A SATELLITE MOBILITY MODEL FOR QUALNET NETWORK SIMULATIONS

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Abstract —Because of the near ubiquitous communication available to network nodes beneath a satellites footprint, satellite network technology has enjoyed a recent and substantial increase in interest from academia, government, and commercial sectors. However, the benefit resulting from being beneath the satellite footprint comes at the cost of a substantial propogation delay, as well as other challenging network characteristics. To study networking over satellites, researchers need a network simulation tool that is capable of modeling existing and proposed satellite networks. This paper addresses the network modeling problem by adding an open source satellite mobility model (SatMob) suitable for Low/Medium Earth Orbit (LEO/MEO) satellites to Qualnet network simulation tool. We perform a basic set of experiments commonly found in network research by using an existing mobility model and SatMob. Our results indicate that our model yields an appreciable improvement over an existing Qualnet approach.

I. INTRODUCTION

All network nodes that are in a Line Of Sight (LOS) and beneath the footprint of a satellite can communicate with each other. However, because of a satellite's distance from the Earth, this benefit comes at a cost of increased delay, jitter, and loss [3], [8], [2]. For instance, it can take approximately 125ms for a one-way trip to a Geostationary Earth Orbit (GEO) satellite. Research has shown that TCP performance suffers significantly under such conditions [1], [10] and it is equally clear that new research is needed to develop protocols that are robust to challenges presented by satellite networks.

Much research towards finding methods to mitigate the challenging satellite network conditions has been done, for example Delay Tolerant Networking [9], [5] (DTN). Simulation tools such as Qualnet [1], OPNet [2], and ns-2 [4] are frequently used by researchers to perform this work.

If researchers could simply add a satellite node to their already completed simulations, much existing work could be reused. Because LEO/MEO satellites move about the sky relative to a user on the ground, a satellite mobility model is needed to simulate their motion. While OPNet Modeler 14.5 and Qualnet 4.0.1 do not provide a satellite mobility model of their own, they provide satellite mobility by using the Satellite Tool Kit (STK). The closed source and separately licensed STK package inputs satellite position data, given in Keplerian Two Line Element5 (TLE) format. Keplerian TLE files are the standard way of specifying a satellite's orbit at a given time.

The STK then changes the satellite's orbital position to match the positions dictated by the simulation time, using an appropriate variant of the Standard General Perturbations (SGP) algorithm [7]. A point in space is calculated for each time step in the simulation and the data is saved to a file. OPNet/Qualnet then reads this file and uses the data to position the satellite in the simulation. The open source and popular ns-2 simulator has a mobility model that uses a simplified version of the SGP orbital propagation equations. This model assumes that a satellite's orbit is not elliptical. Because of this simplification, the user only inputs a subset of the Keplerian TLE's data points into the ns-2 node generator. This method will of course introduce satellite positioning errors when the orbit is elliptical. These errors can be mitigated if the researcher has TLE data available that matches closely with the simulation time. Besides the possibility of orbital positioning errors caused by the simplifications in ns-2, Qualnet has superior wireless models and visualization tools making it the choice of many wireless networking researchers.

Many universities do not provide an STK license for their researchers and students. Because of this, there is a need for an open source solution for satellite mobility in Qualnet. It is this need that is addressed in this paper. Unlike OPNet and Qualnet's existing closed source solution, SatMob is fully integrated into Qualnet. Furthermore, it is comparable in accuracy with standard community tools such as J-Track [3] and Predict [4]. In addition, because of the possibility of positioning errors, we decided not to simplify the SGP algorithms as in ns-2.

The remainder of this paper is structured as follows. Section II summarizes the basics of satellite tracking and positioning. Section III presents the details of SatMob's implementation. Section IV evaluates the model with experiments and finally Section V discusses future work and concludes.

II. SATELLITE TRACKING AND PREDICTION

Prediction of satellite orbits is a well known science. The SGP algorithms calculate a satellite's orbital state vector relative to an Earth Centered Earth Fixed (ECEF)

[1] http://www.scalable-networks.com/
[2] http://www.opnet.com/products/modeler/home.html

[3] http://science.nasa.gov/Realtime/JTrack
[4] http://www.amsat.org/amsat-new/tools/software.php

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coordinate system. The latitude/longitude/altitude coordinate system used in Qualnet is an Earth Centered Inertial (ECI) coordinate system and thus a conversion must be done. We accomplish this conversion by using an iterative algorithm from the 2008 Astronomical Almanac [6]. SatMob uses the Simplified General Perturbations Satellite Orbit Model 4 (SGP4) from the SGP orbital propagation models introduced in SpaceTrack Number 3 report [7]. The report contains 5 algorithms, SGP, SGP4/SDP4, and SGP8/SDP8. SGP was replaced by SGP4/SDP4 which are in standard use today. SGP4 is suitable for satellites orbiting a planetary body and SDP4 is suitable for deep space operations. SGP8/SDP8 attempt to account for orbital decay and re-entry, however, there is no evidence to suggest that either has been implemented for operational TLE's.

SatMob uses a variant of the Simplified General Perturbations Satellite Orbit Model 4 (SGP4) developed by Hoots et. al. SGP4 is a NASA/NORAD algorithm for calculating the orbital position of near Earth satellites (orbital period of 225 minutes or less). SGP4 is adequate for either Low Earth Orbit (LEO) or Medium Earth Orbit (MEO) satellites. Although, a mathematical treatment of this algorithm is beyond the scope of this paper, we will detail the usage of our variant of SGP4.

SGP4 is a standard model for spacecraft orbital prediction and its inputs are Keplerian elements in TLE format. TLE formatted files for in-flight satellites are available from many sources including NASA [5] and AMSAT [6]. For in-flight satellite TLE data, elements that are more than 30 days older/newer than the simulation time should be considered inaccurate because of perturbations in actual satellite orbits.

For given satellite simulations , researchers must generate their own sets of TLE formatted Keplerian elements. Keplerian data consists of seven and sometimes eight elements. The first seven satellite orbital elements are required to define a satellite's position relative to a position on the ground and the eighth optional element defines the drag that a planetary atmosphere places upon a satellite.

Keplerian elements define an ellipse orientated about a planetary body with the planet at the focus and the satellites position on the ellipse at a given time. The Keplerian model is slightly naive in that it assumes the ellipse is of constant shape and orientation. There are variants of SGP4 that attempt to compensate for this inconsistency by considering the unevenness of the planet's gravitational field and the drag placed on a satellite according to its proximity to a planetary atmosphere. However, we did not choose to use these methods as the gain in accuracy was not enough to justify the added complexity.

The first element in a Keplerian TLE set is the Epoch time, the second and third elements are shown in Figure 1

[5]http://science.nasa.gov/Realtime/jtrack/Satellitelinks.html

[6]http://www.amsat.org/amsat-new/tools/keps.php

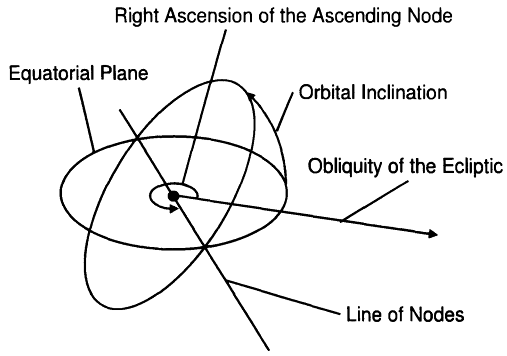

Fig. 1. Orbital Diagram for Keplerian Elements 2 and 3.

and describe a satellite's orbital plane. The next four elements are shown in Figure 2 and describe a satellite's position in its orbital plane. The elements in a Keplerian TLE set are defined as follows:

1. Epoch time: the Julian time at which a snapshot of Keplerian elements was taken. The epoch time is an absolute reference point in time. SGP4 calculates a satellites location by propagating a satellite's orbital position forward/backward from the epoch.

2. Orbital inclination: the angle between the orbital plane of a satellite and the equatorial plane of a planet, its range is [0, 180].

3. Right Ascension of the Ascending Node (RAAN): the angle between the obliquity of the ecliptic and the place where the orbit of a satellite crosses the planetary equator from the South to the North. The obliquity of the ecliptic is the point where the orbit of the Sun, as seen from a planet crosses the Equator from the South to the North on the vernal equinox. The RAAN gives us an absolute reference point in space. ECI coordinate systems such as latitude/longitude/altitude cannot be used for this purpose because of planetary rotation.

4. Argument of Perigee: the angle between the Line of Nodes and the Line of Apsides. The Line of Nodes is the place where the orbital plane of a satellite intersects with the equatorial plane of a planet. The Line of Apsides is the line passing through the major foci of a satellite's orbital ellipse, the center of a planet, and the perigee of a satellite's orbit. The range of the Argument of Perigee is [0, 360].

5. Eccentricity: the shape of a satellite's orbital ellipse. Its range is [0, 1] with zero being a perfectly circular orbit and 1 being a highly elliptical orbit. The ratio of eccentricity is $E_0 = \frac{R_a - a}{a}$ where a is the distance between the

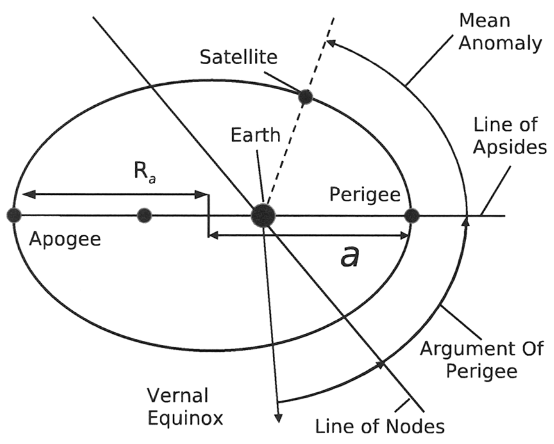

Fig. 2. Orbital Diagram for Keplerian Elements 4 to 7.

apogee and the center of the Earth and a is the distance between the center of the line of apsides and the perigee.

6. Mean motion: describes the satellite's distance from the planet. Distance is specified as an orbital period because Kepler's Third Law states that the square of the period of time it takes a satellite to complete an orbit of the Earth is proportional to the cube of its mean distance from the Earth. However, unless the satellite's orbit is a perfect circle (eccentricity = 0), the mean motion will not be a constant. It is common practice to calculate the mean motion by taking the average of a satellite's orbital speed given in revolutions per day.

7. Mean Anomaly: defines the satellite's position in its orbital ellipse. It is an angle whose range is [0, 360] with 0 degrees being the perigee of the satellite's orbit and 180 being the apogee of its orbit.

8. Drag: the atmospheric effect that causes a satellite to spiral downward. This optional element defines the rate at which a satellite's mean motion is changing due to atmospheric drag. Drag is calculated by taking half of the first time derivative of mean motion.

This brief treatment of the Keplerian elements is necessary for the proper use of the SGP algorithms.

III. SATMOB MOBILITY MODEL DESIGN

SatMob works by distributing a given number of time points throughout the simulation and then calculating a satellite's position in Qualnet style geodetic coordinate points (latitude/longitude/altitude) for each time point. These point and time pairs are then inserted into Qualnet's event queue starting at simulation time zero. To accomplish this, we begin with a variant of SGP4 written by Goddard [7]. SatMob contains all eight of the standard orbital propagation algorithms and the user may select the algorithm of choice via the standard Qualnet configuration file. However, because the work detailed in this paper concerns LEO/MEO satellites, we only discuss the use of the SGP4 algorithm.

The SGP4 algorithm uses Julian time for its input parameters, Qualnet uses nano-seconds, and researchers use GMT. Hence time conversions are necessary. To accomplish this, we first convert from GMT to UNIX seconds then divide by the number of seconds in a day (86400), subtract a constant to account for leap seconds (3651), and add UNIX epoch time (2440588 in Julian). In addition, the SGP4 algorithm returns position coordinates in a geocentric ECEF coordinate system which are converted to Qualnet's geodetic system (latitude/longitude/altitude) using the algorithm from the 2008 Astronomical Almanac. Note that Qualnet does contain a function to accomplish this, however the documentation is poor and we found that returns ambiguous postions.

A Qualnet simulation using satellite nodes has four new configuration parameters specifying which nodes are satellites, how many points to calculate, the starting time of the simulation in GMT, and the name of the TLE file to use. Qualnet then does the initial node placement calculations in a placement model. Any satellite's position will be calculated using SGP4 and our conversion algorithms and is inserted into the queue at simulation time zero. All non-satellite nodes are positioned normally (e.g., uniform placement or file placement).

Next, Qualnet performs the mobility position calculations. For a satellite node, time points are distributed throughout the simulation at intervals of the total simulation time divided by the point granularity parameter. A position is calculated for each time point using SGP4 and our conversion algorithms and then inserted into the event queue at each time point. Once again, mobility for all non-satellite nodes are calculated normally.

Qualnet's Satcom protocol is a simple bent pipe protocol and does not consider a satellite's footprint or antenna alignment, thus realism is sacrificed. All of the nodes in the simulation using Satcom can communicate with any other node that also uses Satcom. The antenna alignment/footprint size problem is beyond the scope of this work; however, it would be difficult to conduct meaningful experiments without some attention to these problems. Satellite antenna alignment depends on the operator's preference and satellite capabilities, so we chose a simple model. The satellites antenna is pointed directly at the center of the earth from its position in orbit, and the footprint size is specified by the user.

IV. EVALUATION

This section presents a representative set of our experiments with SatMob. Our results are aimed at achieving

[7] http://godard.b.free.fr/dotclear/index.php

three goals. First, we want to show that SatMob works as expected. Second, we want to show that using inaccurate mobility models for experiments with satellite nodes can result in incorrect data. Finally, we want to show that SatMob is accurate and consistent with standard tools used for orbital predictions.

A. Integration of SatMob into Qualnet

To show that SatMob is working as expected, we first present a screenshot of Qualnet's animator while using SatMob. This allows us to visually demonstrate that the nodes under the satellite's footprint can communicate and those that are not under the footprint cannot.

Figure 3 shows a screenshot of the Qualnet animator during a typical satellite network experiment. The terrain stretches from -47.4, 164.8 degrees latitude and longitude to -46.96, 167.44 degrees latitude and longitude. This corresponds to an area of about 30 by 129 miles just off the southwestern coast of New Zealand. In the experiment, *Node9* is the Near Field Infrared Experiment (NFIRE), a satellite belonging to the United States missile defense agency launched on April 24, 2006. The TLE for this satellite was obtained from NASA's J-track website. The satellite is modeled with an antenna pointing directly towards the center of the Earth and a footprint of 56,000 meters. NFIRE is flying from the Southwestern coast of New Zealand in a Northwesterly direction in this experiment. NFIRE will fly from the upper left hand corner to the lower right hand corner of Figure 3. The screenshot is taken at about 7 seconds into a thirty second experiment.

Node1 through *Node8* are ground nodes that communicate in pairs through the satellite. There are four Constant Bit Rate (CBR) flows, each beginning at zero simulation time and running for the full 30 second flyover at a rate of one 512 byte packet per second. *Node1* sends packets to *Node2*, *Node3* sends packets to *Node4*, *Node5* sends packets to *Node6*, and *Node7* sends packets to *Node8*. The footprint of NFIRE covers slightly less than half of the terrain. This means that only about two pairs of communicating nodes will be under the footprint at any given time. Hence, only the nodes under the footprint should be able to communicate using the satellite.

In the screenshot of Figure 3, packet flow is indicated by a thick black arrow from the sender to the sink. NFIRE's footprint is indicated by the large black circle. Figure 3 clearly shows that *Node2* receives packets from *Node1*, and that *Node4* receives packets from *Node3*. *Node5* also tries to send packets to *Node6*, and *Node7* to *Node8*. Communication between *Node5*, *Node6* and *Node7*, *Node8* is not successful because the nodes are not within NFIRE's footprint boundary. This result is indicated by the lack of packet flow arrows between *Node5*, *Node6* and *Node7*, *Node8*.

As the experiment progresses, NFIRE's footprint will

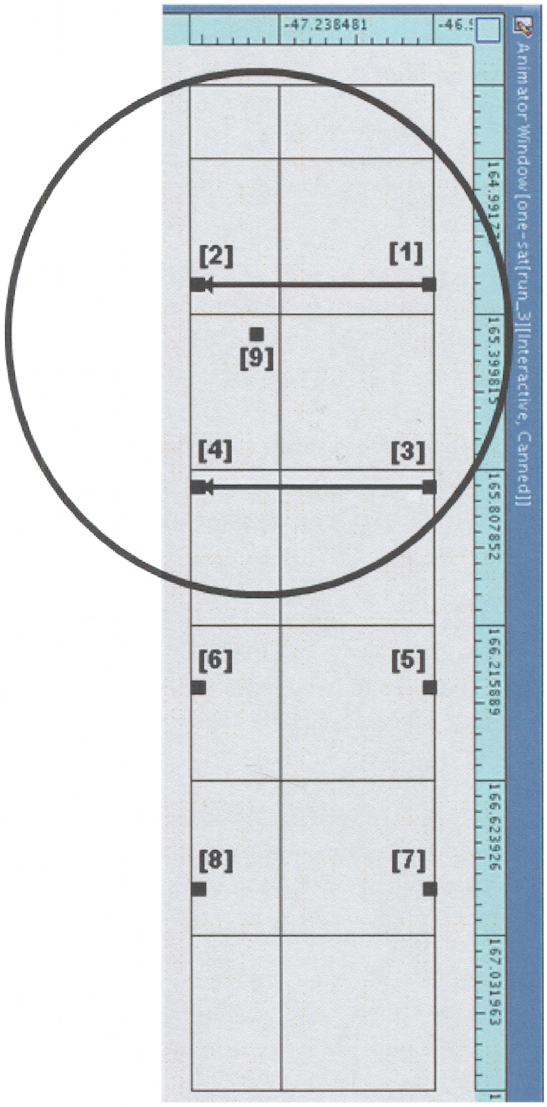

Fig. 3. Ground to satellite communication during 30 second NFIRE flyover.

move across the terrain towards the lower right corner. As NFIRE moves, its footprint will also move leaving behind first *Node1* and *Node2*, then *Node3* and *Node4*, and so on until, at the end of the experiment only, *Node7* and *Node8* are under NFIRE's footprint and can communicate. The observed communication behavior indicates that our model is integrated into Qualnet and produces expected behavior.

B. Qualnet vs. SatMob

In order to demonstrate the importance of having an accurate satellite mobility model, we perform the same experiment, first using SatMob, and then again using Qualnet's file mobility model. In order to use Qualnet's file mobility model for a given satellite, a researcher will have to calculate its velocity and trajectory. While doing this with a simplified version of SGP such as in ns-2, it is likely that there will be errors in velocity and/or trajectory. We injected small errors in both, the velocity and trajectory and repeated the experiment. The errors that we injected into the mobility model are the actual errors that we made at the beginning of this work when we tried to specify NFIRE's velocity and trajectory without the benefit of SatMob. While it may be possible to specify a satellite's orbital position without making errors it is remarkably difficult because of the complexity of orbital mechanics. Because the only difference between the two experiments is the mobility model, the different results demonstrate that an accurate mobility model is necessary to ensure that experiments produce useful results.

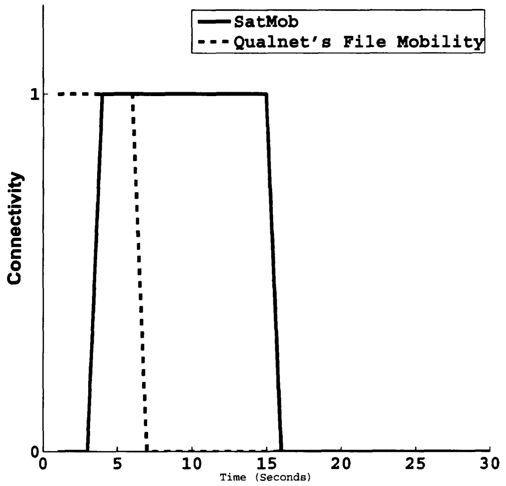

Fig. 4. Time sequence series connectivity for Nodes 1 and 2 NFIRE flyover.

Figure 4 demonstrates a time sequence connectivity graph for *Node1* and *Node2* using both SatMob and Qualnet's file mobility model. The x-axis is simulation time from 0 to 30 seconds. The y-axis is connectivity. Because of our simplified footprint and the fact that we are not using a propagation-fading model, the graph is binary. Zero on the graph indicates no packet flow and one indicates packet flow. This produces a visual representation of SatMob's functionality.

Because *Node1* and *Node2* are nearest to the upper left hand corner of the terrain where NFIRE begins its flyover they are the first to be able to communicate and the first to lose connectivity. The solid line on the graph shows that with SatMob *Node1* and *Node2* gain connectivity at about 3 seconds into the experiment and that they lose connectivity at about 15 seconds into the experiment.

The dashed line on the graph shows that with Qualnet's file mobility model *Node1* and *Node2* gain connectivity almost immediately and that they lose connectivity at about 6 seconds into the experiment. The anomaly near time zero in Qualnet's file mobility model's dashed line is because *Node1* does not start transmitting until 1 second into the experiment. The differences in the data produced by the two experiments are significant. Qualnet's file mobility model gains connectivity sooner (almost immediately) compared to SatMob and maintains connectivity for a shorter duration (about 5 seconds).

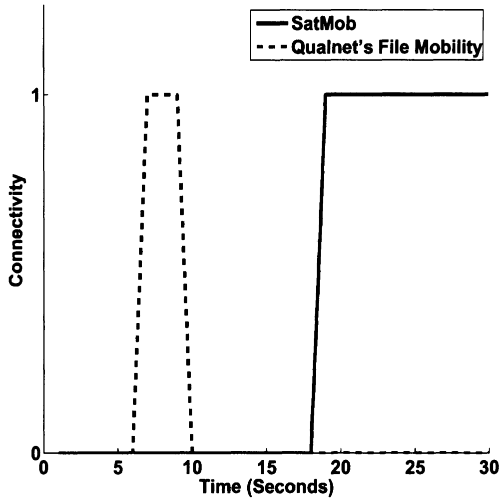

Fig. 5. Time sequence series connectivity for Nodes 7 and 8 NFIRE flyover.

The differences in connectivity are likely because the altitude of NFIRE's orbit is slightly lower in this experiment. This error causes its orbital period to be shorter and its velocity to be greater. In Figure 5, we present a time sequence connectivity graph for *Node7* and *Node8* from the same experiment using both SatMob and Qualnet's file mobility model. Once again, the x-axis is simulation time from 0 to 30 seconds and the y-axis is connectivity. As above, zero on the graph indicates no packet flow and one indicates packet flow.

Because *Node7* and *Node8* are the closest to the lower right hand corner of the terrain where NFIRE leaves the experimental terrain they are the last node pair to gain connectivity and the last to lose connectivity.

The solid line on the graph shows that with SatMob, *Node7* and *Node8* gain connectivity at about 18 seconds into the experiment and they maintain connectivity until the end of the experiment. The dashed line on the graph shows that with Qualnet's file mobility model *Node7* and *Node8* gain connectivity at about 6 seconds into the experiment and that they lose connectivity at about 9 seconds into the experiment.

The difference in connectivity in this case is even more dramatic than in Figure 4. The duration of connectivity is about 12 seconds for SatMob vs. about 3 seconds for Qualnet's file mobility model. Also, the communication start times are considerably different, 6 seconds for Qualnet's file mobility model versus 18 seconds for SatMob. Also, notice that the connectivity durations are different from *Node1*, *Node2* and *Node7*, *Node8* for Qualnet's file mobility model. *Node1* and *Node2* (from Figure 4) have about 6 seconds connectivity time while *Node7* and *Node8* have only three. This is because of two things, the 1 second inter-packet arrival time, and the angle at which NFIRE is flying relative to the nodes. NFIRE's footprint covers *Node7* and *Node8* near the beginning of the inter-packet arrival time using up one second before starting to transmit. Similarly NFIRE's footprint leaves *Node7* and *Node8* near the end of another inter-packet arrival time using up another second.

These series of graphs have demonstrated that using different mobility models for satellite flyovers can produce considerably different results. It is clearly important to have an accurate satellite mobility model that closely portrays the orbital mechanics of a given satellite.

C. SatMob Validation

Finally, we demonstrate the accuracy of SatMob by comparing it's predictions to NASA's J-Track, and the amateur radio community's Predict software. Our metric in these comparisons is Euclidian distance between two predictions i.e., the smaller the distance between SatMob and the other tools, the greater the accuracy.

Figure 6 demonstrates the Euclidean distance between the positions generated by SatMob and the positions generated by Predict. The Y-axis shows distance in kilometers and the X-axis shows time. Clearly, SatMob is consistent with Predict because their position predictions are at most 300 meters apart.

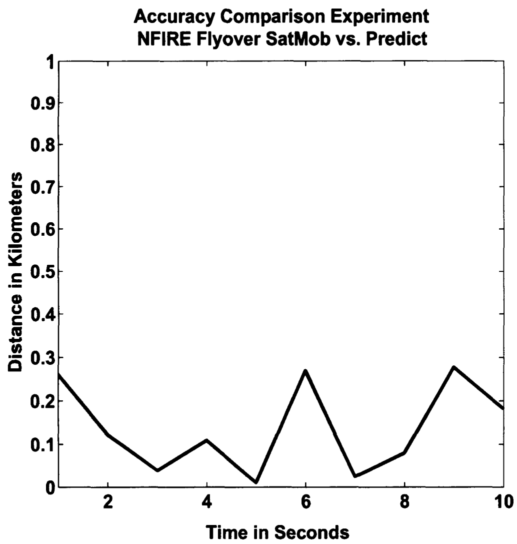

Fig. 6. Difference in Predictions SatMob vs. Predict.

Figure 7 shows the Euclidean distance between the positions generated by SatMob and the positions generated by J-Track. Once again, the Y-axis shows distance in kilometers and the X-axis shows time. The graph shows that SatMob's position predictions are further away from J-track's positions than they are from those produced by Predict. The distance between predictions averages are about 80 to 90 Km. Most of this difference is likely caused because J-Track does not publish their TLE's, hence we are unable to use exactly the same TLE for J-Track comparisons, as we were able to do for Predict comparisons. In addition, J-Track's web interface only allows for 1 decimal place accuracy. The anomaly at around 10 seconds is likely because J-Track's web interface does not allow us to precisely align the time points, as we are able to do with Predict.

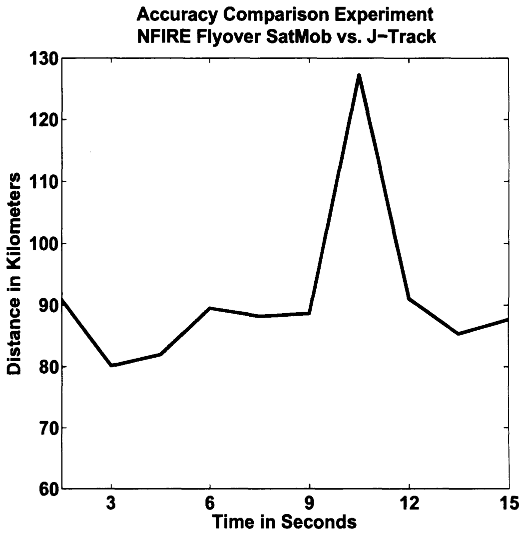

Fig. 7. Difference in Predictions SatMob vs. J-Track

Given the limitations of different TLE's, single decimal place precision, and inexact timing, we assert that 80 to 90 Km is not a large degree of error. In addition, because of SatMob's consistency with Predict, we further assert that SatMob's accuracy is sufficient to produce good quality experimental data.

V. Conclusions and Future Work

We have developed an open source satellite mobility model for the Qualnet network simulator. The model allows users to easily add satellite nodes to their network experiments without the purchase of additional software licenses such as the STK. We have added a variant of the SGP library to Qualnet. Futhermore, we have created a time and coordinate system converter between SGP and Qaulnet formats for integration purposes.

In addition, we have packaged each of these routines as a satellite mobility model for Qualnet. We have demonstrated that errors in satellite position prediction can have significant effects on networking experiments and have demonstrated that SatMob is reasonably correct and consistent compared to standard community tools. Also, we have identified two avenues of future work that need attention: satellite antenna pointing and footprint size. These factors depend on an individual satellite's capabilities and missions. These problems can be solved by collecting a database of information for each satellite and importing this data into Qualnet at initialization time as well as taking terrain into consideration.

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VI. Reviewers Comments

1. This paper describes a simplified model of low orbit satellite motion that can be integrated into QUALNET. The results have been validated against more accurate and computationly complex models and found to be accurate. It promises to be an effective, low cost method of incorporating LEO/MEO satellite motion in Qualnet model simulations.

2. Excellent treatment of satellite orbital mechanics the paper describes an open source satellite mobility model (SatMob)for Low/Medium Earth Orbit (LEO/MEO) satellites to be used as part of existing Qualnet network simulation tools.

3. This paper developed an open source satellite mobility model for the Qualnet network simulator. contribution of this work allows users to easily add satellite nodes to their network experiments without the purchase of additional software licenses such as the STK. The paper is very well written.