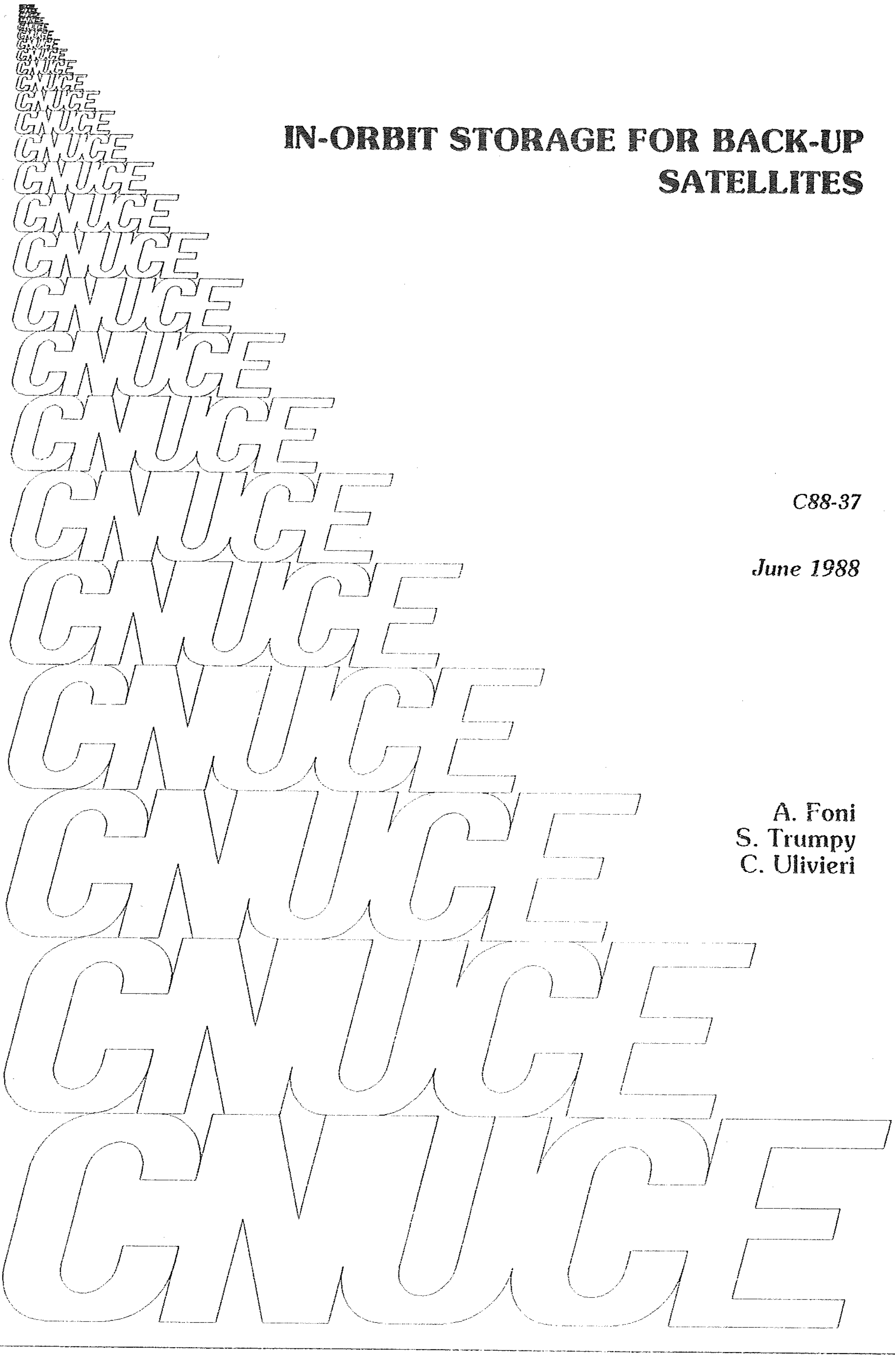

IN-ORBIT STORAGE FOR BACK-UP SATELLITES

C88-37

June 1988

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Abstract

The basic idea developed in this paper is the placement of a satellite in a storage orbit waiting for subsequent utilization instead of actuating the normal launch procedure that aims at an immediate starting of the satellite operational life. The latter case is the traditional one and it is more convenient provided that the operational life of the satellite is planned well in advance and that launch failures or delays do not cause severe damages to the mission objectives. The recent history of the launches demonstrates that to meet the start of a mission operational phase may be critical and very costly. Therefore the utilization of storage orbits may become convenient for those missions that have an obliged or optimal start phase.

Storage orbits which maintain their inclination almost constant for long periods are investigated. A geosynchronous constellation of relay satellites has been addressed. This is, in fact, a typical case where the replacement of a satellite for completion of its operational life or for an unexpected failure implies critical time constraints.

The results demonstrate that the adoption of such orbits is rewarding in terms of fuel consumption independently from the start-of-service date.

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1.0 Introduction

Spacecraft that orbit at low altitudes around the Earth are increasing as the scientific, remote sensing, space station and military programmes are developed. Such spacecraft are only visible from a ground station for a small fraction of the flight. Therefore, systems of geosynchronous relay satellites have been designed and, (up-to-now), partially operated, to allow continuous communications with a ground station.

One of these systems is the United States Telecommunication Data Relay Satellite System (TDRSS) which consists of two geostationary satellites: the one located at 41 degrees of longitude West is already flying, while the second one, to be launched soon, will operate at 189 degrees East . In the final configuration TDRSS will allow complete coverage for spacecraft (S/C) orbiting at altitudes higher than 1300 km., while for lower altitudes the coverage will be more than 95%. It must be noted that with only one of the two TDRSS spacecraft the coverage drops to about 60% of the S/C orbital period.

A similar system, called EDRS, will be implemented and operated by European Space Agency. For both systems it is evident that the failure or the end of operations of a satellite, dramatically degradates the performance of the entire system till a new satellite is positioned in orbit to replace the deactivated one. Even in the best of all cases such operations would require a few months.

To accomplish an almost immediate replacement of a deactivated satellite, some researchers have investigated the possibility of ″storing″ a spare unit in a suitable orbit which would allow the transfer of the satellite to the operational orbit in a very short time (several days) without complex and critical maneuvers. On the other hand, due to the difficulty of accurately forecasting demand for service, active station-keeping before operations would result extremely fuel consuming. The ″storage orbit″ should therefore be designed to minimize the required delta-V for its maintenance during the time the spare unit is stored, this would leave the on-board fuel available for the spacecraft control during the operational phase.

J.K. Skipper has studied storage orbits when the storage time is planned in advance (Ref. 1). In this case, (taking into account the free-drifting of the orbital plane,) the target storage orbit has been defined as a function of the start-of-service date. However, an unexpected failure can anticipate the use of the spare satellite and cause problems in terms of time and energy. Former investigation by the authors on the long-term orbit plane evolution for geosynchronous orbits (Ref.2) has shown that for some initial positions of the satellite orbital pole, the orbit inclination remains for a long time (7 years and more) within small tolerances (a few tenths of degrees) around the initial value without any active control.

Based on this, the present study analyzes orbits which don't significantly vary their inclination. Therefore they are suitable for use as storage orbits without constraining the storage period to a fixed time, thus leaving the start-of-service date free within a reasonable time interval (7 years from the launch).

2.0 Design Criteria for Storage Orbit

Although the validity of the study is general, a TDRSS like system has been chosen in order to give an assessment of the fuel budget in a real case. We assume that the satellite expected lives will end in different years due to the different launch dates.

If the storage orbit criteria are accepted, convenient launch opportunity should be chosen a few years before the end of the operational life of the first satellite composing the constellation.

The call for mission control may happen after storage orbit acquisition and until the orbit plane inclination remains almost constant. Once placed into orbit the spare unit will be ready for:

- replacement of the first satellite of the constellation at the end of its operational life,
- replacement of any satellite in case of failure,
- temporary operations of the constellation of three in case it is decided that an operative back-up is more cost effective and reliable once the spare satellite has reached its orbit.

Some considerations are presented on the storage orbit selection, on the constraints in the launch windows and on the in-plane east-west drift control.

2.1 Orbit Plane Control

The orbit plane behaviour, under the perturbative effects of the Earth's oblateness and of the Luni-Solar attractions, can be investigated in terms of its pole motion, resulting in three simultaneous precessions around the perturbation poles, defined as the angular momentum directions of the perturbing bodies (the Sun and the Moon) and the terrestrial polar axis for the oblateness effect (Ref.3). The motion can be analyzed on a spherical surface where the trajectories performed by the satellite orbital pole consist of series of small arcs of different spherical ellipses which are intersections of the unit sphere with a moving and shape-changing ellipsoid (Ref.4). Each arc is related to a different position of the lunar pole in its precession around the ecliptic one. If short time intervals (a few months) are considered, the lunar orbital pole could be assumed in a time averaged position and the geometry of the motion would result fixed.

For longer periods the lunar pole regression highly influences the satellite pole evolution (Ref.5) and this regression must be taken into account. For the purpose of this study, orbits passively controlled in inclination by the perturbational effects throughout the expected satellite lifetime were investigated by means of the above stated geometrical approach. They satisfy certain operative constraints (tolerance in inclination and satellite lifetime) and determine, on the unit sphere, areas representing all the initial orbit pole locations, at a certain epoch, which verify the given constraints ("compatible zones").

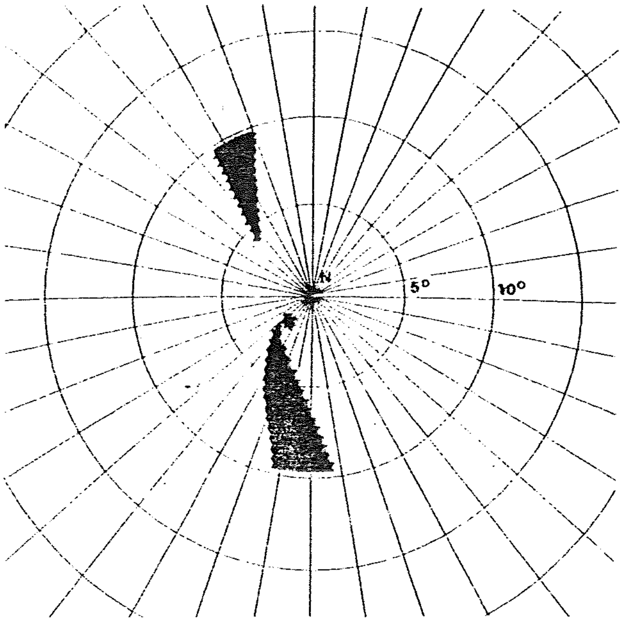

Figure 1. **Inclination tolerance 1 deg.**

Fig. 1 shows a compatible zone, limited to a maximum inclination of 10 degs, corresponding to geosynchronous altitudes and defined by a tolerance in inclination of 1 deg and by a satellite lifetime of 7 years starting from 1992. If more restrictive constraints are chosen, the compatible zone reduces. Fig.2 represents the corresponding compatible zone when a tolerance of 0.5 deg is assumed.

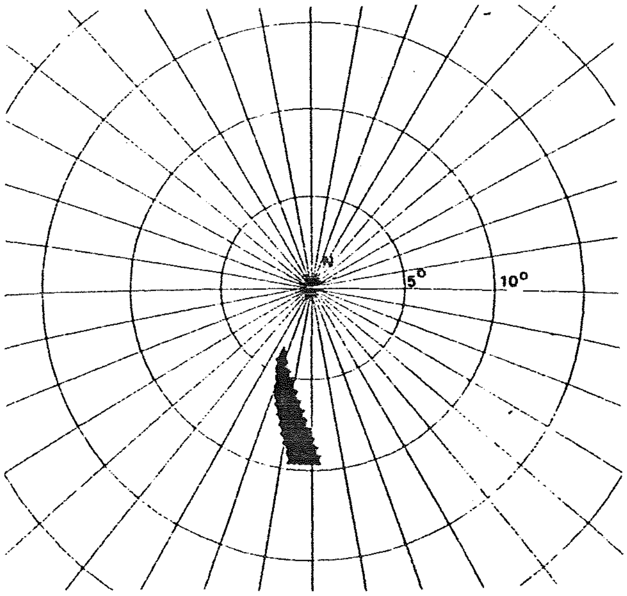

Figure 2. Inclination tolerance 0.5 deg.

The strategy here proposed for a storage orbit is to place the satellite in a suitable orbit such that the corresponding inclination and right ascension node allow the transfer of the satellite into the operational orbit with reasonable fuel consumption. The orbit represented by a * in fig.1, with inclination and ascending node of 3 and 320 degs respectively, is the one proposed as nominal storage orbit.

2.2 *Longitude Control*

The longitudinal control of a geosynchronous satellite is required in order to nullify the effect of the acceleration due to the tesseral harmonics of the Earth, which is the main perturbation affecting the orbit semi-major axis and, consequently, the S/C period. Other forces such as the solar radiation pressure and the Sun-Moon and planets attraction, can be considered negligible.

Even though the fuel requirement for active east-west station-keeping is marginal, two further hypothesis have been considered besides the active East-West station-keeping. They aim mainly to avoid any spacecraft control during the in-orbit storage.

2.2.1 Active Control

The tesseral acceleration value depends upon the longitude of the satellite and, at the geostationary altitude, varies from 0 to 0.002 deg/day^2. Consequently, if a S/C placed in geosynchronous orbit has to be maintained at a fixed longitude by active East-West station-keeping, it will require up to 2 m/sec delta-v per year.

2.2.2 Free-drifting Outside the Geostationary Ring

The satellite period is a function of the orbit semi-major axis (SMA). Any difference of the orbit SMA from the geosynchronous one (42164 km) causes a drift of the satellite longitude. When the satellite is 80 kilometers away from the geosynchronous altitude, the drift is about 1 degree per day, leading to a complete revolution around the Earth in one year. In the case of the satellite is being left to wait for a possible request for operations, many elements must be considered to decide the "drift" SMA. It is not the objective of this paper to assess criteria for deciding which should be the definitive "drift" orbit, nevertheless some background considerations are made:

a) - the S/C should be enough away from the geostationary ring to avoid possible collisions with other objects orbiting in the region. Even the possibility of radio frequency interferences with active satellites should be minimized;

b) - the longitude drift rate should be high enough to minimize the time necessary for positioning the satellite into the operational position. The higher the longitude drift rate the more fuel will be necessary to stop the satellite at the requested station point.

In the following, the necessary delta-v is computed for a few cases:

Orbit SMA (km)	Longitude drift (deg/day)	delta-v for geos. orbit (m/sec)
42084	1.	3.0
42005	2.	5.8
41764	5.	14.6
41204	12.	35.0

In the first and last case, the satellite performs a complete revolution around the Earth in one year and in one month respectively.

If the satellite is not in the vicinity of the operational longitude at the moment of the SMA correction, and if it is not possible to wait until the satellite reaches the operational station point, an additional delta-v has to be spent to accomplish the longitude acquisition in the desired time. Its magnitude has to be determined as a function of the difference between the present and operational longitudes and of the time allowed for the beginning of operations.

2.2.3 Passive East-West Control

The acceleration due to the tesseral harmonics of the Earth's potential is a function of the longitude. Its value vanishes four times and in particular at two longitudes (75.1E and 105.3W degs) the acceleration is directed towards these points which become "stable points". This means that a satellite, left uncontrolled in the vicinity of these points, will oscillate around them with a pendulum-like motion. The pecularity of the stable points can thus be used to perform a passive control of the satellite longitude.

Should this possibility be put into practice, the longitude at which the satellite is left and the orbit SMA have to be defined as a function of the desired oscillation amplitude around the selected stable point. When the satellite is requested to start operations, a double maneuver can eventually be planned in order to accelerate the S/C drift rate and then to stop it at the desired point, depending on its position relative to the operational longitude. As in the former case, a compromise must be reached between fuel consumption and time need to acquire the operational point.

3.0 Delta-v Requirements and Comparison

In this chapter an analysis is performed in order to assess the differences between possible missions for storing a spare unit of a geostationary relay satellite system in orbit. The reference mission is the standard geostationary one and the comparison with the orbit defined in par. 2.1 is performed starting from the time the spare unit is injected by the launch vehicle into the classical elliptic transfer orbit (TO).

3.1 Reference Mission

To assess the requirements, in terms of delta-v, for a geostationary mission control, the following phases have been considered:

- circularization and inclination correction of TO,
- orbit plane control,
- east-west station-keeping.

The profile of a classic geostationary mission has been assumed and the corresponding fuel budget computed. A generalized Hohman transfer for achieving the geostationry orbit has been supposed.

Optimization criteria such as the inclination correction during the perigee and apogee burns, or the bias computation for optimal in-plane parameters, have not been taken into account since they are supposed to be identically applicable to both reference and storage orbits and, therefore do not affect the comparison. The parameters assumed for the transfer orbit are:

Perigee height (km)	300.
Apogee height (km)	35785.86
Inclination (deg)	28.5

The delta-v necessary for the first phase is given by:

$$\Delta V^2 = Vs^2 + Vt^2 - 2Vs\ Vt \cos\theta$$

where

$$Vs^2 = \frac{\mu}{Rs}$$

$$Vt^2 = \frac{2\,\mu Rp}{Rs(Rp + Rs)}$$

θ = inclination of TO = 28.5 deg
Rs = geostationary SMA = 42164 Km
Rp = Perigee radius = 6678.16 km
μ = 398600. km^3/sec^2

For the above assumed parameters it is obtained

$$\Delta V = 1.830 \text{ km/sec}$$

The environmental perturbative effects on a geostationary orbit plane cause the inclination to increase by about 0.8 deg/year. To compensate for this effect the North-South control requires a delta-v of about 43 m/sec per year. The consequent delta-v budget for a geostationary mission lasting 7 years is:

Mission phase	delta-v(km/sec)
a) TO circularization	1.830
b) Orbit plane control	.301
c) E-W station-keeping	.014
Total	2.145

The delta-v for East-West control is the one necessary for active station-keeping (the maximum value of the tesseral acceleration has been assumed).

3.2 Delta-v Requirements for Storage Orbit

In the case of the storage orbit proposed as the nominal one, to pass from TO to this orbit, the inclination change requires the minimum delta-v when the nodal lines of the two orbits coincide, while the highest delta-v will be necessary when the nodes are 180 degrees apart.

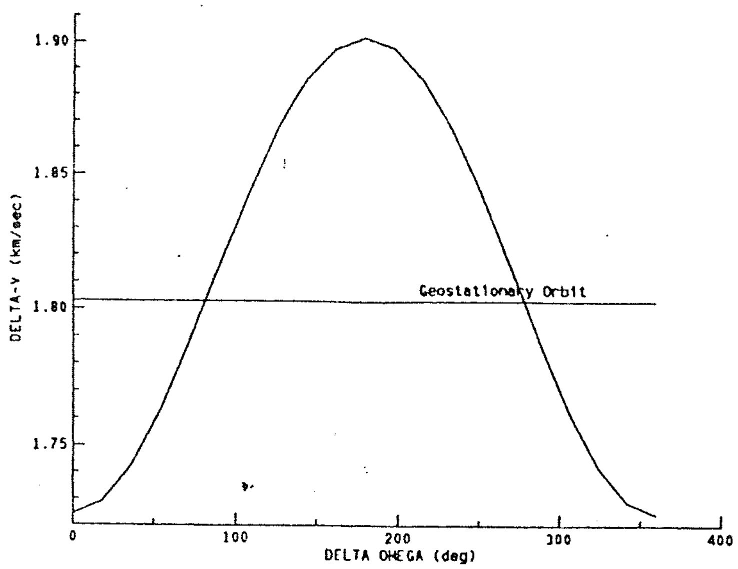

Figure 3. Delta-v requirements for storage orbit

The angle between the two orbit planes depends on the launch time which is constrained by the launch window. In fig. 3 the delta-v is plotted as a function of the angle between the two nodal lines. In the same figure, the delta-v for achieving the geostationary orbit is superimposed.

No delta-v is necessary for orbit plane control during the storage period, since the orbit inclination of the storage orbit is stable within this period.

As far as longitude control, the delta-v required depends on the type of control performed and we assume that a trade-off between energy requirements and time allowance for the operations leads to an estimation of up to 20 m/sec.

3.3 Requirements Comparison

The following table summarizes the delta-v necessary for storage and geostationary orbits achievement and maintenance over a period of 7 years

Phase	geostat.-orbit (km/sec)	storage-orbit (km/sec)
a) TO circularization and inclination control	1.830	1.765 - 1.899
b) Plane control	.301	0.
c) Longitude control	0. - 0.014	0. - 0.020
d) Residual incl. correction	0.	.166
Total	2.131 - 2.145	1.931 - 2.085

The comparison between the requirements of the two orbits cannot be performed by means of a pure arithmetic operation. In fact, some of the above listed numbers have been computed using precise assumptions, while for others, the delta-v has been determined either as an average of possible situations, or as a best/worst case. For instance, a fixed delta-v for TO circularization and inclination control must be delivered irrespective of the initial node of TO. If the same requirement is evaluated for the storage orbit it is not possible to find a unique value, since it depends upon the longitude of the node of TO which can't be decided at this time. Therefore, the maximum and minimum values are computed since it would be meaningless to consider an averaged value.

The longitude control requirement listed as point c) is also a parameter which strictly depends on mission parameters and techniques selected for East-West control. On the other hand, since the delta-v necessary for the control is a minimal part of the total budget, it is an item which doesn't considerably affect the comparison, even if considered variable.

Despite all these considerations, the comparison of the delta-v requirements between the geostationary and the proposed storage orbits indicates that even in the worst of all cases, the latter is preferible because it allows a savings of about 46 m/sec which increases to 214 m/sec if the best case is verified. To give a more concrete idea of such a benefit, it can be translated into mass reduction at launch. If we refer to a satellite of about 2500 kg using a propulsion system characterized by a specific impulse of 200 sec, we obtain a mass savings of about 59 and 274 kg in the worst and best case respectively.

4.0 Concluding Remarks

The comparison performed in the preceeding paragraph shows that if the launch time is such that the transfer orbit nodal line results almost coincident with the storage orbit one, the fuel savings may be quite relevant with respect to the geostationary orbit.

It is our opinion though that advantages in the utilization of the proposed storage orbit concept are to be seen in the overall mission operations planning.

The main aspect that differs from the traditional way of planning a mission is that the launch of a spare satellite may be scheduled well in advance. There is no critical time and it takes into account the advantages of:

- waiting for a good launch opportunity. For example, with a multiple launch optimizing the launch vehicle capacity and then reducing the launch cost,
- choosing a launch window which requires a lower fuel consumption to reach the storage orbit.

Taking into account the above considerations, the launch opportunity can be selected in a period of two, three or more years without having a relevant impact on the overall reliability of the constellation on satellites. Furthermore, if the technology of the satellites forming the constellation is homogeneous and well consolidated, there should be no particular advantage in postponing as much as possible the launch of the unit replacing the one that has reached the end of its operational life.

The advantages in the overall mission operations plan should not be jeopardized by having to set-up a costly procedure for east-west station-keeping during the storage period. During this period the stored unit should be monitored a few times for S/C health check-up and left drifting until it is requested to start operations.

In the case the storage time is requested to be extended after its nominal completion, the only additional cost to be considered is a higher residual orbit inclination to be corrected at the new start-of-operations time.

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