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STUDENT PROJECTS FOR SPACE NAVIGATION AND GUIDANCE

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Abstract

"Space Navigation and Guidance," taught every fall at the University of Maryland, is required of all space track undergraduate aerospace engineering majors. Every student is required to participate in a group project where real observations are used in the solution of a navigation problem with estimation from observations. In this paper, I discuss two such projects, an observatory project in which the students use a telescope to track a satellite and determine its orbit, and a GPS project in which they analyze GPS receiver data to determine the receiver's position.

INTRODUCTION

ENAE 441, "Space Navigation and Guidance," is a class offered by the Department of Aerospace Engineering at the University of Maryland every fall. It is required of all undergraduate majors on the space track. As part of this class, every student is required to participate in a group project. Groups of about four students working together acquire data, analyze, and report on a space navigation topic. The purpose of these projects is to give a practical introduction to the topics learned in class. In particular, the physical process of data acquisition, including observation and interpretation is difficult, time consuming and subject to unexpected limitations; the idealized process of a textbook or lecture usually do not convey the reality of solving these navigation problems. Processing of sometimes messy data shows the limits of the overall orbit determination process and the contribution of instrument accuracy to the accuracy of the result. This paper describes two topics that have been the subject of their investigations, one for observation and determination of satellite orbits, and one for position determination from Global Positioning System (GPS) data.

OBSERVATORY PROJECT

Introduction

In the observatory project, students observe satellites from predictions, recording times and right ascension/declination when a particular satellite is in view. After, they perform orbit determination techniques learned in class and compare the results with the known orbital elements for the satellite observed.

Students acquire the data by using telescopes at the University observatory, located a short distance off campus. On an evening that the observatory is available and all students in a group are able to attend, the students, prepared with visibility predictions from a public web site, go to the observatory prior to dusk to learn how to operate the equipment and practice their coordination. One

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student enters predicted right ascension/declination data onto a keypad that points the telescope. The second student observes through the spotting scope attached to the main scope and moves the ladder before the telescope is re-aimed. The third student reads off numbers and records time when the observation is made. The fourth student provides general assistance such as holding the flashlight. Students may switch roles if they wish to spread the fun, or stay in the roles for which they practice. At dusk when terminator is visible and the satellites appear, they may observe and record data for as many as half a dozen satellites.

The observatory is used primarily by astronomy students, and is run as an education resource by the Astronomy Department of the university. Fortunately, the astronomy students make their observations deep in the night when terminator is no longer visible. The students in my class have usually departed by the time the astronomy students arrive, though on occasion there have been conflicts. The requirement that an observatory staff member be present while the students use the equipment is more of a constraint on availability, but even this has not been a major problem because of generous cooperation from the staff. If the students put off their observations until just before the deadline, then it can be a problem. This problem is resolved by assigning groups to visit the observatory on successive weeks in the middle of the semester.

Once the observations are acquired, they use angles-only initial orbit determination learned in class, either Gauss's or Laplace's method (Ref. 1), to process the observations. From a single pass fit span of, at most, six minutes, accuracy of resultant orbital elements varies greatly by element. If more than three observations for a given satellite are available, they can try to apply a differential correction technique (Ref. 1).

Procedure

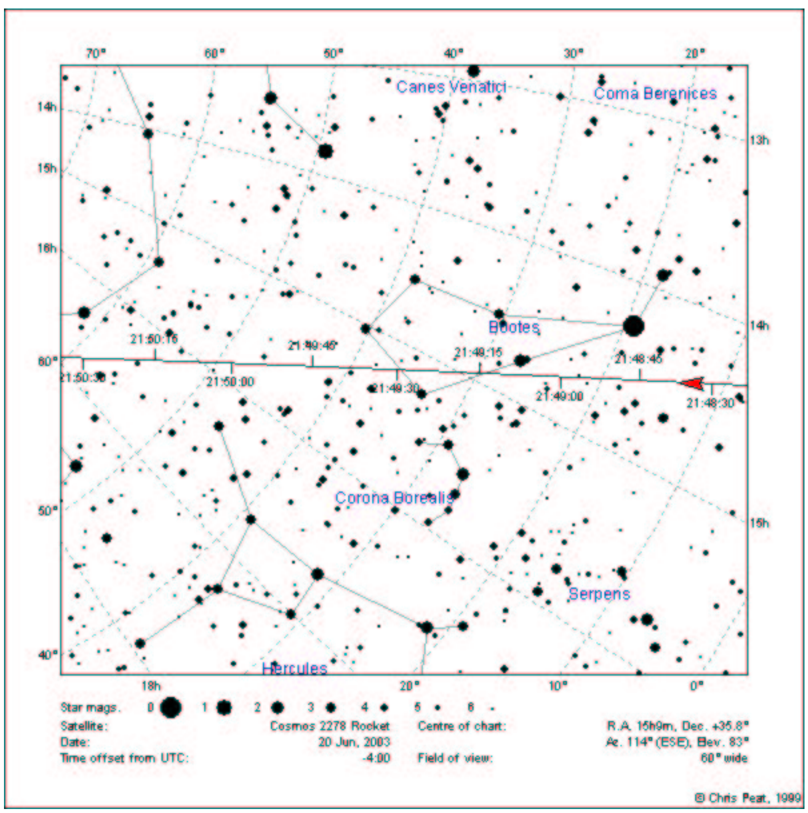

Figure 1: Star chart from Heaven's Above web page, showing the track of the selected satellite.

For the past three years, the staff of the University observatory, run by the Astronomy Department, has generously agreed to allow our students to do their projects there, and has provided staff to calibrate the telescopes and assist the students. The telescope used is usually the 2° field-of-view spotting scope attached to a 14″ Schmidt Cassegrain telescope with digital-input motor drive, calibrated in right ascension and declination. Prior to visiting the observatory, students must prepare by obtaining from Heaven's Above (HA) (`http://www.heavens-above.com`) a prediction of the satellites that will be visible that night. These are invariably satellites in low-earth near-circular orbits. On any given night, it initially appears that there are plenty of satellites to choose from, especially if one lists satellites down to magnitude 4.5. However, a closer inspection reveals limitations: some have a maximum elevation angle too low to provide a useful observation span, or observation periods overlap with other satellites. Students select several satellites with visibility times separated by gaps of several minutes. For each of these satellites, a link on the web page provides a star chart showing the traversal of the satellite across the sky (Fig. 1); from this chart, the right ascension and declination may be extracted. Since they are expected to have three separate satellite tracks, selecting five or more potential passes is prudent, given that some will not be observable due to dimness, clouds, etc. And, it usually takes a practice run when first starting to work the kinks out of the observation procedure.

Other impediments to observation include bad weather, pollution or haze, and trees. Generally, weather in the Washington DC area is clearest in the fall, and observations rarely need to be rescheduled because of clouds or rain. An exception was the fall of 2002, when an unusual weather pattern of clouds and rain prevailed in September and October. So many observation sessions needed to be rescheduled or canceled that groups ended up sharing data for the analysis phase. Pollution and haze ever-present in the Washington area reduce the visibility of the skies, but objects of brightness up to magnitude 3 or 4 are still visible through the spotting scope with a little practice. Due to an unfortunate location and the growth of vegetation along a state road that the university cannot trim, trees obstruct the view towards the north, down to an elevation of about 45 degrees. This can sometimes interfere with observations.

Analysis and Limitations

Students compute the site vector from the known longitude and latitude of the observatory and the sidereal time. Using Gauss's or Laplace's angles-only orbit determination, they solve for the Cartesian state at the middle observation time (Gauss's method uses Gibb's method of the position vectors to achieve this).

The end result of the initial orbit determination is the Cartesian state at the middle observation point. Generally, one wants to obtain classical orbital elements at the end; as they are versed in this calculation, most of them do it. At that point, the results may be compared with what was given on HA or similar source of elements. Since almost all of the satellites observed are very nearly circular, the zero eccentricity singularity gives rise to widely varying results for some of the elements. Computing a percentage error make little sense for e.g. eccentricity, which is near zero, or for elements which require a well-defined perigee.

The estimated Cartesian state may be improved if more than three observations on the satellite were taken. In this case, a differential correction orbit estimation is performed. This should give not only an improved estimate, but standard deviations of the parameters. These techniques are covered in class, based on the treatment of Vallado (Ref. 1). It is common in orbit estimation to correct the observation times first in order to achieve a better fit; because of the rotation of the earth, a correction of the six Cartesian components of the state cannot compensate for clock errors. I demonstrate this in the next section, but the students have not tried this yet.

Understanding how much the spread of observations (or lack thereof) along the orbit shrink or magnify the effect of observation error (noise) on final orbit determination is aided by the concept of "dilution of precision" (DOP) from the GPS community. The position dilution of precision (PDOP) is the square root of the trace of the position part of the covariance matrix. It will tell you how the spread (or lack) of the satellite's positions at the various observation times magnifies a given amount of error before you actually make observations.

One might think that with accurate data from HA, a calibrated telescope, and an accurate timepiece, the exercise of actually taking observations, recording the data, and processing the observations is merely a circuitous way of reproducing the known elements from the two-line element sets that Heaven's Above starts with in the first place. In a sense this is true, but the data from the web site is not reliable; sometimes the element sets are more than a month old and the observer really does need to get an accurate time; a 10 to 20 second error, or over a hundred kilometers in-track, is not uncommon. In this case, careful observation and a calibrated telescope can improve knowledge of the satellite's motion over what is initially available.

Sources of error in the observation include timing, particularly reaction time from observation of the satellite to reading of the clock. Furthermore, time is only recorded in one second increments. Imprecise knowledge of the telescope's location is also a source of error. Also, calibration of the telescope is important, a task left to the observatory staff.

Sometimes the satellite misses the crosshair center, and this information is harder to incorporate into the algorithms. Directional orientation of a telescopic image is notoriously difficult to solve. In order to use the observed crosshair miss in a numerical computation, one needs to know both the direction and magnitude of the error and how that translates into actual right ascension and declination.

Even with a calibrated telescope and very careful observations, it is difficult to determine orbits more precisely than a few kilometers and tens of meters per second. A possible source of error in the estimation is the use of a two-body propagator, instead of using a more realistic force model. The dominant perturbation, the J_2 geopotential perturbation, is about 10^{-3} of two body motion. Therefore, the prediction of position of a typical low-earth circular orbit satellite will be off by about 3 km over the course of a seven minute observation span. While the students do know about perturbations, they are a significant complication in the analysis, and few groups attempt to use them.

These pitfalls put large-scale amateur orbit determination such as Project Starshine (`http://www.azinet.com/starshine/`) into perspective. The possible wide variation in quality of observations of such a project might undo the expected improvement of pass-to-pass observations.

Most observed satellites are near-circular because they are the most reliably observed, being always relatively near the earth, and are moving the slowest when observed. The disadvantage is that it is then very hard to determine the orbital elements and parameters that become singular for circular orbits, such as argument of perigee and true anomaly.

Example

On November 6, 2000, the author with two others observed several satellites from the University observatory. This exercise served to shake out the process so that accurate instructions could be provided to the students, and to provide sample data for analysis. The COBE satellite (SDC #20322) was observed, with data in Table 1.

Applying the Gauss angles-only orbit determination method (see Ref. 1 Sec. 7.3.2 or Ref. 2 Sec. 7.3) on the first (17:31:29), middle (17:34:30), and final (17:37:30) observations to find an initial estimate of the Cartesian state at the middle time. The Gauss method solves for the distance to the satellite from the center of the earth at the middle observation time, and also the ranges at all three times. From this, the Gibbs method may be applied to find the Cartesian state at any of the observation times and then the orbital elements computed. The results of this computation are given in Table 2 on the second line, along with the actual Cartesian position and velocity at the epoch time based on an official element set on the first line.

Vallado (Ref. 1) suggests that the initial result of the Gauss calculation be refined and gives an iterative method to do so. The suggestion apparently comes from Escobal (Ref. 2), who says it was suggested by Moulton but also that it is untested; in fact, it has been my experience and the

Predicted time (EST)	Observed Time	Right Ascension	Declination	Observed offset (0–10)
17:31:30	17:31:29	21:48:00	−16.3°	1
17:32:30	17:32:30	21:41:00	−2.0°	0
17:33:30	17:33:30	21:31:45	19.3°	0
17:34:30	17:34:30	21:14:00	46.9°	3
17:35:30	17:35:29	20:28:00	71.9°	3
17:36:30	17:36:30	15:01:00	84.6°	2
17:37:30	17:37:30	11:03:00	76.1°	0

Table 1: Data from COBE pass over College Park, November 6, 2000. Offset is an estimation of how close the satellite was to the center of the crosshairs at the closest approach, with 0 on the crosshairs, and 10 at the outer edge of the field of view; direction of offset was not recorded.

Parameter	r_I	r_J	r_K	v_I	v_J	v_K
Actual	3528.320	−4313.871	4654.938	−4.103	2.658	5.564
Gauss IOD	3522.654	−4309.333	4646.863	−4.048	2.631	5.499
Estimation	3533.316	−4319.816	4659.711	−4.143	2.676	5.636
σ	14.524	12.545	20.598	0.144	0.086	0.189
Error	4.996	−5.945	4.773	−0.040	0.018	0.072
Estimation, time adj.	3515.942	−4303.236	4632.720	−3.983	2.586	5.404
σ, time adj.	4.921	4.234	6.954	0.049	0.029	0.064
Error, time adj.	−12.378	10.635	−22.218	0.120	−0.072	−0.160

Table 2: Actual and determined geocentric equatorial Cartesian components of state for COBE on 2000-11-06 21:34:30. Positions are in km, velocities in km/sec.

experience of my students that this iteration never converges. Since we will differentially correct the result anyway, it seems unnecessary.

The Laplace angles-only orbit determination (Ref. 1, Ref. 2) is another initial orbit determination method for use when only angles are available. Unlike the Gauss method, which uses approximations to two-body motion to obtain an estimate of distance at the middle observation, it uses a polynomial (Lagrange) interpolation. Like the Gauss method, an eighth order polynomial in this distance is obtained, which then must be solved for a real and realistic root. For near-earth satellites the results are poor because of the polynomial approximation, with three observations. These are in fact just those orbits that will be seen through the telescope. For the data in Table 1, the only positive real solution is at $r_2 = 0.6124\,\mathrm{earthradii}$, obviously not realistic. Several student groups have tried, but invariable they find they must use the Gauss method to obtain a good solution. In principle, the Laplace method can be made to work by extending the order of the approximation and introducing more observations (Ref. 2), but that is considerable work.

Once the initial orbit determination has been computed, we may apply a differential correction to the Cartesian state to minimize the sum square of the residuals of all seven observations. Using the estimated state, we propagate with an analytic two-body propagator to the time of each observation, and computing the difference in the propagated and observation values, and finally sum these differences squared. Finite differencing may be used to obtain a Jacobian matrix; this provides the means to calculate an update of the estimate in a Newton-Raphson solution that minimizes the sum squares of the residuals. When the root mean square of the residuals ceases to change significantly, the iteration is stopped. For weighting purposes, an estimated error of 0.02° in both right ascension and declination was used. The fact that final RMS obtained 0.978 was near 1 indicates that this was a reasonable choice.

The third line of Table 2 begins a set of three rows that give the least-squares estimated state using all seven observations, along with the standard deviation (Ref. 3) and the error, or difference

Obs. #	Predicted	Observed	Corrected	Difference (s)
1	22:31:30	22:31:29	22:31:30.288	1.288
2	22:32:30	22:32:30	22:32:30.110	0.110
3	22:33:30	22:33:30	22:33:29.810	−0.190
4	22:34:30	22:34:30	22:34:30.000	0.000
5	22:35:30	22:35:29	22:35:29.990	0.990
6	22:36:30	22:36:30	22:36:29.347	−0.653
7	22:37:30	22:37:30	22:37:28.577	−1.423

Table 3: Observation times before and after correction; times are UTC.

from the actual state. The time correction is a least-squares differential correction of each observation time and a fixed state. The corrections for these observation are given in Table 3; the initial state estimate from Gauss's method was used as the fixed state. Since a change in the observation time of one observation cannot affect the residual contributed by the other observations, each observation may be corrected separately from the others and this makes the task simpler. The final set of three rows in Table 2 is similar to the previous set, except it is based the set of observations that has been time corrected.

Notice in these results that the estimation without time correction has position errors of ten to twenty kilometers, though the standard deviations are around five kilometers. Conversely, adjusting the observation times prior to estimating the state caused the standard deviations to drop to around five kilometers but the actual errors to leap up over ten kilometers. A similar pattern can be seen in the velocity components as well. Since the adjustment of observation times is not of clear benefit and is a significant hurdle for students, I will be cautious in recommending it to the students.

Parameter	a (km)	e	i	Ω	ω	M	$\omega + M$
Actual	7264.907	0.00100	98.900°	−43.204°	163.259°	−122.706°	40.553°
Gauss IOD	7062.924	0.02625	98.870°	−43.256°	−142.214°	−177.231°	40.555°
State est.	7441.311	0.02300	98.916°	−43.192°	37.549°	2.768°	40.317°
Time est.	6822.066	0.06052	98.895°	−43.253°	−141.282°	−178.103°	40.615°

Table 4: Actual and determined orbital elements for COBE on 2000-11-06 21:34:30. The first estimated element set is from the estimation Cartesian state by itself, the second is from the estimation of Cartesian state after the application of the observation time estimation.

The orbital elements are an easier way to understand an orbit and it is natural to convert the Cartesian state to elements. These results are presented in Table 4. They show that the inclination and the ascending node come out well, the semimajor axis a plausible but somewhat disappointing, and the other elements not very good, principally because the orbit is near-circular; perigee and apogee altitudes differ by only 4 km. Notice that because of the near-circular orbit, elements that become singular for such orbits like mean anomaly M and argument of perigee ω vary wildly, but that their sum, the mean argument of latitude, is quite consistent.

While Cartesian values generally are in a region of a few kilometers and tens of meters per second, the elements can be quite different due to the circular orbit singularity. As this orbit was typical of those that appear on the Heaven's Above visibility table, these results are typical of those the students obtain. It would be nice to have observations of a more eccentric orbit, but these are rarely present on HA.

Assuming a reasonably well-calibrated telescope, it seems likely that the greatest source of error is the recorded time. This is affected by both the reaction time of the observer and the calibration of the the timepiece. It seems reasonable to expect up to a second inaccuracy in the recorded time. For a low-earth orbiting satellite, this translates into about 7 km in-track error. The magnitude is about the parameter standard deviation seen above. It is somewhat puzzling that a time correction does not correct this error but in fact appears to make the fit worse.

Student experience with this project over the past three autumns has been good. Most find at least one orbit with roughly the same results described here, though frequently the students are unable to differentially correct the result, either because of the lack of excess observations or the lack of time. Other than that, the availability of good weather has been the chief obstacle to success. When things go seriously wrong in the calculation, it has been due to failure to convert from local time (EST = UTC−5:00 after late October, EDT = UTC−4:00 before) to UTC. Understandably, this produces very wrong results, though it is possible that a observation time estimation could correct for this error.

Future Enhancements

There are several ways in which this project could be improved. Some are simple and some require quite a bit of development.

- The estimate of how far the satellite was at its nearest approach to the crosshairs is used only for estimate of error at best. An estimate of actual right ascension and declination of the satellite at the recorded time and incorporation of that result in the analysis might produce more accurate results.
- Observation of a satellite that is at least a mildly eccentric $e \gtrapprox 0.1$ should produce orbital elements that can be determined unambiguously. However, it seems that Heaven's Above only has circular satellites in its database. While other database have eccentric satellites, they often don't include the brightness, which is important for determining visibility.
- An improved telescope would have the ability to photograph the satellite against the background stars, with a precise timestamp. This would eliminate the time recording problem. Using star-pattern identification software, the satellite's apparent right ascension and declination could be precisely determined.
- A more realistic force model than two body motion seems appropriate, as the J_2 perturbation has an effect of several kilometers over several minutes. Unfortunately this complicates the analysis significantly.
- Observations of the same satellite over multiple passes will give greater accuracy. In conjunction with the previous enhancement, multi-pass photographs would provide the potential for very accurate orbit determination. In principle it is possible to see the successive passes of the same satellite in the same evening, but this information is hard to extract from HA. A force model more accurate than two body will certainly be necessary for the analysis. A dilution of precision estimate would allow us to predict the expected benefits.

Student Instructions

The following are instructions given to the students.

Introduction

In this project, you will visit the University of Maryland observatory
`http://www.astro.umd.edu/openhouse/obs_info/index.html` on Metzerott Road a couple miles from campus, in order to observe satellites. After you have taken observations with a calibrated telescope, you will use orbit determination methods learned in this class to find their orbital element sets.

As you know, satellites are only visible in terminator (see Figure 11–19 in the text (Ref. 1)), because they do not generate light on their own. That is, the observer should be in darkness, and the satellite in sunlight. These time windows are a couple hours after sunset and a couple hours before sunrise. The observatory staff are as unenthusiastic about pre-dawn observations as you are, so we will confine ourselves to evening visits. Thus, you will want to get to the observatory about sunset on the day(s) of your observations. By two hours after sunset, your observation will be done, and you can clear out to make way for the astronomy students.

The telescope you will be using is a 14″ Celestron Schmidt Cassegrain with a motor drive. Actually, you will not be sighting through the main scope, but through the finder scope. It has a 123 arcminute (about 2°) field of view, and cross-hairs in the sight. The drive includes a sidereal tracker that compensates for the earth's rotation in pointing at a fixed right ascension and declination.

You should plan on two visits to the observatory. The first visit may well not produce any useful data, as you learn the preparation necessary, equipment, and coordination of your group. You should strive for at least five good data points from each of two satellites. If you do not achieve this on the first visit, you should return to the observatory for a second visit.

Arranging a visit

Your observatory contact is Elizabeth Warner. Ms. Warner has numerous duties in her job, of which helping our class is not even one. Nevertheless, she has graciously agreed to help us out. Therefore, please make her job as easy as possible.

Have one person in your group who is easily reached act as a scheduler to arrange observing times. That person should find out from all the members of the group what evenings they are available. When you have selected several days, call Ms. Warner, identify yourself as a ENAE student observing satellites, and find out which is the best day for her. You will not be able to observe the 5th or 20th of any month, as these days are reserved for the observatory open house. When everyone is in agreement on the day, you should do visibility predictions for that evening.

Visibility predictions

The Heaven's Above web site `http://www.heavens-above.com` will give you satellite visibility predictions and has a lot of information, but getting exactly what you need takes a little practice.

1. Visiting Heaven's Above page for College Park
   `http://www.heavens-above.com/main.asp?Loc=College+Park\&Lat=38.981\&Lng=-76.937\`
   `&TZ=EST`
   will automatically enter the observatory location (latitude: 38°58′56″N, longitude: 76°56′14″W).

2. Look under "Satellites" and "Daily predictions" for the list of brightest satellites (up to 4th magnitude) for the day of your visit. Pick out *at least three* satellites from this list whose times in view do not overlap significantly. Some days you will not have a very good selection; you might consider rescheduling your observation if this is the case.

3. For a particular satellite, as you click on the time of "Max. altitude," you will get a sky map with the satellite's trajectory. Pan (move off the side) the chart by clicking outside the border; zoom (get more detail) by clicking on the point of interest.

4. For each satellite you have picked,

   (a) Make a table giving predicted times, right ascension, and declination. This table should be at one minute intervals for at least five points. For maximum accuracy, pick times for which a tick mark is given in the sky chart, and click on that tick mark on the maximum zoomed chart to center it. Then the right ascension and declination can be read at the bottom of the chart. Note that the telescope takes right ascension in hours, minutes and seconds, and declination in degrees, minutes and seconds.

   (b) Click on the name of the satellite. On the page that comes up, note the name, USSPACECOM catalog number, and International Designation Code; these should be included in your report.

(c) Then click on "Orbit." On this page there will be maps and numerical information. Save the orbital element information, including the two line elements; you will want to refer to it later.

You will need to repeat this procedure for every day that you visit; the satellite visibility information changes from day to day.

The day of the visit

Well before sunset:

- Check the observatory weather forecast `http://www.astro.umd.edu/openhouse/obs_info/weather.html` or the National Weather Service forecast, `http://weather.noaa.gov/cgi-bin/iwszone?Sites=:dcz001` particularly the cloud cover image, for clear skies after sunset.
- Call Ms. Warner to confirm your visit; if weather is uncertain, consult with her about observing conditions.
- If there is any reason you cannot make it at the appointed time, call Ms. Warner as soon as you know and cancel your visit.
- Synchronize an accurate (quartz digital) timepiece to the Naval Observatory clock `http://tycho.usno.navy.mil/what.html` 202-762-1401, or better, bring a GPS receiver when you observe, which will give both the precise time and observatory latitude and longitude.
- Record/print out the relevant information from the heavens-above web site, if you have not already done so. Do not write anything in red; it is invisible under the red observatory lighting.
- Plan on arriving before sunset so that you have time to setup and practice moving the scope.
- **Dress warmly** You will be out of doors, at night, under a clear sky, for over an hour, in autumn. Even if the day is warm, it can be chilly under these circumstances.

Observing

- **Observatory staff** When you visit, Ms. Warner or her staff will help you learn how to operate the equipment, but they are not TAs and are not familiar with the problem of sighting satellites and determining their orbit.
- **Division of labor** One person in the group should do keypad entry to aim the telescope, one person should sight through the scope, and one person should record information. The fourth person can hold the flashlight and provide general assistance. If time allows, you can switch roles between satellites to spread the fun. You should practice your signals, because satellites move fast and there is not much time to waste on miscommunication.
- **Aiming the telescope** To aim the scope, enter the right ascension and declination *in advance* of the predicted arrival time at that point. When the last digit is entered, the scope will move to that location. Thus, as soon as the scope is in the right place, the coordinates of the next observation can be entered except for the last digit. When it's time to move again, just enter the last digit, and the scope will start moving
- **Telescope motion** Because the keypad person controls when the scope starts moving and the observer may be looking through the scope, it is important that you coordinate signals. Prior to motion, the observer should get down from the ladder and move it out of the way, then give his/her OK for the keypad person to enter the last digit. If something/someone is in the way, the observer or the scope can be damaged. When changing azimuth so that the meridian line

is crossed on the North, the telescope must go the long way to keep the cables from wrapping up, and it will take at least 45 seconds to complete this motion. This may affect your ability to take an observation on time.

- **Blind spots** There are tall trees to the North from azimuth about 0° to about 20°, which makes it difficult to sight satellites below an elevation of about 45°.
- **Sighting the satellite** Assuming you have aimed the telescope correctly, near the appointed time you should see your satellite come into view as a distinct glint of light moving against the background stars. When it comes as close to the center of the crosshairs as it's going to, the observer should yell out a prearranged signal, and the recorder record the time as shown on the calibrated timepiece. Then note how close to the intersection of the crosshairs it came at the closest points, as a fraction of the whole radius of the field of view, and record that.
- **If you don't see the satellite** It happens; it could be because the coordinates were entered wrong or a cloud got in the way. If you miss one or two observations on a satellite, don't worry; that's why you recorded at least five times of observation. If you do not see the satellite at all, it could be because you got the wrong information off the web site, or the brightness was not as predicted. That is why you are looking for several different satellites.

After the visit

The group should turn in an interim report with the following:

1. The name of the group, and the names of its members.
2. A list of satellites with SDC number and international designator.
3. For each satellite, the date and approximation time of observation, and a table of precise observation times, right ascension, declination, and estimate of miss from crosshairs.

This interim report is due in class on the date your group has been assigned. *Keep a copy of the data for the next phase.* Late reports, unless due to unavoidable circumstances, will be assessed a penalty. Note: failure to schedule a night until the last possible date and then being confronted with bad weather is not what I consider unavoidable. After this interim report is turned in, I will give the instructions for phase 2 of the project.

GLOBAL POSITIONING SYSTEM PROJECT

Introduction

In the second project, students use Global Positioning System data to determine receiver locations. Data is acquired from publicly available repositories. The exact location of the receiver antenna is known and provided with the data, which makes a useful check for the final accuracy. The Receiver Independent EXchange (RINEX) format is a standard used by all sites for formatting raw GPS data. There are two files necessary to compute a location:

OBS Observations from the ground station take the form of computed pseudoranges, signal strengths, and quality of data.

NAV The GPS satellite ephemeris information for all GPS satellites is put into a navigation file.

Once the students have found the files they desire and figured out how to read the RINEX format, they can extract the data and process it to determine where the receivers were, but the first two steps are not as easy as they sound. The navigation of the repositories with data and finding a valid data file and interpreting it once obtained. Some of the files are compressed with different programs such as the *gzip* or *compress* programs, and some browsers incorporate a built-in decompression algorithm that does not work correctly. This has stalled at least one student group for a significant time until they figured out what was wrong.

After the data is collected and properly interpreted, the antenna's location may be determined by trilateration, and, with excess observations, least squares minimization. GPS solutions are not covered in the lectures until the very end of the semester, so students use an advance copy of the lecture notes, and consult references (Ref. 4 and Ref. 5) to gain an understanding of what they need to do.

Retrieval of Data

There are several publicly available repositories of GPS receiver data These data are collected and the sites maintained for precision geodesy and for aid to users of differential GPS and other advanced geopositioning applications. Our purpose in needing receiver data is simply to solve for the station location, and thus much of the information and aids to precision computation are unnecessary. Unfortunately, the data is not well organized, and the sites assume thorough familiarity with the products and their locations. Thus an introduction is necessary. On all the sites, the file extensions (after the ".") mean the same: *yy*o are the OBS files of year *yy*, and *yy*n are the NAV files. There are other kinds of files, but we do not use them for this project.

Continually Operating Reference Stations (CORS)

The *Continually Operating Reference Stations (CORS)* network consists of 387 stations (as of June 2003) primarily in the United States, its possessions, and Central America. They are operated by a number of different organizations, often state highway departments. The CORS web site `http://www.ngs.noaa.gov/CORS` shows a map (Fig. 2) of receiver sites on the home page. Summary status information for each site is available by clicking on a link (Newsletter ➔ Site Status) `http://www.ngs.noaa.gov/CORS/status.txt`. Detailed maps and information about the site is available by clicking on the map. Receiver data is also available this way, or by selecting Download ➔ Standard Files ➔ OPTION: Data Availability. If the standard download of data from this page (OPTION: RINEX2 Data) is selected, one must be careful that data is present because if data that is not present is requested, the web server will simply time out rather than indicating that there is no data available to deliver.

The CORS site has a link to the "User Friendly CORS site" `http://www.ngs.noaa.gov/cgi-cors/ufcors2.prl` which I have found to be much more usable than the main site. Nevertheless, data requests must be chosen carefully. On the main page, one selects principally the date and time period of the data desired:

1. Time Zone $\boxed{\text{UTC(GMT)}}$ relative to observation location.
2. Starting Day $\boxed{\text{June 6, 2003 - day of year 157}}$ and Start Time $\boxed{\text{00:00}}$ of the field observations
3. Number of hours $\boxed{2}$ of data you wish to receive. PLEASE LIMIT 1 SECOND DATA TO 2 HOURS

Two hours is plenty with which to do the analysis, and files are of reasonable size in this case. Following submission of this page, a selection page is presented; the following options are recommended:

1. GPS data are available for the following sites for your specified time interval: $\boxed{\text{GODE}}$
2. This utility will interpolate or decimate the GPS data.
3. How many seconds do you want between individual data points? $\boxed{\text{As Is}}$ LIMIT FOR 1 SECOND DATA IS 2 HOURS

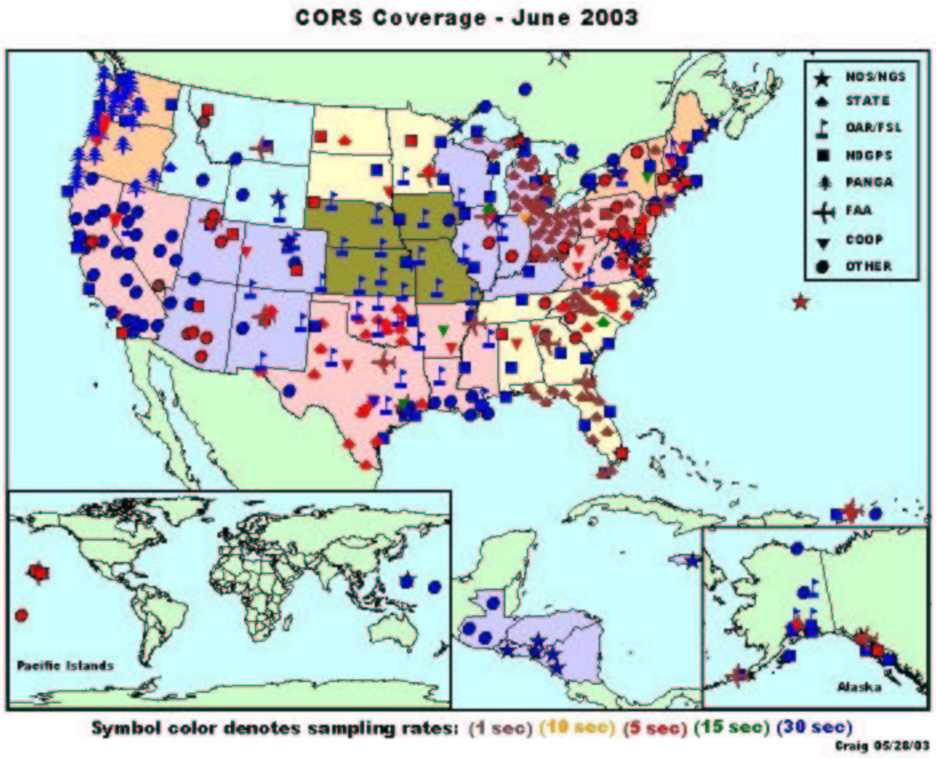

Figure 2: Map of CORS stations.

4. You will automatically receive the corresponding log file, coordinate file, and any available met data for your selected sites.

5. Would you like the corresponding NGS data sheet? No

6. You will automatically receive the appropriate broadcast orbits.

7. Do you wish to receive corresponding IGS Orbits in SP3 format? No

8. Files can be compressed using: pkzip

Numerous site choices are available for selection in the first line. They are referred to by their four-letter site code, but buttons are available with further information. The standard 30 second intervals of CORS data is fine for the purposes of this project, so "As Is" should be selected for the data interval. The data sheets are unnecessary; all that is needed besides the OBS file is the NAV file, and, as stated, that is supplied automatically. The nav file contains the ephemeris data from all the GPS satellites; for any given time period it is the same for all sites. The extra precision of the SP3 format is unnecessary for this project, so has not been selected. The compression option *pkzip* is the only one that should be chosen, as the other options, including *none*, do not bundle the files and the ensuing pile of files that the browser will create on the user's computer is confusing and annoying. In the unzipped bundle, the only two files we will need end with two digits for the year and "n" for the NAV file, and "o" for the OBS file.

International GPS Service (IGS)

The *International GPS Service* (IGS) `http://igscb.jpl.nasa.gov/` is another source of GPS data. There are a four FTP sites that have data from 359 GPS receiver stations around the world as of

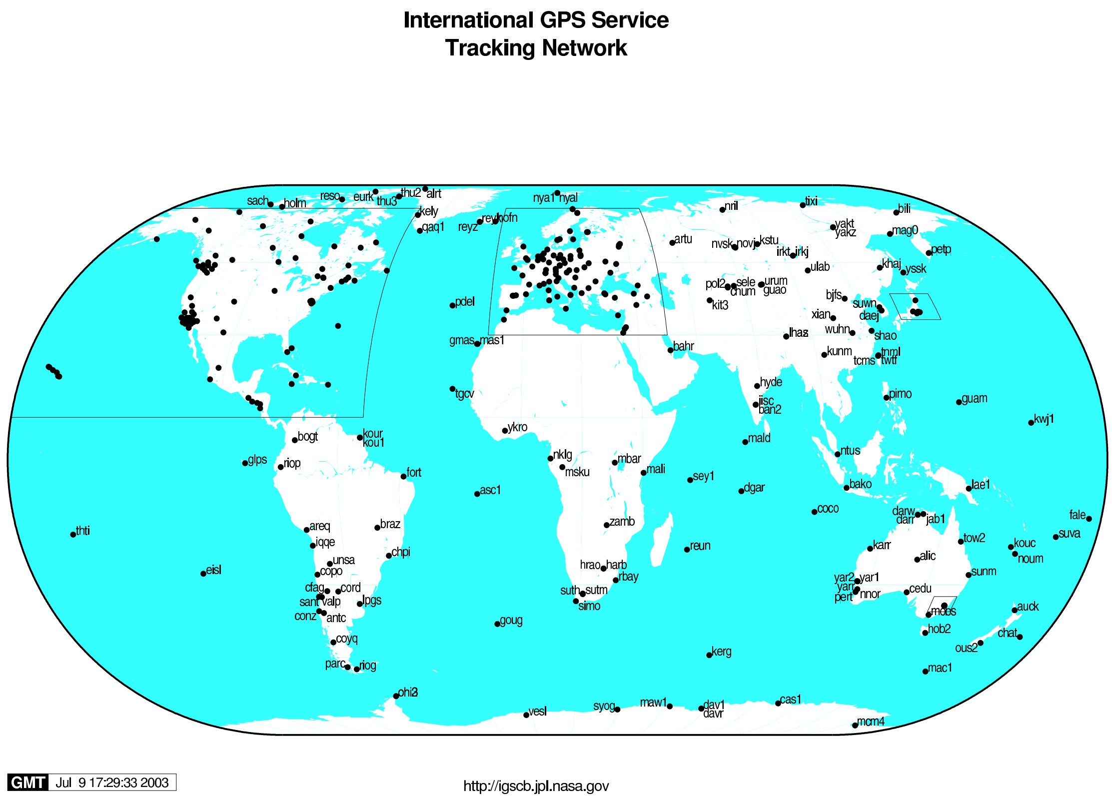

Figure 3: The IGS map of world receiver sites.

June 2003. The web site has maps such as Fig. 3; clicking on a station brings up information about that station. Information about the individual GPS receiver sites for the IGS network is available at `http://igscb.jpl.nasa.gov/network/netindex.html` (from IGS home: Data & Products ➔ Using Data & Products ➔ IGS Tracking sites). This page contains a variety of formats for station information, including clickable maps with links to detailed information on each site. Some of these pages contain photographs of the site in detailed descriptions of the geographic environment. All sites are referenced by their four-character site identification. This identification is important for retrieval of files from the FTP servers.

Each of the FTP servers has the files organized slightly differently, but the data is the same. The links are obtained from Data & Products ➔ IGS Data Products; for the purposes of this project, the "Broadcast" part of "GPS Satellite Ephemerides/Satellite & Station Clocks" section is appropriate. The four sites and their access information are given below. The location of the files is determined by the time and site of the receiver data; *yy* means the two-digit year, *yyyy* means the four-digit year, *ddd* means the day of year, *ssss* means the four-character site code.

CDDIS operated by NASA, `ftp://cddisa.gsfc.nasa.gov/pub/gps/gpsdata/`

> **OBS files** *yyddd*`/`*yy*`o/`*ssssddd*`0.`*yy*`o`
>
> **NAV files** *yyddd*`/`*yy*`n/`*ssssddd*`0.`*yy*`n`.

SOPAC operated by the University of California, `ftp://garner.ucsd.edu/pub/nav/`

> **OBS files** *yyyy*/*ddd*/*ssssddd*0.*yy*o
>
> **NAV files** *yyyy*/*ddd*/*ssssddd*0.*yy*n

IGN in France, `ftp://igs.ensg.ign.fr/pub/igs/data/`

OBS files *yyyy/ddd/ssssddd*0.*yy*d; note this data is only available in a special compact RINEX file format.

NAV files *yyyy/ddd/ssssddd*0.*yy*n.

IGS CB does not have the daily broadcast data we use for this project.

Generally, the sites have the same data, however, they may have different formats or some may be missing some data. The files are compressed with the UNIX utility `compress` and must be uncompressed with that utility. A DOS version is available on the IGS site.

Explanation of RINEX format

Both the NAV and OBS files are presented in the Receiver INdependent EXchange (RINEX) format. A widely-available document by W. Gurtner explains this format; see for example `http://www.ngs.noaa.gov/CORS/instructions2/`. The most useful part of this document for our purposes are the tables at the end; specifically, Tables A1 through A4, which describe the NAV and OBS file formats and show examples. Some familiarity with Fortran formatting is needed to interpret the field specifications; though few students nowadays know this, the information is readily available on the web.

Analysis and Limitations

GPS position determination can be considered an "upside down orbit determination": instead of a known observer finding the unknown orbit of the satellites, the unknown observer position is determined from known orbits. The method is trilateration, but with an extra GPS satellite, or "Space Vehicle" (SV), to determine unknown receiver clock bias. Basic trilateration requires three pseudoranges to find a position in three-space, so a GPS position determination requires four pseudoranges. Extra data can be used to find and reduce the uncertainty.

The first step of the analysis is to extract pseudorandom noise (PRN) pseudoranges from the RINEX file. The simplest analysis is to use exactly as much data as is needed to solve the location; i.e., four pseudoranges. Because the receiver is stationary, they do not need to be recorded at the same time, but there are always at least four data records from different SVs at a given time, so it is easiest to start by taking all four at the same time. The SV ephemeris must be propagated to the time of observation from the nearest epoch given in the observation file. These epochs are every two hours on the even hour. This propagation is described in Kaplan (Ref. 5, Table 2.3).

The solution scheme is to iteratively compute $A^{-1}l$, where A is the Jacobian matrix of derivatives of pseudorange as a function of observer position and l is the residual vector, the difference between actual range and pseudorange (Ref. 4, Sec. 9.4.1). It is also important to include transmitter clock bias which is included in the NAV files; while receiver bias may be solved for, transmitter bias must be known. The differential correction should converge reasonably well to within tens of meters of the actual location of the receiver, which is given in the header line of the OBS file. With this information, the students have completed the basic part of the analysis.

For a more advanced analysis, additional data from the same receiver may be added. This is done in one or both of two ways. Since there are almost always more than four SV signals received, the additional pseudoranges can be added into the set. Since the receiver is stationary, more than one time point may be used. The standard update function for differential correction,

$$\Delta \boldsymbol{X} = \underbrace{(A^{\mathsf{T}} A)^{-1}}_{P} A^{\mathsf{T}} \boldsymbol{l} \tag{1}$$

is seen to reduce to the exactly-determined formula $A^{-1}\boldsymbol{l}$ when A is a square (in our case 4×4) matrix. Thus with a little advanced planning, the coding necessary to solve one problem can be used to solve the other. The quantity P is the covariance matrix and is used to calculate the DOP.

The two precision signals P1 and P2, are at frequencies of 1575.42 MHz and 1227.6 MHz respectively. These frequencies are in the ratio 77/60. We define the square of this ratio $\gamma = (77/60)^2 \approx 1.64694$, which is used to correct the times and pseudoranges.

It is important to compute the transmitter clock bias (Ref. 6, Sec. 20.3.3.3.3.1) because only the receiver clock bias is solved, not the transmitter, and it can be large, up to several tenths of a second. The OBS file has the appropriate coefficients of the constant, linear, and quadratic correction terms, described as "SV clock bias," "SV clock drift," and "SV clock drift rate" in the RINEX explanation.

If only a single PRN pseudorange is used, it should be corrected by subtracting the SV group delay differential T_{GD} (Ref. 6, Sec. 20.3.3.3.3.2) for the P1 signal or γT_{GD} for the P2 signal. T_{GD} is provided in the NAV file and is usually on the order of nanoseconds. If the two PRN pseudoranges from the two frequencies are available, it is possible to correct for ionospheric effects by combining both signals for an effective pseudorange

$$R = \frac{P_2 - \gamma P_1}{1 - \gamma} \tag{2}$$

(Ref. 6, Sec. 20.3.3.3.3.3).

Example

From the IGS site, we may extract the information for THTI, the site at Papeete, Tahiti. Data was obtained from CDDIS:

- `ftp://cddisa.gsfc.nasa.gov/pub/gps/gpsdata/03157/03n/thti1570.03n.Z`
- `ftp://cddisa.gsfc.nasa.gov/pub/gps/gpsdata/03157/03o/thti1570.03o.Z`

and the identical data was confirmed to be present on SOPAC. The time chosen for this analysis was 2003–06–06T12:30:00.000GPS, and all observations from this timepoint up to and including 1 minute later were used. This obs file is typical in that observations were recorded every 30 seconds, so that there were a total of 3 observation time points included. The first observation frame looks like

```
 03  6  6 12 30  0.0000000  0  8G10G17G26G21G 6G29G24G 9
 -10401675.54246   1332017.22245  22730670.0874   22730674.0494         13.7504
        11.0004        -640.4314
 -16129004.40547 -12424625.93646  21295768.0794   21295772.2524         25.7504
        21.5004        1837.9124
 -16141448.12747 -10230114.26346  21351701.2244   21351704.4834         25.2504
        21.5004       -1443.2114
 -11510953.13746  -8801810.40546  22467953.6874   22467955.8324         17.7504
        13.2504        2696.2024
  -8424542.85846  -6398147.05945  22935503.5504   22935506.3284         12.2504
        10.7504       -1388.9494
 -14795840.91146 -11087159.12946  22057291.7254   22057296.0164         16.0004
        13.7504       -2441.9264
  -4743239.55145   4984020.42145  23991944.2294   23991952.9734          8.0004
         6.5004       -3332.7884
 -16002267.83747 -12209540.36546  21379710.2644   21379713.7114         26.0004
        22.0004        1995.1994
```

There were eight SVs (GPS satellites) whose signals were received, which are identified with their PRN numbers, 6, 9, 10, 17, 21, 24, 26, and 29; the computed data received follows in line pairs corresponding to the SV order listed in the first line. A header line given at the top of the file (not shown here) indicates that each of these data records (line pairs) contains seven fields of data: L1

L2 C1 P2 S1 S2 D1. The L1 and L2 refer to the phase measurements (cycles) on the two GPS signals, C1 is the C/A (coarse) pseudorange in meters, P2 is a precision pseudorange, S1 and S2 are signal strengths, and D1 is a Doppler frequency (Hz). We shall use the precision pseudorange; since selective availability was turned off in 2000, there is no reason why the precision signal shouldn't be used. Thus it is the fourth number in each data record that forms the basis for our analysis.

Solving the simplest case with the data above for PRNs 6, 9, 10 and 17 (records 1, 2, 5, and 8 in the frame), we can obtain an exact solution using P2 without correcting the pseudorange

$$\begin{bmatrix} -5246.263213 \\ -3077.204292 \\ -1913.791086 \\ 34.013014 \end{bmatrix} \text{km}, \tag{3}$$

where the first three numbers are the ITRF coordinates and the last is the clock bias measured in light-distance ct. Comparing with the official position of the THTI station given in the header frame of the observation file, this represents an position error of 168.99 m. If the T_{GD} is included, the result improves to 168.875 m.

To get greater accuracy and some knowledge of error, we may include excess information and perform a least squares estimate. Expanding to all eight PRNs from this frame and computing the differential correction until the RMS ceases to change significantly, we obtain a position/clock bias estimate and a standard deviation of those parameters:

$$\begin{bmatrix} -5246.317735 \\ -3077.257708 \\ -1913.823349 \\ 34.058482 \end{bmatrix} \pm \begin{bmatrix} 0.056114 \\ 0.043745 \\ 0.022019 \\ 0.042616 \end{bmatrix} \text{km}. \tag{4}$$

This represents a position error of 96.328 m, about half of what was obtained from the 4 PRNs. Moreover, the magnitude of the position part of the standard deviation is 74.480 m, so our estimated error does approximate the actual error.

Next, we can try including a range of observations times, say three over one minute (12:30:00, 12:30:30, and 12:31:00). Each of these has the same eight PRNs; in addition, the last time has an addition observation from PRN 18 but it does not have a P2 pseudorange signal, for a total of twenty four pseudoranges. We then obtain an estimate

$$\begin{bmatrix} -5246.316121 \\ -3077.257428 \\ -1913.822658 \\ 34.062706 \end{bmatrix} \pm \begin{bmatrix} 0.024948 \\ 0.017654 \\ 0.010993 \\ 0.017885 \end{bmatrix} \text{km}. \tag{5}$$

Notice that the standard deviations are significantly reduced; the position magnitude is 32.479 m. However, the actual accuracy, 97.981 m, is no better than the single time analysis, indicating some kind of systematic bias.

A similar systematic bias is found on every receiver site; they amounts vary, but it's usually in the neighborhood of 50 to 100 meters. The official antenna position given in the OBS file is known to be unreliable, but should be within a meter or so. When computing with the two precision PRN pseudoranges P1 and P2, the application of the dual frequency ionospheric correction (2) typically results in a change of a few meters of pseudorange.

An interesting thing happened when I first processed the observations with four timepoints. The results obtained were wildly inaccurate, putting Tahiti more than 1800 km from its actual location. An analysis of the RINEX file shows that at 12:31:30, PRN 18 is recorded as

```
  -69792.51044                 24609308.6974                              6.7504
                  1704.4254
```

Notice that the precision pseudorange P2, which would be the fourth field and thus columns 49 through 63, is missing. This caused a misalignment of data in the parsing software, which resulted in the wildly inaccurate results. Parsing data files correctly is one of the lessons to be learned in this project, and not just for the students.

It has been my experience that you can always use the center of the earth and a zero clock bias as a starting vector for any GPS observation; no rough guess at the actual position is necessary. At most, one or two extra iterations of the differential correction are necessary over a good guess in the neighborhood. All of these calculations were performed with the center of the earth and zero clock bias as the initial guess.

Student experience with this project in the fall of 2002 was positive, with all two of three groups obtaining results from at least one receiver site with approximately the same accuracy as illustrated above. One group could not get accurate answers from any data tried. Among the problems encountered that were overcome were

- Singular or near-singular update matrix when processing exactly four observations. This is caused by satellites being too close together rather than spread out in the sky.
- Missing ephemeris data in the NAV file for satellites from which pseudoranges were received. This may be resolved by finding another NAV file for that time period that is complete.
- Proper uncompression of files and interpretation of data. Some browsers helpfully attempt to uncompress files encountered on web sites but do a bad job; data then appears in the wrong columns and lines are not properly terminated. In addition, some students were unfamiliar with the "D" notation for exponents, despite being given a reference to Fortran formatting conventions.

Future enhancements

There are some possible enhancements to this project that would given the students a more in-depth knowledge of GPS technology, and might provide more accurate answers. First, of course, the $\approx 100\,\text{m}$ position error should be solved. Utilization of phase pseudorange should give more precise results, and application of differential GPS not only should provide more accuracy, but give the interesting possibility of tracking the positions of the ground stations relative to each other.

Student Instructions

The following are instructions given to the students.

Introduction

In this project, you will compute the position of several ground station GPS receivers. You will read and interpret data from a web site and then apply principals of position determination learned in class to find the positions of the receivers.

Because GPS is not covered in class until the end of the semester, I will supply you with the notes and supplementary reading material from which you can study; although it will require extra work earlier in the semester, you will have the advantage that you will have mastered the material when the rest of the class is studying it.

Gathering Data

There are two kinds of files needed to compute a receiver position:

- The *GPS Navigation Message File* or *NAV* file which contains ephemeris data for each GPS satellite (called "Space Vehicle" or SV) in view over the time period of your received signals. These files have the letter "n" at the end of the name. They are filed separately from the observation data because they are independent of it.

- *The GPS Observation Data Files* or *OBS* file for each of the sites you are studying. This contains receiver data such as pseudoranges to all the satellites in view. These files have the letter “o” at the end of the name.

You will gather data from one of two places which has archived received GPS data from numerous ground stations around the world. These are

- Continually Operating Reference Stations (CORS)(US and territories, plus Central America) use the user friendly CORS page to obtain the data, selecting
  - “No” to NGS data sheet and SP3 format,
  - pkzip as the compression, so that it will bundle all the files.
- International GPS Service (IGS)(worldwide). The map shows the available sites, or consult the list. The two chief repositories of IGS information and their file naming conventions are
  - CDDIS `ftp://cddisa.gsfc.nasa.gov/pub/gps/gpsdata/`
    - OBS files: *yyddd*/*yy*o/*ssssddd*0.*yy*o
    - NAV files: *yyddd*/*yy*n/*ssssddd*0.*yy*n.
  - SOPAC `ftp://garner.ucsd.edu/pub/nav/`
    - OBS files: *yyyy*/*ddd*/*ssssddd*0.*yy*o
    - NAV files: *yyyy*/*ddd*/*ssssddd*0.*yy*n.

  where *yy* is the two digit year, *yyyy* is the four digit year, *ssss* is the site code, *ddd* is the three digit day of year.

Most people use this data for very precise correction of their own GPS receiver data, to enable precision surveying. Your purpose will be slightly different; you will be developing your data interpretation and position determination skills to find where the sites are located (which incidentally are no big secret; the exact location is given in the position POS file).

Each of these services has numerous GPS reporting sites, as you can see by exploring their maps. You should select at least four receiver sites that are not near each other. For each time period, you will need the NAV and the OBS file. Sometimes the file is compressed to save space; in this case, it has a “`Z`” or “`gz`” suffix. Instructions are given on how to decompress these files. Be careful that your browser doesn’t automatically try to uncompress; in the past, there have been problems with the results. Columns of numbers should be neatly lined up. If they are not, try saving again, selecting “plain text” as the option for saving the file.

Interpretation of Data

Data from both services are presented in the Receiver-INdependent EXchange, or RINEX, format, which is explained on the CORS site (click Instructions ➔RINEX-2 Format on the left). Note that the end of this file contains several tables which explain the data format of the two types of files you have downloaded. These are explained line by line, but note that there will be much data that you can ignore. The “FORMAT” given in the right-hand column is a Fortran format specifier, `http://adc.gsfc.nasa.gov/adc/fortran.html>` and is easy to interpret without knowledge of Fortran.

Analysis

You will compute the position of the ground station in two steps:

1. Find each satellite’s ECEF position from the information in the GPS Navigation Message Files. This must be done at each time for which you wish to compute position. It is done in a slightly different way than we learned in class; I have posted a copy of the relevant section of Kaplan (see reference below) in which it is shown how to compute these positions.

2. From the pseudoranges given in the GPS Observation Data Files, a linearized trilateration calculation may be applied to compute the ECEF position of the receiver, the clock bias, and an error estimate of the both. See posted excerpt from Kaplan, and/or my lecture notes. There are two *code pseudoranges*: C1 (coarse acquisition) and P1 or P2 (precision). Use one of the latter if available.
3. Your result may be compared with the location given in the OBS header (which isn't necessarily very accurate, but will suffice for the purposes of this class).

After you have completed the basic analysis on the four ground stations, you should additional observations over time for a particular station and see if the position error can be reduced.

Notes

- Longitude (*not* right ascension) of the ascending node has two time-dependent terms: the product of the node rate (Omega dot) and the time from epoch, and the product of the rotation rate of the earth and the time from *the beginning of the GPS week* which is given in the data record of the GPS Navigation Message File as "Toe." Be sure to keep these times separate. All other rates are multiplied by time from epoch.
- On the CORS site, there is a "data availability" option, which supposedly indicates what dates and times are available. Even when it says a particular time is available, it may not be on the web site and an attempt to download the file(s) will result in a time out.

References

The following two books will be helpful:

- Hoffmann-Wellenhof, Lichtenegger, Collins: *GPS Theory and Practice*, Fifth edition, Springer-WienNewYork, 2001.
- Kaplan, ed.: *Understanding GPS Principles and Applications*, Artech House, 1996.

In addition, I have lecture notes on GPS that I will use at the end of the semester when we cover this topic in class.

PRESENTATIONS

The students are expected to prepare, as a group, a written report on their project, and to give a short oral presentation at the end of the semester. They are told to address an audience that is presumed to know the material from the predecessor class, *Space Flight Dynamics*, ENAE 404, but not from the current class. They are told to divide their written report into several sections:

1. Abstract,
2. Introduction,
3. Results,
4. Conclusion,
5. References,
6. Computer code.

Most groups take the project seriously and do an excellent job in attempting to obtain reasonable conclusions. The quality of the written report frequently leaves much to be desired however. In fall 2002, the students were required to turn in a draft report, and I returned it to them with written comments but otherwise ungraded. It is my experience that doing so increases the quality of the written report, and this requirement will be retained in future semesters. Since students are learning about research papers and generally do not have experience reading them, explanations of what is required in each section are necessary.

CONCLUSION

Space Navigation and Guidance includes a number of concepts that are better learned with practical experience. Two of these, satellite orbit determination and GPS position determination, are viable group projects. Depending on the observatory facilities available, a modestly accurate orbit of several kilometers and tens of meters per second is possible, using predictions available on the web. Conversion to orbital elements yields less satisfying results because invariably these orbits are very nearly circular, so the inaccuracy of the observations translates to wild inaccuracy of the singular elements. Data for the GPS project requires only access to the web, and a certain patience for acquisition and interpretation of data files. Thus, prior mapping of data locations as given in this paper helps overcome this non-educational challenge. Once data has been interpreted, familiar differential correction techniques are readily applied to determine the receiver's position to within about 100 meters.

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