Integration of Air and Space Traffic Management: Establishing Criteria for Tracking of Debris Objects Prior to Uncontrolled Reentry

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ABSTRACT

The planned utilization of space presents an inevitable risk to all airspace. The planned long-term operation of large constellations in Low Earth Orbit and the projected launch vehicle market will present a quantifiable credible hazard. The capability to protect users of the airspace will depend on the ability to track objects. This investigation considers the relationship between precision of orbit tracking and reentry predictions and the corresponding breakup of objects through reentry. With sufficient fidelity in the object track, propagation of debris will permit an actionable time and space distribution of debris objects to permit dynamic airspace closures. This investigation is a brief examination of the correlation in precision of object tracking as characterized by the covariance of tracked objects and the uncertainty in the prediction of debris objects resulting from the breakup through reentry. The measure of uncertainty will determine the capability to protect airspace by informing users of the airspace in order for them to adjust their flight.

1. INTRODUCTION

The growing number of space missions escalates the risk of spacecraft collisions, whether with other spacecraft or space debris. As of June 18, 2024, the number of satellites in orbit was about 12,540, of which about 9,800 were functioning. The Space Surveillance Network (SSN) currently tracks and maintains approximately 35,820 debris objects in its catalog (as of June 18, 2024). [1]

The New Space economy and the proliferation of launch vehicles has enabled private companies to economically develop and manage constellations of thousands of satellites. Most notably, SpaceX has proposed such a Mega Constellation with an ultimate capacity in the tens of thousands of satellites. As of June 2024, there are 6,219 Starlink satellites in orbit, of which 6,146 are operational. [2} The focus of this study is the airspace risk from the Starlink constellation simply because the company has launched and deployed to orbit the greatest number of satellites to-date. The risk to the airspace will become more significant as the reentry of these satellites start to occur, after completing their on-orbit mission or under situations of failed deployment.

The reentry of objects presents a risk to the airspace. The individual risk to a single airplane from a single object reentry would be considered extremely low. However, the cumulative risk to all aircraft from all reentry objects presents creates a credible risk which should not be ignored. From the beginning of 2010 to the end of 2022, 951 intact objects (spacecraft and orbital stages) with a radar cross-section greater than one square meter re-entered the Earth's atmosphere uncontrolled. The total returned mass was about 1500 ton, corresponding to a mean of 116 ton per year, mostly concentrated (80 %) in orbital stages [3].

This loss of a commercial airliner from the reentry of a satellite has been termed as the ultimate black swan event. [4] Such a metaphor describes a catastrophic event that by often unsupported consensus is thought to be de minimus, and is often inappropriately rationalized after the fact with the benefit of hindsight. Currently, there are two schools of thought in the aerospace community, one deeming the loss of a commercial aircraft to be non-credible while the other believes it is a serious and objectively growing concern for which mitigation measures should be developed and perfected now.

There are several options to mitigate the hazard to the airspace.

One potential option incorporates Design for Demise technologies into the construction of new satellites. These are technologies which base component design on the principle that reentry and break up results in an absence of hazards in the lower atmosphere or at least reduces the casualty area to acceptable levels [5] SpaceX has stated that its own satellites are designed to burn up completely when they reenter the atmosphere [6]. Nonetheless, the focus of design for demise has been on the risk on the ground, i.e., the mass and associated energy of constituent debris elements that reach the ground. Commercial airplanes can operate at the service ceiling up to 42,000 ft, depending on the aircraft. Military aircraft can operate even higher.

A second option is to perform a controlled deorbit at the end of a spacecraft service life, for satellites which operate in Low Earth Orbit. Spacecraft propellent is allocated for a series of deorbit propulsion maneuvers so that the spacecraft reaches a remote location away from population, marine and aviation traffic. This pre-determined broad ocean area dubbed the "Spacecraft Cemetery." On-orbit failures may preclude the ability to perform such maneuvers. If satellites utilize design for demise technologies and end-of-life disposal processes, then the hazard to aircraft are significantly mitigated.

A third option in principle is to mitigate the airspace risk is to actively re-route air traffic around the reentering debris components created from the breakup of satellites through reentry. Procedures for rerouting of air traffic is well established. Currently, air traffic is routinely routed away from weather hazards such as hurricanes and tornados. Airspace can also be temporarily closed for security reasons, such as for priority for government aircraft. National airspace has been closed due to volcanic activity.

The options are not mutually exclusive, as all three layers of safety controls should be implemented to offer the best protection to the airspace.

Practically speaking, however, closing airspace to reentering hazards can only realistically be implemented if the time and volume during transit through the airspace are known to high accuracy. There are two reasons for this. The first is that the Notice to Airman will be issued with limited advance warning. It is important to not create new hazards with higher risks. In a crowded airspace, redirecting planes might increase the chance of collision of airplanes when attempting to reduce the risk of being impacted by a small debris fragment. Secondly, a large uncertainty in the reentry prediction corresponds to a large debris footprint. Spread over such a large volume through the airspace, the individual risk is too small to be meaningful to attempt to avoid.

With this introduction to the problem, this brief investigation considers the parameters associated with the tracking of spacecraft and the corresponding uncertainty to prediction of the reentry debris through commercial airspace that must be considered to make active mitigation feasible. The goal is to eventually utilize sufficiently accurate covariance estimates for de-orbiting spacecraft predictions to establish practical exclusion volumes with sufficient warning time for airspace prediction.

2. STARLINK CONSTELLATION CHARACTERISTICS

As stated earlier, the scope of this study is restricted to Starlink satellites.

SpaceX first filed with the FCC for a non-geostationary orbit satellite system that would utilize both the Ku- and Ka- frequency bands in November 2016. The inclinations of the system ranged from 30 to 148 degrees. SpaceX originally proposed to launch 30,000 satellites to a variety of orbits between 328.3 km through 614 km for its Starlink system with 85% of the satellites operating at altitudes of 328 km to 373 km. The Starlink satellites consist of two blocks so far: Block v0.9 and Block v1.5.

Block v0.9 consists of 75 satellites each with a mass of roughly 227 kg and being in a circular 550 x 550 km orbit. Block v1.5 has five groups within it. Group 1 consists of 720 satellites at 550 km and a 53 degree inclination with 72 orbital planes. Each orbital plane has 22 satellites. Group 2 has 720 satellites at a 570 km orbit with a 70 degree inclination and 36 orbital planes. Each orbital plane has 20 satellites. Group 3 has 508 satellites at a 560 km orbit with a 97.6 degree inclination with 10 orbital planes. Each orbital plane has either 43 or 58 satellites. Group 4 has 1584 satellites at 540 km with a 53.2 degree inclination with 72 orbital planes. Each orbital plane has 22 satellites. Group 5 is at 530 km with a 53.2 degree inclination.

For the May 2020 FCC Ka-band Processing Round, SpaceX submitted an application for 30,000 satellites across 75 different panes. At 328.3 km, SpaceX proposed one plane with 7178 satellites with an inclination of 30 degrees. At 334.4 km, Starlink was proposed to have 7178 satellites in one plane with an inclination of 40 degrees. At 345.6

km, SpaceX proposed one plane with 7178 satellites with an inclination of 53 degrees. At 373.2 km, Starlink was proposed to have 1998 satellites in a plane with an inclination of 75 degrees. At 498.8 km, one plane was proposed with 4000 satellites at 53 degrees inclination. For the 604 km orbit, SpaceX proposed twelve different planes with twelve satellites each at an inclination of 148 degrees. The 614 km orbit was proposed to have eighteen planes with eighteen satellites each with an inclination of 115.7 degrees. Finally, Starlink is proposed to have 2000 satellites across forty planes in a 360 km orbit with an inclination of 96.9 degrees.

From the satellite technical specifications [7], based on experience of component survival through reentry, a Starlink satellite will generate approximately twenty-three fragments of varying mass and size.

3. PREDICTING REENTRY

For the purpose of demonstration, re-entering orbit predictions for publicly available and recently decayed Starlink satellites were developed using STK with the HPOP propagator (a propagator that takes into account atmospheric density). The altitude predictions for representative satellites for four inclinations extending back from re-entry are shown in Fig 1. Typically, the mean altitude 1000 (min) prior to entering the sensible atmosphere was about 225 (km), with an orbital period of about 1.5 hour.

For our simulations, the descent force model was on a 1000 kg spherical craft with a drag coefficient of $C_d = 2.2$ and reference area to mass ratio of 0.02 $m^{2/}kg$. The atmospheric model was based on we used the NRLMSIS-2000 (Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar) model to simulate atmospheric drag. This model is an empirical atmospheric model used to predict the temperature, density, and composition of the atmosphere from the Earth's surface (0 km) to the exosphere (~1000 km altitude). It incorporates a variety of data sources, including satellite drag, mass spectrometer measurements, and incoherent scatter radar, to model neutral atmosphere properties. A novel feature of the model is the inclusion of an “anomalous oxygen” component, which accounts for contributions from O+ ions and hot atomic oxygen, particularly affecting drag estimation above 500 km. This model offers improvements over both the MSISE-90 and Jacchia-70 models, especially in predicting total mass density under varying geomagnetic and solar activity conditions [11].

By 125 km, all satellites pierced that atmosphere, below the influence of space weather perturbations, and likely breaking up (behavior generally observed [8]). The satellite positions and velocities at this altitude were identified for the case studies for risk and mitigation. The positions are in earth-geodetic coordinates; the velocities are in fixed frame coordinates. These state vectors (assumed at this altitude to be intact) are input into RRAT (Range Risk Analysis Tool) for final propagation to aircraft and ground exposures [9].

Table 1. State Vector List for RRAT Risk Calculations.

Inclination	Lat (deg)	Long (deg)	Altitude (km)	V_x (ft/s)	V_y (ft/s)	V_z (ft/s)
43	-22.156	141.988	124.91	-16238.5	-11218.9	14638.4
53	40.048	-17.867	124.79	-140.6	218.0873	218.1
70	64.756	9.268	125.45	-16984.7	17356.7	6534.8
98	37.651	-70.125	125.28	59.1	-16344.0	-20120.4

RRAT is a tool which allows risk analysts to estimate the consequences from planned or unplanned debris to ground exposures (people sheltered or not, ships, and infrastructure) and to aircraft, according to the general procedures documented in RCC-321/23 [9]. In brief, it ingests debris information (state vectors) and computes three-dimensional stochastic cloud distributions and two-dimensional impact dispersions. It incorporates several sources of uncertainty, including three from fragment uncertainty (aerodynamic drag, lift to drag information, and initial state estimates from energetic break up). Uncertainty due to meteorological conditions (e.g., wind and density) are modeled. Uncertainty arising from perturbations to nominal trajectories can also be modeled.

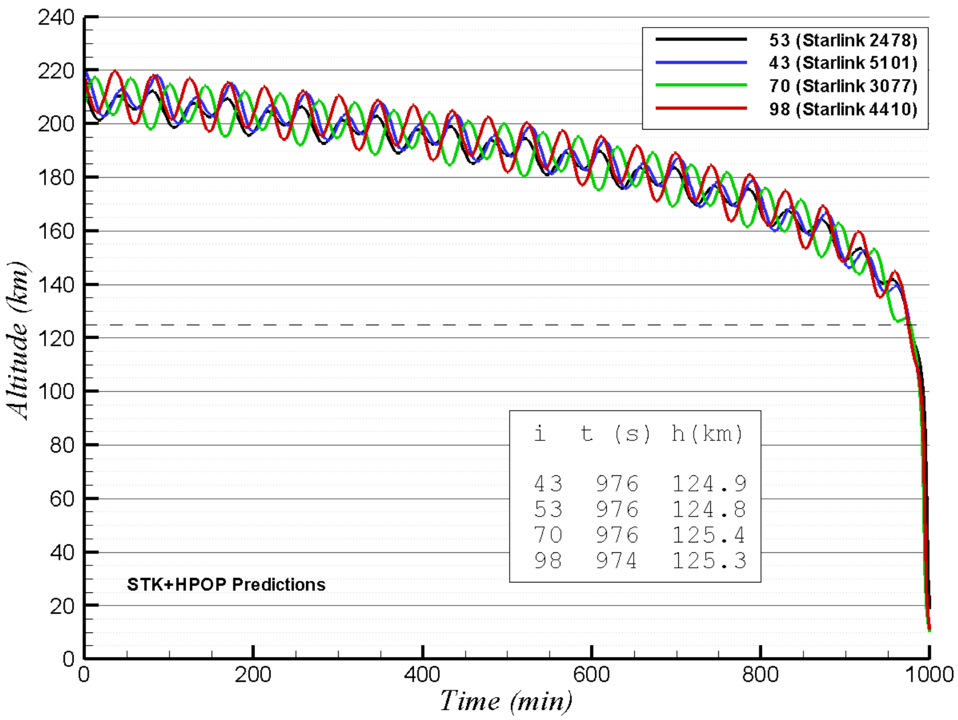


Figure 1. Starlink satellite re-entry predictions at four inclinations.

4. EVALUATING EFFECT OF COVARIANCE

The uncertainty in the tracking of a spacecraft is modeled by the covariance. The covariance matrix is publicly available for several satellites. For this investigation, the covariance of specific Starlink satellites were analyzed.

Covariance data was taken from publicly available ephemeris data on space-track.org. This data is updated for every Starlink satellite every twelve to twenty-four hours. Once acquired, the space-track.org ephemeris file can be converted into an ITC ephemeris file and loaded into STK. Here, the covariance data can be reorganized in a more intuitive fashion and visualized in the 3-D graphics window as a covariance ellipsoid. An example, shown in **Table *2***, is a covariance matrix in the J2000 reference frame from Starlink-31431 from July 9–12, 2024.

Table 2. Covariance for Starlink 31431.

Time (UTCG)	σ_X (km)	σ_Y (km)	σ_Z (km)	σ_{XY} (km)	σ_{XZ} (km)	σ_{YZ} (km)	PosCov Mtx XX (km^2)	PosCov Mtx YX (km^2)	PosCov Mtx YY (km^2)	PosCov Mtx ZX (km^2)	PosCov Mtx ZY (km^2)	PosCov Mtx ZZ (km^2)
16:42.0	0.000986	0.000969	0.000766	0.09744	0.333177	-0.58137	0.000001	0	0.000001	0	0	0.000001

The covariance for the tracking of Starlink-31431 (NORAD ID 59002) is visualized in Figures 2 and 3. These matrices are represented graphically as three-dimensional ellipsoids (shown as purple in the figures).

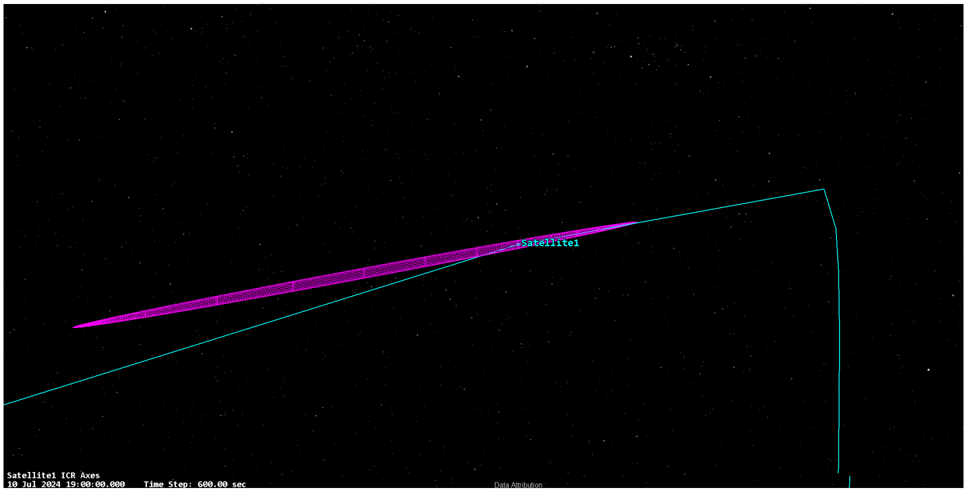


Figure 2. Graphical Illustration of Starlink 31431 Covariance Ellipsoid.

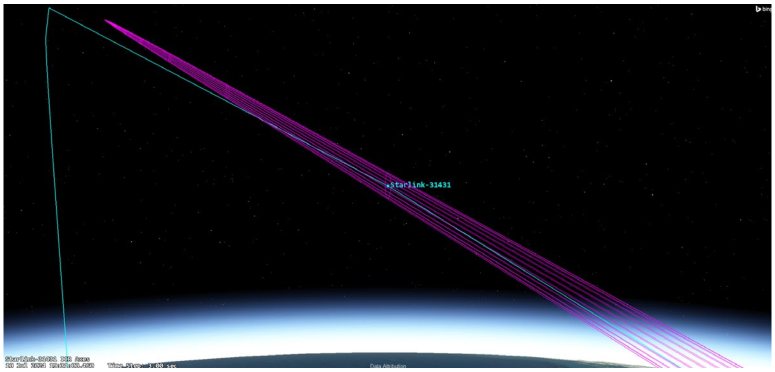
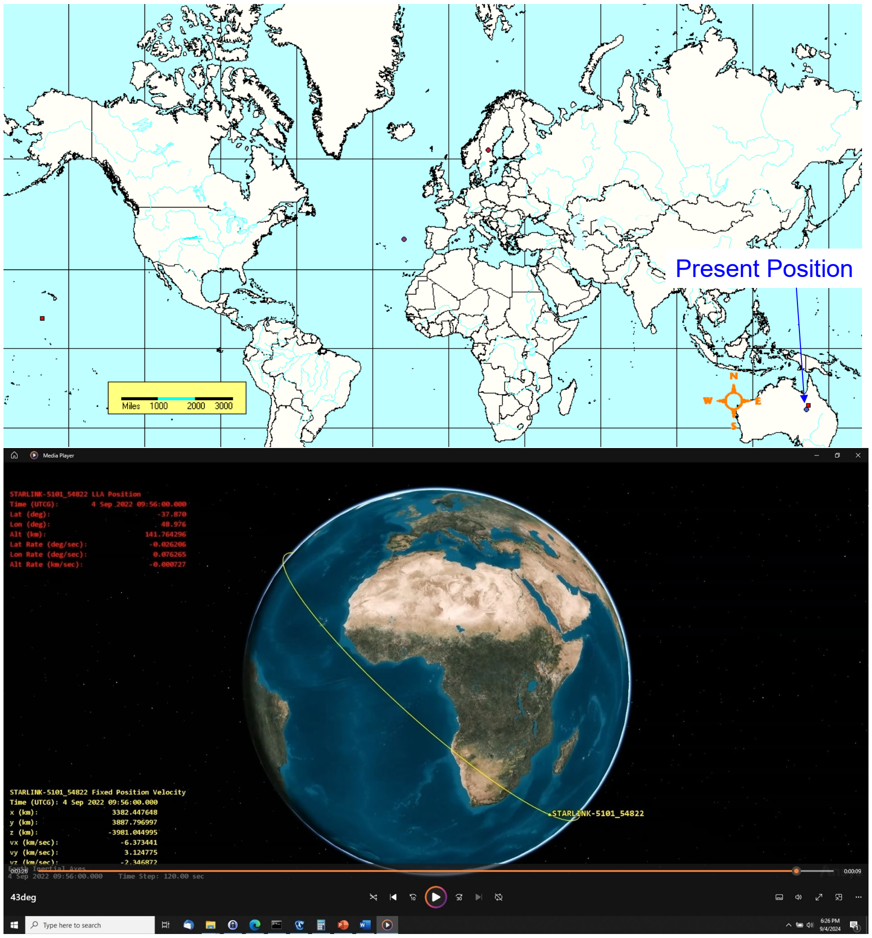


Figure 3. Graphical illustration of Starlink 31431 Covariance Ellipsoid.

5. PROPOGATING RE-ENTRY DEBRIS

A customized tool—RPMTool (Reentry Risk Prediction & Mitigation Tool)—which is based on the Range Risk Assessment Tool (RRAT) [10], is being developed to operate with the state vectors produced by HPOP and propagate the reentering objects to air traffic and ground exposure. An input to the tool is the present position, which is simply the geodetic position projected vertically down to the topography. The present positions for the four state vectors in Table 1 are shown in **Figure** *4* through **Figure** *7* map projections (top plots) and in three-dimensional orbit renderings (bottom plots). Note that because of time granularity in the 3D renderings the exact positions are approximate. The map projections however correspond to the values in Table 1.

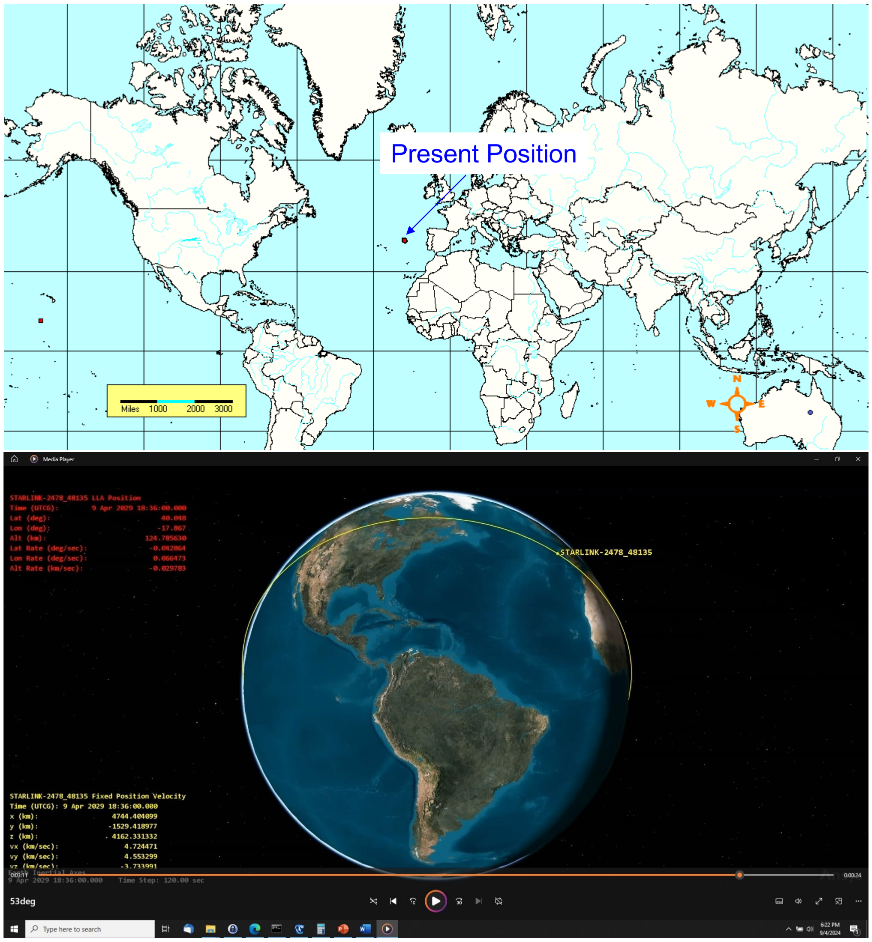
Within RPMTool the atmospheric model used is that built into RRAT.



```
STARLINK-5101_54822 LLA Position
Time (UTCG):        4 Sep 2022 09:56:00.000
Lat (deg):                          -37.870
Lon (deg):                           48.976
Alt (km):                        141.764296
Lat Rate (deg/sec):               -0.026206
Lon Rate (deg/sec):                0.076265
Alt Rate (km/sec):                -0.000727
```

```
STARLINK-5101_54822 Fixed Position Velocity
Time (UTCG): 4 Sep 2022 09:56:00.000
x (km):                     3382.447648
y (km):                     3887.796997
z (km):                    -3981.044995
vx (km/sec):                  -6.373441
vy (km/sec):                   3.124775
vz (km/sec):                  -2.346872
Earth Inertial Axes
4 Sep 2022 09:56:00.000    Time Step: 120.00 sec
```

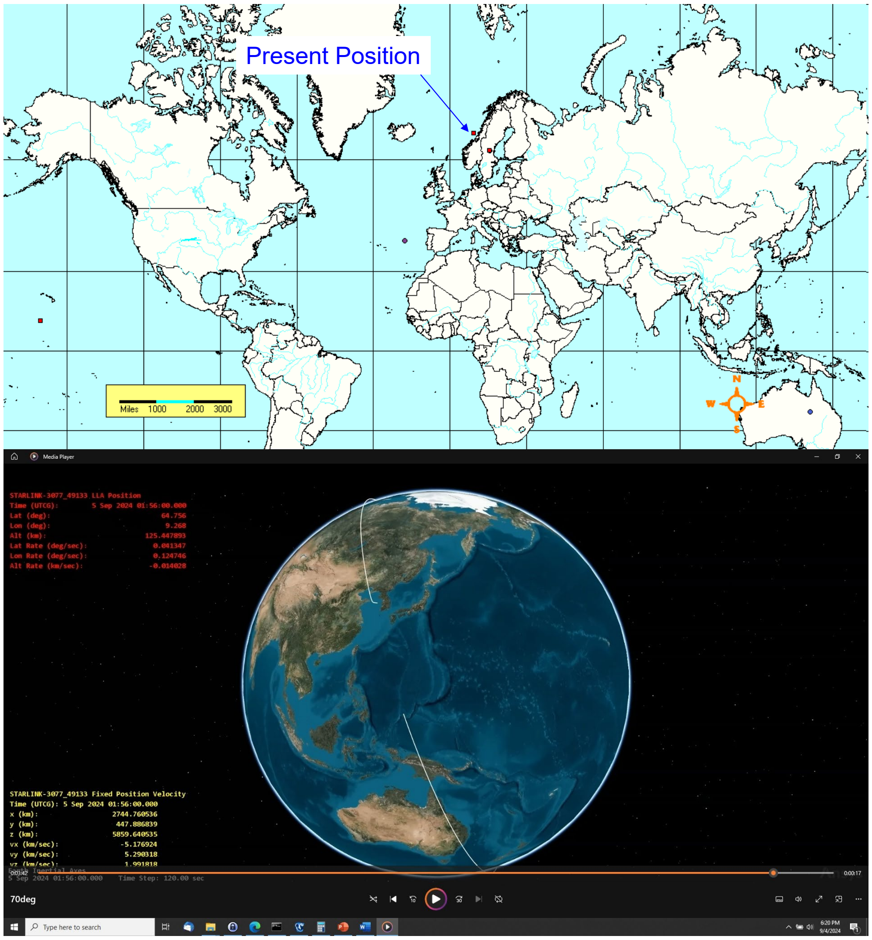
Figure 4. Present position at 124.91 (km), inclination 43 (deg).



```
STARLINK-2478_48135 LLA Position
Time (UTCG):        9 Apr 2029 18:36:00.000
Lat (deg):                           40.048
Lon (deg):                          -17.867
Alt (km):                        124.785630
Lat Rate (deg/sec):               -0.042864
Lon Rate (deg/sec):                0.066473
Alt Rate (km/sec):                -0.029783
```

```
STARLINK-2478_48135 Fixed Position Velocity
Time (UTCG): 9 Apr 2029 18:36:00.000
x (km):                  4744.404099
y (km):                 -1529.418977
z (km):                . 4162.331332
vx (km/sec):                4.724471
vy (km/sec):                4.553299
vz (km/sec):               -3.733991
Earth Inertial Axes
9 Apr 2029 18:36:00.000    Time Step: 120.00 sec
```

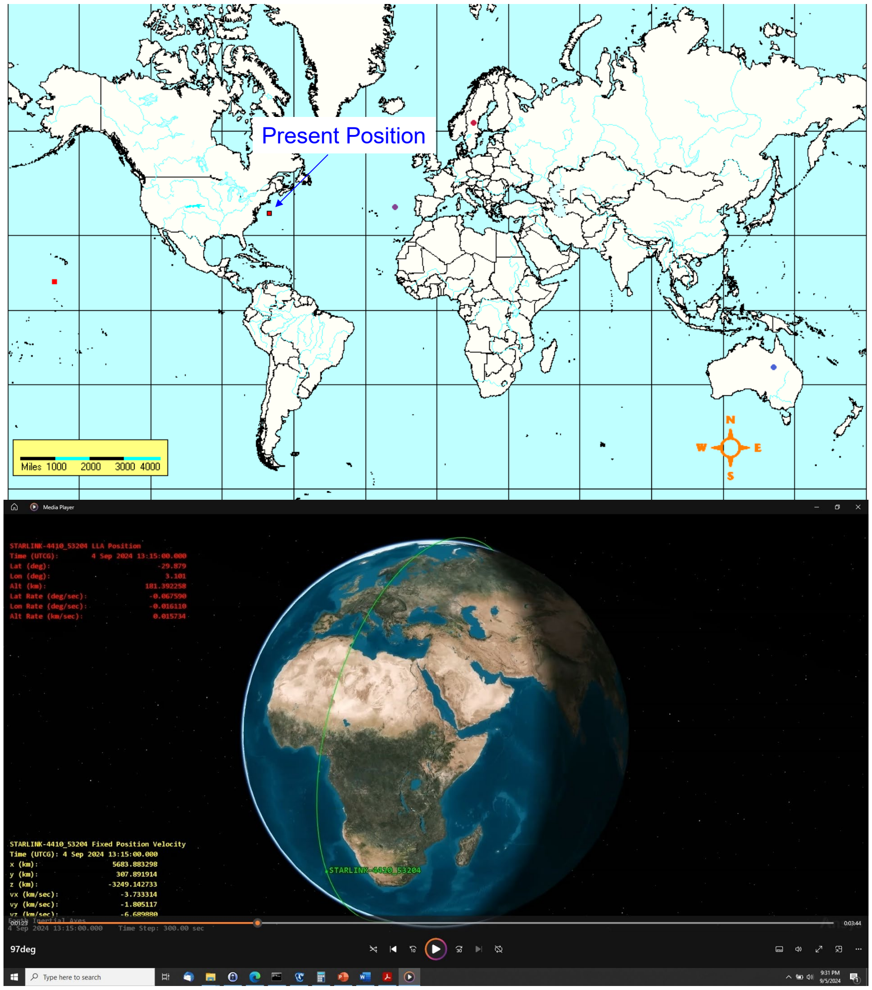
Figure 5. Present position at 124.79 (km), inclination 53 (deg).



```
STARLINK-3077_49133 LLA Position
Time (UTCG):         5 Sep 2024 01:56:00.000
Lat (deg):                            64.756
Lon (deg):                             9.268
Alt (km):                         125.447893
Lat Rate (deg/sec):                 0.041347
Lon Rate (deg/sec):                 0.124746
Alt Rate (km/sec):                 -0.014028
```

```
STARLINK-3077_49133 Fixed Position Velocity
Time (UTCG): 5 Sep 2024 01:56:00.000
x (km):                      2744.760536
y (km):                       447.886839
z (km):                      5859.640535
vx (km/sec):                   -5.176924
vy (km/sec):                    5.290318
vz (km/sec):                    1.991818
Earth Inertial Axes
5 Sep 2024 01:56:00.000    Time Step: 120.00 sec
```

Figure 6. Present position at 125.45 (km), inclination 70 (deg).



```
STARLINK-4410_53204 LLA Position
Time (UTCG):          4 Sep 2024 13:15:00.000
Lat (deg):                            -29.879
Lon (deg):                              3.101
Alt (km):                          181.392258
Lat Rate (deg/sec):                 -0.067590
Lon Rate (deg/sec):                 -0.016110
Alt Rate (km/sec):                   0.015734
```

```
STARLINK-4410_53204 Fixed Position Velocity
Time (UTCG): 4 Sep 2024 13:15:00.000
x (km):                       5683.883298
y (km):                        307.891914
z (km):                      -3249.142733
vx (km/sec):                    -3.733314
vy (km/sec):                    -1.805117
vz (km/sec):                    -6.689880
Earth Inertial Axes
4 Sep 2024 13:15:00.000    Time Step: 300.00 sec
```

Figure 7. Present position at 125.28 (km), inclination 98 (deg).

An example of a risk analysis is provided in Figure 8. The top plot shows the present position at which the STK state vector was input into the RPMTool and propagated into the atmosphere (in this case to the ground). The risk contours are ground casualty, and for this individual case very low. In this scenario, the satellite was assumed to break up during reentry, but the larger components were propagated *without any* melting and ablation. Thus, this result should be considered a conditional worst-case analysis. To the extent that numerous assumptions have been made in analyses thus far, these results should be considered notional and for methodology demonstration purposes only.

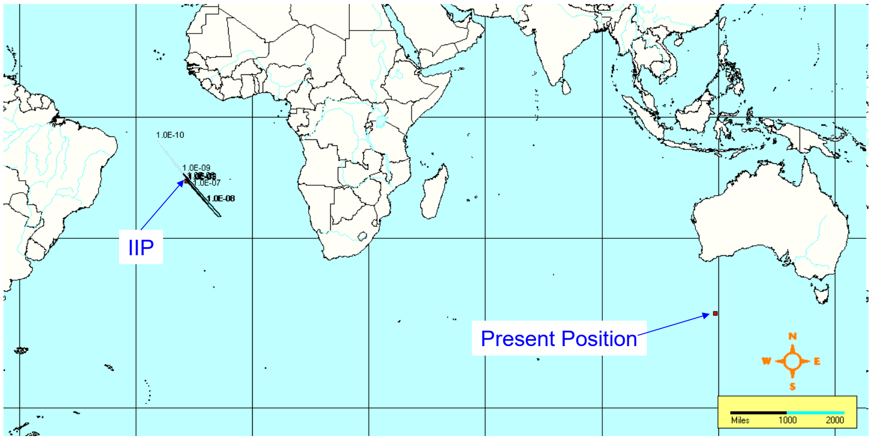


Figure 8. Example of ground risk contours due to worst-case conditional analysis.

The next steps in our work will include performing the risk calculations with ensembles of state vectors sampled from the covariance distribution and incorporate air traffic information to establish individual air traffic risk estimates.

6. SUMMARY

This investigation is a work in progress. The paper summarizes the current status to understand the relation between the covariance and the range of trajectory of constituent elements through the airspace.

7. ACKNOWLEDGEMENTS

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