SSC18-PI-06

# Simulating Iridium Satellite Coverage for CubeSats in Low Earth Orbit

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**ABSTRACT**

This paper will examine the merits of using the Iridium satellite network for duplex inter-satellite communications. The Iridium radio system, relaying data through a 66-satellite constellation in upper LEO, has the potential to provide satellites with superior coverage compared to conventional ground stations. Such stations are limited in range, restricting data downlink and thus the experiments possible on nanosatellites. Use of the Iridium network may therefore be especially appealing for future missions staged in LEO, and specifically for CubeSats due to smaller budgets and shorter lifespans. To satisfy research objectives, simulations run with JSPOC TLEs and SGP4 propagators were used to model the Iridium network and propagate the satellites. Post-hoc validation will be performed by the Thomas Jefferson High School Research and Education Vehicle for the Evaluation of Radio Broadcasts (TJ REVERB) CubeSat mission, scheduled to deploy from the ISS in Q4 of 2018 or Q1 of 2019 as the first non-government-sponsored user of the Iridium satellite radio system for space missions. Future projects requiring similar connectivity could take advantage of the lessons learned, and may utilize the profiles developed in this paper.

## INTRODUCTION

Conventional ground stations utilizing ultrahigh frequency (UHF) radios are limited in range and resident space objects (RSOs) in LEO pass overhead roughly six times daily. The regular but intermittent coverage is unacceptable for missions requiring more frequent uplink/downlink, thus restricting the range of possible experiments and outreach activities. Moreover, ground station equipment is expensive. Antenna tracking systems and the setup of a command and control center can easily exceed tens of thousands of dollars. For satellite missions at small institutions, such hardware may be an exorbitant cost.

Established systems funded by private enterprises such as Globalstar, Iridium, and Orbcomm could potentially be used to vastly improve satellite communications while keeping costs at a minimum. Network satellites are positioned to provide global coverage at ground level, which provides at least some communication windows in LEO. Therefore, the coverage afforded by these networks may exceed that of conventional ground stations. Regular usage fees and initial licensing with the FCC cost far less than building a ground station. As flight-ready UHF radios are expensive, purchasing a standard modem from satellite phone manufacturers promises to vastly reduce development and construction costs. These savings combined with system simplification make small and nanosatellite systems more accessible to educational institutions such as universities and high schools.

To justify use of these networks, comprehensive coverage maps must be made describing the relationship between various orbits, communication time, and total data uplink/downlink capabilities. Furthermore, data rates must be compared to examine the efficacy of the network as the primary radio system for CubeSats and other small satellites. Although the data rate for these systems is lower than that of ground station UHF radios, the superior coverage may offset the difference. From here on, only the Iridium network will be considered.

## LITERATURE REVIEW

### *The Iridium Network*

The Iridium satellite network is composed of 66 operational units and several in-orbit spares in a 780km circular orbit. They operate in six prograde orbital planes with an inclination of 86.4º, spaced alternating between adjacent planes to provide consistent global radio coverage at ground level. Satellites within the planes are spaced 32.7º, while interplanar separation is 16.4º. Co-rotating planes have right ascension of the ascending nodes (RAANs) 31.6º apart, while the two counterrotating planes are separated by 22º.[2,3,8] The satellites are thus at their maximum spacing at the equator and converge at the poles.

Satellite-to-ground communications with the Iridium network are restricted to the L-Band region of 1616MHz to 1626.5MHz. This range contains 240 independent communications channels separated by 41.67kHz and allotted a bandwidth of 31.5kHz. For ground-based targets with low velocity relative to the Earth, the extra frequency space takes into account Doppler effects. Communications exclusively between the Iridium satellites, on the other hand, are in the 2255MHz to 2355MHz range.[8]

Each Iridium satellite uses a three-antenna phased array with 48 total transmit/receive modules to produce a coverage circle approximately 4700km in diameter.[8] At the equator, these beam cones overlap with some margin, but towards the poles, the convergence of the satellites causes beams to intersect significantly. To limit interference and conserve power, outer beam modules are deactivated to still provide total coverage but overlap minimally with adjacent satellites.[3,6]

### *Doppler Shift*

Doppler shift is both a classical and a relativistic effect causing the observed frequency of a wave to shift per the relative motion of the source and receiver. Newtonian physics states that the observed shift is

$$df = \left(\frac{c + v_r}{c + v_s} - 1\right) f_0 \tag{1}$$

where $v_r$ = speed of the receiver; $v_s$ = speed of the source; $f_0$ = frequency in a frame co-moving with the source. The relativistic form of the Doppler shift equation, however, is most accurate when considering high velocities and light waves. If the light pulse travels along the radial vector between the source and receiver, the frequency shift is

$$df = \frac{c - \hat{r} \cdot \vec{v}_s}{c - \hat{r} \cdot \vec{v}_r} \sqrt{\frac{c^2 - v_s^2}{c^2 - v_r^2}} f_0 \tag{2}$$

where $\hat{r}$ = unit vector from sender to receiver. The velocity of the Iridium satellites relative to the ground is roughly 7km/s, which translates to a Doppler shift of 0.003%. For the central frequency of the band, 1621.25MHz, the observed frequency would differ maximally by 40kHz. In practice, due to the co-rotation of the Earth and the minimum elevation angle of 8.2º required to establish a stable connection to the Iridium satellites, the frequency does not exceed the ±37.5kHz buffer imposed by the network.[3]

For satellites in LEO, the Doppler shift can be either less or greater than that relative to ground users. In co-rotating orbits, and specifically those with a high inclination, Doppler shift would be reduced as the satellite is co-moving with an overhead Iridium satellite. In counterrotating orbits, the relative velocity may increase by up to a factor of two, creating an 80kHz shift and rendering communication impossible. Even points where the velocity vectors of the Iridium satellite and test satellite are almost orthogonal, the Doppler shift may exceed network tolerances. Thus, almost all feasible orbits utilizing Iridium communications must be in a prograde orbit to potentially provide more reliable coverage than a standard ground station.

### *Nodal Precession*

Satellites do not orbit in a static plane, but instead drift due to various gravitational forces and atmospheric drag. The most significant of these effects is nodal precession, in which a gravitational torque created by the oblate Earth causes the RAAN of a satellite orbit to precess. Prograde orbits, and thus the Iridium satellites and most LEO objects, precess westward. A reasonable approximation of the precession rate is

$$\omega = -3\pi \frac{R_E^2 J_2 \cos i}{T\left(a(1 - e^2)\right)^2} \tag{3}$$

where $R_E$ = radius of Earth; $J_2$ = 1.083x10$^{-3}$ is the second dynamic form factor of Earth; $i$ = inclination; $a$ = semi-major axis; $e$ = eccentricity; $T$ = orbital period.[4]

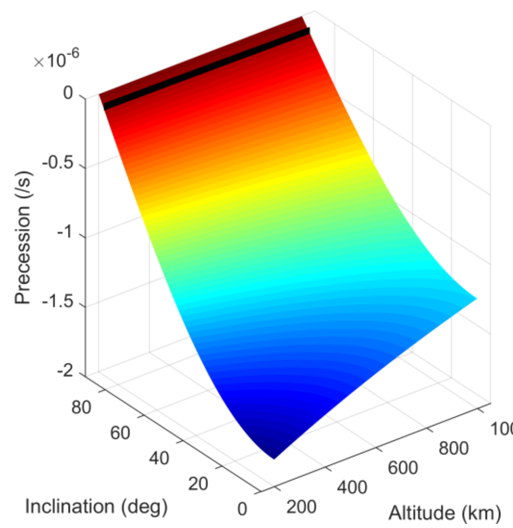


**Figure 1: Precession Plot with Level Curve Designating Rate Equal to Iridium Satellites**

Satellites at higher inclinations and altitudes will precess at slower rates than those in lower orbits. This fact complicates coverage calculations as resonances present at certain configurations may be lost when relative orbital planes drift. To obtain representable results, coverage simulations must involve time scales comparable to the precession of a test satellite from one Iridium plane to another.

The Iridium satellites precess at a rate of 8.44x10$^{-8}$/s, corresponding to about 0.3º per day, meaning that orbits designed to co-rotate with the network must satisfy the equation

$$2.03 \times 10^{-15} = \frac{\cos i}{a^{7/2}} \qquad (4)$$

where $i$ = inclination; $a$ = semi-major axis in kilometers. For any orbit with an inclination below 80º, no semi-major axis exists to fulfill this requirement, meaning that the majority of deployed CubeSats and small satellites (i.e. those not in polar orbits satisfying Eq. 4) will drift relative to the network.

***Previous Study***

Claybrook at the Air Force Institute of Technology studied the effects of various Keplerian orbital elements on Iridium coverage for RSOs in LEO. He used Systems Toolkit (STK) by Analytical Graphics Inc. (AGI) to propagate a test satellite for three days at various inclinations, RAANS, and altitudes. He found that orbits with higher inclinations, lower altitudes, and RAANs equal to that of one of the Iridium planes exhibit greater coverage. Satellites in an orbit with a RAAN not close to that of one of the Iridium planes but with all other orbital elements equal also had significantly reduced coverage. This effect was most prominent at higher inclinations due to the polar configuration of the network.

Periodicity in coverage was noted in most configurations, but it was most pronounced at high inclinations and lower altitudes. An ISS-style orbit in particular exhibited drastic fluctuations in coverage ranging from about 100 seconds per orbit to over 700 seconds, with a period of about nine orbits.

The initial starting point, i.e. true anomaly, had little effect on coverage due to both the symmetry of the network and the differing velocities of the Iridium satellites and test satellite. Since the test satellite orbits faster than the Iridium satellites, it will have coverage spots regardless of initial position.

Recommendations for further studies included taking nodal precession into account and lengthening the simulation duration, analyzing Doppler shift more closely, and examining the impact of eccentricity on coverage.

## METHODOLOGY

***Simulation Interface***

It was deemed necessary to code an orbit simulator rather than rely on commercially available products for two reasons: to allow greater flexibility in data recording and analysis of specific variables, and to take advantage of hardware acceleration, notably multicore parallel computation. The MATLAB programming language was selected due to its extensive library of functions and scientific-computing orientation, as well as a Parallel Computing Toolbox.

A MATLAB-based copy of the Princeton Cubesat Toolbox (PCSTB) was obtained for its orbit propagators and built-in modeling for CubeSat structures. Since it includes many independent functions but few structures which bring functionality into a common environment, code was written to interface the various PCSTB modules into a single interface. A graphical user interface (GUI) was added to provide a visual representation of Earth with appropriate inertial vectors, satellites, and beam cones, thus allowing visual verification of the simulation.

A ground station with an elevation angle of 8º was added to the location of Thomas Jefferson High School for Science and Technology (38°N -77°W) as a point of comparison. The test satellite was assumed to have an omnidirectional antenna to simplify calculations and make the results more applicable to many scenarios.

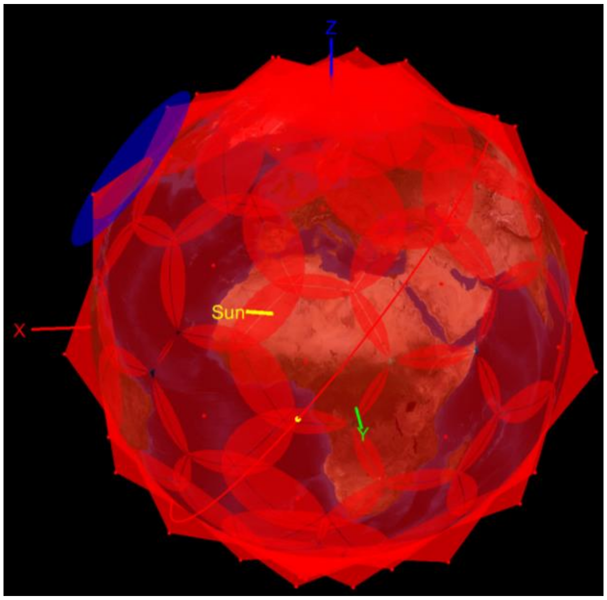


**Figure 2: Simulation GUI**

***Test Satellite***

The test satellite was modeled as a simple 2U CubeSat with solar cells on the ±x, ±y faces and goldized Kapton on the ±z faces to allow the propagator to account for radiation pressures and drag. These forces are expected to minimally change the momentum over the simulation duration, however, and exclusion of these variables could greatly improve simulation speed. An Iridium patch antenna with a beam width of 129º was modeled on the +z face to make simulation with attitude dynamics possible, but this aspect was not included in the final simulation runs due to time constraints.[1]

### *Iridium Satellite Ephemeris*

The telemetry for all operational Iridium satellites is made available by the Joint Space Operations Center (JSPOC) through Space-Track.org and updated daily with new two-line elements (TLEs). Current TLEs for the 66 operational Iridium satellites were downloaded and imported into the MATLAB interface. Each TLE was converted into a NORAD element set containing Keplerian elements as well as drag coefficient and extra functional terms. Orbital propagation was verified by importing the TLEs into the Systems Toolkit (STK) interface and cross-referencing the positions of the satellites with the custom code.

### *Propagation*

The PCSTB includes various propagators utilizing different perturbation models. The Simplified General Perturbations Model 4 (SGP4) was selected due to its robustness, extensive historical use, and reasonable accuracy within the simulation duration. TLEs propagated using SGP4 have error drifts up to 3km per day, meaning that the maximum error after two weeks is 42km.[7] If the error is assumed to be in the orbit direction, a satellite in a 400km orbit would have a temporal error range of about 10s. For this reason, and to provide a reasonable balance between computation duration and accuracy, an integration time-step of 5s was selected. Moreover, all simulated configurations were restricted to no more than 160 orbits, or about 10 days, due to time constraints.

### *Conditions Defining Coverage*

Disregarding the beam cone of the patch antenna on the test satellite, four factors primarily determine whether communication is possible. If the test satellite is located within the projection of an Iridium beam cone on the test satellite's orbital sphere, then communication is possible provided other conditions are met. Since the exact layout of each of the 48 individual beams within the aggregate cone is proprietary, and to limit simulation time, the beam was assumed to be solid with an angle of 122.6º.

Secondly, if the relative velocity between the two satellites is greater than about 7km/s, corresponding to a 37.5kHz Doppler shift, communication is impossible. This condition was implemented by substituting the overhead Iridium satellite velocity and the velocity of the test satellite into Eq. 2.

Since the Iridium satellite beam cones are contracted near the poles, coverage becomes more difficult to model. Due to the proprietary nature of this procedure, an accurate model could not be obtained and thus all potential coverage above ±80º latitude was disregarded. This restriction, however, only affects orbits with an inclination above 80º.

Handshake times further restrict coverage as the Iridium network SBD service requires about 3.6s (mobile-terminated) to establish a duplex connection.[8] Satellites that satisfy all above conditions but are only under a beam cone for a few seconds will thus be unable to uplink or downlink data. As these temporary coverage cases were minimal in the data, this condition was disregarded.

### *Simulation Duration*

Orbital regression of the RAAN in LEO due to the oblate Earth is anywhere from small fractions of a degree to several degrees a day, depending on the angular velocity and inclination of the orbit. Since the Iridium satellite planes are spaced about 31º apart, anywhere from 100 to 2000 orbits are required for a LEO satellite to sweep from a RAAN equal to one of the Iridium planes to the next. Each inclination and altitude was simulated for a duration needed to fulfill this requirement up to 160 orbits.

### *Simulated Orbital Elements*

Since the majority of CubeSats are deployed from the ISS or enter into polar orbits, additional inclinations were selected, clustering around 50º and 85º. See Table 2 for a list of all inclinations and corresponding coverage data. An epoch of June 1, 2018 12:00:00 UTC was selected. Each orbit had the following additional Keplerian elements:

**Table 1: Orbital Elements of Simulated Orbits**

| Element | Value |
|---|---|
| a | $R_E$ + 403km |
| e | 0 |
| Ω | 109º |
| ω | 348.1º |
| ν | 0º |

The RAAN of 109º corresponded at the epoch to the second Iridium plane. The test satellite will thus precess towards the first plane at 78º.

### *Computing Hardware*

The simulations were run in parallel on a quad-core computer using the MATLAB Parallel Computing

Toolbox. One orbit was simulated per core, yielding almost 4x speedup compared to serial processing and allowing greater simulation scope and flexibility.

## RESULTS

### *Average Coverage*

The orbit-average coverages for all inclinations simulated are summarized in the following table. The inclinations 45º and 84º were removed due to errors in the simulated results. The errors section discusses the problems of this study in greater detail.

**Table 2: Orbit-Average Coverage by Inclination**

| Inclination (deg) | Coverage(s) |
|---|---|
| 0 | 486.6 |
| 2 | 492.0 |
| 4 | 499.4 |
| 6 | 507.5 |
| 8 | 515.5 |
| 10 | 525.8 |
| 15 | 556.1 |
| 20 | 592.2 |
| 25 | 638.4 |
| 30 | 674.9 |
| 35 | 702.4 |
| 40 | 731.8 |
| 41 | 742.3 |
| 43 | 754.1 |
| 47 | 788.5 |
| 49 | 805.7 |
| 51 | 831.7 |
| 51.6 | 834.8 |
| 53 | 852.1 |
| 55 | 863.9 |
| 57 | 885.3 |
| 59 | 920.7 |
| 60 | 9389 |
| 65 | 1029 |
| 70 | 1118 |
| 75 | 1372 |
| 76 | 1451 |
| 78 | 1613 |
| 80 | 1926 |
| 82 | 1985 |
| 86 | 1980 |
| 86.4 | 1973 |
| 88 | 1968 |
| 90 | 1915 |

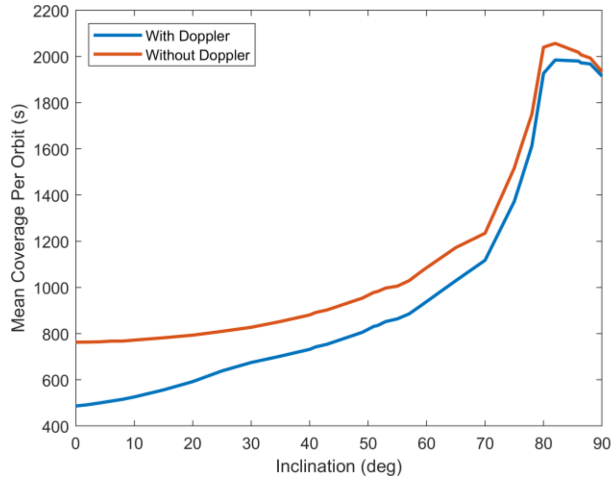


**Figure 3: Orbit-Average Coverage**

As expected, the maximum coverage is attained at high inclinations where the test satellite roughly co-orbits with the Iridium network. Once the test satellite is under one of the Iridium satellites, it will remain there for a much longer duration than in similar situations at lower inclinations.

For satellites deployed from the ISS, an average coverage of about 834s, or 14min, per orbit is likely. Over the course of a day (about 16 orbits), total coverage is 12305s, or 205min (this calculation accounts for the oscillations discussed later). This duration is greater than that of a conventional ground station, which is generally in range in two sets of three consecutive orbits of 8min each. In other words, daily coverage is temporally nearly seven times greater with the Iridium network.

The data is reminiscent of a normal distribution, suggesting the use of a Gaussian to model coverage. High-degree polynomials which achieve similar accuracies are difficult to work with, and were thus not used. The following equation describes the Doppler-inclusive curve:

$$c(i) = 827.7\exp\left(-\left(\frac{i-84.28}{9.353}\right)^2\right) + 2.120 \times 10^{17}\exp\left(-\left(\frac{i-6036}{1039}\right)^2\right) \quad (5)$$

where $i$ = inclination in degrees; $c$ = coverage in seconds.

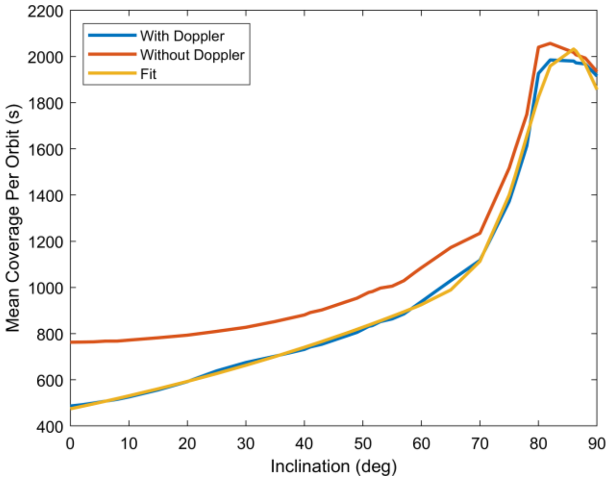


**Figure 4: Coverage with Model Fit**

Doppler shift proved most restrictive at lower inclinations, reducing coverage by a factor of almost two. Higher inclinations experienced fewer losses as the test satellite co-orbited with the network, and at inclinations above about 70º, Doppler reduced coverage by less than 20%.

### *Doppler Effects*

As expected due to the vector nature of the Doppler shift formula, the maximum shift increases sinusoidally and is minimized at an inclination of 0°.

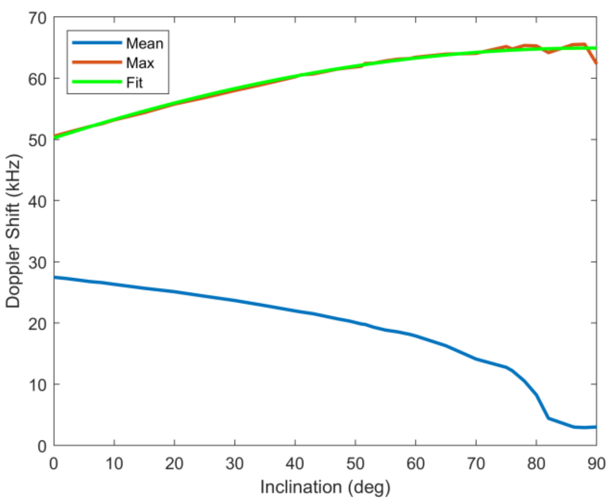


**Figure 5: Doppler Shift**

The equation describing the maximum shift is

$$df = 64.9\sin(0.00769i + 50.7) \qquad (6)$$

where $i$ = inclination in degrees; $df$ = frequency shift in kHz. The mean shift, on the other hand, decreases continuously until 85.6º, contributing to the higher coverage experienced at those inclinations. At no inclination did the average exceed 37.5kHz, which explains why Doppler shift did not reduce coverage by greater than about 40% as shown in Figure 3.

### *Frequency of Coverage*

The frequency at which communications are established is much higher with the Iridium network than with ground stations. The average number of satellites connected to per orbit ranged between three for higher inclinations and 6.5 for lower ones.

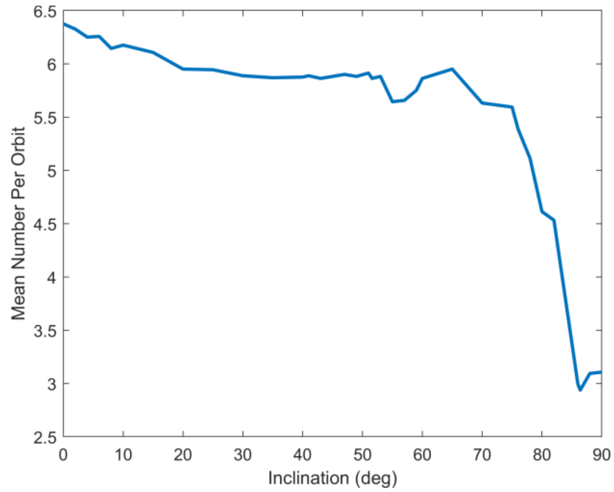


**Figure 6: Mean Number of Iridium Satellites Connected to per Orbit**

The mean duration between loss of signal (LOS) and acquisition of signal (AOS), or gap length, did not exceed 1500s at any inclination. The maximum gaps peaked at 65º at about 5000s. Compared to a ground station, for which gaps between coverage can exceed eight hours, the Iridium network provides far more consistent communications.

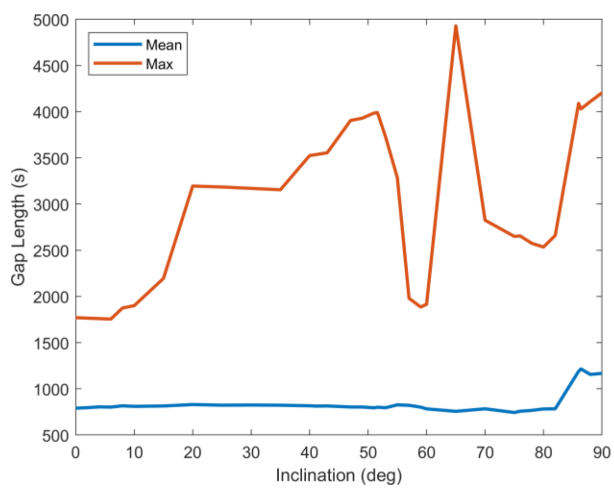


**Figure 7: Coverage Gap Length**

### *Coverage Over Time*

Over time, the coverage for all inclinations was found to oscillate with a period of about seven orbits. It is quite pronounced as coverage for each differs by up to 1000s depending on the current orbit number. Orbits with a higher inclination, or those higher on the plot, have cleaner oscillatory periods and more consistent phase shifts than those at lower inclinations. In all cases, however, the 'waves' begin to noticeably differ in phase as the orbit number increases, which is most likely the result of nodal precession. The individual oscillations, on the other hand, must be independent of the inclination and precession of the RAAN as all orbits exhibit about the same period.

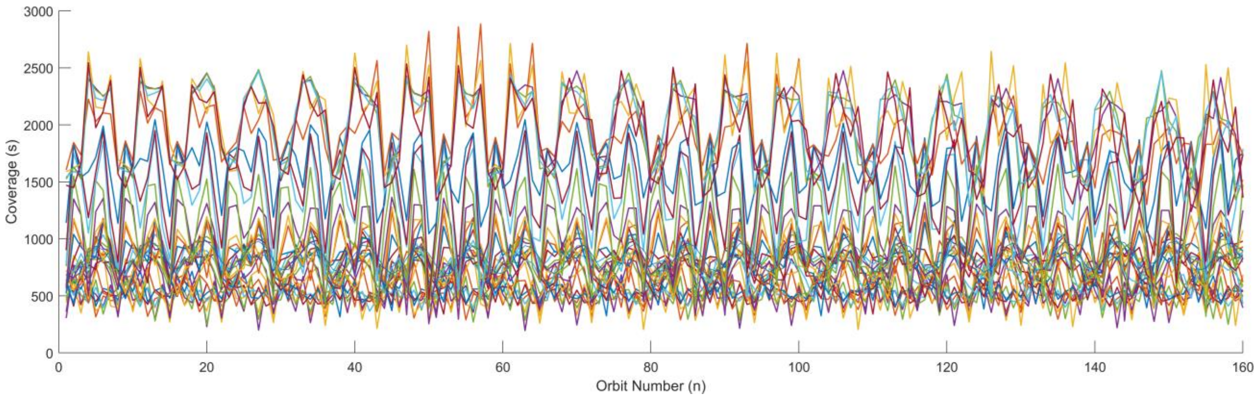


**Figure 8: Orbit-Average Coverage Over Time**

Comparing the results of an ISS-style orbit to that of Claybrook's reveals some key differences. Firstly, coverage over the first 45 orbits in Claybrook's results was significantly lower than that of this study. The most likely cause is his consideration of Doppler shift, notably in that he disregarded coverage above a relative range rate of 7km/s. Although this cutoff is close to that corresponding to 37.5kHz, the additional buffer afforded by doing exact calculations at each time step may have caused at least a portion of the difference. Moreover, since the Doppler shift is dependent on the base frequency, this study's use of the central Iridium communications frequency of 1621.25MHz may have differed from that in Claybrook's considerations. Furthermore, the periodicities of the results differ. No reason for this discrepancy is known, though it may have to do with the differing propagators (SGP4 vs. $J_2$).

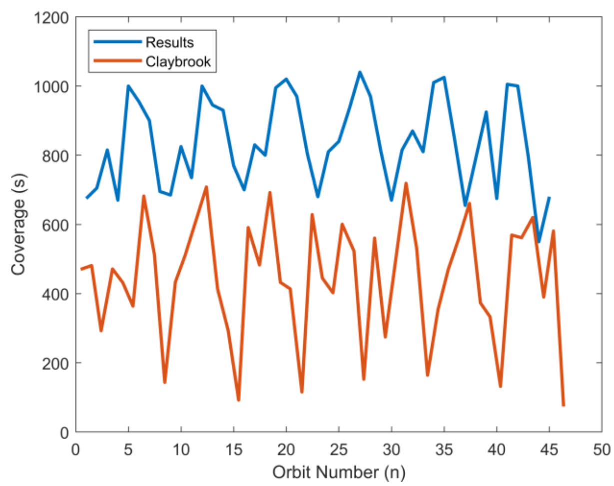


**Figure 9: Coverage Comparison Between Studies for ISS-Style Orbit**

**Note: Plots are from ISS-style orbits, but are not equal in other Keplerian elements. Overlay is to demonstrate periodicity and to facilitate comparison.**

## DISCUSSIONS

### *Data Transmission Comparison*

Once connected to the network, Iridium modems can transmit and receive at approximately 1.2kbps time-averaged.[8] Transmit/receive (TX/RX) for LEO-based UHF radios is usually on the order of 9.6kbps.[5] This means that, for six ground station passes daily at 8min per pass, the combined data uplink/downlink will be roughly 27.6Mb. Due to the periodic coverage of the Iridium as seen in Figure 8, data rates per orbit differ, but the aggregate data rate can be obtained by summing coverage over the first 15 orbits. In this case, 15 is used instead of 16 to provide a conservative estimate.

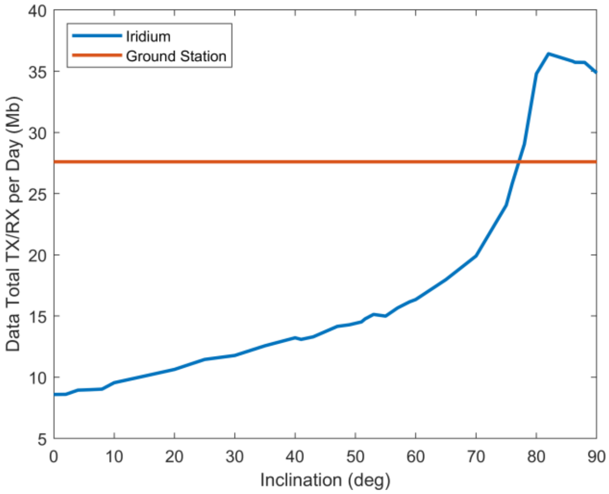


**Figure 10: Daily Iridium and Ground Station TX/RX**

The total data TX/RX does not exceed that of a conventional ground station except at inclinations above 77º. In an ISS orbit, about 14.8Mb of data transmission can be expected, while in polar orbits the rate can be upwards of 36.4Mb. Therefore, the primary advantage afforded by using the Iridium network is not the data rate, but is instead the regularity of the coverage and cost effectiveness of the hardware.

## TJ REVERB

### *Mission*

The Thomas Jefferson Research and Education Vehicle for the Evaluation of Radio Broadcasts (TJ REVERB) is a 2U CubeSat currently under construction by students at Thomas Jefferson High School for Science and Technology (TJHSST). It will be launched to the ISS on November 8, 2018 as part of NASA's CubeSat Launch Initiative (CSLI) ELaNa 21 mission, and be deployed in the subsequent months. The satellite will test two different onboard radio systems: a custom UHF/VHF APRS duplex system and an Iridium 9603 modem. The APRS will communicate via a ground station established at TJHSST and various outreach institutions worldwide. TJ REVERB will be the first NGO to utilize the Iridium network for smallsat communications, thus leading the way for educational institutions to utilize the cost and time saving benefits associated with using the Iridium network.

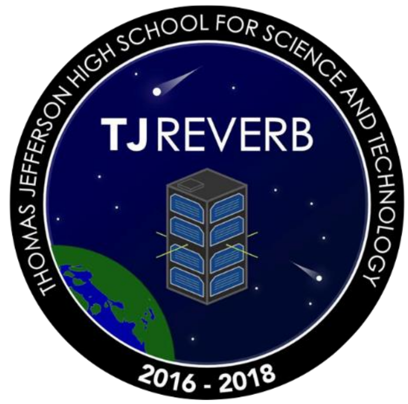


**Figure 11. TJ REVERB Mission Patch**

### *Simulation Validation*

Once steady state has been achieved, the TJ REVERB CubeSat will conduct numerous experiments involving the Iridium radio. Current mission plans involve examining all results from the simulations, thus allowing post-hoc validation of the data. Other aspects that were not discussed but will be explored during the mission are error rates, specific data rates and latency, and the feasibility of using Iridium modems as the sole radio on smallsat missions.

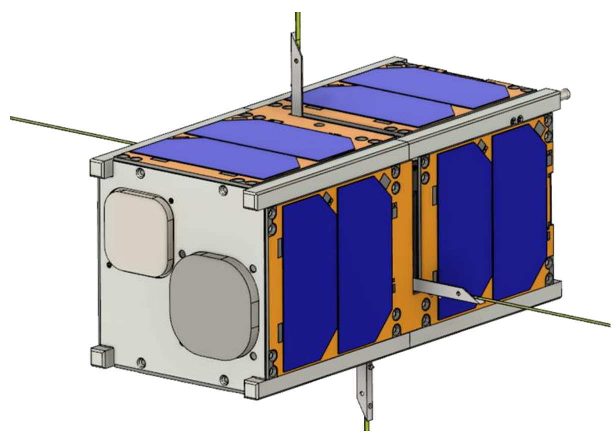

**Figure 12: TJ REVERB CAD Model with GPS and Iridium Patch Antennas**

## CONCLUSIONS

This study examined the feasibility of using the Iridium satellite network for communication with small satellites in LEO. Conventional ground stations are highly limited in total coverage time, thus restricting communications, the range of possible experiments, and the speed of recovery in the event of an error or failure. MATLAB and the PCSTB were used to calculate coverage at 36 inclinations, but the data for 45º and 84º were removed due to errors in the simulated results. Each configuration was simulated for 160 orbits to account for nodal precession. The Iridium satellite beam cones, Doppler shift, polar shutdown were all accounted for in the simulation.

Coverage was found to increase continuously with inclination until 86.4º, which corresponds to the inclination of the Iridium satellites. Doppler shift causes significant communication losses below 70º, above which total losses are less than 20%. Based on these results, we support Claybrook's suggestion that the shift tolerance of ±37.5kHz be increased to ±75kHz. Periodicity in coverage spanning about seven orbits was also observed, but is likely only the result of orbital resonances with the network and not nodal precession nor inclination.

Based on common UHF radio data rates, total data TX/RX was estimated for conventional ground stations and compared to that of the Iridium network. While ground stations can expect about 27.6Mb per day best-case, the Iridium network does not exceed this value until an inclination of 77º. Thus, the major advantage afforded by the Iridium network below this inclination is the more frequent coverage, while satellites above it experience both more data and coverage.

### *Errors*

One important shortfall in this study is the differing rates of nodal precession in the simulation versus theoretical calculation. The nodes drifted fractions of a degree over the 160 simulated orbits, which is far less than expected for most inclinations. The reason is unknown, but likely lies in the SGP4 propagator code in the PCSTB. These results are thus not indicative of long-term Iridium coverage, and thus only apply to RAAN-equal orbits. This error does not explain the discrepancy demonstrated in Figure 9, however, as both curves represent RAAN-equal orbits.

As aforementioned, the data for the inclinations 45º and 84º were discarded due to simulation errors. The results showed coverages less than 10% that of nearby inclinations, suggesting computing error or a massive resonance with the Iridium network. Due to the smooth nature of the average coverage plot, and the absence of any additional anomalies, the former was assumed to be the case. No additional simulations were run to verify this conclusion due to time constraints.

### *Recommendations for Further Research*

Numerous improvements could be made on this study to obtain more accurate and applicable results. Simulating more than 160 orbits could reveal more coverage oscillations with longer periods, as well as the full effects of nodal precession. Since TLEs are only reasonably accurate for two weeks after download when using a SGP4 propagator, different propagation methods that still take into account additional perturbations other than $J_2$ are recommended. Verifying that the propagator accurately models nodal precession is also important to obtain a representable model. A shorter integration time-step would also yield more accurate results but would take longer to simulate. Using a computer with additional compute cores or a propagator written in C++ and executed on a GPU would allow massive simulation speedup.

Further studies could examine coverage in counterrotating orbits, taking into account both the ±37.5kHz and proposed ±75kHz frequency shift limits. Although temporary coverage spots lasting less than 3.6s (MT handshake) were minimal, considering this restriction will yield slightly more accurate results.

As several studies have now been conducted on the feasibility of using the Iridium network for LEO communications, data validation using actual satellites is the next major step. Although the TJ REVERB 2U CubeSat will launch in November of 2018 and be deployed in the months after, it will only analyze coverage in its ISS orbit. More platforms are needed to fully verify the simulated results and conclude on the feasibility of using an Iridium modem as the primary communications mode.

### *Acknowledgments*

We would like to thank Michael Piccione, the Energy Systems research lab director at TJHSST, for leading the TJ REVERB CubeSat project as Principal Investigator and providing guidance on this research. We are also grateful to Philip Cunio for helping develop the research objective and guiding us through the paper writing and submission process. We would also like to thank James Dailey and Sun Hur-Diaz for their invaluable help in mission planning and orbital dynamics. Finally, we would like to acknowledge the TJHSST CubeSat Team for their support throughout the project.

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