by Lockheed Martin (Figure 10). An F-16D, USAF S/N 86-06050, was used to conduct testing in the supersonic region at higher altitudes. An ARDS pod was used on the wingtip to collect TSPI data. A pre-flight and post-flight was conducted for each flight by the TSPI shop. The F-16 did not require a boresight. The TSPI shop created 8 different TSPI files for each SUT location to decrease the uncertainty of the position error calculations by putting the TSPI truth source "point" at the SUT location. The location of the SUTs and the TSPI source can be found in Table 4. Figure 11 shows how the SUTs were mounted in the F-16D. Further information about the F-16D aircraft and its systems is in the flight manual (Reference 2).

Table 4: F-16 System Locations

System	Water Line (in)	Fuselage Line (in)	Butt Line (in)
TSPI IMU	126	435	4 R
iPad	94	123	0
Sentry	105	181.5	12 R
Stratus 3	108	181.5	9 L
Stratus 2	107	181.5	12 R
iPhone	100	189	12 R
Garmin	94	123	0
Bad Elf	104	129	0
Pixel	100	125	0

The F-16 carried AHRS capable SUTs on RAM mount C-clamps attached to the canopy bow between the front and rear cockpit. These SUTs were all aligned in accordance with manufacturer's specification and in a location to provide a high availability of GPS satellite reception. Cellphone SUTs were placed on the towel racks in the front and rear cockpit. The iPad SUT was carried on the aircrew's leg via a PIVOT kneeboard, and other iPads were either carried on a kneeboard or in the map case in the rear cockpit. The Garmin watch was worn on the pilot's wrist, and the Bad Elf was stored in the pilot's flight suit pocket. The SUT layout of the F-16 can be seen in pictures in Figure 11 and Figure 12. Data were transferred by the TSPI team at Edwards AFB.

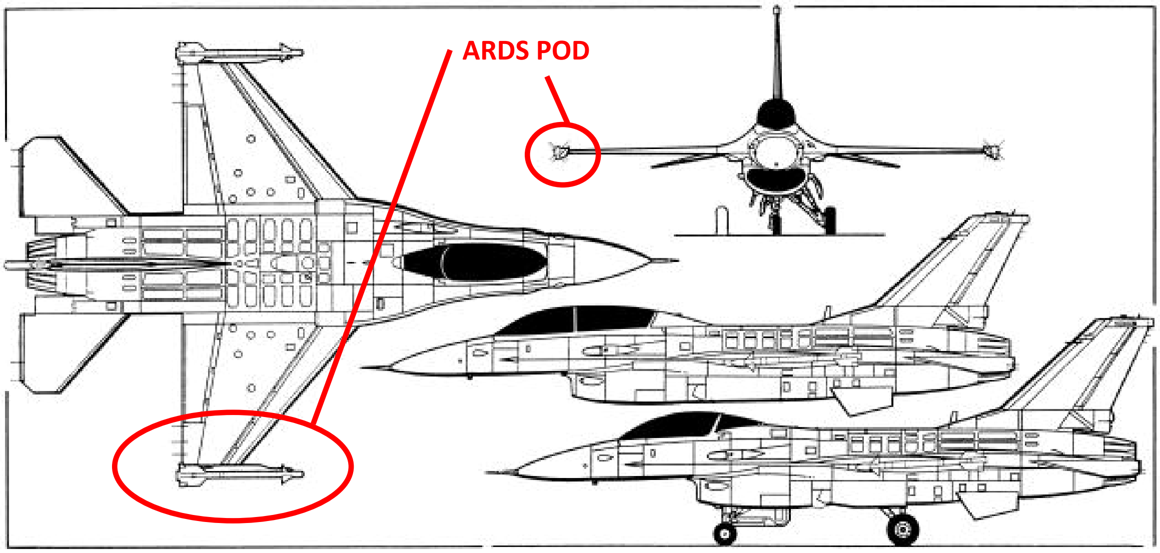

Figure 10: F-16C/D 3-View

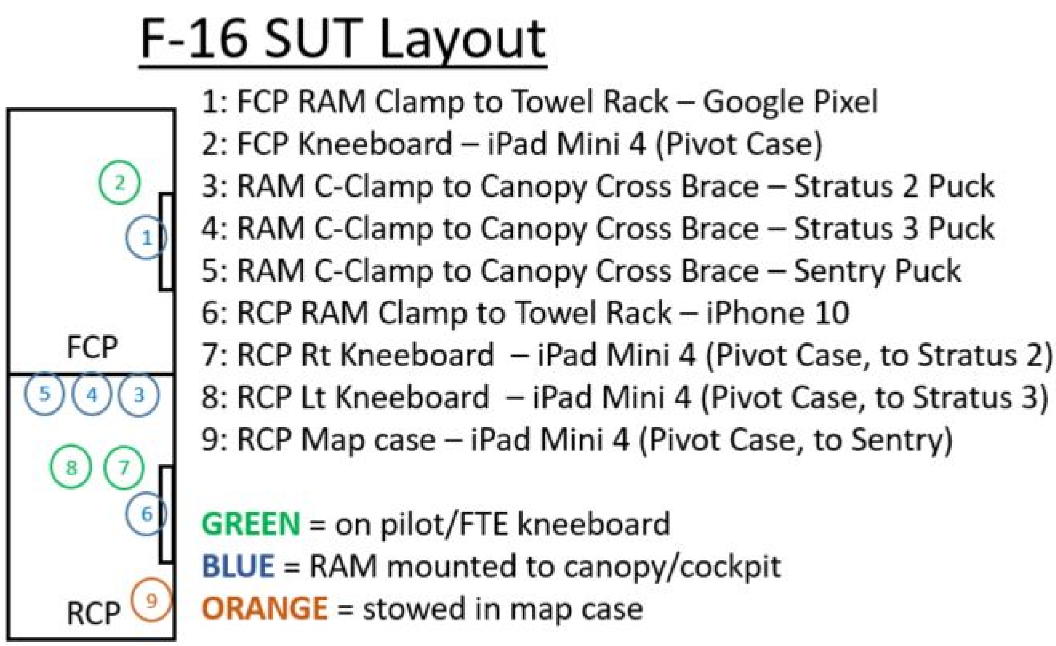

Figure 11: F-16 SUT Layout

Figure 12: F-16 SUTs

T-38C

The T-38 was a two seat (tandem), supersonic trainer built by Northrop Corporation shown in Figure 13. Two T-38C's USAF S/N 64-03302 and 64-13189 was used to conduct testing in the high subsonic regions and middle altitudes as a less expensive alternative to the F-16D. The T-38C housed a GLite (Config C1) rack to collect TSPI data during the test flights. The TSPI shop pre-flighted and post-flighted the GLite rack for each test flight. The GLite as installed on the T-38 did not record Euler angles and corrections from the TSPI source (installed in the nose of the aircraft) to the actual location of each SUT were not performed. As a result, any information presented in the report for the T-38 includes some bias equal to the distance between each SUT and the TSPI source (up to 15 feet). The location of the SUTs and the TSPI source can be found in Table 5. Further information about the T-38 aircraft and systems can be found in the flight manual (Reference 3).

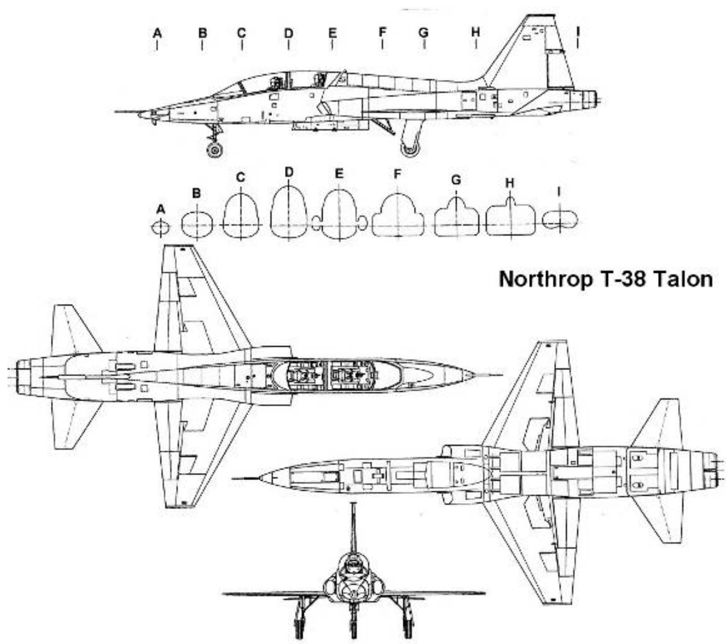

Figure 13: T-38 3-View

Table 5: T-38 System Locations

System	Water Line (in)	Fuselage Line (in)	Butt Line (in)
TSPI Antenna (Tail 189 & 302)	29	408	0
iPad	13	178	0
Sentry	17.5	170	12 L
Stratus 3	33	231	7 L
Stratus 2	33	231	7 R
iPhone	33	234	7 L
Garmin	16	180	0
Bad Elf	25	185	0
Pixel	17.5	173	12 R

The T-38 carried AHRS capable SUTs on suction cups and RAM mount C-clamps attached to either the canopy in the front cockpit, glass between the two cockpits, or right upper instrument panel. These SUTs were not aligned in accordance with manufacturer's specification but were in a location to provide a high availability of GPS satellite reception. Cellphone SUTs were suction cupped in the front and rear cockpit. The iPads were carried on the aircrew's legs via a PIVOT kneeboard. The Garmin watch was worn on the pilot's wrist, and the Bad Elf was stored in the pilot's flight suit pocket. The SUT layout of the T-38 can be seen in pictures in and. Data were transferred by the TSPI team at Edwards AFB.

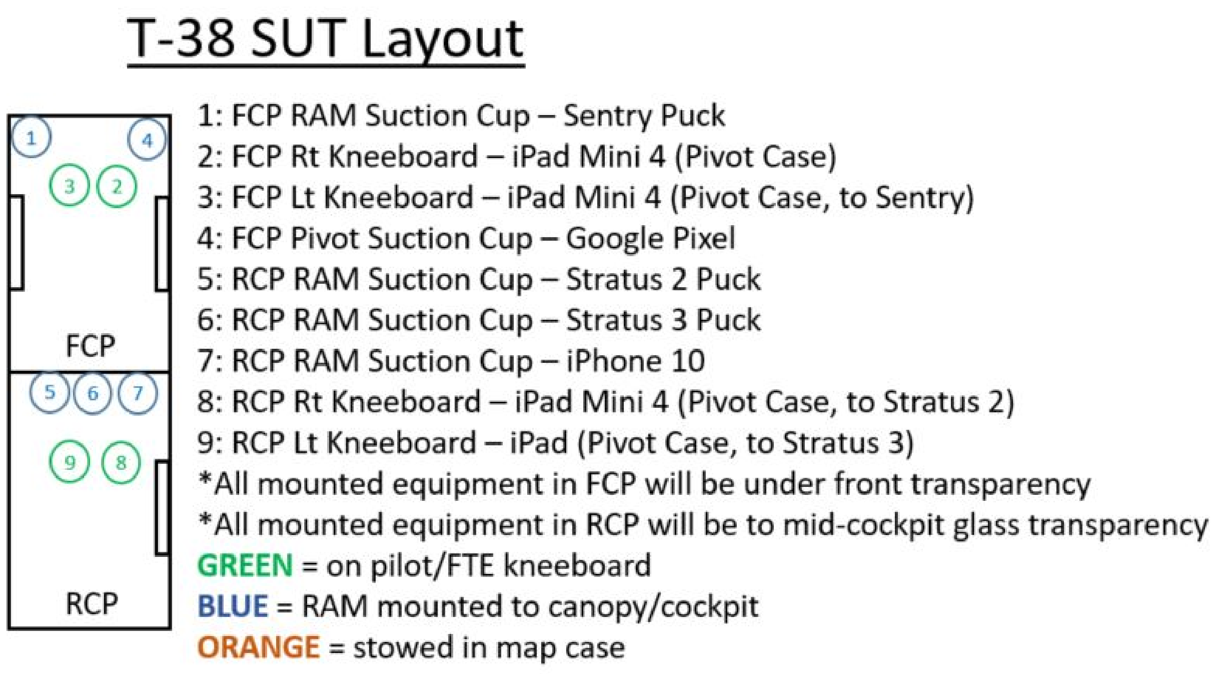

Figure 14: T-38 SUT Layout

Figure 15: T-38 SUTs

International Traffic in Arms Regulations (ITAR)

ITAR was a United States regulatory regime to restrict and control the export of defense and military related technology to safeguard U.S. national security and other additional objectives. ITAR applied to GPS receivers as such that manufacturers were obligated to prevent receivers from producing a navigation solution above a certain speed and altitude. Each manufacturer interpreted and applied these regulations differently such that a receiver might quit reporting data much sooner than the altitudes and speeds stipulated by ITAR. This test is limited to only the data logging solutions available to the general public. It was unknown if any of the information collected from the SUTs documented in this report were affected by ITAR.

Mounting Systems

These SUTs were temporarily mounted in each test aircraft for each flight using commercially available mounting solutions. All SUTs that were mounted in the aircraft were attached through the use of RAM Mounts or Pivot suction. RAM Mounts was a manufacturer of rugged and versatile mounting systems for phones, tablets, GPS units, etc. that are designed to be used in vehicles such as aircraft. These mounts could be configured in a number of different combinations. Products used can be found in Figure 16 and Figure 17

Figure 16: RAM Mount

Figure 17: Suction Cup Mount

Data Formats

Data were downloaded from each SUT following each flight in either a GPX, KML, or NMEA format.

GPX Format

The GPX, or GPS Exchange Format, was an Extensible Markup Language (XML) schema designed as a common GPS data format for software applications that could be used to describe waypoints, tracks, and routes. The format was open and could be used without the need to pay license fees. The GPX format was only capable of logging latitude, longitude, elevation, and GPS data and time. The Bad Elf and Garmin D2 Charlie watch were only capable of GPX format. File sizes from one hour of flight time logging data at 1 Hz was approximately 1 Megabyte.

KML Format

The Keyhole Markup Language (KML) is another XML schema designed for expressing geographic annotation and visualization within internet-based, two-dimensional and three-dimensional Earth Browsers, specifically, Google Earth. This format recorded the same information as GPX but also recorded velocity. Additional parameters recorded, but not used in data analysis contained in this report was course, acceleration, pitch angle, and bank angle. All data downloaded from any SUT associated with ForeFlight was downloaded in a KML format. File sizes from one hour of flight time logging data at 1 Hz was approximately 2 to 3 Megabytes.

NMEA-0183 Format

The National Marine Electronics Association #0183 (NMEA) was a data format used with GPS. The NMEA format provided the most information, although the Google Pixel was the only SUT capable of providing the NMEA format when used with the GNSS logger app. The NMEA format contained all the same information as the KML format but also included information about each satellite used for the position fix for each time stamp to include identification of the specific satellite and what constellation it belonged (A-GPS, GLONASS, etc.) as well as the pseudorange, azimuth, and elevation with respect to the receiver. Additional information included horizontal Dilution of Precision (HDOP), difference in elevation between the geoid and ellipsoid at that position, how many satellites used in the fix, and figure of merit. File size from one hour of flight time logging 1 Hz was approximately 20 Megabytes.

OVERALL TEST OBJECTIVE

The overall test objective was to investigate the accuracy and utility of low cost, commercial GPS navigation systems under a variety of flight conditions. The specific test objectives were to:

1. Determine the position and velocity accuracy of low cost, commercial GPS navigation systems in a variety of flight conditions.
2. Characterize the utility of self-reported Figures-of-Merit (FOM) for applicable low cost, commercial GPS navigation systems.
3. Evaluate the utility of low cost, commercial GPS navigation systems for flight test.
4. Demonstrate the utility of low cost, commercial GPS navigation systems for contingency flight operations.

All test objective were met.

CONSTRAINTS

1. Although HDOP may significantly affect GPS error, HDOP data were unavailable for the SUTs, and HDOP was not experimentally controlled when characterizing position error. Therefore, data was not HDOP normalized, and similar testing done in a different HDOP environment may produce different results.

2. The Stratus 2 and Stratus 3 SUT’s mounted in the Rear Cockpit (RCP) of the T-38C were not oriented in accordance with manufacturer recommendations for the AHRS analysis. This most likely impacted the performance of the AHRS with respect to evaluating these SUTs for contingency flight operations. There were two reasons for this constraint: (1) airworthiness certification limited the mounting locations in the T-38 and (2) limit flight test hours required that all SUTs be flown at the same time.

3. The Bad Elf and Garmin D2 Charlie were not capable of reporting velocity, so the dependence of their SUT velocity accuracy on aircraft velocity was not tested. In addition, their dependence of velocity accuracy on altitude was not tested. The test team did not use changes in latitude and longitude with respect to time to determine velocity because this would have made the results dependent on the position error. Conversely, iPad, iPhone, Sentry, Stratus 2 and Stratus 3 could report SUT velocity and were tested.

4. Quantitative FOM reporting was not evaluated in the Garmin D2 Charlie because the Garmin SUT was incapable of providing FOM numerical values. The FOM only gave qualitative binary feedback.

5. Point-to-point day VMC navigation using the Bad Elf and Google Pixel were not tested because they did not have this capability. While the Garmin D2 Charlie did have the capability for navigation, extensive ground set-up and mission planning were required which was not in line with the scenario the test team generated. Only the iPad, iPhone, Sentry, Stratus 2 and Stratus 3 were tested in this regard.

6. The ability of Bad Elf, Garmin D2 Charlie, Google Pixel, iPad, and iPhone to be used as a primary navigation source during simulated IMC was not tested because they did not have this capability (no AHRS capability). Only the Sentry, Stratus 2 and Stratus 3 were tested in this regard.

7. The GLite as installed on the T-38 did not record Euler angles, and corrections from the TSPI source (installed in the nose of the aircraft) to the actual location of each SUT was not performed. As a result, any information presented in the report includes an uncertainty of ±15 feet.

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TEST AND EVALUATION

All test objectives were met. Testing was conducted from 1 March to 18 March 2019 and consisted of approximately 2 ground test hours and 17.6 flight test hours. Nine sorties were conducted in T-38C, five sorties in the F-16D, and two sorties were conducted in C-12C. All sorties were conducted in the R-2508 complex with the exception of one C-12C sortie that utilized the national airspace over the Pacific Ocean near Santa Barbara, CA. There were eight systems under test: Stratus 2, Status 3, iPhone XS, iPad mini 4, Google Pixel 3, Garmin D2 Charlie Watch, Sentry, and Bad Elf. Google Pixel 3 used the Global Navigation Satellite System (GNSS) Logger application to record position and velocity data, while the Garmin watch and Bad Elf used their native software. In all other cases, ForeFlight was used as the interface to and record data from the system under test.

SUTs were flown in a variety of flight conditions in the T-38C, C-12C, and F-16D aircraft modified with GLite C1, GLite C2B, and ARDS pod as truth data source respectively. Test points included stable cruise flight, low altitude navigation, high speed supersonic flight, and dynamic, high load factor aerobatic flight. Altitudes tested were from 500 feet AGL to 40,000 feet MSL; airspeeds ranged from 150 to 1000 knots groundspeed (KGS). In the national airspace, low altitude over-water flight was conducted to investigate multi-path effects. Testing was also conducted in mountainous terrain to determine the effects of that flight environment on the position accuracy. Data collected included time, latitude, longitude, altitude, and velocity from the SUT and TSPI.

Overall, the SUTs demonstrated much less accuracy than the TSPI systems, and may not be useful for test applications requiring high accuracy TSPI data. Some SUTs provided utility for general flight operations, especially at lower speeds, or test missions with less stringent navigational accuracy requirements. SUT 95% confidence radial position error from the TSPI truth source ranged from 50 to 900 feet. The velocity information, however, was typically within 1-2 knots of the TSPI truth source. The position accuracies of all SUTs during maneuvering were worse than during stable cruise flight. With the exception of the iPad and iPhone, figures of merit (FOMs) as reported real-time by all the SUTs were generally found to be optimistic and not representative of their actual position accuracy. The SUTs that were able to interface with ForeFlight provided great overall situation awareness for general position in the airspace and for general point-to-point navigation. For the SUTs that advertised to provide an Attitude Heading Reference System (AHRS), testing showed that these systems were inadequate to be used with military flight operations as a means of primary flight instruments during contingency operations.

System assessments were made according to the 412th Test Wing Rating Criteria shown in Table A1 in APPENDIX A – RATING CRITERIA.

POSITION AND VELOCITY ACCURACY

The specific test objective was to determine the position and velocity accuracy of low cost, commercial GPS navigation systems in a variety of flight conditions. Position and velocity data was recorded while flying 3 minutes of cruise at varying ground speeds and altitudes. The reported position of each SUT was then compared to recorded TSPI information to assess any position and velocity errors. Furthermore, position and velocity errors were evaluated during maneuvering flight, low altitude flight in mountainous terrain, and over water flight to assess possible multipath effects. Data analysis procedures for evaluating the SUT position and velocity errors are shown in the APPENDIX B – DATA ANALYSIS.

RMS Position and Velocity Error

This test determined position and velocity error of the SUT in a variety of altitude and groundspeed combination.

Test Methods and Conditions

Each aircraft flew a constant altitude and maintained constant heading while holding ground speed constant for approximately 2-4 minutes each (i.e. cruise). Ground speeds varied based on aircraft type and limits and ranged from 150 to 1180 knots grounds speed. Altitudes ranged from 5,000 to 40,000 feet MSL. The test team avoided true north/south and east/west cruise runs to the maximum extent possible to prevent biasing error in one direction.

Data analysis was accomplished via the steps in APPENDIX B – DATA ANALYSIS.

Test Results

The radial RMS position error for each SUT can be found in Table 6. Additional RMS position errors can be found in APPENDIX E – SUPPLEMENTAL DATA POSITION AND VELOCITY ACCURACY.

The data shows that systems without off-board data recording such as the Bad Elf, iPhone, and iPad generally performed better than systems that use Bluetooth communication to an off-board data recorder such as the Stratus 2, Stratus 3, and Sentry which each used the iPad. While there were enough independent data points to make a statistical conclusion, the Garmin D2 Charlie and the Google Pixel did not produce data for multiple flight events and, thus, have a smaller sample size.

Table 6 also shows the 95% upper confidence limit of the radial position error for each SUT. These follow the same trend as the RMS. Additional position errors can be found in APPENDIX E – SUPPLEMENTAL DATA POSITION AND VELOCITY ACCURACY

Table 6: SUT RMS and Upper Confidence Limit Position Error

SUT	2D Radial Position Error (ft)	Radial Position 95% Confidence Interval (ft)
Bad Elf	42	92
Garmin	471	899
Pixel	92	267
iPhone	27	64
iPad	28	53
Stratus 2	197	464
Stratus 3	323	825
Sentry	187	357

Table 7 shows the RMS radial velocity error for the SUTs that were able to record velocity data. Testing shows that these SUTs are highly accurate when they record velocity. During testing, the iPad, Stratus 3, and Sentry randomly recorded a groundspeed of zero. These drop outs produced large errors and were not used in these RMS calculations. Additionally, test results showed the iPhone reports zero groundspeed above 640 KGS. The errors associated with the apparent “speed limit” on the iPhone were not used in these calculations. The velocity accuracy was highly accurate for these SUTs because they use Doppler shift of the GPS signal to determine velocity instead of trilateration. This allows for relatively large position errors while still maintaining a small velocity error.

Similarly, Table 7 depicts the 95% upper confidence limit of the radial velocity errors for the SUTs that recorded velocity.

Table 7: SUT RMS and Upper Confidence Limit Radial Velocity

SUT	RMS Radial Velocity Error (KGS)	Radial Velocity 95% Confidence Internal (KGS)
Pixel	0.33	0.64
iPhone	0.91	2.30
iPad	0.64	1.47
Stratus 2	0.14	0.28
Stratus 3	0.22	0.48
Sentry	0.16	0.32

Velocity Dependence of Position and Velocity Accuracy

This test determined the effect (if any) of aircraft velocity on the SUT's position error and velocity error, by measuring position and velocity accuracies at varying ground speeds. The differing speed capabilities of various airframes were used to span a wide range of test groundspeeds, and a table of these groundspeeds can be found in Table 8.

Table 8: Aircraft Groundspeed Ranges

Airframe	Minimum Groundspeed (KGS)	Maximum Groundspeed (KGS)
C-12	133	270
T-38	346	652
F-16	225	971

Test Methods and Conditions

Each aircraft flew a constant altitude and maintained constant heading while holding ground speed constant for approximately 2-4 minutes each (i.e. cruise). Ground speeds varied based on aircraft type and limits and ranged from 130 to 970 knots grounds speed. Altitudes ranged from 5,000 to 40,000 feet MSL. The test team avoided true north/south and east/west cruise runs to the maximum extent possible to prevent biasing error in one direction.

Velocity accuracy was evaluated for the iPad, iPhone, Pixel, Sentry, Stratus 2, and Stratus 3. Velocity accuracy was not evaluated for the Bad Elf and Garmin D2 Charlie. The Bad Elf and Garmin D2 Charlie file formats did not report or record an independent velocity measurement and therefore a valid assessment of their accuracy could not be determined.

Data analysis was accomplished via the steps in APPENDIX B – DATA ANALYSIS. The team hand faired a line through the position error data; the test team used engineering judgement of the slope of this line to determine if position error was dependent on velocity. The test team analyzed the velocity error growth or shrinkage with velocity and used engineering judgement to determine velocity error dependence on velocity.

Test Results

The position error for each SUT as a function of velocity as recorded by the TSPI are plotted in Appendix C for all SUTs. The velocity error as a function of velocity as recorded by the TSPI are plotted in Appendix C for the iPad, iPhone, Pixel, Stratus 2, Stratus 3, and Sentry. Bad Elf and Garmin D2 Charlie file formats used did not report velocity. Table 9 provides a general summary of test results.

Table 9: Summary of Results

System Under Test	Qualitative Comments
Bad Elf	No dependence of position accuracy on velocity. Device did not record independent velocity measurements.
Garmin D2 Charlie Watch	Position error increased significantly with velocity until 620 KGS. Beyond this speed observed error was significantly reduced. Device did not record independent velocity measurements.
Google Pixel	No dependence of position accuracy on velocity. No dependence of velocity accuracy on velocity.
iPad Mini	No dependence of position accuracy on velocity. No dependence of velocity accuracy on velocity. Stopped reporting velocity beyond 640 KGS.
iPhone XS	No dependence of position accuracy on velocity. No dependence of velocity accuracy on velocity. Unexplained velocity dropouts were observed.
Stratus 2	Position error increased significantly with velocity. No dependence of velocity accuracy on velocity. Unexplained velocity dropouts were observed.
Stratus 3	Position error increased significantly with velocity. No dependence of velocity accuracy on velocity. Unexplained velocity dropouts were observed.
Sentry	Position error increased significantly with velocity. No dependence of velocity accuracy on velocity. Unexplained velocity dropouts were observed.

Position error dependence on aircraft velocity varied significantly among SUTs. The Garmin D2 Charlie, Sentry, Stratus 2, and Stratus 3 all exhibited increasing position error as aircraft velocity increased. This error trended to increase in a linear fashion and was likely attributed to some sort of time delay or bus delay error. An exact determination of the error source could not be determined without the ability to analyze the algorithms and processes used by the SUTs which were not available to the team. The Garmin

D2 Charlie exhibited a strange characteristic and position error went from increasingly linearly to dropping off to less than 50 feet of error beyond 1050 feet/second.

There was no clear dependence of velocity error on actual aircraft velocity for any of the SUTs which self-reported velocity. Velocity dropouts occurred with all SUTs which reported their own velocity. These dropouts were not able to be directly correlated to any specific flight regimes with the exception of the iPhone XS which stopped recording velocity above 640 KGS.

Plots of SUT velocity error as a function of TSPI velocity are found in Appendix D for the iPad, iPhone, Stratus 2, Stratus 3, and Sentry. The Bad Elf and the Garmin D2 Charlie were not capable of reporting velocity, so velocity accuracy and any dependence of position accuracy on velocity were not tested. Bad Elf and Garmin D2 Charlie file formats used did not report velocity.

Bad Elf

Test results showed no dependence of position accuracy on velocity through the flight conditions tested. A plot of radial position error versus TSPI radial velocity can be found in Figure 18. Plots of position error versus velocity for the Bad Elf can be found in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED, Figure C1, Figure C2, and Figure C3.

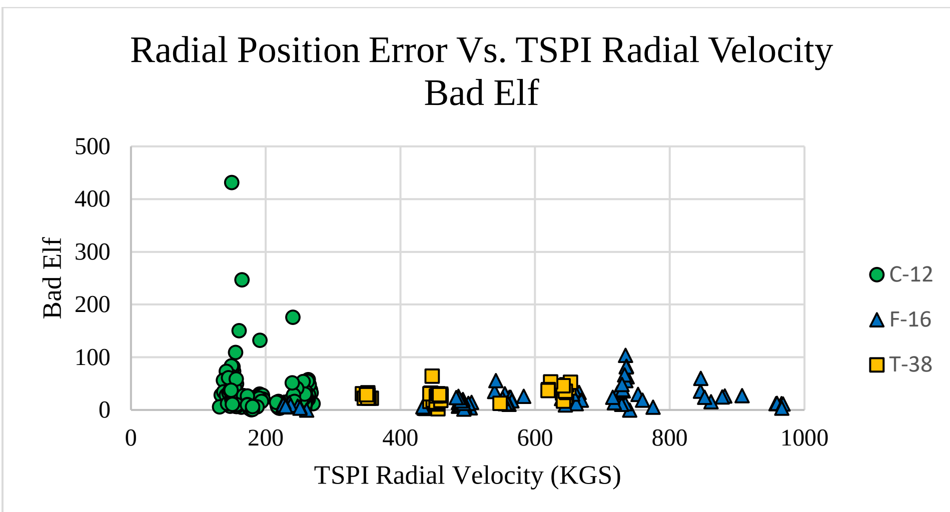

Figure 18: Bad Elf Radial Position Error vs TSPI Radial Velocity

Garmin D2 Charlie

Test results showed a dependence of position accuracy on velocity through the flight conditions tested. However, when flying in the F-16, the error dropped significantly to less than 50 feet. The Garmin D2 Charlie only produced usable data from three test missions, but there was still enough data collected to make a statistical determination. A plot of radial position error versus TSPI radial velocity can be found in Figure 19. Plots of position error versus velocity for the Garmin D2 Charlie can be found in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED, Figure C4, Figure C5, and Figure C6. The test team suspects this result to be unique to the Garmin D2 Charlie. **Complete further testing to investigate the increased accuracy of the Garmin D2 Charlie in the F-16. (R1).**

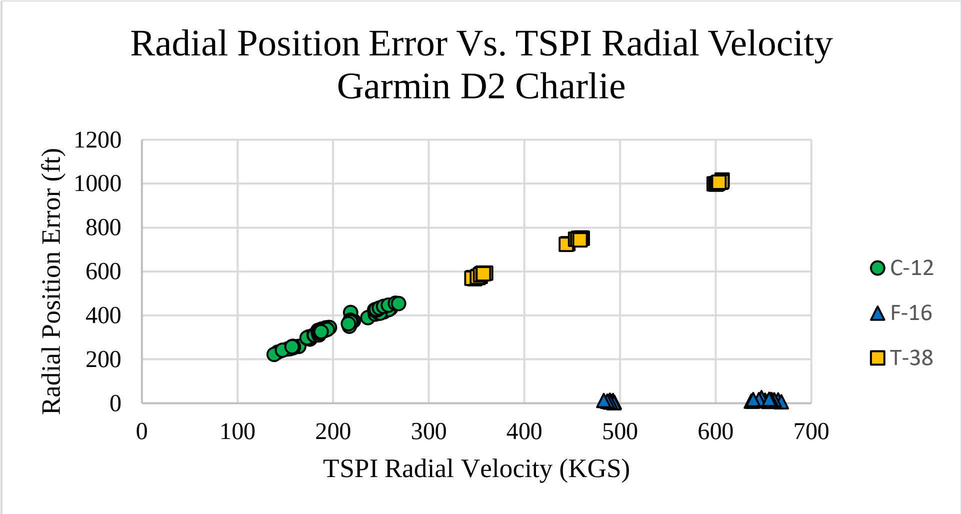

Figure 19: Garmin D2 Charlie Radial Position Error vs TSPI Radial Velocity

Google Pixel

Test results showed no dependence of position accuracy on velocity through the flight conditions tested. A plot of radial position error versus TSPI radial velocity can be found in Figure 20. Figure C7, Figure C8, Figure C9, and Figure C10 show additional position errors versus velocity for the Pixel in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED.

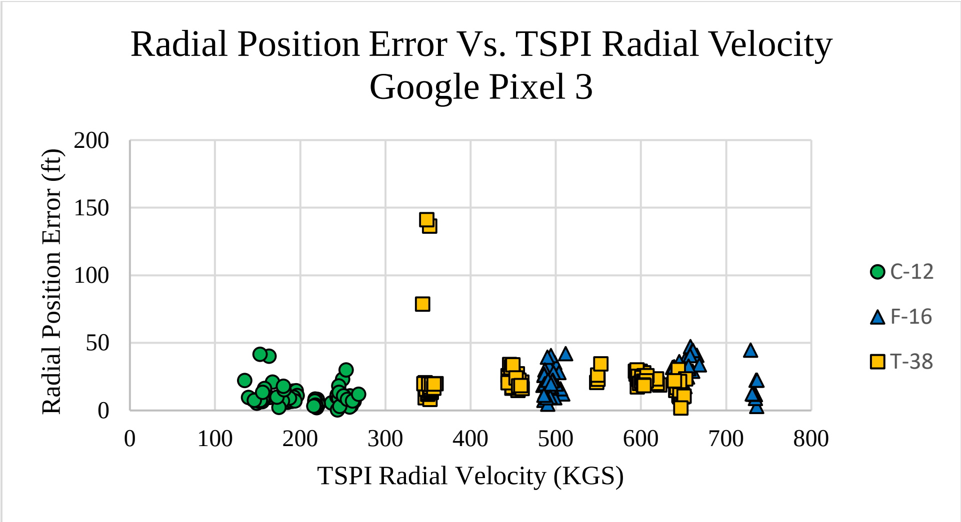

Figure 20: Google Pixel Radial Position Error vs TSPI Radial Velocity

Test results showed no dependence of velocity accuracy on velocity through the flight conditions tested. Figure C11 shows velocity error versus velocity for the Google Pixel in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED.

iPad

Test results showed no dependence of position accuracy on velocity through the flight conditions tested. A plot of radial position error versus TSPI radial velocity can be found in Figure 21. Additional plots of position error versus velocity for the iPad can be found in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED Figure C12, Figure C13, and Figure C14.

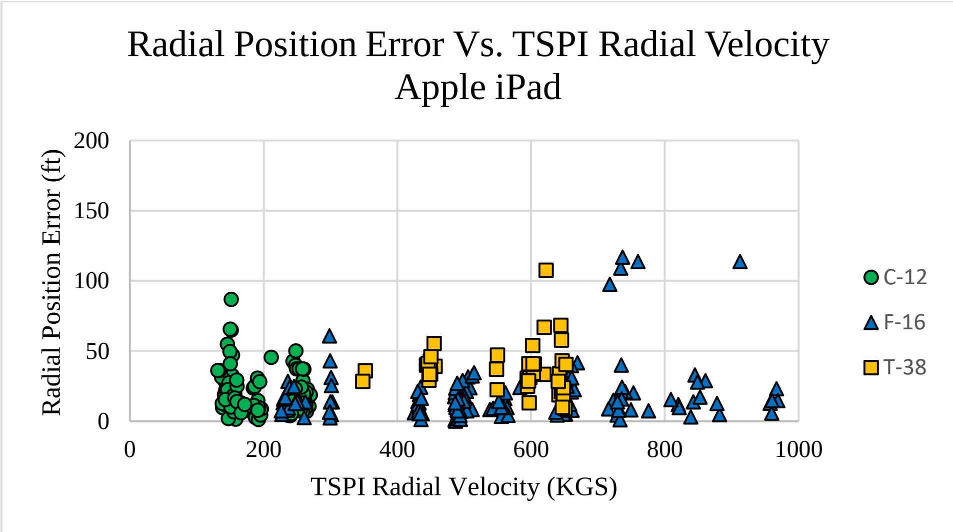

Figure 21: iPad Radial Position Error vs TSPI Radial Velocity

Test results showed no dependence of velocity accuracy on velocity below approximately 640 knots ground speed. Above this speed, the iPad reports zero velocity. Plots of velocity error versus velocity for the iPad are shown in Figure 22 and Figure 23. **Integrate with the manufacturer to determine the sources of position and velocity errors. (R2)**

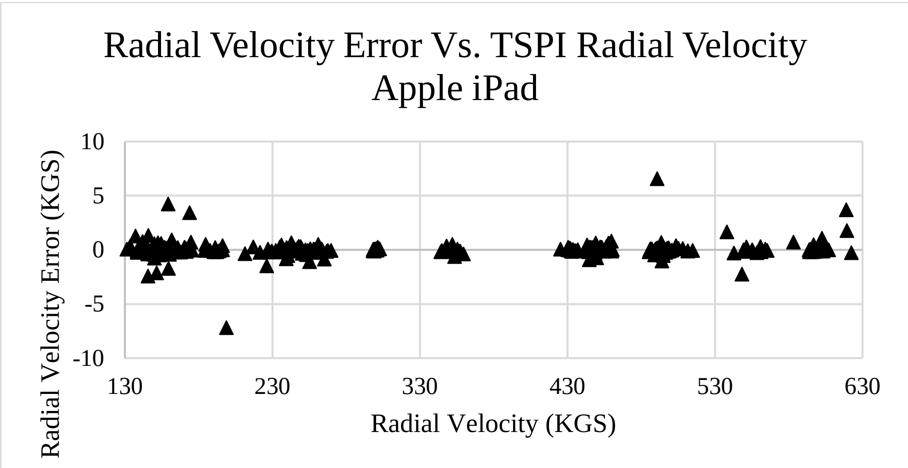

Figure 22: Apple iPad Radial Velocity Error vs TSPI Radial Velocity (0-630 KGS)

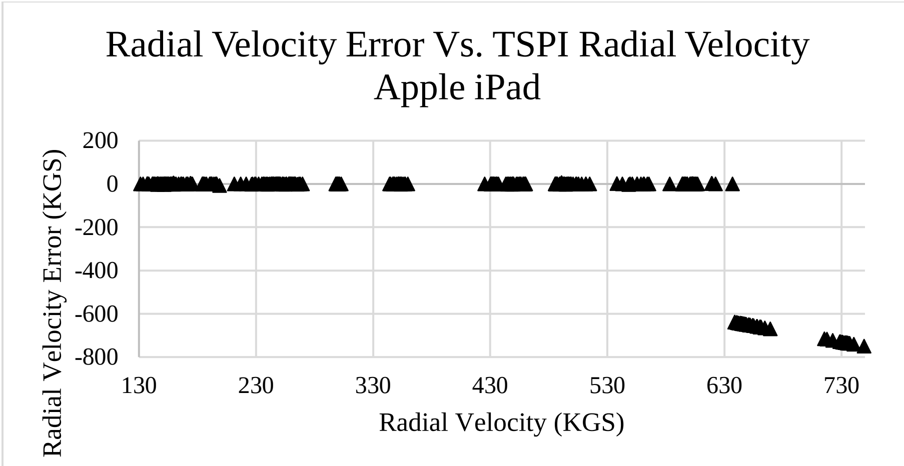

Figure 23: Apple iPad Radial Velocity Error vs Radial Velocity

iPhone

Test results showed no dependence of position accuracy on velocity through the flight conditions tested. A plot of radial position error versus TSPI radial velocity can be found in Figure 24Figure 21. Figure C17, Figure C18, and Figure C19 show position error versus velocity for the iPhone in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED.

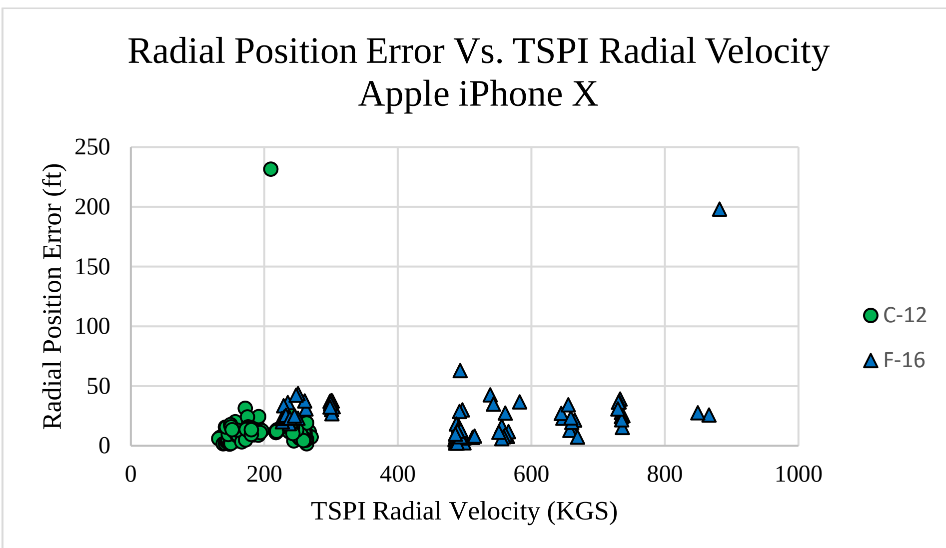

Figure 24: iPhone Radial Position Error vs TSPI Radial Velocity

Test results showed no dependence of velocity accuracy on velocity through the flight conditions tested. The data showed a velocity data drop out which resulted in velocity error with a magnitude near the aircraft velocity. The team was not able to correlate this drop out to flight conditions. Figure C20 and Figure C21shows velocity error versus velocity for the iPhone in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED. **See R2.**

Stratus 2

Test results showed a dependence of position accuracy on velocity through the flight conditions tested. The position accuracy of the SUT decreased as speed increased. Plots of position error versus velocity for the Stratus 2 are shown in Figure 25, Figure 26, and Figure 27.

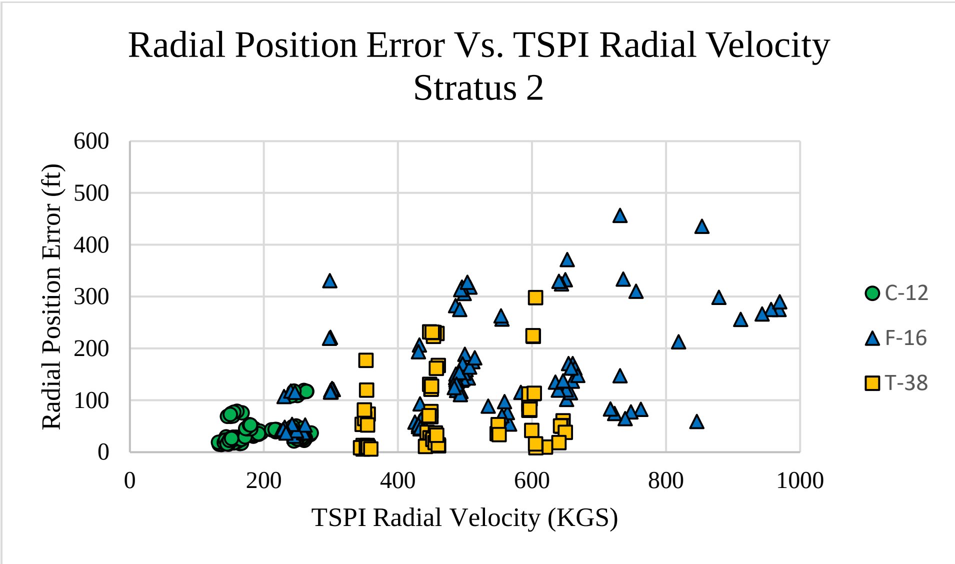

Figure 25: Stratus 2 Radial Position Error vs TSPI Radial Velocity

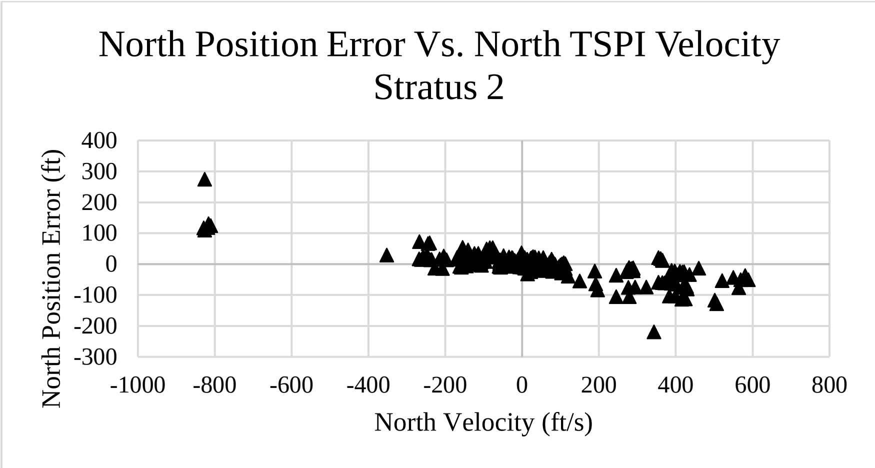

Figure 26: Stratus 2 North Position Error vs North Velocity

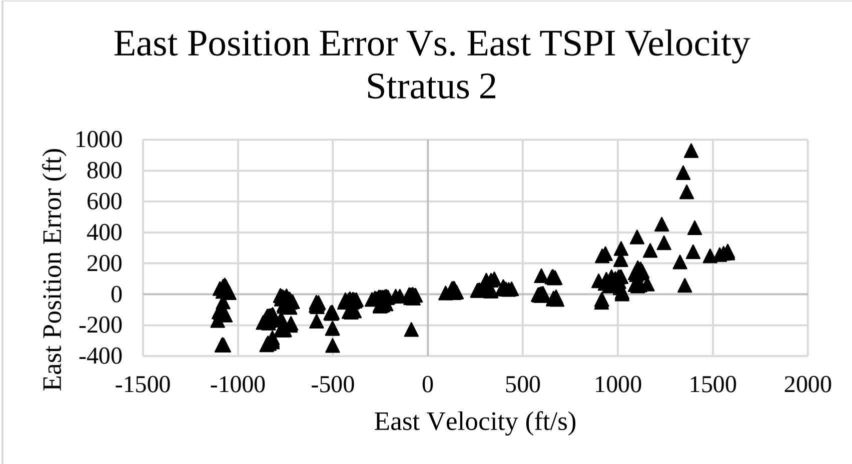

Figure 27: Stratus 2 East Position Error vs East Velocity

Test results showed no dependence of velocity accuracy on velocity through the flight conditions tested. Figure C26: Stratus 2 Radial Velocity Error vs TSPI Radial Velocity shows velocity error versus velocity for the Stratus 2 in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED.

Stratus 3

Test results showed a dependence of position accuracy on velocity through the flight conditions tested. The position accuracy of the SUT decreased as speed increased. A plot of radial position error versus TSPI radial velocity can be found in Figure 28. Figure C27, Figure C28, Figure C29, and Figure C30 show position error versus velocity for the Stratus 3 can be found in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED. These results follow a similar trend to the Stratus 2.

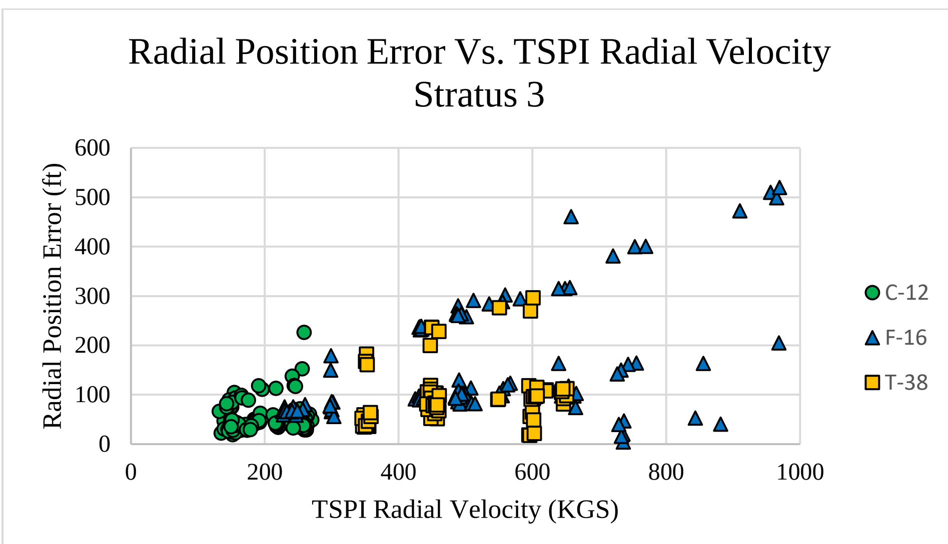

Figure 28: Stratus 3 Radial Position Error vs TSPI Radial Velocity

Test results showed no dependence of velocity accuracy on velocity through the flight conditions tested. The data showed numerous velocity data drop outs which resulted in velocity errors with a magnitude near the aircraft velocity. The team was not able to correlate these drop outs to flight conditions. Figure C31:

Stratus 3 Radial Velocity Error vs TSPI Radial Velocity and Figure C32 show velocity error versus velocity for the Stratus 3 in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED. **See R2.**

Sentry

Test results showed a dependence of position accuracy on velocity through the flight conditions tested. The position accuracy of the SUT decreased as speed increased. A plot of radial position error versus TSPI radial velocity can be found in Figure 29. Figure C33, Figure C34, Figure C35, and Figure C36 show position error versus velocity for the Sentry in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED. These results follow a similar trend to the Stratus 2.

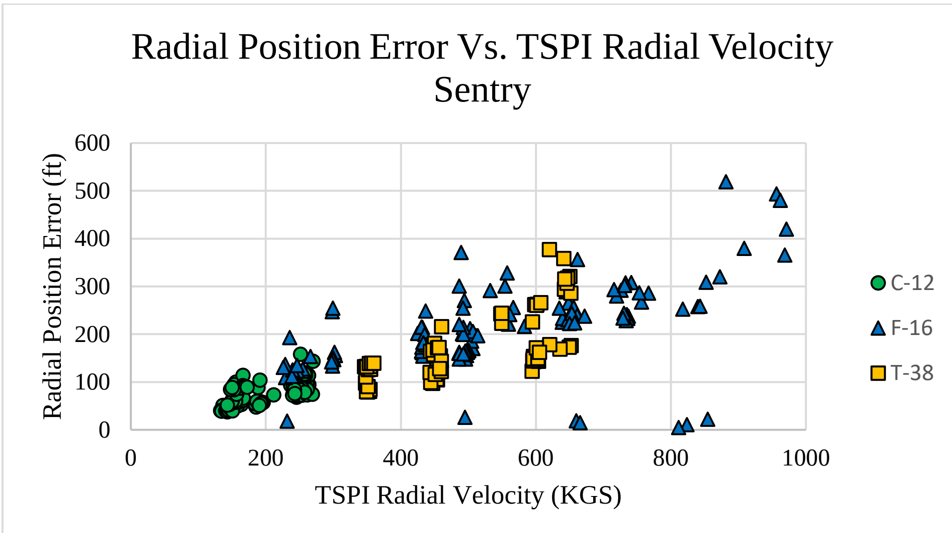

Figure 29: Sentry Radial Position Error vs TSPI Radial Velocity

Test results showed no dependence of velocity accuracy on velocity through the flight conditions tested. The data showed numerous velocity data drop outs which resulted in velocity errors with a magnitude near the aircraft velocity. The team was not able to correlate these drop outs to flight conditions. Figure C37 and Figure C38 show velocity error versus velocity for the Sentry in APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED. **See R2.**

<u>Altitude Dependence of Position and Velocity Accuracy</u>

This test determined the effect (if any) of aircraft altitude on the SUT's position error and velocity error, by measuring position and velocity accuracies at varying altitudes.

Test Methods and Conditions

Data was collected simultaneously with the position and velocity error dependence tests described in the previous section. Test heights ranged from 4,000 to 41,000 feet. Table 10 shows the altitudes different aircraft flew. The test team avoided true north/south and east/west cruise runs to the maximum extent possible to prevent biasing error in one direction.

Data analysis was accomplished via the steps in APPENDIX B – DATA ANALYSIS. The team hand faired a line through the position error data; the test team used engineering judgement of the slope of this line to determine if position error was dependent on altitude. The test team analyzed the velocity error growth or shrinkage with altitude and used engineering judgement to determine velocity error dependence on altitude.

Table 10: Aircraft Altitude Ranges

Airframe	Minimum Height (feet)	Maximum Height (feet)
C-12	4,000	20,000
T-38	5,000	20,000
F-16	20,000	41,000

Test Results

The position error for each SUT as a function of height as recorded by the TSPI are plotted APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE for all SUTs. The velocity error as a function of height as recorded by the TSPI are plotted in for the Google Pixel, iPad, iPhone, Stratus 2, Stratus 3, and Sentry. Bad Elf and Garmin D2 Charlie file formats used did not report velocity.

Bad Elf

Test results showed no dependence of position accuracy on altitude through the flight conditions tested. There were some outliers at 5000 feet, but since these data were only 5000 feet, it was determined the SUT didn't exhibit dependency. Figure 30 and Figure 31 show Bad Elf position error versus altitude. Figure D1, Figure D2, and Figure D3 show position error versus height above ellipsoid for the Bad Elf in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

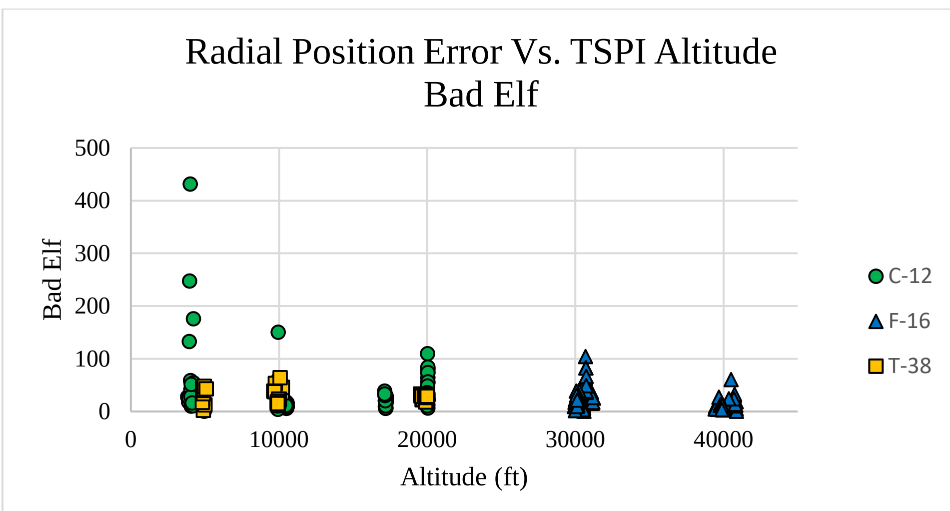

Figure 30: Bad Elf Radial Position Error vs Altitude

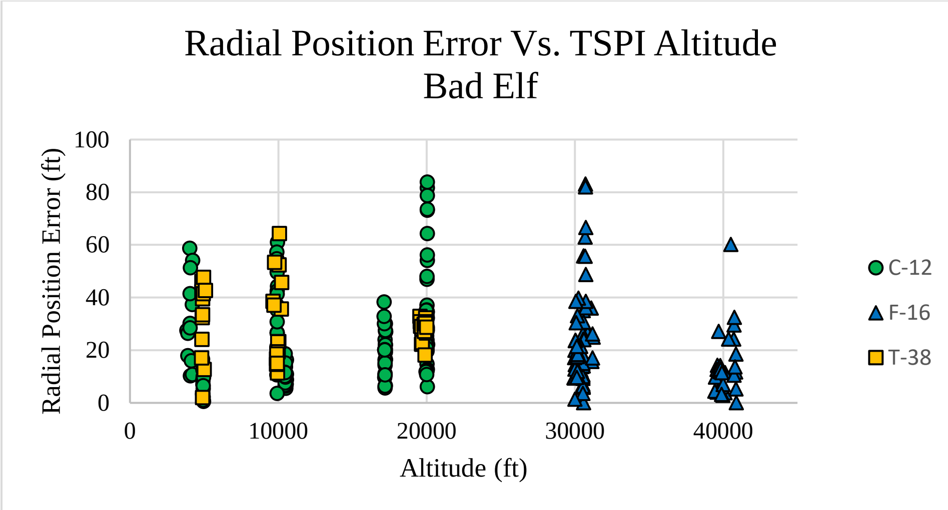

Figure 31: Bad Elf Radial Position Error vs Altitude (without outliers)

Garmin

Test results showed measured position accuracy increased with altitude through the flight conditions tested. However, the points of increased accuracy at higher altitudes are the same points of increased accuracy with respect to groundspeed that were performed in the F-16 (Figure 19). Plots of radial position error versus height for the Garmin can be found in Figure 32.

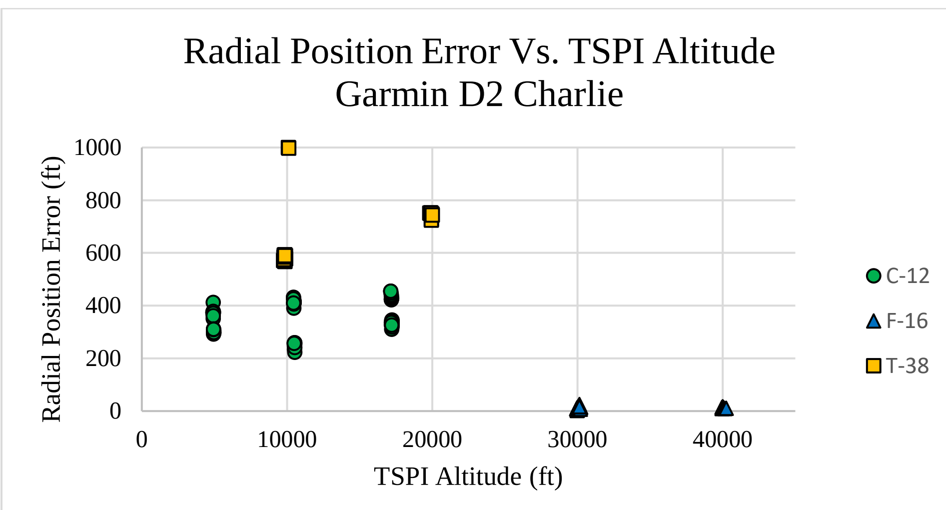

Figure 32: Garmin Radial Position Error vs Altitude

Pixel

Test results showed no dependence of position accuracy on altitude through the flight conditions tested. Figure D8, Figure D9, Figure D10, and Figure D11 show position error versus height above ellipsoid for the Google Pixel in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

Test results showed no dependence of velocity accuracy on altitude through the flight conditions tested. Figure D12 show velocity error versus height above ellipsoid for the Google Pixel in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE

iPad

Test results showed no dependence of position accuracy on altitude through the flight conditions tested. Figure D13, Figure D14, and Figure D15 show position error versus height above ellipsoid for the iPad in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

Test results showed no dependence of velocity accuracy on altitude. Above 640 knots groundspeed, the iPad reported zero velocity (Figure 23). Plots of velocity error versus altitude for the iPad are shown in Figure 33 and Figure 34. **See R2.**

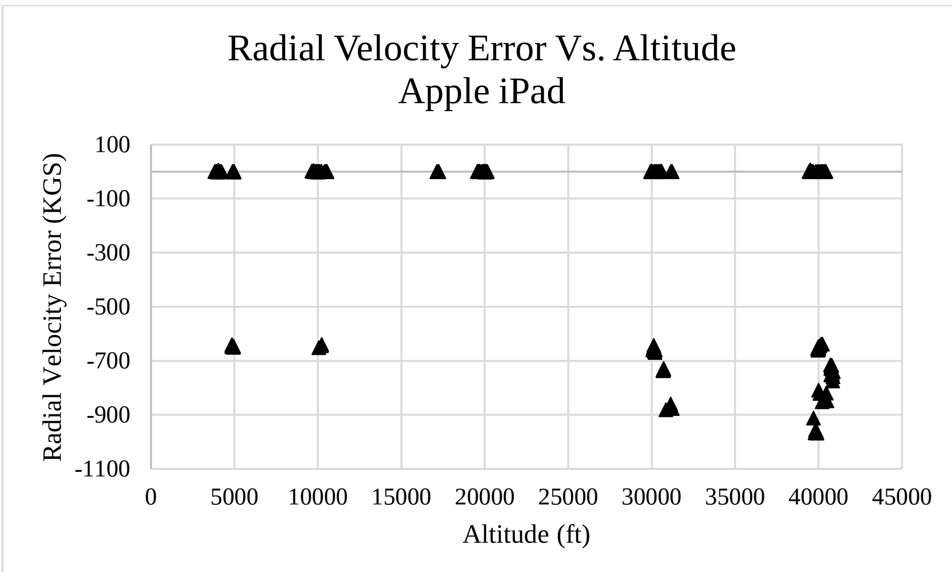

Figure 33: iPad Radial Velocity Error vs Altitude

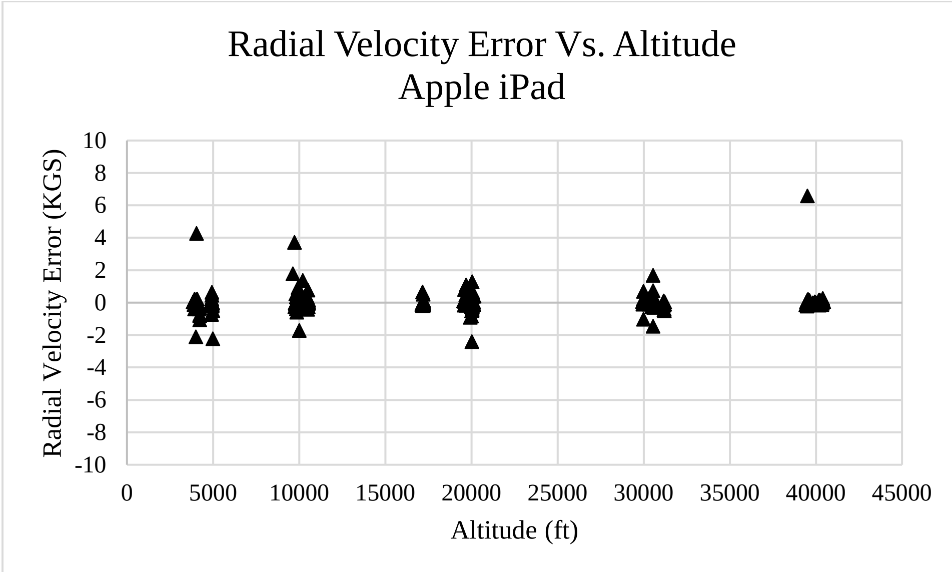

Figure 34: iPad Radial Velocity Error vs Altitude (points < 640 KGS)

iPhone

Test results showed no dependence of position accuracy on altitude through the flight conditions tested. Above 30,000 feet height above ellipsoid, measured position error increased in the data collected. Additionally, above 32,000 feet height above ellipsoid, the iPhone would not record position data and would report "No Fix" on the SUT interface. Figure D18 and Figure D19 show position error versus height above ellipsoid for the iPhone in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE. **See R2**

Test results showed no dependence of velocity accuracy on altitude through the flight conditions tested. The data showed a velocity data drop out which resulted in velocity error with a magnitude near the aircraft velocity. The team was not able to correlate this drop out to flight conditions. Figure D22 and Figure D23 show velocity error versus height for the iPhone in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

Stratus 2

Test results showed a dependence of position accuracy on altitude through the flight conditions tested. A plot of radial position error versus altitude can be found in Figure 35. Figure D24, Figure D25, Figure D26, and Figure D27 show position error versus height above ellipsoid for the Stratus 2 in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

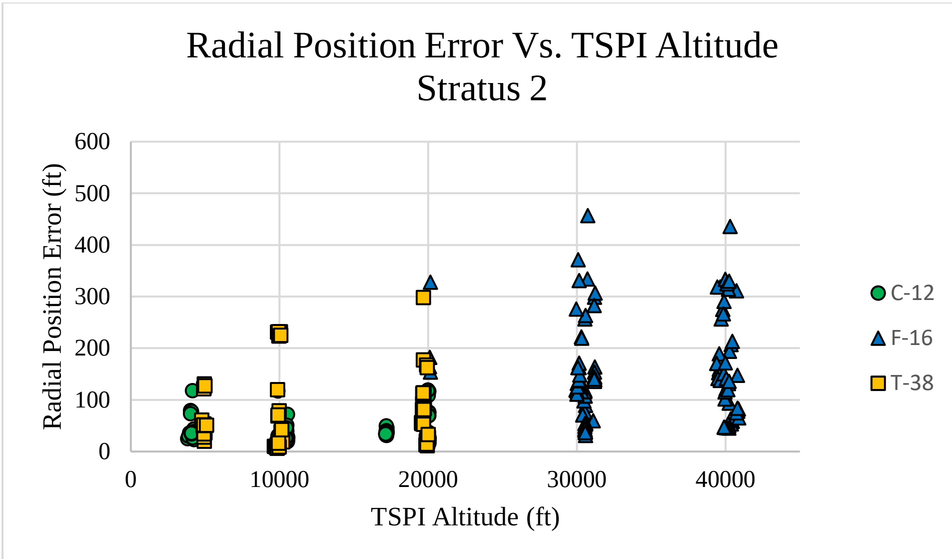

Figure 35: Stratus 2 Radial Position Error vs Altitude

Test results showed no dependence of velocity accuracy on altitude through the flight conditions tested. Figure D28 shows velocity error versus height above ellipsoid for the Stratus 2 in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

Stratus 3

Test results showed a dependence of position accuracy on altitude through the flight conditions tested. A plot of radial position error versus altitude can be found in Figure 36. Figure D29, Figure D30, Figure D31, and Figure D32 show position error versus height above ellipsoid for the Stratus 3 in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

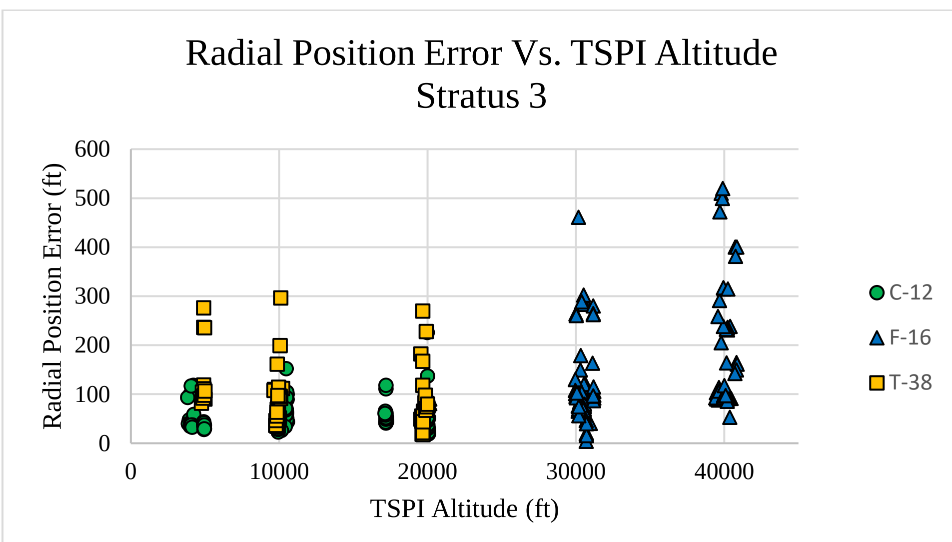

Figure 36: Stratus 3 Radial Position Error vs Altitude

Test results showed no dependence of velocity accuracy on altitude through the flight conditions tested. The data showed numerous velocity data drop outs which resulted in velocity errors with a magnitude near the aircraft velocity. The team was not able to correlate these drop outs to flight conditions. Plots of radial velocity error versus altitude can be found in Figure 37 and Figure 38. Figure D33 and Figure D34 show velocity error versus height above ellipsoid for the Stratus 3 in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE. **See R2.**

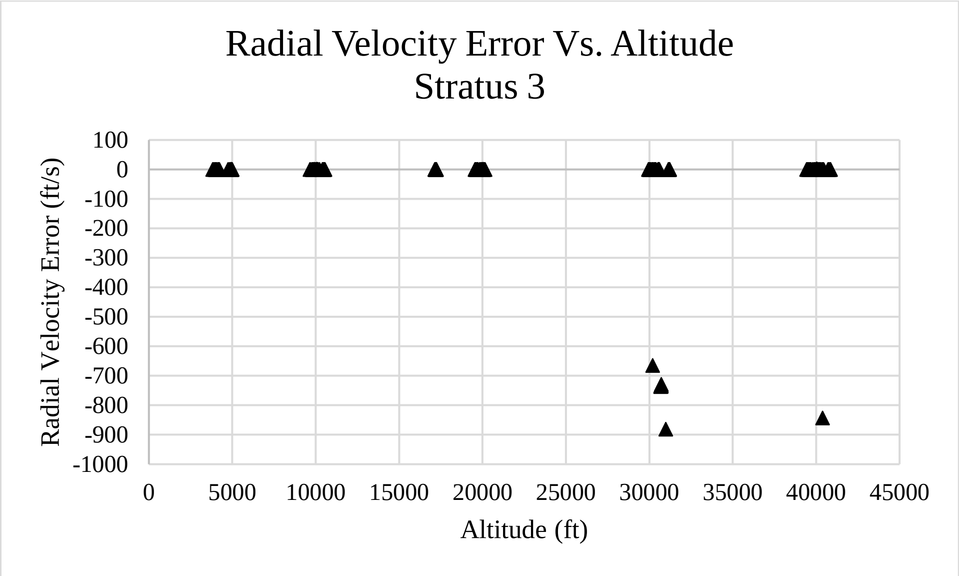

Figure 37: Stratus 3 Radial Velocity Error vs Altitude

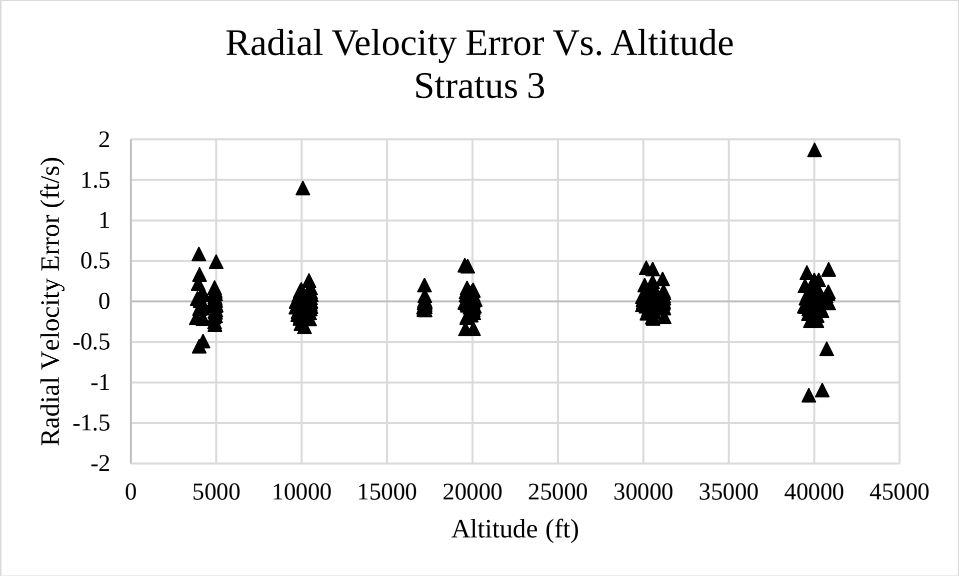

Figure 38: Stratus 3 Radial Velocity Error vs Altitude (without dropouts)

Sentry

Test results showed no dependence of position accuracy on altitude through the flight conditions tested. Figure D35, Figure D36, Figure D37, and Figure D38 show position error versus height above ellipsoid for the Sentry in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE.

Test results showed no dependence of velocity accuracy on altitude through the flight conditions tested. The data showed numerous velocity data drop outs which resulted in velocity errors with a magnitude near the aircraft velocity. The team was not able to correlate these drop outs to flight conditions. Plots of radial velocity error versus altitude can be found in Figure 39 and Figure 40. Figure D39 and Figure D40 show velocity error versus height above ellipsoid for the iPad in APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE. **See R2.**

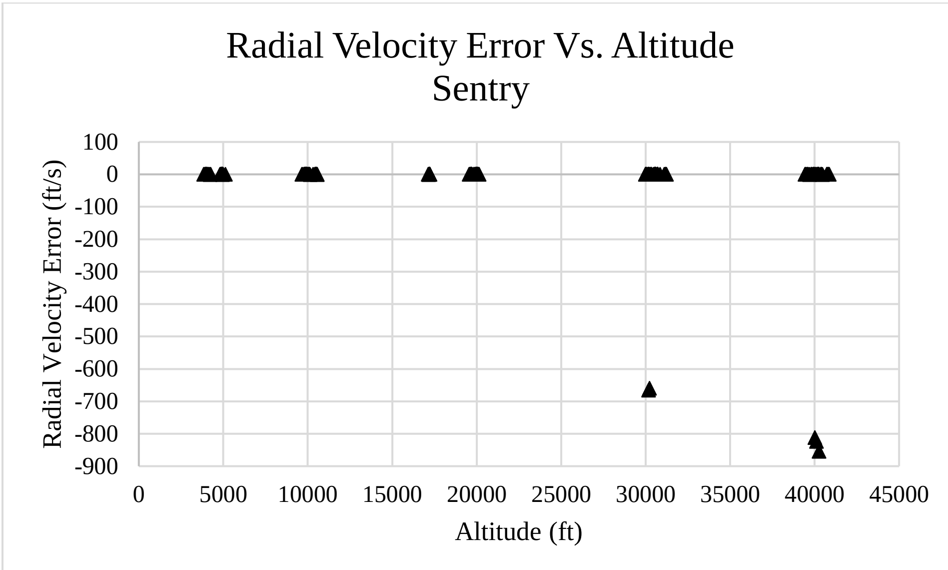

Figure 39: Sentry Radial Velocity Error vs Altitude

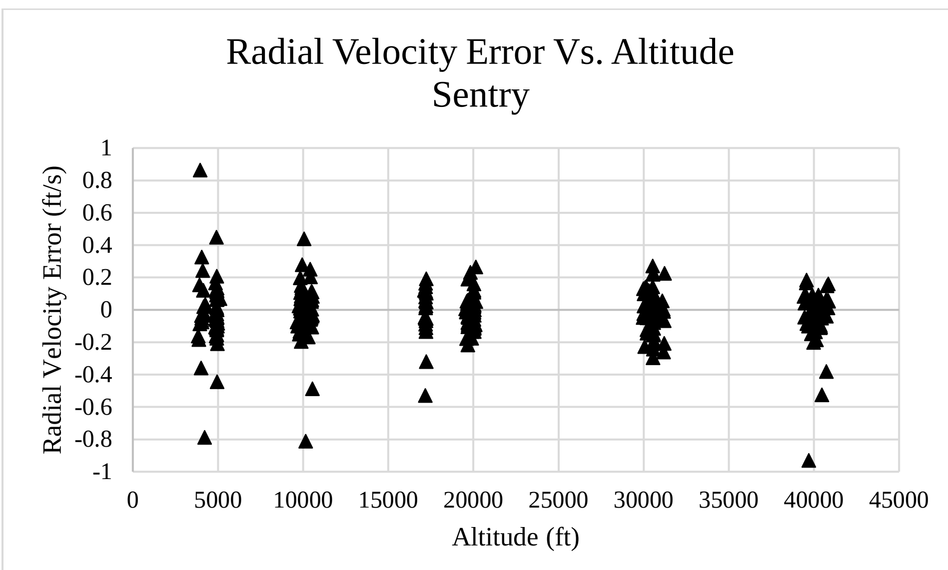

Figure 40: Sentry Radial Velocity Error vs Altitude (without dropouts)

Position and Velocity Accuracy during Maneuvering Flight

This test investigated the ability of the SUT to accurately record position and velocity during three dimensional dynamic aerobatic maneuvers such as aileron rolls, vertical loops, and varying altitude steep turns. The position accuracies of all SUTs during maneuvering were worse than during stable cruise flight.

Test Methods and Conditions

The SUT and TSPI data was recorded for the duration of the event including setup and recovery. Aileron rolls were be performed in the T-38 and F-16. The T-38 loop was performed starting at 400 KIAS and starting with smooth pull to 4-5 g's until capturing approach AoA near the top of the loop and then smoothly reaching 4-5 g's near the end of the loop. The F-16 loop was performed at MIL power at 450 KIAS with a 4-g pull from a starting altitude of 10,000 feet MSL. Maneuvering flight test points in the T-38 and F-16 were accomplished over multiple sorties. The level steep was flown at 60 degrees of bank. The varying altitude steep turn was flown in the C-12 as a descending 60 degree bank turn, aiming to lose 500 feet per 90 degrees of turn. Steep turns in the C-12 were only performed on one sortie. Test points were timed starting at the beginning of the maneuver and stopped when the maneuver was complete.

Data analysis was accomplished via the steps in APPENDIX B – DATA ANALYSIS.

Test Results

In the F-16 and T-38, maneuvering flight was able to be accomplished multiple times and a larger sample was produced for these aircraft. Table 11 shows cruise and maneuvering RMS position errors for the SUTs during sorties in the F-16 and T-38. In general, all SUTs performed worse during maneuver flight. The test team suspects this is due to the SUTs line of sight being blocked by the aircraft during the maneuver.

During varying altitude steep turns, the SUTs had worse RMS position error than during cruise flight. Because of the limited amount of data collected on the C-12 for maneuvering flight, the RMS values are not reported. **Investigate the effects of maneuvering flight in the C-12 on position accuracy. (R3)**

Table 11: SUT Cruise and Maneuvering Flight RMS Position Error

SUT	Cruise Flight			Maneuvering Flight		
	T-38 RMS Position Error (ft)	F-16 RMS Position Error (ft)	Radial Position Error (ft)	T-38 RMS Position Error (ft)	F-16 RMS Position Error (ft)	Radial Position Error (ft)
Bad Elf	27	33	42	71	153	134
Garmin	764	13	471	NT	NT	NT
Pixel	30	27	92	1810	NT	1810
iPhone	NT	33	27	NT	284	284
iPad	34	27	28	298	448	421
Stratus 2	106	305	197	246	447	401
Stratus 3	112	521	323	863	474	609
Sentry	186	256	187	208	257	244

NT = Not Tested

Marine Multipath Effects

Testing was conducted to investigate the effects of multi-path caused by the ocean environment.

Test Methods and Conditions

A C-12C flight was conducted at 500 feet AGL over water within the National Airspace. Three runs of 3-4 minutes of cruise were conducted outside of 5 NM but within 12 NM of the west coast of California. Cruise speeds ranged from 150-250 knots ground speed. Sea states were waves measured to 10 feet with winds approximately 20 knots from a Westerly direction. The three runs generated

Data analysis was accomplished via the steps in APPENDIX B – DATA ANALYSIS.

Test Results

The Radial RMS Position error for marine multipath effects for each SUT can be found in Table 12. Multi-path effects caused by sea states are not well known. The data presented here are only for one sea state and no conclusions can be drawn. **Investigate the effects of multipath effects on GPS accuracy. (R4)**

Table 12: SUT Overwater RMS Position Error

SUT	Radial RMS Position Error (ft)
Bad Elf	178
Garmin	NT
Pixel	11
iPhone	14
iPad	13
Stratus 2	51
Stratus 3	57
Sentry	84

NT = Not Tested

Terrain Masking Effects

This test observed terrain masking effects of low-altitude, mountainous terrain flying on the SUTs.

Test Methods and Conditions

Three F-16 flights flew the Sidewinder Low Level, points A through C, within the R-2508 complex at 500 feet AGL and on average 450 knots ground speed. A map of the Sidewinder Low Level can be found in Figure 41.

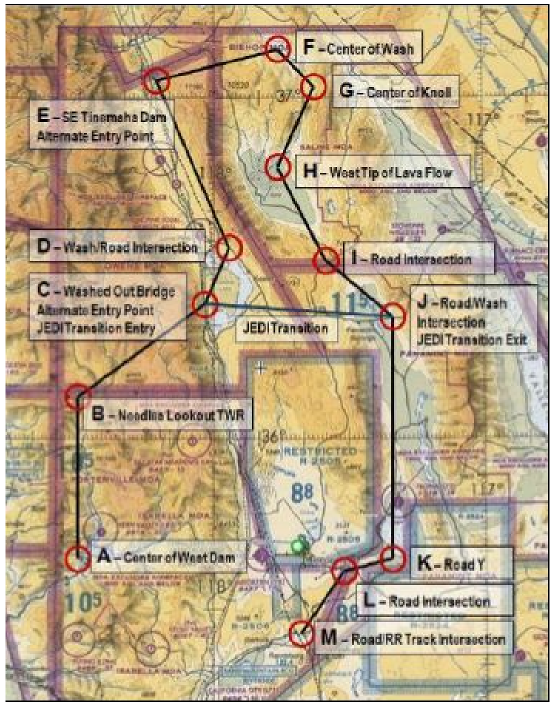

Figure 41: Sidewider Low Level Route

Data analysis was accomplished via the steps in APPENDIX B – DATA ANALYSIS.

Test Results

The Radial RMS Position error during terrain masking testing for each SUT can be found in Table 13. Terrain masking data was only collected in a limited number of conditions, and thus no conclusions can be drawn with respect to terrain masking's effects on positions accuracy.

Table 13: SUT Terrain Masking RMS Position Error

SUT	Radial Position Error (ft)
Bad Elf	282
Garmin	43
Pixel	1790
iPhone	166
iPad	473
Stratus 2	164
Stratus 3	272
Sentry	256

FIGURES-OF-MERIT (FOM) UTILITY

The specific test objective characterized the utility of self-reported Figures-of-Merit (FOM) for applicable low cost, commercial GPS navigation systems. Accuracy and utility of the FOM on each SUT was evaluated throughout the entirety of flight operations. Utility was evaluated through qualitative and handheld data collection during sections of cruise, as well as pre and post maneuver, and then compared to the actual error in relation to TSPI via post processing. Usability was evaluated through the use of surveys and qualitative comments are flight completion.

Accuracy of FOM Reporting

This test characterized the accuracy of the SUT self-reporting FOM. The self-reported FOM was compared to actual performance of the SUT when compared to TSPI data.

Test Methods and Conditions

The test team recorded the SUT self-reported FOM during ground static, ground taxi, cruise, high and low altitude flight, turning flight, high and low speed flight, and dynamic flight. The reported FOM was recorded via handheld methods, and timestamped for comparison to errors calculated in flight. During cruise flight, FOMs were recorded every minute, and during maneuver flight, FOMs were recorded before and after the maneuver.

Test Results

The manufacturer method of calculating FOM in the device was not known. The test team reached out to several manufacturers of the SUTs and were unable to garner a response to the question of how FOM calculation is implemented in their device. The test team took the approach that most users of the system will assume the FOM is a reasonable representation of the position accuracy. The test team quantified this position error for comparison to FOM as the root mean square of the radial position error characterized in position accuracy testing. By this standard, all SUTs fell well short of their claimed accuracy.

The Garmin FOM accuracy was not tested because the FOM only gave binary feedback; see the next section for more information. The Google Pixel FOM accuracy was not tested because GNSS logger did not display a FOM that was usable to the pilot during flight.

iPad and iPhone FOMs were more accurate than the other SUTs. The iPad and iPhone displayed more conservative FOMs (3-10 meters) through ForeFlight and had smaller position errors. All other SUTs had inaccurate and misleading FOMs during all flight phases. The FOMs for theses SUTs consistently reported 1-3 meters of accuracy throughout test points, but position errors of the SUTs was worse. During the sorties, the test team always expected high accuracy from the SUTs because of the FOMs displayed but never saw these results after post flight analysis with the exception of the iPad and iPhone. An example of this data is seen in Table 14.

Table 14: Representative Data for F-16, 30,000 feet MSL, 500 KGS

SUT	FOM (ft)	RMS of Radial Position Error During Test Point (ft)
Bad Elf	13	68
iPad	16	15
iPhone	13	14
Stratus 2	3	185
Stratus 3	3	169
Sentry	3	570

Usability of Self-Reported FOM

This test characterized the usability of the SUT self-reported FOM for their timely reporting, accessibility, and interoperability.

Test Methods and Conditions

Qualitative evaluations of each SUT's self-reported FOM were conducted on all flights. Post-flight, crew members filled out a survey shown in APPENDIX E – SUPPLEMENTAL DATA POSITION AND VELOCITY ACCURACY

Table E1: SUT RMS Position Error

SUT	North RMS Position Error (ft)	East RMS Position Error (ft)	Vertical RMS Position Error (ft)	Radial RMS Position Error (ft)
Bad Elf	28	31	46	43
Garmin	58	468	NT	472
Pixel	81	43	147	92
iPhone	20	18	32	27
iPad	16	22	69	28
Stratus 2	133	145	17	197
Stratus 3	76	314	24	323
Sentry	56	179	22	187

Table E2: SUT RMS Velocity Error

SUT	RMS Radial Velocity Error (KGS)
Pixel	0.33
iPhone	0.91
iPad	0.64
Stratus 2	0.14
Stratus 3	0.22
Sentry	0.16

Table E3: SUT Upper Confidence Limit Position Error

SUT	North Position 95% Confidence Interval (ft)	East Position 95% Confidence Interval (ft)	Radial Position 95% Confidence Interval (ft)
Bad Elf	71	76	92
Garmin	129	1012	899
Pixel	272	133	267
iPhone	58	49	64
iPad	36	49	53
Stratus 2	467	334	464
Stratus 3	205	912	825
Sentry	128	387	357

Table E4: SUT Upper Confidence Limit Velocity Error

SUT	Radial Velocity 95% Confidence Internal (KGS)
Pixel	0.64
iPhone	2.30
iPad	1.47
Stratus 2	0.28
Stratus 3	0.48
Sentry	0.32

APPENDIX F – HUMAN SYSTEMS INTEGRATION SURVEYS utilizing the 412 TW Six-Point General Purpose Scale shown in APPENDIX A – RATING CRITERIA. Aircrew comments for all SUTs can be found in Table F9. A selection of pilots comments are provided in each SUT summary.

Test Results

The SUTs self-reported FOMs in various ways ranging from a small symbol to an estimated position error specified in feet or meters. The FOM Usability was good for all of the SUTs except the Garmin D2 Charlie (deficient) and the Google Pixel (deficient). Table 15 summarizes the results assessments of each SUT's self-reported FOM.

Table 15: SUT Self-Reported FOM Summary

SUT	FOM Usability	Comments
Bad Elf	Good	Timely updates
Garmin	Deficient	Cue was not useful because it only gave binary feedback (degraded or not degraded), not a numerical value.
Google Pixel	Deficient	Far too much text, cluttered display.
iPhone	Good	Good, but text is a little small.
iPad	Good	Good, but text is a little small.
Stratus 2	Good	Good, but text is a little small.
Stratus 3	Good	Good, but text is a little small.
Sentry	Good	Good, but text is a little small.

Bad Elf

Based on pilot comments and survey results, the usability of the FOM displayed on the Bad Elf was good. The results of the surveys are shown in Table F1. Factors relating to Fidelity and Timeliness were consistently scored high among pilots with one noting that it appeared the FOM updated more frequently than any of the other SUTs.

The largest variability in survey scores was related to the size and location of the FOM reporting. Of note, the device was carried in the aircrews left breast flight suit pocket for FOD mitigation and required unstowing and stowing for FOM recording. The following aircrew comments were typical:

- "Fairly small FOM reporting requiring the pilot to hold the device close to face"
- "No color change or additional warning of loss of signal or reduction of accuracy, would be nice if it vibrated past a certain threshold"
- "Had to step through multiple submenus to access self-reported FOM"

The Bad Elf GPS Pro+ had two separate menus that displayed self-reported FOM. The screen shown in Figure 42 below displayed accuracy in feet. A second screen (not shown) displayed both horizontal and vertical accuracy providing users another option for FOM reporting.

Figure 42: Bad Elf GPS Pro+ FOM Location

Garmin D2 Charlie

Based on pilot comments and survey results, the usability of FOM displayed on the Garmin D2 Charlie was deficient.

When the degraded accuracy cue was observed, the readability was clear. However, there was a much higher level of variability in pilot scoring for all other categories. Survey results can be found in Table F2. The scores and comments highlighted below emphasize a lack of fidelity of the self-reported FOM.

- "Only reported a question mark, small, uncertain"
- "Only displayed when GPS signal was lost, very small and difficult to read with no warnings/updates"
- "Front of question mark is the same color and size of aircraft icon, hard to see in any lighting"
- "No idea what question mark means, low fidelity"

The Garmin D2 Charlie Watch has a self-reported FOM on the watch face. The watch does not display a number associated with accuracy, however, it will display a question mark on top of the tail of the aircraft icon as shown in Figure 43.

Figure 43: Garmin D2 Charlie Watch Degraded Cue

Google Pixel Using GNSS Logger

Based on pilot comments and survey results, usability of FOM reported for the Google Pixel using the GNSS Logger as the user interface application was deficient. The survey showed a large variation in results, with the majority of the scores for each category trending on the low side. The largely text-based information provided by the Pixel was adequate for tracking current device accuracy, but the cluttered nature of the display made it difficult to find and process information while airborne. Survey results can be found in Table F3. Applicable pilot comments included:

- “Had to interpret a lot of text, no color changes, liked that it gave number of satellites”
- “No readable FOM, large text file, unsure of where FOM even was, saw a number of satellites, almost impossible to read and interpret in flight with any accurate understanding”

The Google Pixel was used with a data logging application which was not meant to be an aviation application, GNSS logger. The FOM information that was displayed to aircrew during the flight is presented in Figure 44. The FOM reporting is shown on the bottom line of data in meters.

Figure 44: GNSS Logger Screen Shot

iPhone, iPad, Sentry, Stratus 2, and Stratus 3 using ForeFlight

Based on survey results and pilot comments the usability of the FOM reported for iPhone, iPad, Sentry, Stratus 2, and Stratus 3 using ForeFlight as the user interface was good. Pilots liked the color coding at varying thresholds of self-reported accuracy. Survey results had low variation, with scores consistently above 4 in all categories. The largest detractor was the size of the text in relations to all other data on the screen. Survey results for each SUT can be found in Table F4-Table F8. A sample of relevant pilot comments are:

- “Small number on bottom of iPhone screen making it tough to read”
- “I like that the color of the FOM changes with accuracy, but wish a warning message would pop up when it went worse than a certain threshold”

Of note, the iPhone, iPad, Sentry, Stratus 2, and Stratus 3 have no independent self-reporting FOM without the use of compatible software, so the test team chose the ForeFlight application as their interface with all the remaining SUTs.

In ForeFlight, FOM is displayed on the bottom of the display, and is a function that can be added or removed to the display depending on user preferences. Accuracy was displayed in meters, and color coded at varying thresholds as shown below in Figure 45.

Figure 45: Self-Reported FOM using ForeFlight as Interface

UTILITY FOR FLIGHT TEST

The specific test objective was evaluate the utility of low cost, commercial GPS navigation systems for flight test. Aircraft integration, real time usability, and post-processing data use were evaluated through post flight surveys and qualitative comments from aircrew.

SUT Aircraft Functional Integration

SUT aircraft functional integration was intended to verify the proper operation of each SUT for use in the remainder of testing. Integration included aircraft mounting solutions, as well as ability to receive a GPS signal.

Test Methods and Conditions

The test team conducted one ground test in each aircraft with every SUT powered on and recording. SUTs were powered on for a minimum of 20 minutes while in each aircraft in an open air environment (not in hangar or under sunshades) to verify the SUTs' ability to receive satellite signal and record position and velocity data. Battery life was recorded to assess if battery life of each device was sufficient for a typical flight test mission. Track files were downloaded post flight to verify minimum data requirements were recorded.

Test Results

The functional integration of all of the SUTs with the aircraft was adequate. The evaluation focused primarily on general considerations such as size, weight, ease of attachment, etc.

All of the SUTs provided adequate battery life and adequate ease of integration on the ground. Overall, there was no one clear standout device. Mission requirements including type of aircraft, requirement to access in flight, as well as user needs are the driving factors for a SUTs integration into an aircraft.

The Sentry was the smallest and lightest of the mountable SUTs and therefore was easiest to integrate in a variety of locations. This would be ideal in situations where the device may be required to be mounted in an area that requires minimal restriction of pilot FOV (i.e. the front of a T-38 or an aircraft glare shield). The mount used for the Sentry required the device be rotated to lock/un-lock, and this created a potential the device could be inadvertently unlocked from its position if rotated or bumped. This issue could easily be mitigated through the use of a locking device or more permanent integration into the aircraft.

The Bad Elf was extremely small and light making it ideal to be carried for data logging purposes but due to the small size of its display, it would need to be mounted near the user’s eye or in a location where it can be readily accessed.

The Stratus 2 & 3 were the largest and heaviest of the mountable SUTs. This would be less than ideal in cases where space is restricted or the FOV cannot be limited such as the aircraft glare shield or forward canopy. The Stratus 2 and 3 snapped solidly into their mounts making them highly secure under any attitude or loading observed.

The iPad was mounted on an adaptable kneeboard. This allowed extremely easy access and did not limit FOV nor require any aircraft installation. This proved most advantageous in ejection seat aircraft where foreign objects and debris (FOD) in the cockpit is of high concern and mounting things may prove obstructive.

The iPhone and Google Pixel were of similar size and weight. The mounts for the phones were large in order to grip the phones and could be obstructive to ejection seats if mounted incorrectly. The phones also could conceivably have been stored in a pocket or on a kneeboard but this was not evaluated.

The Garmin watch was by far the easiest to integrate since it was worn on the pilot’s wrist. This required no additional effort and would be ideal in cases where modification is not an option or space is of high concern.

Real Time Usability

This test was intended to evaluate each SUTs ability to provide real-time information that aids in mission execution. This included ease of mounting, battery life, storage capacity, ease of use, and information quality during mission execution.

Test Methods and Conditions

The test team recorded battery life at the beginning and end of each mission and assessed the storage capacity of each device after the track file download. Every crew member had the opportunity to mount and dismount each SUT and provided qualitative comments on the process as well as security during aircraft maneuvering. After mission completion, the test team completed a survey shown in APPENDIX E – SUPPLEMENTAL DATA POSITION AND VELOCITY ACCURACY utilizing the 412 TW Six-Point General Purpose Scale shown in APPENDIX A – RATING CRITERIA and provided qualitative comments. Comments for each SUT can be found in Table F18.

Test Results

The real-time usability was good for all the SUTs except the Garmin D4 Charlie (deficient) and the Google Pixel (deficient). Table 16 shows the summarized results.

Table 16: Real Time Usability Summary

SUT	Real Time Usability	Comments
Bad Elf	Adequate	Borderline readability. Good if limited interaction (i.e. start/stop recording) is required.
Garmin D2 Charlie	Marginally deficient	Limited display size requiring multiple menus to view. Better for if only limited interaction (i.e. start/stop recording) is required.
Google Pixel	Deficient	Poor flight interface with extremely cluttered display. Better for if only limited interaction (i.e. start/stop recording) is required.
iPhone	Good	Easy to use and interpret with ForeFlight.
iPad	Good	Easy to use and interpret with ForeFlight.
Stratus 2	Good	Easy to use and interpret with ForeFlight.
Stratus 3	Good	Easy to use and interpret with ForeFlight.
Sentry	Good	Easy to use and interpret with ForeFlight.

Ram mounts and suction cups were the primary mounting solutions used for each of the puck SUTs, and the iPads were strapped to each leg of the aircrew using Pivot case leg straps in the T-38 and F-16. In the C-12, a combination of Pivot case knee straps and RAM mount balls used to mount an iPad to the outside of the front panel. RAM mounts and suction cups were found to be satisfactory for ease of securing to the aircraft.

Battery life was evaluated on all flights by recording the battery charge percentage at the beginning and end of each mission. All SUTs were able to support all missions, with the longest sortie duration being a 2.5 hour flight in the C-12. It was found for the SUTs that used iPads with ForeFlight as the interface, that the iPad would be the limiting factor for battery life with the screen remaining on. Battery life drainage on the iPads were found to be more than double that of the puck based SUTs.

Bad Elf

Based on aircrew comments and survey results, the Bad Elf's real-time usability was adequate, with borderline readability. Generally, when little interaction was required during flight execution, aircrew tended to view the Bad Elf favorably due to its ease of data recording. When interaction was required, the small size of the device and risk of FOD when removing it from their flight suit pocket, as well as the sparse data displayed on each screen, requiring stepping through multiple menus to view. Survey results can be found in Table F10. Some relevant aircrew comments included:

- "Readability fairly small requiring it be held up to pilot's face"
- "Horizontal FOM displayed on home screen, to get component errors, had to go through several submenus"

Best used as a pure recording device, the standalone Bad Elf was capable of recording its position, velocity, and altitude as soon as the device was turned on, and saving the recorded in its internal memory for download after the flight. This required little to no pilot monitoring other than checking device health or battery life.

The Bad Elf also provided a good assortment of navigation information such as current position in latitude and longitude coordinates, GPS altitude, ground speed, GPS time, number of satellites seen, and even a number of points saved.

Unfortunately, the Bad Elf GPS Pro+ had limited functionality with respect to selecting waypoints and navigating to them without the aid of being linked to a tablet with ForeFlight installed.

Garmin D2 Charlie

Based on aircrew comments and survey results, the Garmin D2 Charlie's real-time usability was marginally deficient. The interface was intuitive, enabling the operator to easily verify whether recording had started and stopped. The negative feedback associated with the Garmin D2 Charlie revolved around uncertainty in the accuracy of FOM reporting as well as the limited display size requiring multiple menus to view. Much like the Bad Elf, if little interaction was required during execution, aircrew viewed the watch favorably.

The Garmin D2 Charlie wristwatch provided multiple menus that could be programmed with the desktop app when the watch was plugged in. The watch could provide a moving map display, groundspeed, GPS altitude (or barometric altitude), and other useful navigation parameters to the pilot flying.

Similar to the Bad Elf, the size of the watch limited how much could be displayed on each individual screen, and (inconveniently) required the operator to cycle through separate menus to either look at current position (FOM reporting is only on the moving map display as well), current navigation parameters, or recording status. Once the flight was complete, the user had to stop the recording and verify that the track file was saved for download to the desktop app for post flight data analysis.

Much like the Bad Elf, the Garmin D2 Charlie had limited airborne functionality with respect to selecting waypoints or updating a route. Survey results can be found in Table F11.

Google Pixel using GNSS Logger

Based on survey results and pilot comments, the real-time usability of the Google Pixel, with GNSS logger as the interface, was deficient. If little to no interface from the pilot was required after data recording began (much like the Garmin and Bad Elf), pilots didn't mind the device as interaction was as simple as starting and stopping recording. The low survey scores for the Google Pixel largely revolve around its poor flight interface and extremely cluttered display. Survey results can be found in Table F12. Aircrew comments included:

- "No readable FOM, large text file, unsure of where FOM even was, saw a number of satellites, almost impossible to read and interpret in flight with any accurate understanding"

The Google Pixel did not have an internal data logger for aviation the test team was able to use, so the software selected was the GNSS logger. The GNSS logger was a standalone application that recorded all relevant navigation parameters. While recording, GNSS logger could also display parameters like altitude, airspeed, number of satellites, and self-reported accuracy. Using GNSS logger starting or stopping recording was a single icon push, with the track file being saved to Google Drive post flight.

iPad, iPhone, Sentry, Stratus 2 and Stratus 3 using ForeFlight

Based on pilot comments and survey results, the real-time usability of iPad, iPhone, Sentry, Stratus 2 and Stratus 3 using ForeFlight as an interface during real-time execution was good. Survey scores for all SUTs interfacing with ForeFlight were generally high, with ease of use and interpretability being an emphasis amongst operators. When monitoring parameters via ForeFlight, ground speed and altitude was found to closely match that of what onboard aircraft sensors were reporting. Survey results for each SUT can be found in Table F13-Table F17. A sample of relevant pilot comments are listed below:

- "Groundspeed consistently within 1 knot and altitude worst case 30 feet off"

The iPad, iPhone, Sentry, Stratus 2 and Stratus 3 were each individually evaluated for real-time usability with ForeFlight being used as the device interface. Data recording via ForeFlight was a single icon push and could be verified by an increasing elapsed time underneath the REC button as seen in Figure 46. Post-flight, the data log would automatically save within ForeFlight and could later be emailed in either GPX or KML formats for analysis.

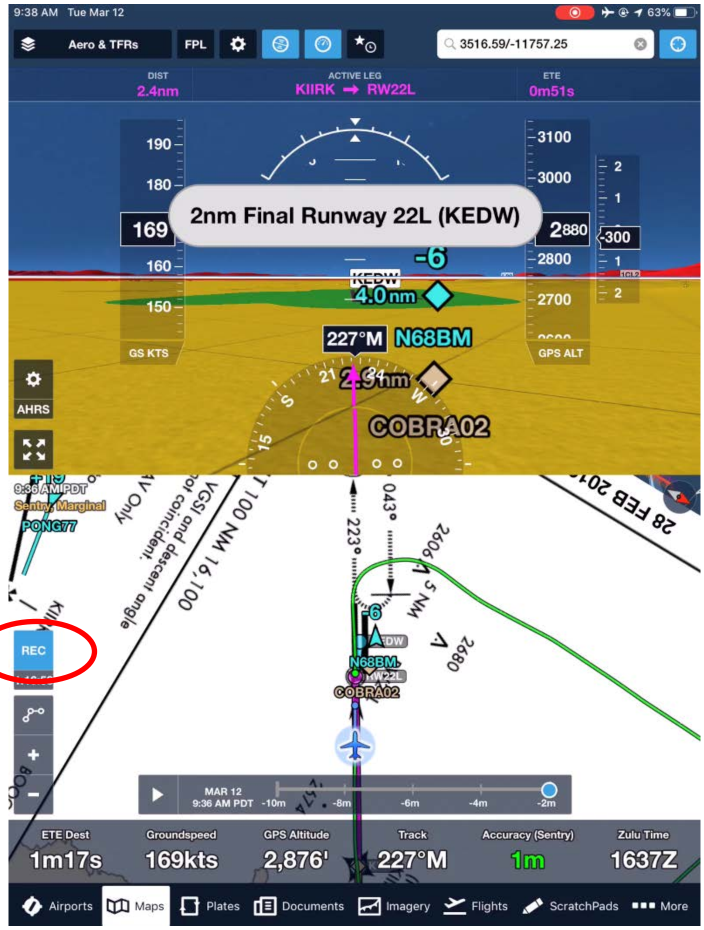

Figure 46: ForeFlight Data Record Icon

CONTINGENCY FLIGHT OPERATIONS

The specific test objective was to demonstrate the utility of low cost, commercial GPS navigation systems for contingency operations. The scope of this demonstration was using the SUTs, as a primary means for point to point VMC navigation, and if the device was AHRS capable, determine its ability to be the primary means of navigation to fly an instrument approach through IMC conditions.

Real-Time Navigation Capability

This test was intended to demonstrate the SUTs usability as a primary navigation source. The SUTs' capability to aid the pilot or crew in safely recovering the aircraft was be examined. Pilot/aircrew evaluated the individual features of each SUT.

Test Methods and Conditions

Bad Elf, Garmin D2 Charlie, and Google Pixel were not evaluated for real-time navigation capability. Specifically for the Bad Elf, the SUT needs to be connected to an iPad with ForeFlight in order to use the navigation function. Due to the lack of space for additional iPads in the cockpit, this feature was not evaluated. Google Pixel was not equipped with an aviation capable application, and as such had no navigation functionality to evaluate. While the Garmin D2 Charlie had capability with respect to pre-flight

flight plan loading and its nearest airfield menu option, it was not evaluated for real-time navigation capability.

The test team executed point-to-point navigation for a minimum of 5 minutes toward a pre-selected waypoint within the R-2508 airspace. The pilot navigated to the selected waypoint via prompts exclusively provided by the evaluated SUT. Pilot comments were recorded during execution. Following each flight, the aircrew member evaluating the SUT completed a survey utilizing the 412 TW Six-Point General Purpose Scale in APPENDIX A – RATING CRITERIA. The surveys were conducted in conjunction with the real-time usability surveys, with survey results and comments compiled in Table F10: Bad Elf Real Time Usability Survey ResultsTable F18.

Test Results

Real-time navigation capability of each SUT (iPad, iPhone, Sentry, Stratus 2 and Stratus 3) using ForeFlight as an interface was good. Pilots enjoyed the ease of interface and airspace overlays.

A Course Deviation Indicator (CDI) was displayed, but only on SUTs equipped with AHRS (the Sentry, Stratus 2, and Stratus 3). SUTs lacking a CDI (i.e. iPad, iPhone) provided a less precise course guidance but were determined to be good enough to get the aircraft within range to identify the point visually. A sampling of pilots comments are listed below:

- "Took some research to figure out what format to type coordinates into ForeFlight. This would not have been possible to figure out airborne"
- "Once the point is entered, it's easy to verify its correct on the map"
- "Showing original direct to point line was useful with restricted airspace overlay. Good awareness for restricted area avoidance"

Real Time Adverse Weather Recovery

This test was intended to demonstrate each SUTs usability as a primary navigation source during simulated instrument meteorological conditions (IMC). The device's capability to aid the pilot or crew in safely recovering the aircraft through the weather, and where required, performing an instrument approach, was examined.

The only SUTs capable of executing this MOP were the Stratus 2, Stratus 3, and Sentry. These SUTs were evaluated using ForeFlight to display navigation, approach information, and attitude information.

Test Methods and Conditions

Only the Sentry, Stratus 2, and Stratus 3 were equipped with AHRS and were the only SUTs evaluated for usage as a primary source of navigation, attitude, altitude, and groundspeed during simulated IMC. Bad Elf, Garmin D2 Charlie, Google Pixel, iPad and iPhone were not evaluated because they lacked AHRS information.

In order to simulate a total navigation or display failure emergency, at a given point in the mission, the non-flying crew member (always the front cockpit pilot) directed the test pilot (always the rear cockpit pilot) to dim navigational displays to the maximum extent practical, or ignore their feedback. The non-flying crewmember then directed the test pilot to an Initial Approach Fix (IAF) at an airfield with an approach that the SUT could perform. The test pilot performed the approach as published to no lower than 300 feet above ground level (AGL). Precision approaches were flown at Naval Air Station China Lake

(RNAV GPS Runway 32), Mojave Air and Spaceport (GPS Runway 22), and Ewards AFB (RNAV GPS Runway 22L).

After the mission, aircrew using the SUT completed the survey utilizing the 412 TW Six-Point General Purpose Scale in APPENDIX A – RATING CRITERIA. Survey results and comments for each of the SUTs are compiled in Table F19-Table F22. Two student test pilots occupied both seats in the F-16 and T-38 to conduct this evaluation.

Test Results

Based on pilot comments and survey results, the Real Time Adverse Weather Recovery for the Sentry, Stratus 2, and Stratus 3 using ForeFlight was deficient and unsafe for use during approaches.

Although all three SUTs scored well with respect to the ForeFlight interface, ease of loading an instrument approach, and subsequently enabling the approach, major deficiencies were noted during the approach with respect to the display and overlays and the quality of information provided by the attitude reference. An example of a ForeFlight interface with an AHRS equipped SUT is shown in Figure 45.

When conducting standard rate turns during the approach, rapid, significant deviations in pitch were noted on the attitude display with pitch changes observed up to 50° and a substantial amount of time for the attitude reference to return to wings level flight after rolling out. These rapid pitch changes were consistently noted amongst all pilots and consistent amongst all three SUTs. The differences between aircraft attitude and attitude displayed for each SUT tested caused issues with executing the approach such that the safety pilot had to take over on multiple occasions. **Do not use the Stratus 2, Stratus 3, and Sentry as a primary attitude reference during IMC operations (R5).**

Overlay issues included an excessively cluttered display if the approach plate was left up and ADS-B was enabled. Additionally, at different portions of the approach, pop-ups obscured the attitude reference on the iPad.

A sampling of pilot comments can be found below:

- “ Pop Up alerts [500’ AGL, 3NM Final, etc.] would completely obscure AHRS attitude reference”
- “Pitch and roll seemed to couple and when rolling into bank, pitch would change, would be disorienting in the weather”
- “Roll seemed fairly accurate, but pitch was consistently off by 5 deg in both directions”
- “Became uncomfortable to fly without using aircraft systems to aid in attitude and altitude control”

TEST RESULTS SUMMARY

In all, eight SUTs were tested: Bad Elf, Garmin D2 Charlie, Google Pixel, iPad mini (internal GPS), iPhone XS, Stratus 2, Stratus 3, and Sentry.

Overall, the SUTs demonstrated much less accuracy than the TSPI systems, and may not be useful for test applications requiring high accuracy TSPI data. Some SUTs provided utility for general flight operations, especially at lower speeds, or test missions with less stringent navigational accuracy requirements. SUT 95% confidence radial position error from the TSPI truth source ranged from 50 to 900 feet. The velocity information, however, was typically within 1-2 knots of the TSPI truth source. The position accuracies of all devices during maneuvering were worse than during stable cruise flight.

With the exception of the iPad and iPhone, Figures of merit (FOMs) as reported real-time by all the SUTs were generally found to be optimistic and not representative of their actual position accuracy.

As an alternative means of point-to-point VMC navigation during daytime contingency flight, five SUTs were good: the iPad, iPhone, Sentry, Stratus 2 and Stratus 3. The Sentry, Stratus 2, and Stratus 3 even provided a CDI. And while the iPad and iPhone lacked a CDI, they were sufficient to get the aircraft within visual range of airports or landmarks. The iPad, iPhone, Sentry, Stratus 2 and Stratus 3 all had good real-time usability.

None of the tested SUTs was useful for as a contingency source of navigation during an IMC approach due to large deviations in attitude information and cluttered displays with popups that sometimes obscured important information.

LESSONS LEARNED

This test effort was intended to only determine the accuracy of the SUTs on an "as is" basis. There was few opportunities during this test effort to determine sources of error and their associated impact on navigation accuracy. Future test programs that wish to conduct a more in-depth analysis of a SUTs accuracy would benefit from identifying a liaison with a technical representative from the manufacturer.

Some considerations that would be helpful to understand from a SUT's manufacturer:

- "Grooming" of data to include any filtering
- How a manufacturer defines accuracy (RMS, CEP90, CEP50, etc.)
- Details of recorded information
- Any additional information capable of being recorded

It is also advisable that any SUT tested be capable of recording information in an NMEA format. This format records a substantial amount of information that could be useful in the determination of anomalous recordings.

Some useful information that is recorded by the NMEA format:

- Number of satellites tracked and used in the fix
- What constellation those satellites belong to (GLONASS, GPS, etc.)
- HDOP
- Elevation an azimuth of tracked satellites

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RECOMMENDATIONS

R1. Complete further testing to investigate the increased accuracy of the Garmin D2 Charlie in the F-16. (Page 22)

R2. Integrate with the manufacturer to determine the sources of position and velocity errors. (Page 24)

R3. Investigate the effects of maneuvering flight in the C-12 on position accuracy. (Page 36)

R4. Investigate the effects of multipath effects on GPS accuracy. (Page 37)

R5. Do not use the Stratus 2, Stratus 3, and Sentry as a primary attitude reference during IMC operations. (Page 51)

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REFERENCES

1. Flight Manual, USAF Series C-12C Aircraft and C-12 Aircraft, T.O. 1C-12A-1, 1 November 2003, Change 3 1 February 2007.

2. Flight Manual, USAF Series F-16 C/D Blocks 25, 30 and 32 Aircraft, Technical Order 1F-16C-1, Lockheed Martin Corporation, 15 April 2009.

3. Flight Manual, USAF Series T-38C Aircraft, Technical Order 1T-38C-1, 8 March 2016, Change 3, 5 October 2017, reflecting TO 1T-38C-1SS-20.

4. AFTCI 91-202 Edwards AFB Supplement, *AFTC Test Safety Review Policy,* 6 September 2017

5. 32 CFR 989, *Part 989 – Environmental Impact Analysis Process (EIAP)*, Volume 6, July 2012.

6. Edwards AFBI 99-105, *Test Control and Conduct*, 412 TW, Edwards AFB, California, January 2014.

7. Edwards AFBI 99-101, *412 TW Test Plans*, 412 TW, Edwards AFB, California, August 2013.

8. Edwards AFBI 99-103, *412 TW Technical Report Program*, 412 TW, Edwards AFB, California, August 2013.

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APPENDIX A – RATING CRITERIA

Table A1: 412th Test Wing Rating Criteria

How Well Does the System Meet Mission and/or Task Requirements?	Changes Recommended for Improvement	Mission/Task Impact	Descriptor	Rating
Exceeds requirements.	None	None	Excellent	Satisfactory
Meets all or a majority of the requirements.	Negligible changes needed to enhance or improve operational test or field use	Negligible	Good	Satisfactory
Some requirements met; can do the job, but not as well as it could or should.	Minor changes needed to improve operational test or field use	Minor	Adequate	Satisfactory
Minimum level of acceptable capability and/or some noncritical requirements not met.	Moderate changes needed to reduce risk in operational test or field use	Moderate	Borderline	Marginal
One or some of the critical functional requirements were not met.	Substantial changes needed to achieve satisfactory functionality	Substantial	Deficient	Unsatisfactory
A majority or all of the functional requirements were not met.	Major changes required to achieve system functionality	Major	Unacceptable	Unsatisfactory
Mission not safe.	Critical changes mandatory	Critical	Unsafe	Failed

Table A2: 412th Test Wing Six-Point General Purpose Scale

Scale Value	Response Alternatives	Definitions
1	Very Unsatisfactory	Task cannot be performed or the item is unusable or unsafe. Mission/Task not accomplished due to equipment deficiencies or procedural limitations.
2	Unsatisfactory	Major problems encountered. Task accomplished with great difficulty or accomplished poorly. Significant degradation of mission/task accomplishment or accuracy.
3	Marginally Unsatisfactory	Minor problems encountered. Task accomplished with some difficulty. Some degradation of mission/task accomplishment or accuracy.
4	Marginally Satisfactory	The item or task meets its intended purpose with some reservations. Meets minimum requirements to accomplish mission/task.
5	Satisfactory	The item or task meets its intended purpose; it could be improved to make it easier or more efficient.
6	Very Satisfactory	The item or task is fine the way it is; no improvement required.

Table A3: HSI 412th Test Wing Six-Point General Purpose Rating Scale Evaluation Criteria

Mean	Descriptor	Rating
Mean equal to 6.0	Excellent	Satisfactory
Mean equal to or between 5.1 and 5.9	Good	Satisfactory
Mean equal to or between 4.5 and 5.0	Adequate	Satisfactory
Mean equal to or between 2.5 and 4.4	Borderline	Marginal
Mean equal to or between 2.0 and 2.4	Deficient	Unsatisfactory
Mean equal to or between 1.1 and 1.9	Unacceptable	Unsatisfactory
Mean equal to 1.0	Unsafe	Failed

Note: In addition to the mean questionnaire response scores, comments during debriefs, flight test reports, engineering judgment, postflight interviews with pilots were used to reach a consensus on the usability ratings.

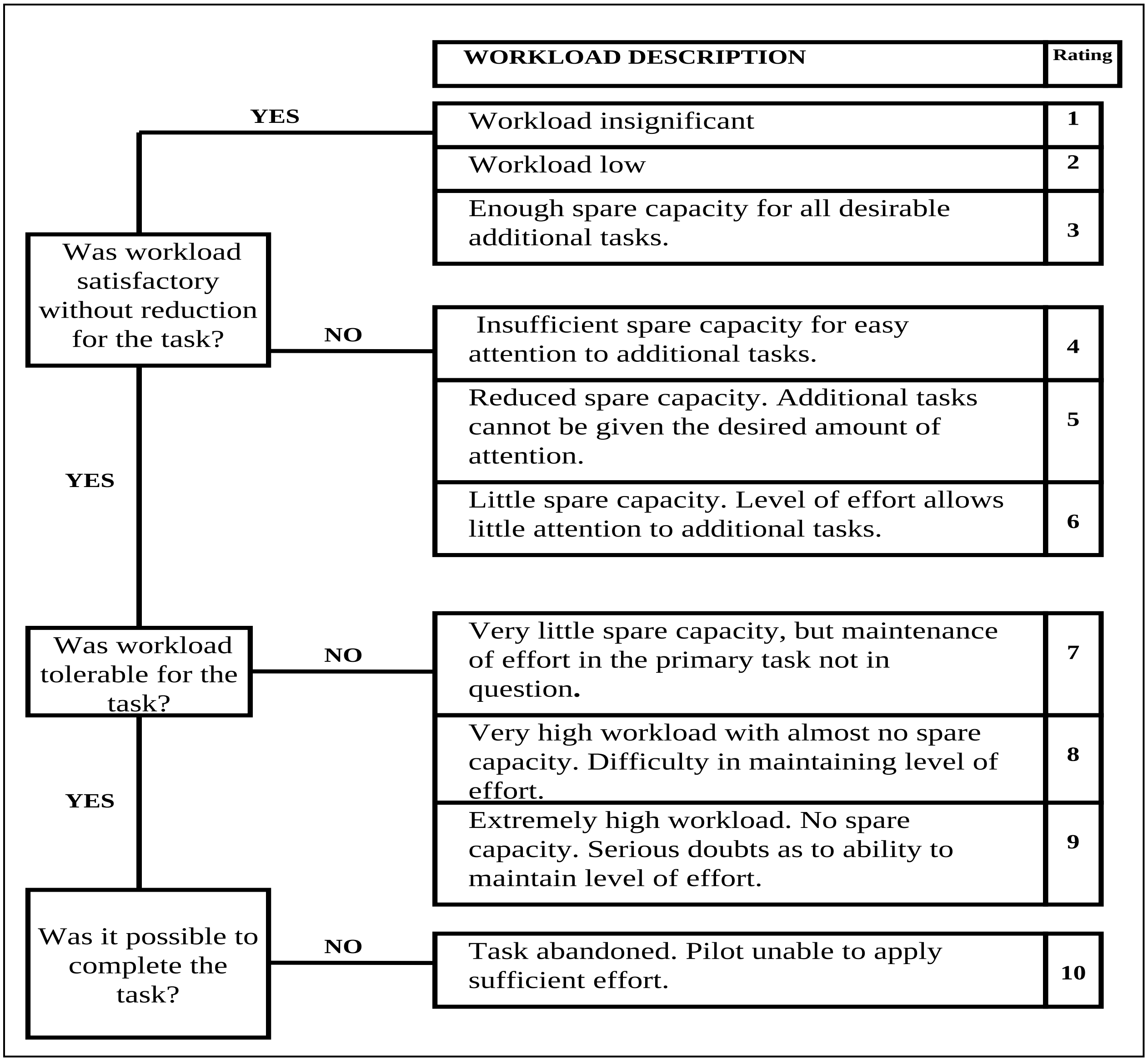

Figure A1: Bedford Workload Rating Scale

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APPENDIX B – DATA ANALYSIS

1. Data Collection

The test team collected the data in Table B1

Table B1: TSPI and SUT Data Parameters Collected

Parameter	**Units**	**Notes**
Handheld Data (Collected in Flight, Recorded by RCP on Test Cards)		
Time Hack	HH:MM:SS	Time from test team time piece. May need to be corrected to GPS time. The DAS “Event” button is not practically useful and time hacks will be used to mark events.
Airspeed	KIAS or KCAS	Recorded from flight instruments during each maneuver
Ground Speed	Knots	Recorded from flight instruments during each maneuver to verify desired conditions
Pressure Altitude	Feet PA	Recorded from flight instruments during each maneuver to verify desired conditions
FOM Report	Varies	Recorded from each SUT at different times during the flight. Each SUT reports different types of FOM.
TSPI Data (Obtained After Post-Processing of Flight Data by TSPI Team)		
HMS, Time of Day	HH:MM:SS	GPS Time from TSPI (Hours, Minutes, Seconds)
Index	N/A	Index Number
SECS	Seconds	Time of Day (total seconds)
LAT	Deg	Latitude (+North)
LONG	Deg	Longitude (+West)
HGT	Feet	Ellipsoid Height
ALT	Feet	MSL Altitude
VT	Ft/Sec	Total Velocity
VG	Ft/Sec	Ground Velocity
VNO	Ft/Sec	Northward Velocity at the Object
VEO	Ft/Sec	Eastward Velocity at the Object
VZO	Ft/Sec	Upward Velocity at the Object
AZO	Ft/Sec^2	Upward Acceleration at the Object
ITHD	Deg	INU True Heading in Degrees (+Clockwise from North)
IPITCH	Deg	INU Pitch Angle (+Counterclockwise)
IROLL	Deg	INU Roll Angle (+Counterclockwise)
SLAT	Feet	Latitude Sigma
SLON	Feet	Longitude Sigma
SHGT	Feet	Ellipsoid Height Sigma
SALT	Feet	MSL Altitude Sigma
SVE	Ft/Sec	East Velocity Sigma

SVN	Ft/Sec	North Velocity Sigma
SVU (SVD)	Ft/Sec	Up (Down) Velocity Sigma
GDOP		Geometric DOP
PDOP		Position DOP
TDOP		Time DOP
HDOP		Horizontal DOP
VDOP		Vertical DOP
EDOP		East DOP
NDOP		North DOP
UDOP		Up DOP
SUT Data (After Downloading from SUT or SUTs hardware interface)		
Count	N/A	Index number from each data point
Time	HH:MM:SS	GPS Time from SUT (Hours, Minutes, Seconds)
Date	M/DD/YYYY	GPS date from the SUT
Latitude	Deg	Latitude, Longitude, Height, and Ground Speed that will be compared to truth source (TSPI) data.
Longitude	Deg	
Height	Feet	
Ground Speed	Knots	

Note: Not all SUTS provided ground speed. If ground speed was not collected, those data were not reported.

2. Post-flight Data Analysis Procedure (After Each Flight)

After obtaining the data (from section 1 above) for a flight, the team members responsible for data collection sent the appropriate file from the SUT to the MATLAB shared drive location. The Garmin D2 Charlie and Bad Elf output a .GPX file. The Google Pixel output a NMEA file. The remaining SUTs, all utilizing ForeFlight, output a .KML file. The following procedures were executed to reduce the data for analysis:

Step 1: Save an unaltered copy of each data file to the Have FLEX designated shared drive location, MATLAB folder.

Scanned copy of FCP and RCP test cards
TSPI Truth Source Data
SUT Data from each SUT

TSPI Truth Source Data was available roughly 72 hours following each flight from 412 RANS/TSPI.

Step 2: Create the test point matrix containing the following data for each maneuver performed:

One row per maneuver
Column 1: Test Point Number
Column 2: Ops Number
Column 3: Maneuver Start Time (GPS Time)
Column 4: Maneuver End Time (GPS Time)
Column 5: Altitude Block
Column 6: Groundspeed Block
Column 7: Maneuvering Flight (0=no, 1=yes)
Column 8: Overwater Conditions (0=no, 1=yes)
Column 9: Terrain Masking Conditions (0=no, 1=yes)
Column 10: Aircraft
Column 11: TMP Flight Number
Column 12: Date

Step 3: Open MATLAB on networked computer. Use appropriate team developed MATLAB script to standardize data formats into single readable file for each SUT using either 'GNSS_import.m', 'GPX_import.m', or 'KML_import_apple_sentratus.m'

Step 4: Use 'data_import_v2.m' to read the TSPI and SUT data into MATLAB, reduce recorded data to specific time slices of the recorded test point, create fields in the structures by assigning values based on the Start and End GPS times in the test point matrix, create data structures for each maneuver

Example file name: (Aircraft)_DDMMM_Test_output_(SUT).mat

Step 5: Use ‘matlabs_the_Final_one.m’ to align TSPI GPS Times with SUT GPS times as closely as possible, execute the Vincinty algorithm and partial autocorrelation, decimate the data, and create output tables for analysis.

The MATLAB function ‘interp1’ was used to linearly interpolate the TSPI data to match SUT times.

The Vincinty algorithm is as follows:

SUT and TSPI points are converted to Cartesian Coordinates (U,V, W) using the latitude (φ) and longitude (λ) and height (h)

$$a = 20925646.32546\,ft$$
$$e^2 = 0.00669437999$$
$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}}$$
$$u = (N + h) \cos \varphi \cos \lambda$$
$$v = (N + h) \cos \varphi \sin \lambda$$
$$w = (N(1 - e^2) + h) \sin \varphi$$

Calculate the Cartesian error vector (aircraft minus TSPI)

$$\Delta u = u_{SUT} - u_{TSPI}$$
$$\Delta v = v_{SUT} - v_{TSPI}$$
$$\Delta w = w_{SUT} - w_{TSPI}$$

Convert error back to North (N), East (E), and height (H) errors at TSPI φ and λ

$$\begin{bmatrix} N \\ E \\ H \end{bmatrix} = \begin{bmatrix} -sin\varphi cos\lambda & -sin\varphi sin\lambda & cos\varphi \\ -sin\lambda & cos\lambda & 0 \\ cos\varphi cos\lambda & cos\varphi sin\lambda & sin\varphi \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta v \\ \Delta w \end{bmatrix}$$

Calculate radial position error using North and East error

$$r_{position} = \sqrt{N^2 + E^2}$$

Calculate radial velocity error

$$error_{radial\ velocity} = \sqrt{v_{SUT} + v_{TSPI}}$$

The MATLAB function ‘parcorr’ was used to determine the number of lags in each set of test point.

The number of lags is used to decimate the data by creating a new structure from the errors calculated but using every value with index n*lags.

Output tables were made in the following format for data analysis.

- North Velocity (TSPI)
- East Velocity (TSPI)
- Radial Velocity (TSPI)
- Height (TSPI)
- North Decimated Error
- East Decimated Error
- Height Decimated Error
- Radial Decimated Error
- Radial Velocity Decimated Error

3. Data Analysis Procedure after the Completion of Flight Testing

After obtaining the completion of flight testing for a given test objective or MOP, the team executed the following procedure to reduce the composite flight test data.

Step 1: Verify the Post-flight Data Analysis Procedure has been completed for all required flights.

Note: The following steps were skipped or performed out of order as appropriate for the MOP or objective being analyzed.

Step 2: Copy all tables from the "Post Flight Data Analysis Procedures" to the appropriate MOP Excel files.

Step 3: Calculate the RMS position and velocity errors

$$RMS_{North_{Position}} = \sqrt{\frac{\sum_{i=1}^{n}(N^2)}{n}}$$

$$RMS_{East_{Position}} = \sqrt{\frac{\sum_{i=1}^{n}(E^2)}{n}}$$

$$RMS_{Height} = \sqrt{\frac{\sum_{i=1}^{n}(H^2)}{n}}$$

$$RMS_{Radial_{Position}} = \sqrt{\frac{\sum_{i=1}^{n}({r_{position}}^2)}{n}}$$

$$RMS_{Radial_{Velocity}} = \sqrt{\frac{\sum_{i=1}^{n}({error_{radial_{velocity}}}^2)}{n}}$$

Step 2: Calculate the 95% confidence interval of RMS position and velocity errors for each test condition from the errors of the independent points determined in the "Post Flight Data Analysis Procedure".

Calculate the average of the squares of the position and velocity errors

Example: $\sum_{i=1}^{n}({\Delta N_{error}}^2)$

Calculate the degrees of freedom for the conditions in question

$$df = \#(independent\ data\ points) - 1$$

Calculate the standard deviation of the squares of position and velocity errors using the STDEV Excel function

Calculate the t-statistic for a 95% confidence interval using the MATLAB or Excel 'tinv' function:

$$t = tinv(0.05, df)$$

Calculate the upper confidence limit on the RMS accuracies

Example: $$Upper\ Confidence\ Limit = \sqrt{\sum_{i=1}^{n}(\Delta N_{error}{}^{2}) + t * \frac{stdev(\Delta N_{error}{}^{2})}{\sqrt{n}}}$$

Calculate the Upper Confidence Limit of the 50th percentile by multiplying the UCL by the shape multiplier, Y.

Y = 1.96 for single dimension position error

Y = 1.73 for radial position and velocity error

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APPENDIX C – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS SPEED

Note: Data collected for this test has a position uncertainly of ±15 feet and ±0.3 ft/s (±0.18 KGS).

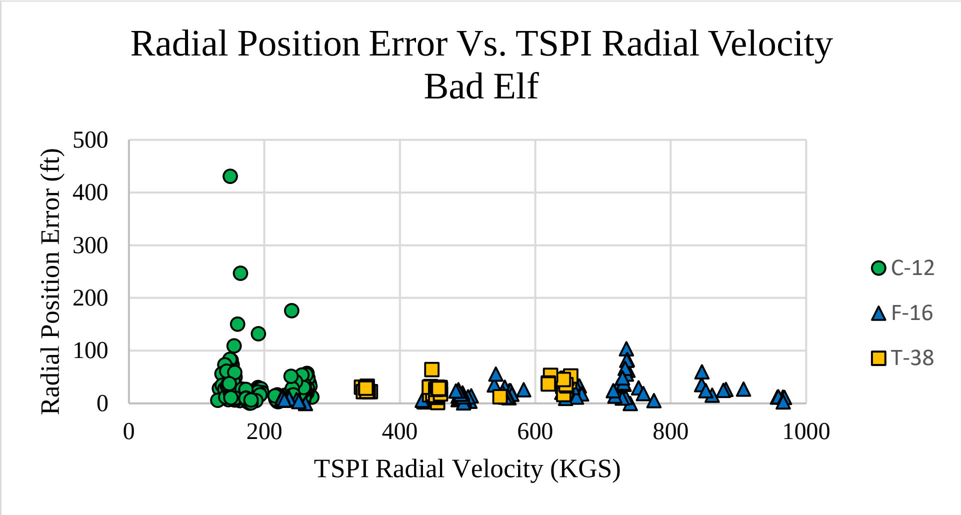

Figure C1: Bad Elf Radial Position Error vs TSPI Radial Velocity

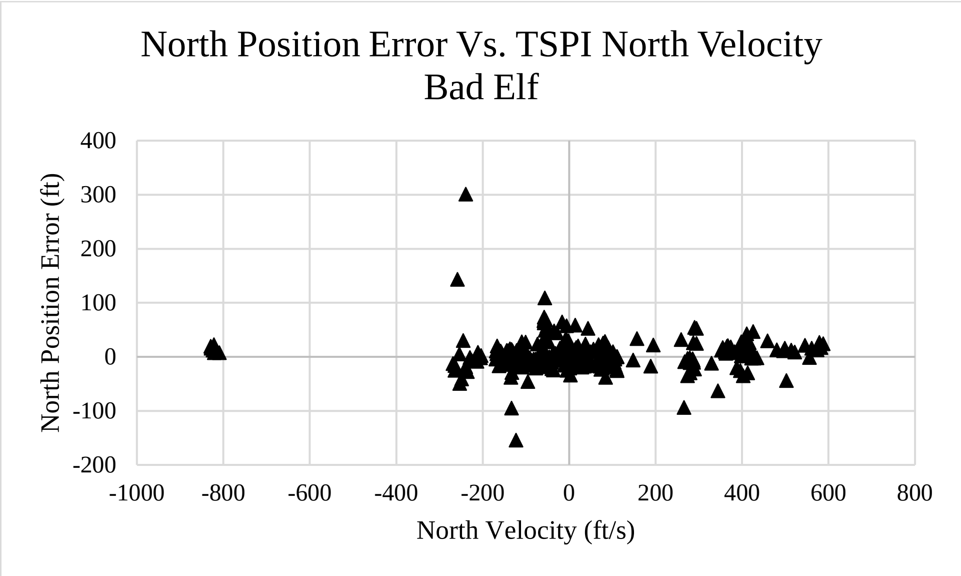

Figure C2: Bad Elf North Position Error vs TSPI North Velocity

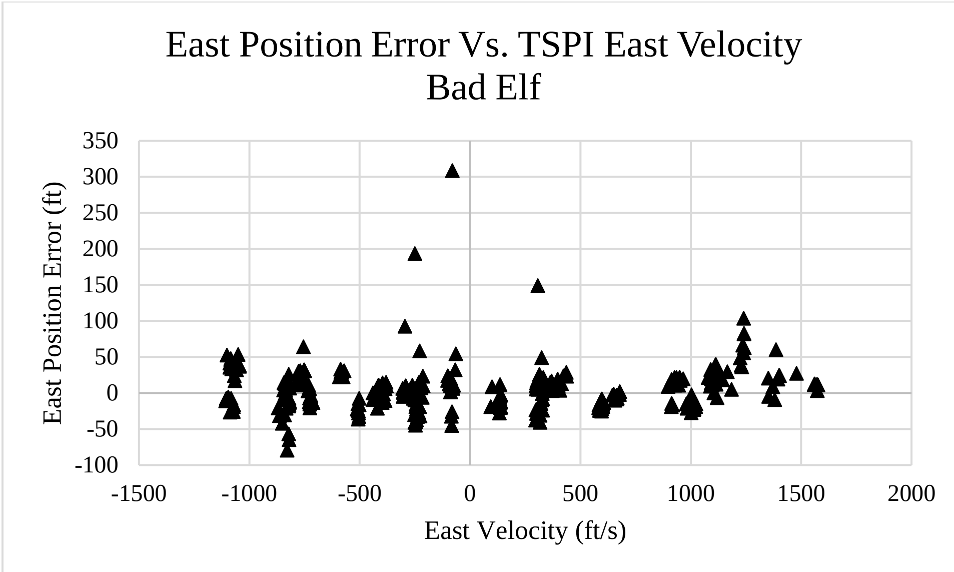

Figure C3: Bad Elf East Position Error vs TSPI East Velocity

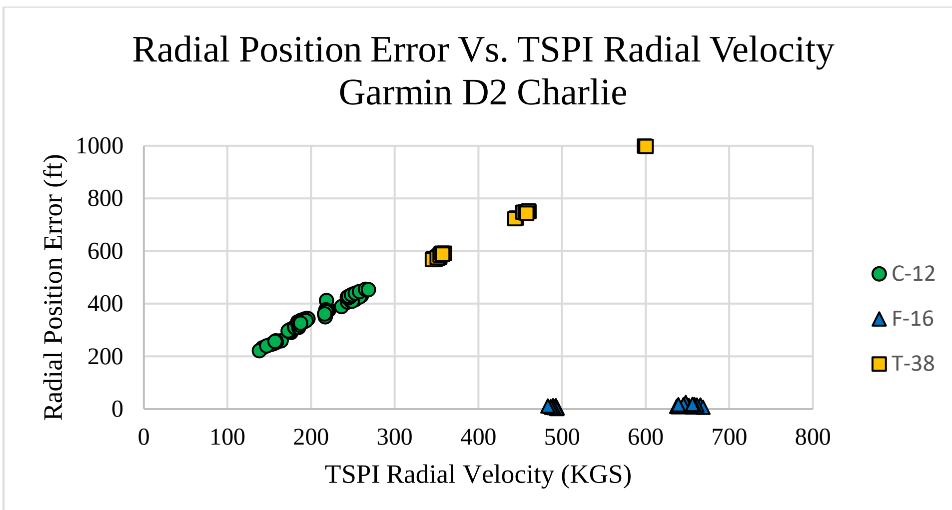

Figure C4: Garmin Radial Position Error vs TSPI Radial Velocity

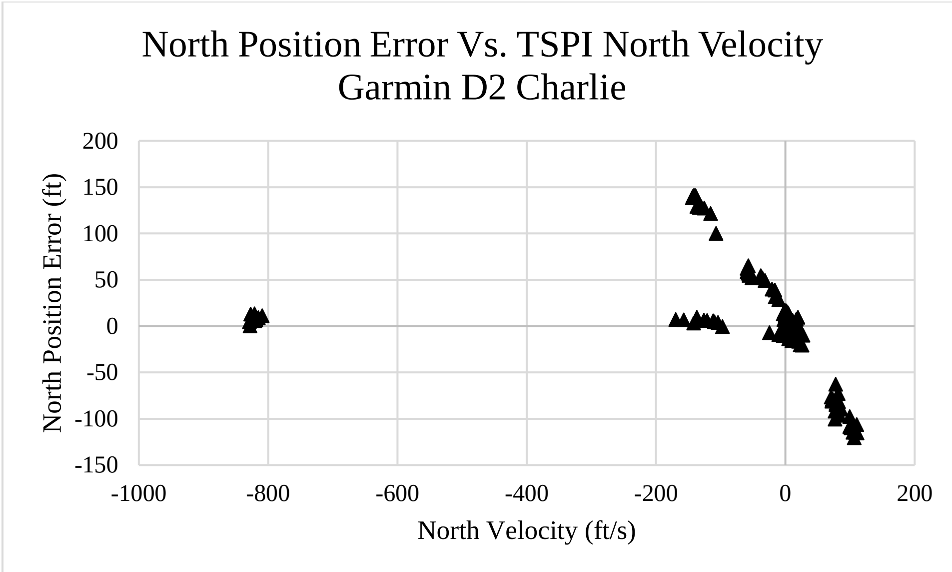

Figure C5: Garmin North Position Error vs TSPI North Velocity

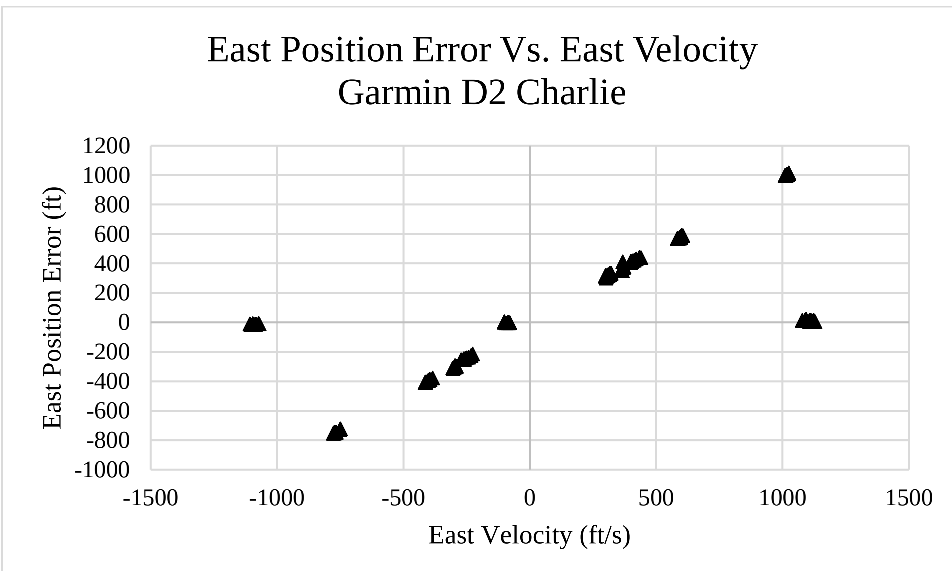

Figure C6: Garmin East Position Error vs TSPI East Velocity

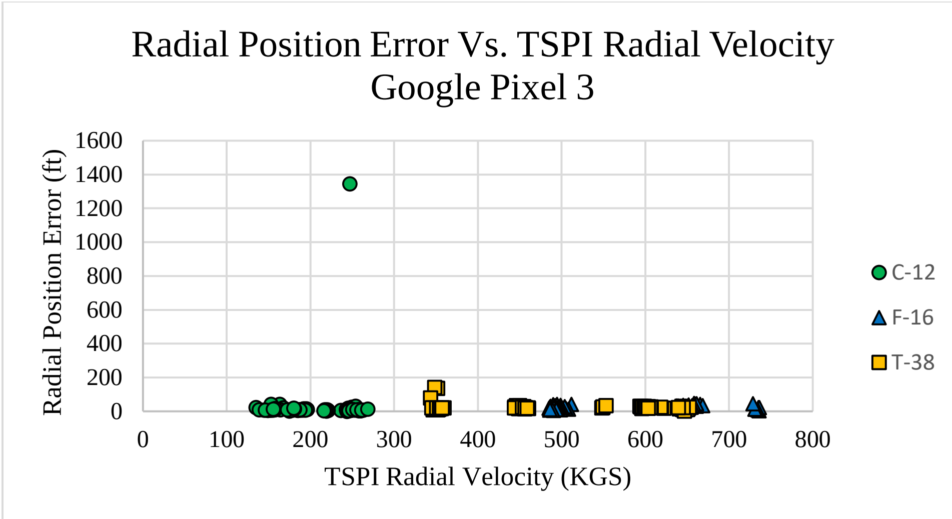

Figure C7: Pixel Radial Position Error vs TSPI Radial Velocity

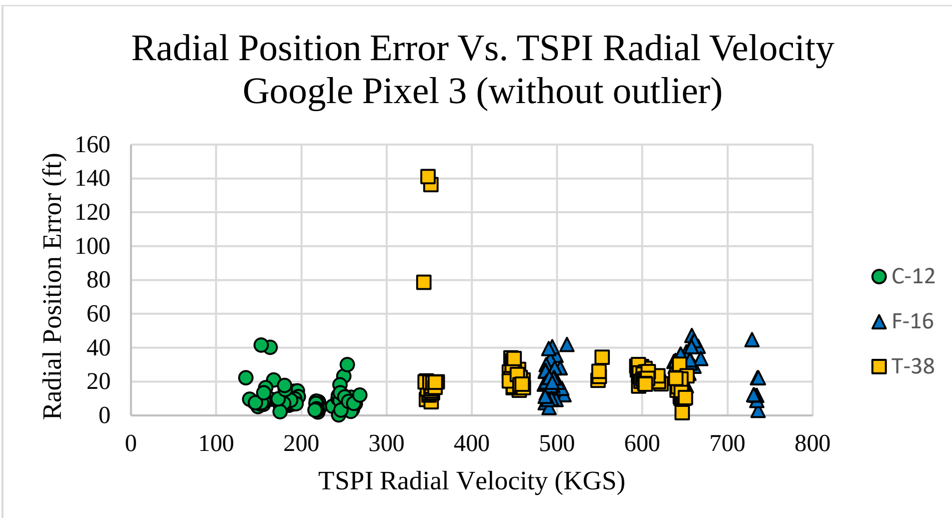

Figure C8: Pixel Radial Position Error vs TSPI Radial Velocity (without outlier)

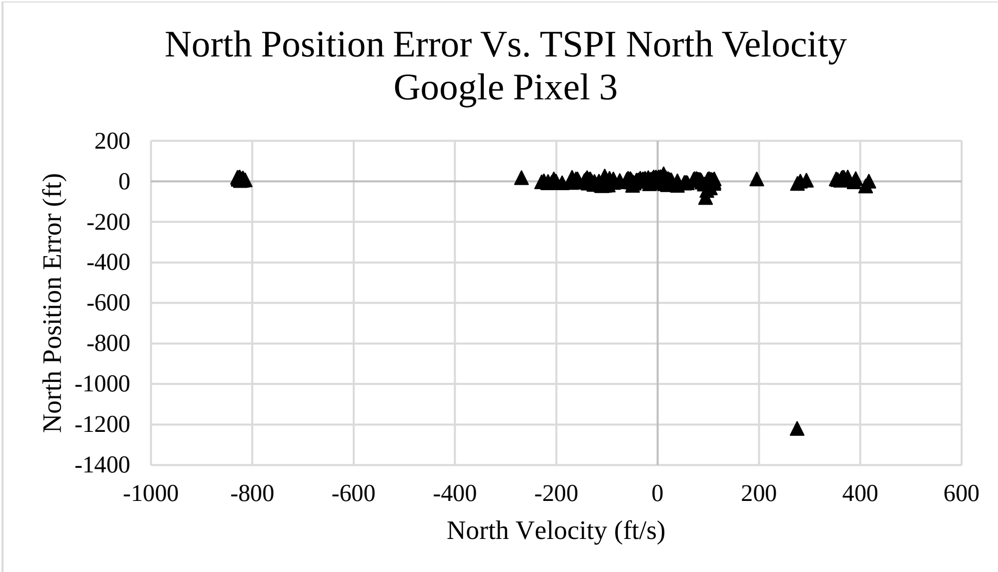

Figure C9: Pixel North Position Error vs TSPI North Velocity

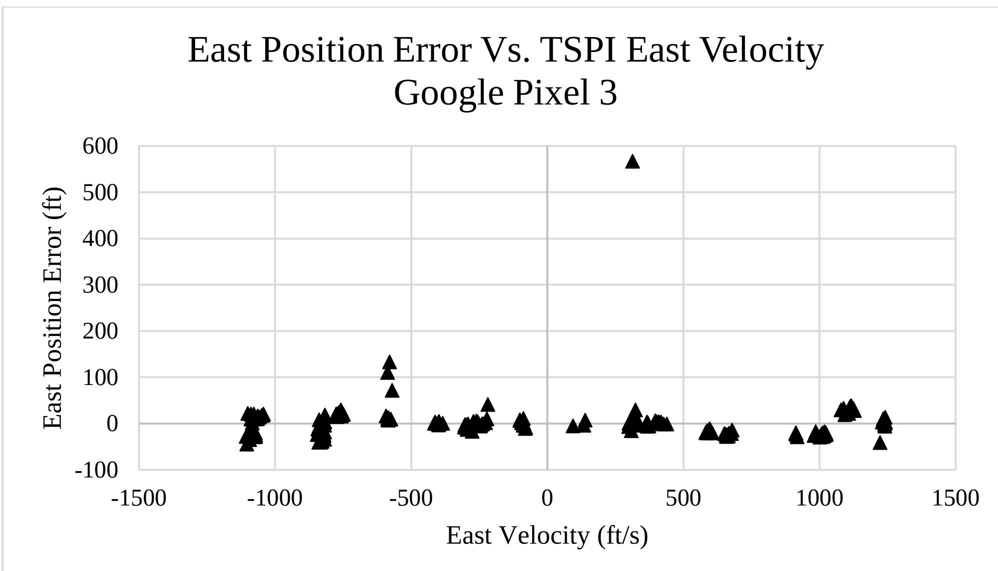

Figure C10: Pixel East Position Error vs TSPI East Velocity

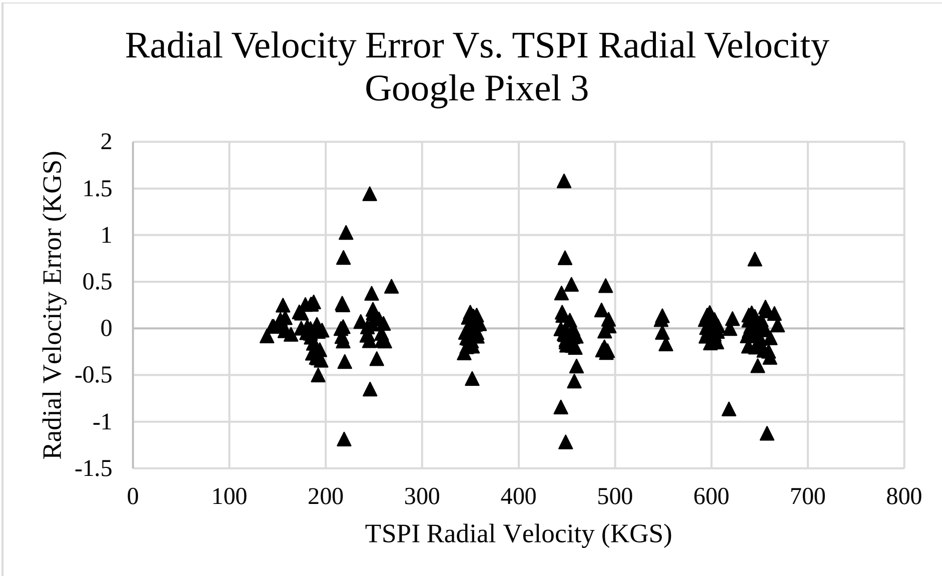

Figure C11: Pixel Radial Velocity Error vs TSPI Radial Velocity

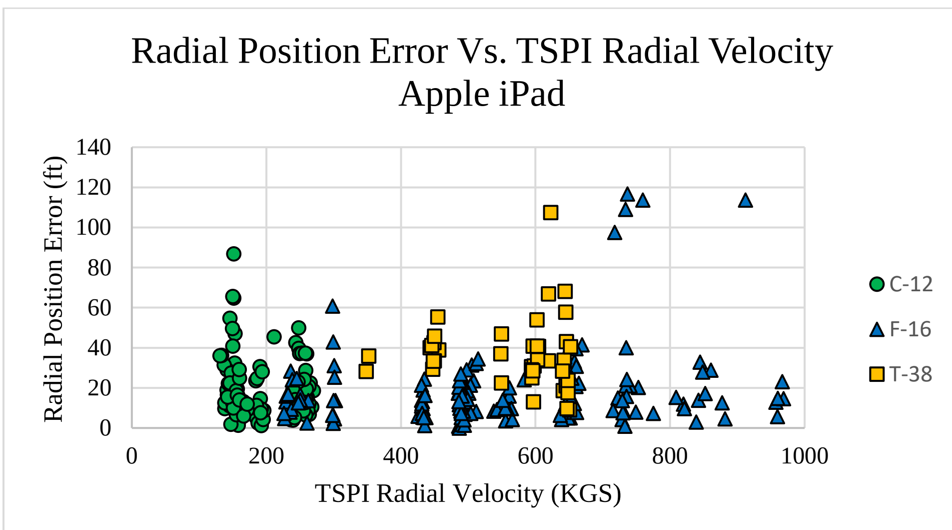

Figure C12: iPad Radial Position Error vs TSPI Radial Velocity

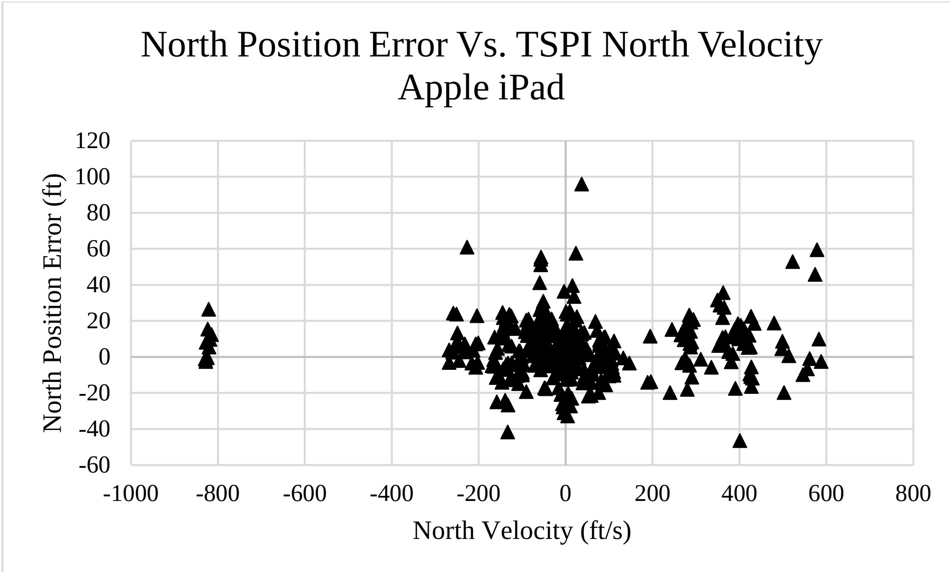

Figure C13: iPad North Position Error vs TSPI North Velocity

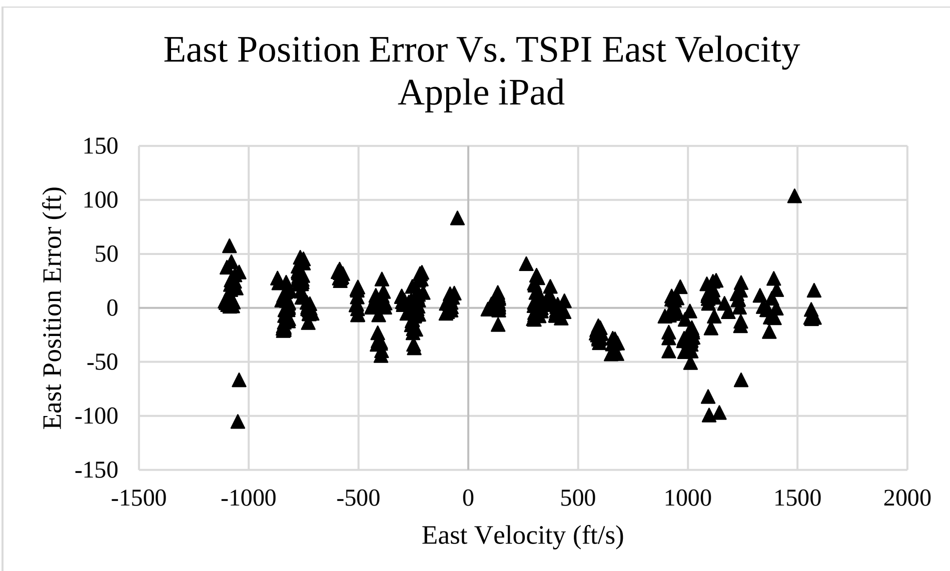

Figure C14: iPad East Position Error vs TSPI East Velocity

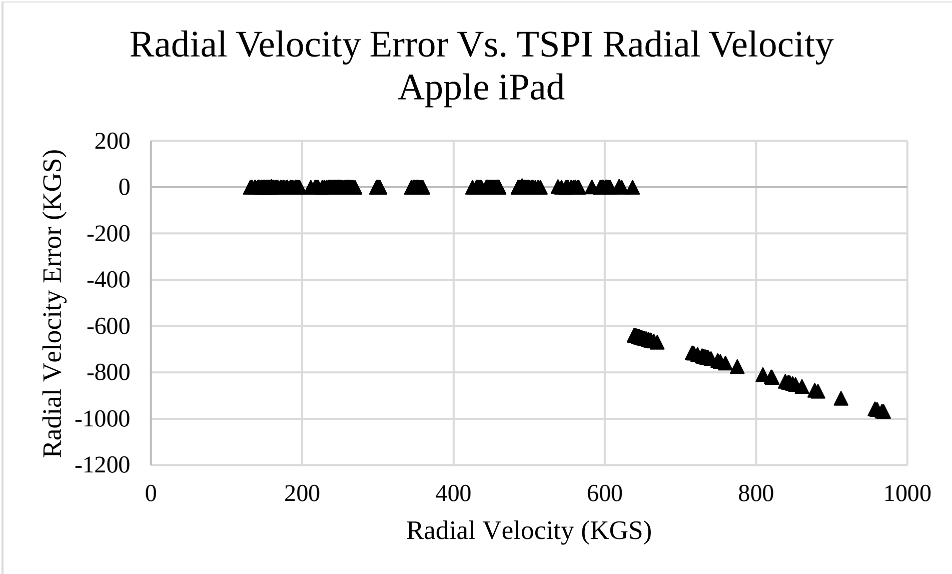

Figure C15: iPad Radial Velocity Error vs TSPI Radial Velocity

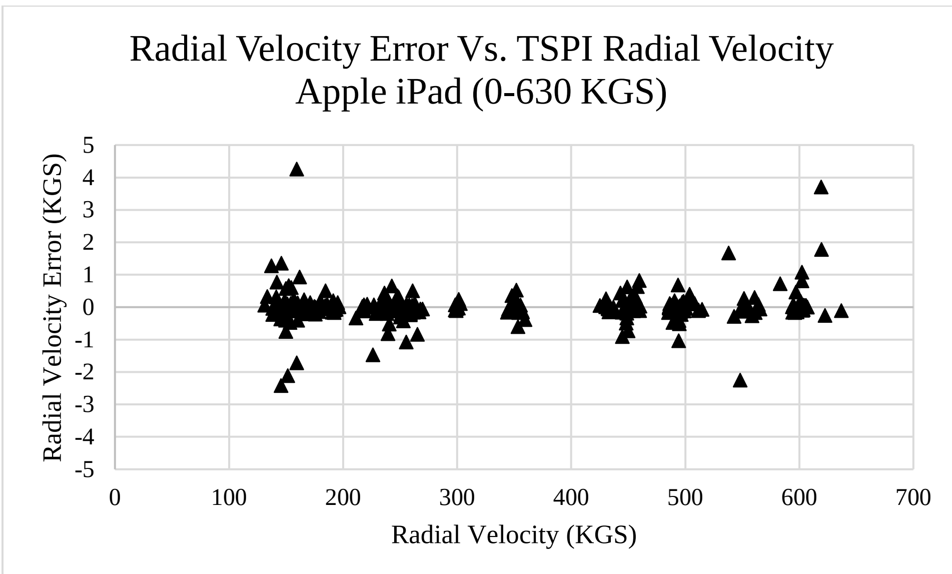

Figure C16: iPad Radial Velocity Error vs TSPI Radial Velocity (0-630 KGS)

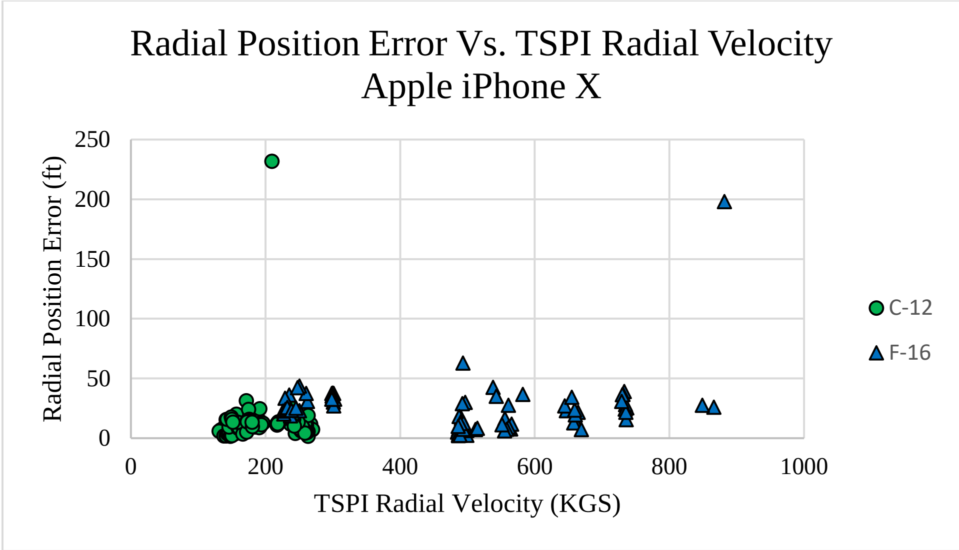

Figure C17: iPhone Radial Position Error vs TSPI Radial Velocity

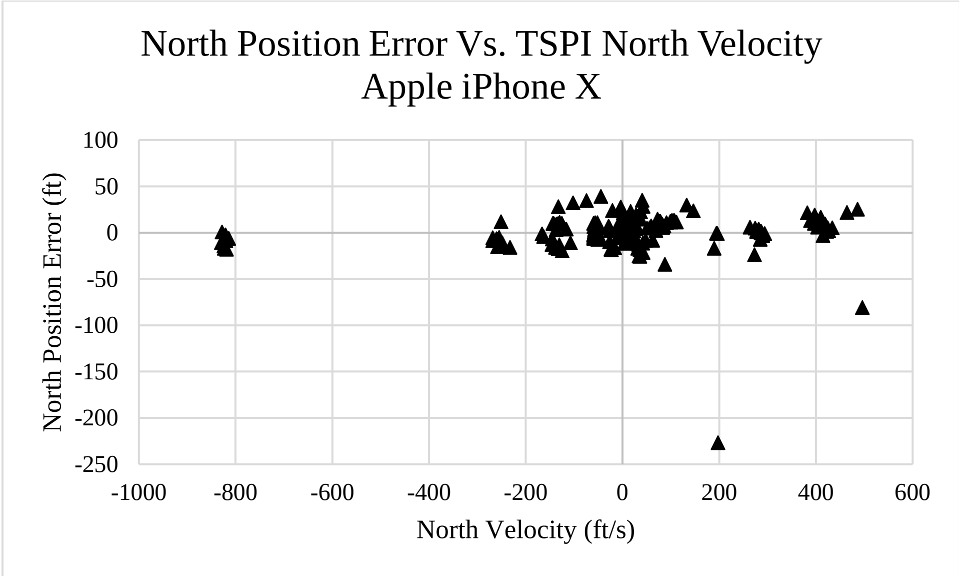

Figure C18: iPhone North Position Error vs TSPI North Velocity

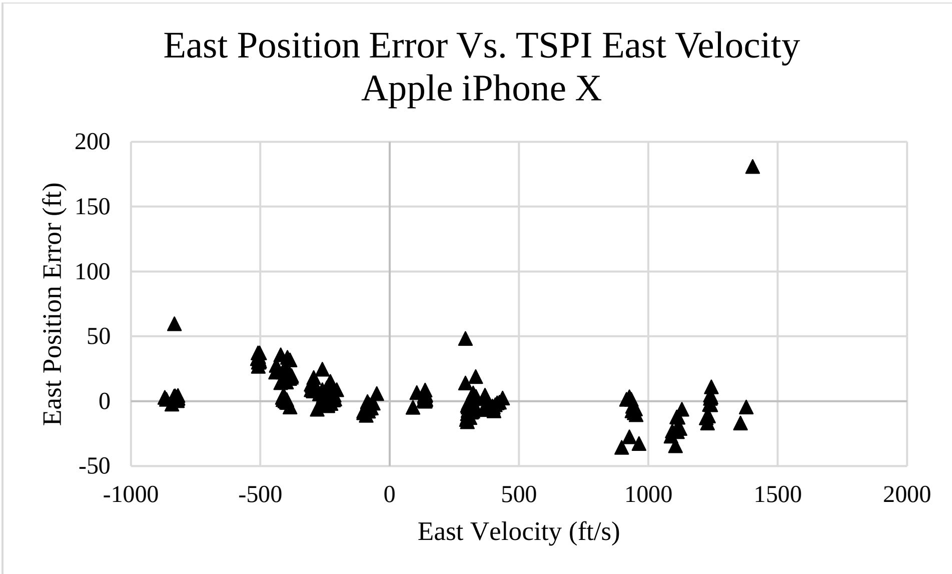

Figure C19: iPhone East Position Error vs TSPI East Velocity

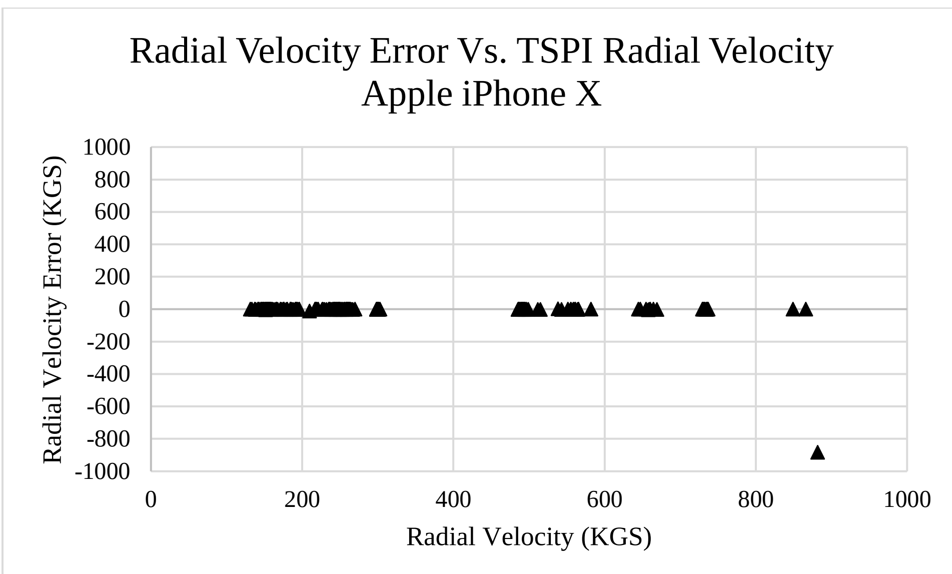

Figure C20: iPhone Radial Velocity vs TSPI Radial Velocity

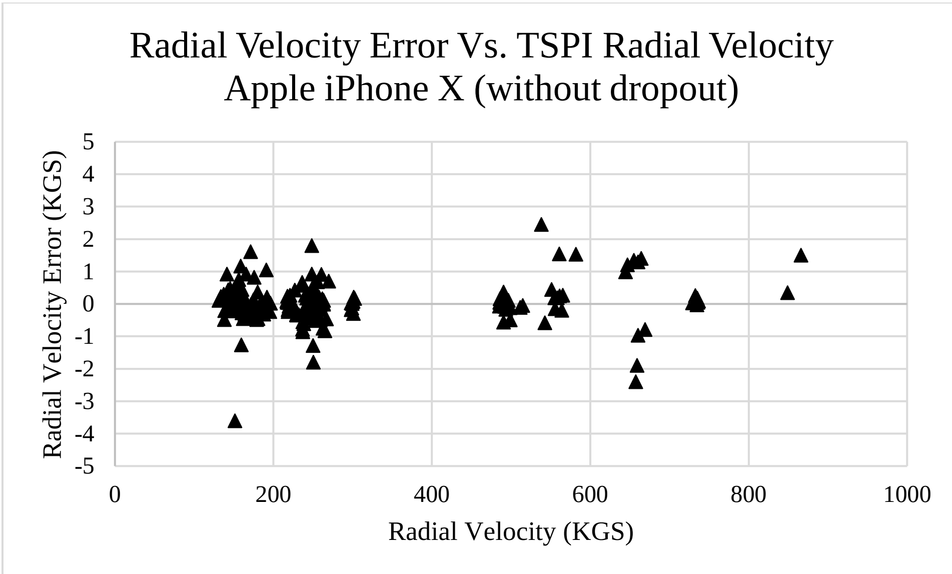

Figure C21: iPhone Radial Velocity Error vs TSPI Radial Velocity (without dropout)

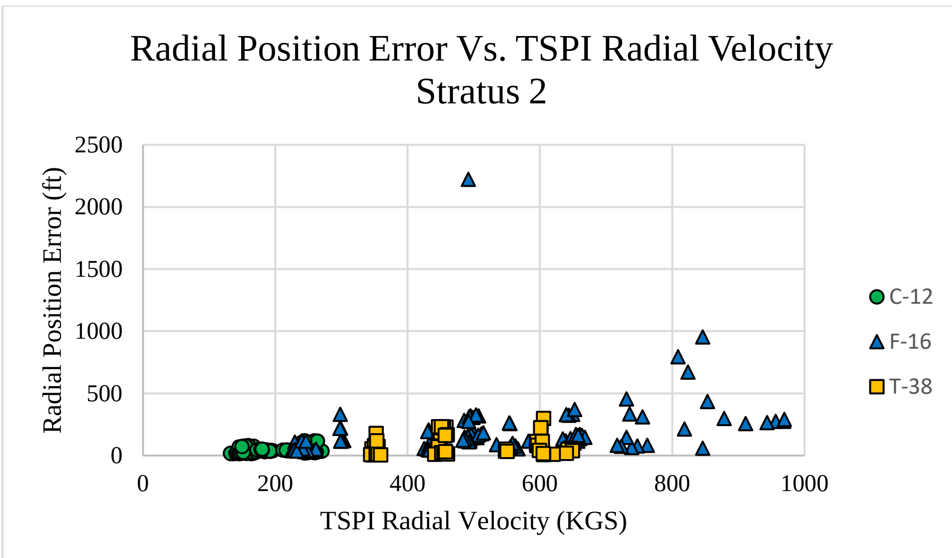

Figure C22: Stratus 2 Radial Position Error vs TSPI Radial Velocity

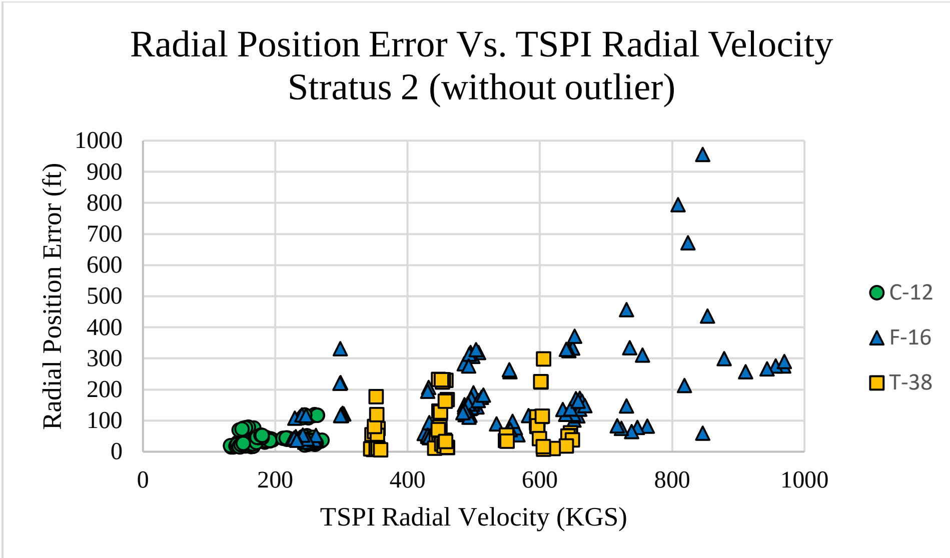

Figure C23: Stratus 2 Radial Position Error vs TSPI Radial Velocity (without outlier)

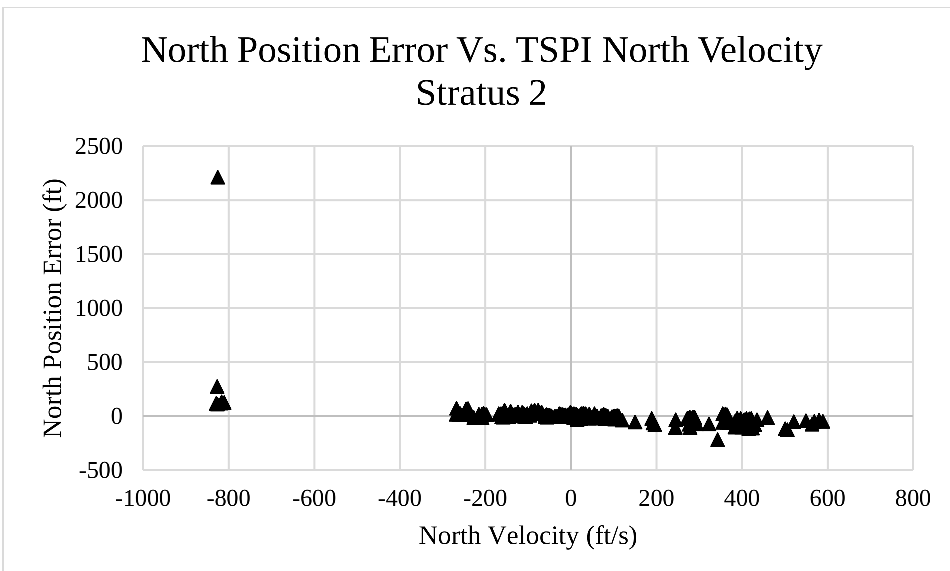

Figure C24: Stratus 2 North Position Error vs TSPI North Velocity

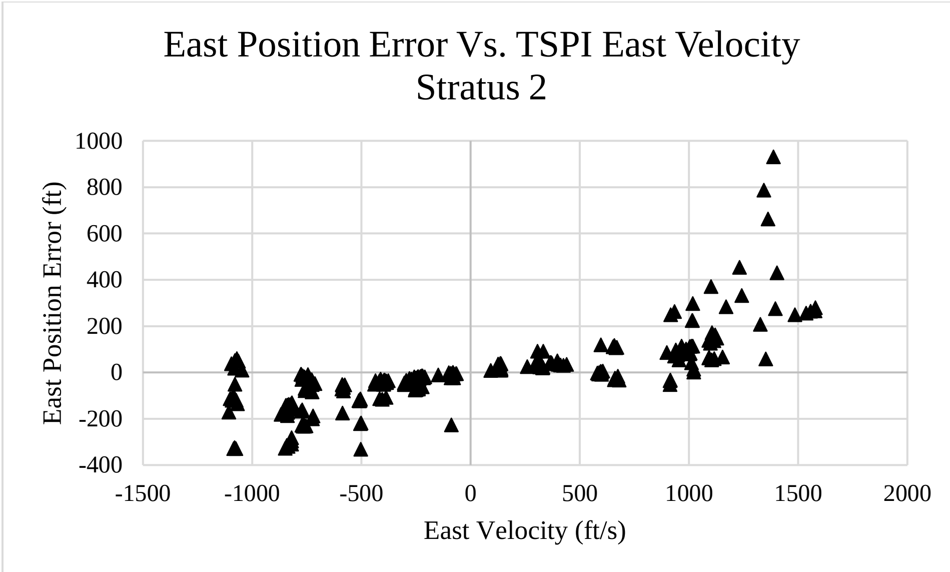

Figure C25: Stratus 2 East Position Error vs TSPI East Velocity

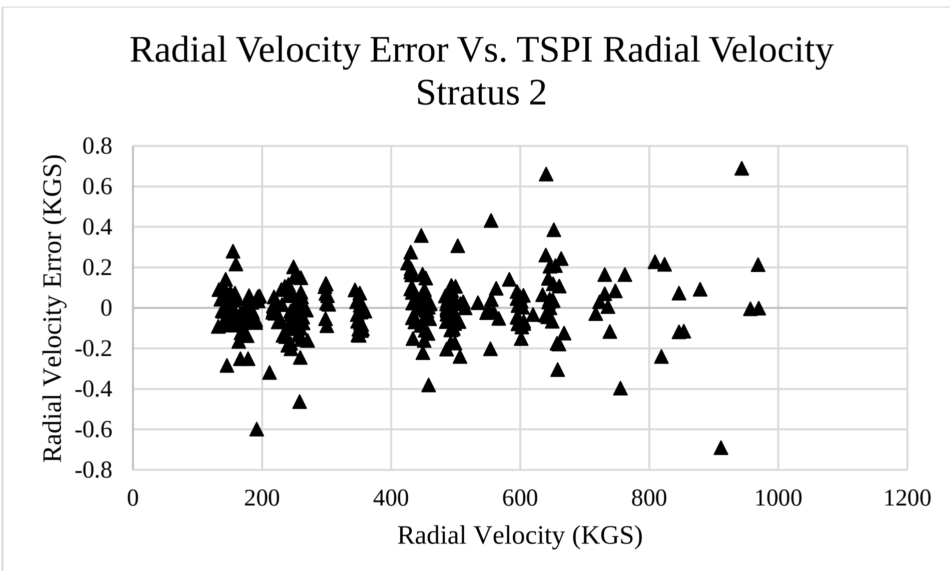

Figure C26: Stratus 2 Radial Velocity Error vs TSPI Radial Velocity

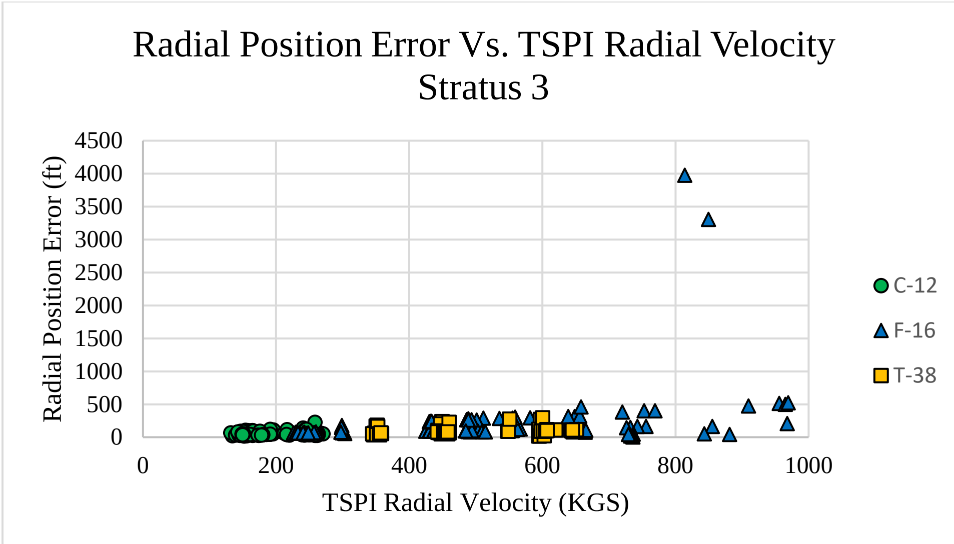

Figure C27: Stratus 3 Radial Position Error vs TSPI Radial Velocity

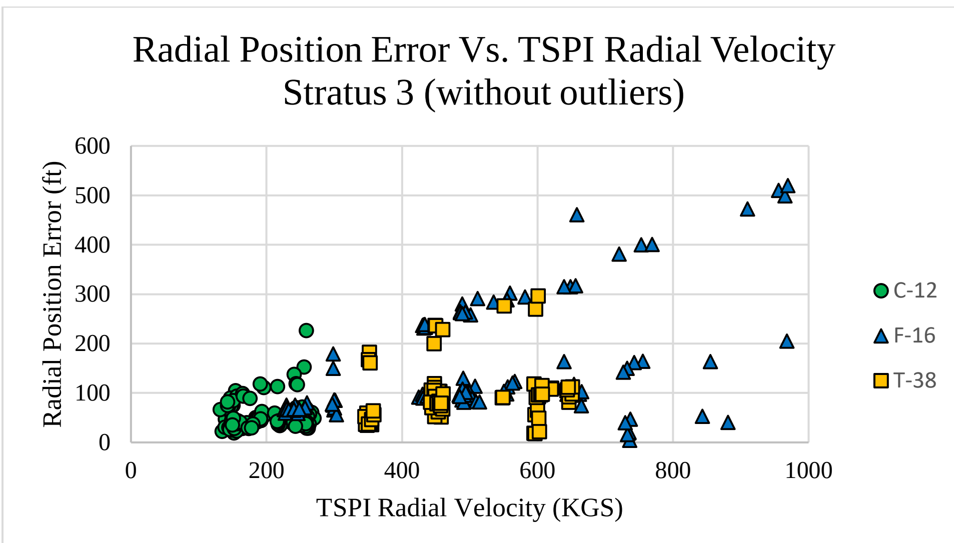

Figure C28: Stratus 3 Radial Position Error vs TSPI Radial Velocity (without outliers)

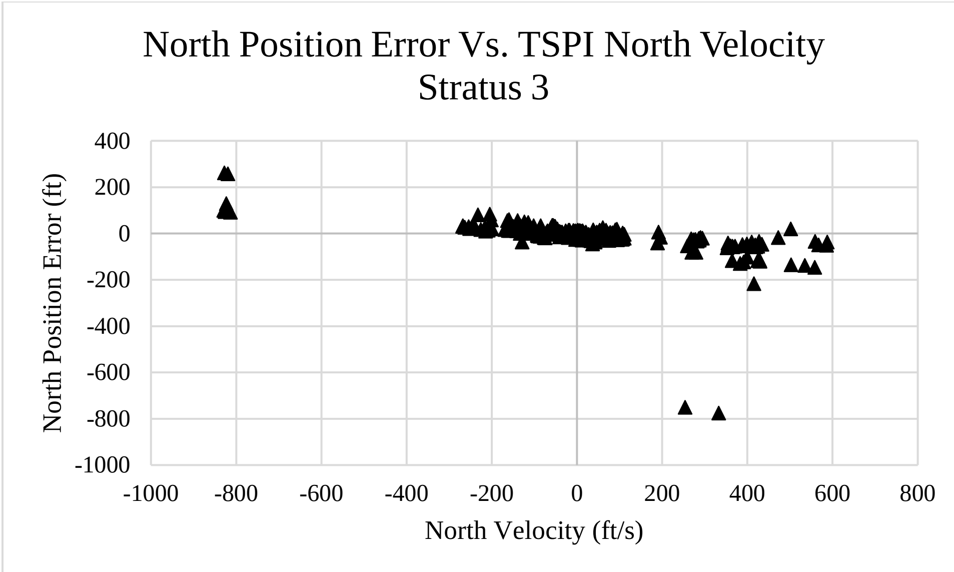

Figure C29: Stratus 3 North Position Error vs TSPI North Velocity

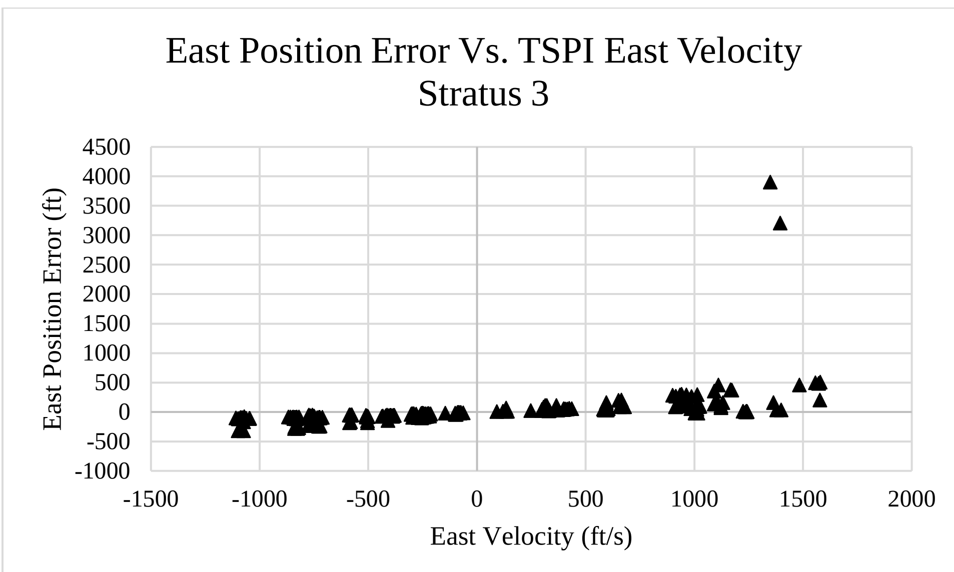

Figure C30: Stratus 3 East Position Error vs TSPI East Velocity

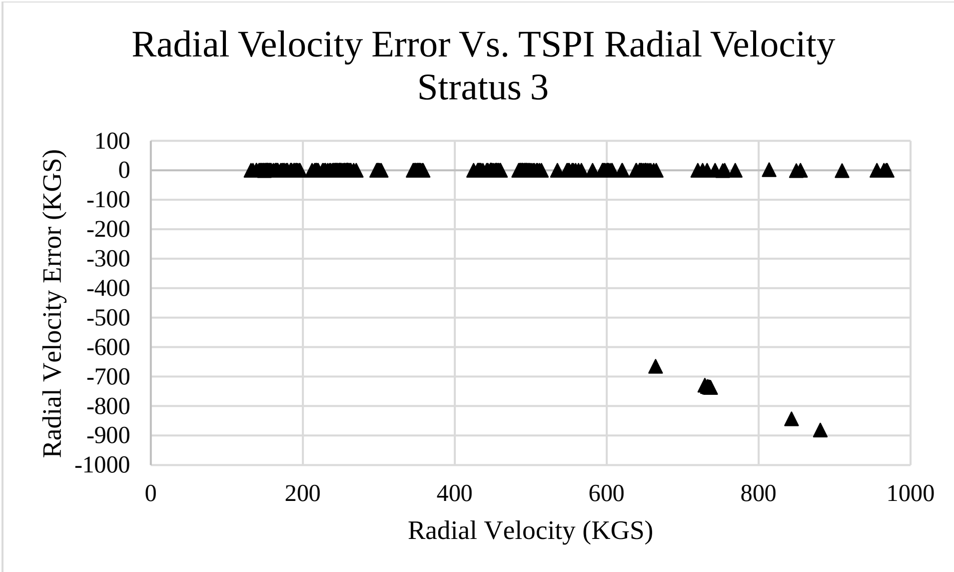

Figure C31: Stratus 3 Radial Velocity Error vs TSPI Radial Velocity

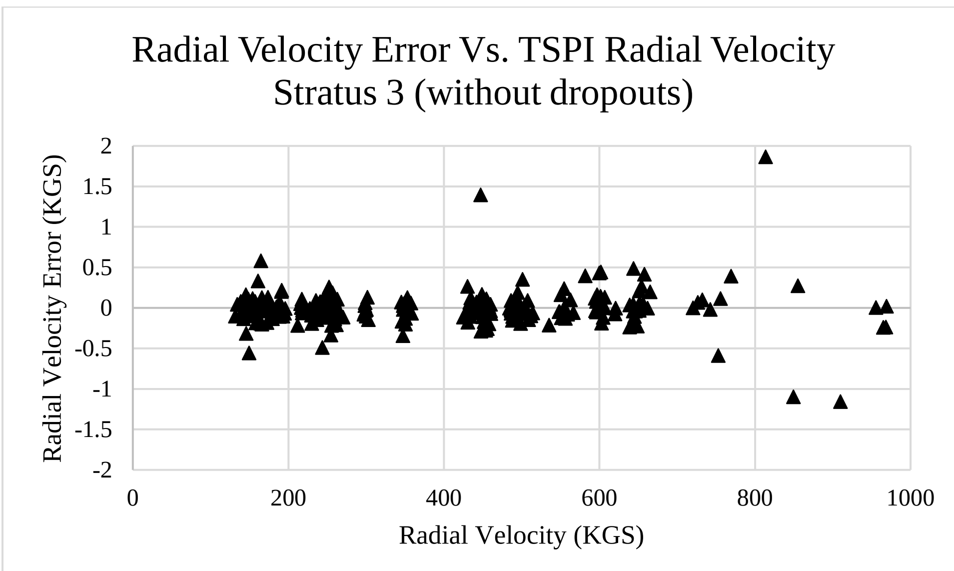

Figure C32: Stratus 3 Radial Velocity Error vs TSPI Radial Velocity (without dropouts)

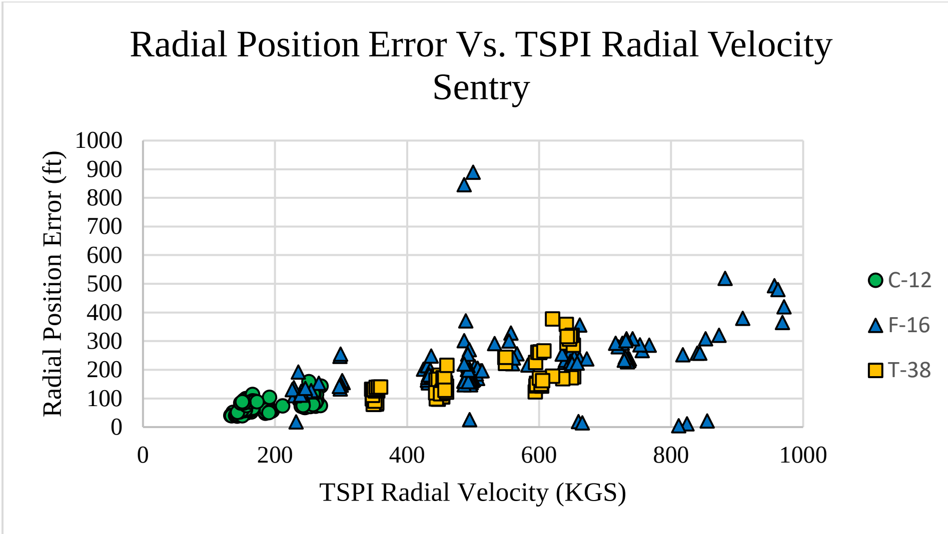

Figure C33: Sentry Radial Position Error vs TSPI Radial Velocity

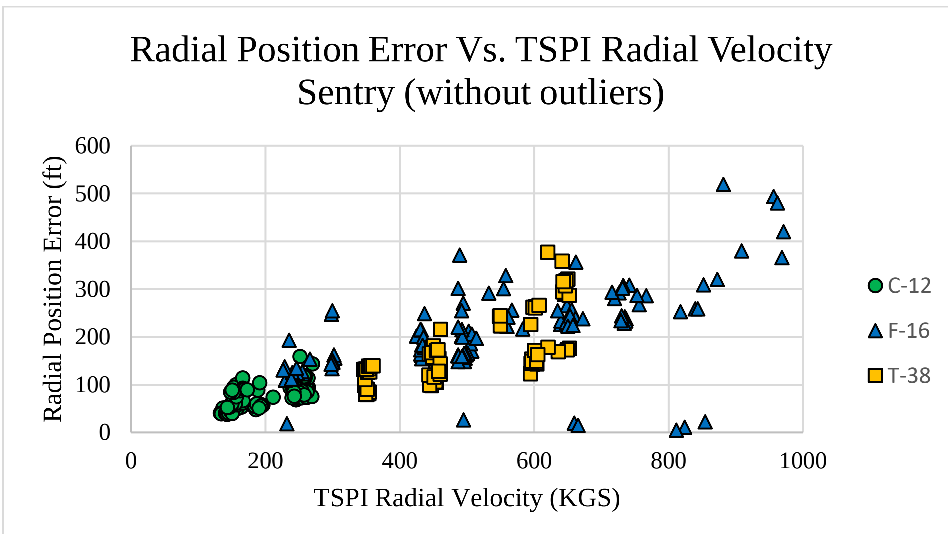

Figure C34: Sentry Radial Position Error vs TSPI Radial Velocity (without outliers)

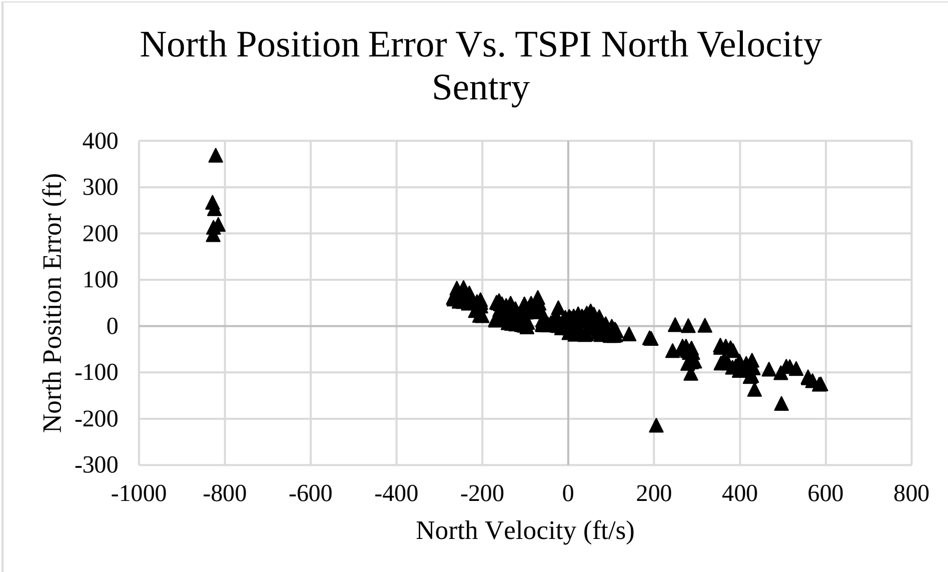

Figure C35: Sentry North Position Error vs TSPI North Velocity

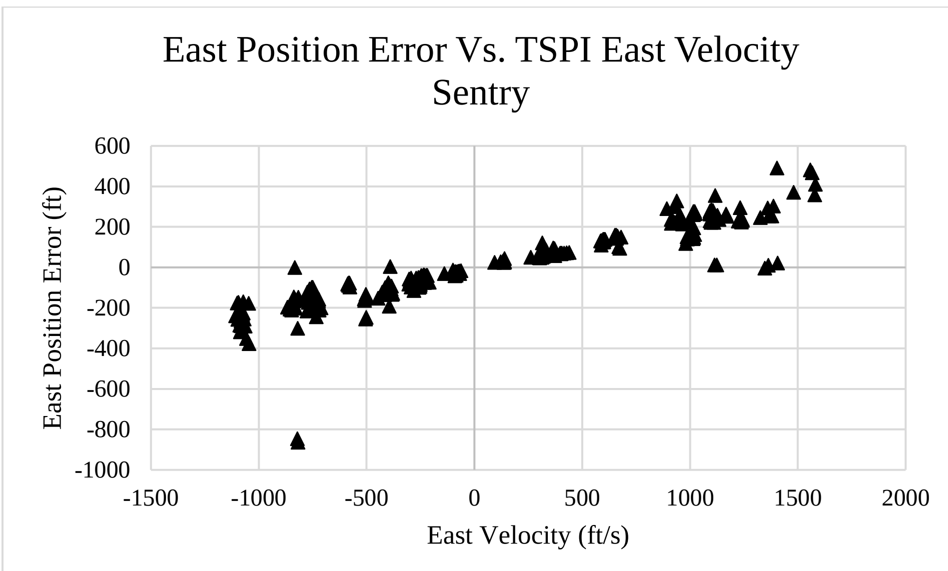

Figure C36: Sentry East Position Error vs TSPI East Velocity

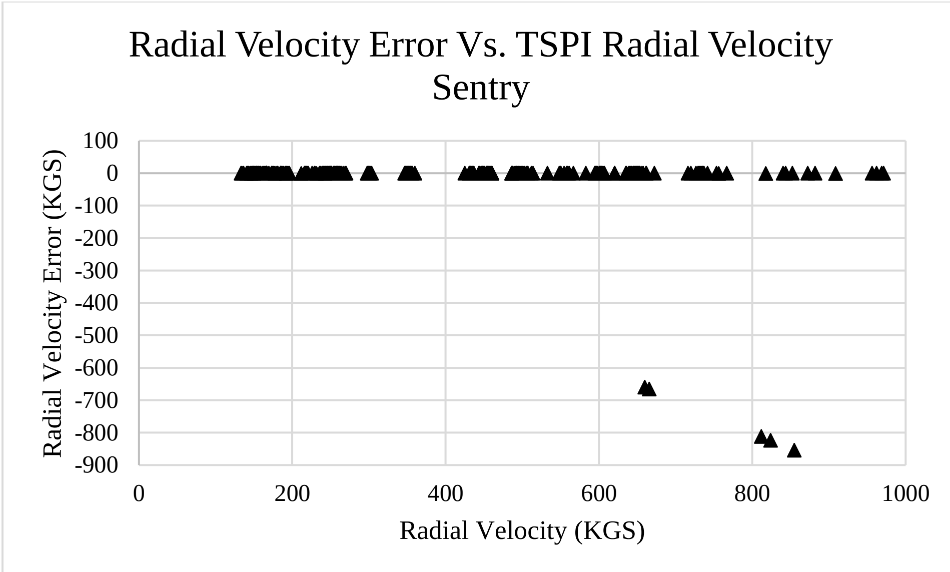

Figure C37: Sentry Radial Velocity Error vs TSPI Radial Velocity

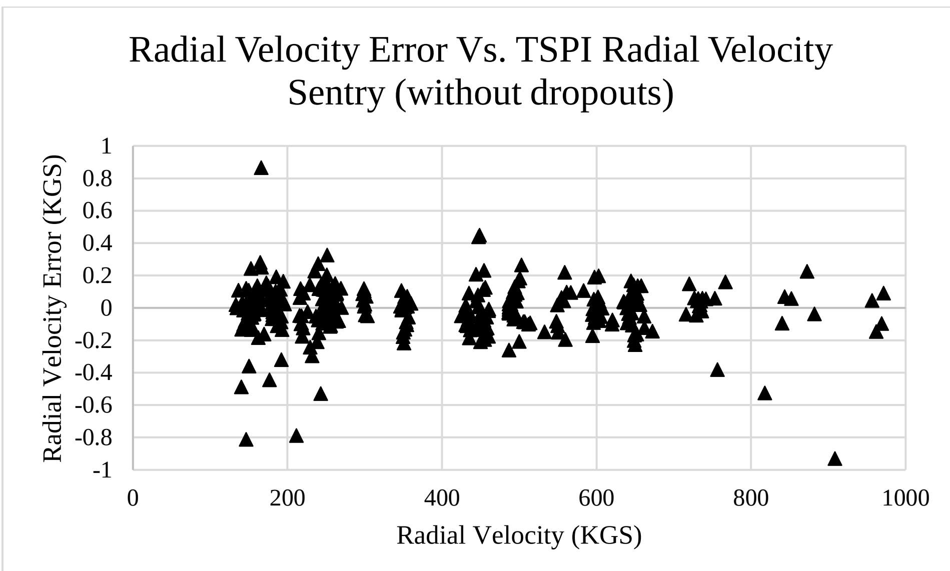

Figure C38: Sentry Radial Velocity Error vs TSPI Radial Velocity (without dropouts)

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APPENDIX D – SUPPLEMENTAL DATA: POSITION AND VELOCITY ERROR VS ALTITUDE

Notes: Data collected for this test has a position uncertainly of ±15 feet and ±0.3 ft/s (±0.18 KGS). Altitude for all plots is height above ellipsoid.

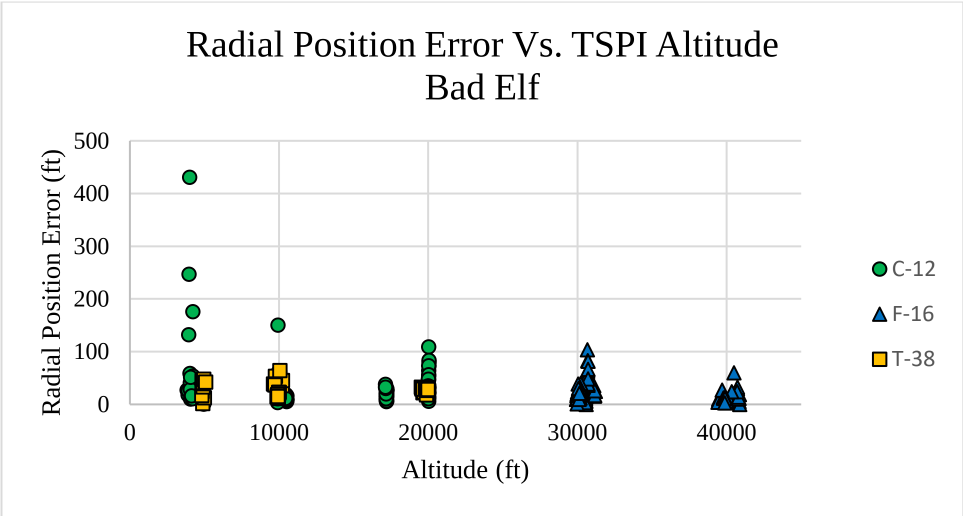

Figure D1: Bad Elf Radial Position Error vs TSPI Altitude

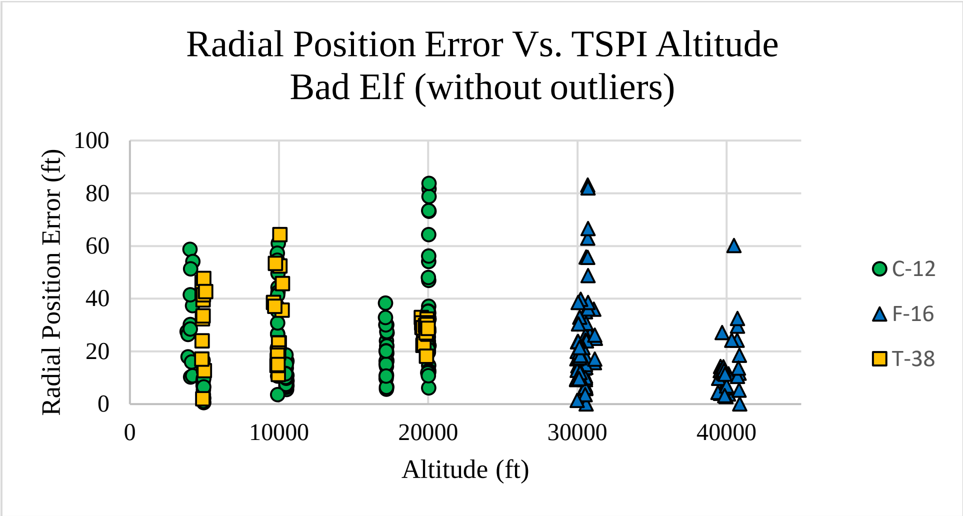

Figure D2: Bad Elf Radial Position Error vs TSPI Altitude (without outliers)

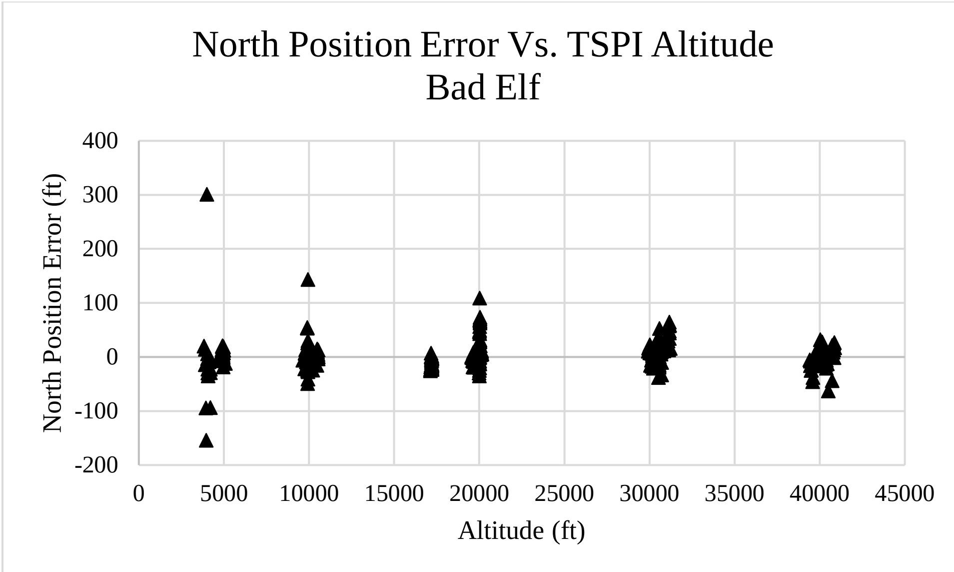

Figure D3: Bad Elf North Position Error vs TSPI Altitude

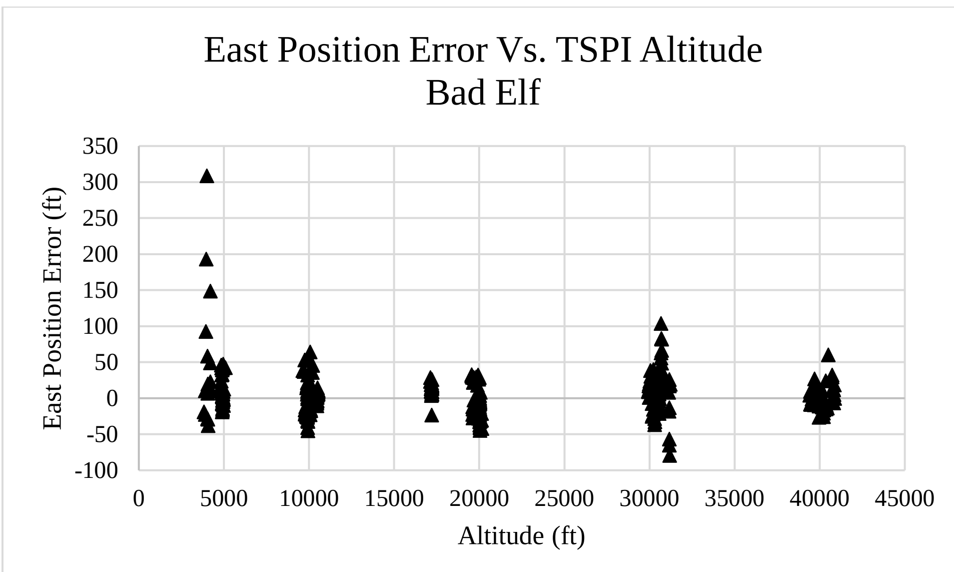

Figure D4: Bad Elf East Position Error vs TSPI Altitude

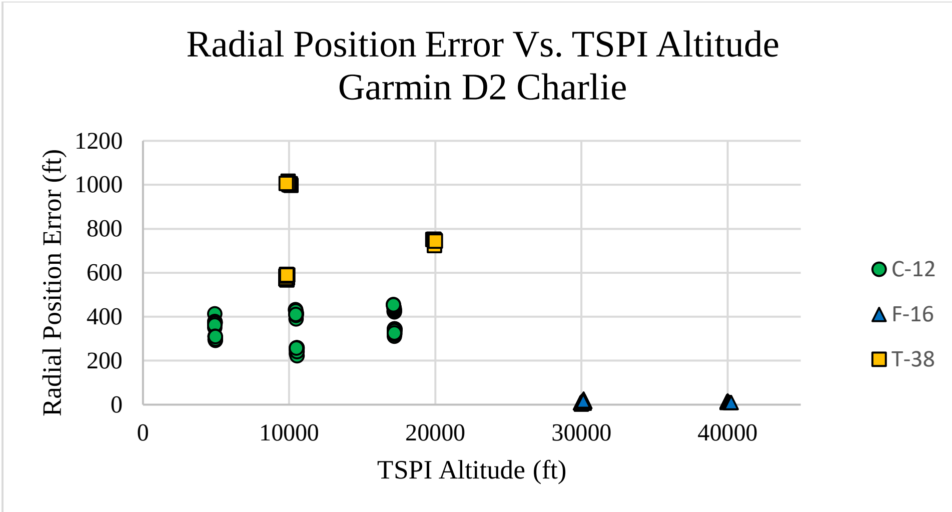

Figure D5: Garmin Radial Position Error vs Altitude

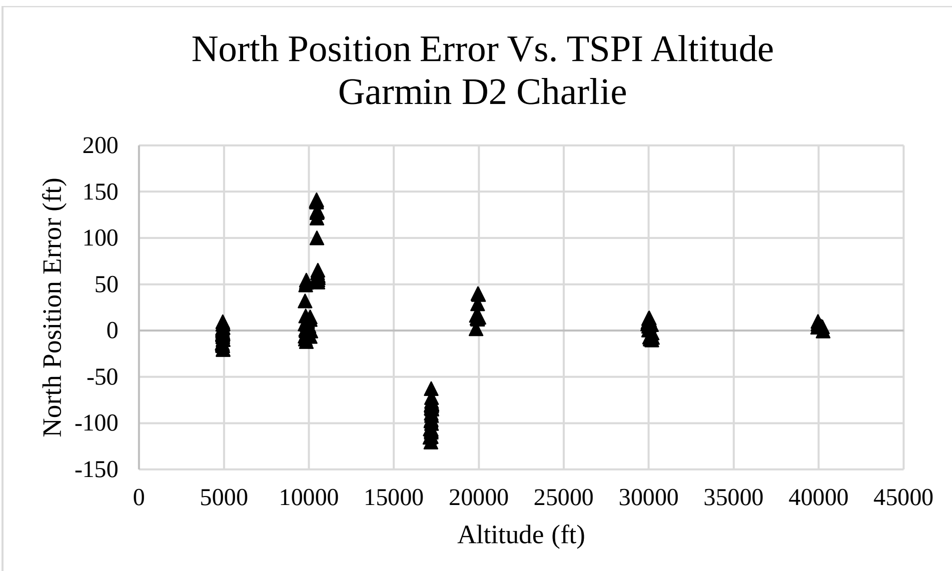

Figure D6: Garmin North Position Error vs TSPI Altitude

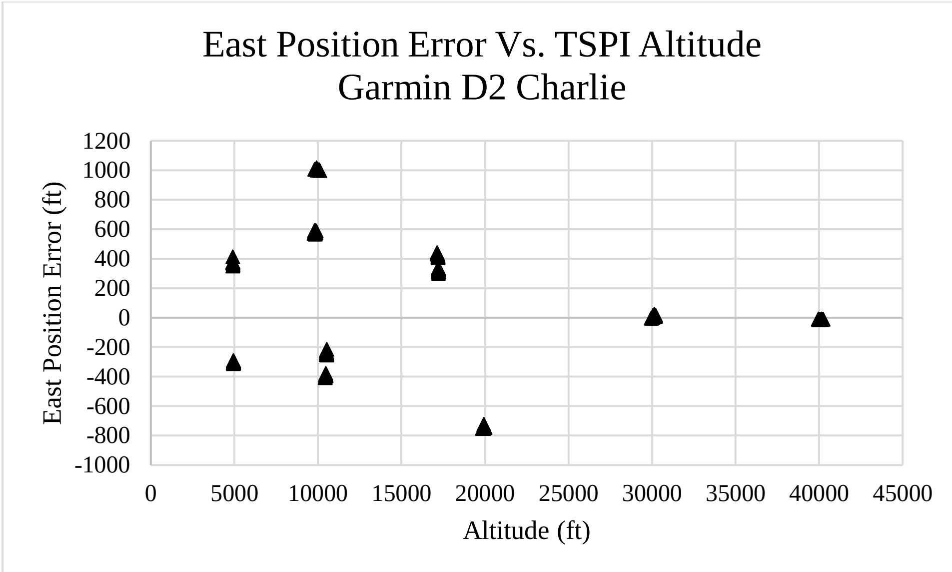

Figure D7: Garmin East Position Error vs TSPI Altitude

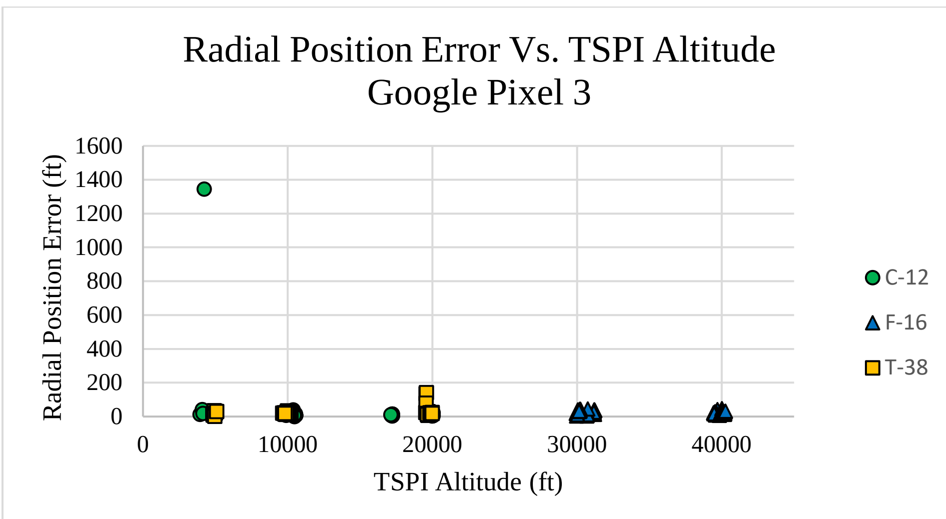

Figure D8: Pixel Radial Position Error vs TSPI Altitude

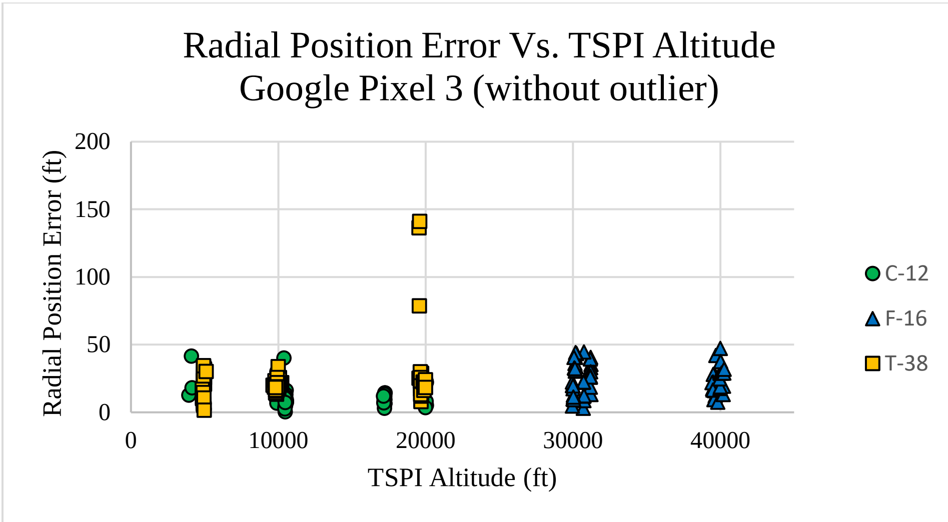

Figure D9: Pixel Radial Position Error vs TSPI Altitude (without outliers)

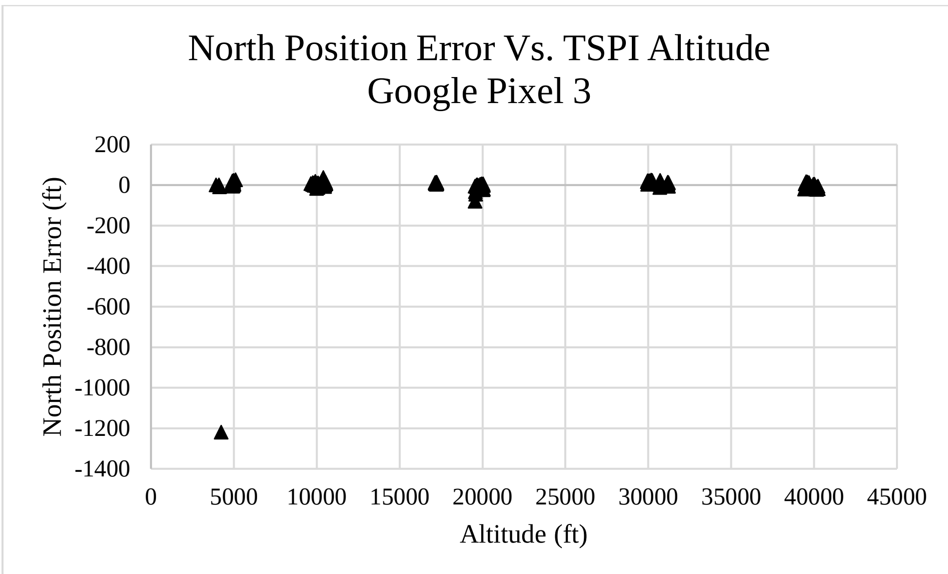

Figure D10: Pixel North Position Error vs TSPI Altitude

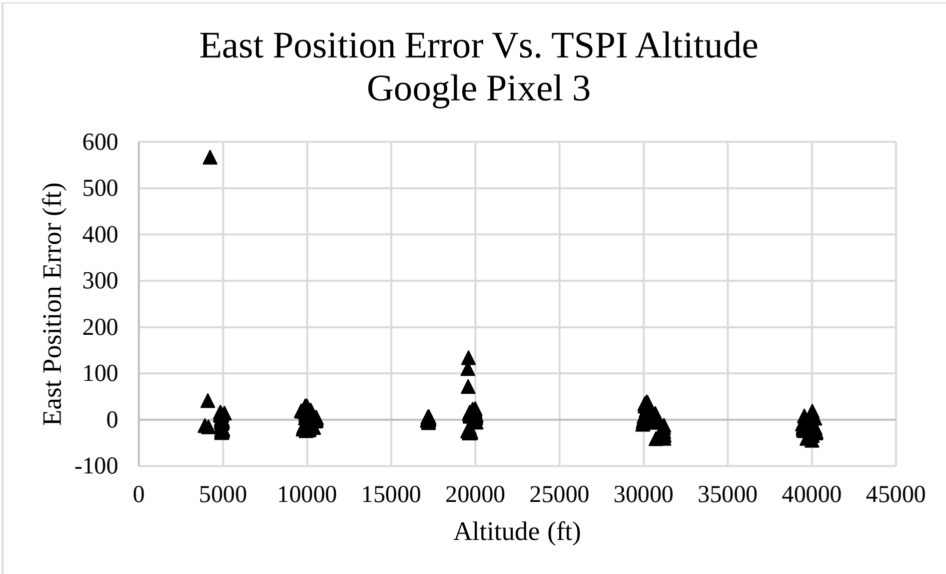

Figure D11: Pixel East Position Error vs TSPI Altitude

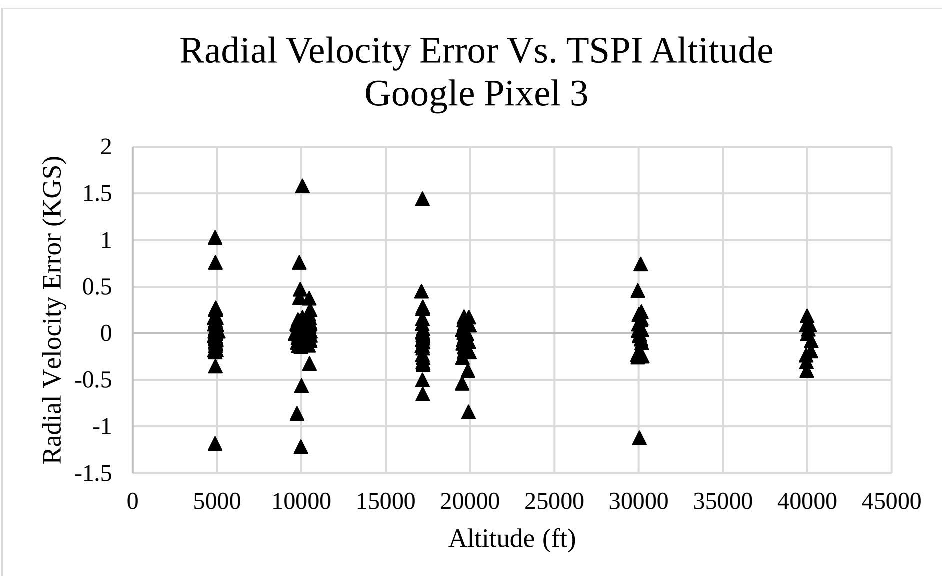

Figure D12: Pixel Radial Velocity Error vs TSPI Altitude

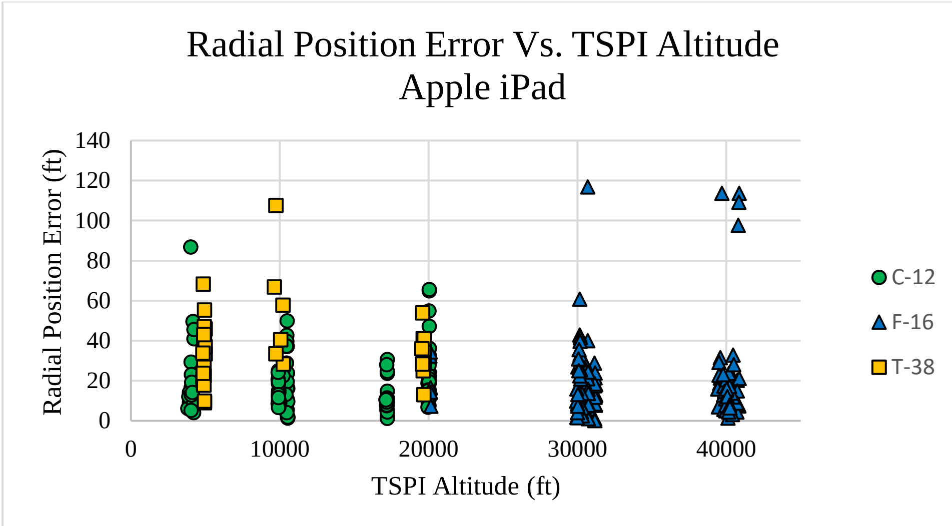

Figure D13: iPad Radial Position Error vs TSPI Altitude

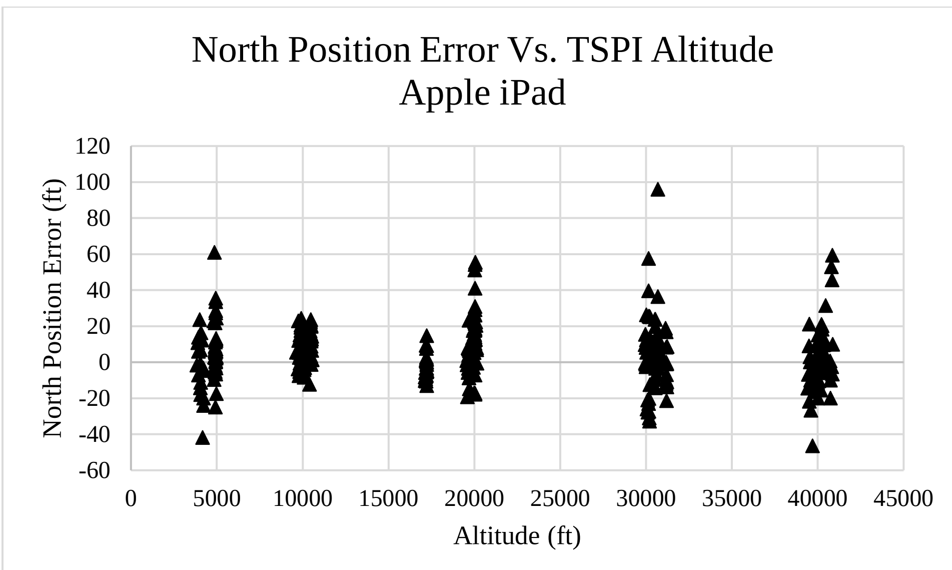

Figure D14: iPad North Position Error vs TSPI Altitude

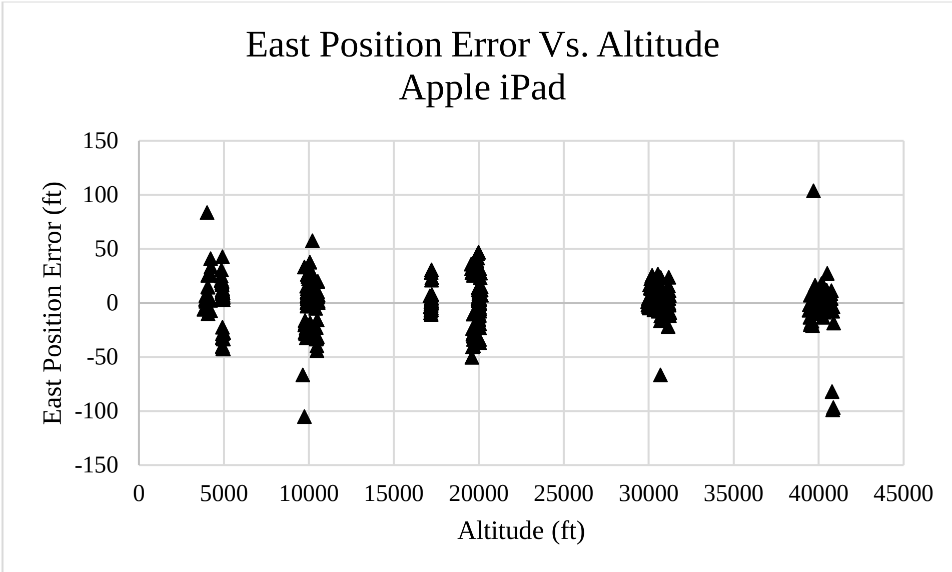

Figure D15: iPad East Position Error vs TSPI Altitude

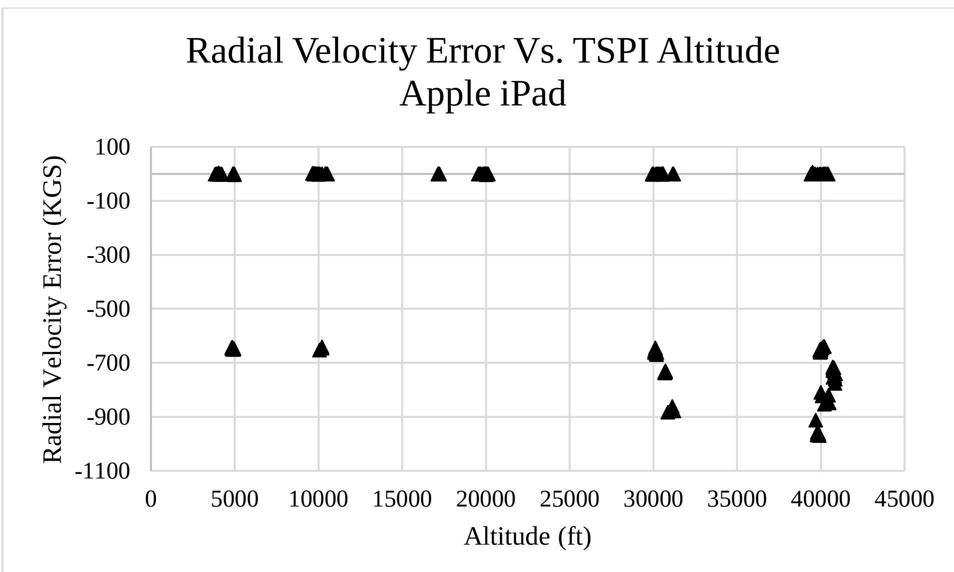

Figure D16: iPad Radial Velocity Error vs TSPI Altitude

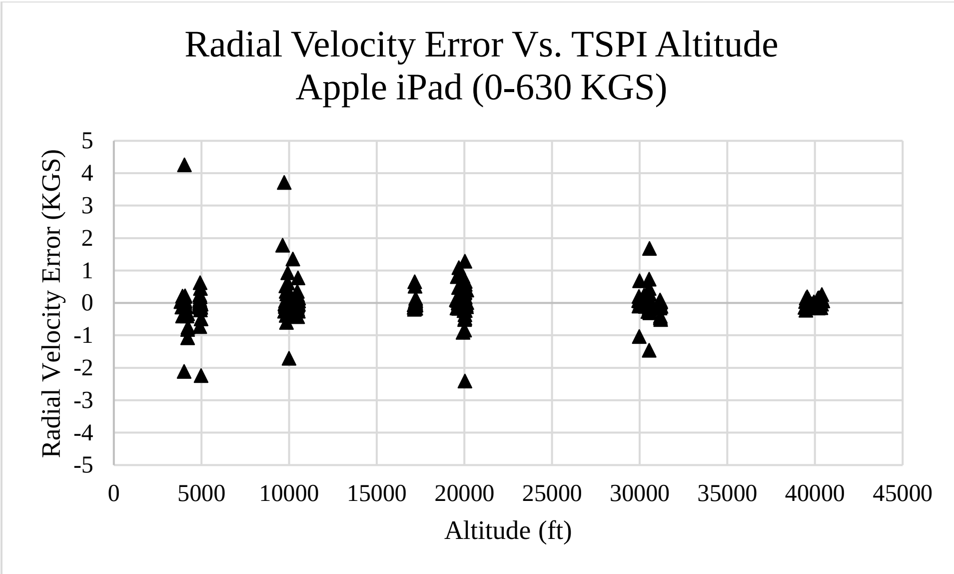

Figure D17: iPad Radial Velocity Error vs TSPI Altitude (0-630 KGS)

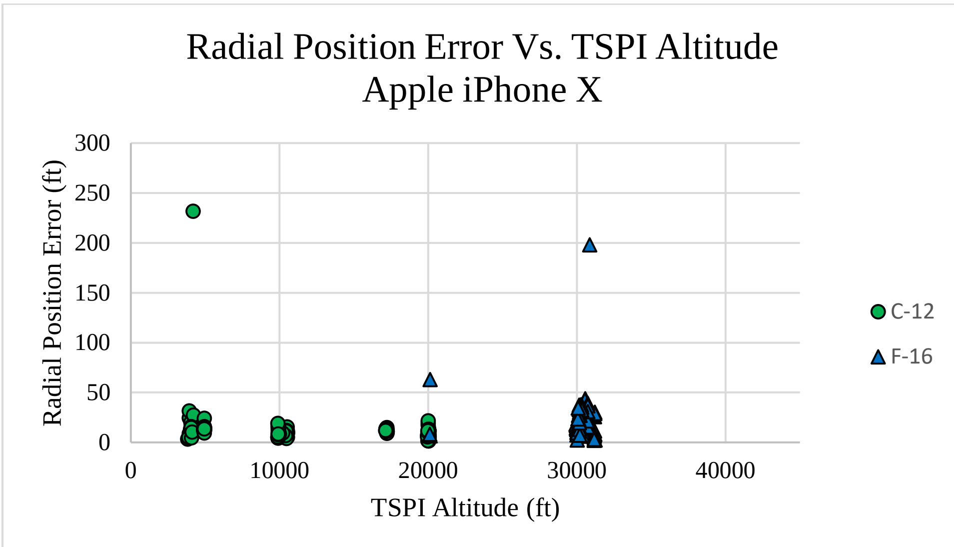

Figure D18: iPhone Radial Position Error vs TSPI Altitude

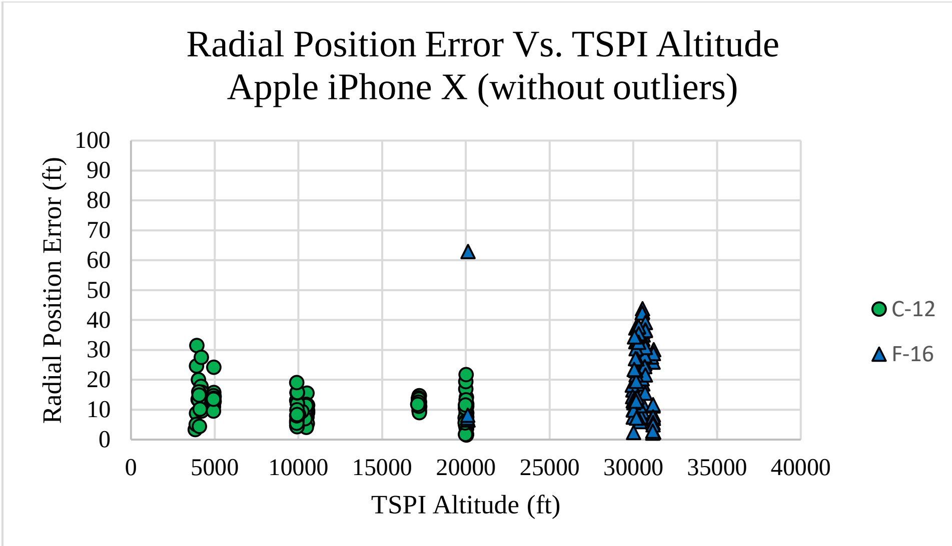

Figure D19: iPhone Radial Position Error vs TSPI Altitude (without outliers)

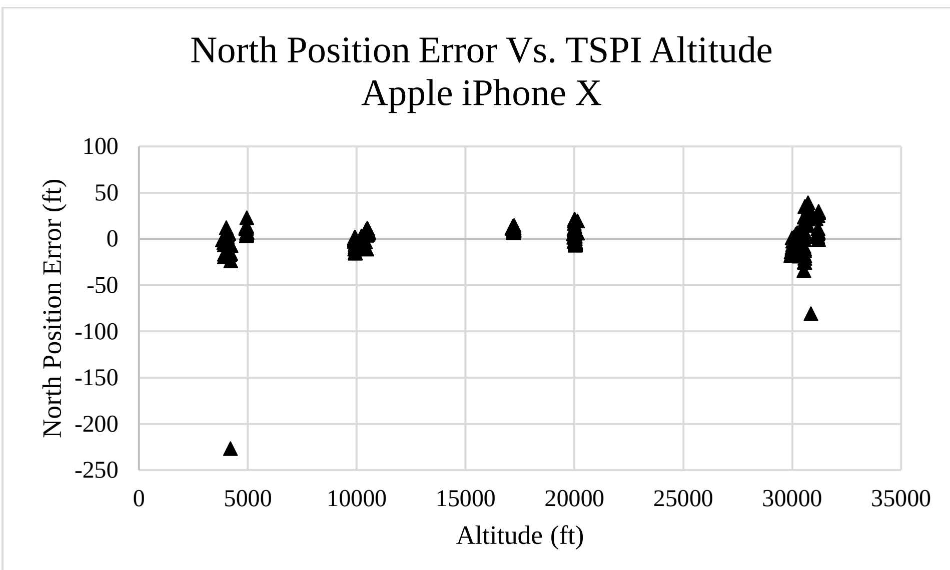

Figure D20: iPhone North Position Error vs TSPI Altitude

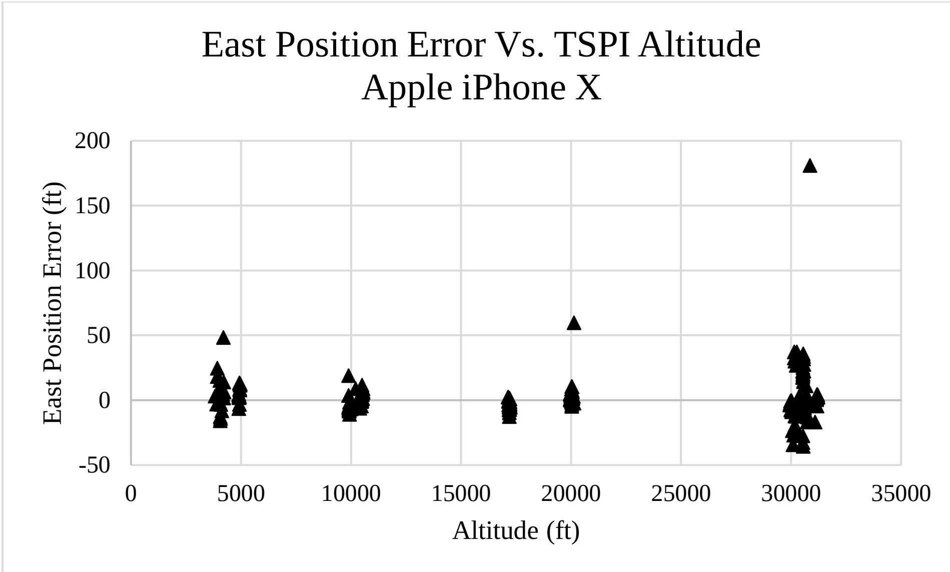

Figure D21: iPhone East Position Error vs TSPI Altitude

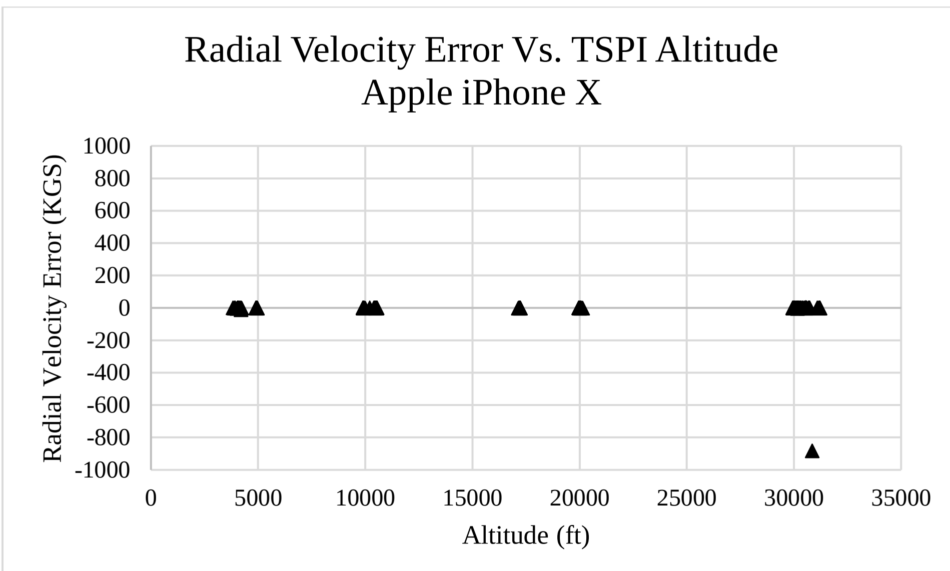

Figure D22: iPhone Radial Velocity Error vs TSPI Altitude

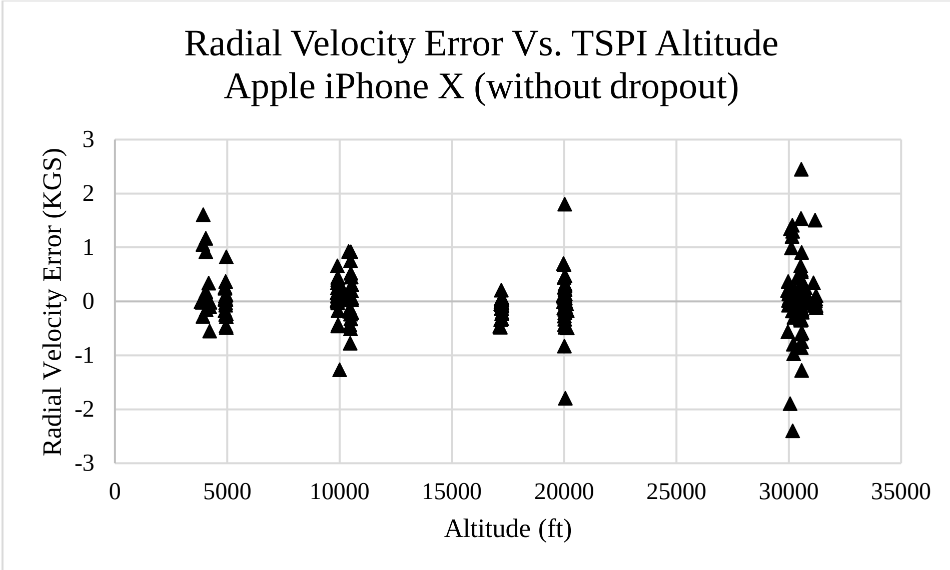

Figure D23: iPhone Radial Velocity Error vs TSPI Altitude (without dropout)

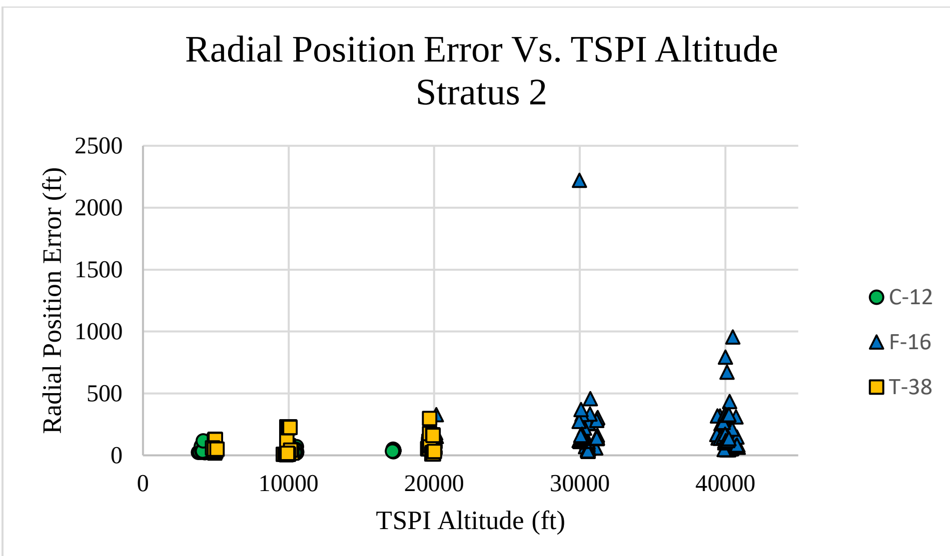

Figure D24: Stratus 2 Radial Position Error vs TSPI Altitude

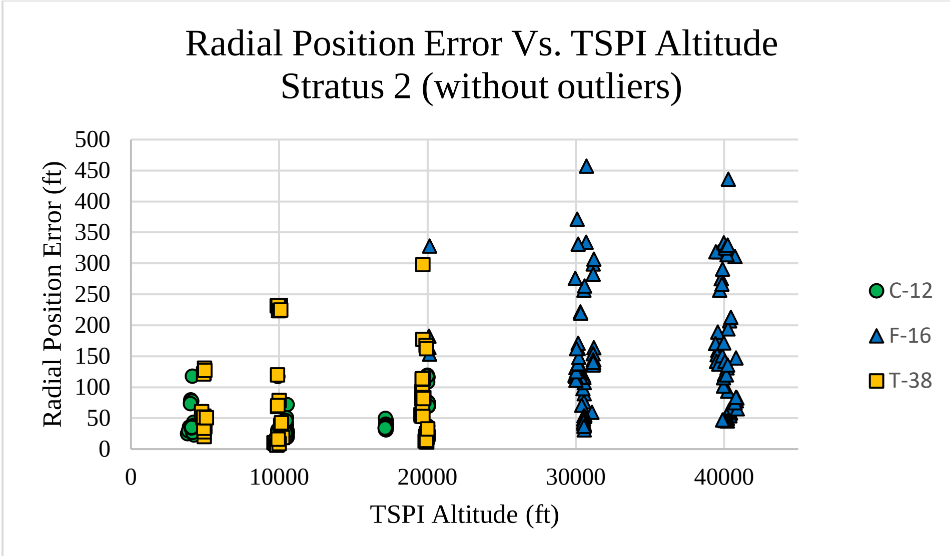

Figure D25: Stratus 2 Radial Position Error vs TSPI Altitude (without outliers)

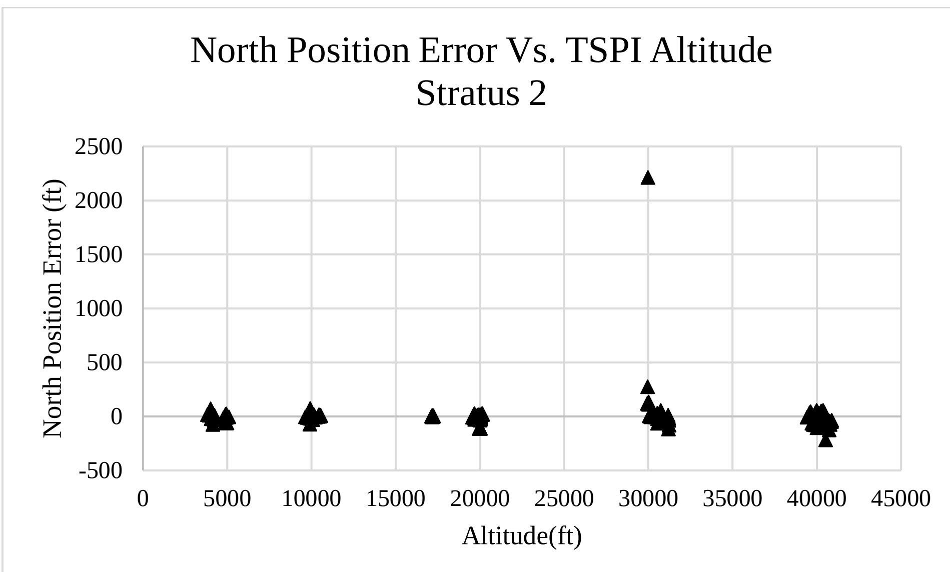

Figure D26: Stratus 2 North Position Error vs TSPI Altitude

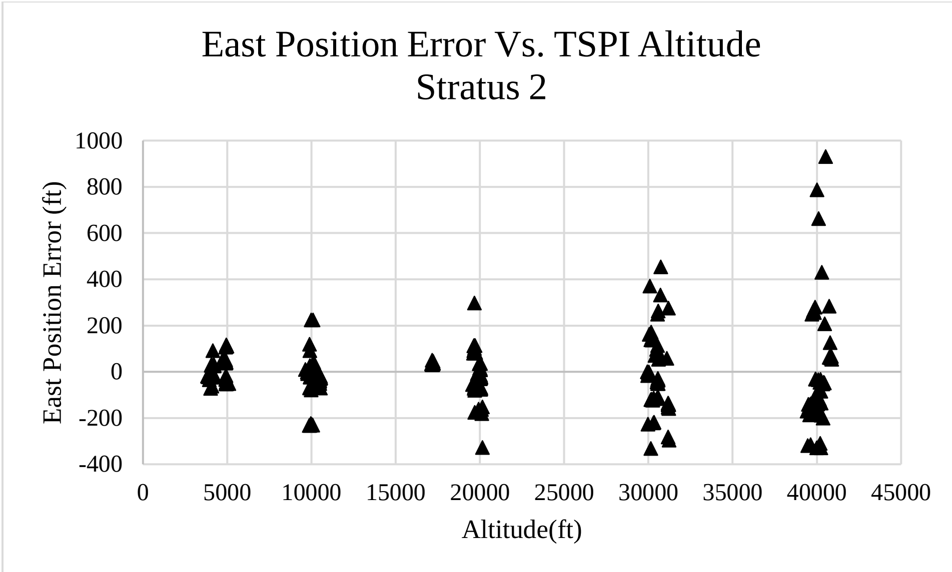

Figure D27: Stratus 2 East Position Error vs TSPI Altitude

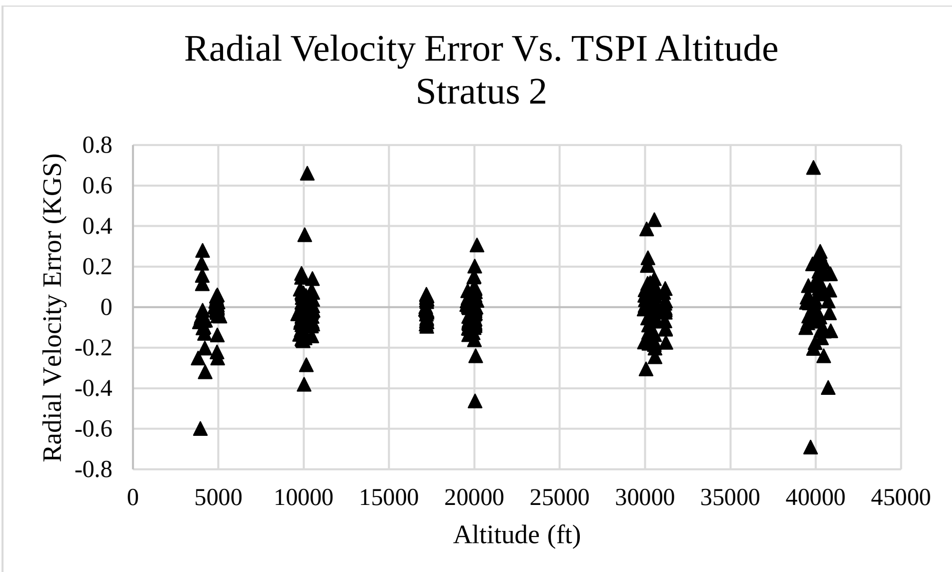

Figure D28: Stratus 2 Radial Velocity Error vs TSPI Altitude

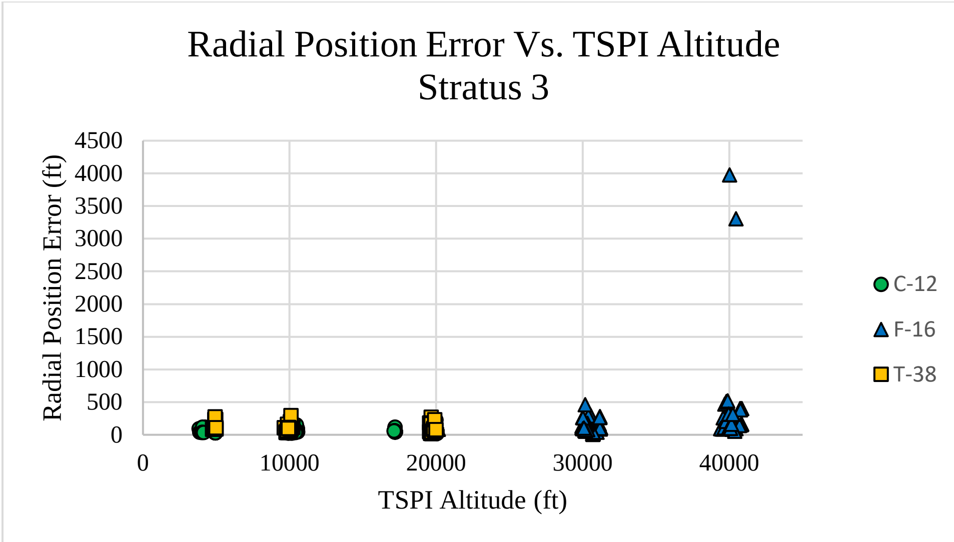

Figure D29: Stratus 3 Radial Position Error vs TSPI Altitude

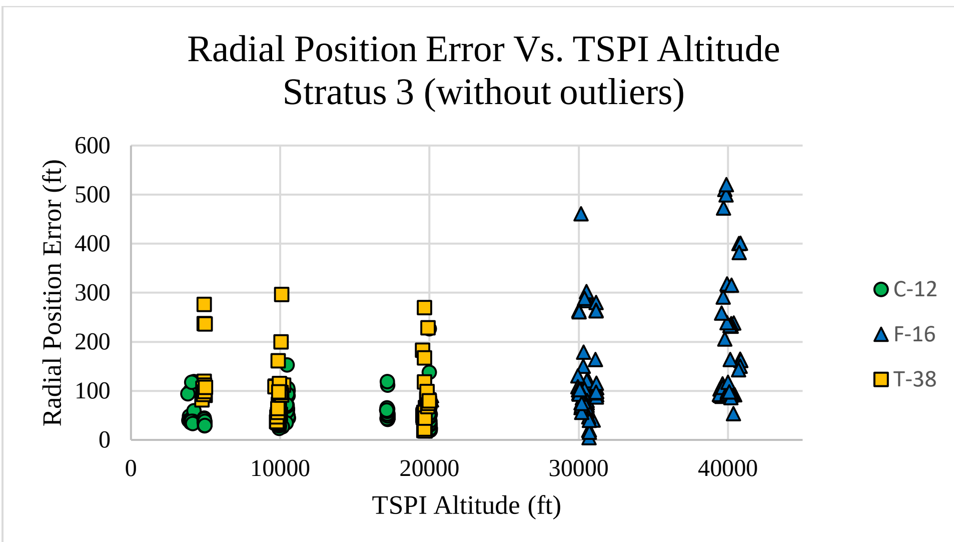

Figure D30: Stratus 3 Radial Position Error vs TSPI Altitude (without outliers)

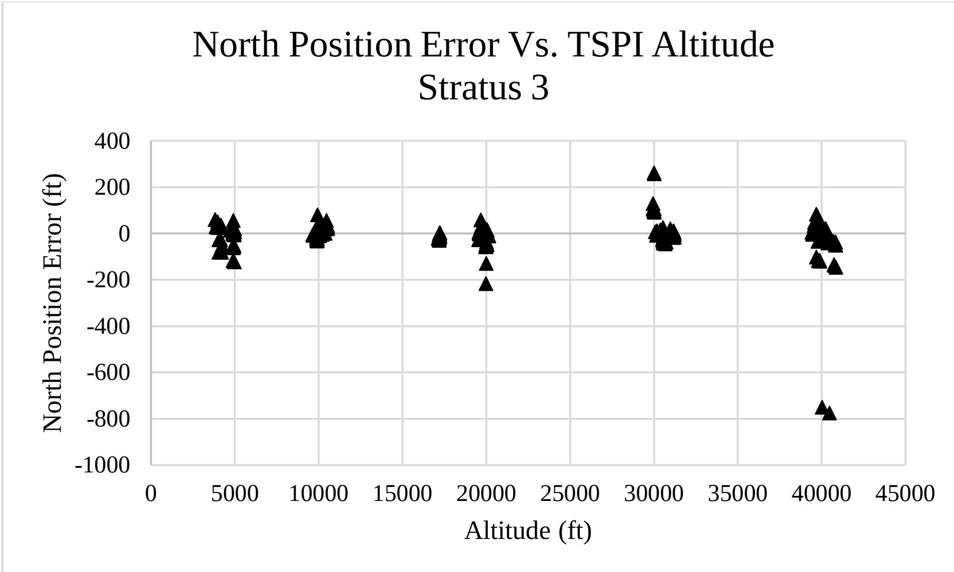

Figure D31: Stratus 3 North Position Error vs TSPI Altitude

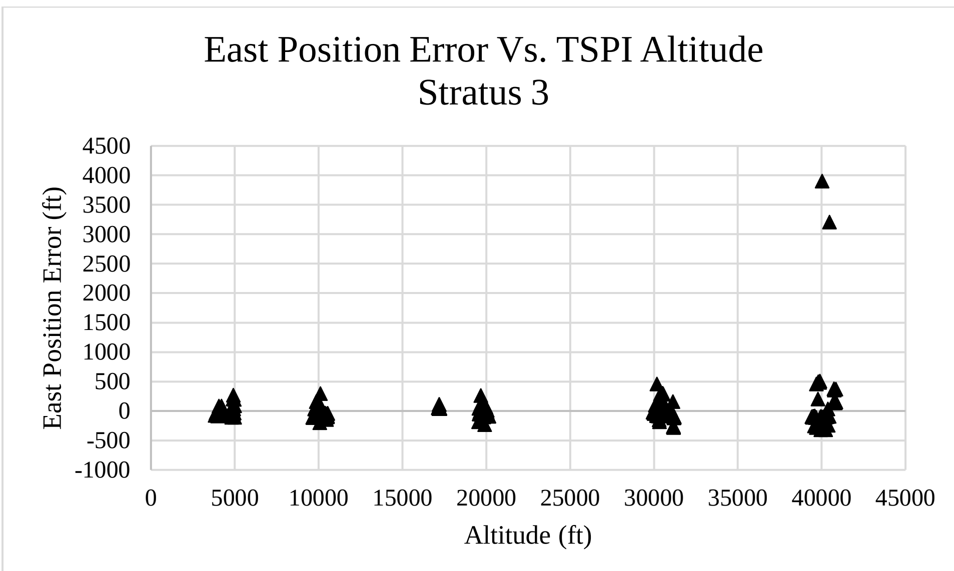

Figure D32: Stratus 3 East Position Error vs TSPI Altitude

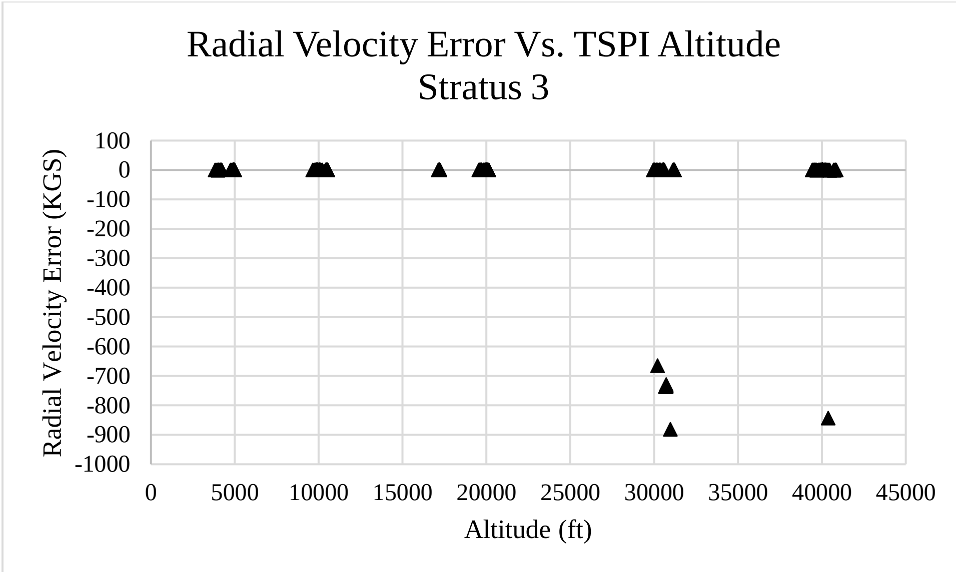

Figure D33: Stratus 3 Radial Velocity Error vs TSPI Altitude

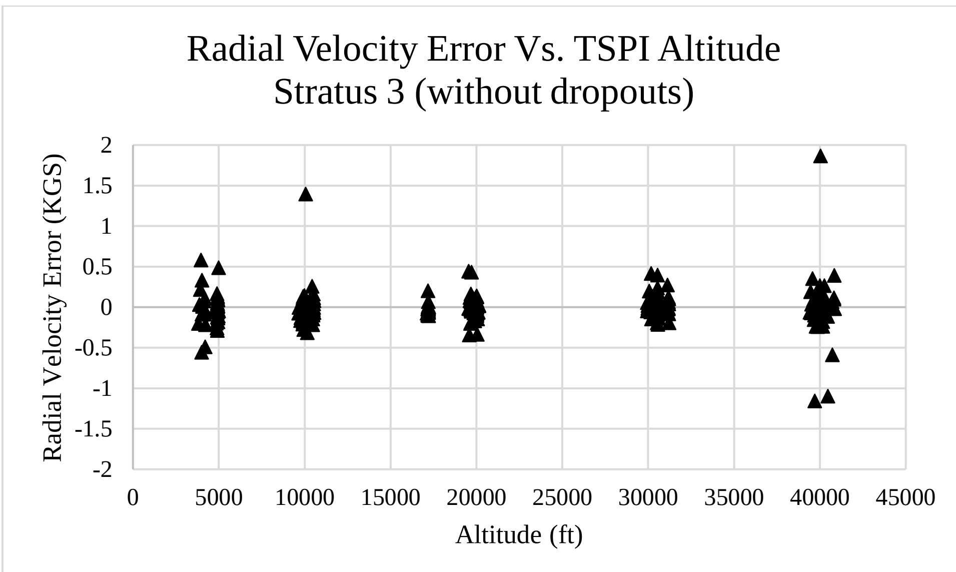

Figure D34: Stratus 3 Radial Velocity Error vs TSPI Altitude (without dropouts)

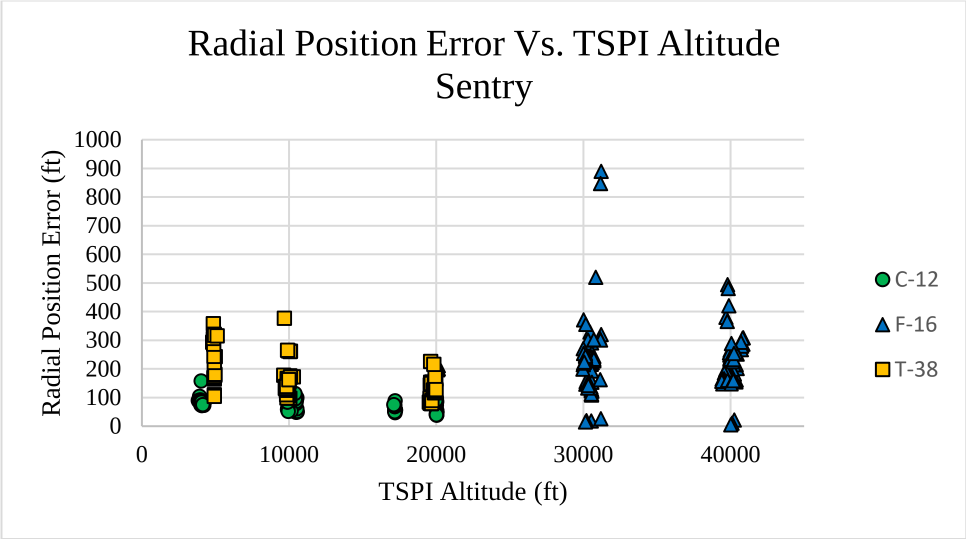

Figure D35: Sentry Radial Position Error vs TSPI Altitude

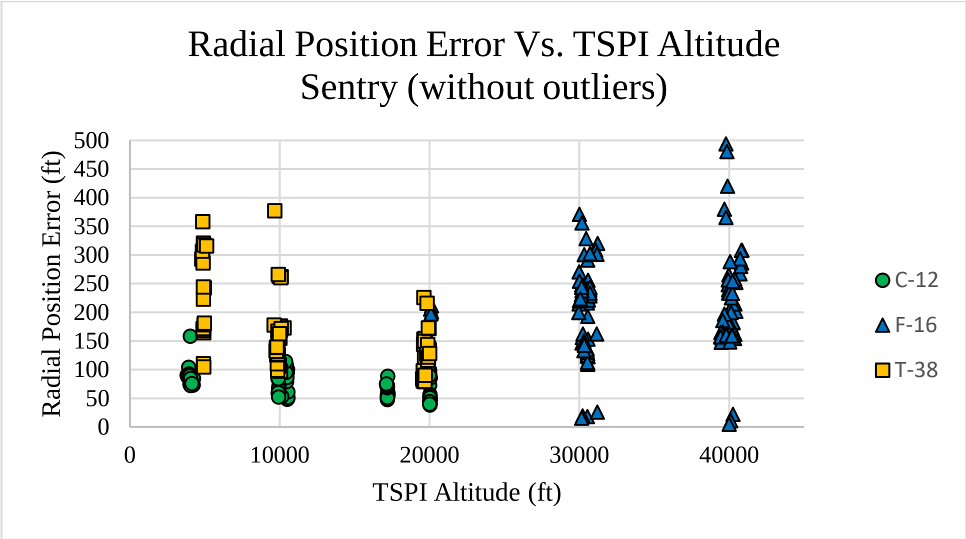

Figure D36: Sentry Radial Position Error vs TSPI Altitude (without outliers)

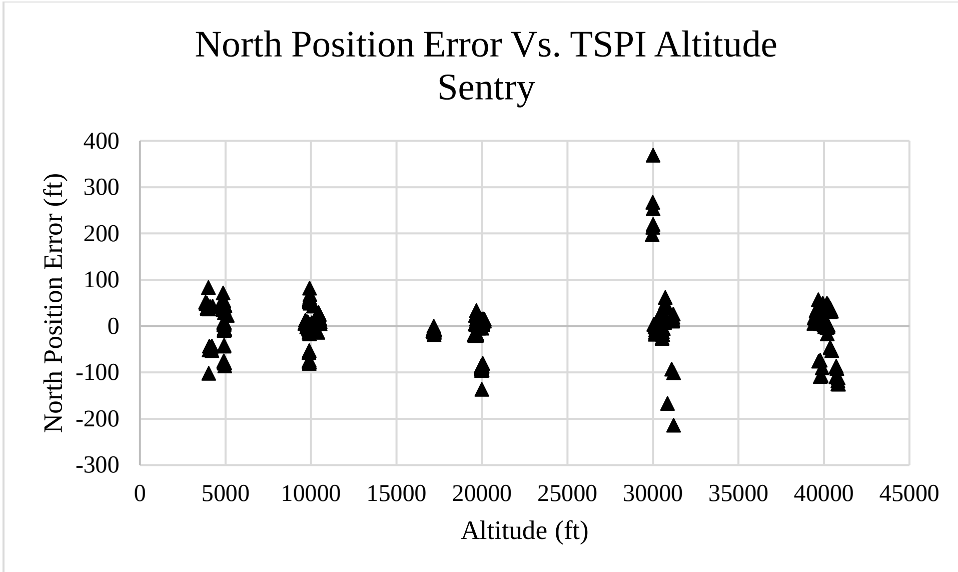

Figure D37: Sentry North Position Error vs TSPI Altitude

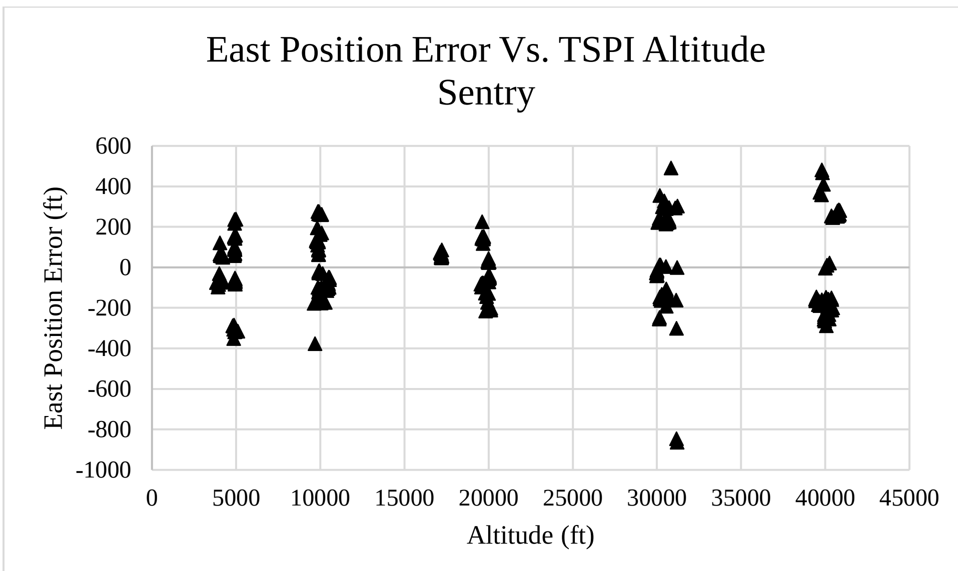

Figure D38: Sentry East Position Error vs TSPI Altitude

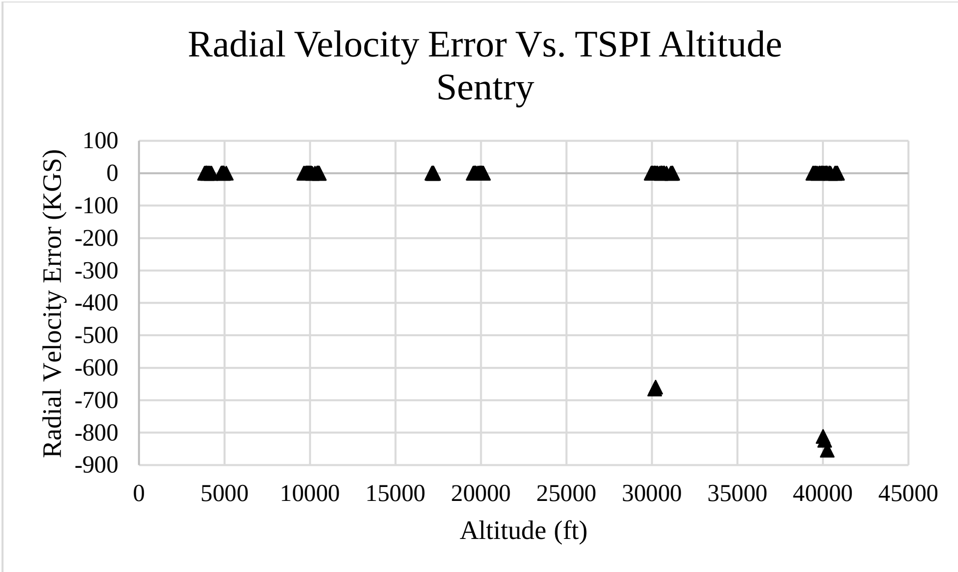

Figure D39: Sentry Radial Velocity Error vs TSPI Altitude

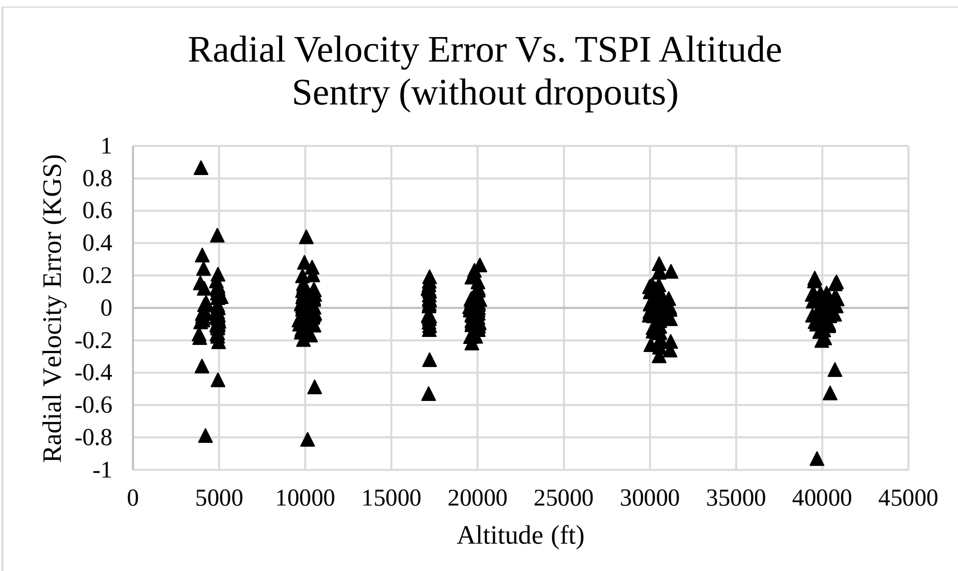

Figure D40: Sentry Radial Velocity Error vs TSPI Altitude (without dropouts)

APPENDIX E – SUPPLEMENTAL DATA POSITION AND VELOCITY ACCURACY

Table E1: SUT RMS Position Error

SUT	North RMS Position Error (ft)	East RMS Position Error (ft)	Vertical RMS Position Error (ft)	Radial RMS Position Error (ft)
Bad Elf	28	31	46	43
Garmin	58	468	NT	472
Pixel	81	43	147	92
iPhone	20	18	32	27
iPad	16	22	69	28
Stratus 2	133	145	17	197
Stratus 3	76	314	24	323
Sentry	56	179	22	187

Table E2: SUT RMS Velocity Error

SUT	RMS Radial Velocity Error (KGS)
Pixel	0.33
iPhone	0.91
iPad	0.64
Stratus 2	0.14
Stratus 3	0.22
Sentry	0.16

Table E3: SUT Upper Confidence Limit Position Error

SUT	North Position 95% Confidence Interval (ft)	East Position 95% Confidence Interval (ft)	Radial Position 95% Confidence Interval (ft)
Bad Elf	71	76	92
Garmin	129	1012	899
Pixel	272	133	267
iPhone	58	49	64
iPad	36	49	53
Stratus 2	467	334	464
Stratus 3	205	912	825
Sentry	128	387	357

Table E4: SUT Upper Confidence Limit Velocity Error

SUT	Radial Velocity 95% Confidence Internal (KGS)
Pixel	0.64
iPhone	2.30
iPad	1.47
Stratus 2	0.28
Stratus 3	0.48
Sentry	0.32

APPENDIX F – HUMAN SYSTEMS INTEGRATION SURVEYS

SUT FOM
Symbology and Imagery
Risk Reduction Data Collection

Pilot Name/Grade: ____
Time/Date:_______________________
Flight/Test No: ___________________A/C Tail No:___________ Mission#: __________________________
Navigation SUT used: _____________________

Please rate the usability of the SUTs self-reported FOM using the following scale. Place the numbers that correspond to your opinions in the RATING column. If an item is not applicable to this mission, write N/A. Please also include comments for any rating of 4 or less.

Very Unsatisfactory	Unsatisfactory	Marginally Unsatisfactory	Marginally Satisfactory	Satisfactory	Very Satisfactory
1	2	3	4	5	6

RATING	FACTOR	DEFINITION
	Format Readability	Is the FOM displayed in a manner that is easily interpretable ?
	Fidelity	Is the FOM provided of sufficient fidelity to be useful?
	Location	Placement of the text and/or symbols on the SUT.
	Jitter / Distortion	Amount of symbology jitter/distortion.
	Feedback	Information provided in the form of cues, symbology, and text of system operation when/if FOM changes.
	Timeliness	Rate at which the FOM is updated

Comments:

SUT Real-time Navigation
Symbology and Imagery
Risk Reduction Data Collection

Pilot Name/Grade: ____

Time/Date:_______________________

Flight/Test No: ___________________A/C Tail No:___________ Mission#: __________________________

Navigation SUT used: _____________________

Please rate the usability of the SUTs symbology and imagery for use in navigation using the following scale. Place the numbers that correspond to your opinions in the RATING column. If an item is not applicable to this mission, write N/A. Please also include comments for any rating of 4 or less.

Very Unsatisfactory	Unsatisfactory	Marginally Unsatisfactory	Marginally Satisfactory	Satisfactory	Very Satisfactory
1	2	3	4	5	6

RATING	FACTOR	DEFINITION
	Format / Readability	Size and shape of the SUT text and symbology.
	Location	Placement of the text and symbols on the SUT.
	Field Of View (FOV)	SUT FOV
	Jitter / Distortion	Amount of symbology jitter/distortion.
	Declutter Levels	The selection and options for SUT on-axis and off-axis symbology declutter.
	Feedback	Information provided in the form of cues, symbology, and text of system operation.
	Location Selection	Ability to cue to the correct location destination using the SUT.
	Location	Ability to verify the correct waypoint was selected using the SUT.
	Data time Lag / Latency	Data on SUT responds without time lag.

Comments:

SUT ADVERSE WEATHER RECOVERY
Risk Reduction Data Collection

Pilot Name/Grade: ____

Time/Date:_______________________

Flight/Test No: ___________________A/C Tail No:___________ Mission#: __________________________

Navigation SUT used: _____________________

Please rate the usability of the SUTs symbology and imagery for use in navigation using the following scale. Place the numbers that correspond to your opinions in the RATING column. If an item is not applicable to this mission, write N/A. Please also include comments for any rating of 4 or less.

Very Unsatisfactory	Unsatisfactory	Marginally Unsatisfactory	Marginally Satisfactory	Satisfactory	Very Satisfactory
1	2	3	4	5	6

RATING	FACTOR	DEFINITION
	Format / Readability	Size and shape of the SUT text and symbology.
	Location	Placement of the text and symbols on the SUT.
	Field Of View (FOV)	SUT FOV
	Jitter / Distortion	Amount of symbology jitter/distortion.
	Declutter Levels	The selection and options for SUT on-axis and off-axis symbology declutter.
	Feedback	Information provided in the form of cues, symbology, and text of system operation.
	Location Selection	Ability to cue to the correct location destination using the SUT.
	Location	Ability to verify the correct waypoint was selected using the SUT.
	Data time Lag / Latency	Data on SUT responds without time lag.

Comments:

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APPENDIX G – HUMAN SYSTEMS INTEGRATION (HSI) SURVEY RESULTS AND PILOT COMMENTS

Table F1: Bad Elf FOM Symbology and Imagery Survey Results

Bad Elf					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	3	6	4.5	4.5	5
Fidelity	5	6	5.6	6	6
Location	3	6	4.2	4	5
Jitter / Distortion	4	6	5.2	5	5
Feedback	1	6	2.8	3	3
Timeliness	5	6	5.3	5	5

Table F2: Garmin D2 Charlie Watch FOM Symbology and Imagery Survey Results

Garmin D2 Charlie Watch					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	2	5	3.6	3	5
Fidelity	1	1	1	1	1
Location	2	5	3.1	3	2
Jitter / Distortion	2	5	4.4	5	5
Feedback	1	5	2.1	2	2
Timeliness	2	5	2.9	3	2

Table F3: Google Pixel FOM Symbology and Imagery Survey Results

Google Pixel					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	1	5	2.3	2	1
Fidelity	1	5	2.4	1	1
Location	1	5	2.5	2	1
Jitter / Distortion	1	5	2.6	2.5	1
Feedback	1	4	1.8	1.5	1
Timeliness	1	4	2.4	2	1

Table F4: iPad FOM Symbology and Imagery Survey Results

iPad					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	6	6	6	6	6
Fidelity	3	6	4.6	5	5
Location	5	6	5.6	6	6
Jitter / Distortion	5	6	5.6	6	6
Feedback	4	6	4.8	5	5
Timeliness	3	6	5.2	5	6

Table F5: iPhone FOM Symbology and Imagery Survey Results

iPhone					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	4	6	5.3	5.5	6
Fidelity	5	6	5.3	5	5
Location	4	6	4.8	4.5	4
Jitter / Distortion	5	6	5.5	5.5	5
Feedback	4	6	5.2	5	5
Timeliness	4	6	5.2	5	5

Table F6: Stratus 2 FOM Symbology and Imagery Survey Results

Stratus 2					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	5	6	5.8	6	6
Fidelity	5	5	5	5	--
Location	4	5	4.3	4	4
Jitter / Distortion	5	6	5.3	5	5
Feedback	5	6	5.5	5.5	5
Timeliness	4	5	4.8	5	5

Table F7: Stratus 3 FOM Symbology and Imagery Survey Results

Stratus 3					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	5	6	5.8	6	6
Fidelity	5	5	5	5	--
Location	4	5	4.3	4	4
Jitter / Distortion	5	6	5.3	5	5
Feedback	5	6	5.5	5.5	5
Timeliness	4	5	4.8	5	5

Table F8: Sentry FOM Symbology and Imagery Survey Results

Sentry					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	6	6	6	6	6
Fidelity	4	5	4.5	4.5	--
Location	4	5	4.7	5	5
Jitter / Distortion	5	5	5	5	5
Feedback	5	6	5.3	5	5
Timeliness	3	5	4	4	--

Table F9: FOM Symbology and Imagery Survey Pilot Comments

Bad Elf	• "Usually carried in your pocket so it's unlikely you will notice what the FOM is. Would be nice if it vibrated as a warning when the FOM goes worse than a certain threshold" • "No color change or warning of changing FOM"
Garmin D2 Charlie	• "Only reported a question mark, very small, uncertain" • "Only observed FOM was a question mark on airplane symbol if GPS was lost, very small and difficult to read with no warnings/updates" • "Font of question mark is same color and size of aircraft on map, hard to see in any lighting" • "No quantitative reading, no idea what a "question mark" really means, low fidelity"
Google Pixel	• "Had to interpret a lot of text, no color changes, liked that gave number of satellites" • "GNPP logger unreadable, unknown how quickly updated and impossible to accurately interpret real time" • "Updated at a fairly frequent rate, showed number of satellites, did not change color or provide warning. FOM of 126.532 m seemed overly specific for purpose and detracted from readability" • "No readable FOM, large text file, unsure of where FOM even was, saw a number of satellites, almost impossible to read and interpret in flight with any accurate understanding"
iPad	• "The only option for FOM appears to be meters. I wish Foreflight would allow feet" • "I like that the color of the FOM changes with accuracy, but wish a warning message would pop up when it went below a certain threshold"
iPhone	• "Small number on bottom of screen" • "Small number on bottom of iPhone screen making it tough to read" • "Its nice that the FOM changes color with accuracy, but I wish it would give a pop up warning message when the accuracy goes worse than a certain threshold"
Stratus 2	• "Small text at bottom of iPad sometimes hard to read"
Stratus 3	• "Small text at bottom of iPad sometimes hard to read"
Sentry	None

Table F10: Bad Elf Real Time Usability Survey Results

Bad Elf					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	3	4	3.7	4	3
Location	4	5	4.3	4	5
Field of View	4	4	4	4	--
Jitter and Distortion	5	5	5	5	5
Declutter Levels	5	5	5	5	--
Feedback	1	3	2.3	3	--
Location Selection	1	1	1	1	--
Location	1	1	1	1	--
Data time Lag / Latency	5	5	5	5	5

Table F11: Garmin Real Time Usability Survey Results

Garmin					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	2	5	2.8	2	2
Location	2	5	3.3	3	2
Field of View	1	4	2.3	2	2
Jitter and Distortion	2	5	4.3	5	5
Declutter Levels	1	4	3	3.5	4
Feedback	1	5	2.5	2	2
Location Selection	3	5	4	4	--
Location	5	5	5	5	--
Data time Lag / Latency	2	5	3.3	3	2

Table F12: Google Pixel Real Time Usability Survey Results

Google Pixel					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	1	3	1.7	1	1
Location	1	4	2	1	1
Field of View	1	3	1.7	1	1
Jitter and Distortion	1	4	3	4	4
Declutter Levels	1	4	2	1	1
Feedback	1	2	1.3	1	1
Location Selection	1	1	1	1	--
Location	1	1	1	1	--
Data time Lag / Latency	1	4	2.3	2	--

Table F13: iPad Real Time Usability Survey Results

iPad					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	5	6	5.4	5	5
Location	5	5	5	5	5
Field of View	5	6	5.2	5	5
Jitter and Distortion	4	6	5.2	5	6
Declutter Levels	4	5	4.6	5	5
Feedback	5	6	5.2	5	5
Location Selection	5	6	5.7	6	--
Location	4	5	4.7	5	--
Data time Lag / Latency	4	5	4.8	5	5

Table F14: iPhone Real Time Usability Survey Results

iPhone					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	4	5	4.6	5	5
Location	3	6	4.7	5	5
Field of View	4	6	5.2	5	--
Jitter and Distortion	5	6	5.1	5	5
Declutter Levels	4	5	4.9	5	5
Feedback	4	6	4.9	5	5
Location Selection	5	6	5.3	5	--
Location	5	6	5.3	5	--
Data time Lag / Latency	3	6	4.6	5	6

Table F15: Stratus 2 Real Time Usability Survey Results

Stratus 2					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	5	6	5.3	5	5
Location	5	6	5.3	5	5
Field of View	4	5	4.3	4	4
Jitter and Distortion	5	6	5.2	5	5
Declutter Levels	4	5	4.8	5	5
Feedback	3	6	4.8	5	5
Location Selection	5	6	5.5	5.5	--
Location	5	6	5.5	5.5	--
Data time Lag / Latency	5	6	5.5	5.5	6

Table F16: Stratus 3 Real Time Usability Survey Results

Stratus 3					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	5	6	5.3	5	5
Location	5	6	5.3	5	5
Field of View	4	5	4.3	4	4
Jitter and Distortion	5	6	5.2	5	5
Declutter Levels	4	5	4.8	5	5
Feedback	3	6	4.8	5	5
Location Selection	5	6	5.5	5.5	--
Location	5	6	5.5	5.5	--
Data time Lag / Latency	4	6	5.3	5.5	6

Table F17: Sentry Real Time Usability Survey Results

Sentry					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	4	6	5.2	5	5
Location	5	6	5.2	5	5
Field of View	4	6	5.2	5	5
Jitter and Distortion	5	6	5.5	5.5	6
Declutter Levels	4	5	4.5	4.5	--
Feedback	3	6	5	5	5
Location Selection	4	6	5.5	6	--
Location	4	6	5.3	5.5	--
Data time Lag / Latency	5	5	5	5	5

Table F18: Real Time Usability and Navigation Survey Pilot Comments

Bad Elf	• "Readability fairly small requiring it be held up to pilot's face" • "Required changing to sub menu to access " • "No color change or additional warning of loss of signal or reduced FOM" • "Updated FOM at a higher rate than most Foreflight devices" • "Horizontal FOM displayed on home screen, to get component errors, had to go through several submenus"
Garmin D2 Charlie	• "Only observed FOM was a question mark on airplane symbol if GPS was lost, very small and difficult to read with no warnings/updates" • "Font of question mark is same color and size of aircraft on map, hard to see in any lighting" • "No quantitative reading, no idea what a "question mark" really means, low fidelity"
Google Pixel	• "Updated a fairly frequent rate, showed number of satellites, did not change color or provide warning. FOM of 126.532 m seemed overly specific for purpose and detracted from readability" • No readable FOM, large text file, unsure of where FOM even was, saw a number of satellites, almost impossible to read and interpret in flight with any accurate understanding"
iPad	• "Standard Foreflight display" • "FOM updated frequently but device consistently showed a worse FOM than other devices" • "Consistently showed 5m FOM at low altitude and when maneuvering"
iPhone	• "Good overlay with planned black line and airspace relationship (similar to Stratus comments). No CDI or course guidance displayed" • "SUT dropped to "NO FIX" and changed to red color with no other warning of degradation" • "Timeliness of updates observed to be up to 30 seconds off" • "Difficult to read in full map mode, still color coded though" • "Did not provide CDI guidance or steering but gave spatial awareness when navigating" • "Smaller size of iPhone relative to other SUTs requires lots of focus to make inputs in flight"
Stratus 2	• "Feedback: pitch and bank angles were wrong; may be due to mounting in RCP; showed 50 degrees nose down and 40 degrees of bank during a 20 degree level turn" • "Feedback - Steering had to be reset after takeoff due to CDI course guidance being from position on ground" • "Feedback - Groundspeed consistently within 1 knot and altitude worst case 30 feet off" • "Format - Showing original direct to point line was useful with restricted airspace overlay. Good awareness for restricted area avoidance" • "Stratus dropped off at high speed (Foreflight crashed with no warning)"
Stratus 3	• "Foreflight closed at high speed but kept recording with no warning" • "Feedback: pitch and bank angles were wrong; may be due to mounting in RCP; showed 50 degrees nose down and 40 degrees of bank during a 20 degree level turn" • "Feedback - Steering had to be reset after takeoff due to CDI course guidance being from position on ground" • "Feedback - Groundspeed consistently within 1 knot and altitude worst case 30 feet off"

	• "Format - Showing original direct to point line was useful with restricted airspace overlay. Good awareness for restricted area avoidance" • "Stratus dropped off at high speed (Foreflight crashed with no warning)"
Sentry	• "Took some research to figure out what format to type coordinates into Foreflight. This would not have been possible to figure out airborne" • "Once the point is entered, its easy to verify its correct on the map" • "Track vector overlaid on nav line made gross course corrections easy, but difficult to do fine corrections without the CDI type display, which only shows up when connected to a device that provides AHRS." • "The attitude display was very erroneous while conducting the point to point navigation. It would be very dangerous to rely on this attitude for unusual attitude recoveries" • "Point to point navigation from takeoff to Honda proving grounds track: due to coordinate entry being cumbersome we entered the point on the ground just prior to takeoff and selected "direct to". The SUT drew a straight line from where we were in the EOR to the point, and did not update after takeoff, so by the time we were airborne turning out of traffic the SUT was attempting to correct us back to the original line rather than an updated heading. We reselected direct to, then it was fine and steered us right down the middle of the Honda track"

Table F19: Stratus 2 Adverse Weather Recovery Survey Results

Stratus 2					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	4	5	4.3	4	4
Location	4	5	4.7	5	5
Field of View	4	6	4.7	4	4
Jitter and Distortion	5	6	5.3	5	5
Declutter Levels	2	4	2.7	2	2
Feedback	1	4	2.3	2	--
Location Selection	5	6	5.3	5	5
Location	5	6	5.3	5	5
Data time Lag / Latency	4	6	5	5	--

Table F20: Stratus 3 Adverse Weather Recovery Survey Results

Stratus 3					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	4	5	4.5	4.5	--
Location	5	5	5	5	5
Field of View	4	4	4	4	4
Jitter and Distortion	5	6	5.5	5.5	--
Declutter Levels	2	3	2.5	2.5	--
Feedback	1	2	1.5	1.5	--
Location Selection	5	6	5.5	5.5	--
Location	5	6	5.5	5.5	--
Data time Lag / Latency	4	6	5	5	--

Table F21: Sentry Adverse Weather Recovery Survey Results

Sentry					
Factor	Min Value	Max Value	Mean	Median	Mode
Format Readability	2	5	3.8	4	--
Location	3	4	3.8	4	4
Field of View	4	6	4.8	4.5	--
Jitter and Distortion	4	6	5	5	5
Declutter Levels	3	4	3.3	3	--
Feedback	1	6	3.3	3	--
Location Selection	4	6	5	5	--
Location	4	6	5	5	--
Data time Lag / Latency	3	6	4.8	5	--

Table F22: Adverse Weather Recovery Survey Pilot Comments

Stratus 2	• " iPad was mounted on leg, which could further contribute to spatial D" • " Pop Up alerts would completely obscure AHRS attitude reference" • "ADS-B info would overlay on top of approach plate making important info unreadable" • " At 60 degrees of bank Stratus lost all attitude information" • "Fairly responsive and accurate bank (up to 30 deg) and pitch (up to 10 deg) when kept small" • "Some minor lagging, maybe 1 second for pitch and half second for roll, but not objectionable" • "Minor lag in AHRS, also paused/glitches for 1-2 seconds" • "Warnings / Advisories would pop up and clutter display" • "Pitch and roll seemed to couple and when rolling into bank pitch would change, would be disorienting in WX" • "Became very cluttered with AHRS, Approach plate, ADS-B traffic" • "Could not read bottom of approach plate without moving plate away from aircraft position"
Stratus 3	• " Lost all attitude information on final, then failed to reconnect for 10 minutes" • "At 45 degrees of bank and level flight Stratus 3 showed aircraft at 30 degrees nose low" • "ADS-B cluttered approach plate to where info was unreadable (non factor traffic) otherwise ADS-B overlays were very useful" • "Pop ups completely obscured AHRS attitude reference" • "AHRS was regularly 10-20 degrees of bank off and 10-30 degrees of pitch off. Poor attitude info made flying approaches uncomfortable" • "Minor lag in AHRS, also paused/glitched for 1-2 seconds" • "Warnings / Advisories would pop up and clutter display" • "Pitch and roll seemed to couple and when rolling into bank pitch would change, would be disorienting in WX" • "Became very cluttered with AHRS, Approach plate, ADS-B traffic" • "Could not read bottom of approach plate without moving plate away from aircraft position"
Sentry	• "Too much info could be displayed (map, approach plate, AHRS, CDI, WX) and caused important info to be displayed in a small size and font" • "Declutter required submenu access which caused more obscuration and was not easily interpretable" • "AHRS would tumble and oscillate up to 30 degrees nose low in level flight. AHRS on glide path would deviate +/- 5 degrees and could be disorienting in the WX" • "Lacked vertical guidance or steering cues which required a lot of pilot interpretation" • "Roll seemed fairly accurate, but pitch was consistently off by 5 deg in both directions" • "At 500' or 2 NM final, large banners appear right on the pitch bars which must be cancelled before disappearing, very SA draining in critical phase of flight" • "Having to reset "direct to" to get a more accurate CDI was a nuisance, too man button pushes required" • "Steerpoint sequencing was too late for an aircraft at fighter speeds, led to massive overshoot"

	• "Became uncomfortable to fly without using aircraft systems to aid in attitude and altitude control" • "Attitude is very erratic and often wrong, not safe to fly off" • "Setting the SUT up for an approach is easy – nice" • "Auto sequencing of points works well" • "Airspeed, position, and altitude were very accurate (matched jet) however, during a climb or descent the altitude lags by up to 200 feet" • "Pop-up messages such as radio freqs and AGL altitude are nice, but position obscured your primary nav display on the SUT" • "One real world traffic warning we encountered was timely and well implemented" • "Terrain color display is very SA-enhancing" • "Hard to reference the bottom of the approach plate without scrolling the map off your current location - I would still want a paper approach plate or a 2nd iPad"

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APPENDIX H – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviation	Definition	Units
ADS-B	Automatic Dependent Surveillance – Broadcast	---
AF	Air Force	---
AFB	Air Force Base	---
AFI	Air Force Instruction	---
AFTO	Air Force technical order	---
AGL	Above Ground Level	---
A-GPS	Assisted GPS	---
AHRS	Attitude Heading Reference System	---
ARDS	Advanced Range Data System	---
App	appendix	---
BDS	BeiDou Navigation System	---
CEP	Circular Error Probable	---
CDI	Course Deviation Indicator	---
COTS	Commerical Off the Shelf	---
DGPS	Differential GPS	---
DoD	Department of Defense	---
DR	deficiency report	---
DTIC	Defense Technical Information Center	---
EAR	Export Administration Regulations	---
Encl	enclosure	---
et seq.	et sequentia	---
i.e.	that is	---
FLEX	Flight Experiment	---
FLTS	flight test squadron	---
FOD	Foreign Object Debris	---
FOM	Figure of Merit	---
FOV	Field of Regard	---
GAINR	GPS Aided Inertial Navigation System	---
GLite	GAINR Lite	---
GLONASS	Global Navigation Satellite System	---
GNSS	Global Navigation Satellite System	---
GPS	Global Positioning System	---
HDOP	Horizontal Dilution of Precision	---
HSI	Human Systems Integration	---
IAF	Initial Approach Fix	---
IMC	Instrument Meteorlogical Conditions	---
IMU	Inertial Measurement Unit	---
KGPS	Kinematic Global Positioning System	---
KGS	Knots Ground Speed	---
KML	Keyhole Markup Language	---
MAJCOM	Major Command	---
IAW	in accordance with	---
ITAR	International Traffic in Arms Regulations	---
NISPOM	National Industrial Security Program Operating Manual	---
NMEA	National Marine Electronics Association	---
NTIS	National Technical Information Service	---
RCP	Rear Cockpit	---
RMS	Root Mean Square	---

SBAS	Satellite Based Augmentation System	---
Sec	section	---
SUT	System Under Test	---
T.O.	technical order	---
TR	technical report	---
TSPI	Time Space and Position Information	---
TW	Test Wing	---
U.S.	United States	---
USAF	United States Air Force	---
U.S.C.	United States Code	---
USMC	United States Marine Core	---
Vol.	volume	---
WAAS	Wide Area Augmentation System	---
XML	Extensible Markup Language	---

APPENDIX I – DISTRIBUTION LIST

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Mr. Chiawei Lee 220 Wolfe Ave Edwards, CA 93523 Email: chiawei.lee@us.af.mil	1	0	1
Total	5	0	5

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APPENDIX J – MANUFACTURER SPECIFICATIONS

Included in this appendix are references to each SUT manufacturer's website containing technical specifications for each SUT. Specifications are summarized here in case these websites are not available in the future.

1. Bad Elf Pro+

https://bad-elf.com/pages/be-gps-2300-detail

PART NUMBER
Model
BE-2300-GPS
GPS SPECIFICATIONS
Accuracy
2.5 meter accuracy[1]
Update Rate
1-10 hZ position update rate
Lock Time
Typically less than 45 seconds
Altitude
60,000ft / 18,000m maximum
Speed
1000mph / 1,600kph maximum
Receiver
66-channel GPS + GLONASS receiver
SBAS
WAAS, EGNOS, MSAS
NMEA
GGA, GSA, GSV, RMC - Talker ID's GP,GL,GN
Storage
~65 hour datalogger memory @ 1hz
COMPATIBILITY
Platforms
iOS, Android, Windows
Mobile App
The Bad Elf GPS App requires iOS 8.0+
Connectivity
Bluetooth SPP, USB Serial
OPERATING SPECIFICATIONS
Battery Powered
14°F to 140°F (-10°C to 60°C)
Externally Powered

-22°F to 140°F (-30°C to 60°C)
Charging Temp
41°F to 113°F (5°C to 45°C)
Storage Temp
-22°F to 140°F (-30°C to 60°C)
PRODUCT SPECIFICATIONS
USB Port
Mini-USB port for charging and ElfPort expansion
Altimeter
Internal Barometer (accuracy ~1 meter)
Display
128x96 dot LCD screen with backlight
Firmware
Field upgradeable via iOS app or via USB
Dimensions
3" x 2.4" x 0.7" (76.5mm x 61.5mm x 17.5mm)
Weight
3.2 oz (90 grams)
PACKAGE CONTENTS
Package Contents
BE-GPS-2300 GPS Pro+ device
3ft (90cm) Mini-USB cable for charging
12-24V DC vehicle USB charger
Detachable Neck Lanyard
User's Manual (downloadable PDF here)

2. Garmin D2 Charlie

https://buy.garmin.com/en-US/US/p/591945

General	
Lens Material	sapphire crystal
Bezel Material	titanium
Case material	fiber-reinforced polymer
QuickFit™ watch band compatible	yes (26 mm)
Strap material	silicone, leather or titanium
Physical size	51 x 51 x 17.5 mm

Display size	1.2" (30.4 mm) diameter
Display resolution	240 x 240 pixels
Display type	sunlight-visible, transflective memory-in-pixel (MIP)
Weight	silicone band: 89 g metal band: 147 g leather band: 95 g
Battery life	Smartwatch mode: Up to 12 days GPS mode: Up to 20 hours UltraTrac™ mode: Up to 35 hours without wrist heart rate
Water rating	10 ATM
Color display	X
Memory/History	16 GB

Clock Features

Time/date	Zulu/UTC, 12/24h, day/date
GPS Time Sync	X
Automatic daylight saving time	X
Alarm clock	X
Timer	X
Stopwatch	X
Sunrise/sunset times	X

Sensors

GPS	X
GLONASS	X

Garmin Elevate™ wrist heart rate monitor	X
Barometric altimeter	X
Compass	X
Accelerometer	X
Thermometer	X

Daily Smart Features

Connectivity	Bluetooth® Smart, ANT+®, Wi-Fi® with sapphire editions
Connect IQ™ (downloadable watch faces, data fields, widgets and apps)	X
Smart notifications	X
Calendar	X
Weather	X
Controls smartphone music	X
Find My Phone	X
Find My Watch	X
VIRB® Camera Remote	X
Smartphone compatibility	iPhone®, Android™
Compatible with Garmin Connect™ Mobile	X

Aviation Features

Worldwide airport database(s)	X
Altimeter with adjustable baro setting	X
3-axis compass with HSI (horizontal situation indicator)	X
Multiple time zones with Zulu/UTC	X

Wirelessly receive flight plans from Garmin Pilot™	X
NEXRAD on moving map	X
Moving Map with aviation airports, navaids, roads, bodies of water and more	X
Waypoint information page	X
Worldwide NAVAID and Intersection database(s)	X

Outdoor Recreation Features

Available outdoor recreation profiles	Hiking, Climbing, Mountain Biking, Skiing, Snowboarding, XC Skiing, Stand Up Paddleboarding, Rowing, Jumpmaster, Tactical
Point-to-point navigation	X
Bread crumb trail in real time	X
Back to start	X
TracBack®	X
UltraTrac mode	X
Around Me mode	X
Elevation profile	X
Distance to destination	X
Barometric trend indicator with Storm Alert	X
Trail run auto climb	X
Vertical speed	X
Total ascent/descent	X
Future elevation plot	X

Preloaded topographical maps	X
Downloadable cartography support	X
Compatible with BaseCamp™	X
GPS coordinates	X
Projected waypoint	X
Sight 'N Go	X
Area calculation	yes (via Connect IQ™)
Hunt/fish calendar	yes (via Connect IQ™)
Sun and moon information	yes (via Connect IQ™)
Dual grid coordinates	X
Connectivity	
Smartphone compatibility	iPhone®, Android™

3. iPad mini 4

https://support.apple.com/kb/sp725?locale=en_US

Finish

- Silver
- Gold
- Space Gray

Capacity[1]

- **Wi-Fi models**
  - 16GB
  - 32GB
  - 64GB
  - 128GB
- **Wi-Fi + Cellular models**
  - 16GB

- 32GB
- 64GB
- 128GB

Buttons and Connectors

- Built-in stereo speakers
- Lightning connector
- Home/Touch ID sensor
- 3.5 mm headphone jack
- On/Off - Sleep/Wake
- Dual microphones
- Volume up/down
- Nano-SIM tray (cellular models)

Weight and Dimensions[2]

- **Wi-Fi models**
  - Height: 8.0 inches (203.2 mm)
  - Width: 5.3 inches (134.8 mm)
  - Depth: 0.24 inch (6.1 mm)
  - Weight: 0.65 pound (298.8 grams)
- **Wi-Fi + Cellular models**
  - Height: 8.0 inches (203.2 mm)
  - Width: 5.3 inches (134.8 mm)
  - Depth: 0.24 inch (6.1 mm)
  - Weight: 0.67 pound (304 grams)

In the Box

- iPad mini 4
- Lightning to USB Cable
- USB Power Adapter

Display

- **Retina display**

  7.9-inch (diagonal) LED-backlit Multi-Touch display
  2048-by-1536 resolution at 326 pixels per inch (ppi)
  Fingerprint-resistant oleophobic coating
  Fully laminated display
  Antireflective coating

Chip

- A8 chip with 64-bit architecture
- M8 motion coprocessor

Camera

- 8MP camera
- Autofocus
- Panorama (up to 43MP)

- Auto HDR for photos
- Exposure control
- Burst mode
- Tap to focus
- Timer mode
- ƒ/2.4 aperture
- Five-element lens
- Hybrid IR filter
- Backside illumination
- Auto image stabilization
- Face detection
- Photo geotagging

Video Recording

- 1080p HD video recording (30 fps)
- Slo-mo (120 fps)
- Time-lapse video with stabilization
- Video image stabilization
- Improved face detection
- 3x video zoom
- Video geotagging

FaceTime HD Camera

- 1.2MP photos
- ƒ/2.2 aperture
- 720p HD video recording
- Backside illumination
- Auto HDR photos and videos
- Improved face detection
- Burst mode
- Exposure control
- Timer mode

FaceTime Calling[3]

- FaceTime audio to any FaceTime-enabled device over Wi-Fi or cellular
- FaceTime video to any FaceTime-enabled device over Wi-Fi or cellular

Microphones

- Dual microphones for calls, video recording, and audio recording

Cellular and Wireless

- **Wi-Fi models**
  Wi-Fi (802.11a/b/g/n/ac); dual band (2.4GHz and 5GHz); HT80 with MIMO
  Bluetooth 4.2 technology

- **Wi-Fi + Cellular models**

  Wi-Fi (802.11a/b/g/n/ac); dual band (2.4GHz and 5GHz); HT80 with MIMO
  Bluetooth 4.2 technology
  UMTS/HSPA/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz); GSM/EDGE (850, 900, 1800, 1900 MHz)
  CDMA EV-DO Rev. A and Rev. B (800, 1900 MHz)
  LTE (Bands 1, 2, 3, 4, 5, 7, 8, 13, 17, 18, 19, 20, 25, 26, 28, 29, 38, 39, 40, 41)[4]
  Data only[5]
  Wi-Fi calling[4]
  Includes Apple SIM

SIM Card

- Nano-SIM (supports Apple SIM)

Location

- **All models**
  - Digital compass
  - Wi-Fi
  - iBeacon microlocation
- **Wi-Fi + Cellular models**
  - Assisted GPS and GLONASS
  - Cellular

Sensors

- Touch ID
- Three-axis gyro
- Accelerometer
- Barometer
- Ambient light sensor

Touch ID

- Unlock iPad
- Secure personal data within apps
- Make purchases from the iTunes Store, the App Store, and Apple Books

Apple Pay

- Pay with your iPad using Touch ID within apps and on the web

Siri[6]

- Use your voice to send messages, set reminders, and more
- Use your iPad hands-free
- Listen and identify songs

Power and Battery[7]

- **All models**
  - Built-in 19.1-watt-hour rechargeable lithium-polymer battery

- Up to 10 hours of surfing the web on Wi-Fi, watching video, or listening to music
- Charging via power adapter or USB to computer system

- **Wi-Fi + Cellular models**
  - Up to 9 hours of surfing the web using cellular data network

Operating System

iOS 12

iOS is the world's most personal and secure mobile operating system, packed with powerful features that help you get the most out of every day.

Accessibility

Accessibility features help people with disabilities get the most out of their new iPad mini 4. With built-in support for vision, hearing, physical and motor skills, and learning and literacy, you can create and do amazing things.

Features include:

- VoiceOver
- Zoom
- Magnifier
- Siri and Dictation
- Switch Control
- Closed Captions
- AssistiveTouch
- Speak Screen

System Requirements

- Apple ID (required for some features)
- Internet access[8]

Syncing with iTunes on a Mac or PC requires:

- Mac: OS X 10.9.5 or later
- PC: Windows 7 or later
- iTunes 12.5 or later (free download from www.itunes.com/download)

Audio Playback

- Audio formats supported: AAC (8 to 320 Kbps), Protected AAC (from iTunes Store), HE-AAC, MP3 (8 to 320 Kbps), MP3 VBR, Dolby Digital

(AC-3), Dolby Digital Plus (E-AC-3), Audible (formats 2, 3, 4, Audible Enhanced Audio, AAX, and AAX+), Apple Lossless, AIFF, and WAV

- User-configurable maximum volume limit

TV and Video

- AirPlay Mirroring, photos, audio, and video out to Apple TV (2nd generation or later)
- Video mirroring and video out support: Up to 1080p through Lightning Digital AV Adapter and Lightning to VGA Adapter (adapters sold separately)
- Video formats supported: H.264 video up to 4K, 30 frames per second, High Profile level 4.2 with AAC-LC audio up to 160 Kbps, 48kHz, stereo audio or Dolby Audio up to 1008 Kbps, 48kHz, stereo or multichannel audio, in .m4v, .mp4, and .mov file formats; MPEG-4 video up to 2.5 Mbps, 640 by 480 pixels, 30 frames per second, Simple Profile with AAC-LC audio up to 160 Kbps per channel, 48kHz, stereo audio or Dolby Audio up to 1008 Kbps, 48kHz, stereo or multichannel audio, in .m4v, .mp4, and .mov file formats; Motion JPEG (M-JPEG) up to 35 Mbps, 1280 by 720 pixels, 30 frames per second, audio in ulaw, PCM stereo audio in .avi file format

Mail Attachment Support

- **Viewable document types**
  .jpg, .tiff, .gif (images); .doc and .docx (Microsoft Word); .htm and .html (web pages); .key (Keynote); .numbers (Numbers); .pages (Pages); .pdf (Preview and Adobe Acrobat); .ppt and .pptx (Microsoft PowerPoint); .txt (text); .rtf (rich text format); .vcf (contact information); .xls and .xlsx (Microsoft Excel); .zip; .ics

Environmental Requirements

- Operating ambient temperature: 32° to 95° F (0° to 35° C)
- Nonoperating temperature: −4° to 113° F (−20° to 45° C)
- Relative humidity: 5% to 95% noncondensing
- Operating altitude: tested up to 10,000 feet (3000 m)

4. iPhone XS

https://www.apple.com/iphone-xs/specs/

iPhone XS
iPhone XS Max
Finish
Gold, Space Gray, Silver

Gold, Space Gray, Silver
Capacity[1]

- 64GB
- 256GB
- 512GB
- 64GB
- 256GB
- 512GB

Size and Weight[2]
Width:
2.79 inches
(70.9 mm)
Height:
5.65 inches
(143.6 mm)
Depth:
0.30 inch
(7.7 mm)
Weight:
6.24 ounces (177 grams)
Width:
3.05 inches
(77.4 mm)
Height:
6.20 inches
(157.5 mm)
Depth:
0.30 inch
(7.7 mm)
Weight:
7.34 ounces (208 grams)
Display

- Super Retina HD display
- 5.8-inch (diagonal) all-screen OLED Multi-Touch display
- HDR display
- 2436-by-1125-pixel resolution at 458 ppi
- 1,000,000:1 contrast ratio (typical)

The iPhone XS display has rounded corners that follow a beautiful curved design, and these corners are within a standard rectangle. When measured as a standard rectangular shape, the screen is 5.85 inches diagonally (actual viewable area is less).

- Super Retina HD display
- 6.5-inch (diagonal) all-screen OLED Multi-Touch display
- HDR display
- 2688-by-1242-pixel resolution at 458 ppi

- 1,000,000:1 contrast ratio (typical)
  The iPhone XS Max display has rounded corners that follow a beautiful curved design, and these corners are within a standard rectangle. When measured as a standard rectangular shape, the screen is 6.46 inches diagonally (actual viewable area is less).
  Both models:
- True Tone display
- Wide color display (P3)
- 3D Touch
- 625 cd/m2 max brightness (typical)
- Fingerprint-resistant oleophobic coating
- Support for display of multiple languages and characters simultaneously
  Splash, Water, and Dust Resistant[3]
  Rated IP68 (maximum depth of 2 meters up to 30 minutes) under IEC standard 60529
  Chip
- A12 Bionic chip
- Next-generation Neural Engine
  Camera
- Dual 12MP wide-angle and telephoto cameras
- Wide-angle: ƒ/1.8 aperture
- Telephoto: ƒ/2.4 aperture
- 2x optical zoom; digital zoom up to 10x
- Portrait mode with advanced bokeh and Depth Control
- Portrait Lighting with five effects (Natural, Studio, Contour, Stage, Stage Mono)
- Dual optical image stabilization
- Six-element lens
- Quad-LED True Tone flash with Slow Sync
- Panorama (up to 63MP)
- Sapphire crystal lens cover
- Backside illumination sensor
- Hybrid IR filter
- Autofocus with Focus Pixels
- Tap to focus with Focus Pixels
- Smart HDR for photos
- Wide color capture for photos and Live Photos
- Local tone mapping
- Advanced red-eye correction
- Exposure control
- Auto image stabilization
- Burst mode
- Timer mode
- Photo geotagging
- Image formats captured: HEIF and JPEG
  Video Recording
- 4K video recording at 24 fps, 30 fps, or 60 fps

- 1080p HD video recording at 30 fps or 60 fps
- 720p HD video recording at 30 fps
- Extended dynamic range for video up to 30 fps
- Optical image stabilization for video
- 2x optical zoom; digital zoom up to 6x
- Quad-LED True Tone flash
- Slo-mo video support for 1080p at 120 fps or 240 fps
- Time-lapse video with stabilization
- Cinematic video stabilization (1080p and 720p)
- Continuous autofocus video
- Take 8MP still photos while recording 4K video
- Playback zoom
- Video geotagging
- Video formats recorded: HEVC and H.264
- Stereo recording

TrueDepth Camera

- 7MP camera
- ƒ/2.2 aperture
- Portrait mode with advanced bokeh and Depth Control
- Portrait Lighting with five effects (Natural, Studio, Contour, Stage, Stage Mono)
- Animoji and Memoji
- 1080p HD video recording at 30 fps or 60 fps
- Smart HDR for photos
- Extended dynamic range for video at 30 fps
- Cinematic video stabilization (1080p and 720p)
- Wide color capture for photos and Live Photos
- Retina Flash
- Backside illumination sensor
- Auto image stabilization
- Burst mode
- Exposure control
- Timer mode

Face ID

Enabled by TrueDepth camera for facial recognition

Apple Pay

- Pay with your iPhone using Face ID in stores, within apps, and on the web
- Send and receive money in Messages
- Complete purchases made with Apple Pay on your Mac

Carriers

AT&T

Sprint

T-Mobile

Verizon

Cellular and Wireless

Model A1920*

- FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 12, 13, 14, 17, 18, 19, 20, 25, 26, 29, 30, 32, 66, 71)
- TD-LTE (Bands 34, 38, 39, 40, 41, 46)
- CDMA EV-DO Rev. A (800, 1900 MHz)
- UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz)
- GSM/EDGE (850, 900, 1800, 1900 MHz)

Model A1921*

- FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 12, 13, 14, 17, 18, 19, 20, 25, 26, 29, 30, 32, 66, 71)
- TD-LTE (Bands 34, 38, 39, 40, 41, 46)
- CDMA EV-DO Rev. A (800, 1900 MHz)
- UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz)
- GSM/EDGE (850, 900, 1800, 1900 MHz)

All models

- Gigabit-class LTE with 4x4 MIMO and LAA[4]
- 802.11ac Wi-Fi with 2x2 MIMO
- Bluetooth 5.0 wireless technology
- NFC with reader mode
- Express Cards with power reserve

Location

- Assisted GPS, GLONASS, Galileo, and QZSS
- Digital compass
- Wi-Fi
- Cellular
- iBeacon microlocation

Video Calling[5]

- FaceTime video calling over Wi-Fi or cellular

Audio Calling[5]

- FaceTime audio
- Voice over LTE (VoLTE)[4]
- Wi-Fi calling[4]

Audio Playback

- Audio formats supported: AAC-LC, HE-AAC, HE-AAC v2, Protected AAC, MP3, Linear PCM, Apple Lossless, FLAC, Dolby Digital (AC-3), Dolby Digital Plus (E-AC-3), and Audible (formats 2, 3, 4, Audible Enhanced Audio, AAX, and AAX+)
- Wider stereo playback
- User-configurable maximum volume limit

Video Playback

- Video formats supported: HEVC, H.264, MPEG-4 Part 2, and Motion JPEG
- High Dynamic Range with Dolby Vision and HDR10 content
- AirPlay Mirroring, photos, and video out to Apple TV (2nd generation or later)[6]
- Video mirroring and video out support: Up to 1080p through Lightning Digital AV Adapter and Lightning to VGA Adapter (adapters sold separately)[6]

Siri[7]

- Use your voice to send messages, set reminders, and more

- Get intelligent suggestions on your Lock screen and in Messages, Mail, QuickType, and more
- Activate hands-free with only your voice using “Hey Siri”
- Use your voice to run shortcuts from your favorite apps

External Buttons and Connectors
Volume up/down
Ring/Silent
Side button
Built-in stereo speaker
Lightning connector
Built-in microphones
Built-in stereo speaker
Built-in microphone
Power and Battery[8]
Lasts up to 30 minutes longer than iPhone X
Talk time (wireless):
Up to 20 hours
Internet use:
Up to 12 hours
Video playback (wireless):
Up to 14 hours
Audio playback (wireless):
Up to 60 hours
Fast-charge capable:
Up to 50% charge in 30 minutes[9]
with 18W adapter or higher (available separately)
Lasts up to 1.5 hours longer than iPhone X
Talk time (wireless):
Up to 25 hours
Internet use:
Up to 13 hours
Video playback (wireless):
Up to 15 hours
Audio playback (wireless):
Up to 65 hours
Fast-charge capable:
Up to 50% charge in 30 minutes[9]
with 18W adapter or higher (available separately)
Both models:

- Built-in rechargeable lithium-ion battery
- Wireless charging (works with Qi chargers[10])
- Charging via USB to computer system or power adapter

Sensors

- Face ID
- Barometer

- Three-axis gyro
- Accelerometer
- Proximity sensor
- Ambient light sensor

Operating System
iOS 12
iOS is the world's most personal and secure mobile operating system, packed with powerful features that help you get the most out of every day.
Accessibility
Accessibility features help people with disabilities get the most out of their new iPhone XS. With built-in support for vision, hearing, physical and motor skills, and learning and literacy, you can fully enjoy the world's most personal device. Learn more
Features include:

- VoiceOver
- Zoom
- Magnifier
- RTT and TTY support
- Siri and Dictation
- Type to Siri
- Switch Control
- Closed Captions

5. Google Pixel 3

https://store.google.com/us/product/pixel_3_specs?hl=en-US

Tech specs
Operating System
Latest Android 9 Pie + Google Assistant
Display
Fullscreen 5.5" display or 6.3" display
Cameras
12.2MP dual-pixel
Processors
Qualcomm® Snapdragon™ 845
Memory & Storage
4GB RAM
Dimensions & Weight
Pixel 3
Length: 5.7 in (145.6 mm)
Width: 2.7 in (68.2mm)
Height: 0.3 in (7.9 mm)
Weight

148 g
Pixel 3 XL
Length: 6.2 in (158.0 mm)
Width: 3.0 in (76.7 mm)
Height: 0.3 in (7.9 mm)
Weight
184 g
Colors
Clearly White • Just Black • Not Pink
Media & Audio
Dual front-firing stereo speakers
Battery
Pixel 3: 2915 mAh battery • Pixel 3 XL: 3430 mAh battery + Qi wireless charging
Wireless & Location
Wi-Fi 5.0GHz • Bluetooth® 5.0
Network
World-wide network/carrier compatibility

Sensors
Active Edge™
Ports
USB Type-C™ USB
Materials
Aluminum frame + hybrid coating
AR/VR
Built for VR to work with Google Daydream View headset
What's in the box
Pixel 3 or Pixel 3 XL
Quick Switch Adapter
USB-C to USB-C cable
USB-C 18W Power adapter
Pixel USB-C earbuds
USB-C to 3.5mm headphone adapter
SIM tool
Quick Start Guide

GNSS Logger Application:

https://github.com/google/gps-measurement-tools

6. Stratus 2S

https://www.appareo.com/wp-content/uploads/2018/10/600890-000050-Stratus-1S-and-2S-Pilots-Guide-PDF.pdf

ABOUT STRATUS 1S/2S

Stratus 1S and 2S are battery-operated portable receivers that work in conjunction with the ForeFlight Mobile app. They provide pilots with subscription-free in-flight weather and traffic and are a source of

accurate Wide Area Augmentation System (WAAS) GPS position. They receive Automatic Dependent Surveillance-Broadcast (ADS-B) weather information (FIS-B), traffic information (TIS-B), and other related data and broadcast it to ForeFlight Mobile via a Wi-Fi network.

Stratus 2S is also an attitude heading reference system (AHRS), flight data recorder, and pressure altitude sensor. See pages 17 and 18 for more information about these features.

These receivers are classified as Personal Electronic Devices (PEDs) and complement the instrument panel in your aircraft. If there is a discrepancy between a receiver and the instrument panel, use the readings on your instrument panel.

ABOUT FOREFLIGHT

Stratus receivers work exclusively with the ForeFlight Mobile app to display the information collected by the receivers. For more information about any of the features available through ForeFlight Mobile, refer to the ForeFlight Mobile Pilot's Guide, which is available within the app or at the ForeFlight Mobile website.

Feature	1	2
AHRS		X
Pressure Altitude Sensor		X
978 MHz weather and traffic	X	X
1090 MHz traffic		X
Flight data recording		X
WAAS GPS	X	X
Remote GPS antenna (optional)		X
Remote ADS-B antenna (optional)	X	X

7. Stratus 3

https://www.appareo.com/aviation/stratus-product-line/stratus-ads-b-receivers/

Specifications

ADS-B WEATHER	**Yes**
ADS-B TRAFFIC	**Dual Band**

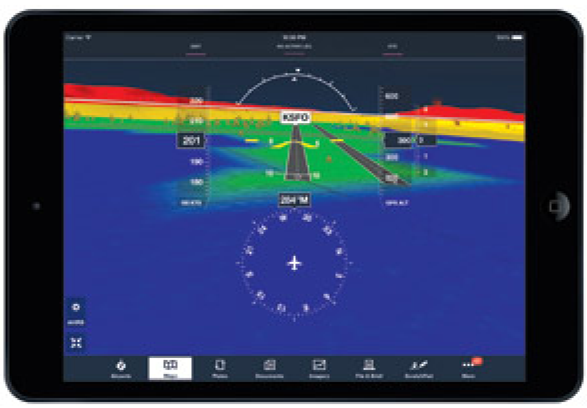
AHRS (ATTITUDE)	**Yes**
ANTENNA	**Internal**
BATTERY LIFE	**8 hours**
BUILT-IN BATTERY	**Yes**
COMPATIBLE APPS	**ForeFlight, Fltplan Go, FlyQ, WingX, iFly GPS**
CONNECTION	**Wifi**
WAAS GPS	**Yes**

New Features:

- Low price - save $200 over Stratus 2S without sacrificing features
- Auto shutoff - Stratus 3 automatically turns off after your flight, saving battery life
- Smart WiFi - use your iPad's LTE connection with non-aviation apps while connected to Stratus 3
- Improved WiFi security - hide network ID or add a password
- Open ADS-B - works with other electronic flight bag apps using GDL 90 protocol
- Receives new ADS-B products - view echo tops, lightning, icing forecast, turbulence forecast, Center Weather Advisories, and G-AIRMETs
- Supports synthetic vision traffic display - get a 3D view of nearby airplanes in ForeFlight
- Two year warranty - helpful, friendly service from our team of pilots

SUBSCRIPTION-FREE IN-FLIGHT WEATHER

You can view in-flight weather on your iPad, including NEXRAD radar, METARs, TAFs, TFRs, AIRMETs, SIGMETs, NOTAMs and more. It's updated every 5-10 minutes and there are no subscription fees – ever. Plus, Stratus Replay allows you to turn off the iPad screen in flight and save battery; when you turn the screen on again, Stratus will automatically send all the weather information you missed. This can double your iPad's battery life.



STUNNING SYNTHETIC VISION DISPLAY

ForeFlight's Synthetic Vision feature rewrites the book on situational awareness. With luminous terrain, night sky view, hands-free declutter, and a brilliant obstacle awareness system, ForeFlight with Synthetic Vision will forever change the way you fly. With Stratus 3, ForeFlight's synthetic vision really comes alive. The built-in AHRS drives a super responsive pitch and bank instrument in the center of the Synthetic Vision view. In an emergency situation, you've got a backup glass cockpit on your iPad.

DUAL BAND ADS-B TRAFFIC

Stratus 3 includes a dual band (978 MHz and 1090 MHz) ADS-B receiver so it can display traffic information right on the ForeFlight Maps page. See relative altitude, climb/descent rate and projected track. Picks up all aircraft equipped with ADS-B Out as well all aircraft equipped with Mode C transponders. Note: ADS-B traffic is limited if your aircraft does not have ADS-B Out installed in the panel.

INTERNAL WAAS GPS

With the built-in WAAS GPS receiver, Stratus allows you to view moving maps, track up displays and high resolution terrain maps in ForeFlight. The smart GPS locks on fast and typically provides 1 meter accuracy. Replaces the need for a separate GPS receiver - Stratus has it all!

BUILT-IN AHRS FOR BACKUP ATTITUDE

Stratus includes a complete Attitude Heading Reference System (AHRS) for backup attitude information in the cockpit. It aligns itself automatically, so you can just turn it on and fly - no complicated calibration. Now you can view a backup attitude indicator, GPS groundspeed and altitude on your iPad in a beautiful split screen mode right in ForeFlight. (Not to be used for primary reference.)

FLIGHT DATA RECORDER

Stratus is the first ADS-B receiver to offer a complete flight data recorder system. When this is enabled, Stratus automatically records your flight - complete with GPS position, altitude, speed and attitude. Flight logs are saved in ForeFlight, and can be viewed online, in Google Earth or in the CloudAhoy app. Ideal for proficiency flights and CFIs.

PRESSURE ALTITUDE SENSOR

With its built-in barometric pressure sensor, Stratus 3 allows ForeFlight to display both pressure altitude and GPS altitude. Plus, ForeFlight’s automatic Cabin Pressure Advisor alerts you when you might need oxygen by flashing a message anytime cabin altitude exceeds 12,000 or 25,000 ft - perfect for turbocharged or pressurized airplanes.

TFR ALERTS

Stratus 3 receives updated information about temporary flight restrictions (TFRs) from the ADS-B network, so you can avoid a costly mistake. Simply turn on the TFR layer in ForeFlight and you'll see red circles on the moving map display. Tap on each TFR for details and effective times. Note: TFR information may not be comprehensive; check with Flight Service or ATC for complete details.

EXTERNAL ANTENNA PORTS

For added convenience, Stratus 3 includes options for external GPS and ADS-B antennas (sold separately). This is ideal for experimental aircraft owners who may want to permanently install Stratus or for anyone who needs to remote mount Stratus. Simply connect the GPS, ADS-B, and power cables and Stratus can be placed almost anywhere.

NOTES

- WiFi connection allows 5 iPads and/or iPhones to connect to Stratus simultaneously.
- ADS-B coverage varies by location and altitude – does not work on the ground in most locations. Coverage not available outside US.
- Comes with charging cable and 110V wall plug; charging cable works with all 2.1 amp cigarette lighter plugs as well (sold separately).
- Also includes non-slip dash mount and pilot's guide.
- GDL 90 support tested with Fltplan Go, FlyQ, WingX, and iFly GPS.
- To enable Open ADS-B mode, download the Stratus Horizon Pro app
- For fleet sales, please contact ForeFlight at sales@foreflight.com

8. Sentry

http://flywithsentry.com/

	Sentry
Price	**$499**

	Sentry
FIS-B	✓
Dual-band Traffic	✓
WAAS GPS with Multi-Constellation Support	✓
Backup Attitude (AHRS)	✓
Internal Battery	✓ (12+ hours)
Firmware Updates Through ForeFlight	✓
Weather Replay	✓
Barometer (for Pressure Altitude)	✓

	Sentry
Flight Data Recorder	Coming in a Future App Release
CO Monitor	✓
Device Management	✓
Optional Remote ADS-B or GPS Antenna	
Power-On Support	
Connector	USB Type C
Connection	Wi-Fi
In The Box	Suction cup mount with quick release, USB-C power cable (no wall plug), rugged carrying case

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APPENDIX K – DIGITAL APPENDIX INSTRUCTIONS

A digital appendix was supplied to Test Pilot School that contained the data collected and the MATLAB code.

The data is organized by flight number and contains the following data:

- SUT Data: DDMMMYY_(SUT)_(Aircraft)_(Pilot Name).gpx/kml/txt
- TSPI data for C-12 or F-16: (Ops Number)_(Aircraft)-(Tail Number)_GL_FLT(##)_TP(#)_SUT.csv
- TSPI data for T-38: T38C-(Tail Number)-(Ops Number_TPS.csv
- Test Point Matrix

The MATLAB folder contains the following files:

- GNSS_import.m to import GNSS file format data
- GPX_import.m to import GPX file format data
- KML_import_apple_sentratus.m ti import KML file format data
- data_importv2.m to cut the data to the desired test points
- tpsread.m is a function called by data_importv2.m
- matlabs_the_Final_one.m to run the Vincinty algorithm and autocorrelation

Not all flights recorded TSPI, and flights where VMC and IMC navigation were evaluated, TSPI support was not requested.