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# Control and Non-Payload Communications Generation 1 Prototype Radio Flight Test Report

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## **Summary**

This report provides an overview and results from the flight test campaign for Generation 1 prototype radios for control and non-payload communications. The radios were developed under cooperative agreement NNC11AA01A between the NASA Glenn Research Center and Rockwell Collins, Inc., of Cedar Rapids, Iowa. Measurement results are presented for seven sets of flight tests that demonstrated bidirectional communications between a NASA aircraft and a ground station. Signal strength measurement data are analyzed relative to aircraft position, specifically addressing the impact of line-of-sight terrain obstructions. Both the radio and the flight test system are described.

## **1.0 Introduction**

Unmanned aircraft (UA) represent a new capability that will provide a variety of services in the Government (public) and commercial (civil) aviation sectors. The growth of this potential industry has not yet been realized because of the lack of a common understanding of what is required to safely operate Unmanned Aircraft Systems in the National Airspace System (UAS in the NAS). The desire and ability to

fly UA is of increasing urgency. The application of UA to perform national security, defense, scientific, and emergency management are driving the critical need for less restrictive access by UA to the NAS.

Existing Federal Aviation Regulations, procedures, and technologies do not allow routine UA access to the NAS. Access to the NAS is hampered by challenges such as the lack of an onboard pilot to see and avoid other aircraft; the ability of a single pilot or operator to control multiple UA; the reliance on command and control (C2) links; the altitudes, speeds, and duration at which the aircraft fly; and the wide variation in UA size and performance.

NASA is working with other Government agencies to provide solutions that reduce technical barriers and make access to the NAS routine. This goal will be accomplished through system-level integration of key concepts, technologies, or procedures and through demonstrations of these integrated capabilities in an operationally relevant environment. This project provides an opportunity to transition the acquired empirical data and knowledge to the Federal Aviation Administration and other stakeholders to help them define the requirements for routine UA access to the NAS. Radio communications channels for UA are currently managed through exceptions and use either Department of Defense frequencies for line-of-sight (LOS) and satellite-based communications links, low-power LOS links in amateur bands, or unlicensed Industrial/Scientific/Medical (ISM) frequencies. None of these frequency bands are designated for safety and regularity of flight. Only recently has radiofrequency (RF) spectrum been allocated by the International Telecommunications Union specifically for commercial UA C2, LOS communication (L-Band: 960 to 1164 MHz, and C-Band: 5030 to 5091 MHz). The safe and efficient integration of UA into the NAS requires the use of protected RF spectrum allocations and a new data communications system that is both secure and scalable to accommodate the potential growth of these new aircraft. Data communications for UA—referred to as control and non-payload communications (CNPC)—will be used to exchange information between a UA and a ground station (GS) to ensure safe, reliable, and effective UA flight operation. The focus of this effort is on validating and allocating new RF spectrum and data link communications to enable civil UA integration into the NAS.

Through a cost-sharing cooperative agreement with Rockwell Collins, Inc., the NASA Glenn Research Center is exploring and performing the necessary development steps to realize a prototype UA CNPC system. These activities include investigating signal waveforms and access techniques, developing representative CNPC radio hardware, and executing relevant testing and validation activities. There is no intent to manufacture the CNPC end product, rather the goals are to study, demonstrate, and validate a typical CNPC system that will allow safe and efficient communications within the L-Band and C-Band spectrum allocations. The system is addressing initial “seed” requirements from RTCA, Inc., Special Committee 203 (SC-203) and is on a path to Federal Aviation Administration certification.

This report provides results from the flight testing campaign of the Rockwell Collins Generation 1 prototype radio, referred hereafter as the “radio.” The radio sets operate within the 960- to 977-MHz frequency band with both air and ground radios using identical hardware. Flight tests involved one aircraft and one GS. Results include discussion of aircraft flight paths and associated radio performance.

## **2.0 Prototype Radio**

Rockwell Collins performed a trade study to identify the fundamental signal waveform characteristics best suited to fulfill anticipated CNPC requirements while maintaining low size, weight, complexity, and power requirements for the UA radio (Chavez, 2014). Rockwell Collins implemented this waveform in an existing hardware platform for the radio. With the modifications to this hardware platform, the radio is tunable from 960 to 977 MHz and produces approximately 4 W of output power.

### **2.1 Waveform Description**

The waveform selected utilizes time-division duplexing (TDD) between the uplink and the downlink. The uplink and downlink are each allocated a subsection of a TDD frame. The TDD frames were chosen to be 50 ms in duration to support a maximum message rate of 20 messages per second as identified by SC-203.

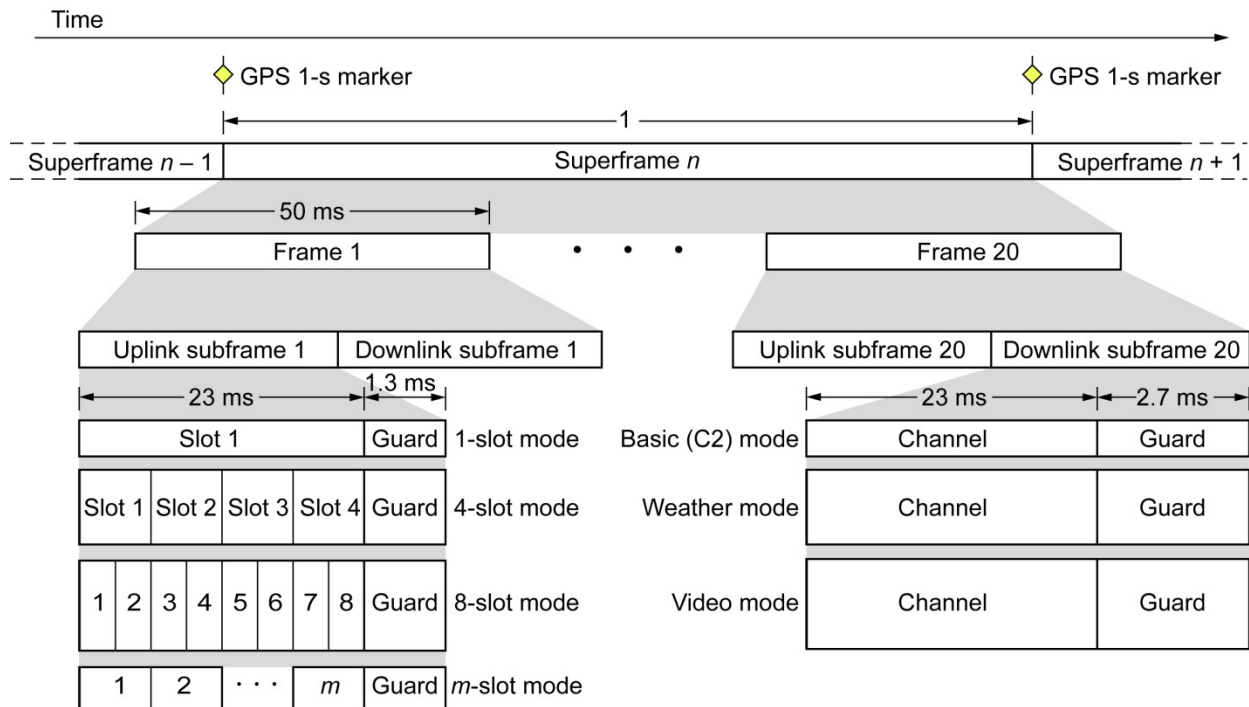


Figure 1.—Waveform overview; GPS, global positioning system; C2, command and control.

The CNPC uplink waveform uses time-division multiple access (TDMA). Each uplink subframe is divided into either 1, 4, 8, 12, 16, or 20 slots, where each slot contains an uplink to a single UA. For the downlink, the CNPC waveform implements frequency-division multiple access, where each UA uses a separate frequency. The number of uplink slots and downlink channels are configured on the basis of the expected number of UA communicating with the GS. Figure 1 shows the overall waveform.

## 2.2 Waveform Modes

The waveform supports several different modes for the uplink and downlink to accommodate various traffic characteristics. For the uplink, the waveform can have several different numbers of slots to support different numbers of UA. This varies from the 1-slot (UL1) mode intended for a single UA to a 20-slot (UL20) mode that can support 20 UA operating at a 20-Hz rate. For the downlink, the waveform has three different channel sizes to support different traffic loads. The C2 mode supports the minimum set of communications necessary for operating the UA. This includes aircraft telemetry, navigational aids information, voice relay for air traffic control (ATC), and surveillance targets. The weather mode supports all of the communications that the C2 mode does in addition to weather downlink information from onboard weather radar. The video mode supports all the C2 communications, the weather downlink, and a video downlink.

Each mode is modulated using Gaussian Minimum Shift Keying. The bandwidth and data rate of each mode differs according to the number of uplink slots and downlink channel sizes. Table I shows the characteristics of each mode.

TABLE I.—CONTROL AND NON-PAYLOAD COMMUNICATIONS (CNPC)  
WAVEFORM MODE BANDWIDTH AND DATA RATE

Direction	Mode	Bandwidth, kHz	Physical data rate, kbps	Maximum user rate, kbps
Uplink	1-slot (UL1)	75	87.5	16.32
	4-slot (UL4)	175	200	8.64
	8-slot (UL8)	350	400	↓
	12-slot (UL12)	525	600	
	16-slot (UL16)	700	800	
	20-slot (UL20)	875	1000	
Downlink	C2	75	87.5	16.32
	Weather	125	150	36.8
	Video	650	750	239.04

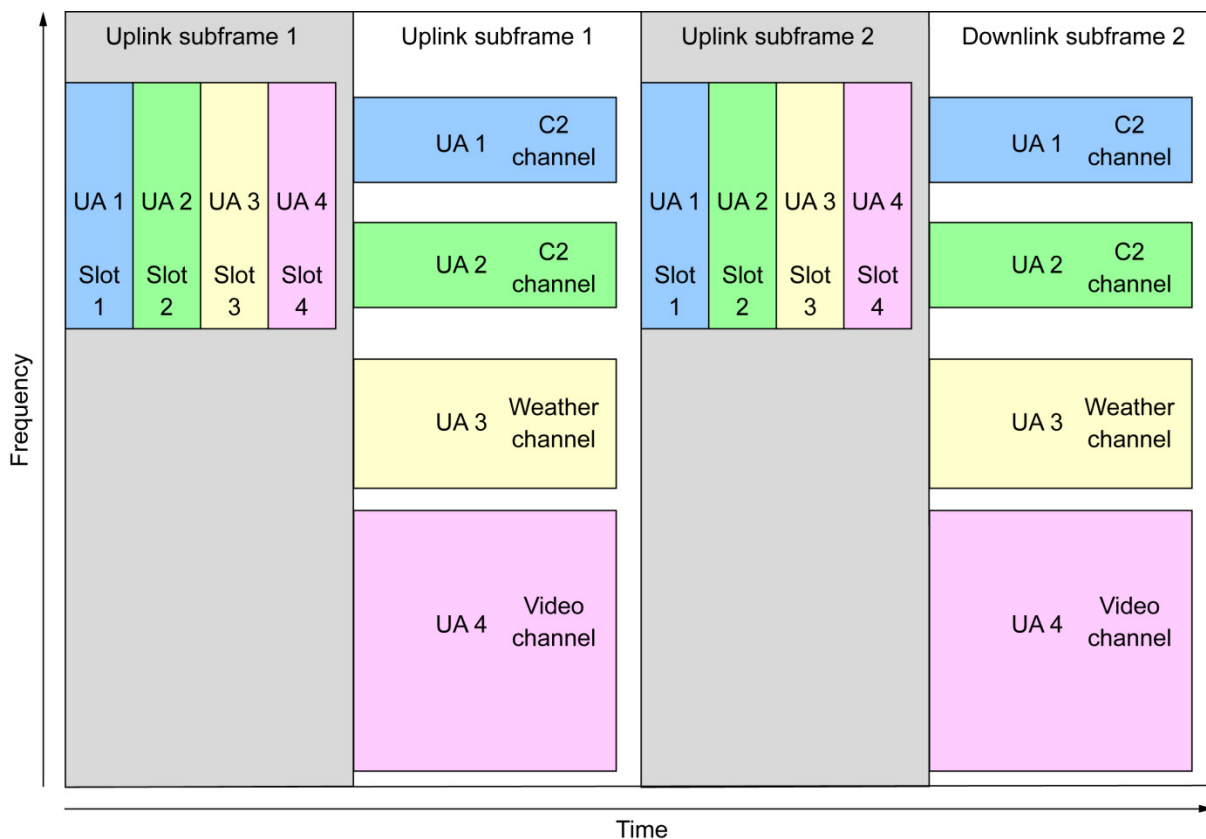


Figure 2.—Example control and non-payload communications (CNPC) usage for four unmanned aircraft (UAs). C2, command and control.

Figure 2 shows the first two frames of an example CNPC system supporting four UA. In each uplink subframe, time is divided into four TDMA slots in which the ground tower transmits sequentially to the four UA. The first slot contains uplink information for UA 1, the second slot for UA 2, and so on. In the downlink subframe, the UA transmit simultaneously on four different channels. UA 1 and UA 2 use C2 channels, UA 3 uses a wider weather channel, and UA 4 uses a video channel. There is no inherent correlation between the uplink and downlink frequencies. In the example, the UA 1 and UA 2 downlink C2 channels overlap the same frequency range as the uplink, but overlap is not required.



## 2.3 Radio Configurations

The radio can use a different uplink/downlink mode and frequency in each TDD frame within a 1-s superframe. A combination of the uplink slot and subframes or of the downlink channel and subframes is termed a “link stream.” For example, a radio may be configured to use the downlink C2 mode on one frequency in all of the even downlink subframes (link stream 1) and to use the downlink video mode on another frequency in all of the odd downlink subframes (link stream 2).

For the flight tests, this feature was used to simultaneously test multiple modes during the same test flight. Each flight test used one or more of the configurations defined in the following paragraphs. Figure 3 shows the seven radio configurations used in the flight tests.

**Configuration 1** consisted of a single uplink link stream using the UL1 mode and a single downlink link stream using the C2 mode. Both link streams used all 20 subframes and operated on the 971.975-MHz center frequency. The data sent over the radio in this configuration were in American Standard Code for Information Interchange (ASCII) text format.

**Configuration 2** consisted of a single uplink link stream using the UL20 mode and a single downlink link stream using the video mode. Both link streams used all 20 subframes and operated on the 971.975-MHz frequency. The data sent over the radio in this configuration were in ASCII text format.

**Configuration 3** was the same as Configuration 1 except that the data sent over the radio were in binary format.

**Configuration 4** was the same as Configuration 3 except the “hijack” mode was enabled. This setting in the radio management program allowed additional packet logging. Note that this configuration was not tested.

**Configuration 5** used two uplink and two downlink link streams. One uplink link stream used the UL1 mode, and the other used the UL20 mode. In addition, one downlink was C2, and the other was video. Each link stream used the 971.975-MHz frequency and used 10 of the 20 subframes. The data sent over the radio in this configuration were in ASCII text format.

**Configuration 6** was similar to Configuration 5 except that it operated on two frequencies. There were four uplink and four downlink link streams in this configuration, with UL1, UL20, C2, and video modes operating on both 963 and 974 MHz. Each link stream used 5 of the 20 subframes. The data sent over the radio in this configuration were in ASCII text format.

**Configuration 7** was similar to Configuration 6 but added link streams for the 4-slot (UL4) uplink and weather downlink modes at both 963 and 974 MHz. Each link stream used 3 of the 20 subframes. The data sent over the radio in this configuration were in ASCII text format.

## 3.0 Test Systems

The test system was composed of an airborne element and a GS element. The airborne element consisted of the Lockheed S-3B Viking aircraft owned by Glenn (registration number N601NA) with the radio and support equipment mounted in the rear of the aircraft. The ground element consisted of an 18-ft trailer platform with an equipment cabinet housing the radio and supporting electronics. Figure 4 shows the aircraft and trailer elements.

The equipment used in these tests was selected for prototyping purposes only, with the objective of recording the performance of the air-ground<sup>1</sup> radio links. Antenna types, antenna placement, and transmit power levels are not necessarily those to be used in the future deployed system.

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<sup>1</sup>Air-to-ground or ground-to-air link.

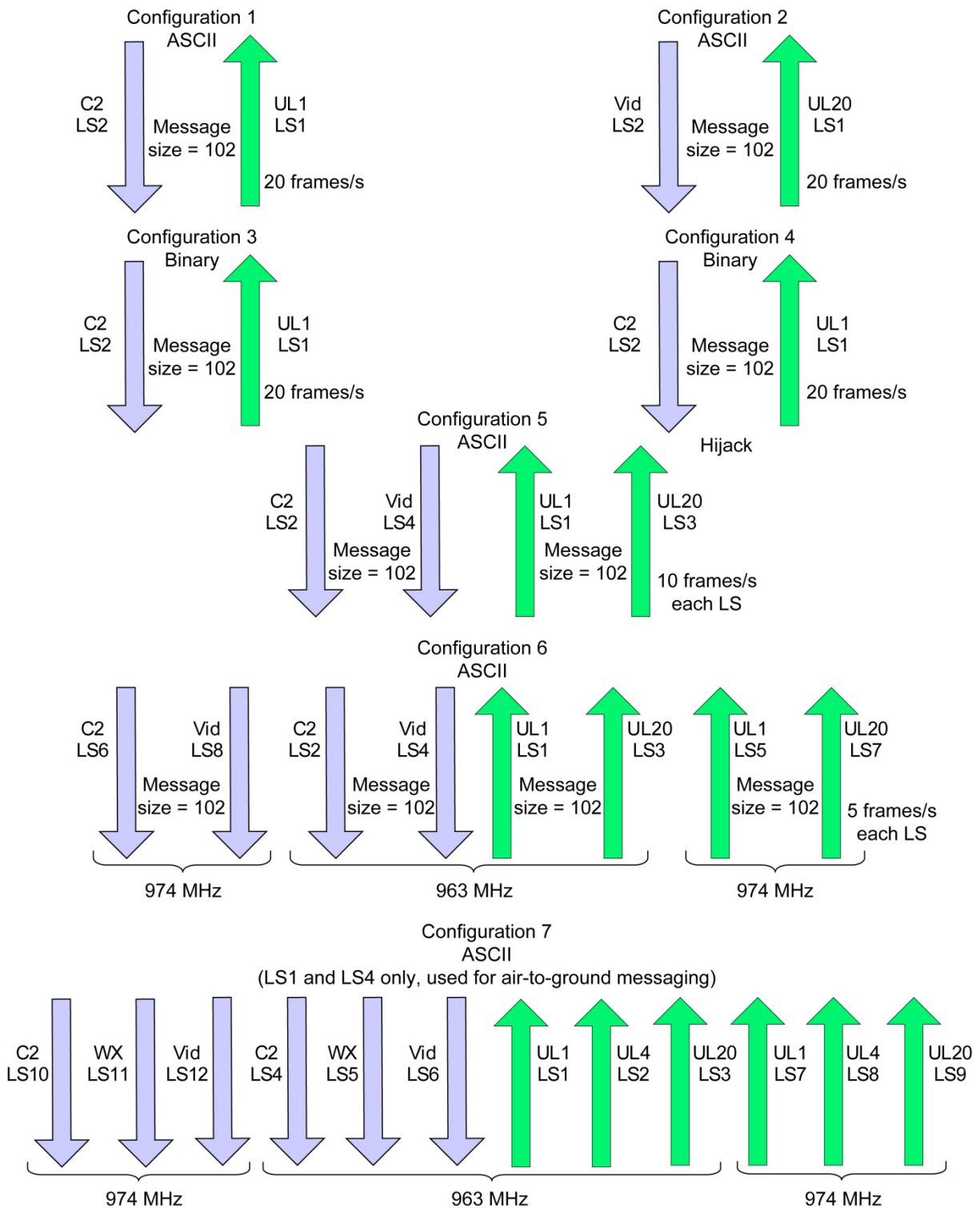


Figure 3.—Radio configurations 1 to 7; ASCII, American Standard Code for Information Interchange; Vid, video; LS, link stream; UL, number of slots; C2, minimum set of communications necessary to operate unmanned aircraft; WX, weather.

### 3.1 Ground Station Baseline Configuration

The GS baseline configuration consisted of a single Rockwell Collins radio, a 28-V power supply, a spectrum analyzer, an antenna controller, a global positioning system (GPS) time server, two computers, networking equipment, and an L-Band antenna. The components were mounted in an equipment rack attached to the trailer along with a self-contained 7-kW diesel generator and a pneumatic mast (Figure 4).

The 28-V power supply provided power to the radio, and the spectrum analyzer was used to monitor and automatically capture plots of the local RF spectral environment. If any degradation of the radio signal was seen, the plots could be referenced to see if any interfering signals existed. The antenna controller was used to precisely rotate the directional antenna to the desired azimuth. The azimuth was checked with a handheld compass. A 60-ft pneumatic mast mounted on the trailer raised the antenna to 65.5 ft above the ground.

A GPS time server using the Network Timing Protocol synchronized the ground computers to provide accurate time stamping of the data. A similar synchronization technique was used on the aircraft. Two computers were directly used with the radio during the tests: one to control the configuration of the radio and the other to populate the frames generated by the link stream to send user data. Additional computers were used in the GS to control equipment, monitor aircraft location, and communicate with the test operations team.

The L-Band antenna is a vertically polarized, directional, transmit/receive antenna mounted on a pan/tilt mechanism on the mast of the trailer. The antenna was steered by the antenna controller to the desired azimuthal direction and elevation needed for the flight test. Each test utilized a fixed azimuth, and the aircraft was not tracked during flight. Figure 5 displays the primary elements and interconnection of the GS in a block diagram.



Figure 4.—Aircraft and trailer elements.

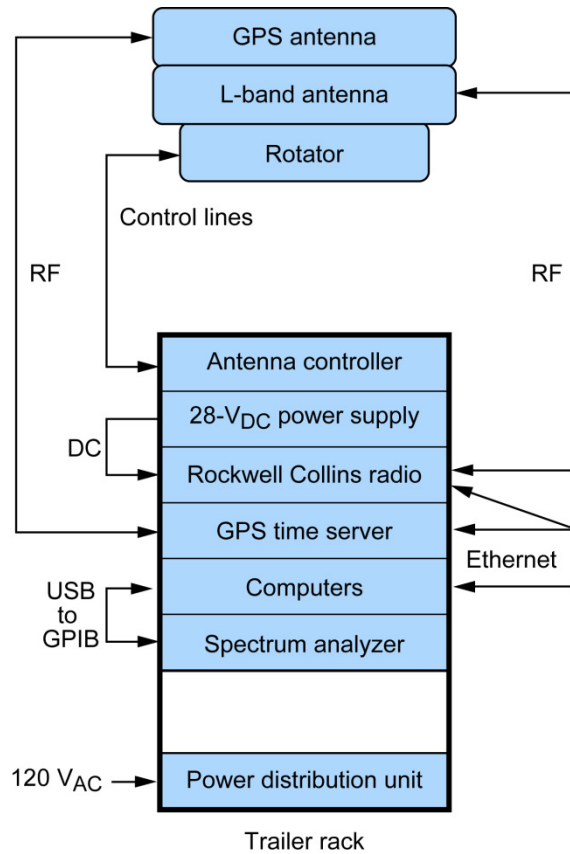


Figure 5.—Trailer rack; GPS, global positioning system; RF, radiofrequency; DC, direct current; USB, universal serial bus; GPIB, General Purpose Interface Bus.

### 3.2 Aircraft Baseline Configuration

The aircraft baseline configuration was similar to the GS configuration and consisted of a Rockwell Collins radio, a spectrum analyzer, a GPS time server, two computers, networking equipment, and an L-Band antenna. The aircraft supplied 28-V power for the radio, so no onboard power supply was required. A low-profile, omnidirectional antenna was used, so no directional-control equipment was used. The components were mounted in two racks in the rear of the aircraft, as shown in Figure 6.

The L-Band antenna was mounted on the bottom surface of the aircraft. The antenna was physically separated from all other antennas by a distance of several wavelengths to reduce antenna-to-antenna coupling. The flattened contour of the bottom of the aircraft provided a clear LOS path to the GS with little or no airframe obstruction (see Figure 7). Figure 8 shows the primary elements and interconnection of the aircraft equipment in a block diagram.



Figure 6.—Aircraft equipment racks.



Figure 7.—Aircraft antenna placement.

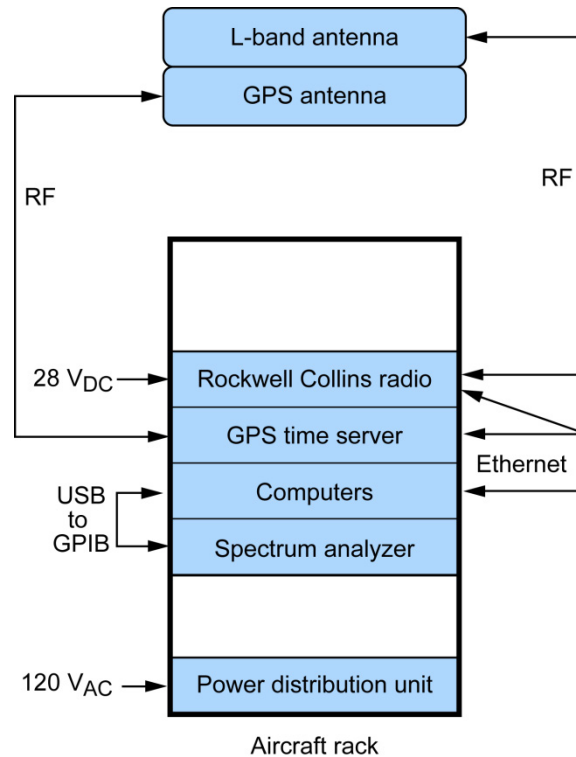


Figure 8.—Aircraft equipment rack; GPS, global positioning system; RF, radiofrequency; USB, universal serial bus; GPIB, General Purpose Interface Bus.

## 4.0 Flight Test Campaign

The flight test campaign for the radios consisted of seven separate flights occurring on 7 days from May 22 through June 18, 2013. Each flight test consisted of multiple, preplanned aircraft maneuvers and flight path segments. The objective of the flight test campaign was to operate the radios in an air-ground flight environment to determine possible limitations to communications range and data throughput performance. Flight and ground data were sent to Rockwell Collins for a more detailed examination so that changes could be made before the Generation 2 radios were delivered. Flight plans were individually tailored to address the type of test being performed. Weather and air traffic issues had only minor effects on the flights.

Each flight test in the campaign included an overhead pass of the GS antenna and a long-range, straight-and-level, constant-velocity “outbound” leg on a predetermined flight vector/heading. This radial path provided the opportunity to collect data on LOS path loss versus distance, leading ultimately to radio operational range information. The outbound path typically continued until the power received by the radio dropped below the radio sensitivity limit and the communications link was lost. The aircraft pilot then performed a course reversal, turning 180° for an “inbound” run on the opposing flight heading. The radios—one at the GS and one in the aircraft—would communicate throughout the inbound and outbound runs. Multiple inbound and outbound segments were sometimes flown on a given test day. Aircraft altitude and airspeed were typically constant during a given segment but were sometimes altered between runs to collect data to investigate terrain obstructions. Airport approach and touch-and-go maneuvers were flown to investigate the effects of terrain and airport-area structural obstructions, and to demonstrate radio signal recovery upon takeoff and ascent. The following subsections present the configurations, goals, and results of each flight test set, and Appendix A provides a summary chart that describes the radio flight test campaign.

The radios were controlled by custom software that not only permitted configuration of the radios but recorded radio performance data throughout the flight test. The software had sufficient capacity to collect data throughout the entire flight, even outside of the time when preplanned flight maneuvers were occurring. As a result, each data set also includes radio performance during setup, course reversal, altitude change, and other miscellaneous maneuvers. Many of these unscripted aircraft maneuvers occurred outside of the main radiation beam of the GS antenna, so data recorded during those periods are not calibrated. Nevertheless, data from the unscripted periods provide interesting insight into the potential operational capabilities of the CNPC system.

A large amount of data was collected from the two radios and from the aircraft during this testing campaign. This report presents only the initial results for propagation loss, operational range, and data throughput that are needed to confirm that the radio capabilities are fundamentally suitable for the development of Generation 2 systems, which are designed for multiple aircraft and GS. The authors plan to present an in-depth analysis of the data in subsequent reports.

Headings are approximate because navigation was generally performed by GPS reference for instrument flight rules and pilotage for visual flight rules. The headings given are magnetic unless noted otherwise. The time used throughout the report is Coordinated Universal Time (UTC), and aircraft altitudes are presented relative to mean sea level (MSL).

## 4.1 Flight Test 1—May 22, 2013—Cleveland, Ohio

### 4.1.1 Purpose

The first flight test of the radios occurred in airspace northwest of Cleveland Hopkins International Airport (airport designation CLE) near Cleveland, Ohio. This area is of generally flat terrain with a limited number of tall structures entering the GS antenna field of view. The northern portion of the flight area was over Lake Erie, offering the opportunity to observe the impact of possible signal reflections from the freshwater surface. This flight region was well characterized during a NASA channel propagation measurement flight campaign conducted earlier in 2013, which would allow subsequent analysis of radio propagation performance anomalies. The UA GS was located at Glenn, with the main antenna beam directed at a  $312^\circ$  magnetic compass direction with a  $0^\circ$  elevation angle. Figure 9 shows the antenna's field of view.



Figure 9.—Antenna field of view for Flight Test 1 (Glenn).

The objective of Flight Test 1 was to verify that a bidirectional communications link could be established between the two radios and that the link could be maintained during aircraft maneuvering. Successfully establishing the radio-to-radio link would also verify operations of the attendant ground electronics and aircraft electronics, including computers, timing equipment, direct-current power systems, RF components, and supporting air-ground communications. Radio operators in the aircraft would observe that simulated flight control signals were uplinked and received into the aircraft from the GS radio and that simulated flight data were being transmitted and downlinked to the ground radio. Simultaneously, the GS radio operator would observe the corresponding transmission and receipt of radio signals.

#### 4.1.2 Flight Profile

NASA's S-3B, NASA 601, launched from CLE at 15:09 UTC and headed west-northwest toward Avon, Ohio, passing south of point B, as shown in the flight track map (Figure 10). The radio was initially in Configuration 1 (refer to Sec. 2.3). The aircraft climbed to 3000-ft MSL, which was maintained for the duration of the flight. After overflying Avon and Lake Erie, the aircraft turned inbound and passed over the NRG Energy, Inc., power plant stacks near point B on a heading of  $48^\circ$  toward the GS at Glenn. Passing over the GS, NASA 601 reversed course for a 25-nmi outbound run along the centerline vector of  $312^\circ$ . At the 25-nmi point, near the Canadian border, the aircraft reversed course and flew toward the stacks again. After passing the stacks, NASA 601 turned northeast to set up a counterclockwise northeast-southwest racetrack pattern between points C and D, approximately along a  $40^\circ$  vector.

After one lap, NASA 601 broke from the racetrack pattern and headed north to align for an inbound run (from the stacks to Glenn). The radio was switched to Configuration 2. After the inbound pass, NASA 601 reversed course for an outbound pass to the same 25-nmi point. The aircraft returned along the inbound path to the stacks, then turned to establish the racetrack pattern. After completing one lap, the radio was switched to Configuration 3. NASA 601 flew one more lap then returned to CLE, landing at 16:50. The average airspeed for the research portion of the flight was 168 kn.



Figure 10.—Research flight track for Flight Test 1—May 22, 2013; GS, ground station. Map created at GPSVisualizer.com. Imaging ©2013 TerraMetrics.



### 4.1.3 Analysis

Figure 11(a) presents plots of the received RF signal strengths for Flight Test 1. The time scale, which is plotted along the horizontal axis of the figure, encompasses the entire test activity from preflight ground and taxi operations through flight maneuvers. Signal strength is plotted along the vertical axis. Ground radio and aircraft radio data are presented on the same grid. The two traces overlap with remarkable precision, indicating that the two radio systems delivered nearly identical performance.

The first controlled flight test segment begins at map point B (Figure 10) and is annotated near time 15:18 in Figure 11(a). The received signal strength (power) curve shows a steady increase as the aircraft approached the GS inbound along the 312° radial. As the aircraft overflowed the GS antenna, the received signal strength dropped rapidly as the aircraft moved into a null in the antenna radiation pattern and then into the background of the antenna. When the aircraft reversed course and again overflowed the GS antenna, the received power peaked and began a steady decrease that continued throughout the 25-nmi outbound flight along the 312° radial. Similar performance was observed for received power during the second pair of inbound/outbound passes beginning near 16:00.

Flight Test 1 included two sets of “racetrack” orbits, each performed approximately 11-nmi down-range from the GS. Signal strength data for the first set began near 15:40, and data for the second set began near 16:20. Throughout the racetrack maneuvers, the signal strength dwelled near -80 dBm, with slightly higher received power during travel on the near-side leg and slightly lower received power during travel on the far-side leg.

The 180° turns at the ends of the racetrack required aircraft banking, which caused shadowing of the aircraft antennas and breaks in the LOS signal path. This shadowing effect caused the received signal power level to drop abruptly and significantly at each turn. The shadowing periods are highlighted in Figure 11(a) (racetrack periods only) for aircraft roll angles greater than 10°.

A trace showing the expected (calculated) signal strength at the receiver was also plotted in Figure 11(a) to aid in the analysis. This trace was computed using the theoretical free-space propagation loss for the ground-air path, transmit and receive antenna gains, transmit power level, and filter and cable losses. Notably, the shape of the theoretical curve is close to that of the in-flight experimental data.

Figure 11(b) presents data on the running, 1-sec average percentage frame loss at the aircraft and at the GS receivers. Individual traces for the UL1, UL20, C2, and video data modes are shown. Where the CNPC communications path was transferring all data without error, the data are presented as 0-percent loss and no trace is visible on the grid. Where errors occurred in the radio link, the lost frame data created a visible trace ranging from 1 to 100 percent (total loss of radio link).

The aircraft remained in relatively close range to the GS throughout the Cleveland-area flight test, so the LOS between the 65-ft tower and the aircraft was never interrupted by terrain obstructions. The periods of packet loss in Figure 11(b) occurred during radio configuration change, wing shadowing (aircraft roll), or when the aircraft was out of the antenna beam.

The first portion of the flight test operated in Configuration 1, so only the UL1 and C2 data modes were active. A small number of frame errors were observed during the first inbound and outbound flight passes, likely the result of multipath interference created by reflections from known local structures. Frame losses occurring during flight in the overhead null and backlobe of the antenna were not studied at this time.

The in-flight changeover to Configuration 2 was made near 15:53. This is made obvious by the brief periods of 100-percent frame loss. After the change, the UL20 and video modes were activated. Data traces for these modes show some frame loss during the aircraft course reversals, as expected. Configuration 3 was activated just prior to 16:32.

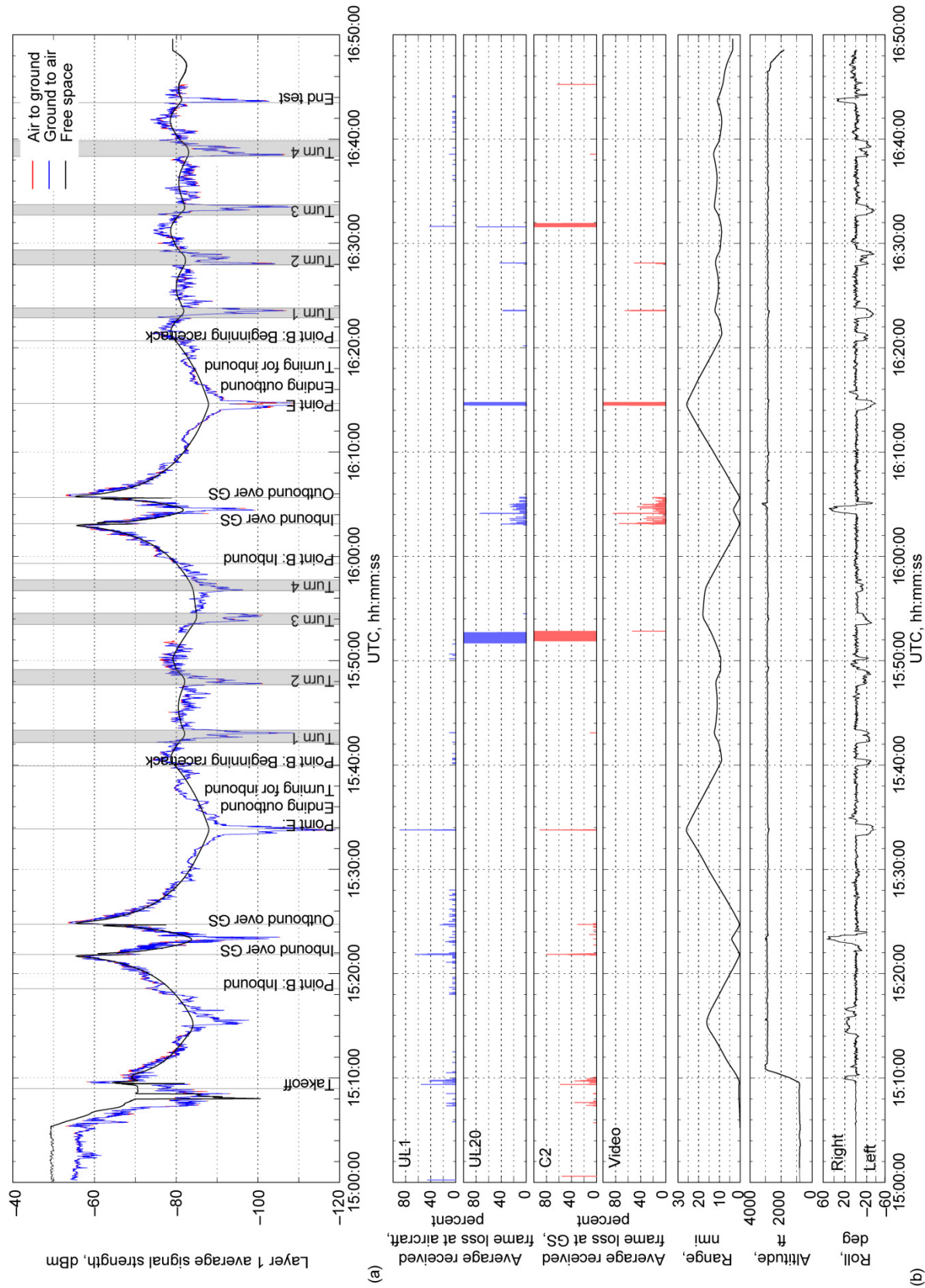


Figure 11.—Flight Test 1 radio performance data and associated aircraft parameters at Cleveland on May 22, 2013; GS, ground station; Rx, receiver; UTC, Coordinated Universal Time.

## 4.2 Flight Test 2—May 23, 2013—Sandusky, Ohio

### 4.2.1 Purpose

The objective of the second CNPC flight test was to begin examining the operating range of the radios. For this test, the communications link was established between the GS and the aircraft radios; then the aircraft flew along a fixed radial vector until the communications link was lost. Data from the test would be used to determine if the CNPC link was lost either because of radio sensitivity limits (from increased propagation losses) or because of LOS signal blockage by ground obstructions.

For the second flight test, the GS was relocated approximately 50 mi west of CLE to Glenn's Plum Brook Station (PBS) near Sandusky, Ohio. This placed the GS in a slightly quieter electromagnetic environment, away from the sources of possible interfering signals. More importantly, the PBS site allowed the aircraft to operate in a less-congested airspace where long-range flight paths and maneuvers could be executed with fewer deviations from the flight plan. An air corridor running approximately 100 nmi to the southwest of PBS was free of tall structures and major terrain elevation changes, and ATC rules in the PBS region allowed greater flexibility in requested aircraft altitudes.

The UA GS was located at an elevation of 651 ft on the southernmost tip of the PBS grounds. The main antenna beam was directed at a compass direction of 212° with an elevation angle of 0°. Figure 12 shows the antenna's field of view for Flight Test 2, and Figure 13 shows the flight track for Flight Test 2.



Figure 12.—Antenna field of view for Flight Tests 2, 3, and 6 at Plum Brook Station.



Figure 13.—Research flight track for Flight Test 2—May 23, 2013; GS, ground system; KMRT, Union County Airport; KUVF, Madison County Airport; B, region of signal loss. Map created at GPSVisualizer.com. Imaging ©2013 TerraMetrics.

#### 4.2.2 Flight Profile

NASA 601 launched from CLE at 15:23 and headed west toward PBS (Figure 13). The radio was in Configuration 5, which was maintained for the duration of the flight. After climbing to 3000-ft MSL, the aircraft turned south-southwest, passing over the GS at PBS. Then NASA 601 flew a heading of 212° toward Madison County Airport (KUYF). Near Marion, Ohio, the aircraft climbed to 4000-ft MSL per ATC direction. At approximately point A, the UL20 signal was lost. The aircraft continued until the UL1 signal also was lost near Union County Airport (KMRT). Then NASA 601 reversed course and set up an orbit between these two points, performing two laps. Breaking orbit, the aircraft returned north-northeast along the same path to overfly the GS at PBS. After course reversal, NASA 601 climbed to 7000-ft MSL and overflew the GS along the original outbound path. ATC directed a climb to 8000-ft MSL approximately 25 nmi past PBS. The flight continued along the original path with one deviation for weather, past KMRT to the airspace near Jeffersonville, Ohio. One orbit of the fringe zone was performed, and the aircraft returned along the established path to overfly the GS. The average airspeed for the research portion of the flight was 238 kn. NASA 601 then returned to CLE, landing at 17:52.

### 4.2.3 Analysis

Figure 14(a) presents plots of the received RF signal strengths for Flight Test 2. Data for the first outbound pass began at approximately 15:33 when the aircraft passed overhead of the GS antenna. As expected, the received signal strength curves show a steady decrease as the aircraft traveled outbound. Approximately 19 min later, near 15:52, the radios began to experience interruption (dropout) of the downlink video signal and uplink UL20 signal, as evidenced by the abrupt increase in the percentage of received packet losses. Although these interruptions appear to have occurred simultaneously in both the aircraft and ground radios, the signal was actually lost first by the ground radio, then seconds later by the aircraft radio. Approximately 1 min later, the C2 and UL1 signals were lost on the respective radios. The received signal strength was approximately  $-107$  dBm when the video signal was lost and was approximately  $-119$  dBm when the C2 signal was lost. The corresponding slant range distance between the GS and the aircraft was 65 nmi at video dropout and 75 nmi at C2 dropout. The aircraft was operating at an altitude of approximately 4200-ft MSL for this test.

To verify the locations at which the communications were lost, the aircraft reversed course to head inbound, remained at the 4200-ft MSL altitude, and entered into the elongated orbit pattern shown near location A in Figure 13. During the first orbit, near 16:00, the received signal strength increased sufficiently that the C2 signal returned to 100-percent operation (0-percent losses), followed shortly thereafter by return of the video signal. A second orbit then confirmed the signal strengths for signal interruption and reacquisition. These repeated interruptions and reacquisitions helped to demonstrate the repeatability of the radio receivers in this flight situation.

At approximately 16:12, the aircraft began a full inbound pass on the  $212^\circ$  radial. As expected, the received signal strengths continued to increase until the aircraft made the overhead pass of the GS antenna. As the overflight occurred, the signal strength dropped abruptly in the overhead null of the ground antenna, resulting in data frame errors. The radios continued to operate, at reduced performance, in the back lobe of the ground antenna.

At approximately 16:32, the aircraft began the second outbound pass. Because preflight calculations predicted that natural obstruction due to the Earth's curvature was likely, the aircraft altitude was raised to 8200-ft MSL. This allowed the radios to achieve an LOS distance of over 90 nmi before signal dropouts occurred. The region of signal loss is identified as location B on the flight track. As before, an elongated orbit allowed the dropout points for both video and C2 signals to be verified.

Figure 14(b) plots the spatial separation of the ground terminal and aircraft, also referred to as the "slant range," occurring during this flight test. The maximum slant range is the maximum LOS distance that is achievable given the local terrain obstructions, Earth curvature, aircraft altitude, and GS antenna height. For Flight Test 2, the maximum slant range was approximately 90 nmi for the video/UL20 signal and approximately 100 nmi for the C2/UL1 signal. Analysis shows, however, that terrain obstruction due to the curvature of the Earth imposes these limits. Higher aircraft altitudes and higher GS antenna elevations will increase the possible LOS distances. Nevertheless, the 90-nmi range reached during this test indicates that the radio capability exceeds the 69-nmi nominal requirement for GS cell size.

Two analytically derived traces are plotted with the signal strength in Figure 14(a). The trace labeled "free space" was computed using the standard free-space propagation loss calculation for the slant range distance. The trace labeled "Terrain based" utilizes the Terrain Integrated Rough Earth Model (TIREM) calculation, which adds reflection and diffraction effects to forecast RF propagation loss over actual terrain. This trace indicates that terrain obstruction in the first outbound pass begins at approximately 15:46. The TIREM model then predicted substantial signal loss for the next 20 min or so, generally tracking the location of nulls and peaks of the actual test data. During the 8200-ft test, the TIREM model again generally tracked the locations of nulls and peaks in concert with measured data before returning to the free-space trace when obstructions cleared the LOS. This was when the data channels returned to operation.

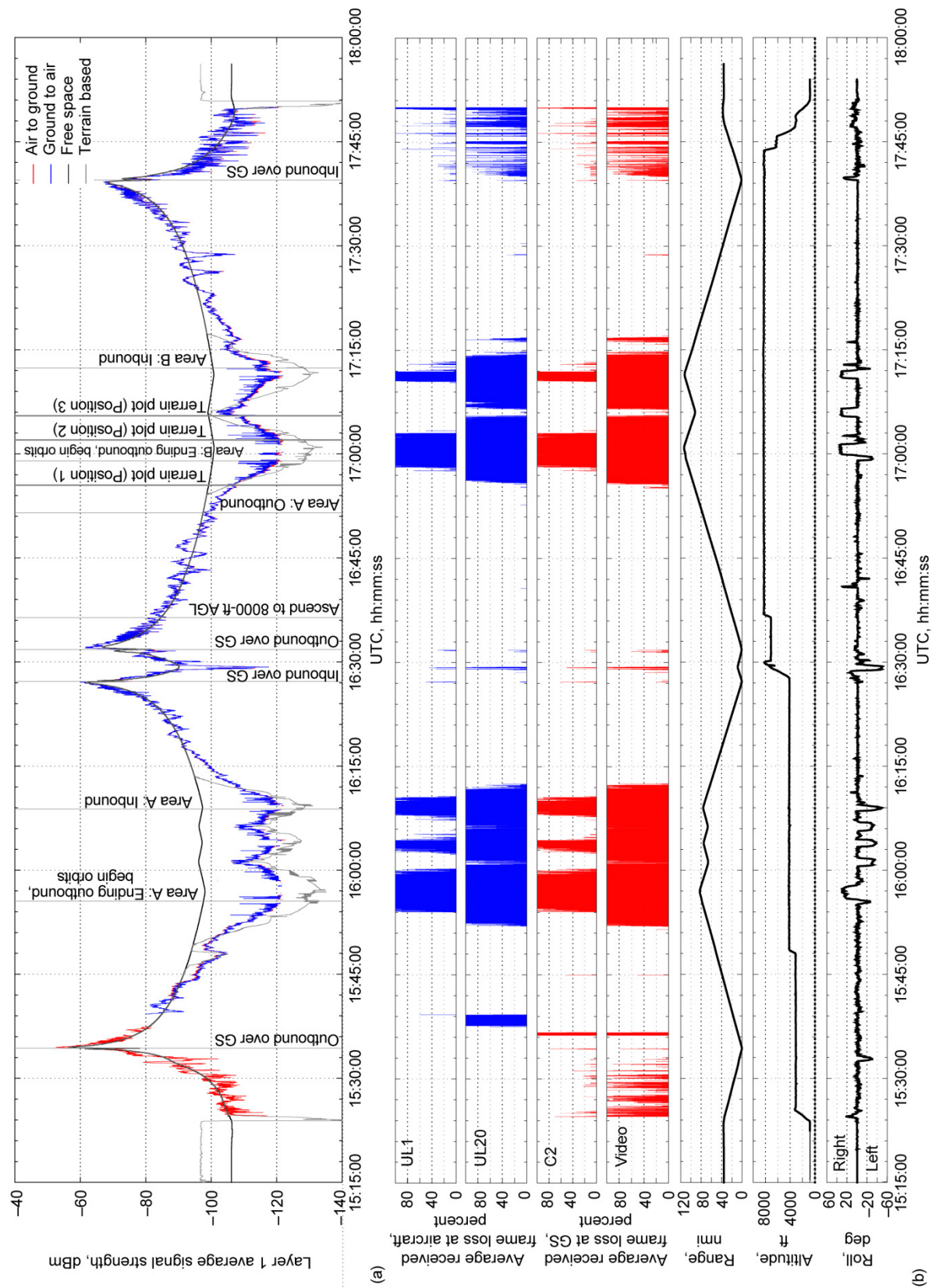


Figure 14.—Flight Test 2 radio performance data and associated aircraft parameters at Plum Brook Station on May 23, 2013; GS, ground system; AGL, above ground level; UTC, Coordinated Universal Time.

Computer software was written to provide near-real-time display of terrain obstruction using in-flight aircraft position data. This software utilizes terrain data from the U.S. Geological Survey with Earth curvature equations to identify the onset of obstructions in the LOS path. Figure 15 presents Earth sectional views arising from three distinct aircraft positions. The uppermost plot shows when the aircraft reached position 1 on the signal strength trace. The terrain plot shows multiple instances where terrain features (ridges, mounds, and hills) blocked the LOS path between the aircraft and ground terminal. As the aircraft moved to trace position 2 at the end of its outbound path, the red area under the curve (center plot in Figure 15) indicates numerous terrain features that caused many obstructions in the LOS path.

As the aircraft reversed course and headed toward the GS on its inbound path, the terrain obstructions diminished to the level shown in the lower plot, indicated as position 3 on the signal strength trace. Positions 1 and 3 directly correspond to the step changes in percent frame loss for the video/UL20 signals. Thus, as the LOS signal between the aircraft and GS was impeded and attenuated by terrain obstructions, the wide-band video/UL20 signals were interrupted. Positions 1 and 3 also correspond to points at which the theoretical path loss curve for free space began to deviate from the terrain-based curve.

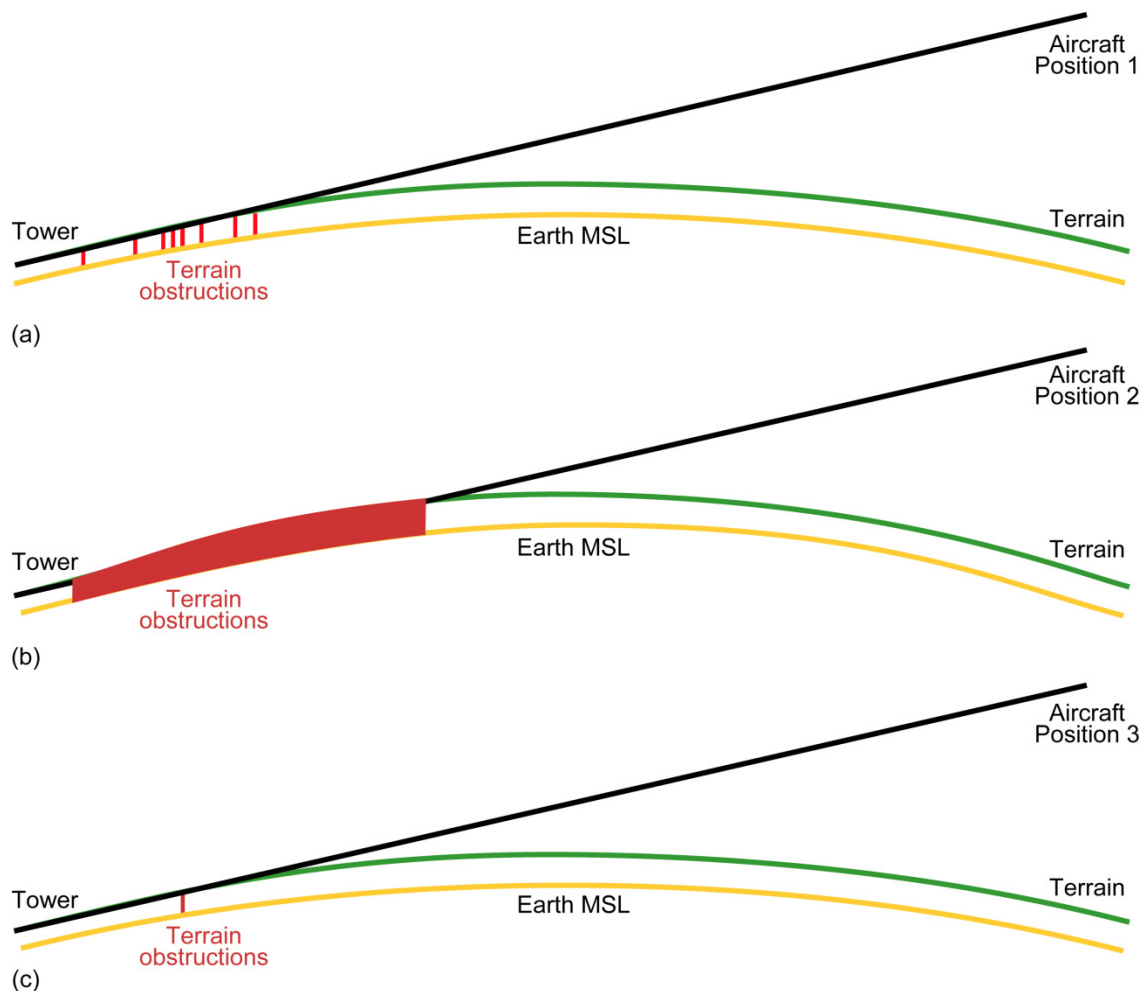


Figure 15.—Terrain line-of-sight obstruction predictions on May 23, 2013; MSL, mean sea level.  
 (a) 16:55:30. (b) 17:02:00. (c) 17:05:30.

## 4.3 Flight Test 3—May 24, 2013—Sandusky, Ohio

### 4.3.1 Purpose

The objective of the third CNPC flight test was to address measurement system repeatability and to gather additional data on aircraft altitude and LOS obstruction. Configurations for both the aircraft and GS were exactly the same as those for Flight Test 2, as were the GS physical setup and site location. The aircraft flight plan included the same air corridor as the previous test and used 3000- and 9000-ft MSL as the aircraft altitudes. Maximum slant range before loss of signal could decrease or increase slightly because of the slight variations in aircraft operating altitude. Figure 12 shows the antenna's field of view, and Figure 16 shows the flight track for Flight Test 3.

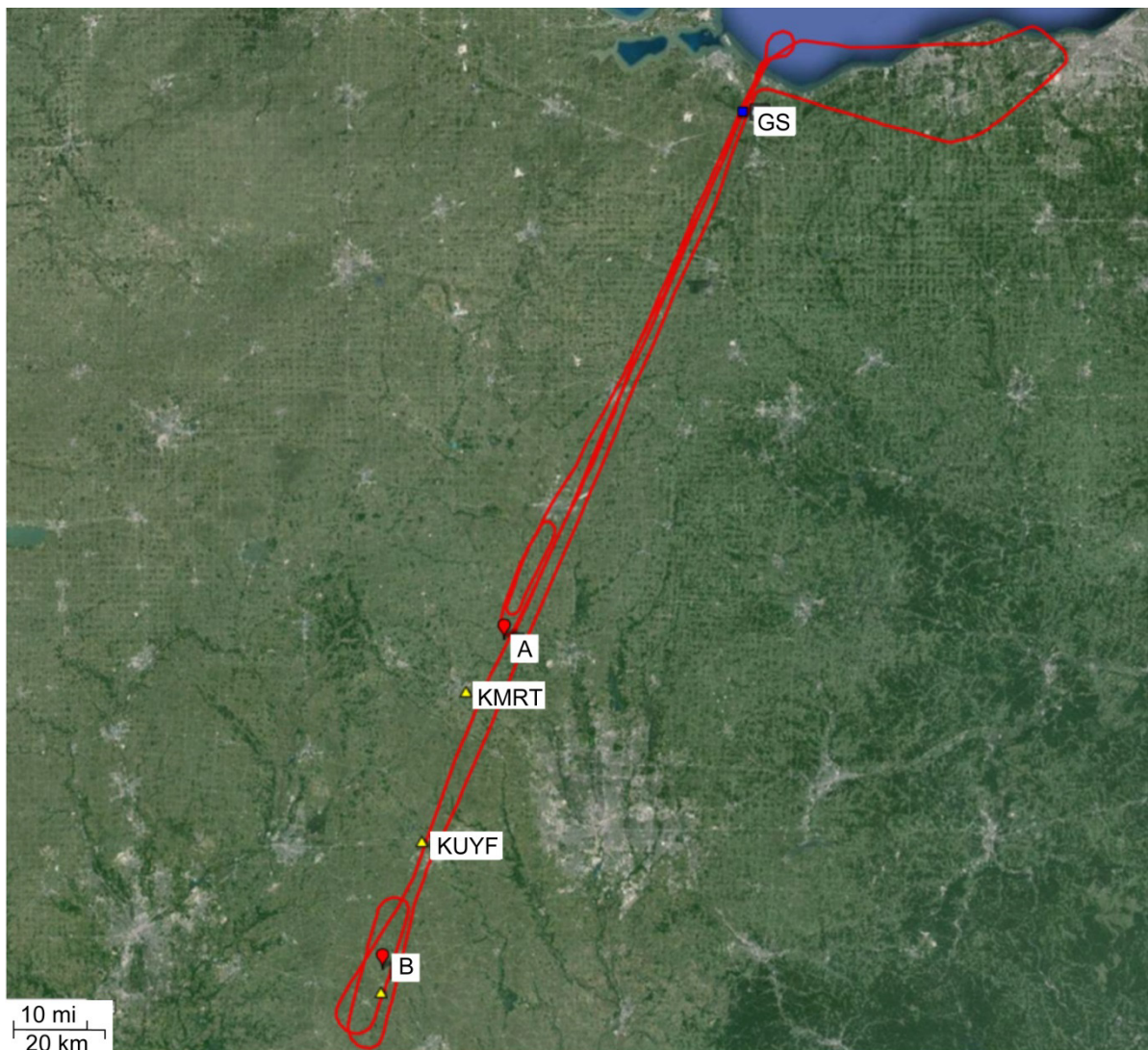


Figure 16.—Research flight track for Flight Test 3—May 24, 2013; GS, ground system; KMRT, Union County Airport; KUYF, Madison County Airport; B, region of signal loss. Map created at GPSVisualizer.com. Imaging ©2013 TerraMetrics.



### 4.3.2 Flight Profile

The research flight on May 24, 2013, was largely a duplicate of the previous day's flight with a variation in altitude. NASA 601 launched from CLE at 14:16 and headed west toward PBS. The radio was in Configuration 5, which was maintained for the duration of the flight. After descending to 3000-ft MSL, the aircraft turned south-southwest, passing over the GS at PBS. NASA 601 flew a heading of 212° toward KUYF. Just past Marion, Ohio, the UL20 signal was lost. The aircraft continued until the UL1 signal was also lost, approximately at point A. Then NASA 601 reversed course and set up an orbit between these two points, performing one lap. Breaking orbit, the aircraft returned north-northeast along the same path to overfly the GS trailer at PBS. After reversing course, NASA 601 climbed to 9000-ft MSL and outbound over the GS along the 212° radial path. The flight continued past KMRT to Jeffersonville, Ohio. NASA 601 performed one orbit of the fringe zone then returned along the established path to overfly the GS and land at CLE at 16:31. The average airspeed for the research portion of the flight was 236 kn.

### 4.3.3 Analysis

Figure 17 presents plots of the received RF signal strengths for Flight Test 3. Data for the first outbound pass began at approximately 14:27, when the aircraft passed overhead of the GS antenna. For this pass, the video and C2 signals were lost at the same received signal strengths as recorded in previous tests, but this occurred approximately 3 min earlier in the flight. The time difference could be due to the aircraft operating at an altitude 1000 ft lower than in the previous test. The slant range at the time of signal loss was 50 nmi for video and 58 nmi for C2.

The 9000-ft MSL high-altitude outbound pass began at approximately 15:19. The video signal for this flight was lost approximately 23 min into the outbound run, with the C2 signal dropout occurring approximately 3 min later. The LOS slant range for these dropouts reached 100 and 105 nmi respectively. Again, both tests were likely limited by the Earth's curvature, but again both tests proved to provide range well beyond the 69-nmi target range.

Constructive and destructive interference due to multipath signals is a common problem at low altitudes. The authors suspect that the perturbations in the signal strength plots are evidence of this effect. This effect, occurring near 14:33, 15:07, 15:30, and 16:12 on the plot, are likely examples of multipath interference.

## 4.4 Flight Test 4—May 28, 2013—Sandusky, Ohio

### 4.4.1 Purpose

The objective of Flight Test 4 was to examine the connectivity between radios when the aircraft was executing a standard airport landing approach. Previous flight test data and LOS calculations would both indicate the likelihood of communication link interruption due to terrain obstructions as the aircraft descended to the horizon. This interruption was always anticipated to be an issue of tower height and placement, so this test was intended to confirm the terrain blockage effects and to observe other performance anomalies, if any. All aspects of the aircraft approach to the airport were directed by standard ATC and control tower instructions.

The standard flight approach pattern was conducted into the Mansfield Lahm Regional Airport (KMFD), which was approximately 32 nmi south of the PBS GS. During the approach and runway alignment, the aircraft remained at its flight altitude of 3000-ft MSL. The aircraft then descended to approximately 50 ft above the airport runway for four low passes along runway 23 (at an elevation of 1280 ft). Four “go-around” repeats of the low pass were executed in the local area of the airport. Data were collected throughout the passes in an attempt to capture the altitude at which communication was lost.

The remainder of the day's flight consisted of outbound/inbound patterns to address the repeatability of radio sensitivity measurements and LOS predictions. Figure 18 shows the GS antenna's close-range field of view, and Figure 19 shows the flight track for Flight Test 3.

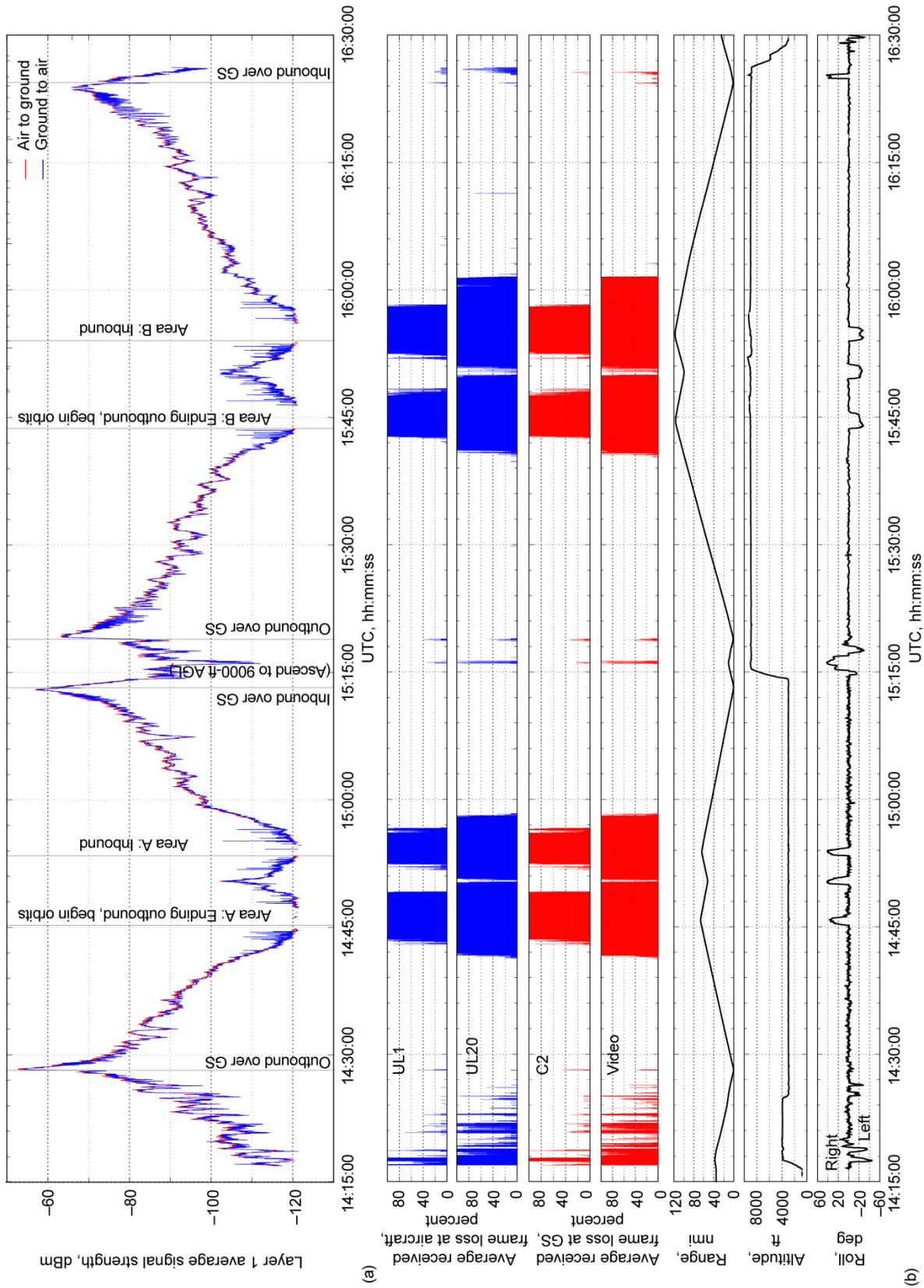


Figure 17.—Flight Test 3 radio performance data and associated aircraft parameters at Plum Brook Station on May 24, 2013; GS, ground system; AGL, above ground level; UTC, Coordinated Universal Time.



Figure 18.—Antenna field of view for Flight Tests 4 and 5 (Plum Brook Station).

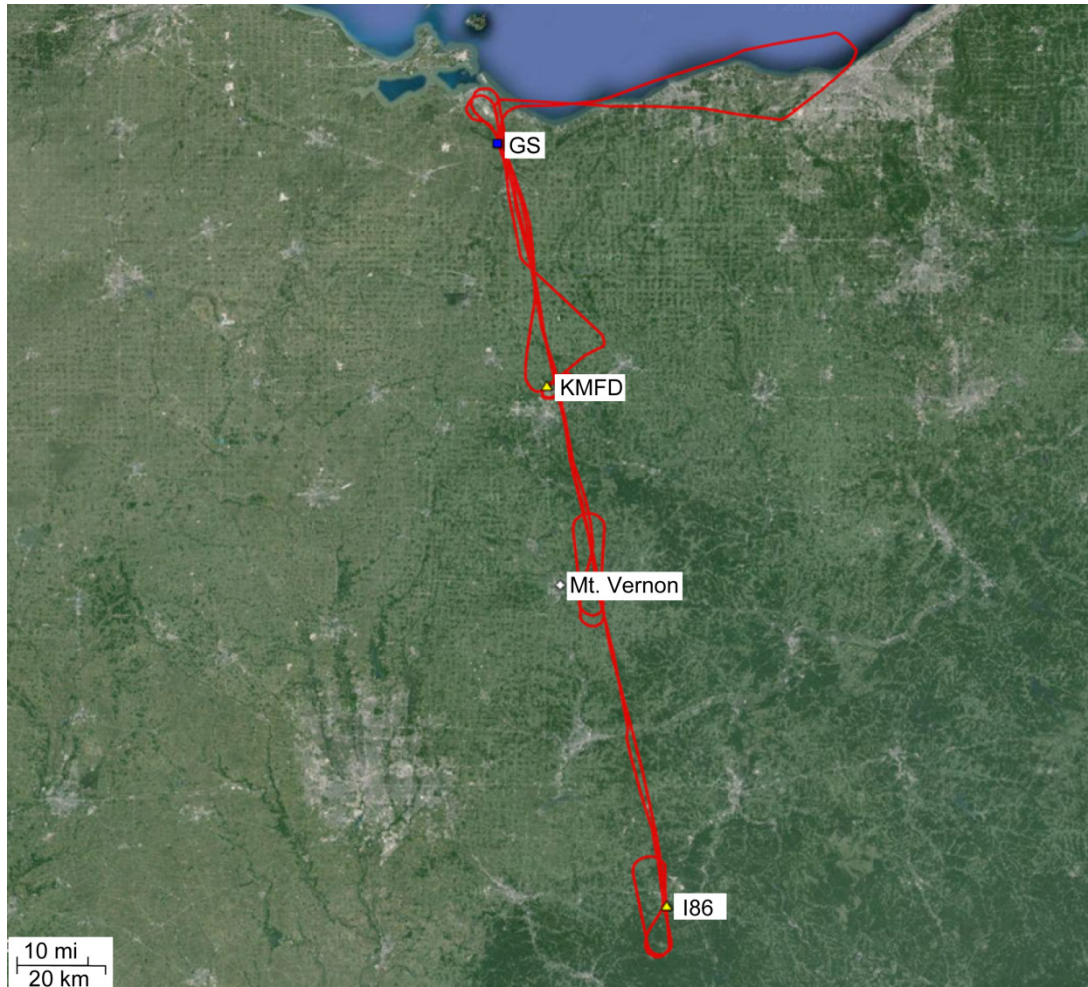


Figure 19.—Research flight track for Flight Test 4—May 28, 2013. GS, ground station; KMFD, Mansfield Lahm Regional Airport. Map created at GPSVisualizer.com. Imaging ©2013 TerraMetrics.

#### **4.4.2 Flight Profile**

NASA 601 launched from CLE at 15:23 and headed west toward PBS. The radio was in Configuration 5, which was maintained for the duration of the flight. After climbing to 3000-ft MSL, the aircraft turned south-southeast on a heading of 178°, passing over the GS at PBS. The flight headed to KMFD to perform four touch-and-go landings. NASA 601 returned to PBS along the same course, then reversed and flew outbound again. Near Mount Vernon, Ohio, the UL1 and UL20 signals were lost, and an orbit was established. Breaking orbit, the aircraft returned to PBS and overflew the GS, then climbed to 8400-ft MSL and reversed course. The flight continued to near Perry County Airport (I86), where the signals were lost. After one orbit at the fringe, NASA 601 returned inbound over PBS, landing at CLE at 17:59. The average airspeed for the research portion of the flight was 239 kn.

#### **4.4.3 Analysis**

The redirection of NASA 601 to begin the Mansfield airport approach began at approximately 15:34, and the first runway descent began at approximately 15:39. As observed in Figure 20, the aircraft descended to the runway and the video/UL20 signals were lost first, followed immediately by the C2/UL1 signals (as was customary in the previous tests.) The signal interruptions were undoubtedly caused by the increase in the LOS propagation losses due to terrain and/or foliage blockage at the low altitudes. Both signals had been fully interrupted by the time the aircraft was approximately 200 ft above the runway surface. Both radio signals resumed operation as the aircraft regained altitude, with the narrower-band C2/UL1 signal resuming prior to the wider-band video/UL20 signal. Similar performance data were collected as the aircraft performed three additional low-approach cycles. The runway tests were concluded at approximately 15:56, and the aircraft returned to inbound/outbound flight patterns.

The flight vectors used for Flight Test 4 were directed along the 178° radial from the PBS ground antenna location. Terrain elevation along this flight path increased at a greater rate than it had along the 212° radial that was used on previous days. As a result, the slant range at which radio signals were lost on the outbound pass was limited to approximately 60 nmi. When aircraft altitude was increased to 8400 ft, the operating range of the radio was extended to approximately 85 nmi for the video/UL20 signal and to approximately 100 nmi for the C2/UL1 signal. These slant range results are significantly greater than the 69-nmi range goal.

At approximately 15:34, the signal strength trace entered a “plateau” region and did not exhibit the customary downward trend observed during previous outbound tests. This is the result of the aircraft realignment necessary for KMFD airport approach, where slant range did not increase at the same constant rate that had occurred during radial outbound flights.

### **4.5 Flight Test 5—May 29, 2013—Sandusky, Ohio**

#### **4.5.1 Purpose**

The objectives of CNPC Flight Test 5 were to assess radio repeatability over the 178° terrain vector and to again examine radio signal interruption during airport approach. For Flight Test 5, the aircraft was piloted through three runway touchdown (“touch-and-go”) passes at KMFD runway 23. The ground terminal was again placed at the PBS site, and the antennas were oriented for the 178° radial flight direction.

For this test, the radios were placed in Configuration 6, which produced two (duplicate) sets of channels, one set centered at the lower end of the RF operating frequency band and the other centered at the higher end of the operating band (963 and 974 MHz, respectively). Although the operating frequencies are quite close, the goal was to investigate any possible differences in radio or channel performance. All other operating parameters of the aircraft and GS remained the same as for Flight Test 4. Figure 18 shows the antenna’s field of view, and Figure 21 shows the flight track for Flight Test 5.

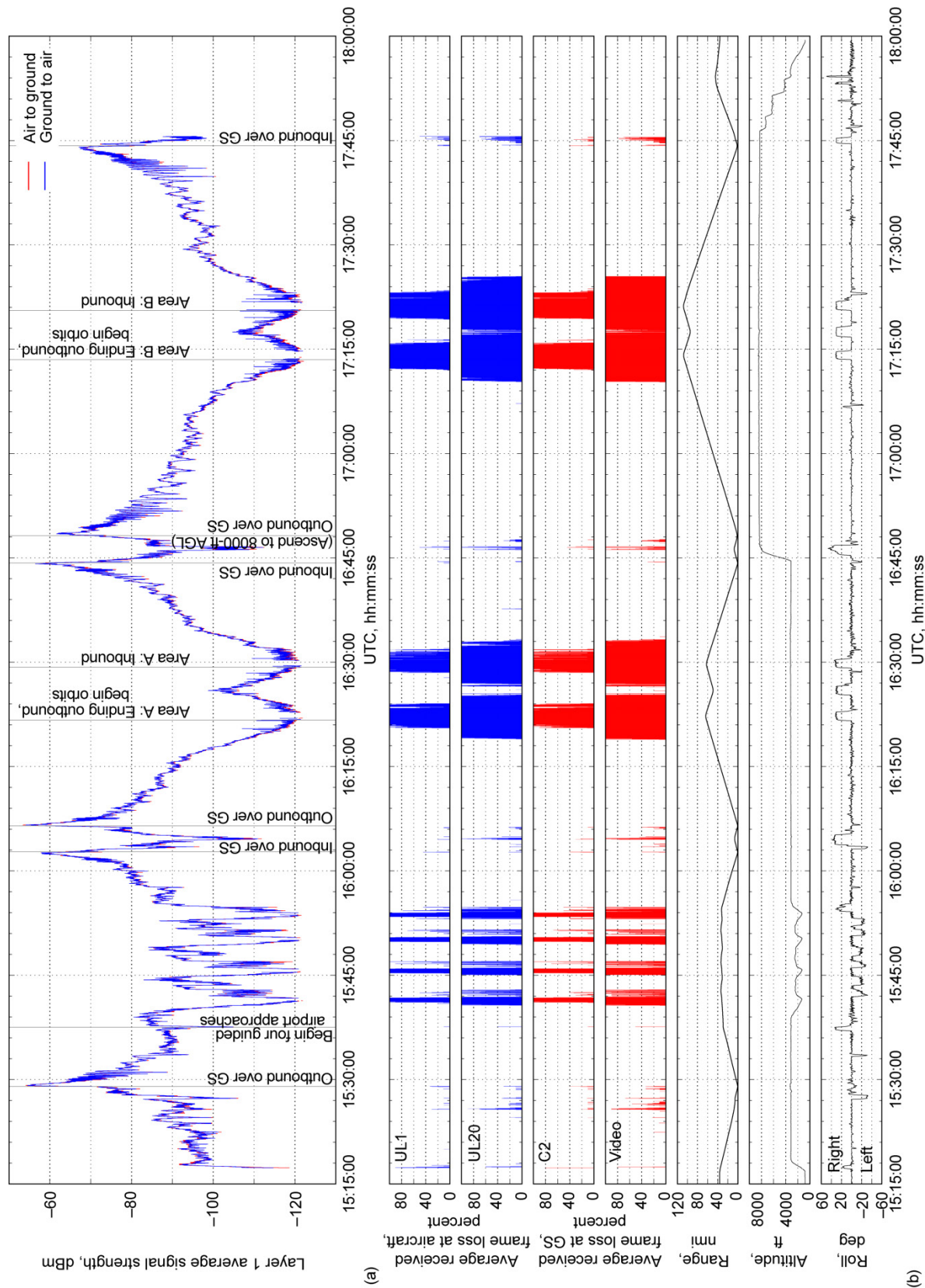


Figure 20.—Flight Test 4 radio performance data and associated aircraft parameters at Plum Brook Station on May 28, 2013; GS, ground system; AGL, above ground level; UTC, Coordinated Universal Time.

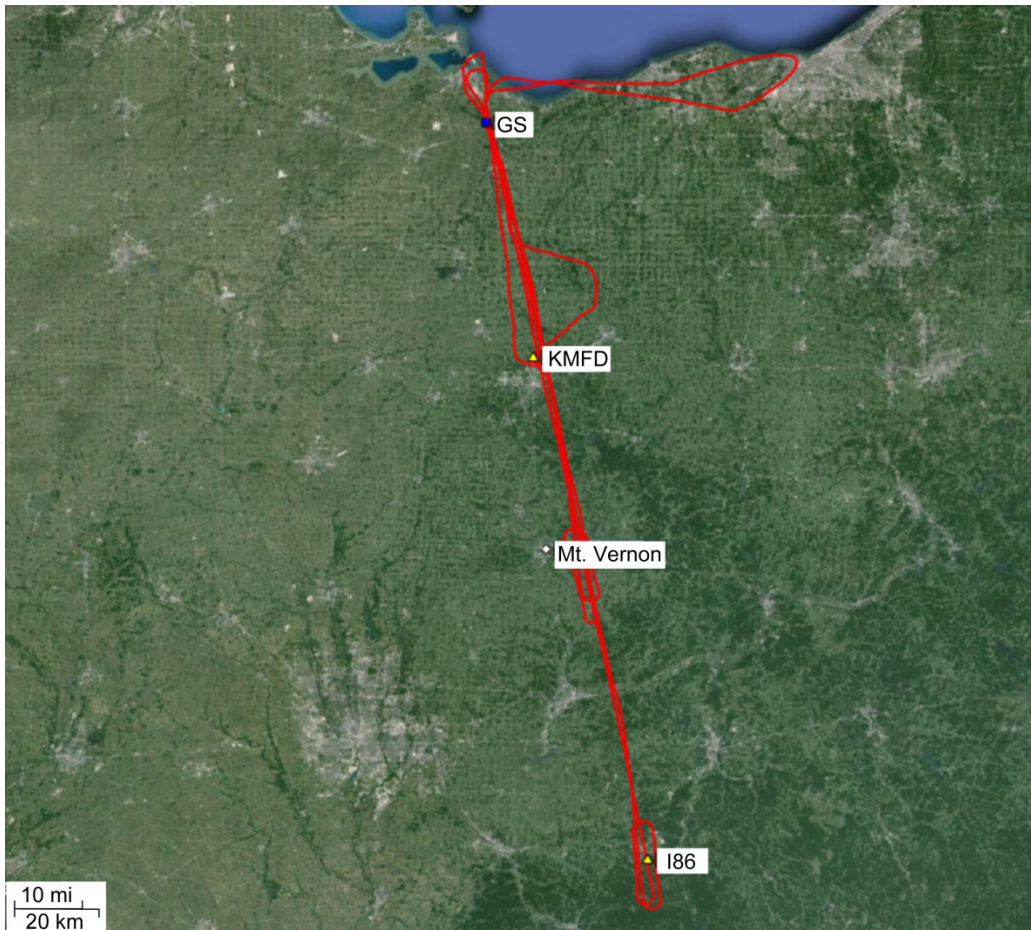


Figure 21.—Research flight track for Flight Test 5—May 29, 2013. GS, ground station; KMFD, Mansfield Lahm Regional Airport. Map created at GPSVisualizer.com. Imaging ©2013 TerraMetrics.

#### 4.5.2 Flight Profile

NASA 601 launched from CLE at 14:14 and headed west toward PBS. The radio was in Configuration 6, which was maintained for the duration of the flight. After climbing to 3000-ft MSL, the aircraft turned south-southeast on a heading of approximately 178°, passing over the GS at PBS. Then the aircraft headed to KMFD to perform three touch-and-go landings. NASA 601 returned to PBS along the same radial, then it reversed and flew outbound again. The aircraft elevated to 4000 ft briefly for traffic, then returned to 3000 ft. Near Mount Vernon, Ohio, the UL1 and UL20 signals for both frequencies were lost, and an orbit was established. Breaking orbit, the aircraft returned inbound to PBS and overflew the GS, climbed to 8000-ft MSL, and reversed course. The flight continued to near I86, where the signals were lost. After one orbit at the fringe, NASA 601 returned inbound over PBS, then on to land at CLE at 16:39. The average airspeed for the research portion of the flight was 256 kn.

#### 4.5.3 Analysis

The radio performance data for Flight Test 5 is presented in two sets of traces: one set for the 963-MHz RF center frequency (Figure 22) and one set for the 974-MHz center frequency (Figure 23). The 974-MHz signal strength trace is slightly lower than the 963-MHz trace, indicating either that there was increased propagation loss or lower transmitted power. This effect is being investigated although this difference has only a minor impact on radio range performance.

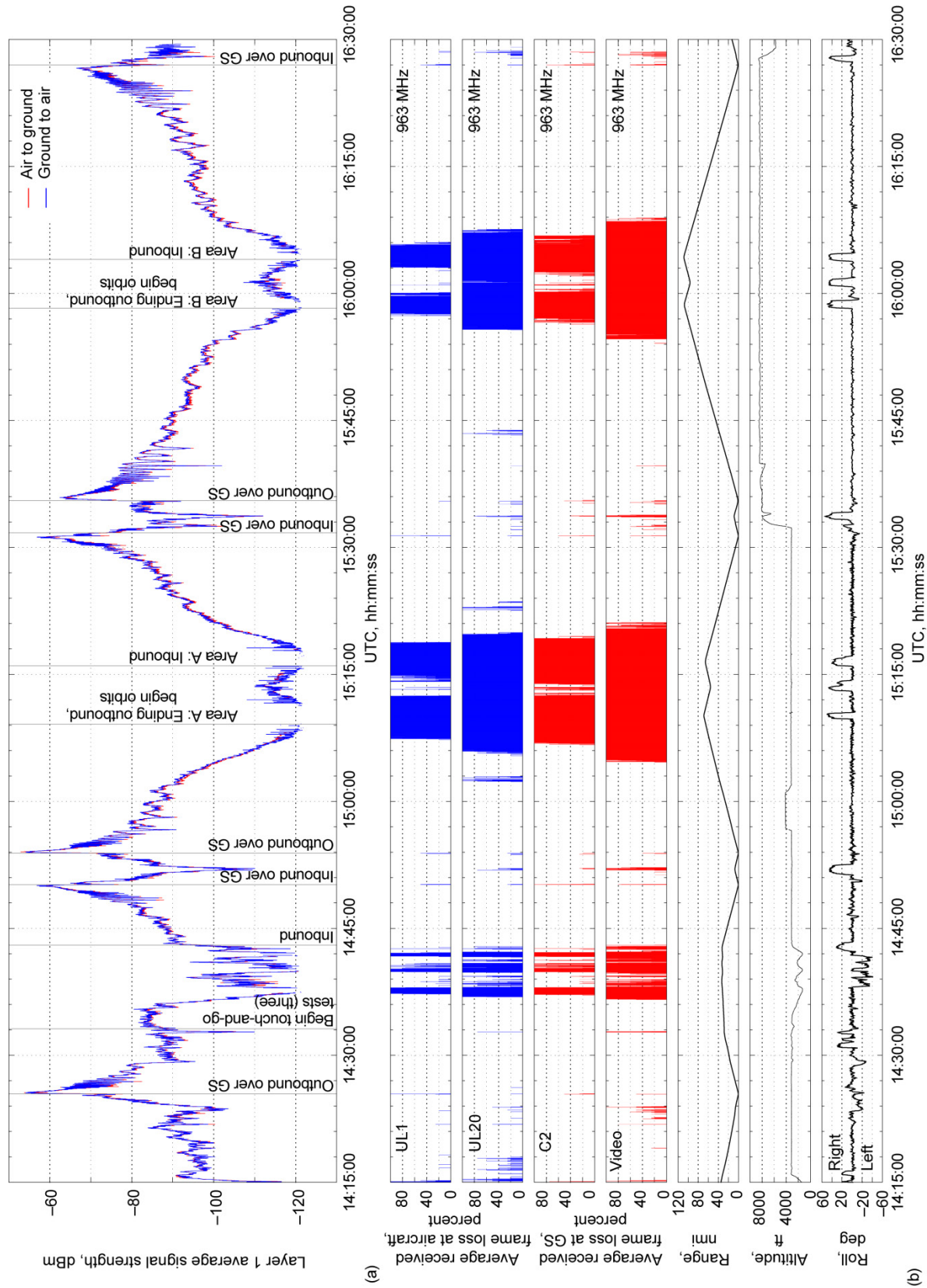


Figure 22.—Flight Test 5 radio performance data and associated aircraft parameters (963 MHz) at Plum Brook Station on May 29, 2013; GS, ground system; UTC, Coordinated Universal Time.

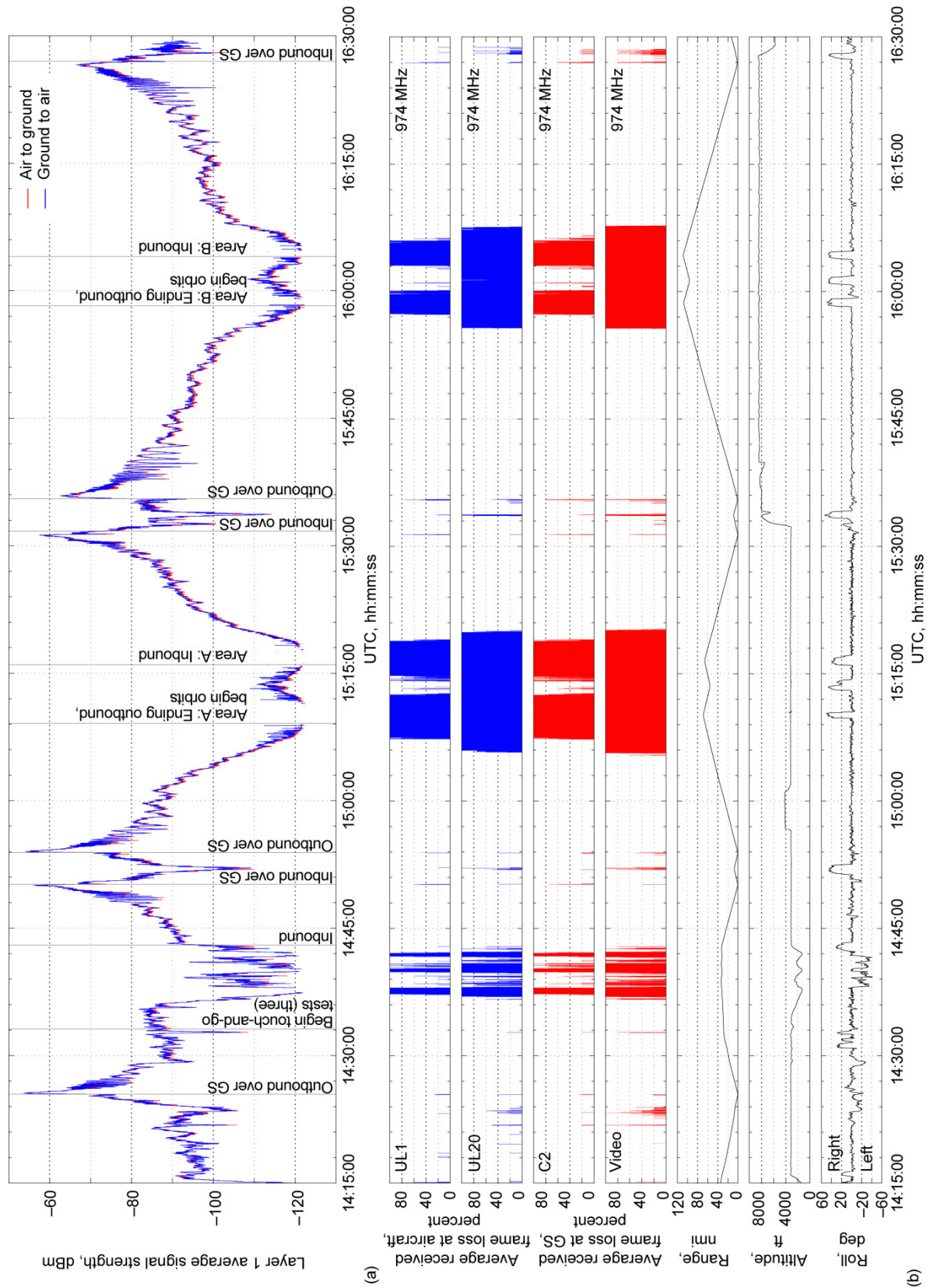


Figure 23.—Flight Test 5 radio performance data and associated aircraft parameters (974 MHz) at Plum Brook Station on May 29, 2013; GS, ground system; UTC, Coordinated Universal Time.



For either frequency case, the radio performance data recorded in Flight Test 5 closely tracked the data from Flight Test 4. The first observation is that signal strength curves for both tests shows the slight plateau as the aircraft began easterly travel to set up for approach to the airport. The three runway touch-and-go maneuvers in Flight Test 5 resulted in radio interruptions very similar to those during the low passes in Flight Test 4. Radio operators on the aircraft observed loss of radio signal at all altitudes below approximately 200 ft off the runway surface.

Similarly, the data from the Flight Test 5 outbound/inbound flight vectors along the 178° radial closely resembled the results from Flight Test 4. Aircraft altitudes for both flight tests were approximately the same, resulting in similar slant range distances at dropout regions A and B on the flight track plots. The radios again delivered an operating range of approximately 85 nmi for the video/UL20 signals and of approximately 100 nmi for the C2/UL1 signals.

## **4.6 Flight Test 6—May 31, 2013—Sandusky, Ohio**

### **4.6.1 Purpose**

The objectives of Flight Test 6 transitioned slightly from the investigation of signal strength, range, and LOS obstruction performance to preliminary studies of data flow and network interfacing. Whereas Flight Tests 1 to 5 relied on computer-generated “canned” digital data streams to serve as content for the air-to-ground transmissions, Flight Test 6 utilized real-time aircraft information that was consistent with data that would be transmitted from a UA. This included aircraft position, attitude, airspeed, and many other real-time flight parameters generated by the aircraft during the flight test. Flight Test 6 was intended to demonstrate the ability to interface with the Live Virtual Constructive—Distributed Environment (LVC–DE) ground network via radio. LVC–DE is being developed as an integrated, collaborative test environment for simulating live UA flying in the NAS. LVC–DE enabled GS personnel to monitor the position of NASA 601 in real time via either of two applications: Cockpit Situational Display developed by the NASA Ames Research Center or the UAS Map software developed by Glenn.

Figure 12 shows the close range field of view of the GS antenna for Flight Test 6, and Figure 24 shows the flight track. The flight pattern generally duplicates the path flown during Flight Tests 2 and 3, aligned with the 212° radial centered at the PBS GS.

### **4.6.2 Flight Profile**

NASA 601 launched from CLE at 13:45 and headed west towards PBS. The radio was in Configuration 6, which was maintained for the duration of the flight. After climbing to 4000-ft MSL, the aircraft turned south-southwest, passing over the GS at PBS. NASA 601 flew a heading of 212° toward KUYF. Near point A, the UL20 signal (both frequencies) was lost. The aircraft continued until the UL1 signals were also lost, near KMRT. Then NASA 601 reversed course and set up an orbit roughly between these two points. Breaking orbit, the aircraft descended to 3000-ft MSL and returned inbound north-northeast along the 212° radial to overfly the GS trailer at PBS. After reversing course, NASA 601 climbed to 8000-ft MSL and again flew outbound over the GS along the 212° radial path. Prior to reaching point A, the aircraft descended to 6000-ft MSL and continued in level flight for dropout tests. After all signals were lost south of KMRT, the flight made one orbit at the fringe. On the inbound course, NASA 601 descended to 5000-ft MSL near point A. After overflying the GS at PBS, NASA 601 returned to CLE to land at 15:56. The average airspeed for the research portion of the flight was 231 kn.



Figure 24.—Research flight track for Flight Test 5—May 29, 2013. GS, ground station; KMRT, Union County Airport; KUYF, Madison County Airport. Map created at GPSVisualizer.com. Imaging ©2013 TerraMetrics.

#### 4.6.3 Analysis

The radio performance data for Flight Test 6 presented in Figure 25 and Figure 26 display many of the same signal strength and data dropout characteristics displayed in previous tests. This is not surprising because the data content should really have no impact on propagation characteristics. The important events to note are the losses in signal (frame loss percent), which are once again the result of terrain obstruction and are directly related to aircraft altitude. The traces in Figure 25 and Figure 26 show that 100 percent of the data were received throughout the long, unobstructed sections of the aircraft flight path. The reader also should note that the regions of the signal strength plot that are suspected of indicating multipath interference (discussed in Section 4.3.3) are again visible in Flight Test 6. Though present, the anomalies do not disrupt data transfer between the radios: there is zero frame loss during these periods.

Aircraft flight data transmitted through the air-to-ground channel was recovered from the ground radio. The data were then used for GS informational displays. GS operators were able to view displays showing the onset of terrain obstruction and increase in data frame errors occurring nearly simultaneously.

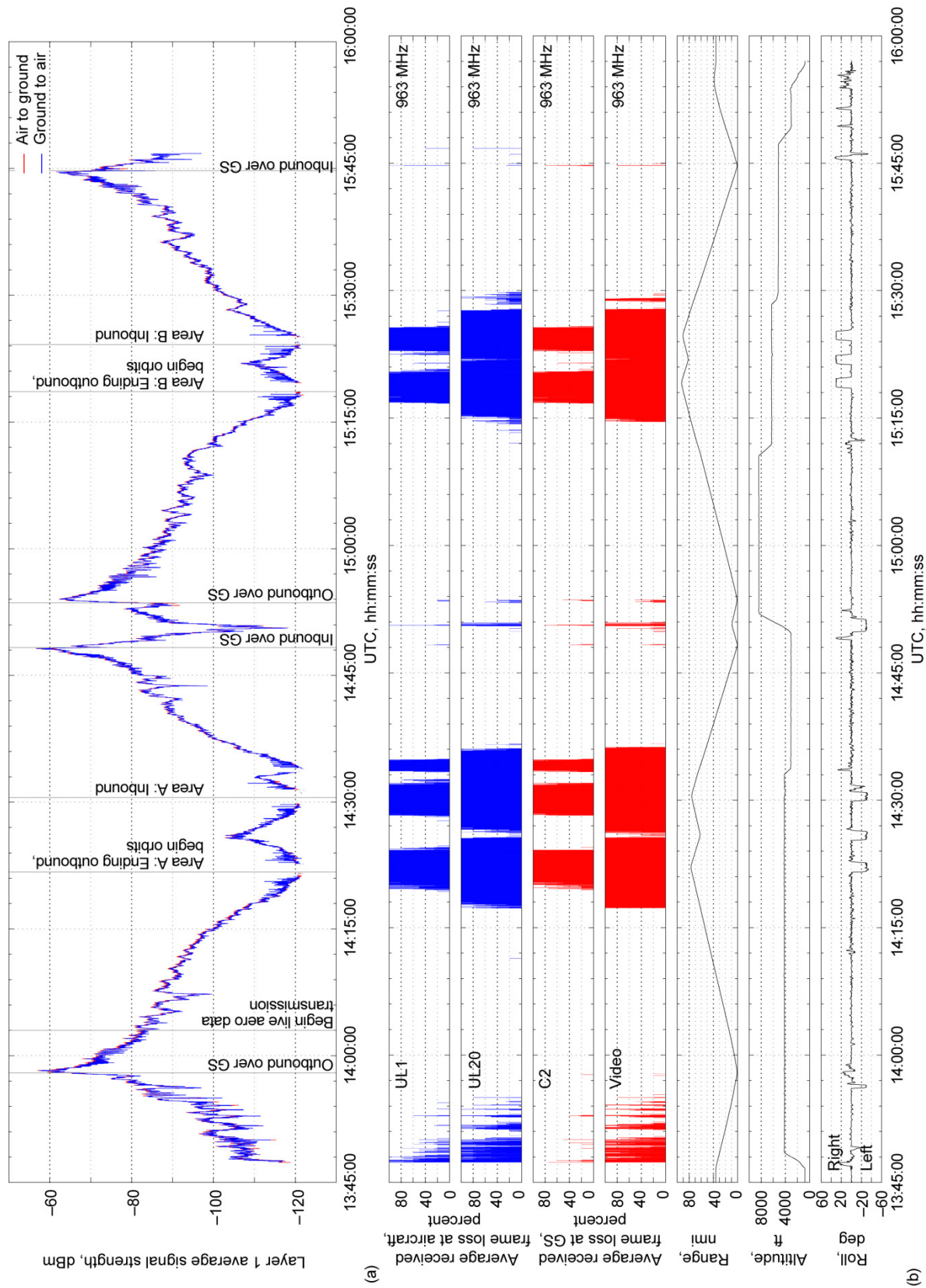


Figure 25.—Flight Test 6 radio performance data and associated aircraft parameters (963 MHz) at Plum Brook Station on May 31, 2013; GS, ground system; UTC, Coordinated Universal Time.

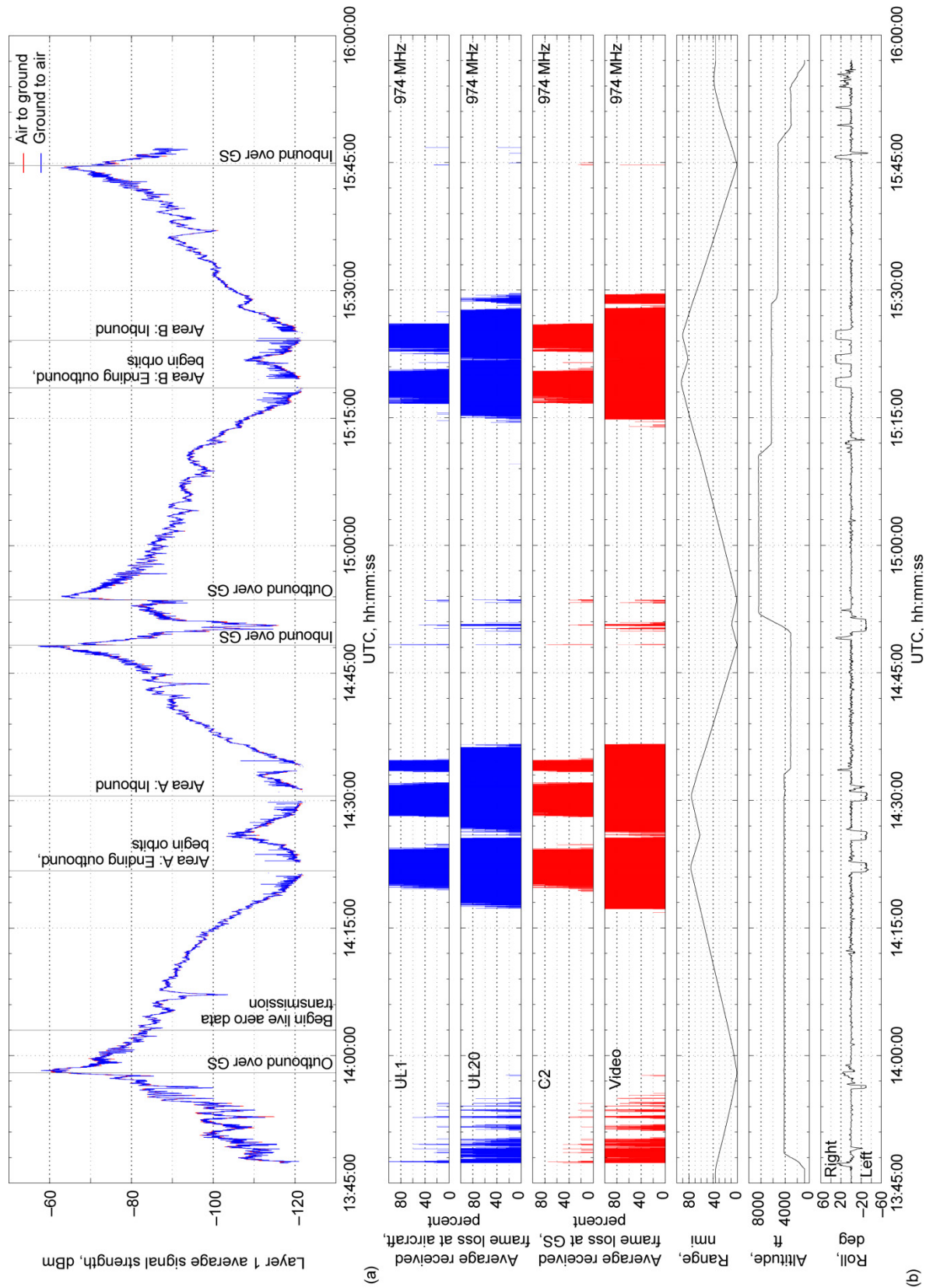


Figure 26.—Flight Test 6 radio performance data and associated aircraft parameters (974 MHz) at Plum Brook Station on May 31, 2013; GS, ground system; UTC, Coordinated Universal Time.

## 4.7 Flight Test 7—June 18, 2013—Cedar Rapids, Iowa

### 4.7.1 Purpose

The seventh and final flight test of the radio test campaign examined the radio signal range from a 300-ft fixed radio tower. The increased elevation of the GS antenna, coupled with the relatively flat and open terrain of eastern Iowa, offered the opportunity to increase the unobstructed LOS slant range to well over 100 nmi. The first goal of Flight Test 7 was to verify that the CNPC communications links could be sustained to greater distances using the standard 4-W RF output power level from the radio, without the need for external amplification. The second test goal was to determine if communications channel dropouts were caused by LOS obstruction or by free-space (distance-induced) propagation loss.

For this test, another copy of the radio was temporarily installed in the radio room at the base of the 300-ft tall tower at the Rockwell Collins facility in Cedar Rapids, Iowa. A low-loss coaxial cable was installed up the tower to an omnidirectional antenna at the top of the tower. The aircraft radio and antenna system remained unchanged from previous tests.

Figure 27 shows the flight track for the Cedar Rapids test, which was an outbound/inbound cycle on a 270° radial west of the tower. There is no field of view for the antenna in Cedar Rapids.

### 4.7.2 Flight Profile

NASA 601 launched from Cedar Rapids International Airport (CID) at 13:48. After climbing to 10 000-ft MSL, the aircraft lined up to overfly the Rockwell Collins 300-ft transmission tower on a heading of 270°. The radio was in Configuration 7. The aircraft proceeded due west until all signals were lost, approximately 139 nmi from the tower near the city of Carroll, Iowa. NASA 601 reversed course, returned inbound along the same radial, passing over the tower, and landed at CID at 16:01. The average airspeed for the research portion of the flight was 297 kn.

### 4.7.3 Analysis

Figure 28 shows the radio performance data for Flight Test 7. Ground-to-aircraft data are displayed for two different operating center frequencies, 963 and 974 MHz. No air-to-ground data are displayed, but previous tests all indicated remarkable similarity between the uplink and downlink signal performance. The test period began with the aircraft passing outbound over the transmitting antenna, which occurred at approximately 13:57. With the radio operating at the nominal 4-W output power level, the aircraft was able to fly for approximately 26 min, until 14:23, before continual signal interruptions occurred. As was expected, the UL20 signals dropped out slightly before the UL1 signals for both frequencies. Close



Figure 27.—Research flight track for Flight Test 7—June 18, 2013. Map created at GPSVisualizer.com. Imaging ©2013 TerraMetrics.

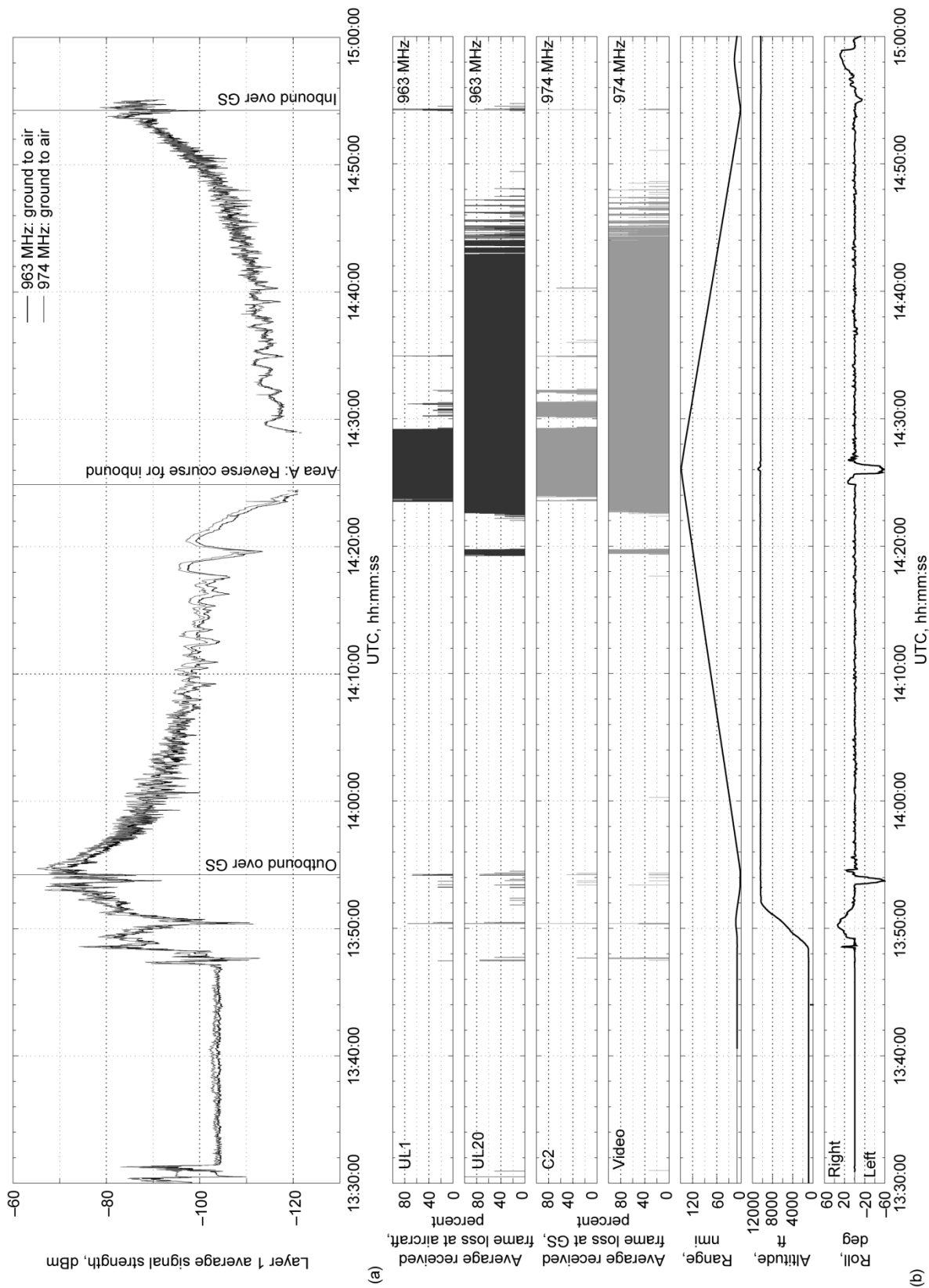


Figure 28.—Flight Test 7 radio performance data and associated aircraft parameters at Cedar Rapids on June 18, 2013; GS, ground system; UTC, Coordinated Universal Time.

examination indicates that the 974-MHz signal actually performed slightly better than the 963-MHz signal in the outbound run. Even in the worst case, the UL20 dropout occurred at a slant range of approximately 130 nmi, well beyond the 69-nmi target range. Consistent with the previous test flights, the communications signal dropouts occurred near  $-107$  dBm for UL20 signals and at  $-119$  dBm for UL1 signals.

One interesting anomaly is the brief loss of communications in the UL20 signals near 14:19. The multiminute dropout and return occurred at both frequencies, but the dropouts were not identical. The authors suspect that the cause of the dropout was destructive multipath interference. The variations in the signal strength plot give support to that hypothesis. Terrain mapping predicts that the curvature of the Earth should begin to obstruct the LOS path at these distances, even considering the 300-ft antenna elevation. The UL1 signals operated continuously throughout the interference period.

While the aircraft executed a course reversal, the output power level of the transmitting radio at the tower was adjusted downward from 4 to 0.2 W. By using this lower power level for the inbound run, test engineers could demonstrate that it was terrain obstruction that caused the drop in received signal strength, not the free-space attenuation of the LOS signal. The UL1 963-MHz trace, for example, clearly shows that signal was lost at approximately 14:23 at a slant range of approximately 130 nmi during the outbound pass. The same signal returned to operation at 14:29 on the inbound pass at the same slant range distance of 130 nmi. Even though the radio output power level had changed from 4 to 0.2 W, the point of signal dropout stayed the same, indicating that terrain obstruction was causing the dropout. Had the LOS been clear of obstructions a slant range of greater than 130 nmi should have been possible with a radio output level of 4 W.

## 5.0 Conclusions

The Unmanned Aircraft System in the National Airspace System (UAS in the NAS) Communications flight test campaign generated a significant amount of empirical data, allowing analysts to begin thorough examination of the L-Band operating characteristics of the Generation 1 control and non-payload communications (CNPC) radios. The primary goals of demonstrating radio-to-radio connectivity in the relevant flight environment, acquiring performance data for system analysis, and verifying suitability of the radio waveforms and hardware for Generation 2 studies were all achieved.

This report discussed only the preliminary findings of the flight test campaign. Efforts are underway to study the radio performance in greater detail to determine the precise communications dropout range, identify the specific obstructions causing the dropouts, and refine the understanding of performance capabilities to assist in applying CNPC radios in future systems. The Generation 1 flight test campaign yielded several important findings:

**Radio Hardware Consistency**—The Generation 1 (L-Band) CNPC radios used in the flight test campaign exhibited excellent unit-to-unit uniformity. This attribute was first noticed during preflight laboratory testing, when output power levels and receiver sensitivity levels measured at similar values across the entire radio set. The remarkable similarity between radio units offered the ability to interchange radios between laboratory, mobile, or flight platforms without making customized changes in the radiofrequency (RF) systems. Also noted was the repeatability of the performance of each radio. Test-to-test and day-to-day radio performance was steady throughout the flight test campaign. No frequency drift, output power drop, or receiver sensitivity changes were recorded. It is interesting to note that the prototype radios were not developed for the CNPC application: the radios were adapted from another software-defined radio product and returned to unmanned aircraft frequencies. The conclusion drawn is that domestic radio manufacturers could produce at least one type of CNPC L-Band radio meeting the fundamental performance goals of the UAS in the NAS Project.

**Terrain Obstructions and Multipath Interference**—The generally flat terrain in the Ohio and Iowa flight test areas allowed researchers to achieve substantial unobstructed line-of-sight (LOS) range to verify RF capabilities. At the same time, small terrain features provided known obstructions that provided valuable data. Using these open range spaces and hilly areas with planned aircraft altitudes allowed a thorough investigation of the LOS obstruction issues. Follow-on investigations of terrain-induced signal

diffraction should provide important information to UAS system planners to help determine optimum GS antenna placement. Test flights in areas of increased terrain obstruction and in areas of manmade structures in the antenna field of view should be examined.

Multipath interference has been a longstanding concern for UAS in the NAS planners, and evidence of multipath interference seems to appear in many of the flight test data sets from the NASA Glenn Research Center. In some cases, the multipath interference created only perturbations in the received signal strength data. In other cases, such as in Flight Test 7 in Cedar Rapids, the multipath interference had a substantial negative impact on radio range. The data from the Generation 1 flight tests are planned to be used in conjunction with the comprehensive L-Band and C-Band channel modeling studies already underway by Dr. David Matolak at the University of South Carolina. Further analysis and possibly additional flight tests are recommended.

***Communications Range Capability***—The prototype radio used in this test campaign provided L-Band connectivity at a range up to approximately 130 nmi using only the 4-W internal transmitter with an aircraft flying at 10 000-ft MSL. This operating range is well in excess of the 69-nmi target range established in early UAS architecture studies. Even though this preliminary result does not include adverse weather conditions, complex terrain features, or congested structural settings, the range provides very encouraging results.



## Appendix.—Radio Testing

Table II shows details of the flight tests.

TABLE II.—ROCKWELL-COLLINS GENERATION 1 CONTROL AND NON-PAYLOAD COMMUNICATIONS (CNPC) RADIO TESTING

Test number and date	Ground terminal location	Tower antenna direction	Tower position		Radio configuration	Filters	Comments
			Latitude	Longitude			
1 5/22/2013	NASA Glenn	312°	41°24'51.90"	-81°51'34.86"	1, 2, and 3	Aircraft: Two cascaded, fixed-value ceramic filters Ground: Rockwell tunable filter	Tower on NASA Glenn Hangar tarmac; sounder flight patterns
2 5/23/2013	PBS <sup>a</sup> 1	212°	41°20'42.02"	-82°38'43.96"	5	-----	PBS <sup>a</sup> location 1; aircraft flying in long-range flight corridor.
3 5/24/2013	PBS <sup>a</sup> 1	212°	41°20'42.02"	-82°38'43.96"	5	-----	PBS <sup>a</sup> location 1; aircraft flying in long-range flight corridor; repeat of 5/23/13
4 5/28/2013	PBS <sup>a</sup> 2	178°	41°20'39.00"	-82°38'46.74"	5	-----	PBS <sup>a</sup> location 2; aircraft flying approach tests into KMFD <sup>b</sup>
5 5/29/2013	PBS <sup>a</sup> 2	178°	41°20'39.00"	-82°38'46.74"	6	-----	PBS <sup>a</sup> location 2; aircraft flying touch-and-go tests into KMFD <sup>b</sup>
6 5/31/2013	PBS <sup>a</sup> 1	212°	41°20'42.13"	-82°38'44.13"	6	Aircraft: ceramic filters Ground: ceramic filters	PBS <sup>a</sup> location 1; aircraft flying inside coverage area with live flight data in CNPC <sup>c</sup> downlink stream
7 6/18/2013	Cedar Rapids, IA	Omni	42°2'0.31"	-91°38'55.32"	7	Aircraft: L-Band ceramic filters Ground: Rockwell tunable L-Band filter	L-Band omnidirectional antenna on 300-ft tower; aircraft flight on 270° radial; 4 W outbound, 0.2 W inbound; custom Rockwell Collins radio configurations

<sup>a</sup>NASA Glenn Research Center's Plum Brook Station.

<sup>b</sup>Mansfield Lahm Regional Airport.

<sup>c</sup>Control and non-payload communications.

## Reference

Chavez, C., et al.: NASA Unmanned Aircraft (UA) Control and Non-Payload Communication (CNPC) System Waveform Trade Studies. NASA/CR—2014-216673, 2014.



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