THE SPACE LOGISTICS CHALLENGE

David B. Wile
Major, United States Air Force
Air Force Space Command
Integrated Logistics Support Directorate

ABSTRACT
As commercial and military activity in space increases, the need for a normalized support infrastructure becomes more apparent. If we consider space unique factors, standard logistic principles can be applied to space. This paper describes some of these space unique factors and various support alternative to consider.

INTRODUCTION
Early space systems were basically research and development efforts. Space vehicles were one-of-a-kind prototypes. The establishment of a support infrastructure was not considered necessary. Today, commercial and military use of space is increasing. A space system may now include an entire constellation of space vehicles. It is also possible to have some subsystems which are common across systems.

As the number of space assets increase, there is a need to determine what space support infrastructure should be developed. There are many factors to consider when designing this infrastructure. These factors include space system segmentation, astrodynamics, and cost factors.

SPACE SYSTEM SEGMENTATION
A typical space system is normally composed of four segments. These are launch, control, user, and space.

The launch segment includes the launch vehicle, payload processing at the launch site, and the launch ranges themselves. The space segment consists of mission and support Space Vehicle (SVs). The control segment performs the Telemetry, Tracking, and Commanding (TT&C) functions of the space vehicle. TT&C functions perform corrections in orbit, are used for collision avoidance, and keep track of satellite location. The user segment includes those activities that use the service of the SV. When designing a space support infrastructure, it is necessary to consider all segments and their interrelationships.

The launch segment is critical for initial system deployment and certain on orbit support activities. Launch facilities must be capable of meeting launch requirements in terms of volume, type, and location. Lack of volume would result in a backlog of launches. This could, in turn, cause loss of mission capability or even loss of the space vehicle. Launch facility requirements are also affected by the type of launch vehicle. An expendable launch vehicle may require different facilities than a reusable vehicle.

Location of the launch facilities is also important, since it affects which orbits the space vehicle can enter.

The user segment is often situated at locations throughout the world. Support of this segment must consider the geographic separation of user sites and variations in supply delivery and maintenance team response time.

The control of space vehicles also require a network of facilities to perform telemetry, tracking, and commanding functions. Some systems have dedicated control facilities, other rely on common use facilities.

The space based segment offers the most challenging environment in which to establish a support infrastructure. A basic understanding of some space unique factors is required.

ORBITAL PLACEMENT
The spatial orientation of an orbit, and its relationship to other orbits, significantly affects support alternatives. The following discussion of the spatial orientation of an orbit is paraphrased from General Space Fact Book compiled by

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the Air Force Space Command Directorate of Astrodynamics. An examination of figure 1 will help in visualizing the various parameters.

The motion of a satellite along an elliptical orbit is confined to a plane containing that ellipse and is called the orbital plane. The orientation of the orbital plane in space is determined by the position and velocity of the satellite at orbital insertion.

The tilt of the orbital plane relative to the equatorial plane is called the orbit's inclination. A satellite orbiting directly above the equator has an inclination of 0°. A satellite orbiting over the poles has a 90° inclination. A satellite with an inclination greater than 90° will travel counter to the rotation of the earth. This type of orbit is called a retrograde orbit.

There is a fixed reference point, which is determined when the sun's center crosses the equatorial plane during the change from winter to spring, from which the position of the orbital plane is measured. The angle made between this fixed reference point and the orbital plane, as measured from the earth's center, is the angle of ascending node. You can select the desired angle of ascending node by waiting for the launch site to rotate under the desired orbital plane.

Finally, the orientation of the orbital ellipse within the orbital plane is specified by giving the location of the perigee point (point the orbit is closest to the earth), with respect to the ascending node. This angle, as measured through the center of the earth, is called the argument of perigee.

Once you have determined the orbital plane, you must be able to locate where in the plane the vehicle is located. The three parameters used for this are the radius, declination, and right ascension.

Radius is the distance from the earth center to the space vehicle. For a space vehicle in an elliptical orbit, this radius is changing throughout the orbit. Declination (equivalent of earth latitude) is the degree of elevation of the space vehicle above or below the equator. Declination ranges from -90° to +90°. Right Ascension (RA) fixes a space vehicle location east of the vernal equinox (X axis on Fig. 1). RA is equivalent to earth longitude and ranges from 0° - 359.99°.

**ORBITAL MANEUVERS**

Now that you have a basic understanding of what is involved in specifying the orbit and location of a space vehicle, we will examine some simple maneuvers that can be used to move around in that orbital plane. The three types of maneuvers we will look at are the Hohmann transfer, the apogee transfer, and the perigee transfer. These can be used to manipulate a servicing or repair vehicle into the correct orbital position so that maintenance can be accomplished.

**Hohmann Transfer**

The Hohmann transfer (Fig 2) will take a servicing vehicle from a lower earth orbit, indicated by radius $R_1$, to a higher earth orbit, indicated by radius $R_2$. It is assumed that both the servicing and mission vehicles are in concentric orbits in the same orbital plane. This maneuver can be timed so that the servicing vehicle will arrive at the same orbital position as the mission vehicle.

At the perigee (point closest to the earth) of the transfer orbit (i.e., Point $P$), boost is applied to the servicing vehicle. This increases its orbital velocity by delta $V_1$. This places the servicer on the elliptical path shown,
heading towards the apogee (point farthest from the earth) of the transfer orbit (i.e., Point A).

As the servicer reaches its apogee, an additional boost is applied, increasing its velocity by delta V2. This boost circularizes the orbit of the servicing vehicle at radius R2.

If the ratio of the radii, R2/R1, is greater than 11.94, the Hohmann transfer is the most fuel efficient one to execute.

Apogee Transfer

If the Hohmann maneuver was not timed correctly, or if a servicing vehicle needs to move from one space vehicle to another in the same orbit, an apogee transfer can be used to allow the servicing vehicle to "catch up" to the mission vehicle. The servicing vehicle cannot speed up to catch the mission vehicle since an increase in its velocity would place the servicer in a higher elliptical orbit.

Perigee Transfer

The perigee transfer is based on the same principle as the apogee transfer (i.e., using an elliptical path with a different orbital period). As shown in Figure 4, instead of taking an elliptical orbit which is smaller than the mission vehicle orbit, a larger elliptical orbit is used.

As shown in Figure 4, at the perigee of the transfer orbit, the servicer increases its velocity by delta V1. This places the servicer on the longer elliptical orbit. The magnitude of the delta V1 is chosen based on the degree of angular separation.

Other Maneuvers

As with most logistics decisions, there are trade-offs that can be made. With the apogee and perigee transfer, we can trade fuel consumption for time. These maneuvers can be executed several times.
with smaller delta V's and achieve the same results. The single revolution transfer is the most time efficient, with the multiple revolution being the most fuel efficient. Fuel efficiency is very important in space operations, since it directly impacts lift-off weight and hence capabilities.

To service satellites in non-coplanar orbits, more complex techniques must be used. A servicer's nodal location and inclination can be changed by applying a change in velocity with a non-coplanar impulse. A three impulse plane change maneuver can be chosen for efficient plane change when the angle is greater than 42°.

Another possibility is to change nodal location by utilizing the nodal regression. Nodal regression/precession is caused by the asphericity of the earth. The oblate shape of the earth causes the space vehicle to reach the node short of the point for a spherical orbit.

For postgrade vehicles (i.e., inclination less than 90°), the vehicle will cross the equator slightly west of the previous orbit. This is called a precession of the orbital plane. For retrograde vehicles (i.e., inclination greater than 90°), the node advances to the east. This is called nodal regression. Figure 5 shows a plane change using nodal regression. Nodal regression effects are more pronounced for low earth, low inclination orbits.

Other maneuvers, or combination of maneuvers, can also be used. Their selection depends on the differences between orbital position, time sensitivity of the move, and fuel economy considerations.

With this as background, we will now examine the basic types of space support.

Space support can be divided into three types of activities. These activities are assembly, maintenance, and servicing.

Assembly is a process where smaller units are assembled into a larger end item. Because of the payload limitations (weight and volume) of launch vehicles, it is not always possible to place a large or heavy space vehicle in orbit with one launch. An alternative approach is to design the space vehicle into smaller segments that are placed in orbit individually and then assembled. Examples of where this technique may be useful are in building a space station or commercial manufacturing facility.

Space maintenance is a process where failed components are identified and repaired or replaced. Space maintenance would also include upgrading of capability using preplanned product improvement techniques.

Space servicing refers to activities such as replenishment of consumables or periodic cleaning. One of the major limitations on the useful life of a space vehicle is the depletion of fuel. Without fuel, a space vehicle will eventually be overcome by the gravitation attraction of the earth or be slowed down by atmospheric drag. This would cause the orbit to decay. Loss of maneuverability could also reduce the areas the vehicle could cover. Maneuverability is essential in many space vehicles, such as those used for geodetic surveys.

SUPPORT OPTIONS

Space assembly could potentially be performed either remotely or directly. Remote controlled assembly could be accomplished from either a ground based or a space based location. Telerobotics is the term used to identify activities utilizing remote controlled robotics techniques.

Direct assembly could theoretically be performed by using autonomous robotic devices or be performed by space technicians. The method chosen must consider cost, technology, timeliness, and the orbital dynamics involved.

There are many potential options for space maintenance. With the development of artificial intelligence and new hardware devices, such as Very High Speed Integrated Circuits (VHSIC), it may become possible for the space vehicle to self-diagnosis its malfunctions and reallocate functions to other components in real
time. Telerobotics techniques could also be used to perform replacement of Orbital Replacement Units (ORUs). If modular design techniques are used, these replacements could also be used to upgrade system capabilities.

Space servicing options could include both manned and robotic recharging of cryogenics or cleaning of optical components. Since requirements for servicing can usually be predicted in advance, it may be feasible to set up a servicing schedule. Orbital dynamics factors, such as nodal regression, could be an efficient method to use in servicing vehicles in non-coplanar orbits.

LOGISTICS CHALLENGE

The space logistics and design engineers must carefully evaluate the impact of supportability on system design and mission accomplishment. The various space assembly, maintenance, and servicing options must be explored in the light of orbital dynamics. This analysis must be performed, not only from a system basis, but also from a space logistics support infrastructure perspective.

The acquisition of telerobotic servicers or cryogenic refuelers may not be cost effective to support a single system. However, multiple systems, using standardized interfaces and modules, may make the acquisition of such equipment feasible.

The challenge is, therefore, to develop an efficient space support infrastructure that will meet our current and future space requirements.

CONCLUSION

In summary, as space usage increases, there is a need to establish a normalized support structure. This structure must consider the unique factors of orbital dynamics and the various types of space support possible. Decisions on what this infrastructure should evolve to must consider the total space support requirements and not be based on just the needs of a particular system.

REFERENCES


BIOGRAPHY

Major Wile is the Chief, Technical Support Branch, Integrated Logistics Support Directorate, Deputy Chief of Staff, Systems Integration, Logistics, and Support, Headquarters, Air Force Space Command, Peterson AFB, Colorado. Previous assignments include a foreign military sales assignment in Saudi Arabia, duty as Deputy Program Manager for Logistics for space defense systems, and service as a supply officer.

Major Wile is a Senior Member of the Society of Logistics Engineers (SOLE), and has earned the society's Advanced Professional Designation. He has earned a Master of Science Degree in Logistics Management from the Air Force Institute of Technology, and a Bachelor of Science in Business and Management (Summa Cum Laude) from the University of Maryland.