



A LIMITED EVALUATION OF THE SATELLITE CONTROL NETWORK ON-ORBIT TEST ASSET (SPHINX)

(Project HAVE TACOS)

BLAKE W. MORGAN, Capt, USAF
Project Manager / Flight Test Engineer

JOHN A. HAMM, Capt, USAF
Project Flight Test Engineer

JOSHUA S. JUDY, Capt, USAF
Project Test Weapon System Officer

CHRISTOPHER B. JOHNSON, Maj, USAF
Project Test Pilot

RONALD H. LEE, Capt, USAFR
Project Test Pilot

KYLE K. MCLEOD, Maj, USMC
Project Test Pilot

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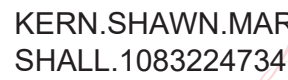
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Prepared by:

This memorandum has been reviewed and is approved for publication:

 Digitally signed by
MORGAN.BLAKE.WILLIAM.13958
16744
Date: 2021.06.06 18:24:27 -07'00'

BLAKE W. MORGAN
Captain, USAF
Project Manager / Flight Test Engineer

 Digitally signed by
KERN.SHAWN.MARSHALL.1083224
734
Date: 2021.06.07 15:18:43 -07'00'

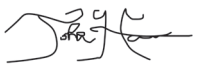
SHAWN M. KERN
GS-14, DAF
Staff Advisor, USAF TPS

 Digitally signed by
JUDY.JOSHUA.STUART.140873004
6
Date: 2021.06.06 18:47:56 -07'00'

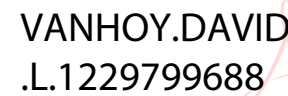
JOSHUA S. JUDY
Captain, USAF
Project Test Weapon Systems Officer

 Digitally signed by
LEE.CHIawei.NMN.1300514088
Date: 2021.06.07 15:15:13 -07'00'

CHIAWEI N. LEE
NH-III, DAF
Test Management Program Director, USAF TPS

 Digitally signed by
HAMM.JOHN.AMBROSE.14052457
40
Date: 2021.06.06 19:27:02 -07'00'

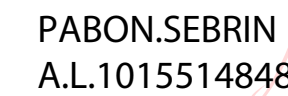
JOHN A. HAMM
Captain, USAF
Project Flight Test Engineer

 Digitally signed by
VANHoy.DAVID.L.1229799688
.L.1229799688
Date: 2021.07.15 11:03:55
-07'00'

DAVID L. VANHoy
NH-IV, DAF
Technical Director, USAF TPS

 Digitally signed by
JOHNSON.CHRIStOPHER.BRADL
EY.1291054338
Date: 2021.06.06 19:13:31 -07'00'

CHRISTOPHER B. JOHNSON
Major, USAF
Project Test Pilot

 Digitally signed by
PABON.SEBRINA.L.1015514848
A.L.1015514848
Date: 2021.07.15 16:54:02
-07'00'

SEBRINA L. PABON
Colonel, USAF
Commandant, USAF TPS

 Digitally signed by
LEE.ROnALD.HY.1259263472
Date: 2021.06.06 20:39:40 -07'00'

RONALD H. LEE
Captain, USAFR
Project Test Pilot

 Digitally signed by
MCLEOD.KYLE.KRISTOPHER.1298
076515
Date: 2021.06.06 18:32:54 -07'00'

KYLE K. MCLEOD
Major, USMC
Project Test Pilot

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Dr. Wendy Chiado The Aerospace Corporation 7250 Getting Heights Colorado Springs, CO, 80916				10. SPONSOR/MONITOR'S ACRONYM(S) N/A	
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14. ABSTRACT This report documents results of the limited evaluation of the Satellite Control Network On-Orbit Test Asset (SPHINX). Testing was requested by the United States Space Force Satellite Control Network program office. The lead developmental test organization was the Air Force Test Center, Edwards AFB, California. The executing test organization was Class 20B of the United States Air Force Test Pilot School, working in partnership with The Aerospace Corporation, El Segundo, CA. Testing was conducted from 08 March 2021 to 19 March 2021 and comprised of 8 sorties totaling 37.8 flight test hours. The overall test objective was to demonstrate the SPHINX payload's utility as an airborne surrogate test satellite for ground station testing. All test objectives were met.					
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a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19B. TELEPHONE NUMBER 719-325-9928

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EXECUTIVE SUMMARY

This report presents the results of the HAVE Test and Check-Out Satellite (TACOS) Test Management Project (TMP). Testing was requested by the United States Space Force (USSF) Satellite Control Network (SCN) program office, Los Angeles AFB, CA. The lead developmental test organization was the Air Force Test Center, Edwards AFB, California. The executing test organization was Class 20B of the United States Air Force Test Pilot School, Edwards AFB, CA working in partnership with The Aerospace Corporation, El Segundo, CA. The 586th Flight Test Squadron provided a C-12J, S/N 86-0080, under the Job Order Number MT20B500. Testing was conducted from 7 March 2021 to 19 March 2021 and comprised of 10 ground test hours and eight sorties totaling 37.8 flight test hours.

The USSF SCN provided launch and early orbit anomaly resolution support required by all satellite systems and assured access to space for time-sensitive satellite control functions. As of 2021, there were no representative test assets dedicated to testing SCN ground stations before going into operational use. Therefore, ground stations relied on operational spacecraft for limited testing. Testing was not a priority for satellite owners and SCN users were often unable to use operational assets for ground station testing. The lack of a dedicated space-based test asset prevented the SCN program office from timely and thorough verification of critical ground station requirements.

The system under test was an airborne prototype of the Satellite Control Network On-Orbit Test Asset (SPHINX). The airborne test of the SPHINX payload was intended as the final stage prior to proceeding with the development and deployment of an on-orbit SPHINX test asset. The SPHINX payload was comprised of three transponders, a GPS receiver, a mission computer, a software defined radio used for interference detection experimentation, and a power distribution unit (PDU). All hardware was integrated into two chassis and installed into a stand-alone avionics rack within the C-12J. Power was provided to the SPHINX payload from the C-12J's mini-PDU. A wideband monopole antenna was installed to the underside of the aircraft for uplink and downlink. The SPHINX payload was operated by a laptop connected to the mission computer via a test specific Graphical User Interface (GUI). The C-12J was flown in a racetrack pattern in the W-532 airspace west of the Vandenberg Tracking Station (VTS). A variety of pre-built test sequences were executed to address the test objectives.

The overall test objective was to demonstrate the SPHINX payload's utility as an airborne surrogate test satellite for ground station testing. There were two General Test Objectives (GTOs): demonstrate SPHINX payload functionality and demonstrate the SPHINX payload's utility for ground station testing. The overall test objective and GTOs were met.

SPHINX payload functionality was demonstrated through execution of auto track, uplink and downlink, telemetry, commanding, and interference detection experimentation. Command packet error ratios observed during testing were outside tolerance for on-orbit assets. The worst case observation valid packet count was 0% and the best case valid packet count was 49%.

The SPHINX payload's utility for ground station testing was demonstrated through range, range rate, and Doppler accuracy determination. Range accuracy varied per sequence, and the average range deviations were between 860 m and 1,040 m. Doppler biases between 754.7 Hz and 795.7 Hz were observed, which resulted in erroneous VTS calculated range rates. Also, VTS crosstalk ratios, antenna pattern data, and dynamic signal strength data were collected. The dynamic flight environment resulted in difficulty executing precise program tracks required for crosstalk ratio and antenna pattern data collection. Therefore, crosstalk ratio and antenna pattern data collection were limited to only one run for each sequence.

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Contents

EXECUTIVE SUMMARY	iii
INTRODUCTION.....	1
BACKGROUND	1
UPLINK AND DOWNLINK	1
TRACKING.....	1
TELEMETRY	2
COMMANDING.....	2
RANGING	2
DOPPLER	2
RANGE RATE	2
ANTENNA PATTERN.....	2
CROSSTALK RATIOS.....	3
DYNAMIC SIGNAL STRENGTH	3
TEST ITEM DESCRIPTION	3
TEST OBJECTIVES	6
CONSTRAINTS.....	7
TEST AND EVALUATION.....	9
TEST METHODS AND CONDITIONS.....	10
FLIGHT PROFILE	10
GENERAL TEST METHODOLGY	11
SPHINX PAYLOAD FUNCTIONALITY	12
AUTO TRACKING.....	12
UPLINK AND DOWNLINK CONNECTIVITY	13
SPHINX PAYLOAD CALIBRATION DATA.....	16
TELEMETRY PERFORMANCE	17
COMMAND PERFORMANCE.....	18
INTERFERENCE DATA.....	19
SPHINX PAYLOAD'S UTILITY FOR GROUND STATION TESTING.....	20
ANTENNA RANGING ACCURACY.....	20
ANTENNA DOPPLER ACCURACY	22
ANTENNA RANGE RATE ACCURACY	24
ANTENNA DYNAMIC SIGNAL STRENGTH DATA.....	25

ANTENNA CROSSTALK RATIOS.....	26
ANTENNA PATTERN DATA	27
APPENDIX A – SPHINX PAYLOAD SEQUENCES	A-1
APPENDIX B – DATA ANALYSIS.....	B-1
REQUIRED DATA AND DATA SOURCE.....	B-1
DATA REDUCTION	B-4
APPENDIX C – DAILY REPORTS	C-1
DAILY REPORT: 8 MAR 2021.....	C-1
DAILY REPORT: 9 MAR 2021.....	C-3
DAILY REPORT: 10 MAR 2021.....	C-5
DAILY REPORT: 11 MAR 2021.....	C-6
DAILY REPORT: 17 MAR 21.....	C-8
DAILY REPORT: 18 MAR 2021.....	C-9
DAILY REPORT: 19 MAR 2021.....	C-10
APPENDIX D – ABBREVIATIONS, ACRONYMS, AND SYMBOLS.....	D-1
APPENDIX E – LESSONS LEARNED.....	E-1
APPENDIX F – DISTRIBUTION LIST	F-1
APPENDIX G – FLIGHT PROFILES & WAYPOINTS	G-1
APPENDIX H – DETAILED TEST ITEM DESCRIPTION.....	H-1
SPHINX	H-1
VTS	H-5
APPENDIX I – TEST AIRCRAFT DESCRIPTION	I-1
APPENDIX J – FUTURE CONSIDERATIONS FOR AIRCRAFT SURROGATES	J-1

TABLE OF FIGURES

Figure 1: SPHINX Payload Test Scenario	3
Figure 2: SPHINX Avionics Rack	4
Figure 3: Monopole Antenna	4
Figure 4: SPHINX Payload Operator and GUI	5
Figure 5: Initial Flight Profile (20,000 feet MSL, Sortie 1)	10
Figure 6: UP2 RSSI with Auto Track	14
Figure 7: VTS Reported RSSI and Corresponding Attenuation Levels	16
Figure 8: SOCSIM Reported GPS Locations during Ranging	21
Figure 9: Doppler Data for All Three DOP Sequences	22
Figure 10: Corrected Doppler Data for All Three DOP Sequences	23
Figure 11: Range Rate Data for All Three DOP Sequences.....	25
Figure B-1: Plotted FINS Data.....	B-4
Figure G-1: Modified Flight Profile (23,500 feet MSL, Sorties 2-5).....	G-1
Figure G-2: Restricted Profile (23,500 feet MSL, Sorties 6-7).....	G-2
Figure H-1: SPHINX Payload Layout, Chassis 1 - Top View.....	H-1
Figure H-2: SPHINX Payload Layout, Chassis 1 - Side View.....	H-2
Figure H-3: SPHINX Payload Layout, Chassis 2 - Top View.....	H-2
Figure H-4: SPHINX Wide-band Monopole Antenna	H-3
Figure H-5: SPHINX Functional Control Document.....	H-4
Figure H-6: SPHINX Control GUI.....	H-5
Figure H-7: VTS Layout.....	H-6
Figure H-8: VTS RBC Summary Screen.....	H-6
Figure H-9: SOCSIM Hardware.....	H-7
Figure H-10: SOCSIM GUI.....	H-7
Figure I-1: C-12J with Monopole Antenna Location.....	I-1
Figure I-2: SPHINX Payload Chassis 1 - Avionics Rack.....	I-2
Figure I-3: SPHINX Payload Chassis 2 - Power Distribution Board.....	I-2

TABLE OF TABLES

Table 1: Test Objective Summary	9
Table 2: Auto Track Sequence Settings and Data.....	12
Table 3: Uplink (U/L) Sequence Settings and Data	14
Table 4: Downlink (D/L) Sequence Settings and Data	15
Table 5: Telemetry Sequence Settings and Data	18
Table 6: Command Performance Sequence Settings and Data	19
Table 7: Range Sequence Data	21
Table 8: Doppler Deviation Statistics.....	23
Table A-1: Auto Track Test Sequences.....	A-1
Table A-2: Uplink Signal Strength Test Sequences.....	A-1
Table A-3: Downlink Signal Strength Test Sequences.....	A-1
Table A-4: SPHINX Payload Calibration Test Sequences.....	A-1
Table A-5: Telemetry Lock Status Test Sequences.....	A-2
Table A-6: Packet Error Ratio Test Sequences.....	A-3
Table A-7: Interference Detection Test Sequences.....	A-3
Table A-8: Ranging Accuracy Test Sequences.....	A-4
Table A-9: Range Rate and Doppler Accuracy Test Sequences.....	A-4
Table A-10: Dynamic Signal Strength Test Sequences.....	A-4
Table A-11: Crosstalk Ratio Test Sequences.....	A-5
Table A-12: Antenna Pattern Test Sequences.....	A-5
Table B-1: Displayed SPHINX Interface Parameters.....	B-1
Table B-2: SOCSIM Log Files.....	B-2
Table B-3: SPHINX Text Files.....	B-2
Table B-4: Available C-12J FINS Parameters.....	B-3
Table B-5: SPHINX Parameters.....	B-5
Table B-6: SPINX Parameter Meanings.....	B-6
Table B-7: IRON Data Rates.....	B-7

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INTRODUCTION

This report presents the results of the HAVE Test and Check-Out Satellite (TACOS) Test Management Project (TMP). Testing was requested by the United States Space Force (USSF) Satellite Control Network (SCN) program office Los Angeles, CA. The lead developmental test organization was the Air Force Test Center, Edwards AFB, California. The executing test organization was Class 20B of the United States Air Force Test Pilot School, Edwards AFB, CA working in partnership with The Aerospace Corporation, El Segundo, CA. The 586th Flight Test Squadron provided a C-12J, S/N 86-0080, under the Job Order Number MT20B500. Testing was conducted from 7 March 2021 to 19 March 2021 and comprised of 10 ground test hours and eight sorties totaling 37.8 flight test hours.

BACKGROUND

The USSF SCN provided launch and early orbit anomaly resolution support required by all satellite systems and assured access to space for time-sensitive satellite control functions. As of 2021, there were no representative test assets dedicated to testing SCN ground stations before going into operational use. Therefore, ground stations relied on operational spacecraft for limited testing. Testing was not a priority for satellite owners and SCN users were often unable to use operational assets for ground station testing. The lack of a dedicated space-based test asset prevented the SCN program office from timely and thorough verification of critical ground station requirements. The SCN's solution to this problem was a dedicated on-orbit asset designed specifically for ground station testing.

Ground stations were required to provide a variety of functions for operational spacecraft users. These functions were critical for basic operation and were required before a ground station became operational. These functions included: tracking, uplink and downlink, telemetry, commanding, ranging, Doppler measurements, and range rate calculations.

Ground station antenna performance characterization was required to understand the antenna system's efficacy for these functions. Antenna performance metrics were antenna pattern, crosstalk ratios, and dynamic signal strength.

UPLINK AND DOWNLINK

Uplink was the ground station's ability to transmit an L-band signals to a spacecraft. Downlink was the ground station's ability to receive S-band signals from a spacecraft.

TRACKING

Tracking was the ground station's ability to track a spacecraft. There were two types of tracking: auto track and program track. For auto track, the ground station received and followed a downlinked tracking signal from the spacecraft to trace the spacecraft's path. For program track, a trace was pre-programmed into the ground station based on the spacecraft's two-line mean element set (2LMES) data documenting the spacecraft's orbital parameters.

For both track types, tracking began when the spacecraft reached the acquisition of signal location within the orbit. The antenna was pre-positioned to the spacecraft's acquisition of signal location. Antenna position was determined by the generation of antenna pointing angles (APAs) derived from the 2LMES. APAs set the antenna's azimuth and elevation angles based on the geometry of the spacecraft and the ground

station. For program track, a series of APAs were generated to manually move the antenna to follow the spacecraft's orbital motion.

TELEMETRY

Telemetry was the information generated or collected by a spacecraft with respect to its health, status, and payload data. The spacecraft transmitted this information to the ground station for subsequent analysis by the user. There were three forms of telemetry: mission data, state of health, and ranging. Spacecraft had the capability to transmit telemetry to the ground station on each of their onboard transponders. Each transponder's telemetry was defined as a telemetry stream. Per USSF SCN ground station requirements, ground stations were required to receive up to five telemetry streams.¹

COMMANDING

Commanding was the process of controlling a spacecraft. Commands were instructional signals sent to the spacecraft from the ground station. Command signals were uplink signals containing digitally encoded binary information, referred to as packets. The spacecraft received the digitally encoded signals and decoded the binary information to execute the desired commands. There were two types of encoding used for commands: Frequency-Shift Keying and Phase-Shift Keying. Frequency-shift keying encoded digital information through discrete frequency changes of the carrier uplink signal. Phase-shift keying encoded digital information through changes in the phase of the constant frequency uplink signal.

RANGING

Ranging was the ground station's ability to determine slant range to the spacecraft using the time difference between a transmitted and received range signal.

DOPPLER

Doppler was the frequency shift of the ranging signal based on the spacecraft's motion relative to the ground station. Doppler was determined by the difference between the known transmitted signal frequency and the received signal frequency.

RANGE RATE

Range rate was the change in spacecraft range over time. Range rate was calculated by the ground station from the measured Doppler shift.

ANTENNA PATTERN

Antenna pattern was the characterization of the main lobe, side lobes, and overall symmetry for uplink and downlink. Antenna patterns were characterized by the power transmitted (uplink) and power received (downlink) as the antenna moved off-boresight of the spacecraft in both azimuth and elevation.

¹ Remote Block Chain Requirements Documents, Section 3.1.3 – Telemetry

CROSSTALK RATIOS

Crosstalk ratios were the ratio of movement in either the azimuth or elevation axis, when one axis was allowed to move and the other is commanded to stay fixed. Crosstalk ratios assessed the overall gimbal performance of the antenna system.

DYNAMIC SIGNAL STRENGTH

Dynamic signal strength was the minimum tracking signal power the antenna could receive from a spacecraft to maintain auto track.

TEST ITEM DESCRIPTION

The system under test was an airborne prototype of the Satellite Control Network On-Orbit Test Asset (SPHINX) (Figure 1). The SPHINX payload was a satellite prototype developed by The Aerospace Corporation to perform ground station testing of the parameters outlined in the background section. The airborne test of the SPHINX payload was intended as the final stage prior to proceeding with the development and deployment of an on-orbit SPHINX test asset. The SPHINX payload was comprised of three transponders, a GPS receiver, a mission computer, a software defined radio used for interference detection experimentation, and a power distribution unit (PDU). All hardware was integrated into two chassis and installed into a stand-alone avionics rack within the C-12J (Figure 2). Power was provided to the SPHINX payload from the C-12J's mini-PDU. A wideband monopole antenna was installed to the underside of the aircraft for uplink and downlink (Figure 2 and Figure 3). The SPHINX payload was operated by a laptop connected to the mission computer via a test specific Graphical User Interface (GUI). A detailed test item description is in Appendix H. Installation and airworthiness approval of the SPHINX payload was completed by the 586th Flight Test Squadron (FLTS). A detailed test aircraft description is provided in Appendix I.

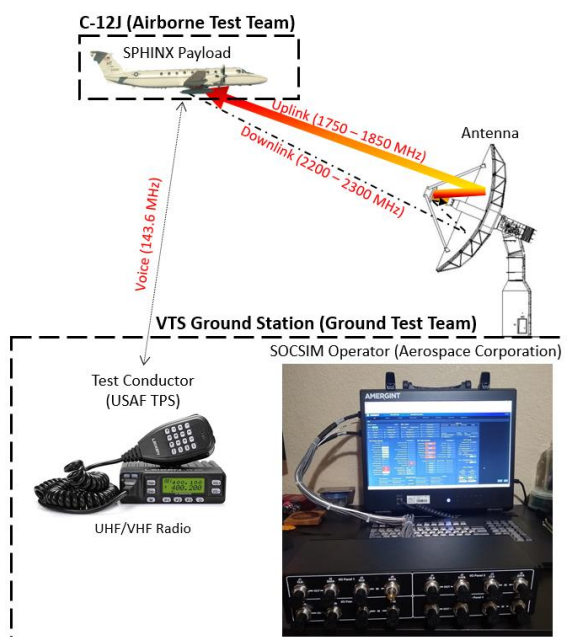


Figure 1: SPHINX Payload Test Scenario



Figure 2: SPHINX Avionics Rack



Figure 3: Monopole Antenna

Much of the SPHINX payload experimentation hardware was Commercial Off-the-Shelf (COTS), space-tested hardware. The SPHINX payload components included:

- Meerkat mission computer
 - Operated all SPHINX payload hardware and interfaced between the SPHINX Payload GUI and the SPHINX payload hardware
- Novatel GPS receiver
 - Provided SPHINX with GPS data
- Cesium Astro Software Defined Radio (SDR)
 - Enabled the addition of interference to the uplink signal through emulation of a tone jammer and additive white Gaussian noise
- Two Innoflight SCR-104 Transponders
 - Received uplink and command signals and transmitted downlink and telemetry signals. One SCR-104 Transponder served as the primary auto track
- SWIFT-SLX Space Ground Link System (SGLS) Transponder
 - Received uplink and command signals and transmitted downlink and telemetry signals. Measured Signal-to-Noise of any interference injected signals sent from the Cesium Astro SDR.

The SPHINX payload received power through C-12J's instrumentation power. The SPHINX payload also tapped into the aircraft's existing GPS antenna. The SPHINX payload sent uplink and received downlink signals through the monopole antenna on the bottom aft fuselage. The SPHINX payload was controlled through a laptop provided by The Aerospace Corporation. A GUI was developed by The Aerospace Corporation to allow a Test Pilot School (TPS) student to operate the SPHINX payload. All SPHINX payload data were stored on the laptop and downloaded at the end of each mission.

The Vandenberg Tracking Station (VTS), operated by 21st Space Operations Squadron (SOPS), authorized and scheduled VTS-A (Remote Tracking System Block Change (RBC) system) and VTS-B (Hybrid system) for test execution. The VTS served as the ground station as well as the control room during test execution. The control room consisted of a TPS test conductor, The Aerospace Corporation engineers, and VTS personnel. Normally, all spacecraft supported by the SCN were operated through a Space Operations Center (SOC). During a spacecraft support, the SOC connected and communicated to the

spacecraft through the VTS to send commands and receive telemetry. No operational SOCs participated in the SPHINX payload test, therefore a Space Operations Center Simulator (SOCSIM) was used to emulate this function. The VTS transmitted commands and received telemetry through the SOCSIM. The SOCSIM was a mature, COTS system frequently used for ground station testing when operational SOCs were unavailable. The SOCSIM connected directly to the VTS and was operated by The Aerospace Corporation engineer throughout test execution via a command GUI. Commands were initiated from the SOCSIM, sent to the VTS' Digital Signal Processor (DSP) for signal generation, converted to the appropriate L-Band uplink frequency, amplified, and then transmitted via the VTS antenna to the SPHINX payload. Telemetry was received by the VTS antenna, converted from the S-Band frequency for processing by the DSP, and then presented to the VTS operator on the SOCSIM. Communication between the C-12J and the TPS Test Conductor was through the use of UHF/VHF radio.

The SPHINX payload was operated through the use of a GUI which enabled the SPHINX payload operator to set the appropriate downlink attenuation level (Figure 4) and execute the desired test sequences provided in Appendix A. Test sequences were pre-built sequences programmed onto the SPHINX payload to address test objectives. Upon running the test sequence on the GUI, the SPHINX payload's configuration was established by setting the appropriate Test Inter Range Operations Numbers (IRONs). IRONs specified how the SPHINX payload and VTS were setup to execute Tracking, Telemetry, and Control (TT&C) operations. Each IRON established command type, transmit power setting, uplink and downlink frequencies, data rates, and all other settings required for the test sequence.



Figure 4: SPHINX Payload Operator and GUI

TEST OBJECTIVES

The overall test objective was to demonstrate the SPHINX payload's utility as an airborne surrogate test satellite for ground station testing. There were two General Test Objectives (GTOs) for this test. Each GTO had six Specific Test Objectives (STOs). All test objectives were met. The GTOs and STOs were:

1. GTO 1: Demonstrate SPHINX payload functionality
 1. STO 1.1: Demonstrate Auto Track
 2. STO 1.2.: Demonstrated Uplink/Downlink Connectivity
 3. STO 1.3: Collect SPHINX Payload Calibration Data
 4. STO 1.4: Demonstrated Telemetry Performance
 5. STO 1.5: Demonstrate Command Performance
 6. STO 1.6: Collect Interference Data
2. GTO 2: Demonstrate the SPHINX payload's utility for ground station testing
 1. STO 2.1: Determine Antenna Ranging Accuracy
 2. STO 2.2: Determine Antenna Range Rate Accuracy
 3. STO 2.3: Determine Antenna Doppler Accuracy
 4. STO 2.4: Collect Antenna Dynamic Signal Strength Data
 5. STO 2.5: Collect Antenna Crosstalk Ratios
 6. STO 2.6: Collect Antenna Pattern Data

CONSTRAINTS

Four constraints were encountered during testing of the SPHINX payload. The first constraint was invalid Fighter Inertial Navigation System (FINS) positional data collected during all range and range rate/Doppler sequences. FINS data was intended to serve as the truth source for aircraft position and velocity within the flight profile. The FINS positional and velocity data were intended to be used to calculate slant range, range rate, and Doppler shift truth values to be compared to the respective VTS calculated values to determine parameter accuracy. Upon analysis of the FINS data after test execution, FINS data were determined to be erroneous. FINS positional data placed the aircraft in a flight profile over the incorrect geographical area. FINS data also drifted throughout the flight, shifting the incorrect flight profile over a swath of area that aircraft never flew over. Therefore, the test team was unable to apply a bias to the FINS data, rendering the FINS data useless for range, range rate, and Doppler accuracy determination. With invalid FINS data, the test team used C-12J GPS information to calculate range, range rate, and Doppler truth values.

The second constraint was inability to effectively execute a program track of the SPHINX payload. The crosstalk ratio and antenna pattern STOs required the VTS to break auto track and manually follow the C-12J in the flight profile using a pre-planned track. The test team provided flight profile waypoints to The Aerospace Corporation in approximately four minute intervals. A timing profile was flown before the execution of the crosstalk and antenna pattern sequences to provide The Aerospace Corporation engineers with a time to reach each waypoint based on aircraft velocity and environmental factors. The Aerospace Corporation engineers took the time to reach each waypoint observed during the timing profile and linearly interpolated aircraft position between waypoints for 0.1 second intervals. The linear interpolation of aircraft position between waypoints was used to program antenna azimuth and elevation pointing angles for crosstalk and antenna pattern sequences. Though the test team attempted to replicate the same timing profile flight conditions for the crosstalk and antenna pattern sequences, the variability between the profiles did not enable sufficient program tracking. This constraint was not attributed to the SPHINX payload. The variability in aircraft flight profile was too high to execute program track and precluded execution beyond a single crosstalk and antenna pattern sequence. A total of 18 crosstalk ratio sequences and three antenna pattern performance sequences were planned.

The third constraint was the inability to effectively execute SPHINX payload test sequences with the RBC antenna. Testing was attempted with the RBC during the second week of execution. However, issues with the antenna's High-Power Amplifier (HPA) caused multiple system resets. These issues were internal to the VTS and not attributed to the SPHINX payload or test setup. Therefore, testing against the RBC antenna was terminated and the remainder of the test execution window was flown against the Hybrid antenna. It was planned to repeat all test sequences with the RBC, therefore approximately half of the desired test sequences were not attempted.

The fourth constraint was the inability to meaningfully determine a 95% confidence intervals for range, range rate, and Doppler accuracy. Issues identified within the SPHINX system's range, range rate, and Doppler parameters led to accuracy errors significantly larger than expected. It was not deemed worthwhile to create confidence intervals for parameters with such large errors.

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TEST AND EVALUATION

Testing was conducted from 7 March 2021 to 19 March 2021 and comprised of 10 ground test hours and eight sorties totaling 37.8 flight test hours. A total of 61 test sequences were executed which generated usable data. For all executed test sequences, the C-12J flew a racetrack pattern in the W-532 airspace west of Vandenberg Air Force Base.

The overall test objective was to demonstrate the SPHINX payload's utility as an airborne surrogate test satellite for ground station testing. There were two GTOs: demonstrate SPHINX payload functionality and demonstrate the SPHINX payload's utility for ground station testing. The overall test objective and GTOs were met. SPHINX payload functionality was demonstrated through execution of auto track, uplink and downlink, telemetry, commanding, and interference detection experimentation. The SPHINX payload's utility for ground station testing was demonstrated through range, range rate, and Doppler accuracy determination. Also, VTS crosstalk ratios, antenna pattern data, and dynamic signal strength data were collected. Table 1 summarizes the test objectives.

Table 1: Test Objective Summary

GTO	STO	# Sequence Types Executed	Overall
Demonstrate SPHINX Payload Functionality	Demonstrate Auto Tracking	7	MET
	Demonstrate Uplink/Downlink Connectivity	3	MET
	Collect SPHINX Payload Calibration Data	6	MET
	Demonstrate Telemetry Performance	11	MET
	Demonstrate Command Performance	7	MET
	Collect Interference Data	9	MET
Demonstrate SPHINX Payload's Utility for Ground Station Testing	Determine Antenna Ranging Accuracy	7	MET
	Determine Antenna Range Rate Accuracy	3	MET
	Determine Antenna Doppler Accuracy	3	MET
	Collect Antenna Dynamic Signal Strength Data	3	MET
	Collect Antenna Crosstalk Ratios	1	MET
	Collect Antenna Pattern Data	1	MET

All data collected from the SPHINX payload, the VTS RBC summary screen, and the SOCSIM data logs were given to The Aerospace Corporation for additional analysis beyond the scope of HAVE TACOS TMP.

A-F. The six waypoints provided the aircrew with a repeatable flight profile and served as re-acquisition points in the event auto track was lost. The profile was flown in a counter-clockwise orbit starting at point F. For the two long legs, the pilot flew between waypoints on a direct-to heading based on the previous waypoint location. For the two short legs, the pilot flew over the waypoint, then initiated a nominal 20-degree bank turn to the next waypoint.

The original flight profile was modified during test execution to better accommodate airspace operating restrictions and improve APAs. A detailed outline of the flight profile changes is provided in Appendix G. The modified flight profiles adhered to the original racetrack pattern, but with different waypoints and altitudes. The flight profile adjustments had no impact to data collection.

GENERAL TEST METHODOLOGY

The general test methodology was constant, regardless of the flight profile. The Aerospace Corporation generated APAs 24 hours prior to each flight based on the flight profile. The APAs were used at the VTS to point the antenna to the appropriate position to acquire the SPHINX payload tracking signal, and attempt to program track the SPHINX payload as required. Prior to takeoff, engineers from The Aerospace Corporation conducted a pre-flight checkout of the SPHINX payload to ensure all critical functions for the sortie were operational. Once the aircrew were in the aircraft and mission power was available, the Flight Test Engineer (FTE) operating the SPHINX payload setup the hardware for the flight and turned the payload on. The FTE initiated the first sequence of the test sortie at approximately 200 feet Above Ground Level during the climb to ensure the sequence was running properly before the aircraft was established in the profile. The aircraft then proceeded to the test airspace and established on the respective flight profile, starting the profile at waypoint F. Prior to the beginning of test execution, the ground test team established the communication link between the SOCSIM and the VTS to enable commanding and data collection between the VTS and SPHINX payload. The ground test team also setup the ground station with the appropriate IRON configuration for the test sequence and loaded all APAs. Either prior to, or soon after the aircraft established in the flight profile, the ground and airborne test teams real-time coordinated an auto track acquisition waypoint. The auto track acquisition waypoints were one of the six aircrew waypoints, A-F. Regardless of auto track status, the pilot provided the ground test team with situation awareness calls when the aircraft was approaching (between 30 seconds to 1 minute prior) and passing through each of the six waypoints.

Prior to auto track acquisition, the VTS operator pointed the antenna to one of the six waypoints, converted from latitude/longitude/elevation to an APA. As the aircraft passed through this waypoint, the VTS antenna would receive signals from the SPHINX payload and begin auto track. If auto track was not established, or was lost for any reason, the VTS operator would point the antenna at the next waypoint in the profile. The test conductor provided feedback to the aircrew regarding auto track status over the radio. Once auto track was established and with the SPHINX payload executing a test sequence, data were recorded on the payload in the aircraft, as well as on the RBC Summary screen and in SOCSIM data logs located at VTS. The FTE operating the SPHINX payload recorded time stamps for the beginning and end of each test sequence, reported GUI indications to the VTS operator when required, and made adjustments to certain parameters (such as attenuation or jamming profiles) in the GUI at the direction of the VTS operator. The VTS operator would provide feedback to the test conductor when sufficient data for each sequence had been gathered, and the test conductor would radio to the aircrew that the run was complete and direct the next sequence. If the next sequence resulted in an IRON change, auto track ceased, requiring reacquisition at the next waypoint.

For certain test sequences, the SPHINX payload operator was required manually adjust to transponder attenuation level. The transponder attenuation level attenuated the downlink signal for all three transponders on the SPHINX payload. The downlink attenuation level was a unit-less integer value between 5 and 60,

with higher integers corresponding to higher signal attenuation. The correlation between attenuation level and downlink transmit power was not present on the SPHINX payload GUI. The default downlink attenuation level was set to five for all sequences and was adjusted at the direction of The Aerospace Corporation VTS operator.

All presented data were collected from the Hybrid antenna system. Multiple sequences were attempted with the RBC antenna, however, the antenna experienced several power resets during the test due to issues with the High-Power Amplifier. These power resets resulted in a significant loss in test efficiency, and the test team decided to cease use of the RBC antenna. This issue was not a problem attributed to the SPHINX payload.

SPHINX PAYLOAD FUNCTIONALITY

The first GTO was to demonstrate SPHINX payload functionality. The GTO was met.

AUTO TRACKING

The STO was to demonstrate the SPHINX payload's ability to be auto tracked by the VTS. All priority one auto tracking sequences were executed, successful auto tracking was demonstrated, and the auto tracking STO was met.

Test Methodology:

The test was executed in accordance with the general test methodology. When executing each auto track test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON and tracking frequency using one of the Innoflight SCR-104 transponders, set with a signal power level of 30 dBm, per the test matrix detailed in Table A-1 in Appendix A. Auto track was terminated at the direction of The Aerospace Corporation VTS operator.

Test Results:

A total of seven auto tracking sequences were executed. Auto track was successfully acquired for all seven auto track sequences. Table 2 summarizes the auto track sequence settings, the time duration of the sequence, and the percentage of time within the sequence auto track was maintained. Given the test setup geometry and the auto track signal power, auto track was expected to be acquired and maintained for 100% of the sequence duration.

Table 2: Auto Track Sequence Settings and Data

Seq #	IRON	Tracking Freq (MHz)	Duration (Min:Sec)	% Maintained
TK1	TEST8625DEF	2262.5	07:28	100%
TK2	TEST2167E	2237.5	07:04	100%
TK3	TEST4090I	2227.5	09:41	100%
TK4	TEST0420DEF	2252.5	12:47	100%
TK6	TEST9757S	2202.5	24:41	100%
TK8	TEST6911A	2232.5	12:04	100%
TK11	TEST0468DEF	2212.5	21:50	98.9%

Along with the dedicated auto track sequences, auto track functionality was incorporated in all other test sequences. While auto track was maintained during dedicated auto track testing, several auto track

drop-outs were observed during execution of non-auto track dedicated sequences. The percent of the duration where auto track was maintained during the non-auto track dedicated sequences was not calculated. However, the loss of auto track prevented successful uplink and downlink until reacquisition or sequence termination.

Two key auto track observations were made during test execution. First, it was observed that if auto track was lost, the VTS attempted to regain auto track for approximately 15 seconds before ceasing to reattempt acquisition. For TK 11, auto track was briefly lost, but the VTS was able to reacquire the auto track signal. For this sequence, the time to reacquire was approximately three seconds for each of the five observed drop-outs.

The second observation was the acquisition of SPHINX payload auto track on the monopole antenna's side lobes. The default attenuation level of the tracking signal resulted in a higher power signal than a typical spacecraft. On several occasions, the VTS antenna picked up the high-power signal from the monopole antenna's side lobes, and initiated an auto track. The VTS operator was able to make the determination that the antenna was tracking the SPHINX payload's side lobe based on the track azimuth and elevation errors. When this was detected, auto track was disabled and the antenna was manually slewed to the next waypoint for another auto track acquisition attempt. This issue was attributed to the use of an aircraft as an airborne satellite surrogate, and not the SPHINX payload's ability to provide a tracking signal.

Conclusion:

Auto track of the SPHINX payload was successfully demonstrated for a variety of IRONs and the test objective was met. Auto track was required to be demonstrated before moving on to further test sequences. The acquisition of auto track on the SPHINX payload was the first demonstration of a SCN ground station operating with a satellite surrogate. Demonstration of auto track was required to show utility of the SPHINX payload to transmit a tracking signal to a ground station, and have the ground station successfully acquire and auto track the signal. Auto track was a required ground station capability to enable TT&C.

UPLINK AND DOWNLINK CONNECTIVITY

The STO was to demonstrate the SPHINX payload's uplink and downlink connectivity. All uplink and downlink sequences were executed, successful uplink and downlink were demonstrated, and the uplink and downlink connectivity STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON or frequency changes were required. When executing each uplink connectivity test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON and set internal signal routing to direct received uplink signals to a specified transponder. One of the two sequences utilized an Innoflight SCR-104 transponder, and the other utilized the SWIFT transponder. When executing each downlink connectivity test sequence, the test sequence configured the payload with a specific IRON and directed one Innoflight SCR-104 transponder to transmit a signal to the VTS at 15 dBm, which corresponded to the SPHINX GUI attenuation level of five. For the SWIFT transponder, power was set to 11 dBm, which corresponded to an attenuation level of five. At the direction of the VTS operator, the SPHINX payload operator attenuated the signal by adjusting the attenuation level in the SPHINX payload GUI. The downlink signal was attenuated in increments of five until the VTS was no longer able to receive the attenuated downlink signal.

Uplink Test Results:

A total of two uplink connectivity sequences were executed. Uplink was successfully established for both sequences, and Received Signal Strength Indication (RSSI) values were recorded throughout the duration of the sequences. Table 3 summarizes the uplink sequence settings, the time duration of the sequence, the maximum and minimum RSSI values reported by the SPHINX payload, and the average RSSI value for the duration of the sequence. The default RSSI value displayed on the SPHINX payload GUI was approximately -120 dBm for the SCR-104 transponder and approximately -40 dBm for the SWIFT transponder. Therefore, it was expected to see RSSI readings on the respective transponder greater than the default values during uplink connectivity sequence execution. The SPHINX payload's minimum usable uplink signal power was not provided by The Aerospace Corporation.

Table 3: Uplink (U/L) Sequence Settings and Data

Seq #	IRON	Transponder	U/L Freq (MHz)	Sequence Duration (Min:Sec)	Max RSSI (dBm)	Min RSSI (dBm)	Average RSSI (dBm)
UP1	TEST1056R	SCR-104	1763.7	7:07	-83.3	-90.8	-87.2
UP2	TEST6910D	SWIFT	1764.3	6:22	-27.4	-29.1	-28.2

For UP1, the maximum RSSI value reported was -83.3 dBm, the minimum RSSI value reported was -90.8 dBm, and the average RSSI value reported was -87.2. For UP2, the maximum RSSI value reported was -27.4 dBm, the minimum RSSI value reported was -29.1 dBm, and the average RSSI value reported was -28.2 dBm. Uplink RSSI values were spot checked against GPS data to observe trends in the data. As expected, uplink RSSI values increased as the SPHINX payload moved closer to VTS due to the reduction in the free space loss.

Successful auto track was required to establish a steady uplink signal between the VTS and the SPHINX payload. Both uplink sequences were initiated before auto track was established. Prior to auto track acquisition, the SPHINX payload began reporting increased RSSI values as the aircraft flew through the VTS antenna's uplink sidelobes. Once auto track was established, the SPHINX payload began reporting RSSI values above the default. RSSI values reset to the original default values when the VTS operator terminated auto track. Auto track effectively served as an "On-Off" switch for uplink connectivity. This concept is shown Figure 6.

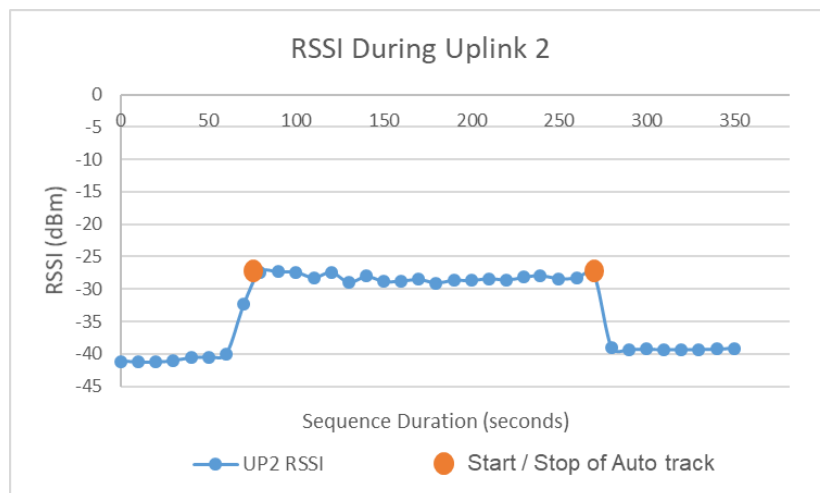


Figure 6: UP2 RSSI with Auto Track

Uplink Conclusion:

Uplink from the VTS to the SPHINX payload was successfully demonstrated and the test objective was met. The ability of the SPHINX payload to receive an uplink signal from the VTS was required to be demonstrated before moving on to further test sequences where information was uplinked to the SPHINX payload. Demonstration of uplink was required to show the utility of the SPHINX payload to assess a ground station's ability to transmit uplink signals. Uplink was a required ground station capability to ensure spacecraft operators could send commands to their spacecraft.

Downlink Test Results:

One downlink connectivity sequence was executed. Downlink was successfully established for the sequence, and downlink signal RSSI values were recorded by the VTS. Table 4 summarizes the downlink frequency, the time duration of the sequence, the maximum and minimum RSSI values reported by the VTS, and the average RSSI value for the duration of the sequence at the respective attenuation level. The default RSSI value displayed by the VTS was -200 dBm. Therefore, it was expected to see an RSSI reading greater than -200 dBm during the execution of the downlink connectivity sequence. The VTS antenna was rated to receive and process signals as low as -195 dBm.

Table 4: Downlink (D/L) Sequence Settings and Data

Seq #	IRON	D/L Freq (MHz)	Attenuation Level	Duration (Min:Sec)	Min RSSI (dBm)	Max RSSI (dBm)	Average RSSI (dBm)
DL1	TEST1056R	2202.5	5	6:24	-117.1	-113.9	-115.6
			10	4:36	-123.7	-115.9	-120.4
			15	3:51	-133.9	-123.2	-125.9
			20	8:33	-143.7	-132.9	-135.9
			25	5:57	-144.5	-138.9	-141.7
			30	2:30	-200	-144.0	-194.7

The SPHINX payload was able to transmit a downlink signal, which was received by the VTS, for attenuation levels between the default value of 5 and a final value of 30. Downlink RSSI values were spot checked against GPS data to observe trends in the data. As expected, downlink RSSI values increased as the SPHINX payload moved closer to VTS due to the reduction in the free space loss.

As expected, the VTS reported decreased RSSI values as the attenuation level increased. When the attenuation level was set to 30, a sharp decrease in RSSI occurred and the signal was eventually lost. When the signal was lost, auto track was terminated and the antenna was setup for another attempt. Figure 7 shows the VTS reported RSSI values and the corresponding attenuation levels.

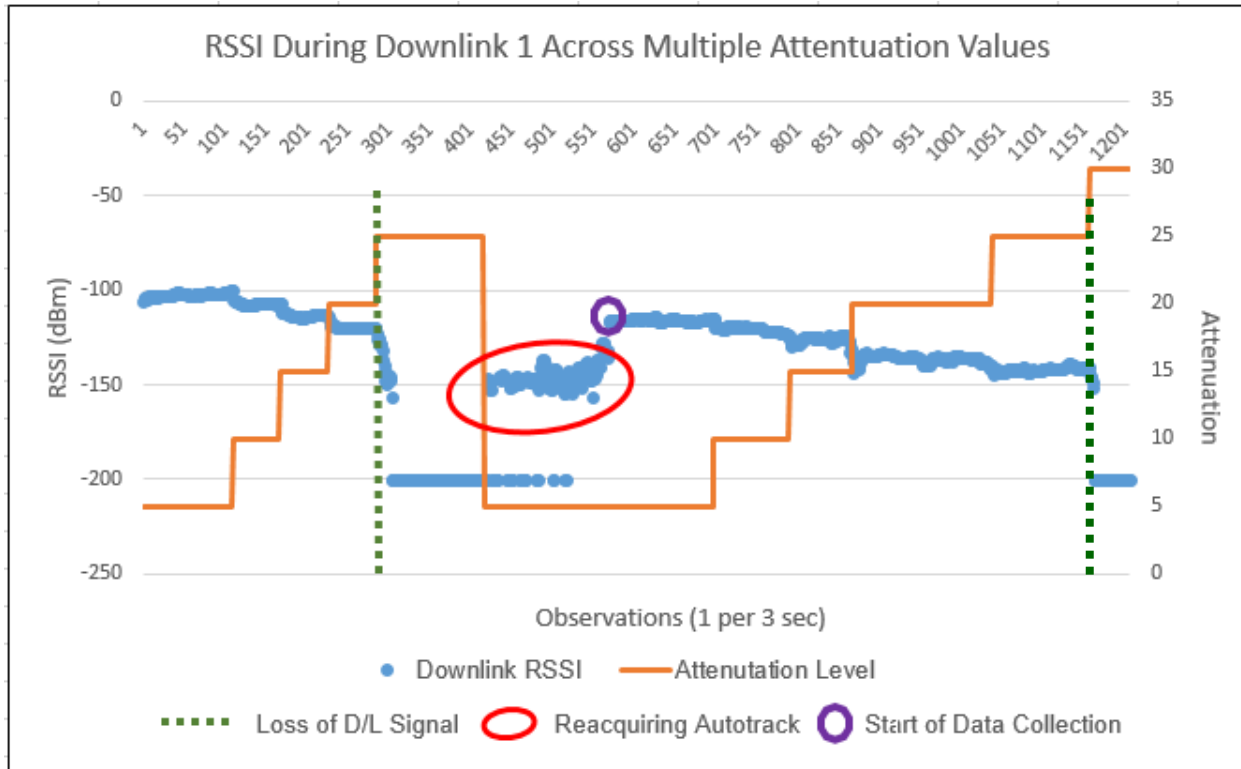


Figure 7: VTS Reported RSSI and Corresponding Attenuation Levels

Figure 7 illustrates the downlink signal received over the course of approximately one hour. The blue line represents the downlink RSSI value and the orange line illustrates the attenuation value set on the SPHINX payload. As the attenuation value was increased, the downlink RSSI was reduced. Around the 300th observation, the attenuation was set to 25 and the signal was lost entirely. Over the next 300 observations, until the 600th observation, the system attempted to reestablish auto track. At approximately the 600th observation, auto track was reestablished and data collection resumed. The RSSI value continued to decrease as the attenuation value was again increased. The results from the approximately 30 minutes from the 600th observation until the 1200th observation were tabulated in Table 4.

Downlink Conclusion:

Downlink from the SPHINX payload to the VTS was successfully demonstrated and the test objective was met. The ability of the SPHINX payload to transmit a downlink to the VTS was required to be demonstrated before moving on to further test sequences where information was downlinked to the VTS. Demonstration of downlink was required to show the utility of the SPHINX payload to assess a ground station's ability to receive downlink signals. Downlink was a required ground station capability to ensure spacecraft operators could receive telemetry from their spacecraft.

SPHINX PAYLOAD CALIBRATION DATA

The STO was to collect SPHINX payload calibration data. All calibration data sequences were executed, SPHINX calibration data were collected, and the calibration data STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON changes were required. When executing each SPHINX payload calibration test sequence, the test sequence configured the payload with a specific attenuator value, and set the a specific transmit power setting in the appropriate transponders, per the test matrix detailed in Table A-4 in Appendix A. The Aerospace Corporation engineers passed attenuator adjustments as required for their data needs, which the SPHINX payload operator input into the payload GUI.

Test Results:

Data from six SPHINX payload calibration test sequences were collected over the course of a single flight for a variety of IRONs. No issues were observed in-flight while executing the sequences, nor were any issues determined during post-flight data review.

Conclusion:

Overall, the data collected by both the SPHINX payload and the RBC summary screen logs for the SPHINX calibration were usable by The Aerospace Corporation engineering team for analysis and future development. Calibration data enabled The Aerospace Corporation to assess the impacts of signal multi-path during uplink and downlink transmission.

TELEMETRY PERFORMANCE

The STO was to demonstrate the SPHINX payload's telemetry performance. All priority one telemetry performance sequences were executed, successful telemetry downlink was demonstrated, and the telemetry performance STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON or frequency changes were required. When executing each telemetry performance test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON and set of downlink frequencies per the test matrix detailed in Table A-5 in Appendix A.

Test Results:

A total of 11 telemetry performance sequences were executed. The SPHINX payload was capable of supporting up to three telemetry streams, with each telemetry stream corresponding to one of the three transponders onboard the payload. Table 5 summarizes the telemetry stream frequency, the time duration of the sequence, and the percentage of time the VTS held telemetry lock. Downlink 1 and Downlink 2 corresponded to the two Innoflight SCR-104 transponders. Downlink 3 corresponded to the SWIFT transponder. It was expected that the VTS would maintain a good telemetry lock on all downlinked telemetry streams for at least 98% of the sequences.

Table 5: Telemetry Sequence Settings and Data

Seq #	IRON	D/L 1 Freq (Mhz)	D/L 2 Freq (Mhz)	D/L 3 Freq (Mhz)	Duration (Min:Sec)	% Maintained
TLM 1	TEST4090I	2227.5	N/A	N/A	13:19	100%
TLM4	TEST8625DEF	2262.5	2267.5	N/A	--	--
TLM5	TEST8625DEF	2262.5	2262.5	2267.5	10:12	100%
TLM8	TEST9757S	2202.5	2257.5	N/A	--	--
TLM10	TEST0468DEF	2212.5	2221.5	N/A	08:03	100%
TLM15	TEST2167E	2237.5	2207.5	2267.5	13:19	100%
TLM18	TEST6910D	2252.5	2252.5	N/A	15:41	100%
MULT3	TEST3268DEF	2247.5	2247.5	2247.5	09:36	100%
MULT4	TEST8625DEF	2247.5	2247.5	2247.5	03:54	100%
MULT5	TEST4961DEF	2262.5	2262.5	2267.5	06:12	100%
MULT6	TEST0420DEF	2204.5	2204.5	N/A	02:36	100%

Sequences TLM4 and TLM8 were executed, however, the RBC summary screen data log files were corrupted for these runs and data were unable to be extracted. Only one instance of less than 100% lock status was observed (TLM5) from the SOCSIM data log. For TLM5, invalid telemetry lock status times were compared against auto track times, and the telemetry drop out was due to a momentary loss in auto track signal. As demonstrated during the downlink connectivity test sequence, auto track was required to downlink telemetry to the VTS. Without auto track, the VTS was unable to receive the downlinked telemetry. However, telemetry was maintained for the duration of the sequence where auto track was maintained.

Conclusion:

Telemetry performance was demonstrated on up to three simultaneous telemetry streams for five different IRONS and the test objective was met. Demonstration of telemetry performance was required to show the utility of the SPHINX payload to test a ground station's ability to receive telemetry. Telemetry was a required ground station capability to ensure spacecraft operators could receive mission and state of health data from their spacecraft.

COMMAND PERFORMANCE

The STO was to demonstrate the SPHINX payload's command performance. All priority one command sequences were executed, successful commanding was demonstrated, and the command performance STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON or frequency changes were required. When executing each Command performance test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON, uplink frequency, and downlink frequency per the test matrix detailed in Table A-6 in Appendix A.

Test Results:

A total of seven command performance sequences were executed. All command performance sequences utilized Phase-Shift Keying encoding. Command packets from the VTS were successfully uplinked to one of the SPHINX payload's Innoflight SCR-104 transponders. Table 6 summarizes the uplink and downlink frequencies, the number of packets sent to the SPHINX payload, the valid packet ratio, the invalid packet ratio, and the missing packet ratio. It was expected that all command packets sent to the SPHINX payload would be received and reported as valid, yielding a missing packet error ratio of 0%.

Table 6: Command Performance Sequence Settings and Data

Seq #	IRON	U/L Freq (MHz)	D/L Freq (MHz)	Packets Sent	Valid Packet Ratio	Invalid Packet Ratio	Missing Packet Ratio
COM1	TEST8625DEF	1811.7	2262.5	5,585	25%	24%	51%
COM3	TEST4090I	1783.7	2227.5	5,875	42%	7%	51%
COM4	TEST3268DEF	1799.7	2247.5	3,765	20%	7%	73%
COM5	TEST9757S	1763.7	2202.5	1,875	49%	4%	48%
MULT1	TEST4090I	1783.7	2227.5	10,250	31%	3%	67%
MULT5	TEST4961DEF	1811.7	2262.5	5,421	0%	65%	35%
MULT6	TEST0420DEF	1765.3	2204.5	7,890	19%	11%	70%

During the command performance sequences, command packets were broken up into three categories: valid packets, invalid packets, and missing packets. Valid packets were packets sent from the VTS and successfully received and processed by the SPHINX payload. Invalid packets were packets sent from the VTS, received by the SPHINX payload, but were not successfully processed. Missing packets were packets sent from the VTS, but were not received by the SPHINX payload.

For all executed command performance sequences, a non-zero percent missing packet error ratio was observed. It was expected that all packets sent from the VTS would be received, processed, and reported as valid by the SPHINX payload. The highest observed valid packet ratio was 49%. All command performance data were given to The Aerospace Corporation for further determination on the causes of invalid and unaccounted for packets.

Conclusion:

Command performance was demonstrated for a variety of IRONS and the test objective was met. However, no executed command performance sequences generated results at or near the expected condition of a valid packet ratio of 100%. Demonstration of command performance was required to show the utility of the SPHINX payload to assess an antenna's commanding capabilities. Commanding was a required ground station capability to ensure spacecraft operators could operate the spacecraft throughout its intended mission set. For spacecraft, a valid packet ratio of 100% was required to ensure correct spacecraft command execution. **R1 – Investigate the cause of invalid and missing packets.**

INTERFERENCE DATA

The STO was to collect SPHINX payload interference experiment data. All interference data sequences were executed, interference experiment data were collected, and the interference data STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON or frequency changes were required. When executing each interference detection test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON, uplink frequency, downlink frequency, and applied a specific jamming technique per the test matrix detailed in Table A-7 in Appendix A. All signal jamming was internal to the SPHINX payload, provided by the Astro Cesium SDR. Jammer power level was manually set by the SPHINX payload operator at the direction of the VTS operator.

Test Results:

Data from 15 interference detection test sequences were collected. No issues were observed in-flight while executing the sequences, nor were any issues determined during post-flight data review.

Conclusion:

Overall, the interference data collected by SPHINX and the VTS logs were usable by the Aerospace Corporation engineering team for analysis and future development. This data assisted The Aerospace Corporation in characterizing the capabilities of the payload and ground stations to overcome interference in a saturated or degraded electromagnetic environment.

SPHINX PAYLOAD'S UTILITY FOR GROUND STATION TESTING

The GTO was to demonstrate the SPHINX payload's utility for ground station testing.

ANTENNA RANGING ACCURACY

The STO was to determine ground station ranging accuracy. All ranging accuracy sequences were executed, ranging accuracy was determined, and the antenna ranging accuracy STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON or frequency changes were required. When executing each ranging test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON and downlink frequency per the test matrix detailed in Table A-8 in Appendix A.

Test Results:

A total of three ranging accuracy sequences were executed. The SPHINX payload successfully provided the VTS with useable data which enabled slant range calculations. However, large deviations between the true range and the VTS calculated range were observed. The Aerospace Corporation engineers confirmed the deviations were higher than expected. Table 7 summarizes sequence IRON, the duration of each sequence, and the minimum, maximum, and average differences between the VTS reported range and true range determined from the C-12J GPS. For this demonstration, it was expected that the SPHINX payload would enable the VTS to calculate slant ranges which would be compared to truth source values to determine the ranging accuracy.

Table 7: Range Sequence Data

Seq #	IRON	Duration (Min:Sec)	Max Δ (m)	Min Δ (m)	Avg Δ (m)	σ (m)
RNG1	TEST8625DEF	8:15	1,133	537	860	200
RNG2	TEST3268DEF	12:14	1,230	639	1,040	209
RNG4	TEST4916DEF	8:50	1,184	663	992	184

For the three sequences executed, the maximum range difference observed was 1,230 m for RNG2. The minimum range difference was 537 m for RNG1. SPHINX payload GPS data were plotted, shown in Figure 8, and matched to the flight profile and were determined to be an unlikely source of the large errors.



ANTENNA DOPPLER ACCURACY

The STO was to determine the ground station's Doppler measurement accuracy. All Doppler accuracy sequences were executed, Doppler measurement accuracy was determined, and the Doppler accuracy STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON or frequency changes were required. When executing each Doppler accuracy test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON and downlink frequency per the test matrix detailed in Table A-9 in Appendix A. The VTS RBC summary screen passed Doppler measurements to the SOCSIM, where the measurements were recorded for data analysis.

Test Results:

All three Doppler accuracy sequences were executed. The SPHINX payload successfully provided the VTS with useable data which enabled Doppler measurements. No Doppler measurement accuracy tolerances were provided by The Aerospace Corporation to assess the level of precision the SPHINX payload could enable the VTS to measure Doppler. Therefore, for this demonstration, it was expected that the SPHINX payload would enable the VTS to measure the downlink range signal's Doppler shift which would be compared to truth source values to determine Doppler measurement accuracy. Figure 9 shows the comparison between VTS measured Doppler shift as reported by the SOCSIM and true Doppler shift. Gaps in the observations within Figure 9 were due to sequence changes and data drop outs.

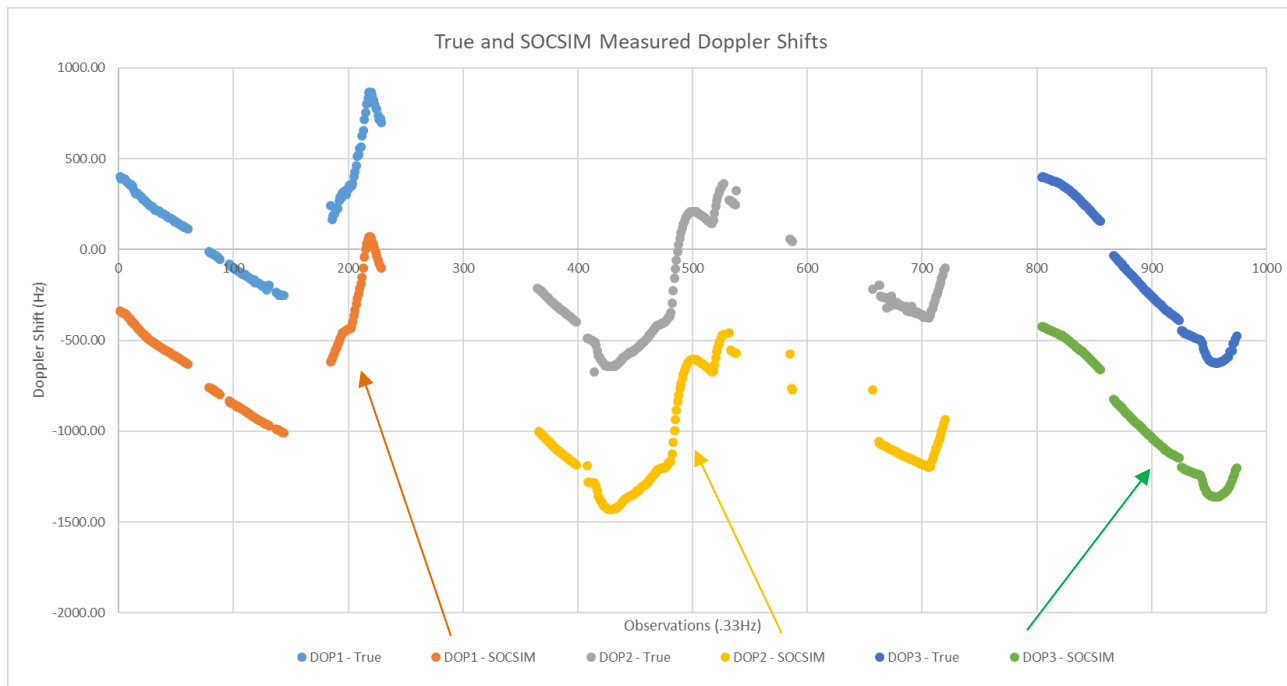


Figure 9: Doppler Data for All Three DOP Sequences

Nearly constant biases were observed between the SOCSIM reported and true Doppler shifts. The SOCSIM Doppler measurements were predominately negative. The trends observed in SOCSIM reported Doppler were determined to be erroneous based on the aircraft profile and the location within the profile where Doppler sequences were executed. Table 8 shows the Doppler deviation statistics between the SOCSIM reported Doppler and the true Doppler for each three sequences.

Table 8: Doppler Deviation Statistics

Seq #	IRON	Min Δ (Hz)	Max Δ (Hz)	σ (Hz)	Avg Δ (Hz)
DOP1	TEST8625DEF	728.3	862.1	19.5	754.6
DOP2	TEST3268DEF	615.8	902.6	20.8	795.7
DOP3	TEST4916DEF	712.3	832.8	35.0	782.6

SOCSIM reported Doppler closely matched true Doppler when corrected by average observed sequence bias. SOCSIM corrected Doppler and true Doppler are shown in Figure 10.

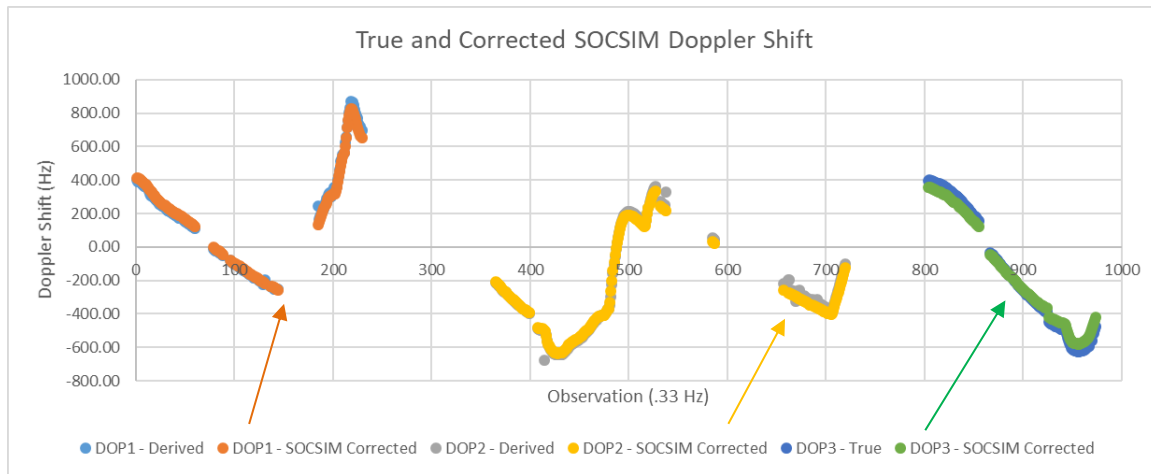


Figure 10: Corrected Doppler Data for All Three DOP Sequences

Since the measured Doppler shift was determined to be erroneous, the data were not separated into bins for positional analysis. Also, a 95% confidence interval was not calculated since the prediction interval was determined to be of no value with erroneous Doppler measurements data. All Doppler accuracy data were passed to The Aerospace Corporation for further analysis.

Conclusion:

Doppler biases were observed in the VTS Doppler measurements during all three sequences. However, the two Doppler values closely matched when the biases were applied to the SOCSIM reported Doppler. The Doppler bias enabled The Aerospace Corporation to identify an issue with the SPHINX Payload preventing the VTS from accurately measuring Doppler. Demonstration of Doppler measurement accuracy was required to show the utility of the SPHINX payload to test a ground station's ability to measure Doppler and subsequently calculate range rates. Accurate Doppler measurement was a required ground station capability to enable calculation of a spacecraft's range rate. **R3 – Investigate the cause of Doppler biases.**

ANTENNA RANGE RATE ACCURACY

The STO was to determine the antenna range rate accuracy. All range rate accuracy sequences were executed, range rate accuracy was determined, and the range rate accuracy STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON or frequency changes were required. When executing each range rate accuracy test sequence from the SPHINX payload, the test sequence configured the payload with a specific IRON and downlink frequency per the test matrix detailed in Table A-9 in Appendix A. Range rate accuracy determination utilized the same three sequences as the Doppler accuracy determination.

Test Results:

A total of three range rate accuracy sequences were executed. The range rate and Doppler accuracy sequences utilized the same three test sequences since Doppler shift was the primary variable the VTS used to calculate range rate. However, from conversations with The Aerospace Corporation, the VTS utilized proprietary methods for calculating range rate from the measured Doppler. The SPHINX payload successfully provided the VTS with useable data which enabled range rate calculations.

As mentioned in the Doppler Accuracy section, a Doppler measurement was observed at the VTS, and the Doppler bias resulted in erroneous range rate calculations. The VTS utilized proprietary methods for calculating range rate from the measured Doppler. No range rate accuracy tolerances were provided by The Aerospace Corporation to assess the level of precision the SPHINX payload could enable the VTS to calculate range rate values. Therefore, for this demonstration, it was expected that the SPHINX payload would enable the VTS to calculate range rates which would be compared to truth source values to determine the range rate accuracy. Figure 11 shows the comparison between VTS calculated range rates reported by the SOCSIM (SOCSIM) and true range rate values (True) calculated from the SPHINX payload GPS data. The figure illustrates three successive Doppler sequence. The oscillatory nature of the range rate was anticipated due to the geometry of the flight profile. Gaps in the observations within Figure 11 were due to sequence changes and data drop outs.

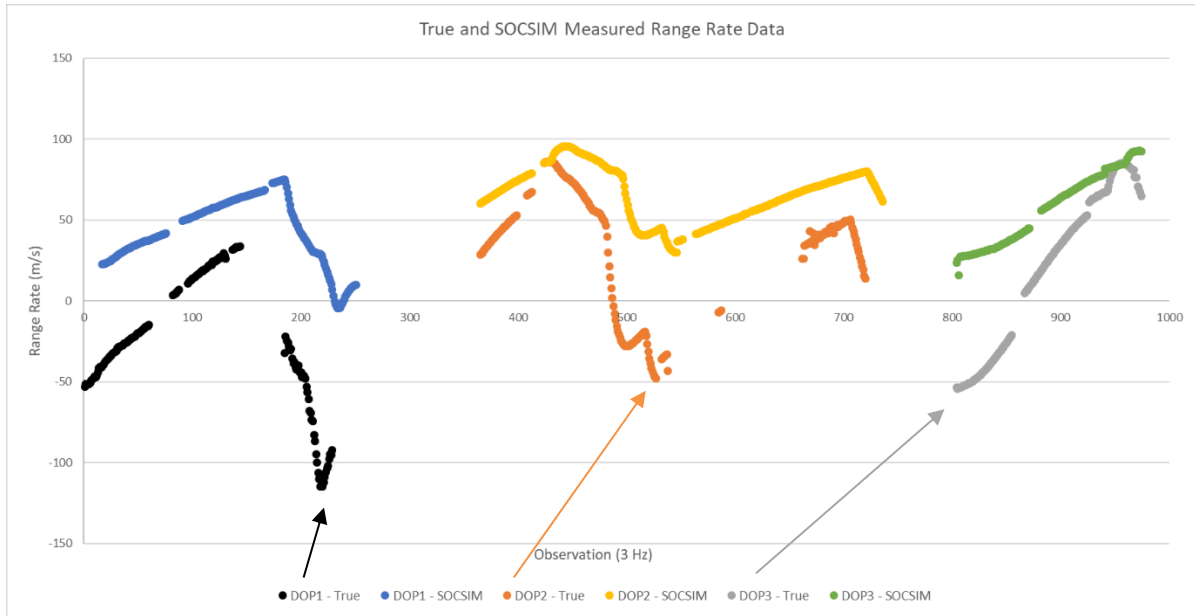


Figure 11: Range Rate Data for All Three DOP Sequences

The erroneous Doppler measurements resulted in almost all positive SOCSIM reported range rates. The number of SOCSIM reported positive range rate observations were determined to be erroneous based on the aircraft profile and the location within the profile where range rate sequences were executed. Deviations between the SOCSIM reported range rate and the true range rate differed by upwards of 143.8 m/s, observed during the execution of DOP1. Though the SOCSIM reported range rates were determined to be erroneous due to incorrect Doppler measurements, Figure 11 illustrates the relative correlation between the SOCSIM reported range rate and the true range rate.

Since the range rate data was determined to be erroneous, the data were not separated into bins for positional analysis. Also, a 95% confidence interval was not calculated since the prediction interval was determined to be of no value with erroneous range rate data. All range rate accuracy data were passed to The Aerospace Corporation for further analysis. Additional sequence settings are presented in Table A-9 in Appendix A.

Conclusion:

Range rate accuracy was determined to be well outside of expected values. From The Aerospace Corporation, range rate errors for operational spacecraft were typically on the order of centimeters per second. The large range rate errors observed enabled The Aerospace Corporation to identify an issue with the SPHINX payload's ability to provide accurate range rate assessments. Demonstration of range rate was required to show the utility of the SPHINX payload to test a ground station's ability to calculate range rates. Range rate was a required ground station capability to provide spacecraft operators with situation awareness on the spacecraft's orbital velocity. **R4 – Investigate the cause of range rate errors.**

ANTENNA DYNAMIC SIGNAL STRENGTH DATA

The STO was to use the SPHINX payload to collect antenna dynamic signal strength data. All dynamic signal strength sequences were executed, dynamic signal strength data were collected, and the dynamic signal strength STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology. Each sequence began after the establishment of a new auto track, or continuation of a pre-existing auto track if no SPHINX payload IRON changes were required. Each sequence began at either Point C or Point F to reduce mid-test heading changes. When executing each signal strength sequence from the SPHINX payload, the test sequence configured the payload with a specific tracking frequency (unchanged between Signal Strength runs), enabled or disabled transponders, and adjusted the tracking signal attenuator level per the test sequence matrix detailed in Table A-10 in Appendix A. The Aerospace Corporation engineers passed attenuator adjustments as required for their data needs, which the SPHINX payload operator input into the GUI. The attenuation level was initially set to zero for all signal strength antenna sequences.

Test Results:

Data from six antenna dynamic signal strength test sequences were collected over the course of several flights. No issues were observed in-flight while executing the sequences, nor were any issues determined during post-flight data review.

One key observation made was in regards to establishing auto track with attenuated auto track signals. This observation was made during the execution of the SS6 on the first day. SS6 was initiated with a default attenuation level of zero and auto track was successfully acquired. Throughout the sequence, the tracking signal power was attenuated by the SPHINX payload operator at the direction of the VTS operator. The VTS lost auto track of the SPHINX payload at an attenuation level of 30. Therefore, the VTS operator disabled auto track and the SPHINX payload operator set the attenuation level to the previous attenuation level (25) where auto track was successfully maintained. The VTS operator manually slewed the antenna to the next aircraft waypoint to reacquire auto track, however, auto track was not established. This process was repeated two more times for a total of three auto track reacquisition attempts with the attenuation level set to 25. After the three failed auto track reacquisitions, the test team decided to remove auto track signal attenuation and reattempt the sequence with default attenuation level of zero. Once auto track signal attenuation was removed, the VTS successfully acquired auto track at the next waypoint. With auto track reestablished, auto track signal attenuation levels were again increased and the VTS was able to maintain auto track with the SPHINX payload as the signal was attenuated to 55. This observation led the test team to deduce there was an auto track signal power threshold where auto track could be acquired, but once acquired, the auto track signal power could be attenuated beyond the threshold for acquisition. An auto track signal power threshold was not expected due to the test setup geometry and the SPHINX payload's attenuated auto track signal power levels being higher than those of on-orbit assets.

Conclusions:

Overall, the data collected by SPHINX and the VTS logs for Antenna Dynamic Signal Strength were usable by The Aerospace Corporation engineering team for analysis and future development. Characterization of the SPHINX payload. The demonstration of dynamic signal strength showed the utility of the SPHINX payload to characterize the ability of an antenna to auto track signals at varying signal powers.

ANTENNA CROSSTALK RATIOS

The STO was to use the SPHINX payload to collect antenna crosstalk data. One crosstalk ratio sequence was executed, cross talk ratio data were collected, and the crosstalk ratio STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology; however, it did not use auto track procedures. In order to collect the crosstalk ratio of the VTS hybrid antenna, the VTS operator initiated a program track of the payload. Prior to beginning the antenna crosstalk ratio sequence, a timing orbit was accomplished with the aircraft maintaining a constant airspeed and hacking the clock at each waypoint to determine the time required for transit with the atmospheric and airspeed conditions. Inputting the timing orbit data into an algorithm, The Aerospace Corporation engineers created an interpolated list of APAs to track the aircraft from when it reached one waypoint to the next, in order to determine if there was any uncommanded azimuth or elevation shifts when the program track commanded the rotation of the antenna. The crosstalk ratio test sequences configured the payload with a specific IRON, tracking frequency, and downlink power setting per the test matrix in Table A-11 in Appendix A.

Test Results:

A single crosstalk ratio sequence was executed and data for the sequence were collected. However, the VTS was only able to maintain a program track for a short period of time, less than a single leg in the orbit. This was suspected to be due to the extremely narrow beamwidth of the VTS hybrid antenna and the displacement from the precise predicted point in both position and time. If the aircraft was even a knot different than the predicted value, or if there was a slight delay in beginning the tracking function, or wind required a slight course correction, the VTS could not accurately program track the aircraft, and there were not methods to adjust slew rates mid-run. The aircraft had to be within approximately 250 feet of the predicted course at the predicted time, which for an asset moving at approximately 225 knots true (380 feet per second) meant that a 1-2 second timing difference would result in the aircraft being out of the antenna beamwidth, causing the sequence to fail.

Conclusion:

Antenna crosstalk ratio data were collected for the duration of VTS program track of the SPHINX payload. All data could be analyzed by The Aerospace Corporation to determine gimbal limitations on the VTS antenna. The test methodology utilized during execution was not suitable for crosstalk ratio characterization using an airborne satellite surrogate.

ANTENNA PATTERN DATA

The STO was to use the SPHINX payload to collect downlink antenna pattern data. One pattern data sequence was executed, pattern data were collected, and the pattern data STO was met.

Test Methodology:

This test was executed in accordance with the general test methodology; however, it did not use auto track procedures. In order to collect the downlink antenna pattern data of the VTS hybrid antenna, the VTS operator pre-positioned the antenna to be pointed directly at a waypoint prior to aircraft arrival at that waypoint. The antenna pattern test sequence was executed on the payload, which established the IRON and tracking frequency per the test matrix in Table A-12 in Appendix A. The pilot then called timing hacks to the waypoint in order to prepare the ground station to receive data.

Test Results:

A single antenna pattern data sequence was executed and data were collected for the antenna pattern; however, the aircraft could not hit the waypoint precisely enough to truly characterize the maximum

strength of the antenna when perfectly centered within the beamwidth. Similar to the crosstalk ratio test, the aircraft's flightpath could not be flown to the exact center of a manually-aimed 500-foot beamwidth, as an airborne asset in moving air currents and with an FMS that was limited to 0.1 NM precision could not fully characterize the antenna pattern data.

Conclusion:

Antenna pattern data were collected for the duration of VTS program track of the SPHINX payload. All data could be analyzed by The Aerospace Corporation to determine the antenna signal pattern of the VTS antenna. The test methodology utilized during execution was not suitable for antenna pattern characterization using an airborne satellite surrogate.

APPENDIX A – SPHINX PAYLOAD SEQUENCES

All sequence priorities were provided by The Aerospace Corporation. Test sequences marked with a strikethrough were planned but not executed. Test sequences marked with an asterisk were designed to address multiple MOPs.

Table A-1: Auto Track Test Sequences

Seq #	Command Type	IRON	Tracking Freq (MHz)	Priority	Radio
TK1	SGLS	TEST8625DEF	2262.5	1	Innoflight 1 (30 dBm)
TK2	SGLS	TEST2167E	2237.5	1	Innoflight 1 (30 dBm)
TK3	SGLS	TEST4090I	2227.5	1	Innoflight 1 (30 dBm)
TK4	SGLS	TEST0420DEF	2252.5	1	Innoflight 1 (30 dBm)
~~TK5~~	~~SGLS~~	~~TEST3268DEF~~	~~2247.5~~	~~2~~	~~Innoflight 1 (30 dBm)~~
TK6	SGLS	TEST9757S	2202.5	1	Innoflight 1 (30 dBm)
~~TK7~~	~~SGLS~~	~~TEST0164A~~	~~2277.5~~	~~2~~	~~Innoflight 1 (30 dBm)~~
TK8	SGLS	TEST6911A	2232.5	1	Innoflight 1 (30 dBm)
~~TK9~~	~~NSGLS~~	~~TEST4916DEF~~	~~2204.5~~	~~2~~	~~Innoflight 1 (30 dBm)~~
~~TK10~~	~~NSGLS~~	~~TEST9199DEF~~	~~2261.1~~	~~3~~	~~Innoflight 1 (30 dBm)~~
TK11	SGSL	TEST0468DEF	2212.5	1	Innoflight 1 (30 dBm)

Table A-2: Uplink Signal Strength Test Sequences

Seq #	IRON	Action(s)	Priority
UP1	TEST1056R	- Mission Computer toggles switch matrix to the two SCR-104 transponders - The mission computer will query the SCR-104 transponders for their RSSI and this value, with time-tag, will be provided on the GUI	1
UP2	TEST6910D	- Mission Computer toggles switch matrix to the SWIFT transponder - Mission computer will query the SWIFT for its RSSI, and this value, with time-tag, will be provided on the GUI	1

Table A-3: Downlink Signal Strength Test Sequences

Seq #	IRON	Action(s)	Priority
DL1	TEST1056R	- Mission Computer sets SCR-104 radio 2 to 15 dBm, attenuator level set to 5 - The Mission Computer directs the SCR-104 radio 2 to send a BPSK signal - Aircrew will adjust the attenuator level on the SPHINX payload GUI, as directed by the ground team, until downlink signal is lose	1

Table A-4: SPHINX Payload Calibration Test Sequences

Seq #	IRON	Action(s)	Priority
ATTN1	TEST1056R	Set attenuator to 5dB, set Innoflight1 to 30dB	1
ATTN2	TEST1056R	Set attenuator to 5dB, set Innoflight1 to 24dB	1
ATTN3	TEST1056R	Set attenuator to 5dB, set Innoflight1 to 18dB	1
ATTN4	TEST1056R	Set attenuator to 5dB, set Innoflight1 to 12dB	1
ATTN5	TEST1056R	Set attenuator to 5dB, set Innoflight1 to 6dB	1
ATTN6	TEST1056R	Set attenuator to 5dB, set Innoflight1 to 0dB, adjust attenuator as instructed	1

Table A-5: Telemetry Lock Status Test Sequences

Seq #	# Streams	IRON	D/L 1 Freq (MHz)	D/L 2 Freq (MHz)	D/L 3 Freq (MHz)	Priority
TLM1	1	TEST4090I	2227.5	N/A	N/A	1
TLM2	2	TEST1399DEF	2262.5	2262.5	N/A	3
TLM3	2	TEST6911A	2232.5	2232.5	N/A	3
TLM4	2	TEST8625DEF	2262.5	2267.5	N/A	1
TLM5	3	TEST8625DEF	2262.5	2262.5	2267.5	1
TLM6	2	TEST3268DEF	2247.5	2247.5		2
TLM7	3	TEST3268DEF	2247.5	2247.5	2247.5	2
TLM8	2	TEST9757S	2202.5	2257.5	N/A	1
TLM9	3	TEST9757S	2202.5	2257.5	2257.5	3
TLM10	2	TEST0468DEF	2212.5	2221.5	N/A	1
TLM11	3	TEST0468DEF	2212.5	2221.5	2221.5	3
TLM12	2	TEST4916DEF	2204.5	2204.5	N/A	3
TLM13	3	TEST4916DEF	2204.5	2204.5	2204.5	2
TLM14	3	TEST4262DEF	2237.5	2232.5	2232.5	3
TLM15	3	TEST2167E	2237.5	2207.5	2267.5	1
TLM16	3	TEST7117F	2237.5	2207.5	2267.5	3
TLM17	2	TEST6910D	N/A	2203.3	2203.3	2
TLM18	2	TEST6910D	2252.5	2252.5	N/A	1
MULT1*	1	TEST4090I	2227.5	N/A	N/A	1
MULT2*	2	TEST0468DEF	2212.5	2221.5	N/A	1
MULT3*	3	TEST3268DEF	2247.5	2247.5	2247.5	1
MULT4*	3	TEST8625DEF	2247.5	2247.5	2247.5	1
MULT5*	3	TEST4961DEF	2262.5	2262.5	2267.5	1
MULT6*	2	TEST0420DEF	2204.5	2204.5	N/A	1

Table A-6: Packet Error Ratio Test Sequences

Seq #	Command Type	IRON	U/L Freq (MHz)	D/L Freq (MHz)	Priority
COM1	SGLS	TEST8625DEF	1811.7	2262.5	1
COM2	SGLS	TEST1399C	1815.7	2262.5	3
COM3	SGLS	TEST4090I	1783.7	2227.5	1
COM4	SGLS	TEST3268DEF	1799.7	2247.5	1
COM5	SGLS	TEST9757S	1763.7	2202.5	1
COM6	SGLS	TEST4262DEF	1791.7	2237.5	3
COM7	SGLS	TEST0164A	1823.7	2277.5	2
COM8	NSGLS	TEST4916DEF	1765.3	2204.5	2
COM9	NSGLS	TEST9199DEF	1810.6	2261.1	1
COM10	SGLS/ TERN	TEST2167E	1791.7	2237.5	2
COM11	SGLS/ TERN	TEST2167F	1791.7	2237.5	3
COM12	SGLS/ EXU	TEST6911A	1787.7	2232.5	3
COM13	NSNRZM/ BI/NRZM	TEST6910D	1764.3	2203.3	2
MULT1*	SGLS	TEST4090I	1783.7	2227.5	1
MULT2*	SGLS	TEST0468DEF	1823.7	2212.5	1
MULT3*	SGLS	TEST3268DEF	1763.7	2247.5	1
MULT4*	SGLS	TEST8625DEF	1799.7	2247.5	1
MULT5*	SGLS	TEST4961DEF	1811.7	2262.5	1
MULT6*	SGLS	TEST0420DEF	1765.3	2204.5	1

Table A-7: Interference Detection Test Sequences

Seq #	IRON	U/L Freq (MHz)	D/L Freq (MHz)	Jam Type	Priority	Signal /Jam Ratio
SWIFT1	TEST6910D	1811.7	2262.5	N/A	1	N/A
SWIFT2	TEST6910D	1783.7	2227.5	N/A	2	N/A
SWIFT3	TEST6910D	1763.7	2202.5	N/A	2	N/A
Baseline1	TEST6910D	1811.7	2262.5	N/A	1	N/A
Baseline2	TEST6910D	1783.7	2227.5	N/A	2	N/A
Baseline3	TEST6910D	1763.7	2202.5	N/A	2	N/A
Measure1	TEST6910D	N/A	N/A	N/A	1	N/A
Measure2	TEST6910D	N/A	N/A	N/A	2	N/A
Measure3	TEST6910D	N/A	N/A	N/A	2	N/A
INTER1	TEST6910D	1811.7	2262.5	AWGN	1	15 dB
INTER2	TEST6910D	1783.7	2227.5	AWGN	1	12 dB
INTER3	TEST6910D	1763.7	2202.5	AWGN	1	9 dB
INTER4	TEST6910D	1811.7	2262.5	TONE	1	6 dB
INTER5	TEST6910D	1783.7	2227.5	TONE	1	3 dB
INTER6	TEST6910D	1763.7	2202.5	TONE	1	0 dB

Table A-8: Ranging Accuracy Test Sequences

Seq #	IRON	D/L Freq (MHz)	Priority
RNG1	TEST8625DEF	2262.5	1
	TEST8625DEF	2262.5	±
	TEST8625DEF	2262.5	±
	TEST8625DEF	2262.5	±
	TEST8625DEF	2262.5	±
RNG2	TEST3268DEF	2247.5	1
	TEST3268DEF	2247.5	±
	TEST3268DEF	2247.5	±
	TEST3268DEF	2247.5	±
	TEST3268DEF	2247.5	±
RNG3	TEST0925DEF	2237.5	2
RNG4	TEST4916DEF	2204.5	1
MULT4*	TEST8625DEF	2247.5	1
MULT5*	TEST4961DEF	2262.5	1
MULT6*	TEST0420DEF	2204.5	1

Table A-9: Range Rate and Doppler Accuracy Test Sequences

Seq #	IRON	D/L Freq (MHz)	Priority
DOP1	TEST8625DEF	2262.5	1
DOP2	TEST3268DEF	2247.5	1
DOP3	TEST4916DEF	2204	1
MULT4*	TEST8625DEF	2247.5	1
MULT5*	TEST4961DEF	2262.5	1
MULT6*	TEST0420DEF	2204.5	1

Table A-10: Dynamic Signal Strength Test Sequences

Seq #	IRON	Tracking Freq	Transponder Usage	Priority
SS#1	TEST0420DEF	2252.5	only enable Swift radio, adjust attenuator as instructed	1
SS#2	TEST0420DEF	2252.5	only enable Innoflight1, Set Innoflight1 to 30dB, adjust attenuator as instructed	1
SS#3	TEST0420DEF	2252.5	only enable Innoflight1, Set Innoflight1 to 21dB, adjust attenuator as instructed	1
SS#4	TEST0420DEF	2252.5	only enable Innoflight1, Set Innoflight1 to 14dB, adjust attenuator as instructed	1
SS#5	TEST0420DEF	2252.5	only enable Innoflight1, Set Innoflight1 to 7dB, adjust attenuator as instructed	1
SS#6	TEST0420DEF	2252.5	only enable Innoflight1, Set Innoflight1 to 0dB, adjust attenuator as instructed	1

Table A-11: Crosstalk Ratio Test Sequences

Seq #	IRON	Tracking Freq (MHz)	D/L Power (dBm)	Priority
AP#1	TEST6910D	2202.5	-115	1
AP#2	TEST2167E	2252.5	-115	1
AP#3	TEST4090I	2277.5	-115	1
AP#4	TEST8625DEF	2202.5	-115	1
AP#5	TEST167E	2252.5	-115	1
AP#6	TEST4090I	2277.5	-115	1
AP#7	TEST0420DEF	2202.5	-115	2
AP#8	TEST2167E	2252.5	-115	2
AP#9	TEST4090I	2277.5	-115	2
AP#10	TEST8625DEF	2202.5	-115	2
AP#11	TEST2167E	2252.5	-115	2
AP#12	TEST4900I	2277.5	-115	2
AP#13	TEST8625DEF	2202.5	-95	2
AP#14	TEST8625DEF	2202.5	-70	2
AP#15	TEST2167E	2252.5	-95	2
AP#16	TEST2167E	2252.5	-70	2
AP#17	TEST4090I	2277.5	-95	2
AP#18	TEST4090I	2277.5	-70	2

Table A-12: Antenna Pattern Test Sequences

Seq #	IRON	Tracking Freq	Power	Priority
AN#1	TEST6910D	2202.5	-90	1
AN#2	TEST2167E	2252.5	-90	1
AN#3	TEST4090I	2277.5	-90	1

APPENDIX B – DATA ANALYSIS

REQUIRED DATA AND DATA SOURCE

Required Data

SPHINX System and Ground Station Data

The primary source of data from the system under test came from the SPHINX payload's internal hardware and the SOCSIM log files from the ground station. The SPHINX payload stored data related to received and transmitted signal information. These data were stored in individual files for each test sequence and were downloaded from the SPHINX payload to external hard drives after each sortie. This source of data was stored as time-series data within .csv and .txt data files. The ground station log files were also downloaded as .csv and .txt files after each sortie. The test team utilized existing processes established by the Aerospace Corporation to extract, process and analyze these data.

The SPHINX payload GUI also presented limited data to the operator during execution through its direct user interface. This system was predominately used during test execution to ensure the test sequence had been properly set up and was executing properly. The GUI also enabled the airborne test conductor to provide real time feedback to the ground station regarding system performance and test execution. Critical pieces of data presented on the interface were:

Table B-1: Displayed SPHINX Interface Parameters

Parameter Name	Parameter Information
Innoflight Transponder #1	RSSI value (dBm)
Innoflight Transponder #2	RSSI value (dBm)
Swift Transponder	RSSI value (dBm)
Switch Matrix	System Health
Interference Generator	System Health
GPS Receiver	System Health
Command Window Signal	Sequence execution / initialization success Valid/Invalid packets received
Location (Lat / Long / Alt)	Current location
Date / Time	Current date and time
Attenuation	Current attenuation value
Test Sequence Command Input	Test sequence number (e.g. COM1, COM2, etc.)

After each sortie, the log files from the SPHINX payload and ground station were be downloaded as .txt and .csv files onto test team hard drives. The following table summarizes the names and contents of each of these files for the ground station.

Table B-2: SOCSIM Log Files

File Name and Format	Parameters	Sample Rate
CXAGC1.csv	Signal power received (dBm) and processed by digital signal processor 1	50 Hz
CXAGC2.csv	Signal power received (dBm) and processed by digital signal processor 2	50 Hz
CXAGC3.csv	Signal power received (dBm) and processed by digital signal processor 3	50 Hz
CXDOP1.csv	Doppler values (Hz) received and processed by digital signal processor 1	1 Hz
CXDOP2.csv	Doppler values (Hz) received and processed by digital signal processor 2	1 Hz
CXDOP3.csv	Doppler values (Hz) received and processed by digital signal processor 3	1 Hz
CXRNG1.csv	Range values (nanoseconds and nautical miles) received	1 Hz
EPOCH.csv	Auto track Status (2 or blank)	50 Hz
SOC_LOG.txt	Ordinal list of command sequences processed by the ground station antenna	

The following table identifies the .txt files produced by the SPHINX payload and downloaded after each sortie:

Table B-3: SPHINX Text Files

File Name and Format	Parameters	Sample Rate
Cmd_window_hist	Ordinal list of command sequences processed by the SPHINX payload	--
GPS_hist	Latitude, Longitude, and Altitude (m) of SPHINX payload	3 Hz
Inno1_hist	Innoflight transponder data organized, stored in alternating rows of data. One row per Innoflight transponder.	10 Hz
Swift_hist	Swift transponder data organized.	10 Hz

In addition to the automatically generated log files, the airborne test conductor also downloaded .txt files after each sortie of any error logs which were presented in the command window or printouts within the command window requested by the ground station crew. These commands were pasted into .txt files and given to the contractor.

Reference Data

The test also collected aircraft FINS data for use as a Time, Space, Positional Information (TSPI) reference. The parameters for the FINS data were provided by the 586th FLTS and are outlined in the C-12J 86-0080 Interface Control Document. An operator from the 586th FLTS flew on each sortie was assisted the test team in downloading the appropriate FINS data at the culmination of each sortie. The table below presents the parameters available within the C-12J FINS data files.

Table B-4: Available C-12J FINS Parameters

Date (YYYYMMDD)	Yaw (deg)	True Ground Track (deg)
Time (UTC sec/day)	Roll (deg)	Ground Speed (knots)
Event Number	Pitch (deg)	Wind Direction (deg)
Latitude (deg)	Yaw Rate (deg/sec)	Wind Speed (knots)
Longitude (deg)	Roll Rate (deg/sec)	Shadin Encoder Altitude (ft)
MSL Altitude (ft)	Pitch Rate (deg/sec)	Target Latitude (deg)
Velocity (ft/sec)	TRUE Heading (deg)	Target Longitude (deg)
Y Velocity (ft/sec)	Mag Heading (deg)	Target HAE Altitude (ft)
Z Velocity (ft/sec)	Velocity East (ft/sec)	Target Selection (#)
X Acceleration (ft/sec ²)	Velocity North (ft/sec)	
Y Acceleration (ft/sec ²)	Velocity Up (ft/sec)	
Z Acceleration (ft/sec ²)	Figure of Merit (Bld, GPS, INS)	

At the culmination of the test, the FINS data was found to not be a viable source of truth data. The FINS data had an error that resulted in GPS positional errors which could not be resolved or utilized by the test team. The positional errors were not consistent between or within sorties. Figure B-1 illustrates where reduced FINS data reported the C-12 as being located, when in reality the aircraft was within the W-532 area off the coast of Vandenberg. Due to the identified errors with FINS positional data the remainder of the FINS data was not used for the analysis.

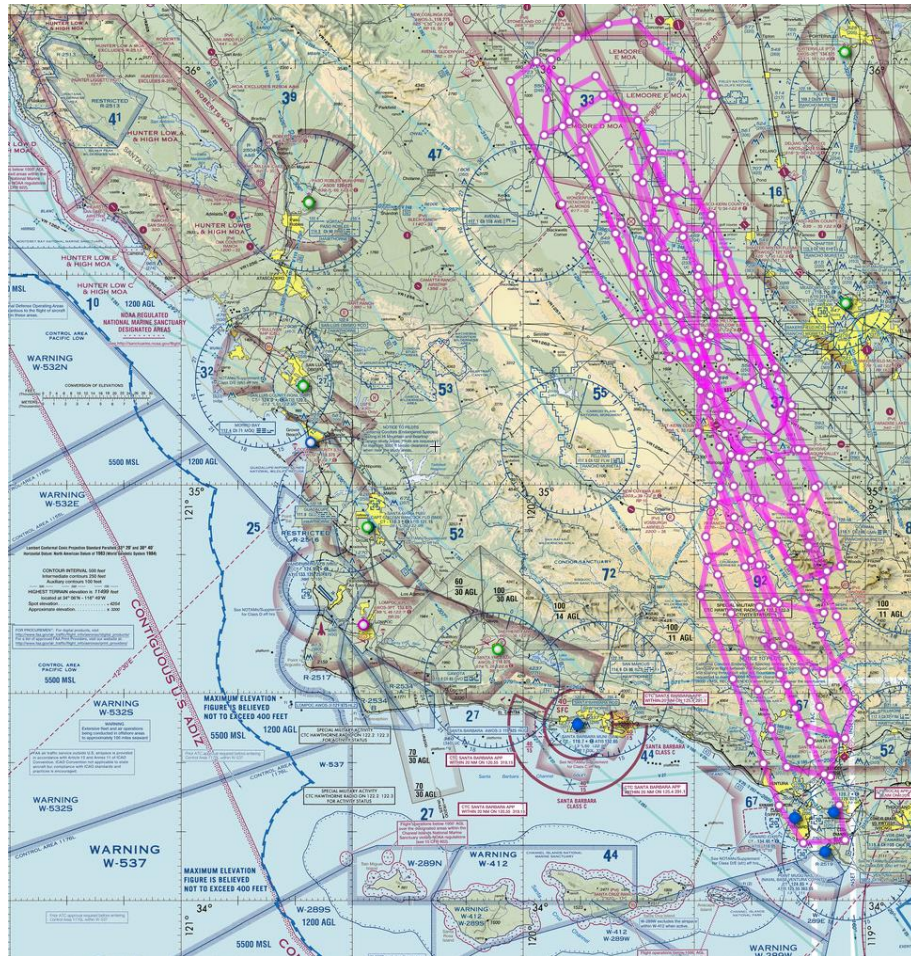


Figure B-1: Plotted FINS Data

The SPHINX payload GPS was utilized as the best alternative truth source in the place of the FINS data. While the data was recorded within the SPHINX payload, the GPS itself was the same GPS antenna as the FINS system. There was no skew or drift identified within the SPHINX recorded GPS data.

DATA REDUCTION

Auto track

The percent of time the VTS maintained auto track of the SPHINX system was determined by dividing the amount of time the system maintained a good auto track into the total amount of time the sequence was running.

$$\text{Autotrack Success Rate} = \frac{\text{Positive Autorack} - \text{Negative Autotrack}}{\text{Length of Test Sequence}}$$

Auto track status was a variable extracted from the SOCSIM data files. The SOCSIM recorded data every three seconds regarding the auto track status. The auto track status could be one of three values: 0 for no auto track, 1 for attempting to auto track, and 2 for successful auto track.

Uplink Signal Power

During uplink signal power test sequences, the uplink signal power was determined by analyzing the Received Signal Strength Indicator (RSSI) found within embedded SOCSIM log files. The SPHINX system recorded a variety of parameters every three seconds and stored the files within the *inno1_his* text file which logs Innoflight transponder data. The text file contents were extracted and time correlated with data files from the SOCSIM. The minimum, maximum and average uplink signal strength was calculated using the average RSSI values during uplink test sequences while the VTS had a positive auto track of the SPHINX payload. Table B-5 summarized the parameters recorded by the SPHINX payload.

Table B-5: SPHINX Parameters

[2021-03-10 20:58:35.500000]:
<<< {'rsp_code': '36'
'version_mss': ['08' '33' '25' 'ce']
'version_fabric': ['57' '0a' '17' '1d']
'sleep_time': ['00' '00']
'wake_time': ['ff' 'ff']
'demod_lock': ['00']
'rssi': -124.75
'uplink_mode': ['00']
'uplink_data_encoding': ['20']
'uplink_frequency': 178374022
'uplink_sym_rate': 2000
'uplink_valid_count': 3892
'uplink_invalid_count': 579202
'downlink_mode': ['00']
'downlink_encoding': '100000'
'downlink_freq': 222749999
'downlink_sym_rate': 32000
'downlink_valid_count': 0
'downlink_invalid_count': 0
'downlink_power_setpoint': ['05' 'dc']
'downlink_attenuation': ['00' '00']
'xmit_enabled': ['00']
'downlink_key_time': ['00' '00']
'fe_tx_fwd_power': ['ff' 'ff' '70' '0e']
'ranging_rate': ['00' '00' '03' 'e8']
'ranging_mode': ['00']
'ranging_key_time': ['00' '00']
'prbs_test_mode': ['00']}]

Downlink Signal Strength

A similar process was utilized to determine the downlink signal strength. The data from the SOCSIM and SPHINX payload were time correlated. The reported downlink signal status was averaged for observations where the recorded downlink signal power was above the noise floor of -200 db. The following equation was used to determine the average downlink signal power of n observations:

$$\text{Average Downlink Signal Power} = \frac{\sum_n^1 \text{Downlink Signal Power}_n}{n}$$

As with uplink signal power, the downlink signal power was only calculated during periods of time when the ground station was successfully auto tracking the SPHINX system

Packet Error Rate

Packet error rate was determined by comparing the number of packets transmitted from the ground station to the number of packets received by the SPHINX system.

The following SPHINX data, Table B-6, were extracted from the flight logs during test sequences in which packets were uplinked from the VTS.

Table B-6: SPHINX Parameters

Parameter Name	Parameter Meaning	Required Value for successful packet uplink
DEU_AUTO_TRACK_STATUS	Auto track status of ground station antenna	2
RHPA_RF_PWR_AVG_FWD_WATTS	Ground station high power amplifier uplink power	> 0
RHPA_RF_OUTPUT_SEL	Destination for Uplink Signal	0
1IFM1_IF_CARR	Intermediate Frequency Modulator (IFM) Carrier Status	1
1IFM1_MOD_SIGNL_TMS1	Intermediate Frequency Modulation Telemetry Simulator Status	1

The data was then analyzed to identify portions of the test sequence in which command packets were successfully uplinked from the ground station to the SPHINX payload. Once the portions of test sequences which packets were successfully identified, the SPHINX payload logs were investigated to determine whether the packets were received properly or not. The number of valid and invalid packets received by the SPHINX system were recorded every three seconds within the *inno1_hist* text file.

The total number of packets sent during the test sequence was determined by multiplying the amount of time the sequence ran while meeting the parameters outlined in Table B-7 by the number of packets transmitted per second.

$$\text{Packets Sent} = \frac{\text{Uplink Data Rate} \left(\frac{\text{bits}}{\text{second}} \right)}{128 \left(\frac{\text{bits}}{\text{sequence}} \right)} * \text{Length of Sequence (seconds)}$$

The uplink data rate varied between IRONS.

Table B-7: IRON Data Rates

IRON	Uplink Data Rate (bits per second)
0164A	2000
0420DEF	1000
0468DEF	2000
0925DEF	1000
1056R	2000
1399C	1000
2167E	10000
2167F	10000
3268DEF	2000
4090I	2000
4262DEF	1000
4916DEF	2000
6910D	32000
6911A	2000
7117F	10000
8625DEF	1000
9199DEF	2000
9757S	2000

Valid packet ratio was calculated using the following equation:

$$\text{Valid Packet Ratio} = \frac{\# \text{ valid packets}}{\# \text{ packets sent}}$$

Invalid packet ratio was calculated using the following equation:

$$\text{Invalid Packet Ratio} = \frac{\# \text{ invalid packets}}{\# \text{ packets sent}}$$

Missing packet ratio was calculated using the following equation:

$$\text{Missing Packet Ratio} = 1 - \frac{\# \text{ invalid packets} + \# \text{ valid packets}}{\# \text{ packets sent}}$$

Range

The following analysis process was used in order to determine the range of the SPHINX system onboard the C-12J to the VTS antenna. The latitude, longitude, and altitude of the antenna were known. The corresponding parameters of the SPHINX system were collected by the system's GPS antenna and stored within the payload. The aircraft's FINS data were unavailable to be used for analysis. The FINS data were corrupted and reported erroneous values for latitude and longitude. The SPHINX GPS system was federated from aspects of the SPHINX system utilized in reported a range value. For that reason, it was determined that the SPHINX GPS data could be used to determine the range values.

The first portion of the range analysis transform the geodetic coordinates of latitude, longitude, and altitude to the earth-centered earth-fixed coordinate system. This was done for both the VTS and the aircraft.

Aircraft and VTS position data were correlated and the lowest recorded frequency of one observation per three seconds. Minor rounding errors, of less than 100 milliseconds, were induced into the analysis to correlate the data. After the parameters were converted into the correct coordinate system, vector subtraction was done to determine the slant range between the VTS and the aircraft for each observation. The relative azimuth and elevation, which were not parameters requested by the Aerospace Corporation, were determined using the trigonometry outlined in the python script below²³.

```
def GEOD2ECEF(latitude, longitude, height):
    """
    Transforms Geodetic Coordinates to Earth-Centered Earth-Fixed Coordinate system
    Inputs:
        latitude          North Latitude          degrees
        longitude         East Longitude          degrees
        height            Height above Sea Level   meters

    Outputs:
        X,Y,Z            ECEF coordinate system    meters
    """
    phi = np.deg2rad(latitude) # Convert latitude to radians for trigonometric functions
    lam = np.deg2rad(longitude) # Convert longitude to radians for trigonometric functions
    h = height # geodetic height above sea level in meters

    N = (a ** 2) / np.sqrt(
        (a ** 2) * np.cos(phi) ** 2 + (b ** 2) * np.sin(phi) ** 2) # Calculate the prime vertical radius
    of curvature

    X = (N + h) * np.cos(phi) * np.cos(lam) # Calculate X position in ECEF
    Y = (N + h) * np.cos(phi) * np.sin(lam) # Calculate Y position in ECEF
    Z = ((b ** 2 / a ** 2) * N + h) * np.sin(phi) # Calculate Z position in ECEF

    return X, Y, Z

def make_APA_2(lat1, lon1, alt1, lat2, lon2, alt2):
    # Convert each location to ECEF
    phi1, lambda1, h1 = lat1, lon1, alt1
    phi2, lambda2, h2 = lat2, lon2, alt2

    X1, Y1, Z1 = GEOD2ECEF(phi1, lambda1, h1 * 1000)
    X2, Y2, Z2 = GEOD2ECEF(phi2, lambda2, h2 * 1000)

    # Find the vector between the two locations
    dx, dy, dz = X2 - X1, Y2 - Y1, Z2 - Z1

    x = -dx * np.sin(np.deg2rad(lambda1)) + dy * np.cos(np.deg2rad(lambda1))
    y = -dx * np.sin(np.deg2rad(phi1)) * np.cos(np.deg2rad(lambda1)) - dy *
    np.sin(np.deg2rad(phi1)) * np.sin(np.deg2rad(lambda1)) + dz * np.cos(np.deg2rad(phi1))
    z = dx * np.cos(np.deg2rad(phi1)) * np.cos(np.deg2rad(lambda1)) + dy *
    np.cos(np.deg2rad(phi1)) * np.sin(np.deg2rad(lambda1)) + dz * np.sin(np.deg2rad(phi1))
```

² Geyer, Michael. Earth-Referenced Aircraft Navigation and Surveillance Analysis, *Federal aviation Administration*. June 2016.

³ Calculating Tunnel Distance between Two Coordinates, *MATHEMATICS Stack Exchange*, May 2018.

```

el = 90 - np.rad2deg(np.arccos(z / np.sqrt(x ** 2 + y ** 2 + z ** 2)))
az = np.rad2deg(np.arctan2(x, y))
rng = np.sqrt(dx ** 2 + dy ** 2 + dz ** 2)

if az < 0:
    az += 360

return az, el, rng

```

The range value was then corrected for associated time delays inherent within the VTS and SPHINX systems which were identified by the Aerospace Corporation. The time delay was provided by the Aerospace Corporation in nanoseconds. This value was converted to meters through the speed of sound. This range bias was removed from the calculated range values. The mean range error was determined by calculating the average ratio of VTS computed range to the calculated true range.

A statistical test was conducted to determine whether or not the north-bound and south-bound legs of the flight profile resulted in statistically identical range errors. The statistical test was conducted by computing the mean and standard deviation for each population sample relative to a portion of the flight profile. These parameters were compared to one another at the 95% confidence level by subtracting the confidence interval produced by each sample mean and standard deviation. They were not found to be statistically identical at the 95% confidence level.

Range Rate and Doppler Shift

The range rate and Doppler shift were calculated using the calculated range values and the time interval between observations. The time interval between observations was three seconds. The range values used were corrected for time delays within the VTS and SPHINX system, as explained above.

$$Range\ Rate = \frac{Range_1 - Range_0}{Time\ Interval} \ (m/s)$$

The Doppler shift was determined using the one-way Doppler equation. The range rate was multiplied by the frequency of the associated test sequence and scaled by the speed of light.

$$Doppler\ Shift = - \frac{Range\ Rate * frequency}{Speed\ of\ Light} \ (Hz)$$

APPENDIX C – DAILY REPORTS

DAILY REPORT: 8 MAR 2021

The HAVE TACOS team successfully executed day 1 of SPHINX Payload testing. The team flew 4.2 hrs in the C-12J, successfully completing four test sequences. Table below summarizes the attempted test points (sequences)

Date	Test Point (Sequence)	Status	Notes	Antenna
8 Mar 21	TK3	COMPLETE	First successful auto track of SPHINX! (Happy Taco)	Hybrid
	TK1	INCOMPLETE	Attempted on RTB, unsuccessful sync	Hybrid
	UP1	COMPLETE	Successful increase in RSSI for both SCR-104 Transponders	Hybrid
	UP2	INCOMPLETE	Unable to turn SWIFT transponder on	Hybrid
	DL1	COMPLETE	Attenuation level varied FTE between 5-30 before track lost	Hybrid
	ATTN1	INCOMPLETE	All transponders on same frequency – resulted in interference and inability to auto track	Hybrid
	ATTN2	INCOMPLETE	All transponders on same frequency – resulted in interference and inability to auto track	Hybrid
	ATTN3	INCOMPLETE	All transponders on same frequency – resulted in interference and inability to auto track	Hybrid
	SS1	INCOMPLETE	All transponders on same frequency – resulted in interference and inability to auto track	Hybrid
	SS2	INCOMPLETE	All transponders on same frequency – resulted in interference and inability to auto track	Hybrid
	SS6	COMPLETE	Successfully auto tracked SPHINX with one SCR-104 transponder w/ attenuation levels set between 5-60 (max attenuation)	Hybrid

Lessons Learned:

- Start of the Antenna down time is the earliest time we will have the ability setup for the test. Today, this resulted in the aircraft taking off before the VTS was ready for the test. However, the transit time to the working area allowed for the VTS to be setup in route. Aircraft pre-taxi procedures were shorter than expected, resulting in the aircraft taking off 17 minutes early.
 - o Mitigation - none

- TC does not have ability to see RBC summary screen from the radio station – all communication needed to be relayed from VTS operator to TC to aircraft. Aircrew commented on how they felt they didn't have enough SA into what was happening during the test.
 - o Mitigation – increase communication between VTS Op and TC to keep TC and the aircrew in the loop on test happenings
- Minor issues observed in the SPHINX sequences. Issues included:
 - o Defaulting attenuation levels to levels too low for signal acquisition
 - o Having multiple transponders transmitting on the frequency, resulting in downlink interference
 - o SWIFT transponder in-op for certain sequences where it was expected to be operating
 - Mitigation – Aerospace tracking issues and will re-code before the next flight.
- Current flight profile placed aircraft within 3nm of W-532 border, which prompted calls from the airspace controller for immediate turns
 - o Mitigation – update profile to have shorter legs that provide ~7nm between the turns and the airspace border
- Lack of precise antenna pointing angles impacted efficiency, with transit up to 10 min to a known waypoint to re-establish auto track after lost track.
 - o Mitigation 1 - add two additional “get well” points to the profile (one extra point on each leg) to cut the transit time to the next waypoint of interest by half.
 - o Mitigation 2 – provide Aerospace with distance and approximate times between waypoints to enable them to program the VTS generate antenna pointing angles to match the flight profile of the aircraft (i.e. point where it thinks the aircraft is) to increase the probability of auto track at anticipated acquisition waypoint.
- For the DL and SS sequences, attenuator level expected/set on the SPHINX payload was not clearly communicated between the FTE and TC/VTS operator.
 - o Mitigation – start test sequences at low attenuation levels and manually increase attenuation; include attenuation levels for each point in the test cards, and have the FTE communicate the attenuator level to the VTS team.

Actions:

- (TPS) Update cards with new profile
- (TPS) Update cards with more standard comm for attenuator settings
- (TPS) Provide new waypoints and anticipated time between waypoints to Aerospace
- (Aerospace) Investigate sequences with issues found during the day 1 flight

V/r,

Blake “BANDIT” Morgan, Capt, USAF

Student, USAF TPS Class 20B

DAILY REPORT: 9 MAR 2021

The HAVE TACOS team successfully executed day 2 of SPHINX Payload testing. The team flew 4.4 hrs in the C-12J, successfully completing 11 of 14 attempted test sequences. Table below summarizes the attempted test points (sequences)

Date	Sequence	Priority	Antenna	Status	Notes
9-Mar-21	DL1	1	Hybrid	COMPLETE	
	UP1	1	Hybrid	INPROGRESS	Took two runs to get to work, successfully passed packets from ground station to SPHINX but identified Will reattempt on the next sortie.
	UP2	1	Hybrid	INCOMPLETE	Will reattempt after successful UP1
	ATTN1	1	Hybrid	COMPLETE	Successfully accomplished ATTN1-5
	ATTN2	1	Hybrid	COMPLETE	
	ATTN3	1	Hybrid	COMPLETE	
	ATTN4	1	Hybrid	COMPLETE	
	ATTN5	1	Hybrid	COMPLETE	
	ATTN6	1	Hybrid	COMPLETE	Successfully evaluated variety of attenuation values for ATTN6, incremented attenuation until we successfully found the limit.
	TK3	1	Hybrid	COMPLETE	Successfully accomplished track sequence 3 and later sequence 1.
	TLM1	1	Hybrid	COMPLETE	
	SS1	1	Hybrid	COMPLETE	
	SS2	1	Hybrid	COMPLETE	
	SS3	1	Hybrid	Not Required	Having accomplished SS1 and SS2 determined no need to accomplished SS3-6.
	SS4	1	Hybrid	Not Required	
	SS5	1	Hybrid	Not Required	
	SS6	1	Hybrid	Not Required	
	TK1	2	Hybrid	COMPLETE	
	TK8	2	Hybrid	INCOMPLETE	System errors during TK8 that we ran out of test time to be able to debug, will incorporate into following sortie plan.

Lessons Learned

- First time around the racetrack pattern we timed the flight from waypoint to waypoint which provided a lot of SA in the control room, have incorporated doing that into future sorties and into the cards. The new plan should also remove the confusion on the ground of trying to sync up aircraft takeoff time and VTS availability and make for more efficient use of our antenna downtime henceforth.
- Determined more appropriate rendezvous point (foxtrot) which will enable better geometry setup for the pilots, have incorporated the new plan into future sorties

Action

- (Aerospace) Planning to make some small adjustments to the code to clarify some questions that came up (changing values to N/A when no value is expected)

Plan for tomorrow involves attempting some new track sequences and telemetry lock status sequences as well as reattaching uplink 1 and uplink 2. We will also begin to investigate packet error ratio sequences.

Capt Hamm

DAILY REPORT: 10 MAR 2021

The following sequences were executed. No notable issues occurred.

Date	Sequence	Antenna	IRON	Status	Notes
10-Mar-21	TK6	Hybrid	9757S	Good	
	TK2	Hybrid	2167E	Good	
	TK1	Hybrid	8625DEF	Good	
	UP1	Hybrid	1056R	Good	
	UP2	Hybrid	6910D	Good	
	TK1	Hybrid	8625DEF	Good	
	TLM1	Hybrid	4090I	Good	
	TLM8	Hybrid	9757S	Good	
	TLM15	Hybrid	2167E	Good	
	TLM4	Hybrid	8625DEF	Good	
	TLM5	Hybrid	8625DEF	Good	
	COM1	Hybrid	8625DEF	Good	
	COM3	Hybrid	4090I	Good	
	COM4	Hybrid	3268DEF	Good	
	COM5	Hybrid	9757S	Good	

Continue with tomorrow's planned sequences.

Josh "Viper" Judy, Capt, USAF

TPS Student WSO, Class 20B

DAILY REPORT: 11 MAR 2021

The HAVE TACOS team successfully executed day 4 of SPHINX Payload testing. The team flew 4.7 hrs in the C-12J, successfully completing 11 of 11 attempted test sequences. Table below summarizes the attempted test points (sequences)

Date	Sequence	Priority	Antenna	Status	Notes
11-Mar-21	TK4	1	Hybrid	GOOD	No issues
	TK11	1	Hybrid	GOOD	Executed twice, second time was to practice manual track procedures required for antenna performance testing
	RNG1	1	Hybrid	GOOD	Range data passed the “sniff” check
	RNG2	1	Hybrid	GOOD	Range data passed the “sniff” check
	RNG3	1	Hybrid	GOOD	Range data passed the “sniff” check
	DOP1	1	Hybrid	GOOD	Range rate/Doppler data passed the “sniff” check
	DOP2	1	Hybrid	GOOD	Range rate/Doppler data passed the “sniff” check
	DOP3	1	Hybrid	GOOD	Range rate/Doppler data passed the “sniff” check
	TLM8	1	Hybrid	GOOD	No issues
	TLM10	1	Hybrid	GOOD	No issues
	UP2	1	Hybrid	GOOD	First successful attempt of UP2 – successfully sent packets up to the SPHINX SWIFT transponder.

Lessons Learned

- We executed sequences faster than expected and didn’t have backup sequences in the cards to execute that lined up with Aerospace’s priorities.
 - Mitigation – Brief in the morning that every test sequence is on the table (from the aircrew side, this changes nothing but what sequence the FTE selects on the SPHINX gui). Aircrew will take the cover card and a table of sequences onboard the aircraft. The VTS team will have a copy of the complete card deck and will walk the FTE through any sequences NOT originally planned for the profile.
- Possible comm out condition at point D, very minor – only about 30 seconds
 - Mitigation – none
- Aerospace Team used the last hour of the sortie for flush out program track, which is required for antenna performance testing. This allowed the Aerospace team to develop procedures to effectively and efficiently execute the antenna performance testing on 12 Mar.
- Some minor issues were observed with the range sequences chip rates. The SPHINX radios were not programmed for chip rates other than 1Mb/s.
 - Mitigation – Aerospace will recode the SPHINX radios to accept range commands at chip rates other than 1Mb/s. They will also add lines in the command window to display to the operator the radio chip rate.

Action

- (Aerospace) make adjustments to the SPHINX code to allow the radios to receive chip rates at rates other than 1Mb/sec
- (Aerospace) provide the SPHINX operator with information as to what chip rate the SPHINX is transmitting at.

Plan for 12 Mar 21

First day of Antenna performance testing! Plan to execute Crosstalk ratio (AP1, AP2, AP3) and downlink signal power (AN1, AN2, AN3)

Bandit

DAILY REPORT: 17 MAR 21

Testing resumed after maintenance issues with the C-12J. The following sequences were executed:

Date	Sequence	Antenna	IRON	Status	Notes
17-Mar-21	UP2	RBC	6910D	Good	
	MULTI7	RBC	2167E	Good	
	MULTI8	RBC	9757S	Good	
	MULTI9	RBC	0164A	Issue	CMD packets not increasing when ranging
	MULTI10	RBC	6910D	Good	
	MULTI1	RBC	4090I	Good	
	MULTI2	RBC	0468DEF	Good	
	RNG1	RBC	8625DEF	Good	1Mcps
	RNG2	RBC	3268DEF	Good	1Mcps
	RNG4	RBC	4916DEF	Good	1Mcps
	DOP1	RBC	8625DEF	Good	1Mcps
	DOP2	RBC	3268DEF	Good	1Mcps
	DOP3	RBC	4916DEF	Issue	1Mcps; No Doppler
	RNG1	RBC	8625DEF	Good	CH2=500kps
				Good	CH3=250kps
				Good	CH4=125kps
	AP1	RBC	8625DEF	Issue	Very difficult to program track
	AN1	RBC	8625DEF	Issue	Very difficult to program track
	COM9	RBC	9199DEF	Good	
	MULTI7	RBC	2167E	Good	
	MULTI8	RBC	9757S	Good	
	MULTI9	RBC	0164A	Issue	Had trouble ranging; not increasing packets
	MULTI10	RBC	6910D	Issue	Did not work
	MULTI1	RBC	4090I	Good	
	MULTI2	RBC	0468DEF	Good	

The RBC antenna had issues running multiple sequences, and had connection issues all day. After discussing with the Aerospace team, further tests with the RBC antenna are scrapped to focus on completing all remaining test sequences with the Hybrid antenna. Manual tracks for AP1 and AN1 were very difficult for the VTS team to accomplish, and the data isn't complete for a full sequence.

Capt John Hamm

DAILY REPORT: 18 MAR 2021

The following sequences were executed. This was the first day testing SPHINX payload jamming.

Date	Sequence	Antenna	IRON	Status	Notes	S/J Ratio	JSON
18-Mar-21	UP2	Hybrid	6910D	Issue	HPA issue; resolved toward end of event; good at end		
	AP1	Hybrid	6910D	Good	Got two patterns		
	AN1	Hybrid	6910D	Issue	Very difficult to program track still		
	SWIFT1	Hybrid	6910D	Good			
	Baseline1	Hybrid	6910D	Good			
	Measure1	Hybrid	6910D	Good			
	Inter1	Hybrid	6910D	Good	Tone; Needed to manually change S/J - started at 15 (but too high so other INTERs will not work); then changed to 50 dBm and went down incrementally;	S/J:15dB	JSON#2
	Inter1	Hybrid	6910D	Issue	DRFM; look at Cesium-Astro SDR/SWIFT tonight	S/J:15dB	
	Inter1	Hybrid	6910D	Good	Tone; Needed to manually change S/J - started at 15 (but too high so other INTERs will not work); then changed to 50 dBm and went down incrementally;	S/J:15dB	JSON#4
	Inter1	Hybrid	6910D	Issue	DRFM; look at Cesium-Astro SDR/SWIFT tonight	S/J:15dB	JSON#5
	Multi3	Hybrid	3268DEF	Good			
	Multi4	Hybrid	8625DEF	Good			
	Multi5	Hybrid	4916DEF	Good			
	RNG1	Hybrid	8625DEF	Good			
	RNG2	Hybrid	3268DEF	Good			
	RNG4	Hybrid	4916DEF	Good			
	DOP1	Hybrid	8625DEF	Good			
	DOP2	Hybrid	3268DEF	Good			
	DOP3	Hybrid	4916DEF	Good			

There were several issues during the test sequences today. The UP2 event had a HPA failure, which required some on-site maintenance actions to fix. AP1 and AN1 both had similar issues as yesterday regarding the manual tracking process, and Aerospace wants to move on from those points due to the difficulty in making a predictive manual track. During the INTER sequences, the S/J ratio was not being decreased as expected, and the DRFM had some data-related issues that Aerospace needs to fix tonight. Aerospace will develop a final list of clean-up test sequences for tomorrow's execution.

Viper

DAILY REPORT: 19 MAR 2021

Final test day! Aerospace provided a list of sequences they wanted to accomplish, focusing on the INTER-INTER6 sequences after making the software fixes overnight.

Date	Sequence	Antenna	IRON	Status	Notes	S/J	JSON/Delay
19 Mar 21	MULTI5	Hybrid	4916DEF	Good			
	SWIFT1	Hybrid	6910D	Good			
	Baseline1	Hybrid	6910D	Good			
	Inter1	Hybrid	6910D	Good	DRFM	S/J:15dB	JSON#3
	Inter2	Hybrid	6910D	Good	DRFM	S/J:12dB	300 ms Delay
	Inter3	Hybrid	6910D	Good	DRFM	S/J: 9dB	Changed to 800ns for 19 Mar
	Inter4	Hybrid	6910D	Good	DRFM	S/J: 6dB	
	Inter5	Hybrid	6910D	Good	DRFM	S/J: 3dB	
	Inter6	Hybrid	6910D	Good	DRFM	S/J: 0dB	
	Inter4	Hybrid	6910D	Good	DRFM	S/J: 6dB	
	Inter5	Hybrid	6910D	Good	DRFM	S/J: 3dB	
	Inter6	Hybrid	6910D	Good	DRFM	S/J: 0dB	
	Multi6	Hybrid	0420DEF	Issue	Analysis needed for Commanding/Ranging problem		
	Multi1	Hybrid	4090I	Issue	Analysis needed for Commanding/Ranging problem		

The INTER sequences all worked correctly today. Further analysis will be required for some data anomalies that the VTS engineers saw while executing MULTI6 and MULTI1.

Test complete! The C-12J has returned to Holloman AFB.

Bandit

APPENDIX D – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

<u>Abbreviation</u>	<u>Definition</u>	<u>Units</u>
ADS-B	Automatic Dependent Surveillance-Broadcast	---
APA	Antenna Pointing Angle	---
COTS	Commercial Off-the-Shelf	---
DSP	Digital Signal Processor	---
FINS	Fighter Inertial Navigation System	---
FLTS	Flight Test Squadron	---
FMS	Flight Management System	---
FTE	Flight Test Engineer	---
GTO	General Test Objective	---
GPS	Global Positioning System	---
GUI	Graphical User Interface	---
HPA	High-Power Amplifier	---
IRON	Inter-Range Operations Number	---
KIAS	Knots Indicated Airspeed	---
MSL	Mean Sea Level	---
PDU	Power Distribution Unit	---
RBC	Remote Tracking System Block Change	---
RSSI	Received Signal Strength Indication	---
SCN	Satellite Control Network	---
SDR	Software Defined Radio	---
SGLS	Space Ground Link System	---
SOC	Space Operations Center	---
SOCSIM	Space Operations Center Simulator	---
SOPS	Space Operations Squadron	---
SPHINX	Satellite Control Network On-Orbit Test Asset	---
STO	Specific Test Objectives	---
TACOS	Test and Check-Out Satellite	---
TMP	Test Management Project	---
TPS	Test Pilot School	---
TSPI	Time, Space, Positional Information	---
TT&C	Tracking, Telemetry, and Control	---
USSF	United States Space Force	---
VTs	Vandenberg Tracking Station	---
2LMES	Two-line Mean Element Set	---

APPENDIX E – LESSONS LEARNED

Overall, the HAVE TACOS test execution underscored the usefulness of an aircraft as a low-cost testbed for testing satellite functions with some limitations. The primary challenge was rooted in the differences between satellites operating in the relative predictability of space versus an aircraft operating in the constantly changing atmosphere.

Multi Domain Challenges

The primary customer for the HAVE TACOS test team was The Aerospace Corporation who have extensive experience building, launching, and controlling satellites in the space domain. This difference in background experience exposed the need to clarify terminology and expectations earlier on in the test planning phase. Satellites are generally kept at one altitude and maintain a straight line track across the sky, leading to predictable and repeatable ground tracks that can be pre-programmed into the ground station to follow in the instance where communications with a satellite was lost. In the case of the aircraft surrogate, the relative velocity (ground speed) and direction of the aircraft relative to the antenna varied throughout the test runs producing a unique challenge for the antenna to track.

Additionally, the aircraft surrogate had to contend with winds and weather aloft which prevented the test team from being able to accurately predict the aircraft's position at a rate of 10 Hz. These 10 Hz predictions were possible for satellites operating in Low Earth Orbit. The customer wanted to test the antenna characteristics using the predicted locations but were unable due to the constantly varying winds aloft which prevented the aircraft from maintaining a precise predicted location at a 0.1 second interval. Clarification of program track requirements and the unique challenges of atmospheric flight could have found this limitation earlier in the test planning process.

Support Equipment

The test team planned to use a commercial FINS racks to provide TSPI data to compare to the data from the SPHINX payload. Initial spot checks showed promising ground tracks but through further post-processing it was determined that the TSPI source was unreliable for multiple flights limiting the utility of comparison between the FINS and SPHINX payload. Future tests should incorporate test sequences earlier into the program where all the required TSPI variables (position, velocity, attitude, etc.) are collected and processed during the test execution window so that errors in the system can be caught prior to the end of the execution window.

The primary support infrastructure for the test was the SCN ground station located at Vandenberg AFB. The ground station was fully-functional and used actively for USSF operations during the test window. When aircraft maintenance issues arose and test execution times had to be adjusted there were instances where test time was limited by the available antenna downtime the team was able to secure. The team would like to emphasize that 22 SOPS were incredibly flexible and accommodating on a very short-notice in providing the team with VTS downtime outside the original test windows.

Additionally, the VTS was setup to communicate with satellites and not aircraft. The team had a plan in place for a dedicated radio-phone circuit to be built in order for the TC to communicate with the aircraft while airborne. Due to the operations tempo at Vandenberg AFB the radio-phone circuit was planned to be built the day prior to execution. The test team had limited access to the ground station prior to test execution and discovered the first day of execution multiple issues with the radio-phone circuit. These issues were quickly corrected, but the test team recommends standing firm on requiring the circuit be built earlier so that the test team could troubleshoot prior to test execution.

While working in the VTS ground station, the test director was able to increase situational awareness for the ground station test team by utilizing a commercial Automatic Dependent Surveillance-Broadcast (ADB-S) tracking website. The ADS-B monitoring website was able to provide the aircraft's position in near real-time which greatly increased the team's ability to initiate/terminate test sequences at specific locations throughout the test orbit.

Airspace Requirements

The primary test area was driven by the requirement to be within line-of-sight of the VTS. The antenna had a minimum pointing angle of five degrees of inclination and was unable to track the aircraft directly overhead the antenna. The Aerospace Corporation defined an area where the aircraft would be trackable by the ground station with the aircraft at 25,000 feet. Due to lower altitude clearance and weather the planned orbits had to be adjusted while still remaining within the confines of the cleared airspace. For future tests, a buffer should be included in the planned orbits relative to planned coverage areas of the ground station. The planned orbit had the aircraft above the minimum inclination angles on the antenna, but the real world antenna angles were lower than minimum causing the VTS to be unable to transmit for short segments of the orbit.

The airspace required for the test was not owned by the Air Force and had a separate scheduling process from the restricted areas surrounding Vandenberg AFB. Due to a misunderstanding, the test team thought the airspace had been scheduled/reserved when it in fact had not been. For future test execution, test teams should follow up and explicitly ask if the ranges/assets are scheduled (to include an ops number) at the earliest possible opportunity (and continue to follow up approaching test execution). The team cannot over-emphasize the need to communicate with outside agencies early and often to prevent misunderstandings earlier in the planning process.

Due to required elevation angles and maximum altitude of the C-12J, testing had to occur within approximately 80 kilometers of Vandenberg AFB. The decision to utilize a civilian airfield near Vandenberg AFB allowed for the test aircraft to climb en-route while minimizing the time spent in orbit to climb to the desired test altitude and also provided the test team with flexibility operations with test windows changing throughout test execution.

APPENDIX F – DISTRIBUTION LIST

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Dr. Wendy Chiado The Aerospace Corporation 7250 Getting Heights Colorado Springs, CO, 80916	1	0	0

APPENDIX G – FLIGHT PROFILES & WAYPOINTS

Based on observations made during the first day of testing, the flight profile and altitude were modified. First, it was determined that the antenna pointing angles around point D and point C were under the five-degree antenna elevation angle requirement for uplink. Second, W-532 airspace controllers were required to provide the aircraft with boundary calls whenever the aircraft was within three miles of the airspace boundary. The turn leg between D and C placed the aircraft within the three-mile boundary call requirement, and the aircrew continually received nuisance boundary callouts from the airspace controllers. Therefore, the long legs of the profile were shortened by removing the end four endpoints. Also, the flight profile altitude was raised to 23,500 feet MSL. The modified profile provided antenna elevation angles of greater than five degrees for all points within the profile, as well as kept the aircraft out of the three-mile boundary call location. The modified profile is shown in Figure G-1.



Figure G-1: Modified Flight Profile (23,500 feet MSL, Sorties 2-5)

The modified flight profile was flown for the next four test sorties. However, for the last two test sorties, the profile was modified again to accommodate other events taking place in W-532. For the last two test sorties, the test team was restricted to the M-1 and M-2 areas within W-532. This required the profile to be moved further east and shortened to adhere to the airspace restrictions. The flight profile altitude was kept

at 23,500 feet MSL since moving the profile closer to the VTS improved antenna elevation pointing angles when compared to the modified profile. The restricted profile is shown in Figure G-2.



Figure G-2: Restricted Profile (23,500 feet MSL, Sorties 6-7)

INITIAL FLIGHT PROFILE (20,000 FEET MSL, SORTIE 1)

Point	Lat	Long
F	34.5737N	121.0858W
	34.5533N	121.0831W
	34.5329N	121.0804W
	34.5125N	121.0737W
	34.4921N	121.0710W
	34.4717N	121.0643W
	34.4513N	121.0616W
	34.4309N	121.0549W
	34.4105N	121.0522W
E	34.3901N	121.0455W
	34.3657N	121.0428W
	34.3453N	121.0401W
	34.3249N	121.0334W
	34.3045N	121.0307W
	34.2841N	121.0240W
	34.2637N	121.0213W
	34.2433N	121.0146W
	34.2229N	121.0119W
	34.2025N	121.0052W
D	34.1821N	121.0025W

Point	Lat	Long
C	34.2038N	120.5100W
	34.2240N	120.5128W
	34.2443N	120.5157W
	34.2645N	120.5225W
	34.2848N	120.5254W
	34.3050N	120.5322W
	34.3252N	120.5350W
	34.3455N	120.5419W
	34.3657N	120.5447W
B	34.3900N	120.5516W
	34.4102N	120.5544W
	34.4304N	120.5612W
	34.4507N	120.5641W
	34.4709N	120.5709W
	34.4912N	120.5738W
	34.5114N	120.5806W
	34.5316N	120.5834W
	34.5519N	120.5903W
	34.5721N	120.5931W
A	34.5924N	121.0000W



MODIFIED FLIGHT PROFILE (23,500 FEET MSL, SORTIES 2-5)

Point	Lat	Long
D	34:22.48	-121:01.32
	34:24.55	-121:01.77
	34:26.62	-121:02.22
	34:28.68	-121:02.67
	34:30.75	-121:03.12
	34:32.82	-121:03.57
	34:34.88	-121:04.02
E	34:36.95	-121:04.47
	34:39.02	-121:04.92
	34:41.08	-121:05.37
	34:43.15	-121:05.82
	34:45.22	-121:06.27
	34:45.28	-121:06.72
	34:49.35	-121:07.17
	34:51.42	-121:07.62
F	34:53.48	-121:08.07

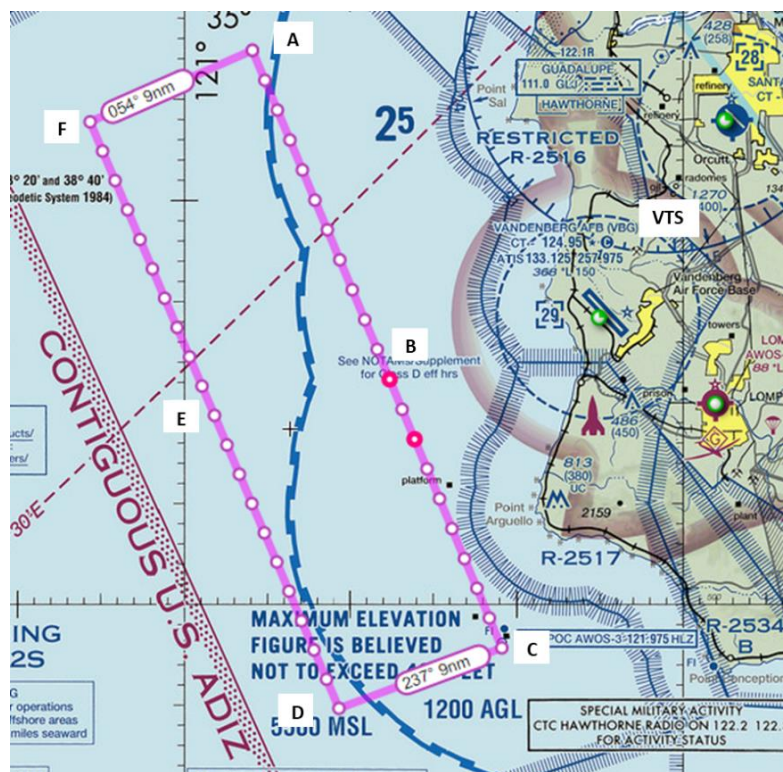
Point	Lat	Long
A	34:55.32	-120:59.05
	34:53.27	-120:58.57
	34:51.23	-120:58.10
	34:49.20	-120:57.63
	34:47.15	-120:57.15
	34:45.12	-120:56.68
	34:43.07	-120:56.20
B	34:41.03	-120:55.73
	34:39.00	-120:55.27
	34:36.95	-120:54.78
	34:34.92	-120:54.32
	34:32.87	-120:53.83
	34:30.83	-120:53.37
	34:28.80	-120:52.90
	34:26.75	-120:52.42
C	34:24.72	-120:51.95



RESTRICTED FLIGHT PROFILE (23,500 FEET MSL, SORTIES 6-7)

Point	Lat	Long
F	34:53.90	-121:05.68
	34:52.45	-121:04.93
	34:51.00	-121:04.18
	34:49.55	-121:03.43
	34:48.08	-121:02.68
	34:46.63	-121:01.93
	34:45.18	-121:01.20
	34:43.73	-121:00.45
	34:42.28	-120:59.70
E	34:40.83	-120:58.95
	34:39.38	-120:58.20
	34:37.92	-120:57.45
	34:36.47	-120:56.70
	34:35.02	-120:55.95
	34:33.57	-120:55.20
	34:32.12	-120:54.45
	34:30.67	-120:53.72
	34:29.20	-120:52.97
D	34:27.75	-120:52.22
	34:26.30	-120:51.47
	34:24.85	-120:50.72

Point	Lat	Long
A	34:57.43	-120:55.92
	34:55.95	-120:55.17
	34:54.48	-120:54.42
	34:53.00	-120:53.67
	34:51.52	-120:52.92
	34:50.03	-120:52.17
	34:48.57	-120:51.42
	34:47.08	-120:50.67
	34:45.60	-120:49.92
	34:44.12	-120:49.17
B	34:42.65	-120:48.42
	34:41.17	-120:47.67
	34:39.68	-120:46.92
	34:38.20	-120:46.17
	34:36.73	-120:45.42
	34:35.25	-120:44.67
	34:33.77	-120:43.92
	34:32.28	-120:43.17
C	34:30.82	-120:42.42
	34:29.33	-120:41.67
	34:27.85	-120:40.92



APPENDIX H – DETAILED TEST ITEM DESCRIPTION

SPHINX

The SPHINX payload was designed to provide USSF SCN SGLS TT&C requirements and space-to-ground interface specifications TT&C and L-Band uplink (1750-1850 MHz) and S-Band (2200-2300 MHz) space-to-ground interfaces to test and verify ground station performance. The SPHINX payload was comprised of a Meerkat mission computer, Novatel GPS receiver, two Innoflight SCR-104 software controlled radios transponders, SWIFT-SLX software controlled radio transponder, Cesium Astro SDR, and a custom made wide-band monopole antenna capable of L-Band uplink and S-Band downlink transmissions. All components were integrated into two chassis which were installed in the host C-12J. The SPHINX payload layout in the chassis is shown in Figure H-1, Figure H-2, and Figure H-3.

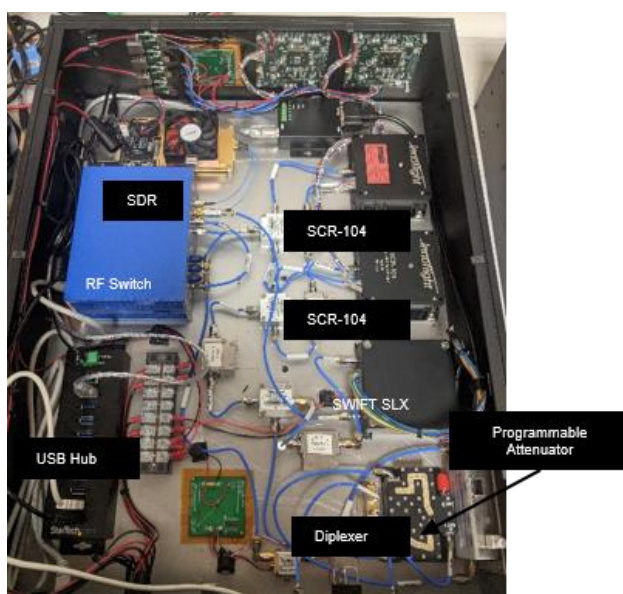


Figure H-1: SPHINX Payload Layout, Chassis 1 - Top View

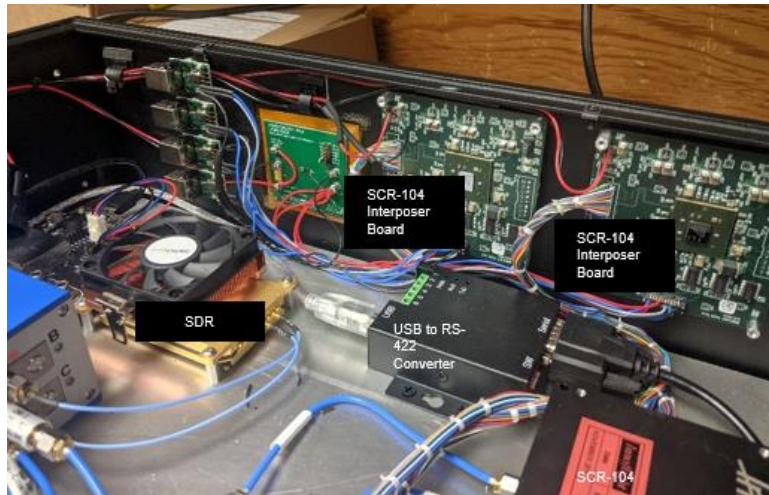


Figure H-2: SPHINX Payload Layout, Chassis 1 - Side View

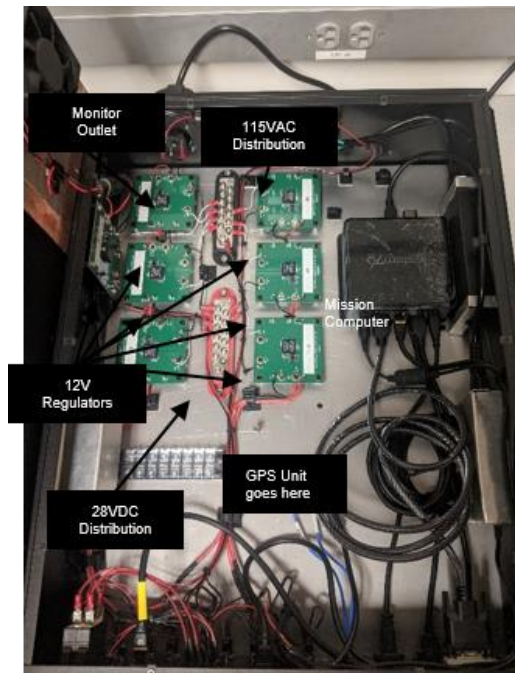


Figure H-3: SPHINX Payload Layout, Chassis 2 - Top View

A wide-band monopole antenna was mounted to the bottom of the C-12J by the 586th FLTS. The wide-band monopole antenna is shown in Figure H-4.

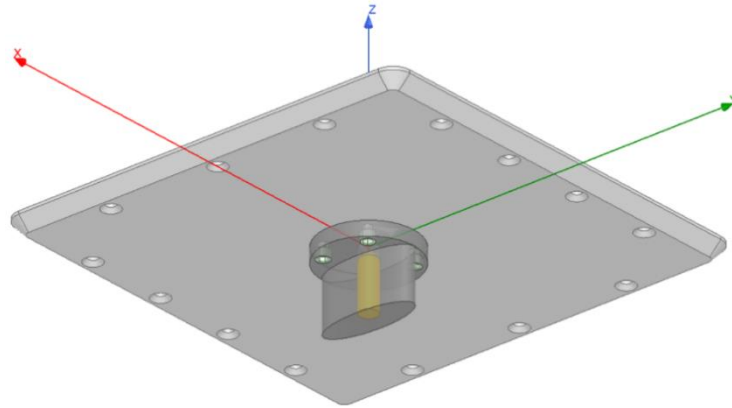


Figure H-4: SPHINX Wide-band Monopole Antenna

The SPHINX payload was setup in various IRON configurations, which established how the SPHINX payload communicated with the VTS. Both the SPHINX payload and the VTS were setup in the appropriate IRON for the test sequence. Each IRON established command type, transmit power setting, uplink and downlink frequencies, data rates, and other miscellaneous settings required for the test sequence. Two command types were used throughout the test: SGLS and non-SGLS commands. SGLS commands were commands in the ternary format, employing frequency and amplitude modulation of three tones, with two tones for data bits (i.e., 1, 0) and one tone (i.e., S) for link management. Non-SGLS commands were commands sent on a binary data stream modulated on a 16 kHz subcarrier.

The SPHINX payload incorporated the following capabilities using a combination of three spacecraft transponders and the Astro Cesium SDR:

- Processed uplink L-Band signals containing commands at data rates from 1 kbps to 100 kbps in any one of 20 SGLS channels or multiple Non-SGLS channels using the SWIFT-SLX SGLS Transponder or one of the Innoflight SCR 104 SGLS Transponders
- Generated downlink S-Band telemetry signals containing simulated Status of Health at data rates from 4 kbps to 7529.5 kbps in any one of 20 SGLS channels or multiple Non-SGLS channels; generated one to three downlink telemetry signals at any one time using the SWIFT-SLX SGLS Transponder, one or both of the Innoflight SCR 104 SGLS Transponders
- Provided a downlink tracking signal in any one of 20 SGLS channels or multiple Non-SGLS channels using the SWIFT-SLX SGLS Transponder or one of the Innoflight SCR 104 SGLS Transponders
- Processed and turned around range and Doppler data using the SWIFT-SLX SGLS Transponder
- Generated simulated uplink interference patterns using the Cesium Astro SDR
- Changed the downlink power level to determine lowest level that the ground station was able to track the SPHINX payload system

- Generated various downlink signals which allowed for execution of antenna tracking and pattern testing objectives

The SPHINX payload Functional Control Diagram (FCD) is shown in Figure H-5.

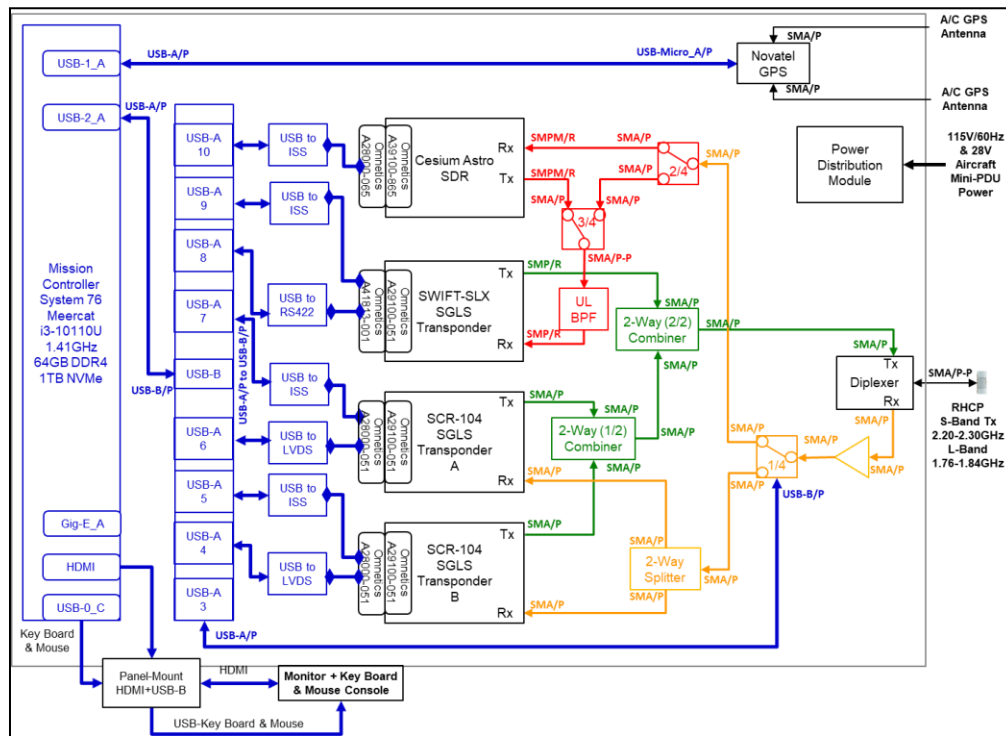


Figure H-5: SPHINX Functional Control Document

All of the individual SPHINX payload components were at a technical readiness level six or higher. The airborne prototype served as a risk reduction effort for the integration of these components prior to installation into a functioning USSF SCN on-orbit test asset. The SPHINX payload components were representative of the components planned for use in the on-orbit test asset.

SPHINX payload was controlled and monitored by the MeerCat mission controller computer via a GUI on a laptop. The GUI was a test support interface required for operating the SPHINX payload on board the C-12J. The GUI provided the test team with SPHINX payload subsystem connection status, selectable pre-programmed test sequences, GPS data, and a command history information window. An example of the GUI is shown in Figure H-6.

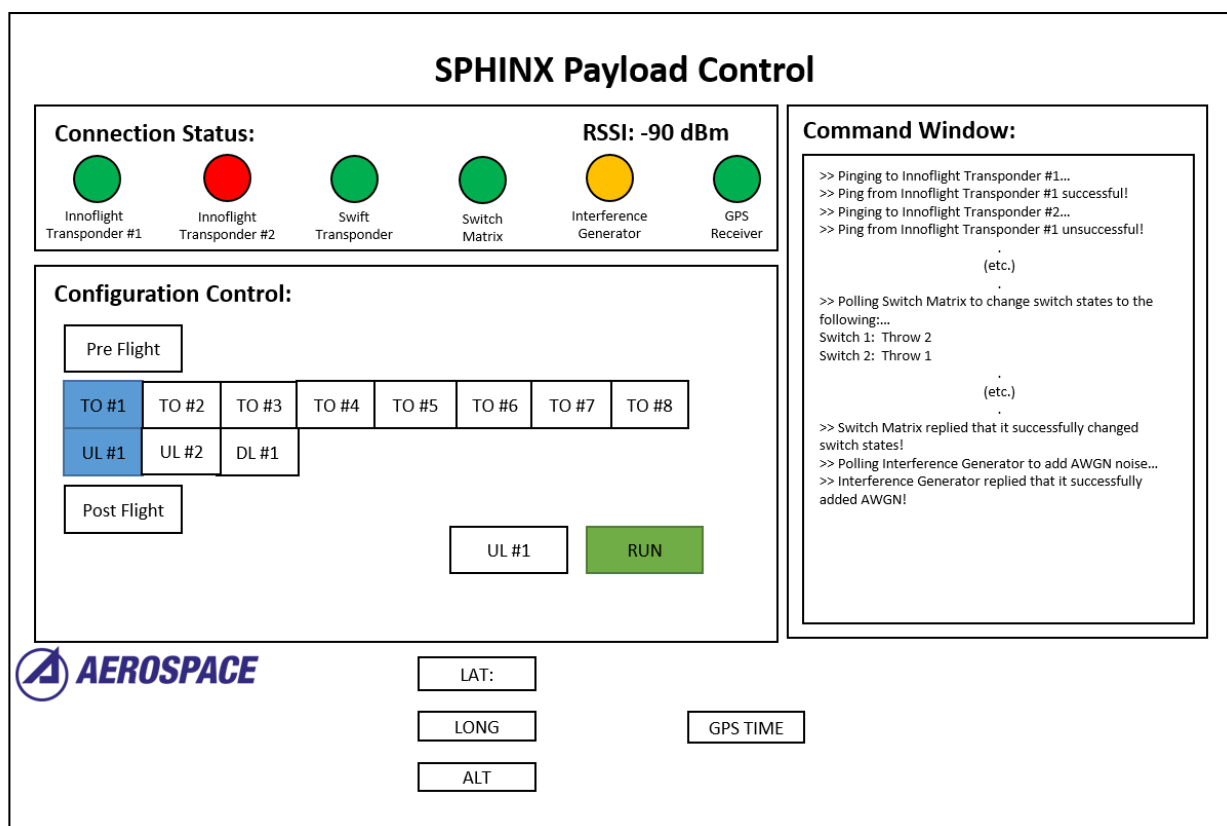


Figure H-6: SPHINX Control GUI

A series of pre-programmed test sequences were built by The Aerospace Corporation for each STO. The test sequences established an IRON, which set the transmit/receive frequencies and power levels, data rates, and other miscellaneous settings required to address each STO outlined in the Test Objectives. The test sequences are presented in Appendix A.

VTS

The VTS was one of 18 antenna systems which made up the USSF SCN. The USSF SCN provided the launch and early orbit anomaly resolution support required by all satellite systems. The USSF SCN also assured access to space for time-sensitive satellite control functions and provided continued support to users that required low data rates for satellite and mission operations. There was a wide range of USSF SCN users to include the Space Force, Air Force, Navy, Army, national agencies, and the National Oceanic and Atmospheric Administration.

The VTS was comprised of an operator station and two antennas. The two antennas were the RBC antenna and the Hybrid RBC antenna. The RBC antenna was a legacy antenna system. The Hybrid RBC antenna was an upgraded RBC antenna system which improved performance capabilities over the RBC antenna system by incorporating modern software, electronics, and gimbals. Both antennas were able to rotate in azimuth 360 degrees and had a minimum elevation pointing angle of five degrees above the horizon. SPHINX payload testing used both the RBC and Hybrid antennas, but only one antenna was used at a time. An airborne image of the VTS is shown in Figure H-7.

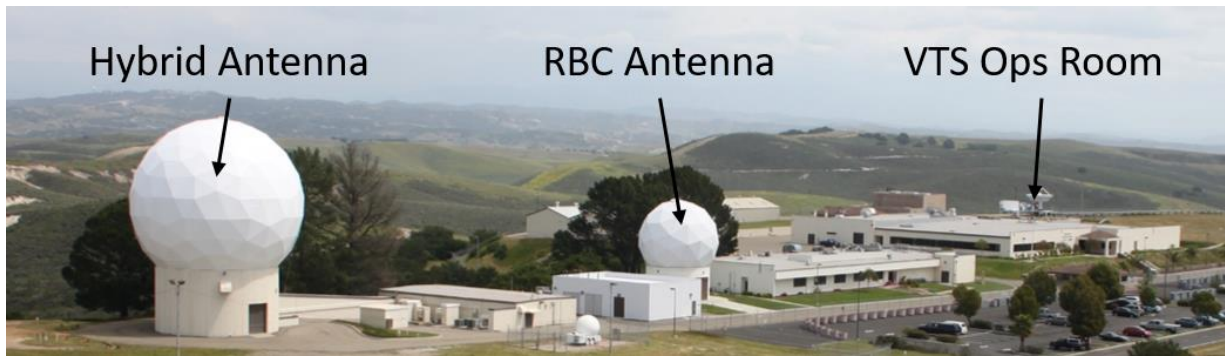


Figure H-7: VTS Layout

VTS operators who supported satellite passes observed all critical support parameters on the RBC summary Screen. Parameters included, but were not limited to: antenna health, IRON, auto track status, antenna elevation and azimuth angles, received signal strength, telemetry data rate, range, range rate, and Doppler shift. The RBC Summary Screen stored all collected data in a timestamped comma-separated values (CSV) file for post-support analysis. An example of the RBC Summary Screen is shown in Figure H-8.

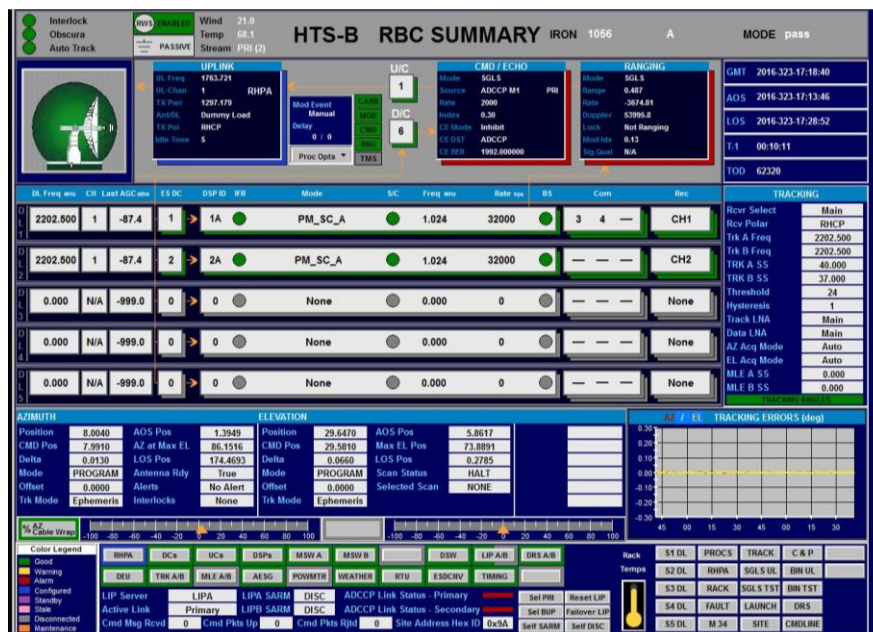


Figure H-8: VTS RBC Summary Screen

All real-world satellites supported by the VTS were operated by a SOC. During a satellite support, the SOC connected and communicated to the satellite through the VTS. While connected through the VTS, the SOC sent commands to the satellite and received telemetry and other data back from the satellite. No operational SOCs participated in the SPHINX payload test, therefore a SOCSIM was used to emulate this necessary function. The SOCSIM was directly connected to the VTS and enabled the ground test team to send commands and receive telemetry from the SPHINX payload. The SOCSIM stored all collected data

in a timestamped CSV file for post-support analysis. Real-time status of the test sequence was monitored on the SOCSIM GUI main window. Figure H-9 shows the SOCSIM hardware, and Figure H-10 shows then SOCSIM GUI. The SOCSIM was operated by a qualified The Aerospace Corporation VTS operator.

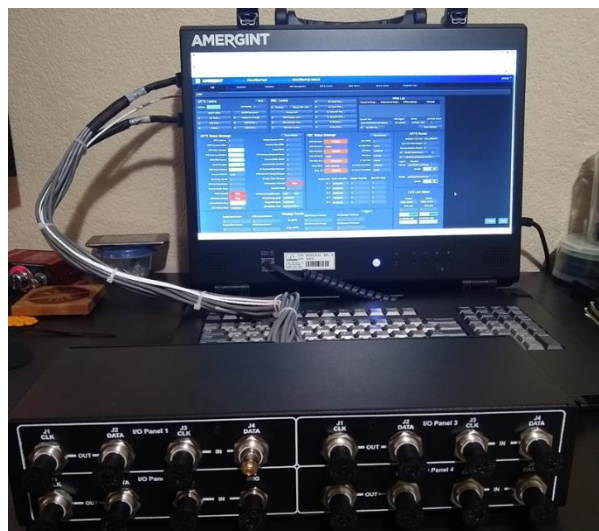


Figure H-9: SOCSIM Hardware

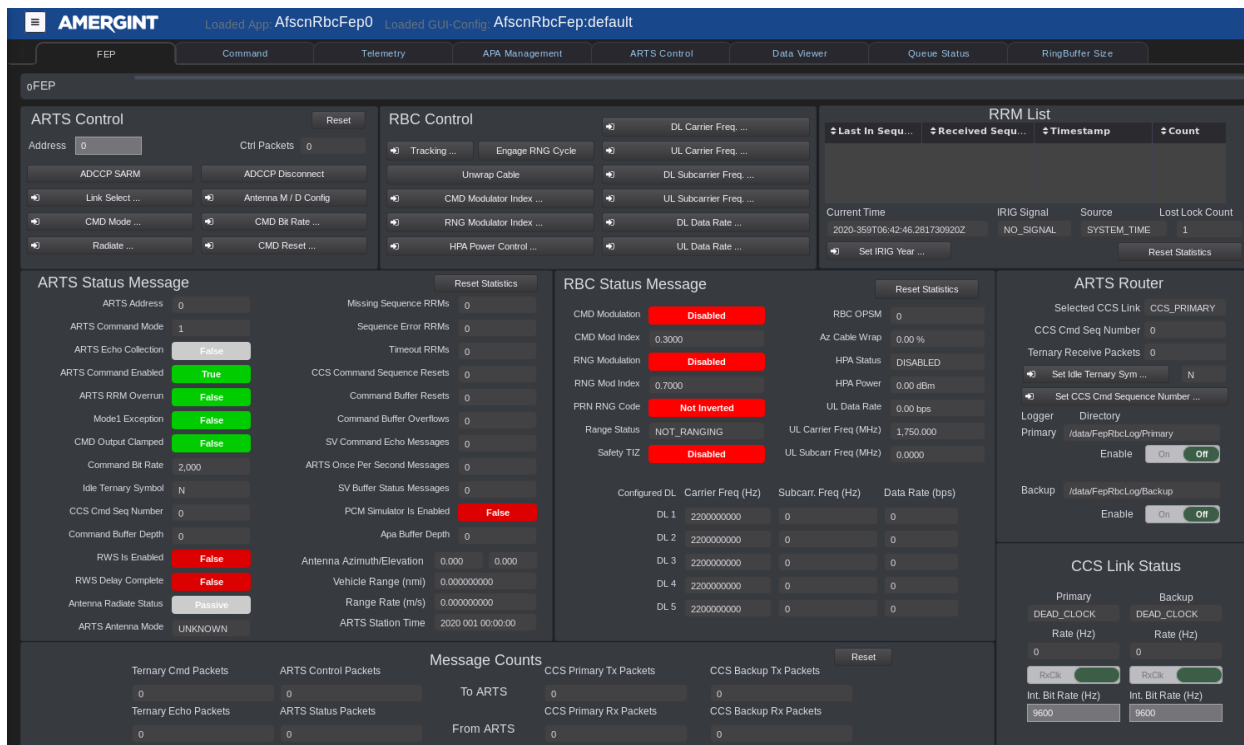


Figure H-10: SOCSIM GUI

APPENDIX I – TEST AIRCRAFT DESCRIPTION

The test aircraft was a C-12J aircraft (USAF S/N 86-0080) operated by the 586th FLTS based at Holloman AFB, New Mexico. The C-12J was a military derivative of a Beechcraft 1900 which had been modified for flight test usage. Modifications to the aircraft included the ability to generate additional power, the ability to quickly add external antennas, and the ability to carry external stores. The C-12J had a two-seat side-by-side cockpit for the pilot and copilot, and was configured with a crew station for the FINS data rack. The FINS provided aircraft TSPI positional data as outlined in Appendix B, and the FINS operator monitored system health during a sortie. The C-12J FINS positional accuracy was estimated to be five meters. The C-12J in this configuration had a service ceiling of 25,000 feet MSL. Best endurance airspeed above 20,000 feet MSL was 120-140 KIAS, and allowed for a flight duration of up to 7 hours.

For the HAVE TACOS test program, one low-profile, externally mounted wide-band monopole antenna was installed on the underside of fuselage as depicted in Figure I-1. Aside from the monopole antenna, no external fixtures or stores were added to the C-12J. The antenna installation used an aluminum antenna mounting plate machined by The Aerospace Corporation to be a direct replacement of the existing C-12J antenna panel. The C-12J airworthiness approval was accomplished by the 586th FLTS and approved by the 704th Test Group Configuration Control Board. The 586th FLTS was responsible for all modifications, and certified the modifications with a T-2 Modification board at Holloman AFB, New Mexico prior to test execution.



Figure I-1: C-12J with Monopole Antenna Location

All components were integrated into two chassis mounted avionics racks, shown in Figure I-2 and Figure I-3. Chassis 1 was the avionics rack that housed all SPHINX payload transponders. Chassis 2 was the power distribution board, which provided power to the avionics rack. Chassis 2 also housed the SPHINX payload GPS receiver and Meerkat mission computer. The SPHINX Payload avionics racks were installed in front of two side-by-side passenger seats, one of which was occupied by the SPHINX payload operator and the other was for an optional observer.



Figure I-2: SPHINX Payload Chassis 1 - Avionics Rack



Figure I-3: SPHINX Payload Chassis 2 - Power Distribution Board

APPENDIX J – FUTURE CONSIDERATIONS FOR AIRCRAFT SURROGATES

Utilizing aircraft surrogates for future testing would allow for satellite designers/manufactures to complete “open-air” testing prior to deploying on-orbit assets. By using real hardware inflight, installed antenna attenuation and interference from environmental sources would be present and would allow for higher-fidelity testing. These characteristics can be measured and mitigated at a relatively low cost to the spacecraft manufacturers.

While allowing manufacturers to investigate real-world characteristics of new space hardware, aircraft surrogates also enable a “fly-fix-fly” capability for manufacturers and users. For most space hardware, following ground tests, the hardware is placed on-orbit. With aircraft surrogate testing, if problems are found during testing, the manufacturer/user will have immediate access to the hardware/software allowing for rapid modifications and updates. The ability to have access to the spacecraft hardware after real-world testing has begun would be a capability previously unafforded to the majority of space programs.

The primary limitation observed during testing was the relative imprecision of the aircraft’s ability to be at a defined location in space and time. Satellite paths are predictable down to the tenth of a second. This predictability allows for certain specific ground stations functions to be tested. The combined test team assessed that an on-orbit asset, which would have a very precise, well-defined, and predictable orbit unaffected by atmospheric effects, would be better suited to complete certain test functions that required the ground station to utilize the program tracking function. To a smaller extent, the maximum altitude attainable by the surrogate aircraft combined with the ground station antenna minimum elevation angle will limit the useable airspace available for testing.

Finally, for programs with limited budgets, testing with aircraft surrogates allow for testing to be completed at a relatively low cost (in the case of the C-12J, testing costs were approximately \$1,000 per hour). NASA currently estimates the cost to send one pound to Low Earth Orbit at \$10,000. Initial testing of future capabilities for satellites can be completed for programs that do not have the budget to deploy an on-orbit asset (or test hardware that has not been fully certified for space operations yet). The ability to conduct testing cheaply with lower-cost hardware would allow real-world testing to be accomplished that would have previously been limited to lab testing.