Geosynchronous Satellite Use of GPS

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BIOGRAPHY

Jennifer Ruiz is a Systems Engineer for the Lockheed Martin Corporation. She received her Bachelor of Science Degree in Electrical Engineering from the University of Delaware and is currently pursuing her M.S.E.E. at Villanova University. She has supported several programs at Lockheed Martin that use GPS technology as a means of navigation and is currently supporting the GPS III program in the areas of Integrity and Position, Velocity, and Timing (PVT) system requirements.

Chuck Frey is a Senior Staff Systems Engineer with Lockheed Martin. He holds a Bachelor of Science Degree in Aerospace Engineering from the Pennsylvania State University and a Masters of Science Degree in Mechanical Engineering from Villanova University. Chuck developed the suite of tools, Precise Real-time Orbits (PRO) capable of ground or orbit determination which was used for this analysis. He has also been involved in several integration efforts for large-scale ground/satellite programs. Chuck currently supports the GPS III program as the integrated program thread lead for Position, Velocity and Timing requirements.

ABSTRACT

The purpose of this study was to determine the accuracy of GPS use for a geosynchronous (GEO) satellite. Current missions at GEO altitude mainly use traditional ranging for orbit determination. With changing mission requirements and the increase in the number of GEO missions, utilizing GPS signals is becoming an increasingly attractive alternative for position and timing determination. A previous ION paper discusses the use of GPS data for a particular geosynchronous satellite mission and is included here as a reference. GPS use at GEO is primarily limited by the availability of the spillover from the GPS earth coverage signal. The availability of the GPS signal at GEO is determined by the GPS block specific antenna patterns and the GEO satellite's receiver antenna. This analysis specifically examined the effects of the GPS constellation availability, antenna gain patterns, and GPS receiver clock stability on position and timing accuracies at GEO.

INTRODUCTION

GPS missions at GEO synchronous altitude use the spillover of the earth coverage GPS signals. The main beam of the GPS antenna varies from approximately 23° to 26° depending on the Block and frequency of the GPS vehicle. In addition to the main earth coverage beam, the GPS vehicles have side-lobe signals which have enough power to reach a user at GEO altitude. Unlike a Terrestrial User or a Low Earth Orbit (LEO) user of GPS, the GPS satellites a GEO satellite will use are beneath the GEO satellite. An illustration of this is given in Figure 1.

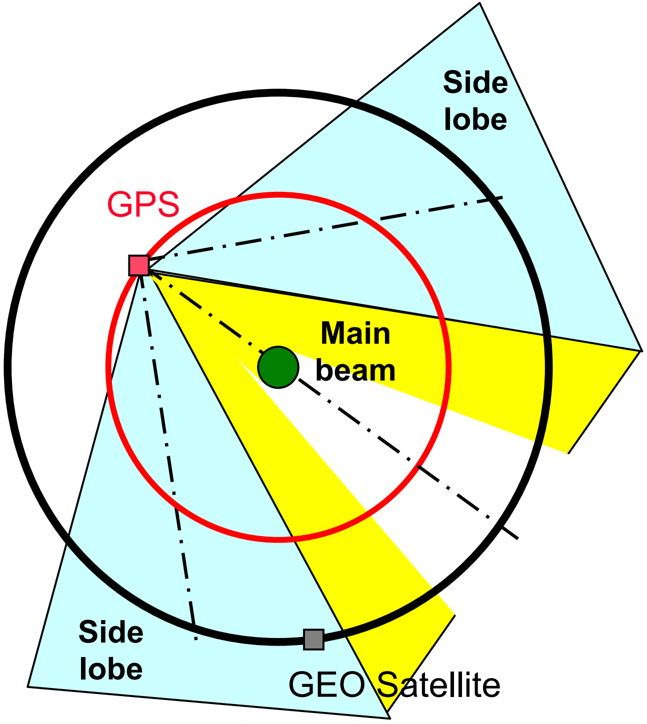

Figure 1 – GPS at GEO diagram

If a GEO satellite is restricted to the main beam of the GPS signal, a significant reduction in the availability of a single GPS satellite is seen. Outages of a couple of hours can be encountered. These outages are a function of the current constellation size and location of the GPS satellites and also of the Block of GPS satellites that are on orbit. Different Blocks of GPS satellites (II, IIA, IIR, IIRM, IIF) have different antenna patterns. For the purpose of this paper, a representative GPS antenna pattern was used and is shown in Figure 2 for the L1 frequency. A similar pattern was used for the L2 Signal Strength. It should be noted that current GPS does not guarantee the accuracy or the signal strength past the earth limb. This is a risk entailed by the user designing a system that uses these signals. However, the current blocks of GPS vehicles have antennas that provide these signals past the earth limb and GPS III (the next generation of GPS) is specifying power, pseudorange accuracy, and satellite signal availability at geosynchronous satellite altitudes.

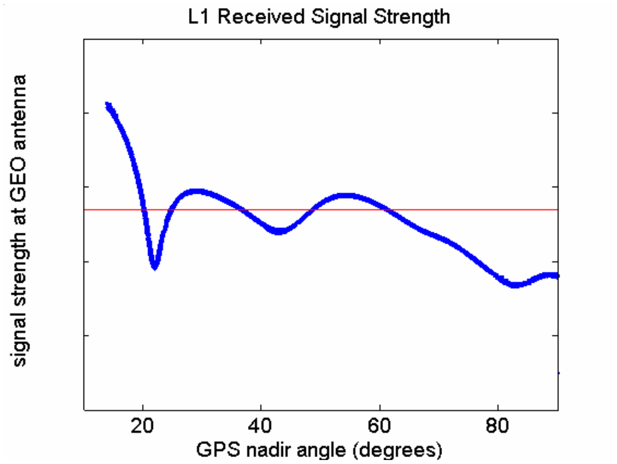

Figure 2 – GPS L1 antenna pattern at GEO

ANALYSIS ASSUMPTIONS

Figure 2 shows the power at the GEO user antenna as a function of off nadir angle of the GPS satellite. For this particular antenna the main beam of the GPS signal was 23.5° off of nadir angle of the GPS satellite. Analysis was performed on main beam use of GPS and also main plus side-lobe use of GPS signals. Availability of the GPS signal at GEO for the main beam scenario was purely done by geometry. If the GEO satellite was not obscured by the earth plus a grazing altitude and resided within the 23.5° nadir angle of the GPS satellite, then the signal was assumed to be attainable. For the main beam plus side-lobe scenario, a power model was used to assess measurement availability. The power model was necessary because of nulls in the GPS signal. The power at the GEO GPS antenna was calculated by using the GPS antenna gain patterns plus the GPS transmit power minus the space loss due to the path length of signal. A threshold prior to the GEO GPS antenna was used to determine GPS signal availability. Trades were performed on accuracy and availability as a function of this threshold. In the main plus side-lobe case, the power model was used to simulate pseudorange code noise on the GPS simulated measurements. This was necessary due to the wide range of signal power levels to accurately determine pseudorange measurement accuracy. If the GPS signal had a power level higher than the threshold, the GEO antenna gain was then applied and pseudorange measurement noise was calculated. Figure 3 shows pseudorange measurement accuracy for the P(y) L1 military frequency and the C/A civilian frequency as a function of signal strength at the GEO GPS receiver. The nominal threshold for this paper was chosen to be -185dBW at the GEO GPS antenna.

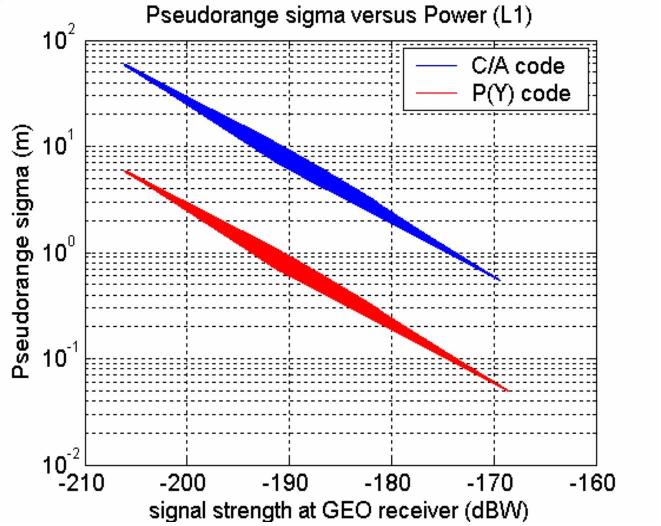

Figure 3 – Pseudorange sigma vs. GEO signal strength

In addition to GPS signal availability and accuracy determination, ionospheric delays were simulated on the pseudorange measurements. Dual frequency users of GPS can correct for the ionosphere using the standard dual-frequency correction. Single frequency users of GPS need to account for this error in accuracy analysis. This un-modeled delay can cause significant accuracy degradation to both position and timing users of GPS. An illustration of the ionosphere is given in Figure 4.

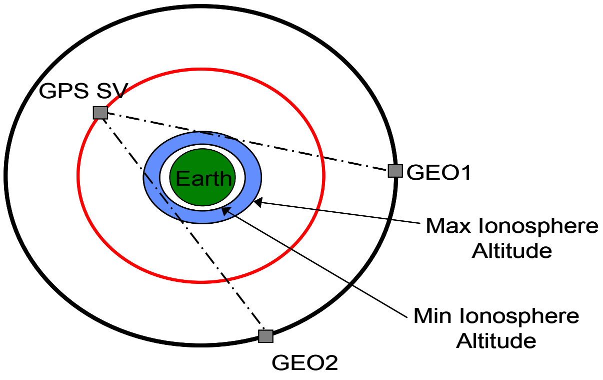

Figure 4 – Ionosphere Layer Illustration

Figure 4 shows that GPS signals collected close to the earth are affected by ionosphere delays. These delays can be minimized by raising the grazing altitude of the earth obscuration. However, this further limits the availability of already scarce GPS signals. The analysis presented in this paper used a 200nm grazing altitude for single frequency analysis and 60nm grazing altitude for dual frequency analysis. 200nm was chosen to minimize the effects of the un-modeled ionosphere delay. Ionosphere delay on the GPS pseudorange measurements was simulated using a Modified Klobuchar model. The Klobuchar model is used by GPS system and its coefficients are broadcast as part of the standard GPS navigation message. These coefficients are used by ground users of GPS to aid in modeling the ionosphere delay for single frequency users. For ionosphere measurement delay simulation, the Klobuchar model was modified to account for the extra path length through the ionosphere and also for the height of the ionospheric pierce point. This model was verified using data collected by a low earth orbiting satellite using the JPL built CHAMP codeless receiver. The CHAMP codeless receiver creates L1 and L2 pseudorange measurements which can be used to calculate the L1 or the L2 ionosphere delay. This delay as a function of elevation angle from the CHAMP receiver is shown in Figure 5.

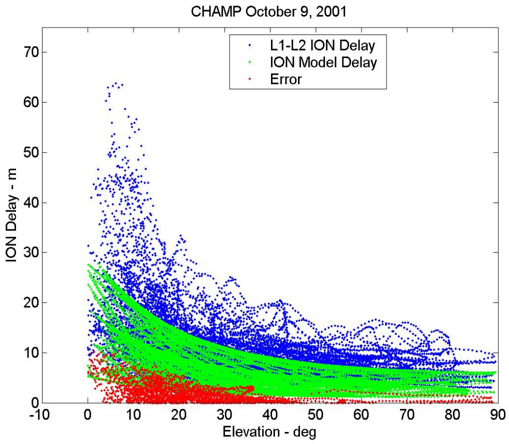

Figure 5 – Ionosphere Model Validation

The Blue points on Figure 5 show the actual ionospheric delay as calculated by the CHAMP pseudorange measurement data. The green points show the ionospheric delay as calculated by the modified Klobuchar model and the red points show the error. This data clearly shows that the modified Klobuchar model adequately models the ionospheric delay for Space applications and thus can be used to simulate delays on pseudorange measurements. The modified Klobuchar model uses the standard inputs as defined by ICD-GPS-200.

Further assumptions for the analysis include a standard 24 satellite 6 plane GPS constellation and also a User Range Error of 1.5m on the GPS signal. 1.5m is the current estimate of the accuracy of the GPS signal. Analysis was performed against this current value as well as improved accuracy to simulate future GPS systems.

MODELING AND SIMULATION SOFTWARE

Precise Real-time Orbits (PRO) was used to simulate the GPS at GEO scenario. PRO consists of a measurement simulator and processor used for Monte-Carlo like and covariance analysis. Verification of PRO models and algorithms was done using real tracking data collected by ground and space users of GPS. GPS receiver characteristics which include number of channels, receiver clock accuracy, satellite selection algorithm and GEO user antenna characteristics along with the GPS satellite parameters are used as inputs to the simulator. The measurement processor then processes the simulated measurements using process noise models tuned to the specific errors in a Kalman-like filter. The GEO output of estimated ephemeris (position, velocity and time) along with the covariance information is compared against the truth ephemeris to assess accuracy achievable by a GEO user of GPS. The accuracy results are summarized in the next section.

ANALYSIS RESULTS

- **Availability**

A parametric study was done on the number of GPS satellites in view of the GEO satellite based upon the power threshold. In order for the signal to be considered "in view", both the L1 and L2 (for dual channel) power level had to be stronger than the specified threshold. Since the portion of the main lobe available at different thresholds does not vary much, this study focused on the scenario where the power from the side lobes is usable. Figure 6 shows the minimum number of GPS satellites as a function of power threshold at the GEO GPS antenna for the main plus side-lobe scenario.

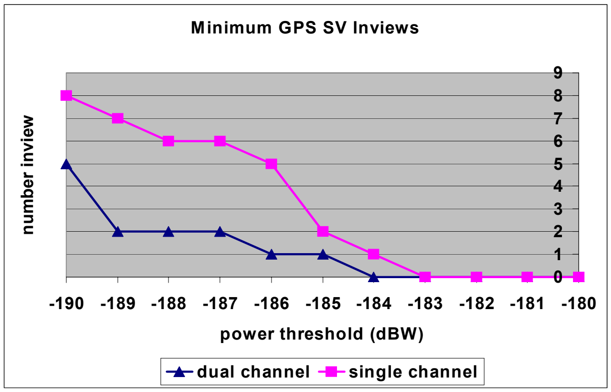

Figure 6 – Availability as a function of power

These statistics were collected over a full 48 hour run and show that 100% single satellite availability is achieved at

-185dBW for dual channel and -184dBW for single channel. Full coverage for the single frequency scenario can be achieved at a higher power threshold since it only performed a check on the L1 signal whereas the dual channel performed the check on both L1 and L2. For comparison purposes the main lobe only scenario experiences approximately 80% availability of a single GPS using the 23.5° half nadir cone angle. Significant GPS signal availability is achieved using the main plus side-lobes.

- **Position, Velocity and Time Accuracy**

Position, Velocity and Time (PVT) accuracy assessments were done by comparing the estimated ephemeris against the truth ephemeris for both the single and dual frequency cases and the main and main plus side-lobe scenarios. A nominal power threshold of -185dBW was used for the main plus side-lobe scenario. At this threshold 100% availability is achieved for both dual and single frequency. The main lobe only scenario used the 23.5° half nadir cone angle only.

Figures 7 and 8 show the position accuracy of the GEO satellite for the main lobe scenario and the main plus side-lobe scenario respectively.

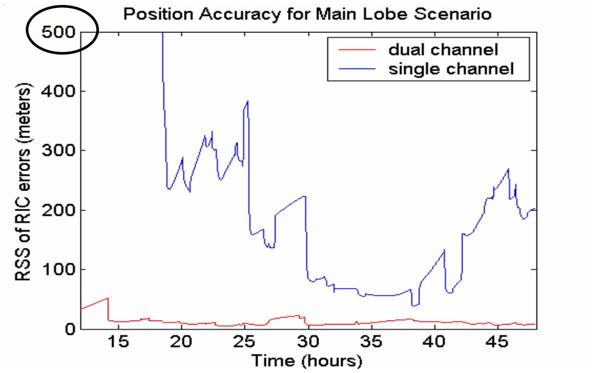

Figure 7 – Main Lobe Position Accuracy

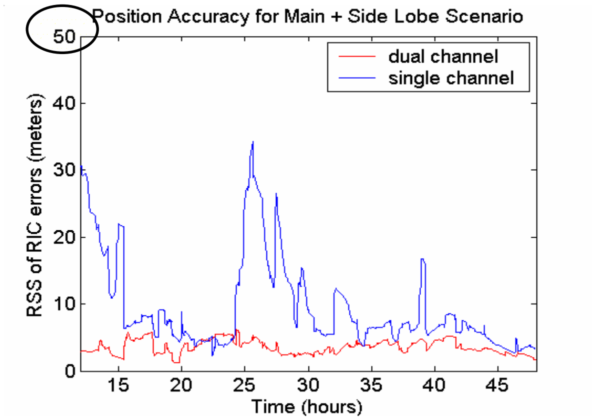

Figure 8 – Main plus Side-Lobe Position Accuracy

These plots clearly show that dual frequency performs better than single frequency and the main plus side lobe scenario outperforms the main lobe only scenario. The main contributor to accuracy degradation for the single frequency case is the ionospheric delays. Even though the simulation used a 200nm grazing altitude for single frequency GPS pseudorange measurement collection, significant delays still exist above this altitude. These un-modeled delays significantly affect GEO orbit accuracy. These errors are not necessarily reflected in the covariance. This is due to the fact that the un-modeled ionospheric delays on measurements above 200nm grazing altitude were accounted for in the Kalman filter by increasing the measurement noise. The dual frequency solution had a more believable covariance since the ionospheric delay was accounted for. The main plus side-lobe scenario had better accuracy due to the higher availability of the GPS signals.

	Main Lobe Only		Main+ Side-Lobe	
	single	dual	single	dual
RSS Position Error	160 m	12 m	11 m	4 m
Max Position Error	365 m	22 m	31 m	7 m

Table 1 – Position Accuracy Summary

Figures 9 and 10 show the time accuracy achievable for the same scenarios as the position accuracy. For the simulation a low grade crystal oscillator was assumed.

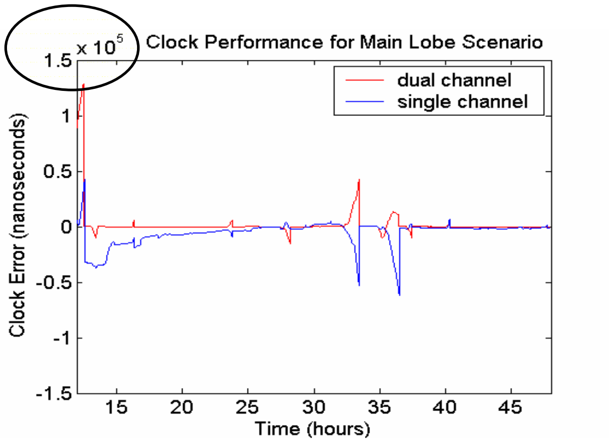

Figure 9 – Main Lobe Timing Accuracy

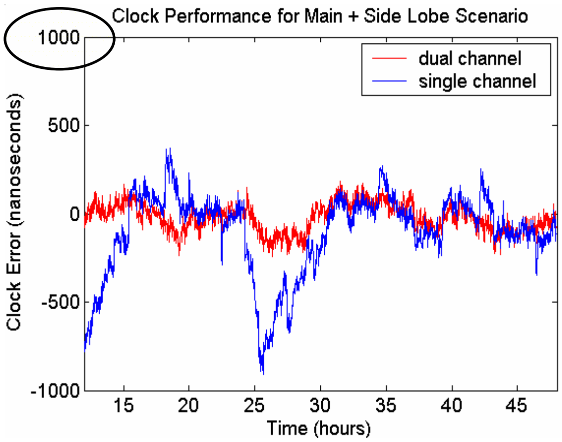

Figure 10 – Main plus Side-Lobe Timing Accuracy

Significant timing accuracy degradation exists for the main lobe scenario. Please note the scale of the plots in figures 9 and 10. This degradation occurs during the GPS signal outages that exist due to the unavailability of the GPS signal. This coupled with the low grade crystal oscillator limit time transfer accuracy during outages. Further improvements to time transfer accuracy can be obtained for the main lobe scenario by using a higher grade crystal oscillator or an atomic frequency reference. It should also be noted that this degradation only exists when GPS signals are not available. This is illustrated in Figure 11.

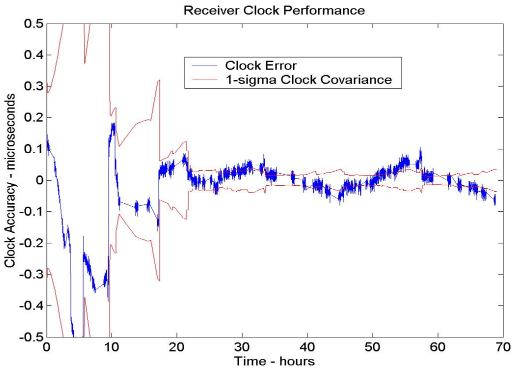

Figure 11 – Dual Frequency Time Transfer

Figure 11 is the dual frequency time transfer accuracy for the main lobe scenario plotted only when GPS signals are available. The red solid line is the 1-sigma covariance of the GPS receiver phase solution and the blue line is the difference between the estimated and truth GPS receiver phase solutions. This graph shows that time transfer can be achieved if the mission is limited to when GPS signals are available, even with a low grade crystal oscillator. Single frequency time transfer has similar results.

Figures 12 and 13 show the position and time transfer accuracy as a function of the power threshold at the GEO GPS antenna.

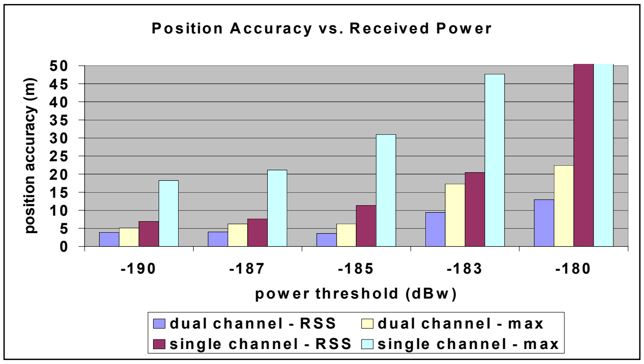

Figure 12 – Position Accuracy vs. Power Threshold

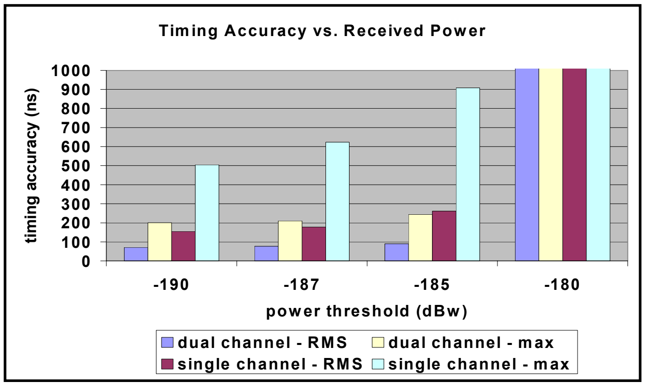

Figure 13 – Time Transfer Accuracy vs. Power Threshold

Figures 12 and 13 show the sensitivity of position and time transfer accuracy achievable as a function of usable GPS signal at GEO as defined by the power level threshold. The lower the power threshold that can be used the higher the accuracy achievable. The knee in the curve for dual frequency is at about -185dBw. Diminishing returns on accuracy below this level are shown. This is a result of the 100% GPS signal availability at this power threshold under the given assumptions of the GPS constellation and GEO user satellite. Both curves are cut off on Figures 12 and 13 for -180dBw. Single frequency position accuracy and dual and single frequency timing accuracy were severely degraded at this power threshold level.

- **URE Sensitivity**

Final analysis showed the sensitivity of URE to position and time transfer accuracy for the dual frequency user. The URE used for all previous analysis was 1.5m. This is today's estimate of the GPS constellation. Sensitivity of URE between 0.5m and 2.0m is shown in Figures 14 and 15 for position and time transfer accuracy respectively.

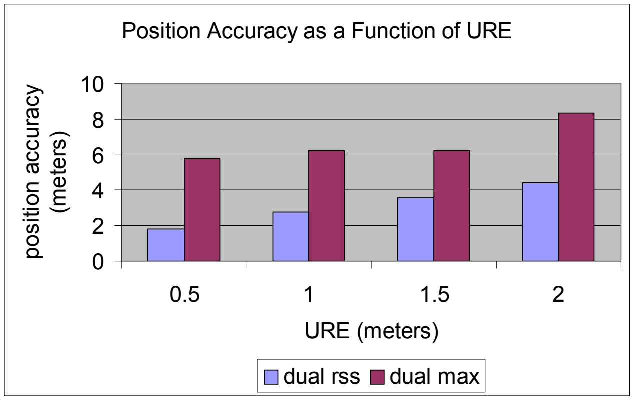

Figure 14 – Position Accuracy vs. URE

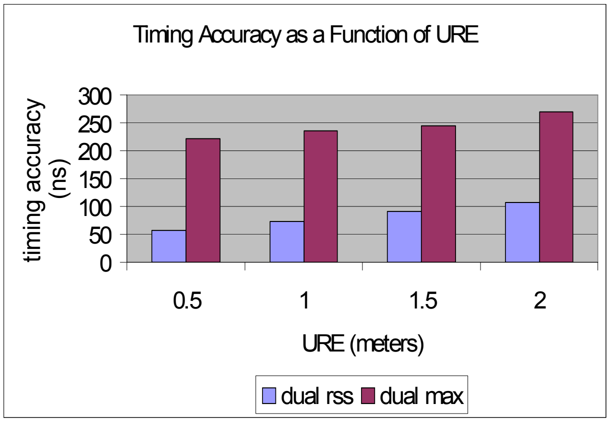

Figure 15 – Time Transfer Accuracy vs. URE

For the dual frequency user approximately 50% improvement in position and time transfer accuracy is achievable between a URE of 2.0m and 0.5m. The single frequency user is less sensitive to this URE range since the single frequency user accuracy is limited mainly by the errors caused by the ionospheric delays.

CONCLUSIONS

Based on this analysis, GPS use for geosynchronous satellites is not only feasible but also provides good accuracy.

The advantages of dual (L1/L2 P(Y)) channel mode are quite clear, and this operation mode is highly recommended. As seen by the results, the ionosphere error correction capability achievable by dual channel operation significantly improves position and velocity accuracy. Timing accuracy with dual channel operation is also better than single channel with 100% availability.

Another strong recommendation is to maintain 100% availability; that is, ensure that no outages occur. It was found that maintaining at least 1 SV in view at all times is necessary in order to maintain time transfer accuracy. In order to achieve 100% availability, a power threshold of -185dBW is necessary. A power threshold of -185dBW also proved to be the knee in the curve for dual channel operation. Accuracy improvement over higher thresholds was significant; however, reducing the threshold further showed little or no added improvement.

ACKNOWLEDGMENTS

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REFERENCES

IS-GPS-200; Navigation User Interface Control Document; Ionosphere Delay Parameters

J.D. Kronman; "Experience Using GPS For Orbit Determination of a Geosynchronous Satellite," Proceedings of ION GNSS 2003