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Lessons Learned Using Iridium to Communicate with a CubeSat in Low Earth Orbit

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Abstract

This paper presents the design and approval process for operating an Iridium transceiver on orbit and provide on-orbit performance data obtained from a CubeSat platform in Low Earth Orbit (LEO) (500 km orbit). On-orbit data demonstrates that use of a commercial, low-cost Iridium transceiver can serve as a valuable communication approach for low volume telemetry with less than a 30-minute lag for approximately 90% of the time. We also demonstrate that a radial differential velocity of 7 km/sec corresponding to about a 37.5kHz doppler shift and a distance of less than 2,000 km can be used for mission planning.

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1. Introduction

Setting up a dedicated radio communication link with a CubeSat in Low Earth Orbit (LEO) presents several challenges, especially for institutions with limited funding or resources. The traditional approach of using one or more dedicated radio ground stations to communicate directly with the satellite is often prohibitively expensive for university groups or organizations with limited involvement in space-based applications, and it also requires a significant amount of expertise. The approval and licensing process for radio spectrum allocation with the Federal Communications Commission (FCC) may introduce additional difficulties.

From an operational standpoint, relying on a terrestrial line-of-sight ground station limits the period of time in which the operator can communicate with the satellite. For a satellite in LEO, the typical duration is about 5-15 minutes per day per ground station, depending on the altitude and inclination of the satellite, as well as the latitude of the ground station. This means the operator is oblivious to the current state of the satellite most of the time, even if multiple ground stations distributed across the Earth are used. It also means the operator must plan far ahead in terms of commanding the spacecraft, which can be an issue if the command and data handling unit reboots due to a single-event upset, latch-up, or similar causes.

Several satellite-based communication networks exist to overcome the short communication window problem. NASA set up the Tracking and Data Relay System in the early 1970s, using geosynchronous satellites in an effort to provide near-continuous communications with its LEO satellites. More recently, satel-

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lite operators have begun to use existing LEO crosslink communication networks, such as Globalstar and Iridium[1]. While the primary purpose of these networks is to offer communication between two modems on the ground, they also offer an inexpensive means for satellite operators to establish quasi-continuous communication with their spacecraft.

For the present study, we chose to take advantage of the Iridium network for communication with our MiniCarb satellite, a joint venture between NASA Goddard Space Flight Center (GSFC) and Lawrence Livermore National Laboratory (LLNL). The MiniCarb satellite was intended to:

1. Test the CubeSat Next Generation Bus standard developed by LLNL and several of its partners (Riot et al., 2014).
2. Test several custom hardware components. These consisted of a radio board populated with an Iridium 9523 transceiver, solar panels developed at LLNL that employed a patent-pending deployment mechanism, and several other custom electronics boards.
3. Measure greenhouse gases in Earth's atmosphere using a GSFC-designed Laser Heterodyne Receiver-based science payload.

Unfortunately, due to a deployment anomaly (MiniCarb had an unexpectedly large tipoff rate of over 20 degrees/sec after being released from the Cygnus NG-12 vehicle), the attitude control system (Blue-Canyon XACT) was unable to stabilize the spacecraft using its magnetorquers to the threshold needed for the reaction wheels to turn on. This prevented the solar panels from properly charging the batteries, and as a result the total operational mission duration was limited to ~17 hours. We were thus unable to collect data with the science payload. However, we did advance several hardware components to TRL-8. These include our custom solar panels and deployment system, our custom battery power system unit and our command and data handling system. In addition, we achieved successful ground communication using the Iridium network.

Although 17 hours is not a long period of time, the spacecraft continuously attempted to transmit telemetry messages at least every five minutes, and sometimes as often as every five seconds. This cadence allowed us to measure the average delays between attempted message transmission and successful delivery in both directions, as well as the calculated differential velocities and ranges to the Iridium satellites for 161 message transmissions. This paper will present these empirical results for our MiniCarb satellite, which had a 51.6-degree inclination, 471 km orbit. It will also cover details regarding the licensing and approval process for using an Iridium transceiver on a satellite in LEO.

2. Previous Heritage with Satellite Telecom Crosslinking from Low Earth Orbit

MiniCarb was obviously not the first space-based mission to propose using an Iridium crosslink or demonstrate successful ground communication with an Iridium transceiver. In 2008, Kahn showed the potential of using a number of Satellite Personal Communication Networks (S-PCNs), including Globalstar, Thuraya, Inmarsat, and Iridium, for nano-satellite-to-ground communication (Kahn, 2008). Since the present work is focused on results using Iridium, the short history that follows will focus on the Iridium network only. For a more detailed treatise on the history of using S-PCNs for nano-satellite communications, the reader is referred to Rodriguez et al. (2016).

Recent hardware miniaturization has allowed two networks to stand out in terms of use in CubeSats, with commercial transceiver form factor now being within the 10 x 10 x 10 cm^3 footprint. These are the Globalstar and Iridium networks, both of which provide 100% coverage for the MiniCarb spacecraft orbital parameters.

The Globalstar constellation is designed to have 48 satellites in eight orbital planes of six satellites each. The satellites are in LEO at 1414 km, with an inclination of only 52 degrees. Detailed on-orbit performance has been presented using the Globalstar constellation

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[1] Here and throughout this paper, we use the term "crosslink" more broadly to refer to communication between a satellite of interest and a terminal on the ground via one or more satellites in the chosen communication network.

(Voss et al., 2014), but many other missions have used Globalstar using the NSL-EyeStar commercial system developed specifically for on-orbit operation. One of the issues with using Globalstar is the low inclination of the constellation, significantly reducing coverage for polar orbit missions.

The Iridium constellation is designed to have 66 satellites in six orbital planes of 11 satellites each. The satellites are in LEO at 783 km with an inclination of 86.4 degrees. Iridium has the advantage of an increased coverage near the pole (beneficial for polar missions), but the lower altitude increases the range of Doppler shift that has to be supported. Satellites in the Iridium constellation are equipped with transceivers that have a carrier frequency of 1621.25 MHz and an allowable frequency shift of +/-37.5 kHz. This frequency shift translates to a maximum relative velocity of about 7 km/s between the source and receiver. In 2013, Claybrook used Systems Toolkit (STK) to examine communication opportunities with the Iridium network, analyzing expected Doppler shifts for various orbits, orbital coverage, etc. (Claybrook, 2013). He concluded that orbits with a lower semi-major axis and a higher inclination were preferred. David et al. improved upon this study in 2018, taking into account nodal precession and eccentricity, lengthening simulation duration, and analyzing Doppler shift more closely (David et al., 2018). Their study showed that Iridium coverage for an ISS-style orbit was significantly higher than Claybrook had estimated.

In 2013, NASA Ames Research Center sought to examine the feasibility of using Iridium for crosslinking on its TechEdSat-2 (TES-2) satellite (“Successful PhoneSat Mission Completed”). They launched several follow-on satellites: TES-3p, TES-4, TES-5, SOARE X-8, and SOARE X-9 (Murbach et al., 2016). These satellites demonstrated that it was possible to use Iridium transceivers to receive commands and send low-volume telemetry using the Iridium Short Burst Data (SBD) messaging protocol.

Despite the number of missions that have successfully used an Iridium crosslink, to the best of our knowledge, no one has published empirical information regarding measured transmission delays or calculated Doppler shifts using an Iridium crosslink from a satellite in LEO. It is also important to note that the NASA Ames satellites communicated with the original generation of Iridium satellites. On February 6, 2019, communications switched entirely to the Iridium Next generation of satellites, which features different hardware specifications. It appears that no one has yet published results on crosslink communications between a LEO spacecraft and the Iridium Next constellation.

3. Iridium Hardware and Experimental Configuration

The MiniCarb satellite, along with an expanded view of its in-house-designed Iridium carrier board, is shown in Figure 1. The transceiver shown in the lower right picture is an Iridium Core 9523 model. The Iridium patch antenna is a Taoglas unit part number IP.1621.25.4.A.02.

At the time the MiniCarb spacecraft was designed, two units were available from Iridium resellers. The 9603 SBD-only unit and the more capable 9523 unit, both next generation of earlier models. Both units have a form factor compatible with a CubeSat, well below the 10 x 10 x 10 cm^3 footprint.

The Iridium Core 9523 model provides the capability to do both SBD messaging and Router-based Unstructured Digital Inter-working Connectivity Solution (RUDICS) messaging. We chose the 9523 in the hopes of using RUDICS for faster data rates. However, we eventually chose to use SBD for both Mobile Originated (MO) and Mobile Terminated (MT) messages due to its simplicity and reliability[2], even though it provides slower data rates than RUDICS.

We measured effective SBD data rates during ground testing, using the same Taoglas IP.1621.25.4.A.02 antenna that was used for the MiniCarb flight unit. The testing was conducted from a third-floor balcony at LLNL, with the antenna pointed towards zenith. The balcony position had relatively unobstructed views to the north, east, and west,

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[2] MO messages are ones transmitted from the remote transceiver to the Iridium network and MT messages are ones sent in the opposite direction.

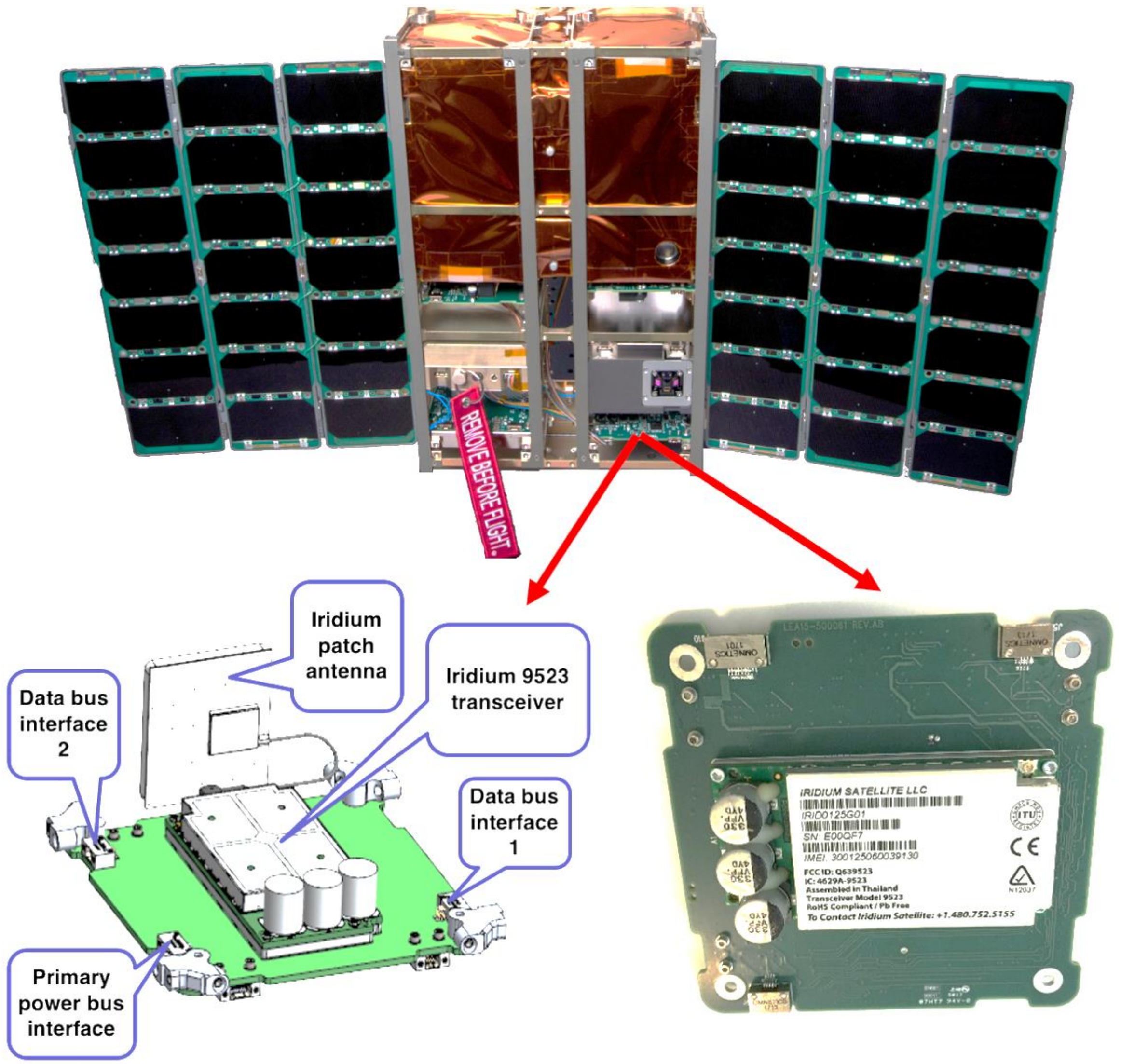

Figure 1. The MiniCarb satellite is shown at top. The left red arrow points to a drawing of the radio board. The right red arrow points to an actual picture of the radio board, with the 9523 transceiver facing the viewer.

Table 1. Parameters for the Radio Board Used on MiniCarb[a]

Parameter	Performance estimate
Mass	85.9g
Interface power	100mW
Bus Power	0.48W average (11W peak)
Height	1.7cm
Uplink/Downlink frequencies	L-Band 1.6GHz
Effective SBD Data Transmission Rates	> 0.44 kbits/sec (Mobile Originated) > 0.35 kbits/sec (Mobile Terminated)
Transmit RF power	7W peak
Receiver sensitivity	< 97 dBm @ 9.6kbps

[a] Note the effective data transmission rates were calculated by repeatedly sending bursts of 10 messages of 1960 bytes each and measuring the time it took for all 19,600 bytes to be successfully delivered with the experimental setup described above. The minimum effective rate that we observed for one of those bursts is reported in the table. Note also that the interface power is specifically devoted to the CAN communication interface and microcontroller on the board; the radio is powered by the bus.

but the view to the south was partially blocked by a wall that covered approximately 50 degrees but the view to the south was partially blocked by a wall that covered approximately 50 degrees from the horizon. Over the course of several hours, the effective data transmission rates were measured by repeatedly sending bursts of 10 messages of 1960 bytes each and calculating the time it took for all 19,600 bytes to be successfully delivered. In all, about a dozen bursts of MT messages and a dozen bursts of MO messages were attempted during this time. Our experimentally-measured SBD data rates, along with other parameters for the radio board are shown in Table 1. Our measured rates are slightly lower than the 0.98 kbits/s rate reported by McMahon and Rathburn (2005). McMahon and Rathburn also report a 2-3% packet error rate, although we did not perform a corresponding measurement to corroborate this.

On orbit, each of our MO Iridium SBD messages consisted of 200 bytes of data. These messages consisted of telemetry for our electrical power system, attitude determination and controls system, and various other subsystems. We used MT messaging to command the spacecraft. The MT messages generally consisted of 40-60 bytes.

Based on the hardware configuration, a communication link budget was generated. It showed that a maximum distance of roughly 2,000 km would guarantee positive link margin as shown in Table 2.

3.1. Iridium Data Plan Selected for MiniCarb

The Iridium service provider we used for our SBD plan was a company called MetOcean, located in Nova Scotia, Canada. They offer several data plans that vary slightly in monthly fees. We purchased their “Plan F,” details for which (as of March, 2020) are shown in Table 3. Given our telemetry data volume of approximately two 200-byte messages every five minutes, this would result in a daily fee of approximately $160.00 USD.

Figure 2 shows an example of how we used DirectIP for our operations. With a dedicated telemetry and command server running at LLNL, all data to and

Table 2. Radio Link Budget for the MiniCarb Configuration[a]

Item	Units	MiniCarb to Iridium (DQPSK)			Iridium to MiniCarb (DQPSK)		
Frequency	GHz	1.626	1.626	1.626	1.626	1.626	1.626
Wavelength	M	0.184	0.184	0.184	0.184	0.184	0.184
Range	Km	2000	2000	2000	2000	2000	2000
Space Loss	dB	-162.7	-162.7	-162.7	-162.7	-162.7	-162.7
System Noise Temperature	K	350	350	350	290	290	290
Required Eb/No for BER 10^{-5}	dB	9.1	9.1	9.1	9.1	9.1	9.1
Data Rate	kbps	25	25	25	50	50	50
Receiver Bandwidth	MHz	0.035	0.035	0.035	0.200	0.200	0.200
Transmitter Power	Watts	1.48	1.48	1.48	4.00	4.00	4.00
Transmitter Power	dBW	1.7	1.7	1.7	6.0	6.0	6.0
Transmitter Antenna Gain	dBi	2 (zenith)	-1 (avg)	-3 (60 degree)	24.87	24.87	24.87
Transmitter Losses	dB	-7	-7	-7	0	0	0
Transmitter EIRP	dBW	-3.3	-6.3	-8.3	30.9	30.9	30.9
Receiver Losses	dB	0	0	0	-7	-7	-7
Receiver Antenna Gain	dBi	24.9	24.9	24.9	2 (zenith)	-1 (avg)	-3 (60 degree)
Receiver Noise Figure	dB	3	3	3	3	3	3
Received Carrier Power	dBW	-141.1	-144.1	-146.1	-136.8	-139.8	-141.8
Received Carrier Power	dBm	-111.1	-114.1	-116.1	-106.8	-109.8	-111.8
Total Received Noise Power	dB	-154.7	-154.7	-154.7	-147.9	-147.9	-147.9
C/N	dB	13.6	10.6	8.6	11.2	8.2	6.2
Eb/No	dB	15.1	12.1	10.1	17.2	14.2	12.2
Eb/No Margin	dB	6.0	3.0	1.0	8.1	5.1	3.1

[a] The link budget shows expected range to be around 2,000km for a 120 degree beam angle (60 degrees on each side of zenith driving the lowest antenna gain). Link budget numbers as they relate to Iridium components have been collected from the redacted publicly available FCC Form 312, exhibit 2 submitted by Iridium as a response to questions from the FCC internal bureau following their application of April 16, 2013.

from the satellite was handled with a Red Hat Virtual Machine.

Table 3. Fees and Message Sizes for SBD Plan F, Offered by MetOcean[a]

Quantity	Value
Monthly SBD Subscription Fee	$19.50 USD
Monthly Data Included	17 Kbytes
Airtime Fee	$1.40 USD per Kbyte
Minimum Message Size	10 bytes
Activation Fee	$40 USD per IMEI
MT DirectIP Setup Fee	$500 USD

[a] The Airtime Fee is applied after the 17 Kbytes in the Monthly Data Included has been exceeded. The DirectIP Setup Fee is a fee required to forward all MO messages to a designated IP addresses over TCP/IP.

3.2. Direct IP Setup for a Command and Telemetry Server

The last row in Table 3 shows a $500 USD fee for a “DirectIP setup.” As part of the base plan, each MO message is sent to one or more email addresses. Paying the DirectIP enables each MO message to also be forwarded to a designated server via TCP/IP.

3.3. Telemetry Transmission Handling

As mentioned previously, our Flight Software (FSW) was configured to send one or more MO telemetry packets to the ground every 300 seconds (five minutes). If a MO transmission was unsuccessful (as indicated by the response from the transceiver), the FSW would try to transmit the message every five seconds until the transceiver confirmed they were successfully transmitted. If, after another 300 seconds, a MO transmission was not confirmed, more messages would still be added to the outgoing queue. When a link was finally established with an Iridium node, a burst of the queued messages would be sent to the node. By comparing the FSW-generated timestamp on these messages with the arrival time on our DirectIP telemetry server, we were able to measure transmission delays with a resolution of approximately one minute.

4. Iridium Hardware and Experimental Configuration

Radio licensing is an important aspect of mission planning, as demonstrated by the TechEdSat-1 mission, which did not secure approval in time and had to disable the Iridium radio in order to launch. MiniCarb, being owned by LLNL, had to go through the National Telecommunications and Information Administration (NTIA) process, but generally the process is similar for commercial spacecraft as they go through the FCC.

While using Iridium simplifies the ground segment significantly, in the sense that a user does not have to procure, own, and operate a communication station, but instead can operate using only a server, licensing still needs to be secured for both the spacecraft and for the Iridium system. This is similar to what a traditional ground station setup would require (one license for the spacecraft to the ground station link and one license for the ground station to spacecraft link). As mentioned previously, the approval to transmit from the spacecraft on-orbit to the Iridium constellation was

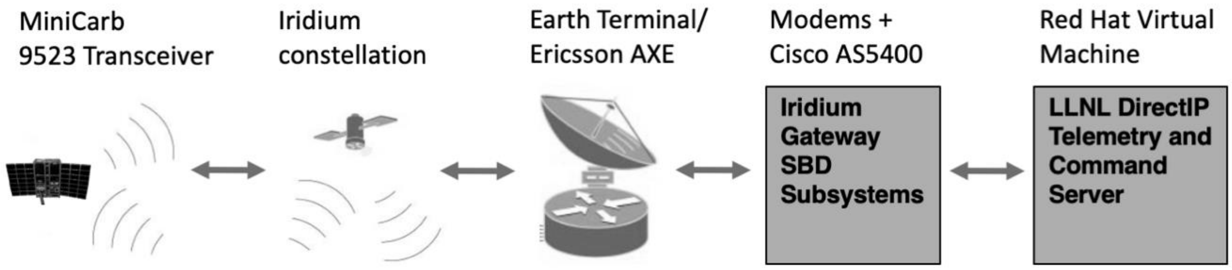

Figure 2. End-to-end messaging diagram for MiniCarb. Commands are sent from the DirectIP server through the Iridium Gateway SBD Subsystems and forwarded to MiniCarb via the Iridium constellation. Command responses and telemetry flow in the opposite direction.

done via the NTIA because of the spacecraft government ownership, but the approval for transmitting from the Iridium Constellation to the MiniCarb spacecraft specifically required FCC approval, since Iridium, the owner, is a commercial entity.

Securing FCC approval to use the Iridium network to communicate with the MiniCarb spacecraft took about five months from December 2018, when we first engaged with MetOcean, and when we received the approval letter in April 2019. The process to secure approval on the Iridium side was as follows for MiniCarb. The first step was to contact our Iridium reseller, which we used to procure the Iridium transceiver and service plan, and let them know we wanted to operate the system in space. In turn, they reached out directly to Iridium, serving as the primary point of contact. Several questions had to be answered so that Iridium could submit an experimental application, including: a description of the mission and its duration; the nature of the data to be transferred using the network; the model number of the transceiver unit to be used; expected orbital parameters; whether transmission occurred during launch and re-entry, or just on-orbit; and the status or plan for the spacecraft licensing request. Two months after initially engaging with MetOcean, Iridium filed a two-tier experimental application and provided a printout of the FCC form 442 in February 2019, which was used as reference in support of the spacecraft side application. Approval of the spacecraft side proved to be more time consuming.

The NTIA process starts with generating an EL-CID file containing all the information about the link. The EL-CID file is generated using software that is freely downloadable at the ntia.gov website. Most of the required information can be obtained by downloading the FCC documents submitted by Iridium when they had their FCC approval to operate the system. The FCC reference number is Q639523N, which allows one to download from the FCC key documents including the EMC exposure report, EMC Part 15B report, and the EMC Test Report. This information allows one to create the entries related to bandwidth, number of channels, power, and other parameters. In addition, a memo describing the system as well as the Iridium FCC form 442 must be attached to this EL-CID form for submission to the Spectrum Planning Committee (SPS). Upon submission, an SPS number is assigned, which is useful for tracking progress. In the meantime, it is recommended for short missions (less than six months planned) to apply also through the SPS to secure an International Telecommunication Union (ITU) registration waiver. This prevents the system from requiring a lengthy, multi-year process to obtain an ITU number. For MiniCarb, the EL-CID file was started in December 2018 and was submitted to the SPS in February 2019, followed by the ITU waiver submission in March 2019. In May 2019, the ITU waiver was granted. In July 2019, a preliminary assessment of the EL-CID request was provided recommending authorization via a memo. This memo was useful to provide information to the launch provider that licensing was on track. Final authorization was secured on August 2019, nine months after the process started, and provided via form NTIA-44, Certification of Spectrum Support. However, this authorization is not sufficient to launch. Upon receipt of the certification of spectrum support form, a request must be made to secure the Radio Frequency Authorization (RFA) document, which requires an additional month.

Overall, CubeSat Developers planning to use an Iridium crosslink should plan to start their licensing application 12 months ahead of the insertion into the dispenser to ensure that authorization is secured in time for integration. For more complex systems that cannot benefit from waivers, additional time should be considered.

5. On-Orbit Performance Data

The MiniCarb CubeSat, in its final dispenser, was launched on a CRS-19 International Space Station (ISS) resupply mission from Space Launch Complex 40 (SLC-40) at Cape Canaveral Air Force Station, Florida on December 5, 2019, at 9:29am PT. The Dragon spacecraft separated from the Space-X Falcon 9’s second stage about nine minutes after liftoff and attached to the space station on Sunday, December 8. At that time, the MiniCarb Spacecraft was transferred to the ISS for storage. At 6:00am PT on January 30, 2020, five weeks later than anticipated due to ISS scheduling delays, the MiniCarb spacecraft in its final dispenser was mounted to the Cygnus NG-12 spacecraft as part of the post mission. On January 31, 2020, the Cygnus vehicle was released from the ISS and reached the deployment orbit by end of day.

On February 1, 2020, the Cygnus vehicles released CubeSats in three batches, the first batch at 7:44am PT, the second at 11:40am PT, and the last one at 1:15pm PT. MiniCarb was released on the last bat ch at 471 km and 51.6-degree inclination. A Two-Line-Element (TLE) orbit estimate was provided at time of release, which has been used for the analysis in this section.

The MiniCarb mission started immediately with first deployment of the solar panel at ~1:22pm PST and activation of the radio at 2:05pm PST (to meet non-interference regulation, 45 minutes is required before activating the radio). MiniCarb started sending messages as expected, and the first messages were received around 2:15pm PST on the LLNL server.

Telemetry data was received for about 17 hours, which resulted in 161 messages of 200 bytes being received and 41 commands sent. The spacecraft had a high tipoff rate of 20 degrees/sec at time of release, resulting in an inability to slow down the rotation enough before batteries were depleted. Therefore, radio data was obtained with a significant tumbling rate, demonstrating the robustness of the link under non-standard conditions.

Data received on the ground from Iridium contains metadata with time of receipt. Data provided by the spacecraft included data at time of generation. That time was adjusted on the ground via a command (the real-time clock super-capacitor on board was not able to stay charged after one month of storage), and cross-checked against known time of release so accuracy on time for the analysis in this section is about one minute.

Overall, the system allowed semi-real-time access to the telemetry. The data was queued for transmission every five minutes and unsuccessful transmissions were retried every five seconds. With this scheme, operators on the ground were able to receive about 90% of the telemetry within 30 minutes of generation, which is invaluable when short response times are needed. Figure 3 shows the statistics across the 161 messages received.

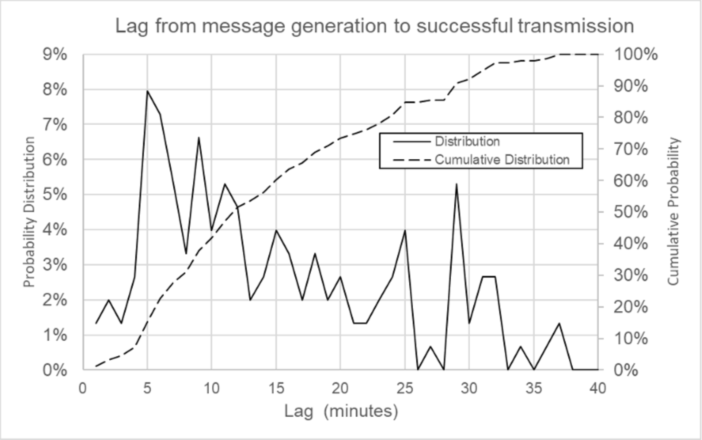

Figure 3. This plot shows the lag between message generation and successful transmission. Upon *failure* to transmit, the system was programmed to retry after five seconds. Messages were generated every five minutes and queued for transmission. In such an application, telemetry was retrieved within 30 minutes of generation more than 90% of the time, which is useful for near-real-time diagnostics.

Commands were sent periodically, and acknowledgements were tracked via the telemetry, which reported the MT count from the Iridium on-board transceiver. Figure 4 shows that about 70% of the commands were received within 15 minutes. This is one of the issues of using this system, as direct commanding has some time uncertainty compared to a traditional ground station when in range. The software on board was designed to allow execution at a specific on-board time so that command can be queued internally and provide time deterministic capability to address this limitation.

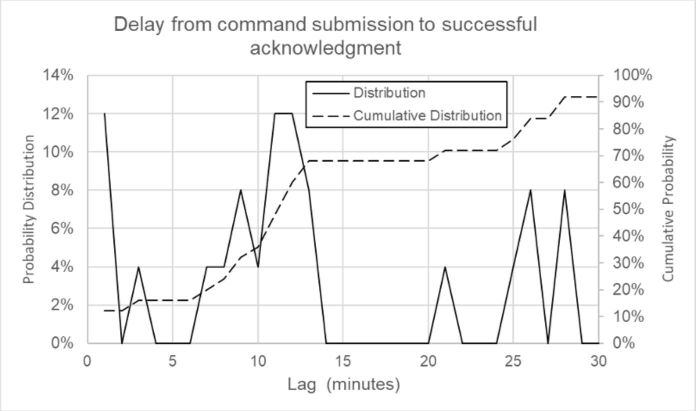

Figure 4. A plot showing the delay between sending a command and confirming acknowledgement. Acknowledgements internal to the spacecraft had a delay of five minutes. Overall, 70% of the commands were acknowledged within 15 minutes.

An interesting feature of the Iridium commercial transceiver is its position, navigation, and timing (PNT) capability. Iridium uses a Doppler-based positioning system that provides a latitude/longitude (geolocation) and corresponding circular error probability (CEP) radius in the header of each SBD message. The CEP radius has been demonstrated to be 1-2 km in the best cases for a transceiver on the ground (Landry, 2019). While it is expected that these PNT errors will increase for a transceiver in orbit due to the higher relative radial velocity between itself and the Iridium satellites (Tan, 2019), we could not find published, empirically measured values for a transceiver in LEO.

Figure 5 shows a comparison between a) the CEP values obtained from the SBD message headers received while MiniCarb was in orbit (top plot) and b) the error calculated by propagating the TLE using the Standard General Perturbations Satellite Orbit Model 4 (SGP4) using the corresponding time tag in the headers (bottom plot). Figure 6 shows the PNT-based positions with respect to the propagated spacecraft TLE.

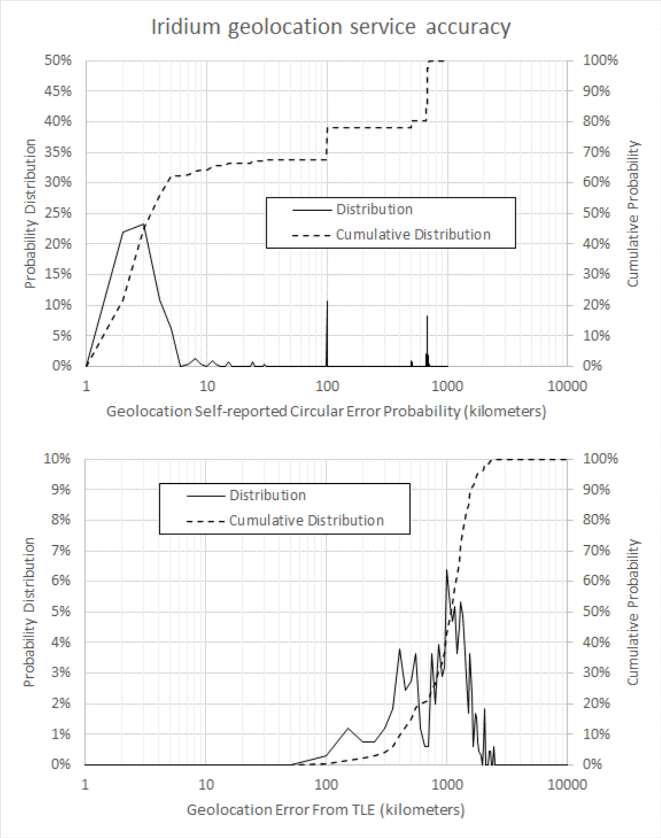

Figure 5. The top figure shows a plot of the Iridium CEP radius reported in the SBD message headers. The bottom figure shows the error calculated by propagating the MiniCarb TLE to the reported time and comparing to the reported PNT latitude and longitude.

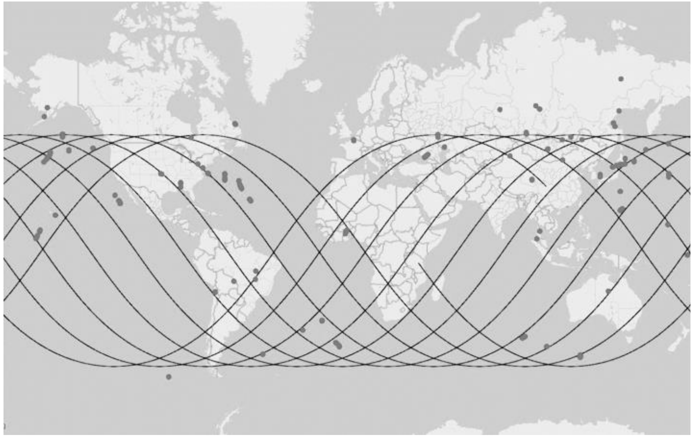

Figure 6. The MiniCarb orbital path from the TLE received from the launch provider at time of release and propagated with SGP4 (lines) versus the Iridium reported geolocation latitude/longitude (dots). The reported location, while showing small error probabilities (see Figure 5), does not always match well with the propagated TLE. While the TLE itself likely had some serious uncertainty, it appears that the Iridium transceiver geolocation capabilities had difficulties, especially at the highest latitudes. This is likely due to the high altitude of the MiniCarb transceiver and the accompanying high relative radial velocity it had with respect to the Iridium satellites while in orbit.

While several reported locations are a relatively good match to the locations predicted by propagating the TLE given the uncertainty of the TLE itself, many high-latitude reported locations are significantly mismatched and certainly not possible based on the inclination of the spacecraft orbit. The error against the TLE-predicted latitude and longitude is around 10 degrees (corresponding to ~145 degrees angular pointing error from the ground for the 471 km orbit) for the peak of the error distribution, but can be as good as 1 degree (~15 degrees angular pointing error from the ground for the 471 km orbit). The geolocation values reported by the transceiver were therefore not good enough to refine the orbit TLE and would not have been adequate to adjust pointing a dish from the ground for alternate radio communication if one had been available on the spacecraft, but they do provide enough accuracy to determine whether the spacecraft is illuminated by the sun for missions that would not provide their own GPS or attitude determination on board. It is likely that the large inaccuracies in geolocation reporting are due to the high altitude of the MiniCarb transceiver and the accompanying high relative radial velocity it had with respect to the Iridium satellites while in orbit.

During mission planning, the MiniCarb team struggled with defining the parameters to be used for designing the telemetry rate and amount of data to attempt to send. The link budget (Table 2) gave some sense of the range to use and the channel spacing of the Iridium RF link some indication of the maximum Doppler shift that could be handled. On-orbit data allows investigating these parameters based on failed attempts versus successful attempts. The predicted predeployment TLE for the MiniCarb spacecraft, as well as the publicly available TLEs for the Iridium NEXT constellation, were compiled just before launch and propagated with SGP4. These TLEs were then analyzed to compare the times of attempted and successful transmissions. While the TLEs have their own uncertainty when propagated for a day or so, they still provide insights on the validity of the range and differential radial velocity leading to a successful connection. Figures 7 and 8 show the overlaid plot of successful connections versus all attempts. One can see that ranges past 2,000 km to the closest Iridium satellite have a low chance of succeeding. On the other hand, the differential radial velocities driving the Doppler shift seem to be less of a factor. Higher Doppler shifts tend to fail more often but seem to qualitatively still be successful across the range. Generally, the 7 km/sec differential radial velocity value appears to remain a good number to use during mission planning exercises. The presence of successful connections with high radial velocity differential is possibly an artifact of selecting the velocity for the closest approach in the analysis. In these cases, it is possible that the next closest Iridium satellite with a lower differential velocity contributed to the successful transmission. However, the metadata received from Iridium does not provide the level of detail necessary to identify which satellite was used.

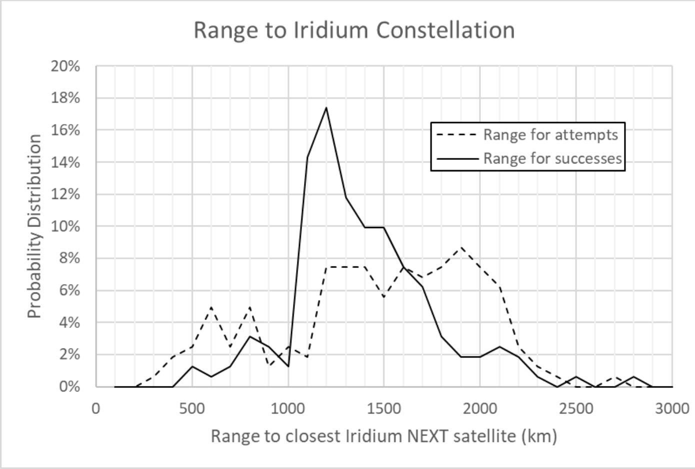

Figure 7. A plot showing the range in km between MiniCarb and the closest Iridium NEXT satellite. This was computed using SGP4, the MiniCarb TLE received from the launch provider at time of release, and the most up to date TLE for each Iridium NEXT just prior to launch. Data shows that most successful transmission occurred when the range was less than 2000 km, which is consistent with the link budget shown on Table 2.

6. Conclusions

Crosslinking using existing commercial networks is a growing area for small satellite LEO missions. It is especially attractive as it removes the need for developing and maintaining a ground station. Licensing for operation requirement and process is similar to more traditional communication approaches and requires a 12-month timeframe. Using the Iridium net-

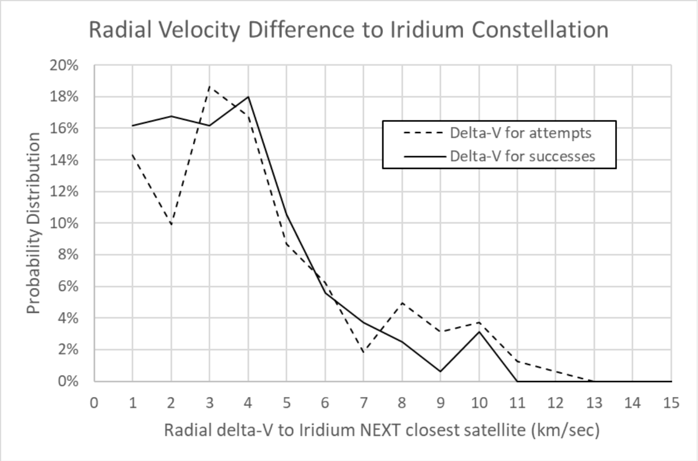

Figure 8. This plot shows the radial velocity difference in km/sec between MiniCarb and the closest Iridium NEXT satellite. This was computed using SGP4, the MiniCarb TLE received from the launch provider at time of release and the most up to date TLE for each Iridium NEXT just prior to launch. Data shows that the Doppler shift does not seem to be a major factor for a successful transmission except possibly for the very high Doppler shifts. The 7 km/sec differential radial velocity expectation is likely a good number to use for mission planning.

work from a CubeSat platform works well even in situations with limited attitude control, providing near-real time access to telemetry and commanding with 30-minute lag for approximately 90% of the time. The latitude/longitude reported in the Iridium SBD message headers had errors on the order of hundreds or thousands of kilometers when compared to those predicted by the MiniCarb TLE, making them unusable for anything but the coarsest position estimates. Teams supporting mission planning can use a 2,000 km maximum range and 7 km/sec maximum differential radial velocities when designing data rates and downlink configurations while using commercially available Iridium transceivers.

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