Simulating Iridium Satellite Coverage for CubeSats in Low Earth Orbit

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Rationale

Conventional ground stations utilizing UHF radios are limited in range and 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, antenna tracking systems and the setup of a command and control center can easily exceed tens of thousands of dollars, which, for satellite missions at small institutions, may be an exorbitant cost.

Established satellite 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 coverage in LEO. Therefore, the coverage afforded by these networks may exceed that of conventional ground stations. Regular usage fees and initial licensing costs with the FCC are also far less than building a ground station without prior established systems. As flight-ready UHF radios are expensive, purchasing a standard modem from satellite phone manufacturers promises to vastly reduce satellite development and construction costs. These savings combined with system simplification makes small and nano-satellite systems more accessible to educational institutions such as colleges and high schools.

Background

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. The relativistic equation describing the shift between two satellites is

$$d\nu = \frac{c - \hat{r}\cdot\vec{v}_s}{c - \hat{r}\cdot\vec{v}_r}\sqrt{\frac{c^2 - v_s^2}{c^2 - v_r^2}}\,\nu_0$$

where v_r = speed of the receiver; v_s = speed of the source; v_0 = frequency in a frame co-moving with the source; c = speed of light. Since satellites in LEO are moving at a velocity on the order of 7km/s, Doppler shift of RF communications is a significant issue, especially since the Iridium satellite network has a built-in buffer of only ±37.5kHz.

Nodal Precession

Orbital planes drift due to various disturbances. The most significant of these effects is nodal precession, in which a gravitational torque created by the oblate Earth causes the right ascension of the ascending node (RAAN) to precess. A reasonable approximation of the precession rate is

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

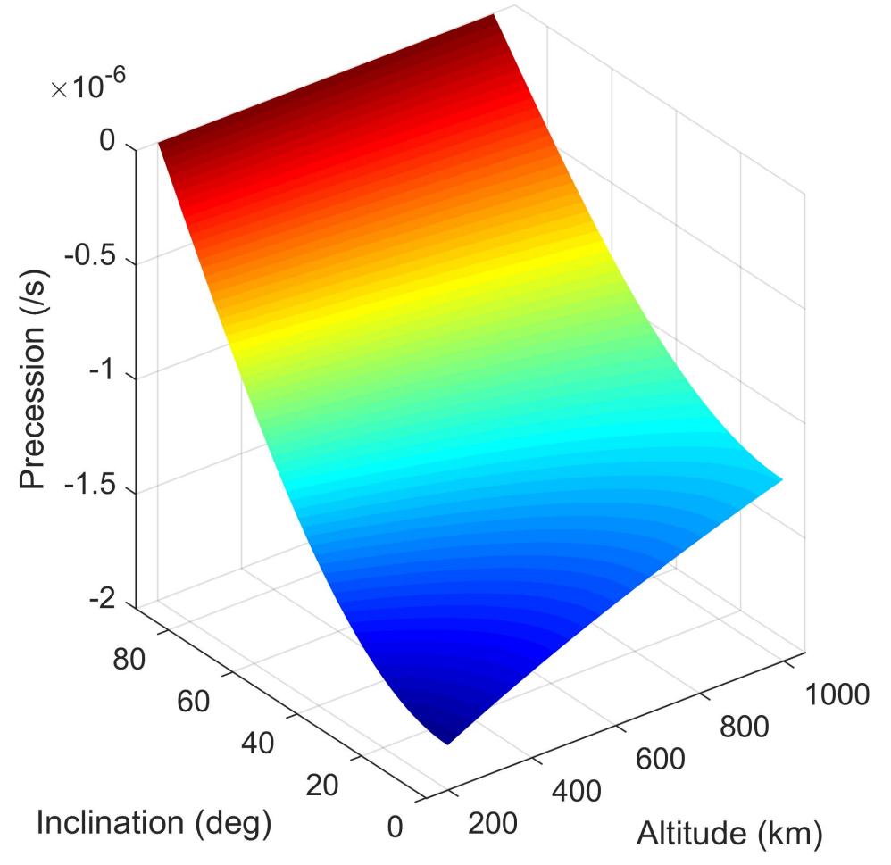

Figure 1. Precession

where R_E = radius of Earth; $J_2 = 1.083\text{x}10^{-3}$ is the second dynamic form factor of Earth; i = inclination; a = semi-major axis; e = eccentricity; T = orbital period. This effect 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.

Iridium Satellite 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. Co-rotating planes are 31.6º apart, while the two retrograde planes are separated by 22º.

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. Each Iridium satellite uses a three-antenna phased array with 48 total transmit/receive modules to produce a coverage circle approximately 4700km in diameter.

METHODS

Simulation Interface

It was deemed necessary to code an orbit simulator rather than rely on commercially available products for two reasons. The MATLAB programming language was selected due to its extensive library of functions and scientific-computing orientation. A copy of the Princeton Cubesat Toolbox (PCSTB) was obtained for its orbit propagators and built-in modeling for CubeSat structures. Code was written to interface the various PCSTB modules into a single interface and provide a visual representation of Earth with appropriate inertial vectors, satellites, and beam cones.

Ephemeris and Propagation

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 TLEs. Current TLEs for the 66 operational Iridium satellites were downloaded and imported into the MATLAB interface. For propagation, the Simplified General Perturbations Model 4 (SGP4) was selected. TLEs propagated using SGP4 have error drifts up to 3km per day, meaning that the maximum error after two weeks is 42km. To provide a reasonable balance between computation duration and accuracy, an integration time-step of five seconds was selected. Moreover, all simulated configurations were restricted to no more than 160 orbits, or about 10 days, regardless of nodal precession.

Simulated Orbits

Since the majority of CubeSats are deployed from the ISS or injected into polar orbits, additional inclinations were selected clustering around 50º and 85º. An epoch of June 1, 2018 12:00:00 UTC was selected. Each orbit had the following additional Keplerian elements: $a = R_E$+403km; $e = 0$; $\Omega = 109º$; $\omega = 348.1º$; $\nu = 0º$. In total, 36 orbits were simulated in the range of 0º to 90º.

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. 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.

Computing Hardware

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

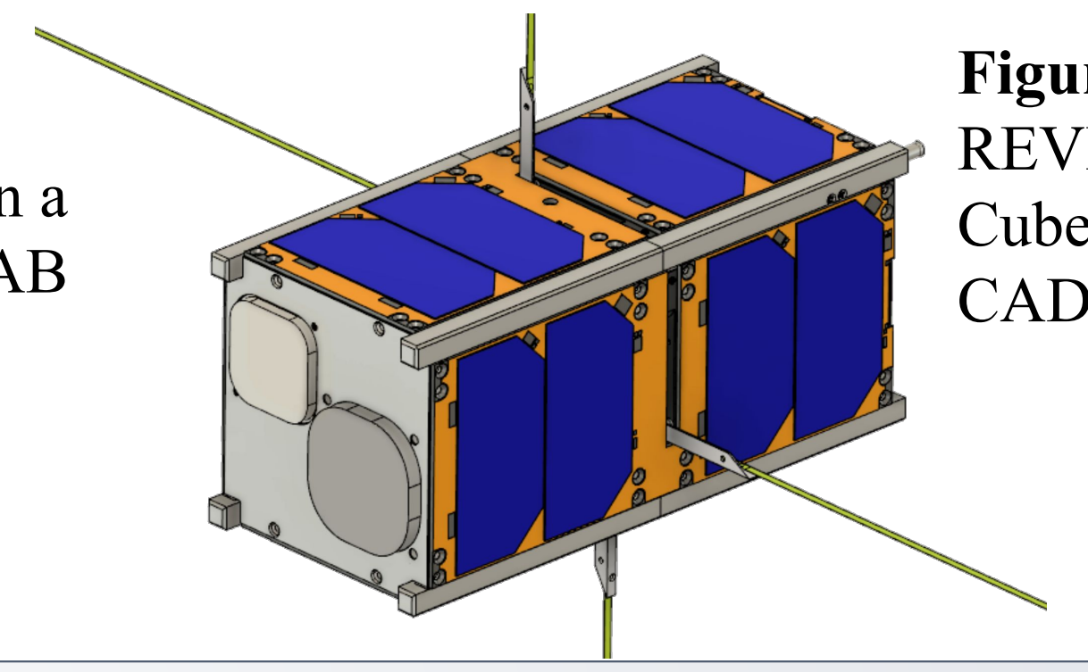

Figure 2. TJ REVERB CubeSat CAD Model

RESULTS

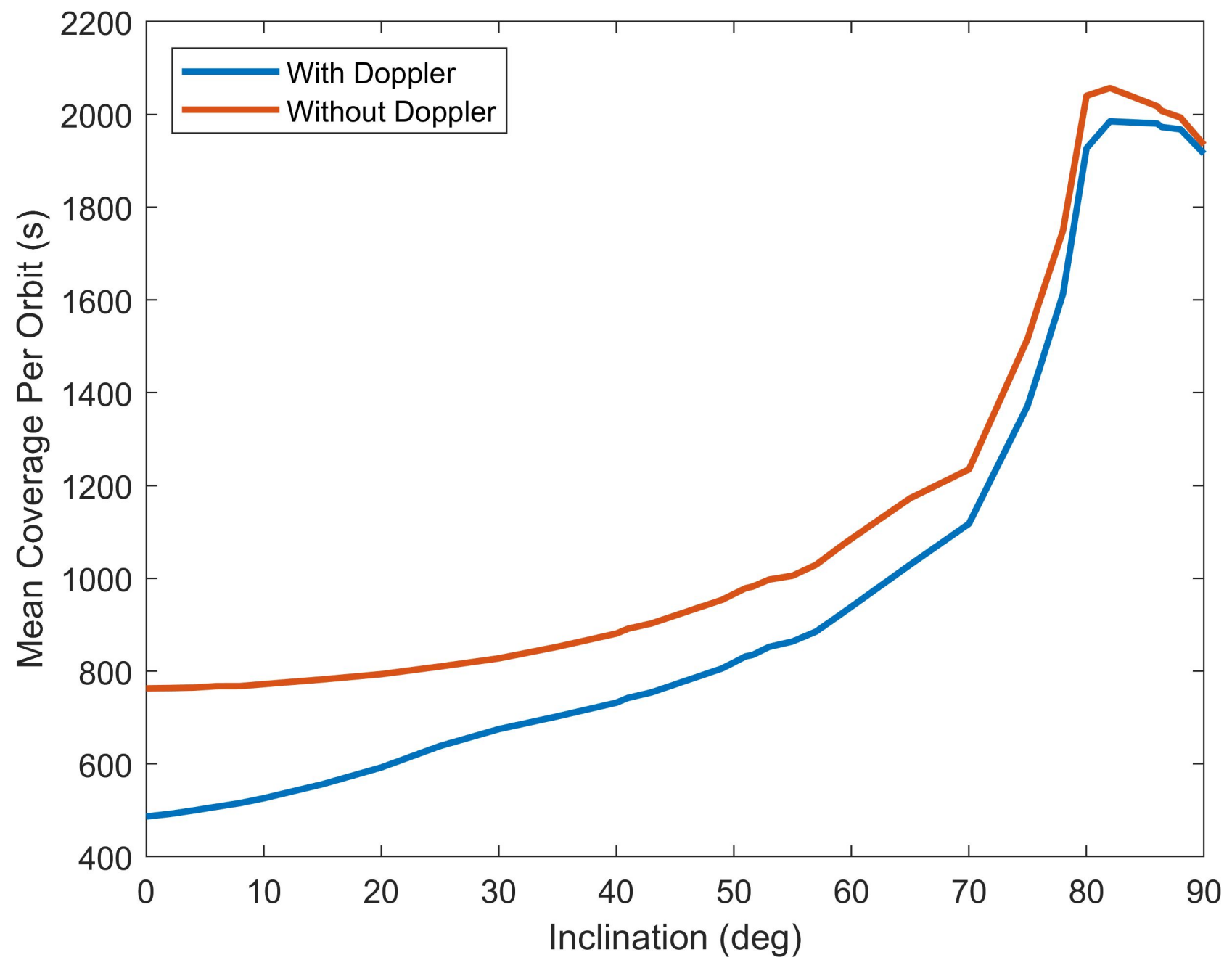

Figure 3. At higher inclinations, the test satellite is closer to co-moving with the Iridium network, meaning that once it is under an Iridium satellite, it will remain within range for a long time. Total coverage thus increases with inclination. Doppler shift significantly reduces coverage for inclinations below 70º, and at 0º, the coverage is almost halved. For a satellite deployed from the ISS, an orbit-average coverage of 834s is expected, while those in polar orbits can expect about 1800s to 2000s.

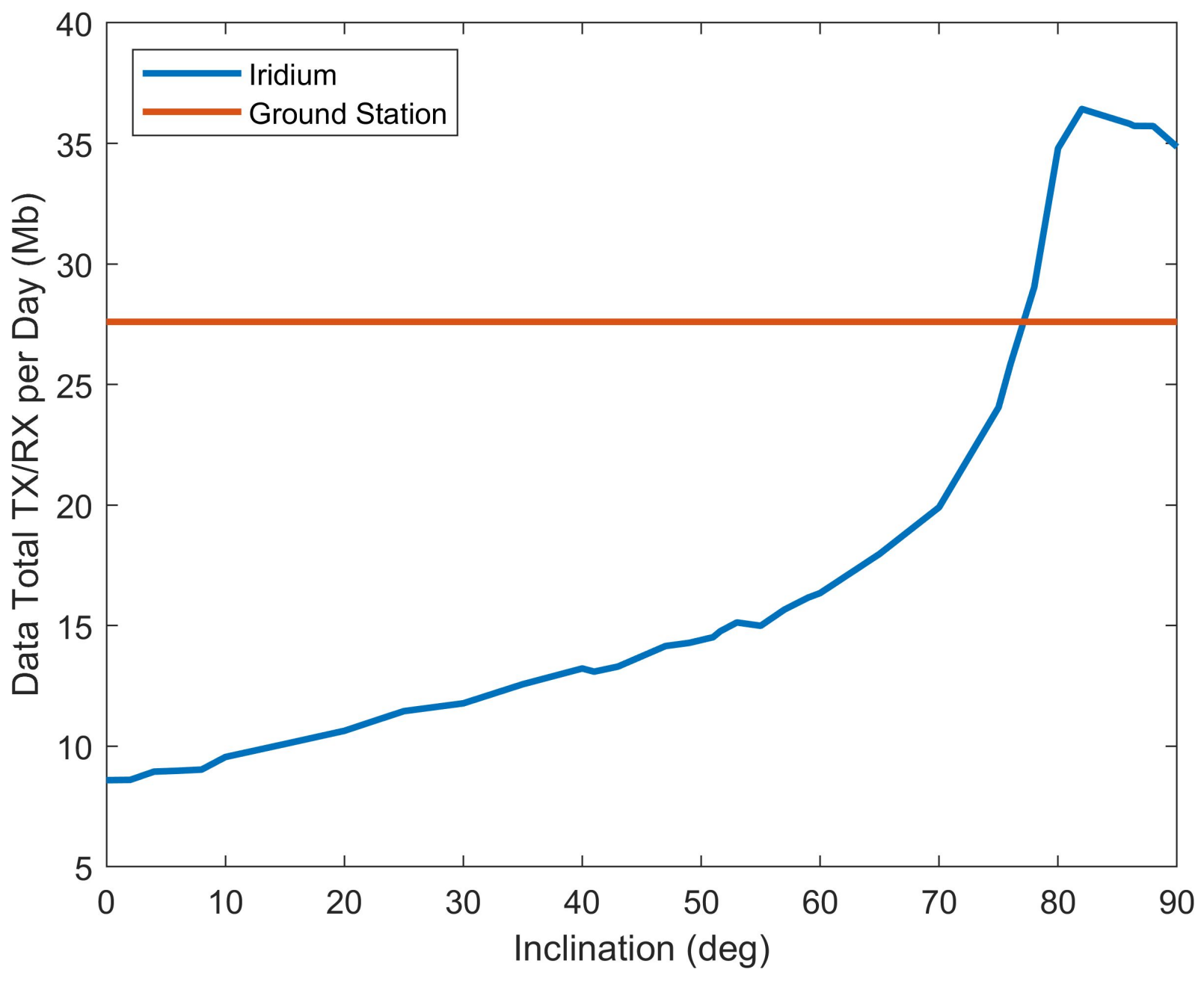

Figure 4. The daily data uplink/downlink can be obtained by summing coverage over the first 15 orbits and multiplying by the maximum TX/RX of 1.2kbps. A standard value for a UHF ground station, for comparison, is 27.6Mb. The total data Iridium TX/RX does not exceed that of a ground station except at 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.

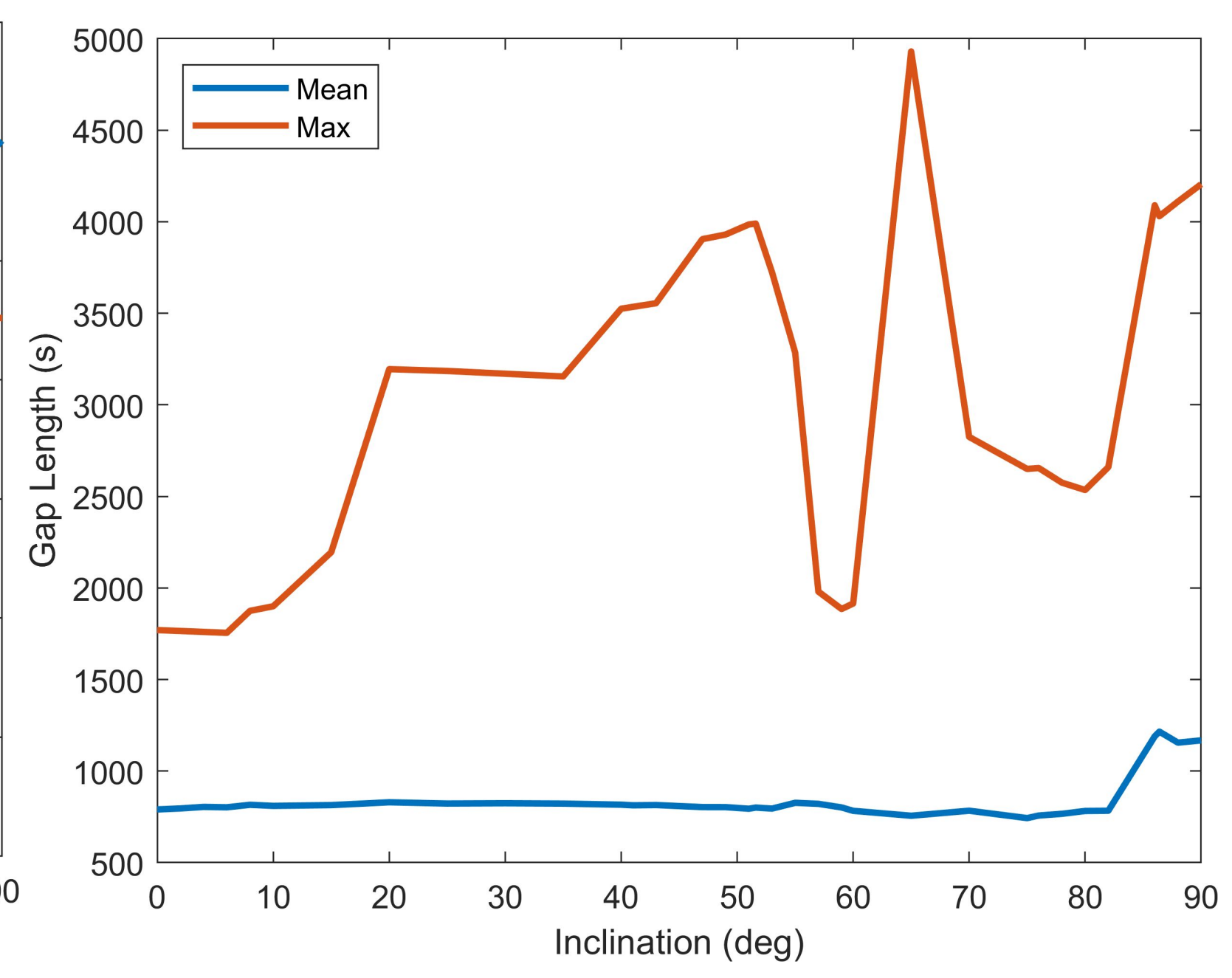

Figure 5. The mean duration between consecutive LOS and AOS was less than 1500s for all inclinations. Maximum coverage gaps were greater at higher inclinations but peaked in the 50º to 70º and 80º to 90º ranges. These numbers are far smaller than best-case coverage gaps for conventional ground stations, which often exceed 30000s, or eight hours.

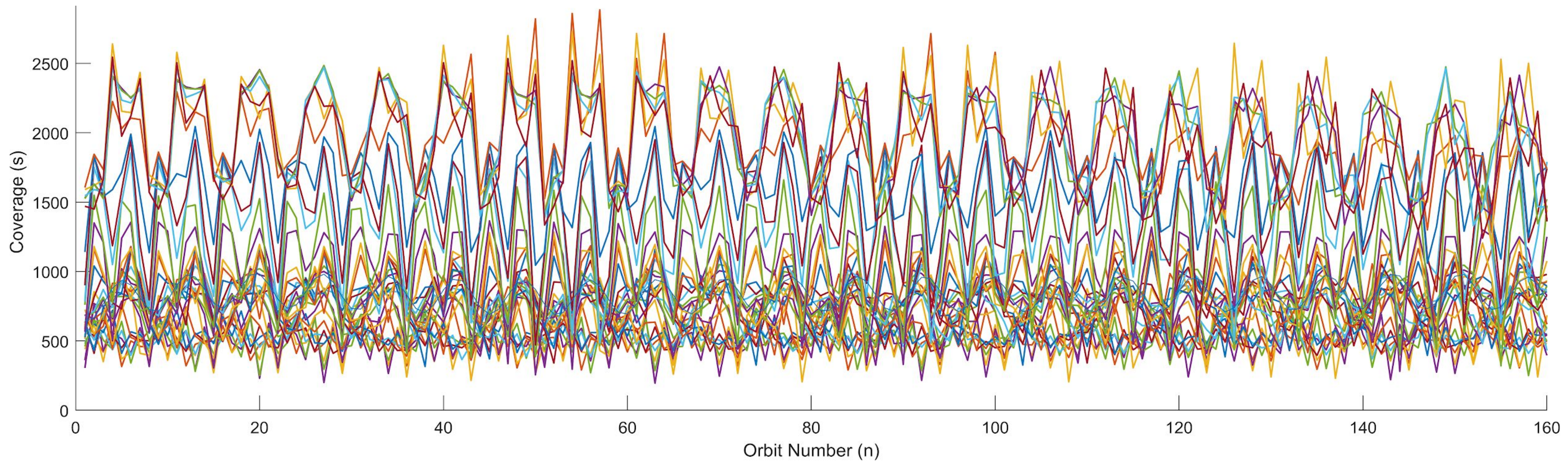

Figure 6. All inclinations exhibit sinusoidal coverages with a period of about seven orbits. This is not due to nodal precession nor inclination, however, as the period is independent of these variables. There is a growth in the difference of phases as time passes, which is most likely the result of nodal precession and other disturbances.

CONCLUSIONS

Major Findings

The Iridium satellite network can provide more regular coverage than conventional ground stations utilizing UHF radios. Although data TX/RX is lower for the Iridium network than a ground station until an inclination of 77º, the main advantage afforded at lower inclinations is the frequency of communications. 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. Implementing this limit would also enable retrograde orbits.

Recommendations for Improvement

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 reasonable accurate for two weeks after download when using a SGP4 propagator, different propagation methods that still take into account additional perturbations other than J2 are recommended. A shorter integration time-step would also yield more accurate results but would take longer to simulate.

Data Validation with TJ REVERB

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 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 deploy in the subsequent months. It 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 across the country and throughout the world. TJ REVERB will be the first NGO to utilize the Iridium network for smallsat communications, thus leading the way for educational institutions to benefit from the Iridium network by saving money and development time.

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 these 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, latency, and the feasibility of using an Iridium modem as the sole radio on future CubeSat missions.

REFERENCES

1. Antcom Iridium antenna [PDF]. (2015, February 28).
2. Cakaj, S., Kamo, B., Lala, A., & Rakipi, A. (2014). The coverage analysis for low Earth orbiting satellites at low elevation. International Journal of Advanced Computer Science and Applications, 5(6), 6-10.
3. Claybrook, J. R. (2013, March). Feasibility analysis on the utilization of the Iridium satellite communications network for resident space objects in low Earth orbit [PDF].
4. Klofas, B., & Leveque, K. (2013, April). A survey of CubeSat communication systems: 2009:2012
5. NanoRacks Cubesat Deployer (NRCSD) Interface Control Document [PDF]. (2013, December 10). NanoRacks
6. Pratt, S. R., Raines, R. A., Fossa, C. E., Jr., & Temple, M. A. (2009). An operational and performance overview of the Iridium low Earth orbit satellite system [PDF].
7. Riesing, K. (2015). Orbit determination from two line elemens sets of ISS-deployed CubeSats. 29th Annual AIAA/USU Conference on Small Satellites.
8. U.N. International Civil Aviation Organization. (2007, March). Manual for ICAO aeronautical mobile satellite (route) service.

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