Hot Start of GPS Receivers for LEO Microsatellites

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ABSTRACT

While spaceborne GPS receivers can in general be considered as a well established tracking tool for LEO (low Earth orbit) satellites, their use on micro- or nano-satellites may pose various problems from a systems engineering point of view. Representative examples include the mass budget, the lack of a suitable attitude stabilization system, antenna allocation problems, restricted command and telemetry links as well as limited onboard power resources. As a result of the latter constraints a discontinuous operation of the receiver is frequently required, which necessitates appropriate means for a hot (or at least warm) start of the receiver. To cope with these limitations, a signal acquisition aiding concept based on an analytical orbit model, which regularly calculates the approximate position and velocity of the receiver has been implemented inside the Orion GPS receiver. The receiver is based on the Mitel design information and the GP2000 chipsets. Data from the orbit model are used to compute the list of visible satellites and the expected Doppler shift for allocation and steering of the correlator signal tracking channels. In case of a temporary loss of track, the receiver is thus able to rapidly reacquire GPS signal and provide a navigation solution. Signal simulator tests for a LEO scenario demonstrated the 'hot start' capability of the receiver with a time to first fix (TTFF) of better than 20 seconds. Preliminarily results from the flight experiment onboard the microsatellite PCsat (Prototype Communication Satellite) also demonstrated rapid signal acquisition performance and 'warm start' capability of the receiver operating in LEO.

INTRODUCTION

After intensive research and development, GPS technology is nowadays widely applied as a navigation sensor for many existing and forthcoming space missions. The use of spaceborne GPS technology, especially in LEO (low Earth orbit) satellite missions has continued to be one of the major driving forces for the continuous effort in this field of research. Although the technology has been successfully applied in many LEO satellite missions, their use on micro- or nano-satellites may pose various problems from a systems engineering point of view. Such new generation of space platforms introduces a new set of constraints or limitations, such as a much more restricted mass budget, the lack of suitable attitude stabilization system, antenna allocation problems, restricted command and telemetry capabilities as well as limited onboard power resources.

These limitations have a direct influence on the overall performance of the GPS receiver. For example, the receiver may face difficulties in tracking GPS satellites continuously due to the uncontrolled attitude of the spacecraft, causing an unfavorable antenna orientation with respect to the GPS constellation. Limited exterior surface area and other mechanical restrictions, poses limitations on the selection of the GPS antenna and may results in a degradation of the received signal strength, thus affecting the receiver tracking performance. Last but not least, the limited onboard power resources, may lead to the frequent discontinuous operation of the GPS receiver, in favor to other primary mission payloads. For example, the GPS receiver onboard the German BIRD micro-satellite is required to be switched off when the onboard infrared camera is switched on due to power limitation. Such interruption to the operation of the GPS receiver may significantly affect the receiver signal re-acquisition process, due to the high dynamics of the receiver with respect to the GPS constellation. As a possible solution to this problem, the Onboard Navigation System (ONS) of BIRD operates a simple orbit propagator inside the onboard computer. Upon ground command, the ONS generates a state vector for the desired initialization epoch and transmits it to the GEM-S GPS receiver after power up. With almanac data stored in non-volatile memory, the receiver thus achieves a typical time to first fix (TTFF) of about 1 minute [1].

To better combat these limitations and to maximize the performance of the GPS receiver, a more advance approach has been taken, in which a signal acquisition aiding process is developed, implemented and tested on the Mitel Orion GPS receiver. The receiver is a L1 C/A code receiver with 12 tracking channels, it is developed at DLR based on the Mitel design information and employs a GP2021 correlator and an ARM60B 32-bit microprocessor. Originally designed for terrestrial applications, it has received numerous modifications and fixes to provide accurate and reliable tracking under the highly varying signal dynamics encountered in space applications [2]. Instead of relying on a separate navigation computer to execute the orbit model to provide the receiver with position and velocity in orbit, the current implementation will directly integrate the orbit model inside the GPS receiver. Such approach will eliminate the need for an external board computer and hence further minimizes the power consumption and the overall complexity of the system.

The signal acquisition aiding, which is based on the Doppler aiding concept greatly improve the receiver tracking performance in the case of signal re-acquisition and frequent discontinuous operation of the receiver. For example, a receiver operating in cold start mode in a LEO scenario, takes almost 25.5 minutes for TTFF [3]. Such long signal acquisition period is due to the high dynamics between the receiver and the GPS satellites, where the Doppler shift varies ±50 kHz (for a terrestrial receiver, the maximum Doppler shift is ±5 kHz). Such tracking performance will simply make the use of such receiver impossible due to the limitations stated above. On the other hand, the reduction of TTFF of a Doppler aided receiver will facilitate its operation and maximize its tracking performance under the influence of the above limitations. Depending on the GPS orbit information used in the Doppler aiding process, a 'warm start' is achieved when the GPS almanac information is available. A 'hot start' is achieved when the GPS satellite ephemeris is used in the Doppler aiding process.

Apart from a series of successful ground simulation tests using a signal simulator, the receiver is onboard PCsat (Prototype Communication Satellite) built by the United States Navy Academy, which launched into a 800km circular orbit in late September, 2001. Preliminary data demonstrated the receiver was able to rapidly acquire and re-acquire GPS signal during orbit and it is also able to perform a 'warm start' from the frequent discontinuation of receiver operation.

DOPPLER AIDING WITH ANALYTICAL ORBIT MODEL

The Orion GPS receiver employs a signal search process, which dynamically steers the signal tracking loops to search for the C/A code of a particular GPS satellite within a Doppler frequency search bin (the default bandwidth of the search bin is set at 500 Hz) [4]. Due to the relative motion between the GPS satellite and the receiver, the received GPS signal is Doppler shifted from its nominal frequency of L1 (1575.42 MHz). For a receiver in a LEO (altitudes of 300 - 1500 km) orbit, the incoming GPS signal will be significantly Doppler shifted (~ ±50 kHz) due to the high dynamics relative to the GPS constellation. Apart from that, the rate of change of the Doppler offset will be significant during orbit. With this large variation and large Doppler shifted signal, the signal tracking algorithm of the receiver will experience difficulties in initial signal acquisition and reacquisition in the case of temporary loss of track of a GPS satellite. This is because the signal tracking algorithm employed by the Mitel Orion GPS receiver begins searching the C/A code of a GPS satellite from a pre-defined frequency search bin. If no C/A code is found within this search bin, the signal search process will proceed to the next search bin, which is ±500 Hz away from the current search bin central frequency. The signal search algorithm cycles through all frequency search bins until the C/A code of the corresponding GPS satellite is found.

The bandwidth of the frequency search bin will ensure no C/A code is left undetected. A small frequency search bin will significantly increase the time required to search through the entire carrier frequency range. This is because the receiver takes about 4 seconds to perform a complete code search. A wider frequency search bin will lead to uncertainty in the C/A code detection process. In the case of a 'warm start', the receiver will search through a range of carrier frequency based on the maximum expected error in the receiver reference oscillator. In a 'hot start' or the receiver is already navigating, where the receiver reference oscillator error variance has been resolved from the navigation solution, the receiver will only search at ±250 Hz of the estimated carrier frequency (i.e. only search within 1 search bin). But in a 'cold start', the receiver will search through a frequency range, which consists of the maximum carrier frequency change, caused by the relative motion between the receiver and the GPS satellite plus the maximum expected error in the receiver reference oscillator [4].

Due to the rapid variation of the Doppler shifted GPS signal as received by the receiver in LEO, the efficiency of such sequential signal search technique will be significantly reduced and the amount of time required to locate the C/A code of a particular GPS satellite will be lengthened noticeably. To overcome this limitation, a Doppler aiding algorithm is implemented to steer the central frequency of the Doppler search bin with an estimated Doppler shift value calculated based on the results from the orbit model for the user satellite and the GPS satellite (almanac or ephemeris orbit model). Such enhanced signal acquisition technique will ensure the frequency search bin that contains the C/A code to be searched first, hence significantly shortening the TTFF. To facilitate a 'hot start' capability of the receiver, non-volatile memory of the GPS receiver will be used to automatically store a set of GPS almanac data and ephemeris data obtained during previous operation. Therefore, once the receiver is switched back on, it can rapidly acquire GPS signal by calculating the expected Doppler shift value of all visible GPS satellite based on the time given by the real-time clock in the receiver. In normal operation, the fit interval of the GPS ephemeris is 4 hours. Hence, the receiver must switch on and acquire the latest ephemeris data no longer than 4 hours from previous activation, in order to achieve 'hot start' for sequent operation.

The NORAD SGP4 analytical orbit model developed by Ken Cranford in 1970 from the SGP (Simplified General Perturbations theory) series has been selected to provide the receiver states vector (position and velocity) at a given epoch based on the NORAD twoline elements (TLE). This model is obtained by simplification of the more extensive analytical theory of Lane and Cranford (1969), which uses the solution of Brouwer (1959) for its gravitational model and a power density function for its atmospheric model. SGP4 assumes the mass of the satellite relative to the mass of the Earth is negligible. The satellite should also have a low eccentricity, near-Earth orbit and not be in a rapidly-decaying orbit along with an orbital period of less than 225 minutes. The gravitational model inside SGP4 includes zonal terms up to J_4 and the drag model assumes a non-rotating, spherical atmosphere. The complete SGP4 model, which is implemented in the receiver for Doppler aiding application, takes into the consideration of secular, long periodic and short periodic perturbations. Atmospheric drag and gravitation give rise to secular changes in the orbital elements. The satellite motion affected by long periodic perturbations depends on the argument of perigee. Short periodic perturbations caused by J_2, leads to the variation in argument of right ascending node and orbital plane inclination.

The maximum accuracy of SGP4 is on the order of 2 km for position and 2 m/s for velocity. To obtain maximum accuracy and consistent predictions from SGP4, it is necessary to use only the NORAD TLE which contains mean orbital parameters, that are obtained by removing periodic variations in a particular way from the osculating orbital parameters, that is defined by the SGP4 orbit model. Hence these elements must be reconstructed by the orbit model in exactly the same way they were removed in the generation process [5]. The NORAD TLE is available on the Internet and frequently updated depending on the rate of change of the mean orbit elements of the satellite, which makes the SGP4 model more attractive and convenient to operate during a mission. The long validity period of TLE, which is on the order of 1-2 weeks, without causing significant degradation of the model accuracy, makes the model more robust from an operational viewpoint, since the interval between TLE uploads can be maximized in the case of limited telecommunication capability onboard micro- and nano- satellites.

Fig. 1 illustrates the TLE validity period by calculating the change in Doppler prediction using different set of TLE of PCsat provided by NORAD (from 2001/10/26 to 2001/11/09). The difference in Doppler prediction with respect to the reference TLE increases as the age of the TLE increases. Significant difference is observed from the prediction by the 11 days old TLE and onwards. The 13 days old TLE introduced a maximum Doppler prediction difference of 612.2 Hz. Since the Orion GPS receiver has frequency search bin with a bandwidth of 500 Hz (±250 Hz), it is recommended that a once per week TLE upload strategy should be adopted, in view of Doppler prediction degradation and error in the receiver reference oscillator.

The consideration of atmospheric drag acting on an LEO satellite by SGP4 made it a better choice than other available simple analytical orbit models with no atmospheric drag modeling, such as the J2 propagator, the almanac orbit model and the broadcast ephemeris orbit model, which are used to describe the GPS satellite orbits. Apart from that, the readily available mean elements distributed in the form of TLE for the SGP4 model makes it much more convenience to work with than others. For example, it is very difficult to obtain orbital elements of a satellite for the broadcast ephemeris orbit models. And since mean elements of TLE are only suitable for use with SGP4 (as stated above), this makes SGP4 superior than other analytical models in terms of accuracy and availability.

Since SGP4 is an analytical orbit model, its allows the calculation of spacecraft's position and velocity at any given epoch in an orbit with a single computation process as compared with numerical models, which require to propagate in time until the desired epoch is reached. Despite the complexity of the SGP4 model, the computation burden on the processor is at a level, which is well suited for real-time application, to provide real-time position and velocity information of the receiver. Also for Doppler aiding application, the required accuracy of the orbit model is not required to be at the level achieved by numerical orbit propagators, since the predicted Doppler shift can be estimated to ±250 Hz (the bandwidth of the Doppler frequency search bin) with respect to the true Doppler value.

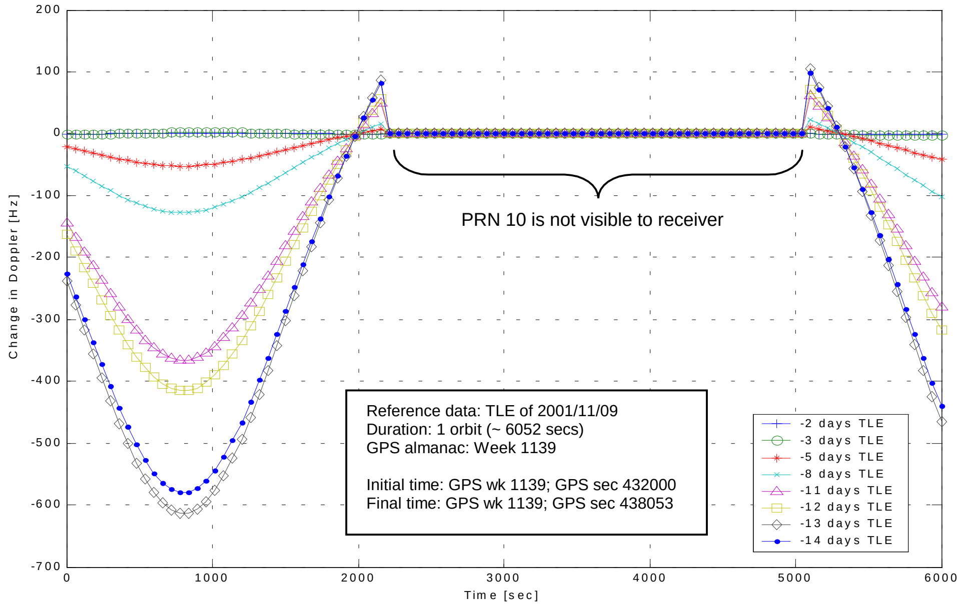

Fig. 1. Comparison of the change is Doppler prediction for PRN 10 using different set of TLE of the 800 km PCsat orbit

SOFTWARE IMPLEMENTATION

The software of the Mitel Orion GPS receiver is based on a task-switching operating system, where tasks are executed by the onboard processor according to their pre-defined priority and the specified activation time. Tasks with a high priority will be executed by the processor at activation time, while other tasks with a lower execution priority will be either suspended or interrupted by the operating system until the higher priority task is completed [4].

Based on this software architectural design, the SGP4 orbit model for the user spacecraft is implemented as a separate task, which is executed by the operating system at 16 seconds interval. The SGP4 task has the lowest execution priority, which minimizes the interference with other critical progresses inside the receiver, such as signal acquisition, measurement extraction and computation of navigation solution.

The NORAD twoline elements required as input for the SGP4 model are uploaded to the receiver via a command interface. Upon receiving the twoline element, the mean Kepler elements are extracted and computed along with the secular effects of atmosphere drag derived from the ballistic coefficient, which is also required by the SGP4 to model atmospheric drag acting on the satellite. Based on these mean orbital elements, the SGP4 model will compute the position and velocity of the satellite for a given epoch. The SGP4 task is only activated every 16 seconds. A simple state extrapolation routine is used to extrapolate the position, velocity and acceleration of the spacecraft in between two SGP4 updates to minimize the computational load on the processor.

The 16 seconds SGP4 task activation interval is found to have negligible impact on the Doppler prediction. Error analysis based on Taylor series expansion of the 3rd order position error and 2nd order velocity error for a 800 km circular orbit in 16 seconds, resulted in errors of 5.480 m and 1.028 m/s. Assuming maximum Doppler, the error in Doppler prediction due to these errors is only 5.402 Hz, which is well below the required accuracy of 500 Hz of the frequency bin width. The maximum activation interval of the SGP4 is found to be 150 seconds, where the error in Doppler prediction is 474.674 Hz. The use of a 16 seconds SGP4 activation interval will ensure a fast response of the receiver in providing Doppler prediction while it has small impact on the processor load. For example, the processor load of the receiver when it is navigating with 7 tracked satellites stays at 55% while SGP4 is activated at 16 seconds in the background.

Once the user satellite state is available along with the GPS satellite's position and velocity (calculated from the broadcast GPS almanac), the visibility of the GPS satellite with respect to the receiver can be estimated as a function of the relative position between them and the pre-defined elevation mask set in the receiver. The corresponding Doppler value of the received signal from visible GPS satellite can then be computed as a function of the range rate between the user satellite and the GPS satellite. To facilitate a 'hot start' of the receiver, a copy of the GPS almanac and ephemeris is stored on non-volatile memory of the receiver from previous operation. Upon activation, the receiver can readily compute the GPS constellation visibility and the corresponding Doppler value for those visible GPS satellites based on the stored GPS almanac data. The re-chargeable backup battery onboard the receiver can maintain data stored in the non-volatile memory for up to two months once it is fully charged. Hence a set of GPS almanac can be stored on the receiver prior to launch to ensure rapid signal acquisition once it is first activated in orbit. Once the Doppler information is available, it is feed to the receiver's signal tracking loops to steer the cental frequency of the frequency search bins. Fig. 2 represents the Doppler aiding algorithm and details the operation of the implementation.

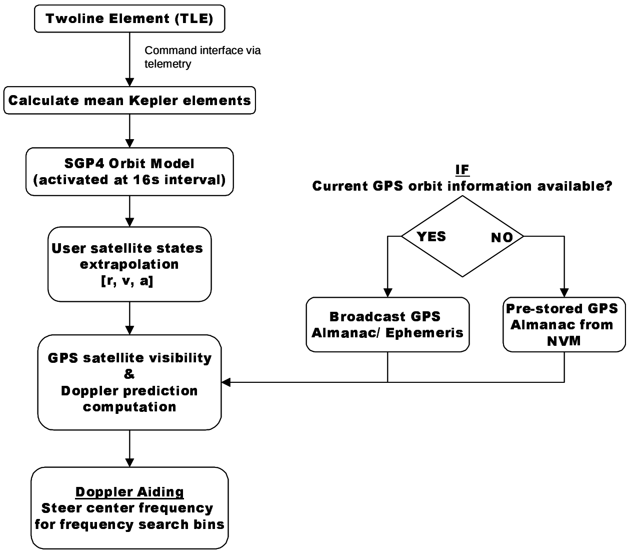

Fig. 2. Flow chart for the Doppler aiding implementation

GPS SIGNAL SIMULATION

A series of GPS signal simulator tests were performed to validate the Doppler aiding implementation and the overall performance of the receiver software in a LEO scenario. The scenario simulates the BIRD micro satellite, built by DLR, in a 550 km circular orbit, with an inclination of 97.6°. The satellite is modeled to have inertially fixed attitude, hence, the visibility of the GPS antenna is reduced during parts of the orbit (around 18h spacecraft local time) due to Earth shadow effect (see Fig. 3) [6].

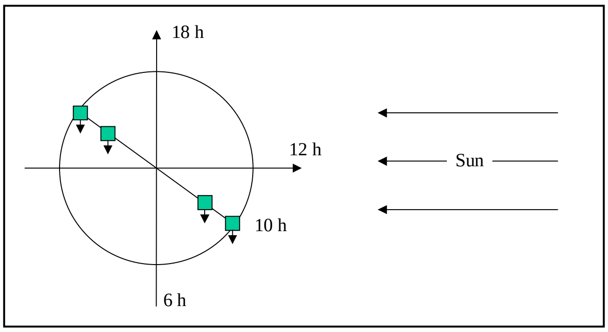

Fig. 3. The BIRD orbit plane as seen from the Earth's North Pole. The spacecraft arrow indicates an inertial orientation of the GPS antenna zenith towards 6h spacecraft local time

The STR2760 GPS signal simulator can simultaneously simulate 10 GPS satellites. The GPS signal generated by the simulator was radiated via a passive antenna. The receiver connected via an active antenna was located approximately 1.0 m from the transmitting antenna and the boresight angles of maximum of 60°. The software signal amplification was set at 12 dB, along with a dual stage hardware amplification (2 x 24 dB nominal), such setting will led to a signal-to-noise ratio (SNR) at the Orion receiver between 10 dB to 24 dB, which is realistic as in LEO environment. In the simulation both S/A and ionospheric propagation delay was not modeled, to allow a better understanding of the receiver navigation performance [7].

The performance of the Doppler aiding implementation and the 'hot start' capability of the receiver was validated by switching the receiver on and off during a simulation session to simulate the frequent discontinuous operation of the receiver onboard micro- or nano- satellite due to limited onboard power budget. A set of GPS almanac data was stored on the non-volatile memory of the receiver before the experiment and the clock of the receiver was set to simulation time. Upon activation, the receiver used this information along with the uploaded twoline element of the satellite to predict the Doppler shifted value for those visible GPS satellites and to steer the signal tracking loop of the corresponding tracking channel inside the receiver for signal acquisition.

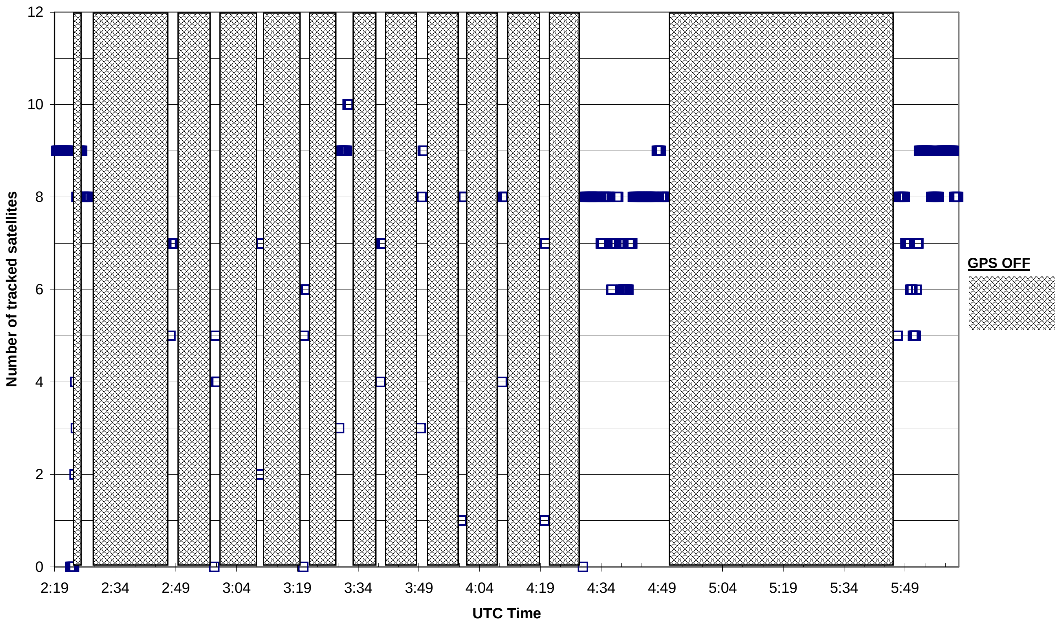

Fig. 4. A series of on-off tests were performed on the receiver with different duration. The receiver was able to rapidly reacquire GPS satellites signal and provide navigation solution once the receiver was switched back on

Fig. 4 illustrates the receiver's ability in reacquiring GPS signal from a series of discontinuous operation. In all occasions, the receiver was able to obtain 3D navigation by acquiring a minimum of 6 to a maximum of 9 satellites in 20 seconds after switched on. This observation applies to all off-on sequence with a different duration of deactivation, ranging from 1 minute to 57 minutes. This result demonstrates the 'hot start' capability of the receiver and its ability to very rapidly acquire large number of visible GPS satellites once it is switched on during orbit. The ability to provide 3D navigation solution within 30 seconds after switch on in orbit, will allow the receiver to operate even under the tightest onboard power budget scenario where the receiver is required to be switched off frequently to minimize power consumption.

In a separate 'warm start' test case, where the correct YUMA almanac, the TLE of the satellite and the time of the simulation were uploaded to the receiver with an elevation mask set at -15°. The receiver had 4 satellites in lock after approximately 70 seconds and achieved 3D navigation with 8 satellites in lock in approximately 1.5 minutes into the simulation. This observation demonstrates the Doppler aiding algorithm is providing the correct Doppler prediction to the signal search loops for initial signal acquisition.

MICROSATELLITE GPS EXPERIMENT

As part of the Kodiak Star mission, the PCsat satellite of the United States Naval Academy (USNA) was launched from Kodiak Island, Alaska, on September 30, 2001 (02:40 UTC). The Lockheed Martin built Athena 1 rocket carried a total of four microsatellites (PICOSat, Sapphire, PCsat and Starshine 3) with a combined weight of about

200 kg into orbit. PICOSat, PCsat and Sapphire were built under the Department of Defense Space Test Program (STP), whereas NASA provided funding for the Starshine 3 satellite. While the first three satellites were released into a circular orbit of 800 km altitude and 67° inclination, Starshine 3 was later on injected into a 500 km orbit after lowering the orbit in a series of upper stage maneuvers [8].

The Orion GPS receiver built by DLR/GSOC (see Fig. 6) is part of the experimental payload of the PCsat satellite mission. The satellite serves as a spaceborne extension of the terrestrial Amateur Radio Automatic Position Report System (APRS), which allows the distribution of position/status reports and short messages using handheld or mobile radios. The GPS receiver provides position and velocity information of the satellite, allowing users to locate the satellite with a handheld or mobile radio [9]. The aims of the GPS experiment are to validate the Doppler aiding concept, the tracking performance of the receiver in LEO and the overall performance of the receiver in terms of hardware and software. Due to limited surface area of the satellite, a monopole antenna is selected instead of a patch antenna (see Fig. 7).

PCsat has limited onboard power resources, the receiver is required to be switched off on most occasions to allow for the operation of the communication and telemetry system onboard. In routine operation, it is expected the GPS receiver will be switched on for a maximum duration of less than 9 minutes per orbit under favorable sun condition over USNA ground station. Since launched, the receiver has only been operated for a total of four passes, each with a duration of no longer than 9 minutes. Preliminary results show that the receiver is able to achieve a 'warm start' and produce 3D navigation solution by tracking a maximum of 12 GPS satellites. But due to the severe power and telemetry limitation, where the receiver is only switched on at most once per day, the 'hot start' capability of the receiver has not been validated at the writing of this paper.

Fig. 5 illustrates the tracking performance of the receiver at a 'warm start' on 2001/11/06 based on telemetry update at 30–60 seconds. Tracked satellite represents the ephemeris has been received by the receiver and the locked satellite represents the receiver may still acquiring the ephemeris for navigation but is already collecting pseudoranges. The receiver took about 4 minutes to obtain a 3D navigation solution. This significant delay in TTFF as compared with signal simulation results was largely due to the slow tumbling motion of the satellite and unfavorable orientation of the GPS antenna, which caused difficulties for the receiver to maintain lock onto those visible satellites [7]. In addition, the monopole antenna plus 27 dB pre-amplifier configuration resulted in an average SNR of only 10 dB, such low signal strength had significantly reduced the receiver tracking performance.

Based on the observation in Fig. 5, assuming ephemerides of the GPS satellites are available to the receiver at activation for a 'hot start', the receiver could obtain 3D navigation solution within 60 seconds after switched on. This proved that the Doppler aiding algorithm is assisting the receiver in signal acquisition as expected but due to the limitations posed on this experiment, the performance of the receiver cannot be fully validated at this stage.

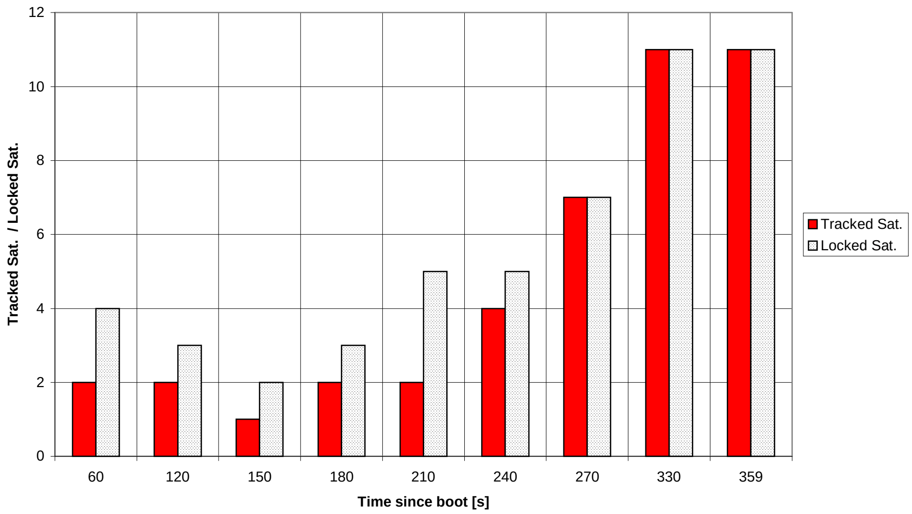

Fig. 5. GPS receiver track log (2001/11/06)

Due to the very limited power budget, which severely limited the operation of the GPS receiver, no conclusive observation of the receiver's performance can be obtained at this stage of the experiment. It is expected in early January next year, increase in the satellite power budget due to improve sun condition over USNA ground station, a more detail study of the 'hot start' performance of the receiver can be realized.

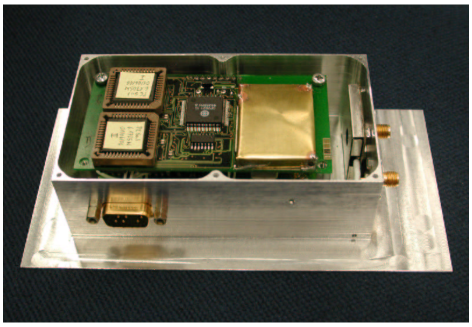

Fig. 6. Orion GPS receiver (PCsat flight unit)

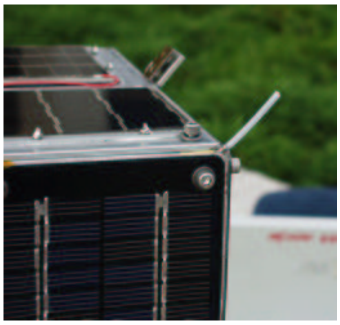

Fig. 7. Monopole antenna (λ/4) for GPS reception

CONCLUSIONS

Limitations in micro- and nano- satellites operation, introduces many challenges to the use of GPS receiver onboard these new breed of space platforms. To combat these limitations and to increase the performance of the receiver, a Doppler aiding algorithm using the SGP4 orbit model is implemented into the Orion GPS receiver built by DLR/GSOC. Such aiding process will ensure very rapid GPS signal acquisition and reacquisition. Along with non-volatile memory support from the receiver, the 'hot start' capability can be achieved, where the receiver can significantly minimize the TTFF even after a long period of deactivation (depending on the validity of the stored GPS ephemerides, which is on the order of 4 hours during normal operation). Such capability will greatly increase the operational flexibility of the receiver and overcome many major system limitations when operating onboard micro- and nano- satellites. Simulation results demonstrated the 'hot start' capability of the receiver, achieving a TTFF within 20 seconds after switched on by tracking a minimum of 6 to a maximum of 9 GPS satellites. Due to the very limited power resources onboard PCsat, the receiver was only tested for its 'warm start' capability at this stage of the experiment. In a 'warm start' of the receiver, significant delay in TTFF (about 4 minutes) was observed, which was attributed to the slow tumbling motion of the satellite, unfavorable antenna orientation and low SNR. No conclusive statement can be made on the 'hot start' performance of the receiver due to limited information available at the writing of this paper. More detail studies of the performance of the receiver are planned once the sun condition over USNA ground station has improved.

ACKNOWLEDGMENT

The authors would like to gratefully acknowledge Kayser-Threde GmbH, Germany for providing the GPS signal simulator and the United Stated Naval Academy for providing the flight opportunity of the PCsat mission.

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