Student Projects for Space Navigation and Guidance

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Two Group Projects

• Determination of a satellite orbit from telescope observations of a satellite.

• Position determination of a Global Positioning System (GPS) receiver from data on the web.
The Class

- This class: ENAE 441 *Space Navigation and Guidance* covers orbit determination, including estimation, and GPS

- Previous class: ENAE 404 *Space Flight Dynamics* covers basics of orbit and attitude mechanics

- Students have spent the semester mastering orbit determination techniques

- Differential correction (Newton's method) as a solution to nonlinear vector equations, including least squares for estimation
The Project and its Goals

- Group project is required of all students
- Ideally 4 students in a group
- Teach the concepts learned in class, but in a practical setting with real data, acquired the hard way
- Not as easy as a textbook, but ideas still work
- Verbal and written expression of what was done and what was learned
Observatory project

- University observatory near campus
- 2° field of view spotting scope for 14" Schmidt Cassegrain
- Keypad entry RA, dec
- Trees, haze
- Move quickly!

Students from 2001 class at the observatory; James Clark, Troy Sookdeo, Brian Kujawa, Ben Lee, Neal Gupta
Photo from their report
Predict satellites from Heaven's Above

- [http://heavens-above.com](http://heavens-above.com)
- Given lon, lat, shows visible satellites that evening
- Star chart available with more precise data
- Details on satellite (TLE, etc.)
- Sometimes old elsets
Starchart from Heaven's Above

- Clicking on “Max Altitude” (elevation) time brings up star chart
- Sky track with 30 second ticks
- Click to center, read RA/dec at bottom
Making Observations

• Students arrange for observatory time
• Prepared with information about several satellites
• Data 1 minute apart, several minutes between satellites
• Jobs: Secretary, keypad, observer, flashlight
• Practice; first satellite is usually a lost cause
• Weather must be reasonably clear
Observation data and processing

- As satellite comes nearest the crosshairs, time is recorded
- Fractional estimate of how close it came
- Not always exact: old elements, etc.
- Gauss angles-only orbit determination
- Orbit estimation
- Several satellites for good luck
COBE observations
Seven observations in one pass
November 6, 2000

<table>
<thead>
<tr>
<th>Predicted Time (EST)</th>
<th>Observed Time (EST)</th>
<th>Right Ascension</th>
<th>Declination</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>17:31:30</td>
<td>17:31:29</td>
<td>21:48:00</td>
<td>-16.3°</td>
<td>1</td>
</tr>
<tr>
<td>17:32:30</td>
<td>17:32:30</td>
<td>21:41:00</td>
<td>-2.0°</td>
<td>0</td>
</tr>
<tr>
<td>17:33:30</td>
<td>17:33:30</td>
<td>21:31:45</td>
<td>19.3°</td>
<td>0</td>
</tr>
<tr>
<td>17:34:30</td>
<td>17:34:30</td>
<td>21:14:00</td>
<td>46.9°</td>
<td>3</td>
</tr>
<tr>
<td>17:35:30</td>
<td>17:35:29</td>
<td>20:28:00</td>
<td>71.9°</td>
<td>3</td>
</tr>
<tr>
<td>17:36:30</td>
<td>17:36:30</td>
<td>15:01:00</td>
<td>84.6°</td>
<td>2</td>
</tr>
<tr>
<td>17:37:30</td>
<td>17:37:30</td>
<td>11:03:00</td>
<td>76.1°</td>
<td>0</td>
</tr>
</tbody>
</table>
### COBE Cartesian processed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>X (km)</th>
<th>Y (km)</th>
<th>Z (km)</th>
<th>Vx (km/s)</th>
<th>Vy (km/s)</th>
<th>Vz (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>3528.320</td>
<td>-4313.871</td>
<td>4654.938</td>
<td>-4.1033</td>
<td>2.658</td>
<td>5.564</td>
</tr>
<tr>
<td>Initial Orbit Determination</td>
<td>3522.654</td>
<td>-4309.333</td>
<td>4646.863</td>
<td>-4.048</td>
<td>2.631</td>
<td>5.499</td>
</tr>
<tr>
<td>Full Estimation</td>
<td>3533.316</td>
<td>-4319.816</td>
<td>4659.711</td>
<td>-4.143</td>
<td>2.676</td>
<td>5.636</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>14.524</td>
<td>12.545</td>
<td>20.598</td>
<td>0.144</td>
<td>0.086</td>
<td>0.189</td>
</tr>
<tr>
<td>Difference estimated-actual</td>
<td>4.996</td>
<td>-5.945</td>
<td>4.773</td>
<td>-0.040</td>
<td>0.018</td>
<td>0.072</td>
</tr>
<tr>
<td>Time adjusted estimation</td>
<td>3515.942</td>
<td>-4303.236</td>
<td>4632.720</td>
<td>-3.983</td>
<td>2.586</td>
<td>5.404</td>
</tr>
<tr>
<td>Time adjusted standard deviation</td>
<td>4.921</td>
<td>4.234</td>
<td>6.954</td>
<td>0.049</td>
<td>0.029</td>
<td>0.064</td>
</tr>
<tr>
<td>Difference time adjusted-actual</td>
<td>-12.378</td>
<td>10.635</td>
<td>-22.218</td>
<td>-3.983</td>
<td>-0.072</td>
<td>-0.160</td>
</tr>
</tbody>
</table>

Positions within a few km, velocities tens m/s
### COBE Elements

Convert the previous Cartesian results to elements:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>a (km)</th>
<th>e</th>
<th>i</th>
<th>RAAN</th>
<th>Arg. perigee</th>
<th>Mean anomaly</th>
<th>Mean arg. latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>7264.91</td>
<td>0.00100</td>
<td>98.900</td>
<td>-43.204</td>
<td>163.259</td>
<td>-122.706</td>
<td>40.553</td>
</tr>
<tr>
<td>Gauss IOD</td>
<td>7062.92</td>
<td>0.02625</td>
<td>98.870</td>
<td>-43.256</td>
<td>-142.214</td>
<td>-177.231</td>
<td>40.555</td>
</tr>
<tr>
<td>State estimate</td>
<td>7441.31</td>
<td>0.02300</td>
<td>98.916</td>
<td>-43.192</td>
<td>37.549</td>
<td>2.768</td>
<td>40.317</td>
</tr>
<tr>
<td>Time + state estimate</td>
<td>6822.07</td>
<td>0.06052</td>
<td>98.895</td>
<td>-43.253</td>
<td>-141.282</td>
<td>-178.103</td>
<td>40.615</td>
</tr>
</tbody>
</table>

- Agreement for inclination, RAAN are good (green)
- Semimajor axis could be better (yellow)
- Near circular orbit, eccentricity and elements based on perigee are bad (red)
- but mean argument of latitude, sum of mean anomaly and argument of perigee, is very consistent
GPS Project

• Two web sites with GPS receiver data:
  – CORS Continuously Operated Reference Stations
    http://www.ngs.noaa.gov/CORS
  – IGS International GPS Service
    http://igscb.jpl.nasa.gov/

• Data is in industry-standard RINEX format

• Not as much fun as hands-on data acquisition, but plenty challenging nonetheless
CORS: 387 sites, US & Possessions
IGS: 359 International Sites
Position determination with GPS

- **Upside-down orbit determination**: satellite orbit known, but not observer's position
- **Trilateration**: minimum of 4 satellites (solve for receiver clock bias)
Solving position equations

- Simultaneous solution of 4 equations (one for each satellite)
- 4 unknowns (three position + clock bias)
- Linearized equations, iterate to converge to solution
- Any starting position is OK: center of earth
- Differential correction: add rows to Jacobian matrix $A$
Interpreting Data

• Two RINEX files,
  - OBS (.03o) with receiver data
  - NAV (.03n) with SV (GPS sats) ephemeris

• Algorithms for computing ITRF position at any desired time from NAV data

• Code pseudoranges from OBS data

• Reading file: compressed gzip, zip, or compress, some browsers do a bad job

• Finding fields and interpreting columns correctly
THTI: Papeete, Tahiti receiver data

- On 2003-06-06 12:30:00 GPS, there were signals received from 8 GPS satellites

- Process
  - 4 lowest PRN#s: 6, 9, 10, 17
  - then full 8 for one time
  - then 8 for three times (24 points, one minute period, 30 second data interval)
## THTI Position determination

<table>
<thead>
<tr>
<th>Parameter (km)</th>
<th>4 PRN Determination</th>
<th>8 PRN Estimation</th>
<th>8 PRN Standard Deviation</th>
<th>Actual</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITRF x</td>
<td>-5246.263</td>
<td>-5246.318</td>
<td>0.056</td>
<td>-5246.412</td>
<td>0.0945</td>
</tr>
<tr>
<td>ITRF y</td>
<td>-3077.204</td>
<td>-3077.258</td>
<td>0.044</td>
<td>-3077.276</td>
<td>0.0187</td>
</tr>
<tr>
<td>ITRF z</td>
<td>-1913.791</td>
<td>-1913.823</td>
<td>0.022</td>
<td>-1913.825</td>
<td>0.0018</td>
</tr>
<tr>
<td>Clock bias ct</td>
<td>34.013</td>
<td>34.058</td>
<td>0.043</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

distance (m) 96.31
Accuracy of results

- All sites tried show 50-100m error; student experiences similar
- Error not in a notable direction (e.g. up)
- Ionospheric correction only helps a tiny bit
- Adding more data does not help, not random noise
- Still a mystery
Experiences

- Observatory last three fall semesters, GPS last fall; both will be repeated
- Students take project seriously, and do an excellent job in the investigation
- Written and oral reports leave something to be desired
- I have started working with them during the semester on the reports so they understand how to write/present research papers