Tracking the Relative Motion of Four Space Payloads Launched from a Sub-Orbital NASA Rocket

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BIOGRAPHIES

Mr. Martell is President and co-founder of Waypoint Consulting Inc. Mr. Martell has eight years of experience in GPS software development. His current interests lie mainly in the area of high dynamic GPS applications. He received an M.Sc from the University of Calgary, Department of Geomatics in 1993.

Mr. Bull is an Electrical Engineer in the Guidance, Navigation and Control (GN&C) Center of NASA's Goddard Space Flight Center. Mr. Bull's primary responsibilities are in development of GPS systems for sub-orbital payloads on balloons and sounding rockets. He received a BS degree in Aerospace and Ocean Engineering from Virginia Polytechnic Institute and State University in 1980.

ABSTRACT

One problem, which is comparatively new in the field of GPS applications, is the determination of the relative trajectories of space vehicles. Applications include the docking of spacecraft, collision avoidance in the area of space stations, and trajectory reconstruction of multiple payloads. The required precision in any of these applications will vary, according to the requirements of the task and abilities of GPS to cope with the environment and the dynamics.

This paper describes the post-mission reconstruction of the relative trajectories of four GPS receivers attached to four payloads jettisoned from a rocket in a sub-orbital NASA science mission. It is shown that relative payload to payload coordinate accuracies at the sub-decimetre level were achieved with single frequency GPS receivers.

INTRODUCTION

This report describes the use of moving baseline software in tracking post-mission, the relative trajectories of 4 Ashtech G12 HDMA GPS receivers attached to payloads jettisoned from a Black Brant XII rocket. This vehicle was launched by the National Aeronautics and Space Administration (NASA) in January 1999 from the Poker Flats Research Range near Fairbanks, Alaska. The Black Brant XII is a sub-orbital rocket designed to carry payloads from 100 to 500 kg into space. Flight time is generally in the 10 - 20 minute range, with maximum altitude of up to 1500 km. Down range flight distances are in the order of 500 – 1000 km. Waypoint Consulting's GrafMov software was used to process code and phase measurements from the 4 on-board GPS receivers, on order to determine to high relative accuracy the trajectories of the 4 payloads with respect to each other.

Personnel from the Goddard Space Flight Center Wallops Flight Facility (GSFC/WFF) in Virginia are responsible for the overall management of the NASA Sounding Rocket Program. These are generally scientific missions returning a variety of scientific data including; chemical makeup and physical processes taking place in the atmosphere, natural radiation surrounding the Earth, data on the Sun, stars, galaxies and many other phenomena. In addition, sounding rockets provide a reasonably economical means of conducting engineering tests for instruments and devices to be used on satellites and other spacecraft prior to their use. Along these lines, there is a large potential in the idea of using GPS for absolute and relative tracking of space vehicles.

MISSION DESCRIPTION

The subject mission was unusual in that the payload consisted of four separate sections, the Optical Sensor Package (OSP), the Plasma Diagnostic payload, (PDP), and two exploding portions (ETG-1 and ETG-2). After booster burnout and jettison, the four sections separated and the two ETGs exploded whereupon instruments in the other sections measured quantities of interest.

The receivers used were all based on Ashtech G12-HDMA engines, with power and interfaces designed and packaged for the missile environment by personnel from the Guidance Navigation and Control Branch of GSFC/WFF. Each payload uses an eight-element microstrip wraparound antenna.

In this particular flight, the rocket traveled about 850 km in a northerly path while drifting some 50 km to the west. The maximum altitude of the vehicle was approximately 350 km. Figure 2 illustrates the maximum absolute velocities achieved by the rocket and payloads. These were on the order of 2000 m / s in the north and vertical components.

Of primary concern in relative processing of the payloads was the ability of the G12 High Dynamic Missile Application (HDMA) receivers to maintain phase lock under the high acceleration and velocities experienced by the spinning rocket. If carrier phase lock could be maintained, the next question was whether there was sufficient data in the 120 –180 seconds from liftoff to payload separation to perform Kinematic Ambiguity Resolution (KAR) from one GPS receiver to the next in the payload chain. If KAR could be initiated successfully before the payload jettisoned from the rocket, then a strong indicator of the GPS relative accuracies could be provided by examination of the GPS derived distances computed from one payload antenna to the next.

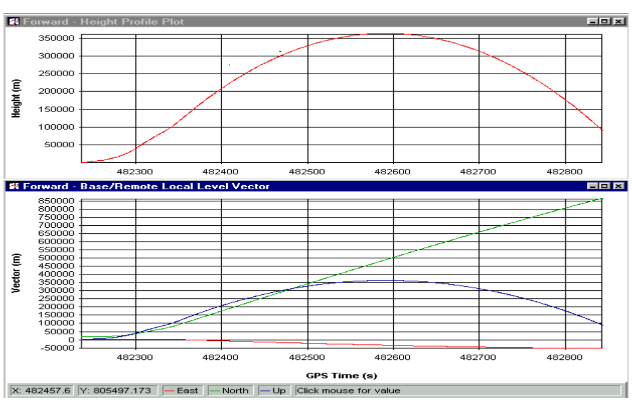

Figure 1:
Horizontal and Vertical Coordinates with respect to the Fairbanks Base Station

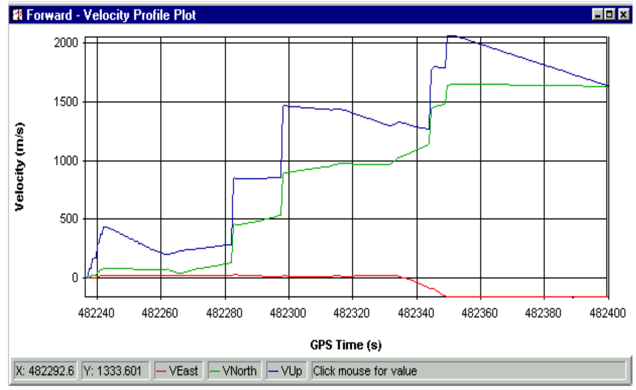

Figure 2: Rocket Absolute Velocity Components

Relative Processing

The principal concern of this report lies in reconstructing the relative trajectories of 4 payloads which separated from the rocket between GPS times 482366 and 482406, at altitudes ranging from approximately 150 – 220 km. The G12 receiver on payload OSP was used as the base station. The relative velocity and position from OSP to the remaining 3 payloads were computed from liftoff through loss of telemetry due to explosion or horizon masking of the telemetry antenna.- During the flight and prior to separation, an error analysis of the relative accuracy from antenna to antenna can be obtained by computing the relative GPS-derived antenna offsets between the receivers from liftoff to payload spin-off.

The GPS-computed antenna distances can be directly compared to the nominal distance separation from one payload antenna to the next as given by a plan of the rocket configuration. For instance, the nominal distance from OSP to the antenna on payload ETG1 was given as 3.23 m from plans. During flight it is possible to re-compute from GPS-derived coordinates the antenna to antenna distances at each epoch. These computed distances can then be compared against the nominal as a measure of the relative GPS precision throughout the mission.

Error Analysis – Liftoff to Payload Separation

The following graphs depict, epoch by epoch, the computed relative distances between antenna OSP and the other 3 payload antennas, ETG1, ETG2, and PDP1, while the rocket was climbing to an altitude where the individual payloads were launched from the carrier. During this phase of the mission, a period of 2 to 3 minutes following liftoff, the antennas are at a fixed and known distance from each other. The maximum antenna separation, OSP to ETG1 was approximately 3.23 m. The minimum distance was 1.03 m, from OSP to antenna PDP1.

Two items should be mentioned here. First of all, the fixed antenna separations given here are nominal. They are derived from plans, not measurements. The preferred method of finding the actual distances between the phase centres of these antennas would be to compute them just prior to launch. Unfortunately there was very little data available on the launch pad. The data that was logged while the rocket was on its stand is affected very badly by multi-path. Code residuals of up to 10 m are prevalent while the rocket is in the launch position. One further complication lies in the fact that these antennas are composed of thin bands some 44 cm in diameter and 15 cm wide. These bands wrap around the outside of the rocket surface. Consequently, the phase centre of the antennas is not well known. Although it is difficult to estimate the actual accuracy with which the nominal fixed separations have been determined, it is felt that they are known to the nearest 5 cm.

Figure 3 illustrates the GPS-computed distance derived from measurements at each epoch following lift-off through separation of ETG1. The nominal distance from OSP to the ETG1 payload antenna is 3.23 m. There are a number of things to notice about the plot. The first is that just after liftoff, the coordinate accuracy obtained from GPS is basically off the scale for a few seconds. It is most probably at the 5 m level. This is not surprising given first of all the serious multi-path on the launch structure and secondly the sudden high acceleration and vibration occurring at this stage.

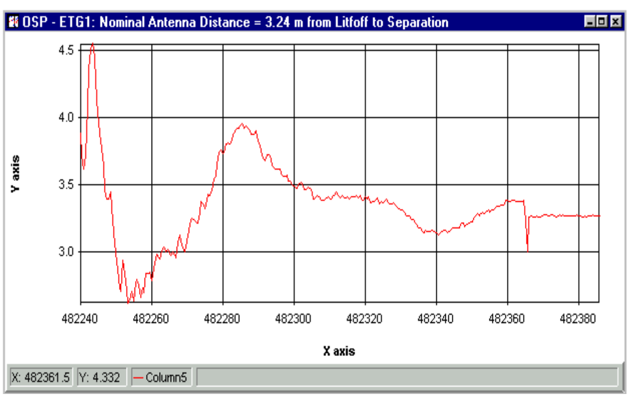

Figure 3: GPS-Derived Antenna Distance on Relative Baseline OSP-ETG1 from Liftoff to Payload Separation

This plot basically can be broken up into two distinct sections delineated by the "spike" at GPS time 482366. This spike is caused by a loss of lock in the phase tracking loop. The reason for loss of phase tracking at this point is not known, however in response to this GrafMov immediately attempts to re-resolve the phase ambiguities and at GPS time 482371, the program successfully performs Kinematic Ambiguity Resolution (KAR). The GrafMov program "restores" the fixed ambiguities back in the data set as far as possible. Unfortunately, the loss of lock 5 seconds prior to KAR is not bridgeable in terms of transferring the ambiguities backward in time. The spike in the plot is a result of the sudden change in coordinates due to the imposition of integer ambiguities at that time.

To elaborate on the explanation above, the coordinates from liftoff to GPS time 482365 are the results of a "floating ambiguity" code and phase solution. The precision here is limited by the non-integer nature of the phase ambiguities. On the other hand, the coordinates from GPS time 482371 to separation at 482386 to detonation at time 482580 are the results of a fixed ambiguity solution on the fly. In Figure 3, this processing dichotomy is clearly visible. The GPS derived antenna separation prior to the spike at 482366 varies in amplitude by about 1 m. On fixing the phase ambiguities, it can be seen on the far right hand side of the graph that the antenna distance stabilizes at a constant value of 3.27 m.

The bottom line in this analysis is that the GPS-computed antenna separation should nominally be 3.23 m. In other words, Figure 3 should plot a horizontal line crossing the Y axis of the graph at a value of 3.23. In actuality, it can be seen that the "float" solution portion of the graph has an average value of approximately 3.1 m with an amplitude of about 1 m.. The fixed solution section of the plot shows up as a more or less constant horizontal line representing a computed antenna separation of 3.27 m, or an error of 0.04 m in the GPS derived baseline. It can then be stated that as the payload separates from the rocket, the relative GPS solution is accurate to the sub-decimetre level. Furthermore, as long as the payload maintains phase lock after being jettisoned from the rocket, it can be assumed that this level of accuracy is maintained, at least on a short baseline, say less than 5 km or so. Figure 4 shows that phase tracking was maintained in a relatively clean and unbiased fashion for the large duration of this flight, at least in a relative sense. Recall that both GPS receivers will undergo the same dynamics and certainly experience the same common mode errors on the short, indeed very short baselines found in this experiment. High G-forces and vibration experienced by the individual GPS units are probably cause for the most concern in this type of environment.

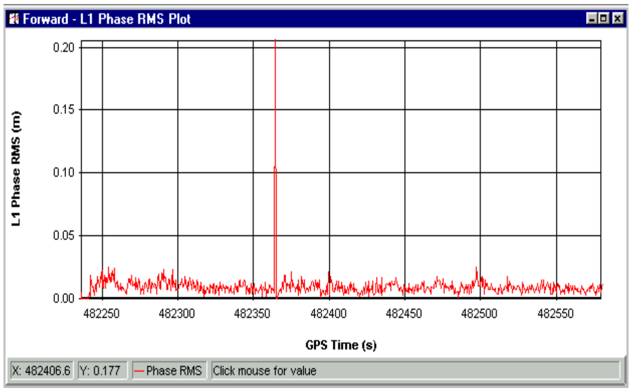

Figure 4: OSP-ETG1
RMS Residuals on the Phase Measurements for the Entire Flight

The Figure above is a depiction of the RMS L1 phase residuals for the entire flight. Once again, the loss of phase lock or cycle slip at GPS time 482366 is clearly visible, as an anomaly in the plot. Otherwise, the data is remarkably clean considering the nature of the mission.

A similar analysis, from liftoff through the jettison point, was performed for OSP to ETG2, as well as OSP to the PDP1 payload antenna. Figure 5 presents the results for the baseline between OSP to ETG2 existing while the rocket was a single rigid body.

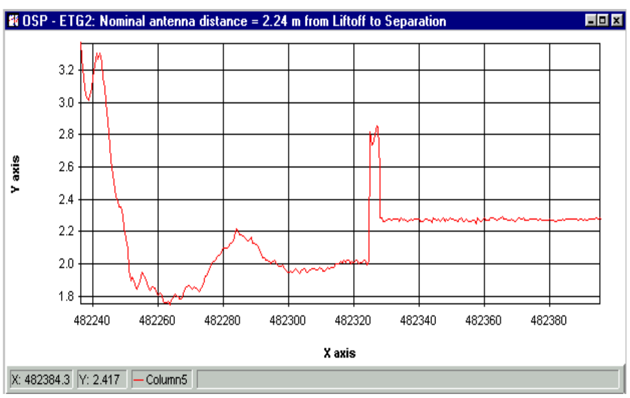

Figure 5: GPS-Derived Antenna Distance on Relative Baseline OSP-ETG2 from
Liftoff to Payload Separation

Figure 5 can be analysed in exactly the same manner as was given for the first relative baseline from OSP to ETG1. A float code and phase solution is available until GPS time 482326.5. The spike plotted at that time is largely a function of the on the fly ambiguity resolution at that point. The float solution can be seen to converge in a general sense to the "true" baseline distance of 2.24 m. When the L1 phase ambiguities are resolved, the baseline length remains at a more or less constant value of 2.28 m until the payload is released from its bay. Just as in the first relative baseline, the computed distance is 0.04 m short of the distance derived from plans.

The extrapolation that can be made from the baseline distance graph presented above is that, if phase lock is continuously maintained after payload separation it can be assumed that the relative coordinates computed from OSP to ETG2 are accurate to decimetre level. Figure 6 indicates that lock was actually only maintained until GPS time 482575, some 3 minutes after the ETG2 payload separated from the main rocket.

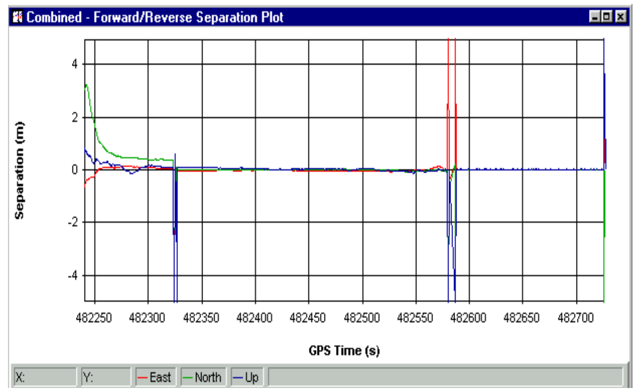

Figure 6: Differences between Processing in Forward and Reverse Directions in Time
On Baseline OSP – EGT1

The graph above is a plot showing the coordinate differences between the data processed in forward and reverse directions. These are independent code and phase solutions, one processed forward in time beginning at liftoff and one processed backwards in time from a point just prior to breakup on reentry. The close agreement between GPS times 482326 and the end of the trajectory is a function of the ability of the software to resolve ambiguities during almost all of that period in the trajectory. The discontinuities seen in the plot at these times are a result of losses of phase lock at these points. Prior to time 482326 and roughly at GPS time 482575, the relative coordinates are a result of a float solution accurate to the 1 –5 m level, depending on data noise. During the period for which ambiguities were resolved in both the forward and backward process, it can be assumed (within limits) that the relative baseline from the OSP payload to the ETG2 payload is computed to sub-decimetre precision, whether fixed to the rocket or separated from it.

The third and final relative baseline in this mission was computed from antenna OSP to payload antenna PDP1. This baseline posed the most problems in processing, partly due to phase noise possibly caused by vibration on the PDP1 GPS oscillator, and partly due to a significant data dropout from time 482289 to 482331, likely caused by loss of telemetry on ETG2 .

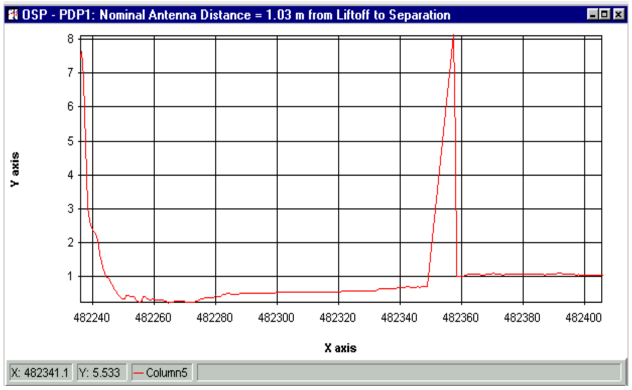

Figure 7: GPS-Derived Antenna Distance on Relative Baseline OSP-PDP1 from Liftoff to Payload Separation

Despite the noise in the data, including the large data spike at time 482355, on the fly KAR solution was still made at GPS time 482358. The fixed rigid baseline plot from liftoff at GPS time 482236 to payload jettison at time 482406 is presented above.

The nominal relative baseline length from OSP to the PDP1 payload antenna is 1.03 m. Note the data gap represented by the straight line beginning at GPS time 482289. It can be seen that the code and phase float solution above agrees with plan to the sub-metre level until successful ambiguity resolution . At that point the computed baseline distance matches the plan baseline separation to the nearest few centimetres. Both the float and fixed ambiguity solutions present in the first two baselines show considerably less data noise then is found in this last baseline. Figure 8 illustrates this phenomena.

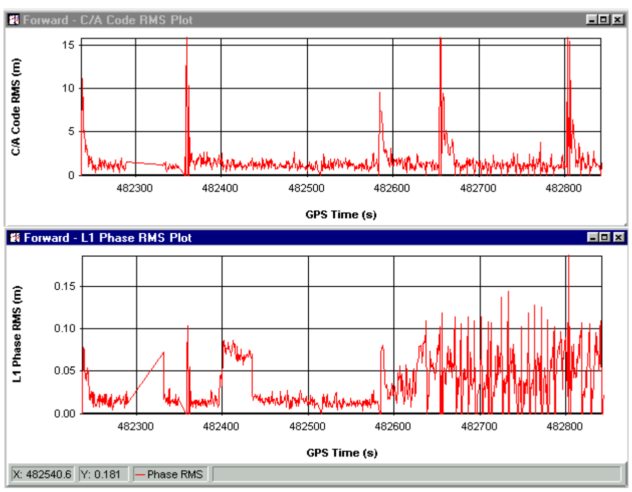

Figure 8: Plots of the RMS Code and Phase Residuals for Baseline OSP to PDP1

The reason for the extremely high noise in the L1 phase residuals following payload separation is unknown. Note also the telemetry dropout is shown very clearly, as well as spikes in both code and phase at intervals throughout the mission.

Payload Separation to Reentry

An error analysis of the probable, extrapolated accuracies for the relative GPS positioning before and after payload separation has been performed above. The graphs below depict the coordinate behavior of the payloads with respect to the OSP antenna, after the other 3 payloads were released from their bays in the main rocket and allowed to drift through space and then reenter the atmosphere, or be detonated as the case may be.

It can be seen that relative to the antenna attached to payload OSP, all of the other payloads headed in a westerly direction at approximately 5 m/s. In addition, in all cases there was a slight drift to the north and downward at about 1 m/s. Time for free flight of the payloads was 214 seconds for ETG1, 331 seconds for ETG2 and 438 seconds for PDP1.

The analysis above demonstrates that coordinate accuracy in free flight for baseline OSP to ETG1 is expected to be at the decimetre level. Baseline OSP to ETG2 is thought to have similar accuracy until loss of lock at GPS epoch 482575, 179 seconds into its free trajectory. Following this, the baseline coordinate determination is felt to be accurate to the 1- 2 m level until destruction 152 seconds later.

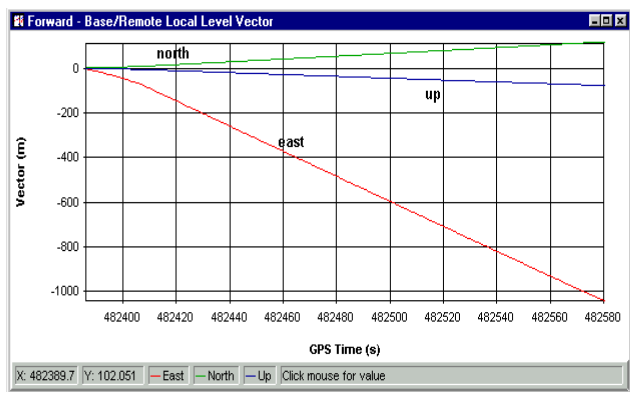

Figure 9: Relative Coordinates OSP-ETG1 Following Separation of ETG1 from the Rocket

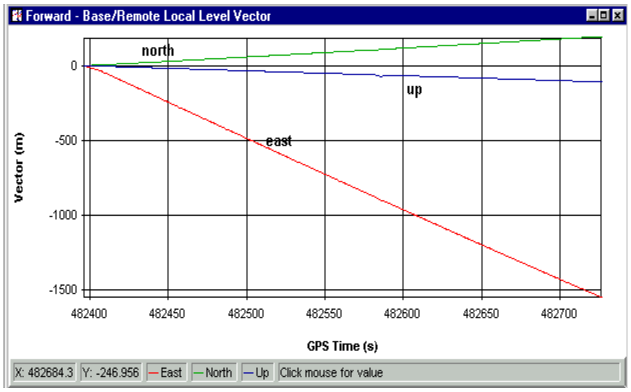

Figure 10: Relative Coordinates OSP-ETG2 Following Separation of ETG2 from the Rocket

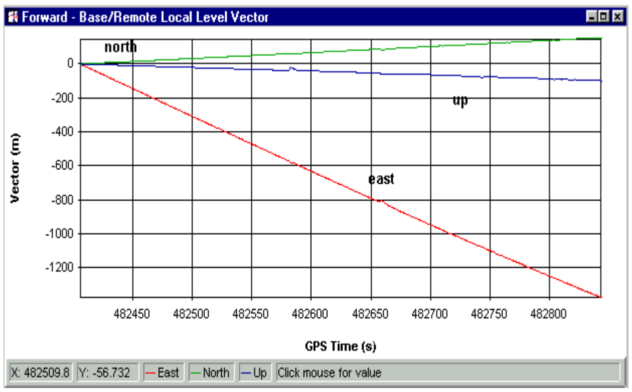

Figure 11: Relative Coordinates OSP-PDP1 Following Separation of PDP1 from the Rocket

The free trajectory for the relative computations on the baseline from OSP to PDP1 is the result of a float solution with noisy data and is likely only accurate to the 1 – 2 m throughout the mission.

Conclusions

Relative processing has been performed for a series of payloads launched into space from a sub-orbital rocket under the direction of the National Aeronautics and Space Administration. The GPS receivers in place were Ashtech G12 HDMA series receivers. The software used to post-process the GPS data was Waypoint Consulting's GrafMov product. Despite absolute velocities in the order of 2500 m/s, high G-forces experienced in the rocket burns, and a spin rate of 4 Hz, the G12 receivers tracked phase measurements in a fashion which allowed single frequency on the fly ambiguity resolution for a significant portion of the mission. Those parts of the mission which relied on only code and phase floating ambiguity resolution were still deemed to be accurate enough for the science involved in the mission. In the results presented above, it can be seen that based on comparisons of the known fixed distances of the GPS payload antennas with respect to plans, the precision of the relative coordinates can be shown to be at the sub-decimetre level, provided ambiguity determination can be successfully invoked on the fly. More research still has to be performed on the behaviour of the GPS receivers in this very high dynamic environment, but it is felt that given the results achieved here, high precision space vehicle to space vehicle GPS processing is possible and practical.

ACKNOWLEDGEMENTS

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