An Introduction to Space Mission Planning

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A space mission starts with a technical objective - a science objective, a technology objective, a political objective, or some combination of the three. Missions with science objectives include Magellan, Mars Observer, Galileo, and Ulysses. Missions with technology and science objectives include the Clementine mission, currently on the way to the Moon, and the most prominent set of missions with combined science, technology, and political objectives were the Apollo missions.

The focus of this presentation is the mission planning / mission design process. However, this process cannot be separated from the design of the spacecraft itself, as the mission design and scenario strongly affects the design of the spacecraft and the available technologies strongly affects the design of the mission. This was graphically demonstrated during the Apollo program. Early mission designs called for the entire assembly which left earth orbit to land on the Moon. Then, the upper stage of the assembly which landed on the Moon would enter lunar orbit and would return to earth. Thus, the fuel (and associated hardware) required to initiate the trip home from the moon, had to be carried to lunar orbit, deorbited and soft landed on the moon, boosted back to lunar orbit, and then burned to send the Apollo spacecraft back to the earth. The total mass required to do this would have required two Saturn V boosters to place in low earth orbit (LEO) and would have required an Earth Orbit Rendezvous (EOR) at the beginning of the mission.

Mission planners in NASA suggested the scenario that we actually used (Lunar Orbit Rendezvous - LOR) which cut the size of the booster required to one Saturn V. In the LOR scenario, we parked the return capsule, its engine, its return fuel, and one of the astronauts in Lunar orbit. We sent a much smaller vehicle (the Lunar Descent Module and the Lunar Ascent Module) to the lunar surface, which required much less fuel to deorbit and land. We then sent a much smaller ascent module back to lunar orbit - again requiring less fuel. Finally, we left the ascent module to crash into the moon -- and did not accelerate it back toward the earth -- again saving fuel. In this case, even more than with most missions, the mission plan strongly affected the design of the spacecraft.
The hardware design most often affects mission design in many ways. The current state of technology, what we can do and what we can't do is the primary driver. Many missions are limited by the amount of velocity change available (amount of fuel - types of fuel, etc.). Missions are also limited by other factors such as sensor capabilities, battery lifetimes, duration of time that we can sustain life, the radiation environment, the positions of the planets, etc. Finally, missions are limited by their costs and by errors in the planning process.

What I'd like to do now is to show you a very simplified version of the planning process for one of the most common missions which has been flown to date - the placing of a geostationary satellite in orbit using the Space Shuttle as a booster.

Geostationary Orbit (GEO)-

A geostationary orbit is an orbit which lies in the equatorial plane of the earth (or very close to that plane), which has a period of rotation equal to that of the earth, and which then seems to stay fixed at a point over the equator. We can see images from these satellites on the weather news each night. We saw events such as the winter Olympics from Lillehammer, Norway, relayed via communications satellites in Geostationary orbits.

The period of a geostationary orbit is NOT 24 hours. It is 23 hours, 56 minutes, and 4 seconds. The difference of 3 minutes and 56 seconds is due to the difference between the solar day (time from noon to noon) and the time that it takes the earth to rotate 360°. The earth rotates almost 361 degrees in 24 hours because it moves almost a degree in its orbit around the sun each day. The radius of a geostationary orbit is 22,766 nautical miles (26,199 statute miles, 42,162 km).

Space Shuttle Orbit (LEO)

The space shuttle, on missions on which it is to launch deploy satellites for boost to GEO, launches due east into an orbit which has an inclination of 28.5°, the latitude of the launch site at KSC. This is the lowest inclination orbit which the space shuttle can achieve launching from KSC. (The lowest inclination orbit which ANY booster can achieve -- without some fancy and costly (in fuel terms)
maneuvering -- is equal to the latitude of the launch site. The ground track of the space shuttle orbit is the familiar track which looks like a sine wave - which we see on the plotting boards at mission control. This track - and especially where it crosses the equator -- is a key to the timing of our mission planning process. The points at which the satellite crosses the equator are called node crossings and these are the points at which important events occur on this type of mission. The radius of a typical Low Earth Orbit for satellite deployment is about 3600 nmi (6670 km, 4142 statute miles) The corresponding altitudes are 157 nmi, 290 km, and 180 statute miles. These orbits are approximately circular. Their eccentricities are VERY small -- usually $0.002 < e < 0.009$. (perigee and apogee differ by less than three nautical miles).

Transfer Orbits

The transfer orbit from LEO to GEO is based on the Hohmann transfer. The Hohmann transfer is a transfer between two coplanar circular orbits in which the transfer ellipse is orbits. The transfer orbit which we shall use is not exactly the classical Hohmann transfer, because there is a plane change involved. Somehow, during the transfer, we must change the inclination of the orbit from $28.5^\circ$ to $0^\circ$. The amount of fuel which the transfer will require is highly dependent on the scenario used for the transfer. Basing the transfer on the Hohmann transfer limits us to transfers between the nodes of the orbits and sets the requirement that our rocket be capable of providing two impulses (we assume impulsive velocity changes during the first stage of mission planning). The following diagram shows some of the possibilities and the amounts of delta V required for three of the scenarios. The three scenarios are:

1. Make the plane change at the low point in the transfer orbit
2. Make the plane change at the high point in the transfer orbit
3. Make part of the plane change low (during the first burn) and part of the plane change high (during the second burn).

It is obvious from the cases 1 and 2 that making the plane change low is very costly. However, we must make a substantial velocity change low, and adding a small plane change to this burn might not cost much and might reduce the delta V required at the other end of the orbit. Let me show you the result of a numerical experiment in
which I let the amount of plane change done at the low point of the transfer orbit vary from zero to 28.5°. We have plotted the total delta V required for the mission versus the amount of plane change done low. The minimum is obvious here, and this is the way that LEO-GEO missions are done. Note: these results hold ONLY for launches from a launch site which is at a latitude of 28.5° (North or South). Similar plots hold for launch sites at other latitudes.

The first plot indicates that there is a minimum around 2° for Delta i in LEO. It also indicates that we should never consider doing all of the plane change low. It would cost us over 7000 ft/sec extra to do it this way (over 50% more). The second plot shows the minimum much more clearly. It shows that we save about 90 ft/sec if we do 2.2° of the plane change low rather than doing it all high. The third plot shows the relative amounts of delta V in LEO and GEO for the various mission scenario options.
Now let us recap what we know about the mission. We will launch from KSC, initiate our transfer at a node, end our transfer at the next node, and will do most (27.3°) of the required 28.5° plane change at GEO. The first burn will be about 8000 ft/s and the second will be about 6000 ft/s. To put this into perspective, the TOTAL delta V carried by the shuttle - once on orbit, is only about 1000 ft/s. This includes the delta V needed for the deorbit burn. The shuttle is a massive vehicle.

Satellite Placement at the Correct Longitude

Now let us consider how we place the satellite where we want it. The earth turns about 15 degrees per hour (15.041°/hr) and the transfer from LEO to GEO is one half of the period of the elliptical transfer orbit. This turns out to be 5 hr 16 min 6 s. If we use rough numbers, the transfer takes 5 1/3 hours and the earth turns at 15 degrees per hour. Thus, the earth turns 80 degrees while the satellite is in transit from LEO to GEO (79.23° to be exact). The satellite moves 180° while the earth moves 80° and the satellite is back at a node (crossing the equator again) when it reaches GEO. This means the node at the end of the transfer is about 100° east of the node at which the transfer started (100.77° to be exact). Thus, the "shuttle" must be crossing the equator 100° east of the target longitude when the transfer initiation burn occurs.

Now let us look at how we use the information which we have just developed to determine when -- in the mission -- the transfer takes place. We go back to the ground track of the shuttle -- which depends on the orbit into which the shuttle is inserted. The nodes shift westward each orbit by an amount determined primarily by the rotation of the earth (and secondarily by the oblateness of the earth). The earth rotates 360° per day under the orbit and the orbit moves about 7° per day due to the oblateness of the earth (this effect is called orbital precession). The westward shift of the nodes then depends sum of the two node rates and the period of the orbit itself. Most shuttle orbits have periods between 90 and 96 minutes, giving node shifts per orbit of between 23.1° and 24.5°. NASA provides printed ground tracks for its missions which are used by all those associated with the mission. I have brought one of those ground tracks with me.
Let us suppose that we wanted to deploy a satellite to be inserted into GEO at a longitude of 160° west longitude - south of Hawaii - call it HulaSat. The target longitude is then 160° west longitude and the transfer should be initiated about 100 degrees west of there - at about 260° West or 100° East Longitude. We must find a node (equator crossing) at about 100° East Longitude -- and we find several near there on the ground track which NASA provided.

The transfer must be initiated at one of these nodes - this determines when -- in the mission -- the satellite must be deployed. NASA procedures call for the satellite to be deployed from the shuttle at the node prior to the transfer initiation node (45-48 minutes before transfer initiation) and for the shuttle to move to a point above and behind the transfer vehicle (about 10 nmi away). the shuttle then turns so that its rear end faces the transfer vehicle to minimize damage from exhaust particles.

To recap, we now know how to plan a LEO to GEO mission for a geosynchronous satellite deployed from shuttle. We need a target longitude and a groundtrack plot (or a list of the node crossings), and that is about all. We know that the transfer will initiate about 100 degrees west of the target longitude, and we use this information to determine the nodes at which the transfer initiation can occur. The choice of which node to use depends on other mission factors such as sleep cycles, what else is going on, etc. Usually two (or more ) opportunities are chosen, on as the primary and the second as a backup in case something happens so that the deployment could not occur at the primary opportunity. Our transfer will take 5 hr 16 minutes and there will be a plane change of 2.2° at the first burn. The remainder of the 28.5° plane change occurs at the GEO insertion burn.
From The News

The article attached below comes from the newspaper. With it, and with what we have learned today, we can fairly easily determine the final location of the satellite above the Atlantic ocean. Note that the satellite was not launched from the shuttle, and that the mission scenario is not that which we have just described. However, with a couple of very good assumptions, we can determine where the satellite is located above the Atlantic.

Assumptions / initial calculations:

1. The booster launched due east on Thursday evening at twilight from KSC. Twilight on Feb. 26 is about 6:40 PM at KSC -- KSC is at 80°West, 5° west of the center of its time zone.

2. The first node crossing was at 5 degrees east (85 degrees east of the KSC (see the shuttle ground-track). An approximation can also be obtained by considering how long it takes to boost and to cover one fourth of a low earth orbit (28.5 min) how far the earth turns in that time (a little less than 5 degrees).

3. The first node crossing was at about 7:15 PM on Thursday, February 26.

4. LEO was at 140 statute miles or 121.7 nmi - it doesn't have to be as high as for shuttle, because we don't intend for the booster to stay in orbit for long.- in fact, we want it to come down soon.

5. The period of the transfer orbit was 10 hrs 29 min 58 sec.

6. Earth turns at 15.041 degrees per hour.

From this, and from the information in the article, we see that the satellite is at apogee (GEO) about 5 hours and 45 minutes after launch and then is back there every 10 hours 29 minutes 58 seconds (10.5 hours at the level of accuracy that we are keeping). Looking at this in terms of the launch time and date and the clock, we see that the only possible time that the satellite could be inserted into orbit on Saturday evening can be determined by building a table of events.
Half of transfer orbit period 5.25 hours  
One and one half transfer orbits 15.75 hours  
Two and one half transfer orbits 26.25 hours  
Three and one half transfer orbits 36.75 hours  
Four and one half transfer orbits 47.25 hours

Each time the satellite crosses the equator, the Earth has turned about 80° east while the satellite has traveled 180° east. Thus, the satellite moves about 100° east between node crossings and one half of a transfer orbit period elapses between node crossings. Taking these facts into account, we can construct the following table.

<table>
<thead>
<tr>
<th>Perigee</th>
<th>Apogee</th>
<th>Transfer Duration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 E</td>
<td>105 E</td>
<td>0.5 orbits</td>
<td>0030 Fri</td>
</tr>
<tr>
<td>205 E</td>
<td>305 E (55°W)</td>
<td>1.5 orbits</td>
<td>1100 Fri</td>
</tr>
<tr>
<td>405 E</td>
<td>505 E (145°E)</td>
<td>2.5 orbits</td>
<td>0930 Fri</td>
</tr>
<tr>
<td>605 E</td>
<td>705 E (15°W)</td>
<td>3.5 orbits</td>
<td>0800 Sat</td>
</tr>
<tr>
<td>805 E</td>
<td>905 E (175°W)</td>
<td>4.5 orbits</td>
<td>0630 Sat</td>
</tr>
</tbody>
</table>

Satellite inserted into GEO on Sat. at 8:00 AM EST at about 15°W.
Getting the Numbers Right

Many of us in engineering often read the papers with a jaundiced eye. The press often gets things wrong, and sometimes, mother nature or circumstances makes it tough even on the better technical reporters -- Aviation Week, for example. One common error made by the press is based on the fact that the period of a geostationary orbit (GEO) is 23 hrs 56 min 4 sec and not 24 hours. Not many know this, and it leads to some erroneous data being placed in the press.

**CORRECT NUMBERS**

Based on Period of 23 hrs 56 min 4 sec for GEO

<table>
<thead>
<tr>
<th></th>
<th>nmi</th>
<th>mi</th>
<th>km</th>
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</thead>
<tbody>
<tr>
<td>$R_{geo}$</td>
<td>22766.8</td>
<td>26199.6</td>
<td>41614.2</td>
</tr>
<tr>
<td>$H_{geo}$</td>
<td>19322.9</td>
<td>22236.4</td>
<td>35786.0</td>
</tr>
</tbody>
</table>

**INCORRECT NUMBERS**

Based on Period of 24 hours for GEO, the often quoted erroneous values are

for $R_{geo}$ | 22808.3 | 26247.4 | 42241.2 |
| for $H_{geo}$ | 19364.4 | 22284.2 | 35863.0 |

The erroneous commonly published numbers are (41.5 nmi, 47.8 miles, 77 km) too high.