GPS TRACKING FOR SMALL SOUNDING ROCKETS

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ABSTRACT

The middle atmospheric region (~40 to 140 km) is too low to be directly probed by satellites and too high to be probed by research airplanes or high altitude balloons. Sounding rockets are the only vehicle that can carry instruments for *in situ* measurements. Up until now only a few methods have been available to track the location of a sounding rocket - radar skin tracking, radio beacon tracking, and inertial reference platform tracking. In this paper a joint NASA - Utah State University (USU)/Space Dynamics Lab (SDL) project to develop a Global Positioning System (GPS) based solution for tracking small sounding rockets (10D DARTs to be specific) in the middle atmosphere is presented. The size of the DART casing and the acceleration created by the booster present various obstacles in the implementation of a GPS receiver. Rockwell's Jupiter GPS receiver designer's kit has shown that it is capable of overcoming these obstacles. Test results reveal the Toko DAK series dielectric patch antenna in an active, back-to-back configuration in conjunction with the aforementioned receiver will provide tracking for DART flights.

I. Introduction

A. History

There are various means of observing phenomena in the "middle atmospheric region" defined as the area from about 40 km up to 140 km above the earths surface, but the majority of them take place from the ground. Observations have been made from space vehicles orbiting above this region, but satellites cannot effectively maintain orbits within the region due to the drag that rapidly terminates their missions. Balloons, research airplanes and other similar vehicles cannot attain a high enough altitude to make measurements within the region.

The critical element of observation that is missing from the previously mentioned methods is the element of "being there" or having an "in-situ" measurement device. Ground stations, along with all the other previously mentioned methods make remote observations. For truly high resolution, in-situ measurements, sounding rockets are the only option available [1].

The short duration of sounding rocket flights has made this type of observation very expensive when compared to remote based observations. Research has been done at USU/SDL and NASA Goddard Space Flight Center to develop a low cost sounding rocket for making measurements in the middle atmosphere [2]. The research team has thus set out to provide an economical means for accomplishing this task by creating a standard payload for the "housekeeping" aspect of the rocket, while allowing a well-defined space in the rocket for science experiments. The key issue in the design goals for this research is a method of tracking the rocket during flight.

Using a commercial vehicle produced by Orbital Sciences called a 10D DART along with a Viper III booster, the research team has put together a very inexpensive skeleton for the rocket. In order to keep the system highly modular and cost effective, miniaturized electronics are used in the housekeeping and lighter than usual payloads are placed in the science section. Thus researchers can have multiple rocket launches for the same cost it would normally take for a single flight using traditional methods.

The focus of my research in the scheme of making small sounding rockets cheaper and more flexible for scientific observation is to examine tracking issues. Obviously the researcher wants to know the location within the middle atmosphere at which his instruments are located when they take data samples. Once again, traditional methods are fairly confining or expensive - or both - in one way or another. Two methods are typically used by NASA to track sounding rockets - radar skin tracking and radio beacon tracking. Both are costly in terms of ground station facilities. Radar skin tracking requires a radar and the manpower to support the

operation. This is an expensive proposition and limits the scientist to making observations where there is an established range. Also, the high velocity and small cross-sectional area of the sounding rockets in general make tracking them with radar a bit of a challenge in and of itself. The method of beacon tracking has its challenges as well. It also requires a tracking receiver system at an established launch range. Antennas are required on the vehicle for the transponder, which must also be included in the payload, both of which are an issue for a small rocket in terms of power and available space.

The possibility of using GPS offers a much simpler alternative for determining the actual trajectory of a sounding rocket. With recent improvements in GPS receivers, miniaturized, inexpensive models are available that make tracking for the DART possible as proposed in this paper. Integrating a self-contained receiver and antenna into a sounding rocket would theoretically enable the determination of position to be done in real-time without reliance on expensive radars or receivers. Thus, not only would researchers have an inexpensive, easy to build, modular rocket, but it could be flown basically anywhere that had enough area to support such a flight without concern for existing tracking facilities.

At face value, one might be concerned about accuracy when considering a GPS solution for tracking. Using the civilian Course/Acquisition (C/A) code without Selective Availability (S/A) turned on, errors are estimated to be a nominal value of 22 meters in a three dimensional sphere [3], but can get as high as 300 meters [4] with S/A turned on. This performance can be improved to within 10 meters of error if a Differential Global Positioning System (DGPS) is used. DGPS is accomplished with a "base station" receiver providing corrections to the active receiver.

While DGPS might make the accuracy of each individual measurement more accurate, further inspection of the task leads us to believe that this may not be necessary. The relatively well-defined and smooth trajectory of the rocket provides additional information to the manipulation of the positional data, reducing the effect of the errors introduced by using the C/A code (versus the more precise P-code), let alone having S/A turned on. The accuracy, therefore, does not present any concern in our application, as the predicted error is at most the same as that introduced by remote radar skin tracking, which is sufficient for most scientific studies of the middle atmosphere.

B. GPS Basics

The positional solution provided by GPS is basically a situation of having four equations with four unknowns. The receiver gathers information from at least four satellites and is then able to solve the equations. The satellites provide ephemeris data and a very precisely timed signal that determines the "range" or distance to that particular satellite. Knowing where the satellites are and how far the receiver is from the satellites allows the receiver to calculate its own position. The range terms actually include errors due to atmospheric, ionospheric, and hardware noise sources, and thus the receiver actually uses "pseudorange" values in its calculations.

Typical GPS receivers vary from one manufacturer to another as far as what type of information they are capable of providing to the end user. The information that the GPS receiver extracts is put into "packets". Of the available packets, the user can select which ones are actually communicated by the receiver to the user, allowing him to control how much information is actually produced by the receiver for the purpose of analysis.

One of the problems associated with using GPS receivers for sounding rockets and spacecraft is that governmental export regulations require commercial models to have limitations built into the firmware such that they will not calculate valid positional solutions (latitude, longitude, altitude, and user time) at altitudes greater than 30 km and velocities greater than 950 m/s in order to protect national security. It is these commercial receivers which have received the greatest development efforts from industry, and are small and cheap enough to allow our proposed application to be developed. The "software locks" can be turned off for U.S. Government applications, given the cooperation of the specific receiver manufacturer. Because of the mass production of receivers, the manufacturer generally requires a hefty sum of money to make a receiver without the software locks, or else require the customer to purchase a large quantity to justify changing the standard production line setup. Some manufacturers, however, don't even entertain the idea of producing receivers without software locks, as they try to avoid any legal complications that might arise.

With the inherent complexity in having to use raw pseudorange measurements to calculate positional solutions for the receiver, we initially planned on getting a receiver with the software locks turned off. This would allow for valid positional solutions to be calculated for the entire flight. Since NASA was the entity that actually purchased the receivers, making a request to

have the software locks turned off was within standard protocol. We were not successful, however, in reaching this goal.

II. The Receiver

A. Selection of the Receiver

The first and foremost issue for selecting a GPS receiver for the small DART rocket was size. The 10D DART has an inner diameter of less than 2-1/8 inches, which severely limited the potential models from which to select. Beyond compact size, other desirable characteristics for the receiver included: low power consumption, active and passive antenna configurations, and, in the event of relying on raw pseudorange measurements, ease of extracting the pertinent positional information.

The literature accompanying the Rockwell Jupiter card does not mention anything about providing ephemeris data directly upon request, but after some experimentation on our own, we found that this information is embedded within one of the messages able to be requested, and by manipulating this message correctly, ephemeris data can be obtained. The Junipers' message packet adheres to the IEEE binary floating point format (with inherent scaling factor), making the aforementioned ephemeris manipulation fairly straightforward. The architecture of the Jupiter allows for 12 channels to simultaneously track satellites - easily enabling an over-determined solution. Lastly, be it an oversight on the part of Rockwell or simply our good fortune, the Rockwell receiver provides raw pseudoranges even when the software locks are activated. This enabled us to have the flexibility we needed to accomplish our tracking goals for the project.

One minor inconvenience that has been found with the Jupiter is the fact that it will only accept an initialization velocity of up to 300 m/s. This has proven to slow the re-acquisition process for the receiver after losing lock due to launch conditions.

B. Goddard Facilities

Roger Hart, an aerospace engineer at NASA Goddard Space Flight Center, orchestrated the testing scenarios and facilities. The first testing that took place happened with real satellite signals. Then the Northern Telcom GPS Simulator was used to simulate various test scenarios. This very expensive piece of hardware had the capability of producing multiple simultaneous GPS signals such that when plugged into the receivers antenna, the receiver responded as if receiving signals from real satellites.

As an additional check performed at Goddard, the receiver was subjected to the shaker table test. This was an effort to see how the receiver hardware would respond to the physical stresses encountered during a typical flight. Although there were some complications due to faulty connector configurations, the receiver performed marvelously. The tests consisted of "sinusoidal" shakes, and one, two and three dimensional tests up to 20 g's in all directions. One hint of caution suggested by Roger, however, is that the actual parts on the receiver board may need to be glued down to prevent any chips on the board from breaking a solder connection.

C. Preliminary Simulation Scenarios and Results

Once the basic operation of the Jupiter card was verified, scenarios were systematically created to test one specific aspect of the receiver in order to better define how the software locks were implemented and how the receiver would perform under flight conditions. The tests included the following: the velocity limit, the altitude limit, and the acceleration limit (Doppler shift limit). Once these had been explored, we made various combinations of them to eventually arrive at the desired flight scenario.

Throughout the testing process, as long as no other limit was surpassed, the receiver consistently remained locked up to velocities of 7,500 m/s. The altitude limit showed similar results under the same conditions of exclusive limit violation testing - it basically was only limited by the altitude of the GPS satellite orbital altitude. The acceleration simulation proved that the receiver could withstand 10.2 g's. Through our testing, we were able to conclude that Rockwell's software locks are activated when both the velocity and altitude are surpassed simultaneously.

D. Flight Simulation Scenario and Results

After modifying the representative trajectory given in the NASA Review Package for the DART 94.1 Plasma Dynamics Payload [5] to meet the scenario format criteria for the simulator, the receiver was tested for its ability to stay locked for the entire trajectory. This modification resulted in a reduction of the launch acceleration experienced by the receiver during the initial seconds of takeoff by roughly a factor of four.

Not to our surprise, the receiver lost lock very close to launch, as the g-force was too great for the physical capabilities of the receiver. By the time the rocket had recovered from the g-force shock (with no help from us),

it had surpassed the altitude limit and would not re-acquire until after it had fallen again below the limit on the way back down to earth. Inspection of the NASA Review Package shows that an actual DART rocket would experience roughly 75 g's of acceleration within the first 2.5 seconds of flight. Because of the factor of four reduction in acceleration on the simulator, the modified trajectory created about 20 g's. The time-to-first-fix (TTFF) of the receiver is typically 48 seconds, and the DART covers approximately 30 km in 23 seconds, so it did not have sufficient time to re-acquire before the altitude limit had been exceeded.

Although the receiver was not producing valid solutions after losing lock, it was, for a good portion of the flight, providing raw pseudorange measurements. After extracting the pseudorange measurements and calculating the trajectory provided by this data, we were not completely satisfied with the trajectory coverage that we obtained. Increasing the trajectory coverage tracked by the receiver meant helping it to gain lock again as soon as possible after the g-force caused it to lose lock. Throughout the tests the receiver never did lock under 30 km, which would have allowed valid calculated position values to be output by the receiver. Re-initializing the receiver as soon as lock was lost, however, helped it to provide the pseudorange measurements quicker and thus allow maximum coverage of the trajectory. Re-initialization consisted of entering new values for latitude, longitude, altitude, velocity, and course over ground.

Extracting the pseudorange information from the message packets, manipulating it, and comparing this calculated trajectory to the trajectory data from the NASA Review Package confirmed that indeed the raw pseudorange measurements provided valid data for the majority of the flight. Figure 1 shows the trajectory calculated from the pseudorange data, the NASA Review Package trajectory path, and the calculated output positional data from the receiver. The true trajectory as given by the NASA Review Package is represented by the path of circles, the pseudorange determined path is represented by the solid line, and the direct receiver output is the dashed line.

Prior to launch for the actual flight, the receiver would

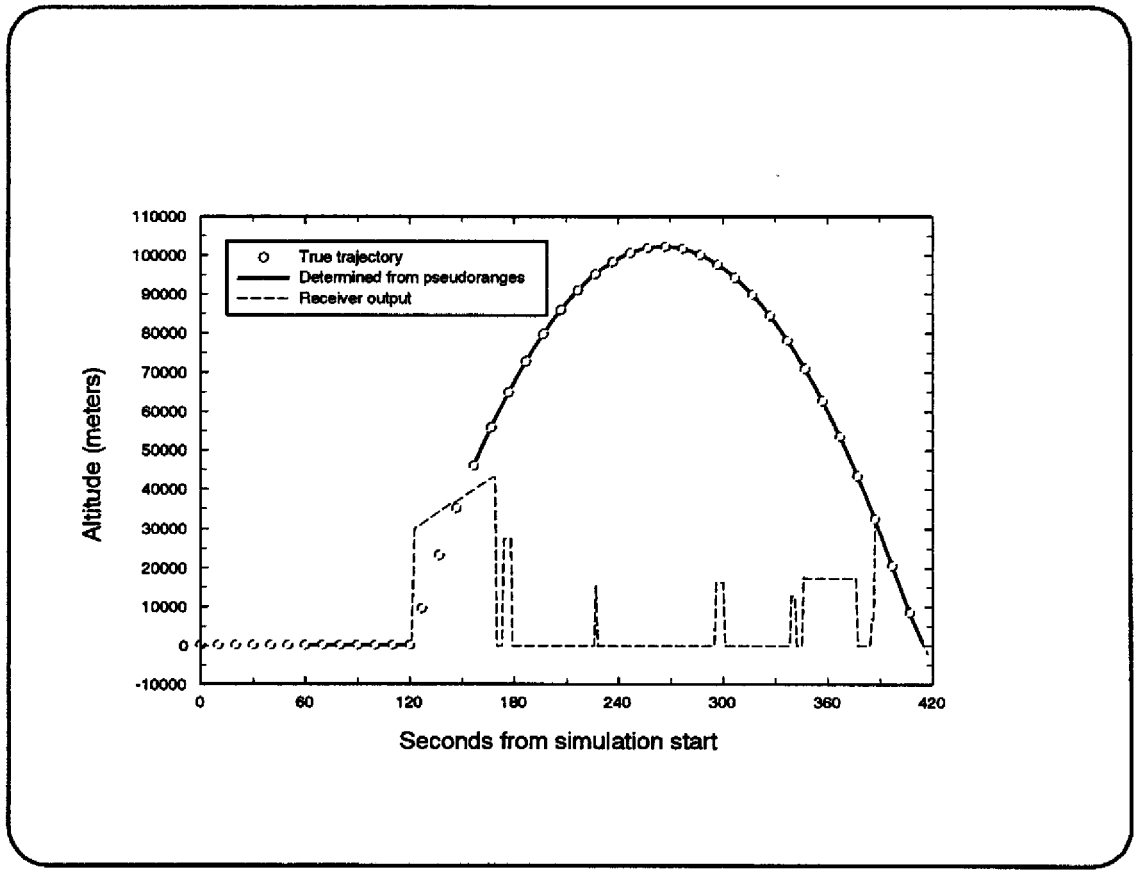

Figure 1 - Receiver Performance Under Flight Conditions

require at least 15 minutes on the pad to ensure it had signal lock and the ephemeris data for all the satellites had been updated inside the receiver. After launch and signal drop, the receiver would need to be re-initialized using information pre-stored in a memory device on the rocket which could be fed into the receiver at the proper time.

Payload integration for the receiver unit is not a trivial matter, but conceptually it is rather simple. Using an RS-232 interface between the GPS receiver and the main microcontroller for the rocket allows for minimal interface concerns and maximum reliability. There also needs to be a memory device that can provide the re-initialization information in a timely fashion. Once this interface is settled upon, the design will be complete.

III. The Antenna

A. Selection Criteria for the Antenna

The search for an antenna system was governed by four concepts. Physically, the antenna system had to be small enough to fit within the 2-1/8 inch diameter of the DART body and be optimally placed within the rocket. The pattern from the antenna had to provide isotropic signal coverage to allow the GPS receiver to operate on a potentially spinning and tumbling rocket. The antenna needed to provide enough gain so that the C/No (Carrier to Noise Ratio) would be great enough for the receiver to re-acquire rapidly and provide accurate solutions. Lastly, the power consumption by the antenna system needed to be small.

For ideal GPS signal reception, the antenna pattern needed to be isotropic (spherical) so that regardless of the antenna configuration or placement, it would provide maximum visibility to the sky. Although the microstrip antenna was not an option for our project, results from flights using this type of antenna have proven that indeed an isotropic pattern results from this type of design. Since this was not an option, we designed a system that most closely imitated this type of pattern using patch antennas.

A single patch antenna has a fairly hemispherical pattern, which led to the belief that if they were placed in a back-to-back configuration, a decent isotropic pattern might be formed. Of course one might expect some sort of null in the pattern at the plane connecting the two antennas, but as will be discussed in the next section, the antenna system proved that expectation to be wrong.

Antenna Configuration and Placement

Considering dimensional characteristics, an antenna that would fit the constraints of the DART was not too challenging conceptually. The UHF frequencies that GPS utilizes have very small wavelengths, and therefore very small antennas can capture the energy of the waves. Patch antennas of the L_1 center frequency type are good examples of this fact. According to the equation:

$$\lambda = c/f$$

the wavelength of this signal is 19.04 cm, and without delving into too much math, the area of the patch antennas is based on a fraction of this number. The Toko patch antenna that we selected actually has a 25x25 mm^2 footprint, which includes the ceramic insulator material.

Given the size of the antenna and the diameter of the rocket, a maximum of five antennas could be placed in the same circular plane and still fit within the body of the DART. Theoretically, more than five antennas could be used in the design, but they wouldn't be able to fit on the same planar surface. The decision for how many antennas to include in the design relied heavily upon the ground plane specification that came with the Toko antennas, as well as mission objectives. Several locations present themselves as possibilities, such as the nose-cone, the fore, mid, and aft sections of the body, and the tail-fins.

For example, a single antenna could be placed in the tip of the nose-cone, providing excellent coverage during the pre-apogee stage of flight. Although very simple to implement, this solution has very poor reliability once the rocket re-enters the atmosphere. Before encountering the atmosphere on the way back to earth the rocket remains with the nose-cone facing upward, but, then it tumbles as it finishes its flight. The GPS signals would be potentially blocked by the rocket for extended periods of time. Any other location throughout the DART would only provide inferior performance for a single antenna.

Another possibility for the antenna system would be some configuration involving three or more antennas. A solution of this type is definitely more complex than a single antenna or a back-to-back antenna (to be discussed in the following paragraphs). In this situation, the designer needs to take into account the phase of the signals received by the antennas. The GPS signals would be received simultaneously by at least two of the antennas, and given that some finite distance separates the two antennas, destructive interference would be a concern. Considering the expertise and time required (both of which was lacking) for an in-depth analysis of the signal phase problem and an impedance matching circuit, this method was not pursued.

A back-to-back configuration of two antennas presented a solution that would eliminate the signal phase problem, as a particular signal from a given satellite would be visible by only one of the antennas at any specific moment of time. This type of configuration would allow the antenna package to be placed basically anywhere in the rocket, excluding the tail fins (because there are three of them). The final decision for placement of the antennas stemmed from one of the mission goals - to make the rocket as modular as possible. By placing the antenna system in the mid-section of the DART as part of a joint, we were able to have an easy access to either end of the rocket with a stable separator between the "science end" and the "house-keeping end" of the rocket.

Antenna Gain and Power

In order to complete the antenna design, a lower limit on C/No was needed. This limit provided the basis for determining whether or not a passive antenna system would be feasible, and therefore determined the power consumption. The testing was done by Roger on the simulator at NASA. He ran many scenarios, varying the signal strengths of the satellites individually and collectively. After monitoring the response of each scenario, and noting that poor, slow, and even non-functional behavior was observed for given scenarios, he averaged the C/No's of the satellites and found that the lower limit was 33 dB.. Therefore, this value became our design criteria.

After doing the testing it became apparent that a passive antenna system design would not meet the 33 dB threshold limit. To compensate, an active solution was devised which consists of using an existing, commercial, active-antenna which draws 90 mA, and attaching a second patch antenna to the existing antenna at a point prior to the LNA (Low-Noise Amplifier).

B. Passive Antenna Test Results

All data collection during the tests took place over at least a 12 hour period to allow each satellite in the same subset of visible satellites to complete one entire arc across the sky, with each test taking place over the same general 12 hour time period. To establish a baseline from which to work, the original active antenna that came with the GPS development kit was used to record data. Each test was performed with the antenna in a fixed position, and then rotated 90° with respect to that fixed position to determine if polarity had any effect on the performance. Conductive grease was placed between the ground plane and the antenna to provide maximal grounding plane contact, and all tests took place from the roof of the engineering building at Utah State University, allowing for a relatively un-obstructed view of the sky. Data points were recorded for each visible satellite every four minutes, theoretically allowing one data point per degree change in elevation.

One final comment must be made on the methods used to compile the data used in this section. There are obvious limitations in the data collection. The passive antenna patterns only reflect a two-dimensional world, ignoring azimuth completely. The satellites do not carve out the same path in the visible sky each time they complete their 12 hour orbit, and thus one more incongruities has been introduced. Ionospheric conditions change drastically from day to night, and of course, this has not been taken into account either. With this in mind, I will proceed with the results.

The baseline test merely consisted of the single, active, patch-antenna lying on a flat surface taking data for the prescribed time period. The ensuing tests followed: a single passive antenna with a flat 70 mm^2 ground plane; two passive antennas connected back to back on flat 70 mm^2 ground planes; a single passive antenna on a cylindrical section of ground plane with a flat section barely big enough to fit the antenna; two passive antennas connected back to back on the same type of cylindrical ground plane as the previous test; a single passive antenna on a cylindrical section of ground plane with a full 70 mm flat plane in the axis; two antennas back to back on the same ground plane configuration as the previous test; a single antenna whose line of sight was disrupted by a chopper; and finally, the performance of a single passive antenna on the flat ground plane, covered with the radome material was tested.

As mentioned earlier, the simulations allow for data from each visible satellite to be tracked at four minute intervals. A program was used to interpret the message packets from the receiver and output a separate file containing pertinent information from each data cluster for each visible space vehicle such as C/No, azimuth, elevation, etc.. A MATLAB file then takes the C/No and plots it as a function of elevation. The resulting plots generate an antenna pattern of sorts that would serve as simulation criteria for the simulator at Goddard.

A plot of the C/No vs elevation of the baseline results, with the elevation representing the elevation from the antenna horizon to the satellites, show that under ideal conditions the mean signal strength is 44.6 dB, with a standard deviation of 4.7 dB. In the subsequent tests, the mean signal strength decreased most dramatically when the cylindrical ground planes were used that only had a

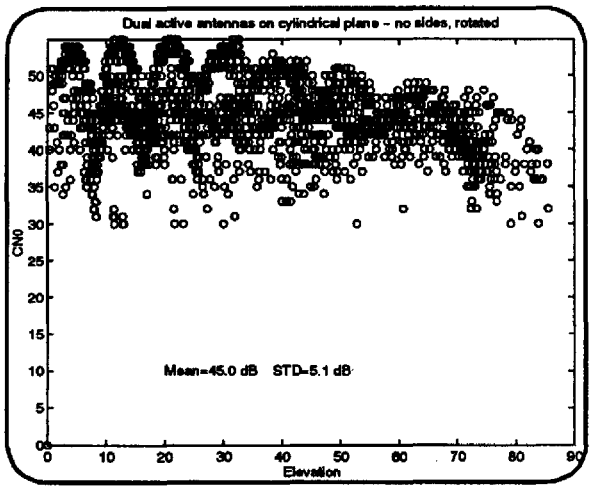

Figure 2 - Active Back-to-Back Antenna

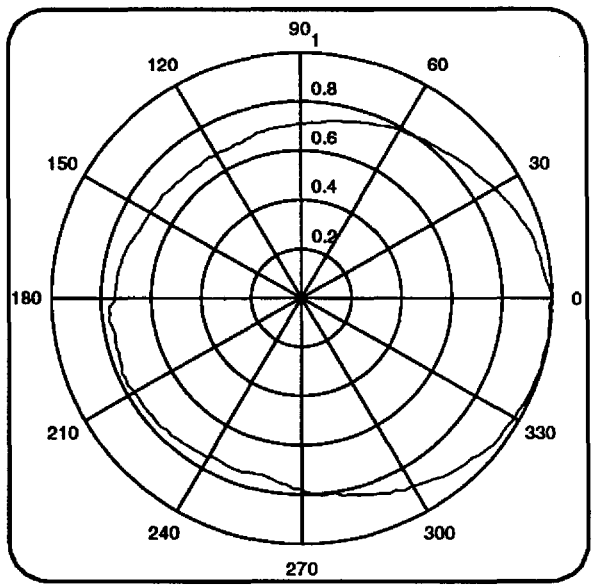

Figure 3 - Far Field Pattern

flat portion big enough for the antenna. In fact, signal strength was reduced so much that the receiver was too slow in responding to these weakened signals to be of any value for the flight. Cutting away the rest of the axis plane improved things to the point that the receiver could still function with signal strengths at a mean of 36.1 dB and a standard deviation of 3.0 dB.

In order to simulate something that would resemble the spin rate of the DART body during flight, we took a single passive antenna with a flat ground plane and disturbed the line-of-sight of the satellite signals with a chopper apparatus. This apparatus was a spinning wheel that had four equally sized sections, two of which were open, making them look something like the blades of a helicopter. I spun it at speeds ranging from 2 Hz up to 20 Hz (surpassing the expected DART spin-rate). The receiver would stay locked and continuously produce valid solutions, even though the signals themselves would register as strengths alternating between full strength and zero strength. These results bolstered our confidence that even with somewhat of a null in the antenna pattern of the back-to-back configuration, the receiver would still obtain the necessary information from the GPS data stream to provide the solution data.

As mentioned previously, the radome material reduced the signal strength by roughly 5 dB, which dropped the aforementioned 36 dB signal strength below an acceptable value for the receiver to operate properly. The active antenna brought the signal strengths back up into the 45 dB range (40 dB after the loss from the radome material). Figure 2 shows the test results for the final antenna system design.

C. Active Antenna Test Results

Once we determined the necessity for an active antenna we began formulating tests to measure the actual antenna pattern for our particular configuration. With the help of Dr. Ronney Harris of the USU faculty, I was able to set up a testing environment that allowed me to determine the relative field strength of the antenna, in effect producing an antenna pattern. I connected a signal generator producing a 1.5 GHz signal amplitude-modulated by a 1 kHz sine wave to the antennas. With the antenna acting as a transmitter, I was able to measure the relative signal strength at any point with a corner reflector hooked up to a VSWR. The spinning table was marked in degrees, so I took measurements at 2-degree increments.

The data points were collected around the entire circumference of the antenna system for four different trials, and the average of them has been plotted. Keep in mind this exercise was merely a test to see if indeed the antenna pattern had a null in it that would require special attention. Plots for the near and far fields show that there is no significant null in the pattern, although the pattern is not symmetric (see Figure 3). The reason for this is to be discussed.

During the first two tests, the antenna system was set up such that one antenna was facing in the direction of the 0-degree mark on the graph, and the other facing 180 degrees. For the single-antenna with radome test, the antenna was facing 90 degrees. Observing the near-field pattern clearly shows the effects of not having a precisely

connected antenna system. The antennas were connected back to back by a rigid wire, and then a separate wire was soldered to the rigid one in a 'T-shape' for an 'outside world' interface. Inspection of the actual connection reveals the fact that the rigid wire had a slight bend in it, and the T-connection is not in the center of the rigid wire. The lop-sided pattern is therefore a result of the active element boosting the signal for one antenna more than the other. This might have had an effect on individual measurements from the roof tests, but the averaging process nullifies this effect, making the mean dB value valid.

The most important thing to be noted from these tests is that the antenna configuration has a smooth pattern, with no null in it. According to this test, we should have continuous reception of the GPS signals with no noticeable reduction in signal strength at any point in the spin cycle of the rocket. But, the radome is responsible for decreasing the overall signal strength by a factor of roughly 0.20, which confirms our previous results.

D. Antenna Summary

The antenna is a critical component to the success of the GPS receiver. We arrived at a robust design that not only provides sufficient signal strength (in the 40 dB range), but also exhibits a very close approximation to a spherical antenna pattern. Although we failed to find a passive solution, the power consumption by the active system can be tolerated by the system power source. Most importantly, however, is the solution that we arrived at was very inexpensive, was fairly easy to assemble, and did not take an inordinate amount of time to develop.

The testing methods described in this section are by no means exhaustive, but the results are still valid for the simple reason that we see absolutely no sign of a null in the antenna pattern, both from the passive and active tests. Regardless of all of the variables that are not taken into consideration, if there was a null in the pattern, we would have seen it.

IV. Conclusion

Using a GPS receiver for tracking a rocket is not only feasible, but tests have shown that it could be a very efficient solution for tracking issues on small rockets. On top of that, it is a self-contained unit that is easily integrated with the rest of the payload. The unit is very inexpensive, and the performance matches or surpasses existing methods. With the impending integration of the GPS tracking unit into a DART rocket payload, researchers will have an additional, more economical method for taking observational data in the middle atmosphere.

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