FIGARO (5G Phased Array Antenna for Lunar Relay Operations) High-Altitude Balloon Flight Test

Seth Waldstein, James Downey, Bryan Schoenholz, Sarah Dever, Mick Koch,
Taylor Pember, Lauryn Leslie, Casey Baron, James Nessel
NASA Glenn Research Center, Cleveland, Ohio 44135, 216.433.5812
seth.w.waldstein@nasa.gov

Satish Sharma and Sanghamitro Das
San Diego State University, San Diego, California, USA

ABSTRACT

NASA's Space Communications and Navigation (SCaN) Program has outlined lunar internet (LunaNet) requirements for beyond-line-of-sight (BLOS) communications between lunar surface assets. These requirements include providing a Ka-band, high-resolution video link to relay between a dynamically moving Lunar Terrain Vehicle (LTV) and stationary lunar habitat or Human Landing System (HLS). The NASA 5G Array for Lunar Relay Operation (FIGARO) project's aim is to demonstrate this architecture using a High-Altitude Balloon (HAB) hosting an active phased array (APA) antenna bent-pipe relay system to communicate between two ground terminals using 5G FR2 band beamforming integrated circuits. Fundamental objectives for this demonstration are successfully tracking the position of each terminal, establishing communications links between ground users via HAB relay, streaming high-resolution video, and transferring of >100 MB of data between ground users. The successful demonstration of FIGARO's flight payload shows this architecture is viable to meet LunaNet requirements for communication between lunar surface users without line-of-sight conditions.

INTRODUCTION

The FIGARO (5G Array for Lunar Relay Operations) project is a collaboration effort between the NASA Glenn Research Center (GRC) and San Diego State University (SDSU) to develop active flat-panel phased array antennas that provide a low-cost, high-performance, and light-weight solution for small satellite communications. The requirements and performance metrics were derived for a phased array antenna operating as the primary communications payload for a small satellite relay node within the LunaNet architecture [1].

The FIGARO transponder payload can radiate four independent circularly polarized arrays with agile and accurate steering that can operate with two transmit and two receive beams. As such, it can provide a direct solution for operation as a lunar relay by supporting multiple access communications links to provide connection between lunar surface assets in beyond line of sight (BLOS) conditions. Its transparent bent-pipe configuration provides a simplified architecture and a lower cost option than a regenerative satellite with on-board processing capabilities.

Each FIGARO phased array has an operable bandwidth from 22.3 GHz to over 30.0 GHz, which encompasses the 5G n257 and n258 bands (24.25 to 29.50 GHz) and overlaps with NASA's Ka space research frequency bands (22.55 to 23.55 GHz and 25.25 to 27.50 GHz) and commercial Ka intersatellite return link bands (27.50 to 30.00 GHz). This wide bandwidth enables a single antenna system that can serve both transmit and receive links and is interoperable between NASA, military, and commercial satellite systems.

High Altitude Balloons (HABs) provide an analogous mission architecture to a low Lunar orbit communications relay, allowing for a relatively low-cost but valuable experiment. Various communications based HAB experiments have been conducted, such as Google Loon deploying LTE internet at 700 MHz [2], Cubesat image transmission [3] and streaming 4K video with a fixed Tx and Rx beam to stationary assets [4]. The FIGARO flight demo attempts to advance the state-of-the-art by facilitating streaming of high-resolution video with dynamic beamforming of Tx and Rx cross-links to mobile surface assets.

CONCEPT FOR OPERATIONS

The FIGARO flight demo system diagram, shown below in Figure , represents the communications link between both ground stations facilitated by the FIGARO bent-pipe payload transponder. Two dedicated ground terminals, deployed as the user nodes, are the mobile phased array-based Cesium Ground Terminal (CGT), representing an LTV, and the stationary Wideband

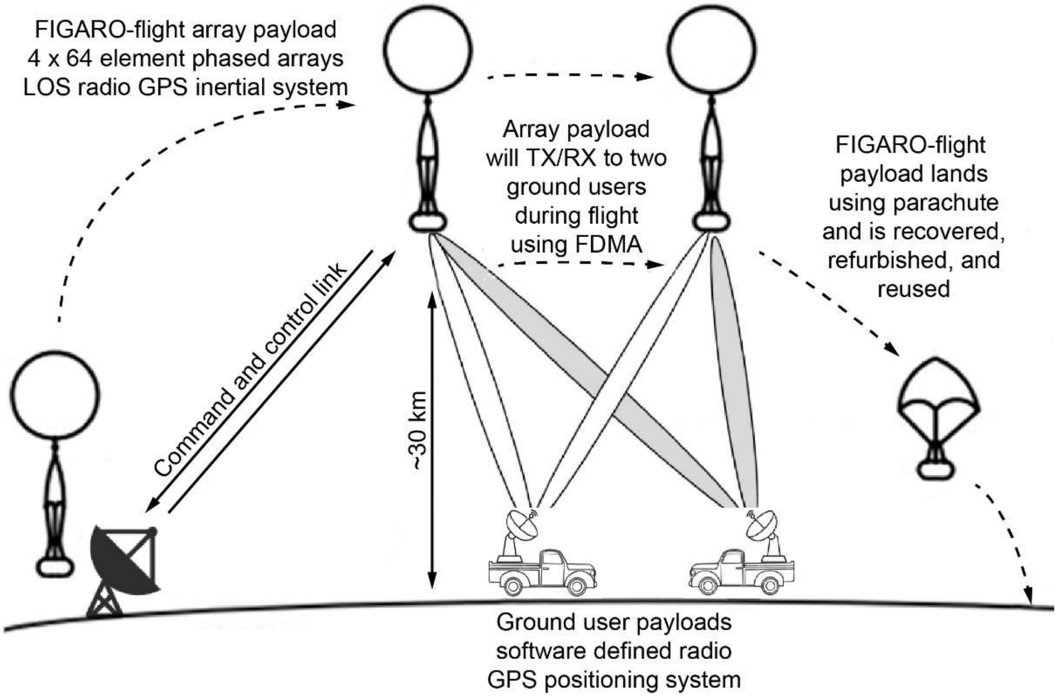

Figure 1: The FIGARO con-ops flight diagram.

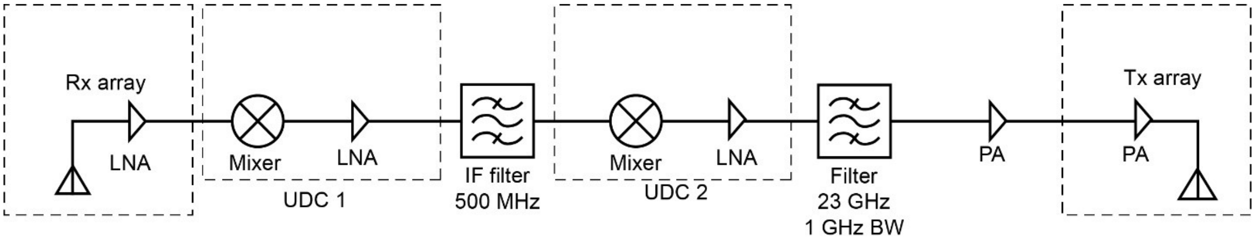

Figure 2: Block diagram of the FIGARO Balloon Payload Transponder (1 of 2 identical paths shown).

Ground Terminal (WGT), representing a Lunar habitat.

The flight vehicle of the FIGARO transponder is a non-station keeping Cyclone balloon provided by Aerostar. Flight time for this mission is approximately 8.0 h which includes 1.5 h for ascent, 6 h of float time once it reaches 30 km, and 1 h for descent back to the ground. Two acquisition sites were planned for the ground stations to attempt connection through the HAB. The uncontrolled, non-stationing keeping balloon, only allows for 30 min to 1 h of coverage at each acquisition site.

The two main objectives for the FIGARO flight demonstration are:

1. To establish communication link between the relay platform and more than one user on the ground, and
2. To transfer 100 MB of data between the ground users through the HAB relay.

The payload transponder and each ground terminal run a tracking system to maintain antenna beam pointing. All three terminals are networked together on the same local area network (LAN) via a Silvus virtual private networking (VPN) system used to publish each user's position, and orientation needed for dynamic beamforming. The assumption is that a lunar relay would have ephemeris to aid in tracking and that lunar surface assets have a reasonable knowledge of their own location. A blind tracking system could have been developed; however, it was deemed out of scope for this demo.

Communications Flight Payload

A block diagram of the Balloon Payload Transponder (BPT) is shown above in Figure 2.

FIGARO's flight payload consists of 4 novel 64-element Ka-band active phased array (APA) antennas, two designated for transmitting and two for receiving. The antennas are cross connected with dual-channel up-down converters that implement a bent-pipe relay function between up-link (27.00 GHz) and down-link (23.00 GHz) frequencies. The two FIGARO Rx arrays receive independent signals at 27.00 and 27.25 GHz and are spatially separated through beam steering. The array architecture uses frequency domain multiple access (FDMA) to communicate to multiple users through multiple single beam apertures. Complete antenna characteristics of the custom designed FIGARO APAs can be found here [5]. Supporting electronics in the flight payload include an on-board computer, a 100 MHz frequency reference, a transmit drive amplifier, band-pass filters, DC-DC voltage converters, and a PIC32MZ microcontroller. Figure 3 shows the FIGARO flight payload transponder connected to the HAB.

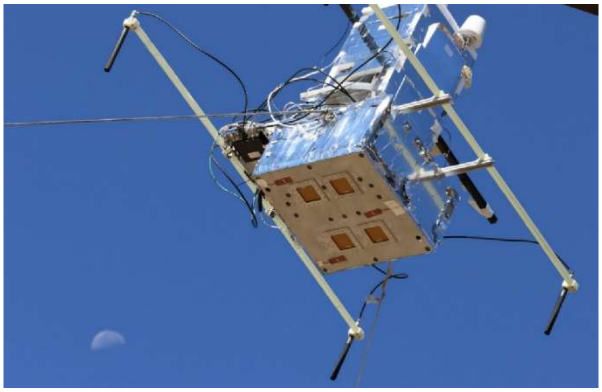

Figure 3: The FIGARO Flight Payload Transponder attached to Aerostar's Flight Control Unit.

Ground Stations

A stationary and a mobile ground station were both deployed with independent transmit and receive apertures. The modems included are Digital Video Broadcasting – Satellite – Second Generation (DVBS2) compatible systems that can modulate Quadrature Phase Shift Keying (QPSK) at ½ rate coding. They are mounted into the back of 4×4 flatbed trucks using pallets that are ratchet strapped to the truck bed.

Ground Station 1—WGT (Stationary)

The WGT was developed under a previous internal NASA effort back in 2021 and retrofitted for use with the FIGARO flight demo [6]. Its aperture is a 0.7 m parabolic gimbaled dish antenna. The backend of the WGT consists of peripheral hardware necessary for tracking and handling of the communications signal. Table 1 lists the WGT antenna figures of merit and figure 4 shows the final set-up.

Ground Station #2—CGT (Mobile)

The CGT consists of independent Tx and Rx 190-element single-beam electronically steerable, phased array antennas, built by commercial vendor Cesium Astro. These arrays were developed under a grant from the NASA's Small Business Innovation Research (SBIR) program. They are mounted on a heavy-duty mobile stand on top of a mechanical gimbal, allowing for shifting elevation angle. Table 2 shows the CGT antenna figures of merit and figure 5 shows the final set-up.

Figure 4: The Wideband Terminal mounted into the back of a 4×4 pick-up truck on preparation for flight demonstration.

Table 1: Wideband Antenna Ground Terminal Figures of Merit

Frequency bands	
Receive	17.7 to 23.55 GHz
Transmit	25.25 to 31.0 GHz
Antenna diameter	0.7 m parabolic reflector
Polarization	LHCP / RHCP
3-dB beamwidth	1.5
EIRP	56 dBW
G/T	12 dB/K

Figure 5: The Cesium Terminal mounted into the back of a 4x4 pick-up truck on preparation for flight demonstration.

Table 2: Cesium Ground Terminal Antenna Characteristics

Frequency bands	22.0 to 28.00 GHz transmit and receive
Antenna	190-element active phased array
Polarization	LHCP
3 dB beamwidth	8
EIRP	34 dBW
G/T	–4 dB/K

FIGARO Payload Transponder Characteristics

Associated figures of merit of the flight transponder payload are shown in Table 3.

Table 3: FIGARO Flight System Figures of Merit

$\mathrm{BPT}_{G/T}$	–6.0 dB/K
$\mathrm{BPT}_{\text{transponder gain (max)}}$	145 dB
$\mathrm{BPT}_{\text{EIRP(max)}}$	22 dBW*

The return link EIRP of the BPT Tx array is dependent on the forward link performance, gain of the BPT, and associated losses, mostly driven by path loss and steering loss which are both dependent on distance from the ground stations to the BPT.

System Readiness Assessment

The full system including ground stations and payload were built and tested at the Aerospace Communication Facility (ACF) at GRC. The flight payload's mechanical structure was rated to handle 6g acceleration in all six directions to ensure safety under flight dynamics. Both structural and bolt analysis achieved ultimate safety factors above 3.0. Thermal analysis and Thermal Vacuum Chamber Testing (TVAC) were performed to determine the transient rate of heat rise and assure nominal electronic operation during cold start. Numerous field tests were performed at GRC. These include pointing and tracking using inertial GPS solutions, RF loopback testing, and modem data flow. Final field tests were performed at Aerostar's facilities South Dakota in the days leading up to the launch to verify nominal operation of the system.

RESULTS

The FIGARO flight communications payload was launched from Hurley, South Dakota, on September 26, 2024. The balloon ascended for 1 h and 30 min before reaching float altitude of 30 km. A 360° camera with fisheye lens mounted onto boom attached to the payload periodically provided photos like the one shown below in figure 6.

Figure 6: The FIGARO Flight Communications Payload flying aboard an Aerostar Cyclone balloon floating at an altitude of 30 km.

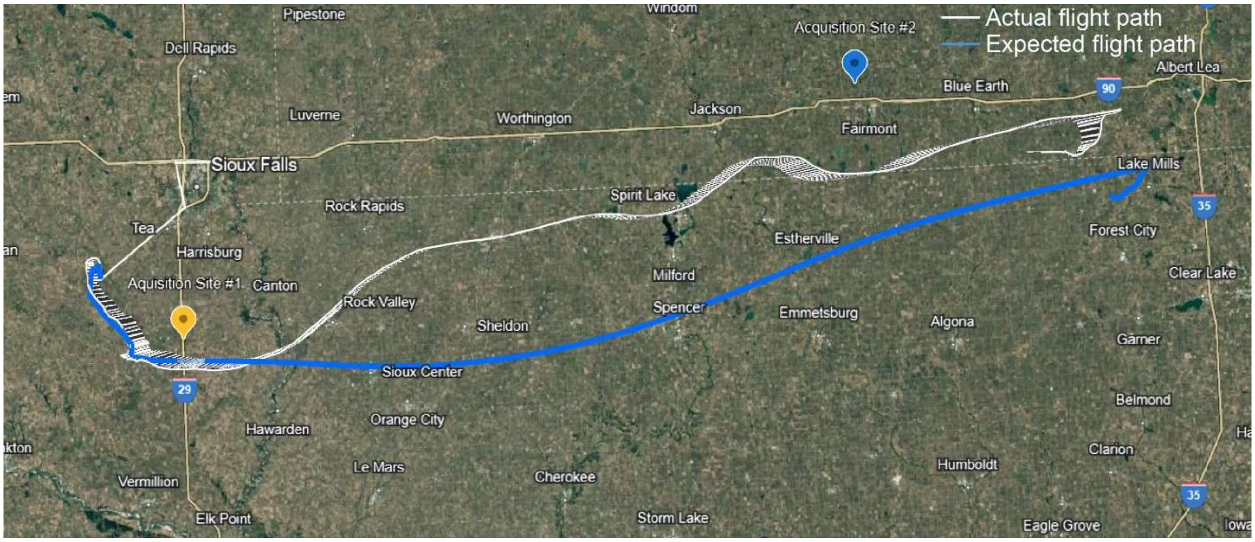

Figure 7: Predicted (blue) and actual (white) fight path of the FIGARO HAB the day of the flight, September 26, 2024.

The expected flight path, based on wind predictions and weather forecast is shown as the blue path in figure 7. The actual flight path, shown in white, started off accurate, but deviated away from the expected flight path beginning around 2 h into the flight. Acquisition Site #1 was Beresford, South Dakota, and acquisition site #2 became north of Fairmont, Minnesota. The ground station teams traversed into three states, South Dakota, Iowa, and Minnesota during the 8-h flight.

Anomalous issues within the payload at acquisition site #1 limited successful connectivity. A healthy signal was observed coming into and out of the balloon payload in the form of elevated current readings implying compression within the transmit arrays of the HAB, however, we were not able to achieve a modem lock or transfer data. Some troubleshooting revealed a frequency off-set we believe was preventing modem lock, but this discovery came at a point at which the balloon was already traveling out of range. We theorize that this offset was due to the initial g-force shock during lift-off throwing the frequency reference off its nominal state, which required power cycling and resynchronization to fix.

The ground stations packed up and began their journey to site #2 after the balloon had drifted out of range at site #1. The landing site for Acquisition site #2 ended up being much farther away from the balloons actual flight path due to last minute changes in the balloon's trajectory. The minimum range of the balloon to the ground stations at site #2 was 34 km, while it was within 30 km at site #1. This increased distance resulted in increased pathloss and steering loss.

Even with this increased distance and losses, a communications relay link was established at 24,400 s from launch at site #2. Both ground stations data rates at the receiver reached a symbol rate of 10 MBd during video transfer, shown in figure 8, while using QPSK with ½ rate coding for the DVB-S2 video transmission, which happened around 27,300 s into the flight. In total 102 MB of data was received across both ground terminals. Symbol rate peaked at 10 MBd. We switched to 5 MBd to improve link margin.

Figure 9 shows the measured C/No (dB-Hz) for both ground stations during acquisition site #2. Video streaming was successful when both C/No were above 60. There were significant drops in C/No observed that correspond to symbol rate changes at the modem resulting in the modem having to reaquire a signal. WGT has substantially more G/T than CGT and the auto gain control on the relay was not implemented so we did not have optimal conditions at all times.

After successful transferring of 100 MB of data via video stream the modems were switched into bit error rate test (BERT) mode where the WGT continued to receive Pseudorandom Binary Sequence (PRBS) data transmitted by the CGT. The PRBS data allowed evaluation of link condition and tracking without an operator monitoring a video feed. Both the CGT and WGT were positioned close to each other at each acquisition site until, after the video stream, when the CGT became fully mobile.

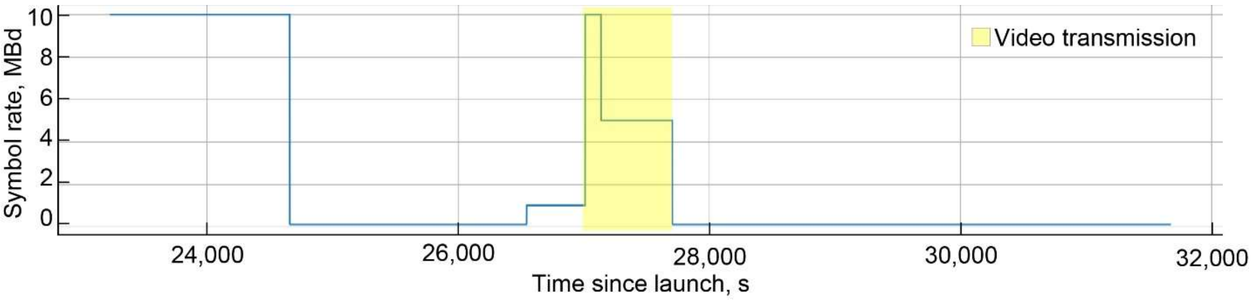

Figure 8: WGT symbol rate at acquisition site #2.

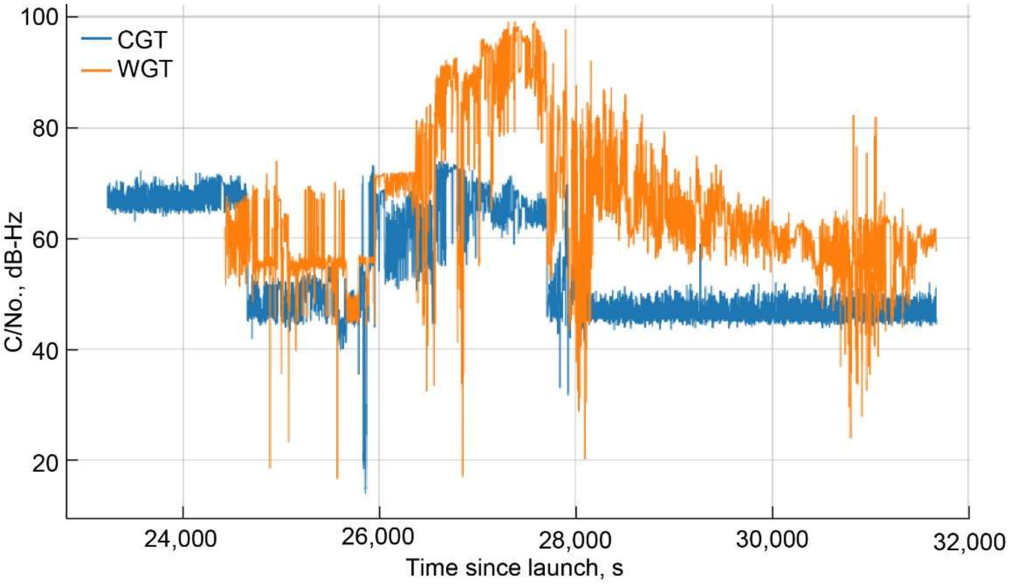

Figure 9: Expected vs. measured C/No for both return links at acquisition site #2.

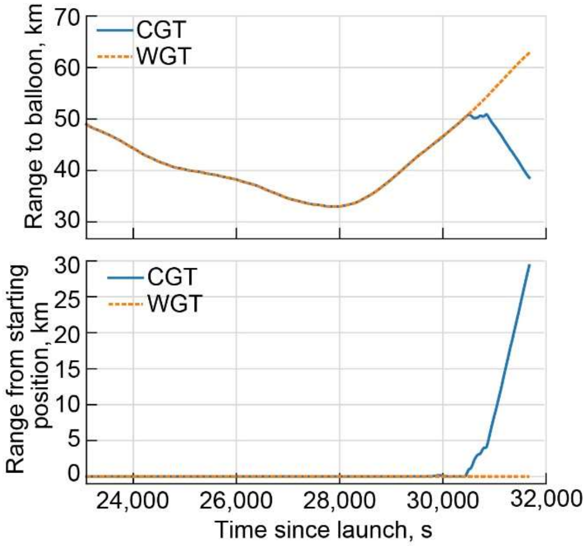

Figure 10: Timeline of Range to Balloon and range to stationary ground terminal of both CGT and WGT terminals as site #2

At around 30,500 s after flight the CGT began driving across the state while tracking the balloon until its final descent while the WGT stayed stationary in the same location for the remainder of the test. The range of the CGT and WGT to the balloon can be seen to start separating after 30,500 s after launch, shown in figure 10. The CGT reached a maximum separation distance of 30 km from the WGT while still maintaining modem lock.

CONCLUSION

A novel Ka-band multi-beam bent-pipe relay transponder was flown on-board a HAB to approximately 30 km to successfully facilitate the transfer of high-resolution video between dynamically moving surface assets. Two dedicated ground terminals, deployed as full duplex user nodes, transferred > 100 MB of data between each other at a maximum data rate of 10 Mbps. The stationary ground terminal maintained Rx modem lock for over 30 min while the second mobile terminal separated at more than 25 km, demonstrating the relay transponder's functionality in a BLOS condition.

The FIGARO transponder is a low-cost and low power option for connecting between dynamically moving Lunar surface assets. Its transparent bent-pipe topology is a simplified and lower-cost alternative to regenerative satellites. A network of multiple FIGARO small sat transponders, flying at low lunar altitudes, could provide continuous coverage for mobile surface assets. Signals can be routed to the Lunar Habitat for local processing or relaying the Earth-bound return link via a large ground station, rather than assuming that burden onto a satellite.

The HAB platform provided an analogous mission architecture and low-cost flight vehicle for demonstrating a functional relay to communicate between an LTV and a Lunar Habitat.

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