DELFT UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF AERONAUTICAL ENGINEERING

Report VTH - 171

GEOSYNCHRONOUS SPACE TUG MISSIONS

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Summary

This report presents the results of a three-month study on the application of a European Space Tug for geosynchronous missions. The study is related to the Phase "A" study performed for ELDO by a group of European Companies headed by Hawker Siddeley Dynamics Ltd.

In the first part of the report pertinent data on the Space Shuttle and a selected Space Tug concept are given. Then the assumptions and restrictions used in this study are mentioned.
Placement, retrieval and roundtrip flights are considered for a geosynchronous mission with an orbital inclination of 28.5^{o}, as well as for the geostationary mission. For both missions different strategies are discussed and payload capabilities are calculated as a function of the Tug initial mass for all strategies. Finally, the best strategy for each mission is determined.

Contents

1. Introduction

The object of this study is to define a mission strategy for a Space Tug which is optimal in that sense that the propellant consumption is a minimum.

Two types of missions are studied:

1. Missions to an orbit at geostationary altitude with an inclination of $28^{\circ}.5$ (geosynchronous missions).
2. Missions to geostationary orbit.

For each of the two types of missions different strategies are defined whereafter detailed performance calculations are made for each of the defined strategies. That strategy which results in maximum payload mass is defined as the optimal strategy.

Since the timelines of the missions are dependent on the earth longitude of the station where the payload has to be placed (retrieved) no general timelines are given. However, general performance calculations could nevertheless be made because the ELDO Tug data assumes a fixed loss of fluid from the Tug for each coast phase. So coast duration between two main engine burning phases has no effect on performances.

The propellant consumption is calculated using a ΔV which is the sum of the theoretical derived impulsive ΔV (zero burning time), the ΔV loss due to finite thrust (non-zero burning time) and a 2% contingency ΔV.

All considered transfer trajectories are Hohmann trajectories which are optimal in the case of infinite thrust. Since the propellant losses due to finite thrust are very small (< 1%) it may be expected that Hohmann trajectories are practically optimal for the considered missions.

Finally, timelines, required ΔV's and major event sequences are determined for placement, retrieval and roundtrip missions to a prescribed station in target orbit using the optimal strategy.

2. Space Shuttle data

As far as this study is concerned only a limited number of pertinent Shuttle data are required.

These data, derived from ref. 1, are:

1. The present Space Shuttle is a two-stage vehicle consisting of a booster and an orbiter. The booster which has no flyback capability is a conventional rocket stage and can land on water only. The reusable orbiter will fly back to earth after completion of the mission and make a horizontal landing. Launch sites and launch azimuths are thus constrained by range safety requirements. Therefore, if the whole mission programme, as defined by the simplified mission model given in ref. 1, should be flown, two launch sites should be considered:

   Eastern Test Range (Cape Kennedy, ETR): $28\overset{\circ}{.}5$ N; $80\overset{\circ}{.}6$ W
   Western Test Range (WTR) : $34\overset{\circ}{.}7$ N; 120° W

   The launch azimuth limits are:
   ETR: $44^\circ - 110^\circ$; WTR: $163^\circ - 300^\circ$.

   The achievable inclinations are:
   ETR: $28\overset{\circ}{.}5 - 55^\circ$; WTR: $80^\circ - 135^\circ$.

2. The Space Shuttle payload capability is given in Fig. 1 and Fig. 2. Fig. 1 shows the payload the orbiter can place in a 100 n.mi. circular orbit as a function of the orbital equatorial inclination. Fig. 2 shows the payload the orbiter can place in a circular orbit as a function of the orbital altitude if the Shuttle is launched from ETR such that the orbital inclination is $28\overset{\circ}{.}5$. Both Figures refer to an orbiter with no air-breathing engines.

3. The dimensions of the cargo bay of the orbiter are:
   diameter: 4.55 m
   length : 18.20 m

4. If launched from ETR to a 100 n.mi. circular orbit with an inclination of 28°.5 the first descending node occurs at an earth longitude of 10° E of Greenwich.

3. Space Tug data

The present study is performed for a single-stage Tug with a nominal useful propellant mass of 23000 kg, denoted in ref. 2 as Concept 2, current technology, RTS 23.
Mass and performance data of this Tug are derived from ref. 2 and are given in Table 1 and Table 2.

The Tug main engine (LOX-LH) has a specific impuls of 460 s, which, with a mass flow rate of 20 kg/s, gives a thrust of 9.2 tonne.
The auxiliary propulsion system (APS) with hydrazine as propellant has a specific impuls of 220 s.

The nominal total stage mass consists of:

- The dry structure mass: total mass of hardware comprising the vehicle with the exception of any propellant, fluids, gases and exclusion of payload mass.
- The miscellaneous fluids mass: unburnable propellants, residual liquids and gases, fuel-cell reactants, etc., and nominal usable hydrazine.

  The nominal usable hydrazine mass as given in Table 1 is based on the assumption that the APS is used only to align the Tug before starting the main engine, for which 54 kg of hydrazine are needed, and that only four main engine burns are required.
  Some mission strategies presented in this report require more than four main engine burns, while the APS will in some cases also be used for orbital manoeuvres.
  Therefore the usable hydrazine mass may differ considerably from the nominal usable hydrazine mass.

- Nominal useful propellant mass : total propellant burnt by main engine to deliver thrust impulse under nominal flight and systems operation conditions. Maximum nominal useful propellant is 23 tonne.
- Reserve propellant mass: the amount of any propellant foreseen to compensate any deviation from nominal objectives due to perturbations in flight, environment or engine functional deviations.
- Mass of precool propellant, pressurization and boost pump bleed, engine start losses, boil-off propellant.
  The total nominal mass of these propellants again is based on four engine starts with a loss of 68 kg/start and three coast phases with a fixed boil-off of 10 kg/coast. Again, since some strategies require more engine burns the actual propellant losses may differ from the nominal losses as given in Table 1.

The Tug net mass is defined as the sum of the dry structure mass and the mass of the residual liquids and gases and trapped propellants. The Tug initial mass finally is the sum of the total stage mass and the payload mass in case of placement and roundtrip missions, while it is equal to the total stage mass in the case of retrieval.

The Tug initial mass will be designated by M_o, while the notation for the other masses is:

Payload mass: M_u
Tug net mass: M_c
Useful propellant: M_{pu} }
Propellant losses: $M_{p\ell}$ } usable propellant: $M_p = M_{pu} + M_{p\ell}$
Reserve propellant: M_{pr}
Hydrazine used for attitude control: $M_{f\ell}$
Hydrazine used for orbital manoeuvres: M_{fu}
Usable hydrazine: $M_f = M_{fu} + M_{f\ell}$

So for placement and roundtrip:

$$M_o = M_c + M_{pr} + M_u + M_p + M_f$$

and for a retrieval mission:

$$M_o = M_c + M_{pr} + M_p + M_f$$

The Tug empty mass M_e is:

In case of a placement mission : $M_e = M_c + M_{pr}$

In case of retrieval or roundtrip: $M_e = M_c + M_{pr} + M_u$

4. Mission definitions, assumptions and restrictions

Definitions

- Placement mission

  Tug and payload are initially in base orbit (B.O.). By means of a transfer orbit (T.O.) and, if necessary, a phasing orbit (P.O.) the payload is placed in the target orbit (if necessary exactly at a prescribed earth longitude). After placement of the payload the Tug returns to base orbit and docks with the Shuttle.

- Retrieval mission

  Tug is initially in base orbit and enters by means of a transfer orbit and, if necessary, a phasing orbit the target orbit. Here it captures the payload and retrieves this payload back to the Shuttle.

- Roundtrip mission

  Tug and payload are initially in B.O. Again by means of a T.O. (and a P.O.) the payload is placed in target orbit (at a prescribed station).

  The Tug will then manoeuvre to rendez-vous and dock with another payload (by means of a drift orbit (D.O.)). This payload is assumed to be of the same mass and dimensions and in the same target orbit, but displaced by 15^o.

  After capture this payload is retrieved back to the Shuttle.

Assumptions and restrictions

- Maximum mission duration will be 7 days.

- Tug deployment and Tug check-out requires one revolution in base orbit: 1.47 h.

- Fine placement and release of payload or rendez-vous and capture of payload requires 3 h.

- All trajectories will be impulsive ones, while the impulses will only be given in the apses and, if target orbit plane and base orbit plane do not coincide, in the nodes.

- To account for finite thrust, corrections on ΔV will be applied.

- The theoretically derived ΔV impulses and the losses due to finite thrust will be enlarged with a 2% contingency ΔV.

5. Missions to geosynchronous orbit with 28°.5 inclination

5.1. Mission definition

For this missions base orbit will be a circular orbit at an altitude of 185.2 km (100 n.mi) and an inclination of 28°.5. More data on this base orbit and the geophysical constants used in the calculations are given in Table 3.
Target orbit will be a circular orbit at an altitude of 35788.8 km and with an inclination of 28°.5. Target orbit data are given in Table 4.

Object of mission: Placement and/or retrieval of a payload in/from target orbit at any demanded earth longitude with minimal propellant consumption.

Since target orbit has an inclination different from 0°, a satellite in target orbit will not be geostationary. The ground track of such a satellite will be a curve shaped like an 8 with the center of the 8 lieing on the crossing of the earth's equator and the nodal line. So the earth's longitude (and latitude) of the satellite will oscillate. Therefore, if in the following the longitude of a station in target orbit is mentioned, the earth longitude of the center of the ground-track (i.e. the equator crossing) is meant.

Since base orbit and target orbit are in the same plane no inclination changes are necessary, while any station in target orbit can be reached without a phasing orbit just by choosing the right time of departure from base orbit.
So for this mission a Hohmann transfer directly from base orbit to target orbit will be optimal.
The transfer orbit then is an elliptical orbit (185.2/35788.8 km) with an inclination of $28\overset{\circ}{.}5$. Further data on this transfer orbit are given in Table 5.

The required impulsive ΔV's to leave base orbit and to enter target orbit and vice versa on the return flight are also given in Table 5. The propellant consumption however cannot be calculated with these ΔV's since the thrust is finite, so ΔV losses due to finite thrust have to be added to the impulsive ΔV's.

5.2. Losses due to finite thrust

These losses were calculated by integration of the complete equations of motion for a finite thrust. A tangential steering law was used, which means that at any time the thrust direction coincides with the velocity direction.
The optimal thrust direction lies somewhere between the local horizontal direction and the direction of the velocity vector. However, in the cases considered here the angle between local horizontal and velocity is so small that tangential steering can be said to be optimal.

Continually during this integration the trajectory was calculated which the Tug would follow if thrust was cut off at that moment, while also the required impulsive ΔV to enter the same trajectory (starting from the same initial conditions) was calculated. The real (finite thrust) propellant consumption was then related to a ΔV by $\Delta V = c\ell n(M_o/(M_o - M_p))$ The difference between the in this manner calculated ΔV and the impulsive ΔV was defined as the ΔV_{loss} due to finite thrust.

This procedure was repeated for different values of the initial mass M_o and for the following cases:

- departure from base orbit
- arrival into target orbit
- departure from target orbit
- arrival into base orbit.

It turned out that losses at the transition from transfer orbit to target orbit and vice versa, as well as the losses at the transition from transfer orbit to base orbit were very small (0-1 m/s) either due to the small velocity or the relative large thrust-to-weight ratio. Therefore these losses are neglected in the following.

The only substantial ΔV losses were found to appear at the transition from base orbit to transfer orbit. Fig. 3 gives the engine burning time (and the propellant consumption) as a function of impulsive ΔV at departure from base orbit. In Fig. 4 ΔV_{loss} is given as a function of the impulsive ΔV for different values of the initial mass M_o. Fig. 5 shows ΔV_{loss} as a function of initial mass M_o for an impulsive ΔV of 2459.710 m/s, which is just the impulsive ΔV required for the transition from base orbit to transfer orbit.

For all burning phases the fuel consumption was calculated using the sum of the impulsive ΔV, the ΔV_{loss} and a 2% contingency ΔV.

5.3. Strategies

The strategies adopted to complete this mission are described in the following.

Strategy 1 (A, B) (Fig. 6, 7)

1. Shuttle reaches first descending node at 10°E at t = 0. Deployment and Tug check-out beginning at t = 0, ending at t = 1.470 h (one revolution in base orbit). Earth longitude is then $12^{\circ}.095$ W.

2. 1.470 h ≤ t ≤ 3.035 h.
   Tug burns at right time, dependent on longitude Λ of station in target orbit that has to be reached, and enters transfer orbit. The time in seconds is given by the formula:

$$t = 5288.5 + (\Lambda - 88.85)/0.0638947 \quad \text{(s)}$$

   where Λ is the longitude of the station in degrees east of Greenwich ($88^{\circ}.85 \leq \Lambda \leq 88^{\circ}.85 + 360^{\circ}$).
   The required impulsive ΔV is 2459.710 m/s, while finite thrust losses follow from Fig. 5.
   The Tug then coasts half a revolution in transfer orbit (5.256 h).

3. 6.726 ≤ t ≤ 8.291 h.
   Tug reaches apogee of transfer orbit and burns such that target orbit is entered.
   Required impulsive ΔV is 1479.116 m/s.
   No finite thrust losses have to be taken into account.

4. In case of placement or roundtrip mission: placement of payload.
   In case of retrieval mission: rendez-vous and capture of payload.
   This operation takes 3 h.

5.[x] In case of roundtrip mission:
   1A: thrusting phase with main engine
   1B: thrusting phase with APS.

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[x] This phase occurs only in a roundtrip mission.

The thrusting phase must be such that a drift orbit is entered, with a period such that after one (or more) revolution(s) a drift of 15^{o} has taken place.

If an easterly drift is required the period of the drift orbit has to be smaller than the period of the target orbit, while for a westerly drift the period has to be larger. Data of drift orbits are given in Table 6a and 6b.

The required impulsive ΔV's are:

15^{o}E drift in 1 rev.: ΔV_i = 44.567 m/s ; t = 22.94 h
15^{o}W drift in 1 rev.: ΔV_i = 40.988 m/s ; t = 24.93 h
15^{o}E drift in 2 rev^{s}.: ΔV_i = 21.807 m/s ; t = 46.87 h
15^{o}W drift in 2 rev^{s}.: ΔV_i = 20.905 m/s ; t = 48.87 h

The Tug then coasts for one (or more) revolutions in drift orbit.

6*. In apogee (easterly drift) or perigee (westerly drift) of drift orbit a thrusting phase such that target orbit is entered:

1A: thrusting with main engine
1B: thrusting with APS.

The required impulsive ΔV's are the same as above.

The Tug then rendez-vous with and captures the payload taking 3 h, and stays in target orbit until position relative to Shuttle is such that at arrival of the Tug in base orbit the Shuttle is at the same longitude (max. waiting time: 1.565 h).

7. Thrusting phase such that transfer orbit is entered.
Required impulsive ΔV is 1479.116 m/s.
No losses due to finite thrust are taken into account.
The Tug then coasts half a revolution in transfer orbit (5.256 h).

8. Tug reaches perigee of transfer orbit and burns such that base orbit is entered.

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* This phase occurs only in roundtrip mission.

Required impulsive ΔV = 2459.710 m/s.
Again, no finite thrust losses have to be considered.

9. Rendez-vous with Shuttle.

The maximum mission duration for roundtrip missions is:

1 rev. in drift orbit: 46 h.

2 rev. in drift orbit: 70 h.

For placement and retrieval missions the maximum mission duration is 18.2 h.

5.4. Results

Placement, retrieval and roundtrip payload capabilities have been calculated for these missions. The results of these calculations are presented in Fig. 8, 9, 10 and 11, where the payload mass is given as a function of the Tug initial mass.

The maximum payload that can be placed is 3762 kg. This restriction results from the fact that the maximum Tug initial mass is 29500 kg being the Shuttle performance limit.
The maximum payload mass for retrieval and roundtrip missions results from the constraint on nominal useful propellant mass (max. 23000 kg).
These maximum payload masses are:
retrieval: 1837 kg
roundtrip, strategy 1A, 1 rev. drift W: 1131 kg
2 rev. drift W: 1176 kg
strategy 1B, 1 rev. drift W: 1185 kg
2 rev. drift W: 1241 kg
For an easterly drift these figures will be somewhat less since the required ΔV's are larger.

Comparing Fig. 10 and 11 it can be concluded that strategy 1B (transition from target orbit into drift orbit and vice versa by APS) is the best one. Although the specific impuls of the APS is less then half the specific impuls of the main engine, which results in a much larger fuel consumption,the main engine start losses are clearly decisive in this case.

In the next section examples of a placement, a retrieval and a roundtrip mission with maximum payload are given.

5.5. Examples

5.5.1. Placement of a 3762 kg payload in a 35788.8 km circular orbit with 28°.5 inclination at an earth longitude of 20°W.

Payload mass	3762	kg
Tug net mass	3162.3	kg
Reserve propellant	46	kg
Propellant losses	302	kg
Useful propellant	22012	kg
Usable hydrazine	216	kg
Tug initial mass	29500.3	kg
Tug empty mass	3208.3	kg

1. t = 0

   Shuttle in base orbit (185.2/185.2 km, 28°.5 inclination) passes first descending node at earth longitude $\Lambda = 10^{o}$E. Tug deployment and check-out. APS uses 54 kg of hydrazine to align the Tug for the first burn.

2. t = 9219.2 s = 2.561 h.

Tug burns for 631.3 s providing a ΔV of 2534.71 m/s (consisting of an impulsive ΔV of 2459.71 m/s, 25.3 m/s velocity loss due to finite thrust and a 2% contingency).

Initial mass   29446.3 kg

Propellant used   12693.5 kg (including 68 kg start losses)

Final mass   16752.8 kg

Transfer orbit is then entered.

Tug coasts half a revolution (18921.7 s = 5.256 h) in transfer orbit and uses 54 kg of hydrazine to align for next burn, while 10 kg of propellant is lost by boil-off.

3. t = 28140.9 s = 7.817 h.

Tug reaches apogee of transfer orbit at an altitude of 35788.8 km and burns for 236.2 s providing an impulsive ΔV of 1479.116 m/s plus a 2% contingency.

Initial mass   16688.8 kg

Propellant used   4792.7 kg (including 68 kg losses)

Final mass   11896.1 kg

Target orbit is then entered at a mean earth longitude of 20^{o} W.

4. Placement of payload, requiring 3 h.

Tug stays in target orbit until t = 12.268 h, while 54 kg of hydrazine is used to align Tug for next burn and 10 kg of propellant is lost.

7. t = 44165.7 s = 12.268 h.

Tug burns for 113.7 s, providing an impulsive ΔV of 1479.116 m/s plus a 2% contingency; Tug enters transfer orbit.

Initial mass   8070.1 kg

Propellant used   2342.8 kg (including 68 kg losses)

Final mass   5727.3 kg

Tug then coasts half a revolution in transfer orbit (5.256 h) and uses 54 kg hydrazine to align for next burn and 10 kg of propellant is lost by boil-off.

8. t = 63087.4 s = 17.524 h.

   Tug reaches perigee of transfer orbit and burns for 119.3 s providing a ΔV of 2459.71 m/s plus a 2% contingency ΔV. By this manoeuvre base orbit is entered in the neighbourhood of the Shuttle.

Initial mass	5663.3 kg	
Propellant used	2455.0 kg	(including 68 kg losses)
Final mass	3208.3 kg	

   Tug rendez-vous with Shuttle and the combination returns to earth.

5.5.2. <u>Retrieval of a 1837 kg payload from a 35788.8 km circular orbit with 28°.5 inclination at an earth longitude of 20°W.</u>

Payload mass	1837 kg
Tug net mass	3162.3 kg
Reserve propellant	46 kg
Propellant losses	302 kg
Useful propellant	22998.8 kg
Usable hydrazine	216 kg
Tug intitial mass	26725.1 kg
Tug empty mass	5045.3 kg

1. t = 0

   Shuttle in base orbit (185.2/185.2 km, 28°.5 inclination) passes first descending node at earth longitude Λ = 10°E. Tug deployment and check-out. APS uses 54 kg of hydrazine to align the Tug for the first burn.

2. t = 9219.2 s = 2.561 h.

   Tug burns for 570.9 s providing a ΔV of 2530.43 m/s (impulsive

(impulsive ΔV = 2459.71 m/s, ΔV_{loss} = 21.1 m/s, 2% contingency ΔV).

Initial mass 26671.1 kg

Propellant used 11487.3 kg (including 68 kg losses)

Final mass 15183.8 kg

Transfer orbit (185.2/35788.8 km) is then entered.

Tug coasts half a revolution in transfer orbit and uses 54 kg of hydrazine to align for next burning phase; 10 kg of propellant is lost by boil-off.

3. t = 28140.9 s = 7.817 h.

Tug reaches apogee of transfer orbit at an altitude of 35788.8 km and burns for 213.9 s providing an impulsive ΔV of 1479.116 m/s plus a 2% contingency ΔV.

Initial mass 15119.8 kg

Propellant used 4346.7 kg (including 68 kg losses)

Final mass 10773.1 kg

Target orbit is then entered at a mean earth longitude of 20°W.

4. Rendez-vous and capture of payload requiring 3 h. Tug stays in target orbit until t = 12.268 h. APS uses 54 kg of hydrazine and 10 kg of propellant is lost by boil-off.

7. t = 44165.7 s = 12.268 h.

Tug burns for 177.4 s providing an impulsive ΔV of 1479.116 m/s plus a 2% contingency; Tug enters transfer orbit.

Initial mass 12546.1 kg

Propellant used 3615.1 kg (including 68 kg losses)

Final mass 8931.0 kg

Tug then coasts half a revolution in transfer orbit (5.256 h) and uses 54 kg hydrazine to align for next burn and 10 kg of propellant is lost by boil-off.

8. t = 63087.4 s = 17.524 h.

Tug reaches perigee of transfer orbit and burns for 187.7 s providing an impulsive ΔV of 2459.71 m/s plus a 2% contingency ΔV. Base orbit is then entered in the neighbourhood of the Shuttle.

Initial mass	8867.0 kg
Propellant used	3821.7 kg (including 68 kg losses)
Final mass	5045.3 kg

Tug rendez-vous with Shuttle and returns to earth.

5.5.3. Roundtrip with a 1185 kg payload to a 35788.8 km circular orbit with 28°5 inclination. Placement of satellite at 20°W, retrieval of satellite from 35°W.

Payload mass	1185 kg
Tug net mass	3162.3 kg
Reserve propellant	46 kg
Propellant losses	302 kg
Useful propellant	22998.8 kg
Usable hydrazine	604.7 kg
Tug initial mass	28298.8 kg
Tug empty mass	4393.3 kg

Strategy 1B: one revolution in drift orbit

1. t = 0

   Shuttle in base orbit (185.2/185.2 km, 28°5 inclination) passes first descending node at earth longitude Λ = 10°E. Tug deployment and check-out. APS uses 54 kg of hydrazine to align for first burn.

2. t = 9219.2 s = 2.561 h.

   Tug burns for 605.1 s providing a ΔV of 2532.87 m/s (impulsive ΔV = 2459.71 m/s, ΔV_{loss} = 23.5 m/s, 2% contingency ΔV).

Initial mass	28244.8 kg
Propellant used	12171.0 kg (including 68 kg losses)
Final mass	16073.8 kg

Tug then enters the transfer orbit.
Tug coasts half a revolution in transfer orbit using 54 kg hydrazine to align for next burn and 10 kg of propellant is lost by boil-off.

3. t = 28140.9 s = 7.817 h.
Tug reaches apogee of transfer orbit and burns for 226.6 s, providing an impulsive ΔV of 1479.116 m/s plus 2% contingency.

Initial mass	16009.8 kg	
Propellant used	4599.7 kg	(including 68 kg losses)
Final mass	11410.1 kg	

Target orbit is then entered at a mean earth longitude of 20°W.

4. Placement of payload requiring 3 h.

5. t = 38900.9 s = 10.817 h.
Thrusting phase with APS such that a drift orbit is entered with a period of 89754.2 s, an altitude of 35788.8/38114.6 km and 28°.5 inclination.
Required ΔV = 40.988 m/s.

Initial mass	10225.1 kg
Hydrazine used	195.8 kg
Final mass	10029.3 kg

The Tug then coasts for one revolution (24.93 h) in drift orbit.

6. t = 128655.1 s = 35.737 h.
Thrusting phase with APS in perigee of drift orbit such that target orbit is entered again, but now at a mean earth longitude of 35°W.
Required impulsive ΔV = 40.988 m/s.

Initial mass	10029.3 kg
Hydrazine used	192.9 kg
Final mass	9836.4 kg

Rendez-vous and capture of payload requiring 3 h. Tug then waits in target orbit for 0.647 h for the right moment to return to the Shuttle.

7. t = 141786.4 s = 39.385 h.
Tug burns for 154.8 s, providing an impulsive ΔV of 1479.116 m/s plus a 2% contingency ΔV and transfer orbit is entered.

Initial mass	10957.4 kg
Propellant used	3163.5 kg (including 68 kg losses)
Final mass	7793.9 kg

Tug then coasts half a revolution in transfer orbit using 54 kg of hydrazine, while 10 kg of propellant is lost by boil-off.

8. t = 160708.1 s = 44.641 h.
Tug reaches perigee of transfer orbit and burns for 187.7 s providing an impulsive ΔV of 2459.71 m/s plus 2% contingency.
Base orbit is then entered in neighbourhood of the Shuttle.

Initial mass	7729.9 kg
Propellant used	3336.6 kg (including 68 kg losses)
Final mass	4393.3 kg

Tug rendez-vous with Shuttle and returns to earth.

6. Geostationary missions

6.1. Mission definition

Since the minimal inclination the Shuttle can attain without in-flight plane change is 28°.5, base orbit for this mission will also be a circular orbit at an altitude of 185.2 km and with an inclination of 28°.5 (Table 3).
Target orbit will be the geostationary orbit (0° inclination) (Table 7).

Object of mission: Placement and/or retrieval of a payload in/from target orbit at any demanded earth longitude with minimal propellant consumption.

Since base orbit and target orbit have different inclination, plane changes will be necessary. These plane changes can take place at base orbit altitude and at target orbit altitude. If the total impulsive ΔV required to leave base orbit and to enter target orbit is determined as a function of the total plane change at base orbit altitude, an optimum for this plane change is found, being $-2^{\circ}.16$ (Fig. 12). The inclination change at geostationary altitude is then $-26^{\circ}.34$.

The total ΔV is then 4273.349 m/s, consisting of 2482.691 m/s at base orbit altitude and 1790.658 m/s at target orbit altitude.

6.2. Phasing orbits

The major problem of this mission is that the payload must be placed exactly at a prescribed earth longitude in the geostationary orbit. As a result of the adopted restriction that impulses will only be given on the nodal line and in the apses, only a discrete number of stations in geostationary orbit can be reached if transfer from base orbit to geostationary orbit takes place directly.

The first descending node passage takes place at an earth longitude $\Lambda = 10^{\circ}$E. First possibility of departure from base orbit is at the second descending node passage. The earth longitude is then $12^{\circ}.095$ W. During the transfer time from B.O to geostationary orbit (5.256 h) every station in geostationary orbit covers an angular distance of $79^{\circ}.055$ eastwards with respect to the line of nodes. So the first point in geostationary orbit that can be reached directly is located at an earth longitude of $88^{\circ}.85$ E ($180^{\circ} - 79^{\circ}.055 - 12^{\circ}.095$). This point is indicated as 2D in Fig. 13 (the point that is reached if departure from base orbit takes place at the 2nd descending node passage). If departure from base orbit takes place at the 3rd descending node passage the point 3D is reached, where 3D is located $22\overset{\circ}{.}095$ to the west of 2D, etc.

Departure from base orbit at the ascending node can take place for the first time at the 2nd ascending node passage. The station in geostationary orbit that will be reached then has a longitude of $102\overset{\circ}{.}198$ W (2A), while the next station (3A) lies again $22\overset{\circ}{.}095$ to the west of 2A, etc.

Now if a station, lieing between the "direct attainable stations" (2D, 3D, ... 2A, 3A, ...) has to be reached, there are a number of possibilities to accomplish this. For example, if a station between 7D and 8D must be reached this can be accomplished by:

1. Low-altitude phasing

   At the 6th descending node passage a ΔV_1 is given such that a phasing orbit is entered. The period of the phasing orbit must be such that the stations in geostationary orbit cover an angular distance during this period which is equal to the angular distance between 6D and the prescribed station. If θ_ℓ (the phasing angle) is the angular distance between 7D and the station, the period of the phasing orbit must be $(22\overset{\circ}{.}095 + \theta_\ell)/\omega_{geost.} = P_{b.o} + \theta_\ell/\omega_{geost.}$ where $\omega_{geost.}$ is the angular velocity of the stations in geostationary orbit and $P_{b.o}$ is the period of base orbit.

   For $\theta_\ell = 0$ the phasing orbit is identical with the base orbit, while for $\theta_\ell = 22\overset{\circ}{.}095$ the phasing orbit has a period which is twice the period of the base orbit.

   The Tug then coasts one revolution in this phasing orbit and at perigee a second impuls, ΔV_2 is given such that transfer orbit is entered.

   The inclination changes at the transitions from base orbit to phasing orbit and from phasing orbit to transfer orbit follow from the fact that the sum has to be $-2\overset{\circ}{.}16$ while the total $\Delta V = \Delta V_1 + \Delta V_2$ has to be a minimum (Fig. 14). Fig. 15 gives the optimal split in total inclination change as a function of phasing angle θ_ℓ.

Fig. 16 shows ΔV_1 and ΔV_2 as a function of θ_ℓ while in Fig. 17 the apogee altitude of the phasing orbit is given as a function of θ_ℓ. Fig. 18 finally gives the time from first descending node passage to arrival in geostationary orbit as a function of the earth longitude of the station. This time is the sum of the waiting time in base orbit, the period of the phasing orbit and half the period of the transfer orbit. This subdivision is also indicated in Fig. 18. It follows from this Figure that a maximum time of about 21 h is needed to reach any station in geostationary orbit.

2. High-altitude phasing

Here two possibilities can be distinguished:

a At the 7th descending node passage a ΔV is given such that transfer orbit is entered. The Tug then coasts half a revolution in the transfer orbit and at arrival at geostationary altitude an impulse is given such that a phasing orbit is entered. The period of this phasing orbit must be larger then the period of the geostationary orbit, since a westerly drift of θ_ℓ is required after one revolution in this phasing orbit.

b At the 8th descending node passage a ΔV is given such that transfer orbit is entered. The Tug then coasts half a revolution in this transfer orbit and on arrival at geostationary altitude (8D) an impulse is given such that a phasing orbit is entered with a period such that after one revolution in this phasing orbit an easterly drift of θ_h has taken place. After one revolution in this phasing orbit the Tug then enters the geostationary orbit at the demanded longitude.

The last method (b), with an easterly drift, will be the best one, since if the inclination change from transfer orbit to geostationary orbit is split optimally in a Δi_3 at the transition from transfer orbit to phasing orbit and a Δi_4 at the transition from phasing orbit to geostationary orbit, the total ΔV required at geostationary

altitude will not be influenced by the phasing orbit. In case (a), however, the total ΔV at geostationary altitude will increase if the phase angle θ_ℓ increases (Fig. 19).
Even if the total inclination change of $-26^\circ.34$ is not split optimally, but is given at the transition from transfer orbit to phasing orbit, an easterly drift will be optimal for drift angles until $21^\circ.3$. For the maximum drift angle of $22^\circ.095$ the extra ΔV required if no optimal inclination split is applied is only 5.666 m/s. Therefore, only method b is used in the performance calculations.

Fig. 20 gives the ΔV requirements as a function of drift angle θ_h and in Fig. 21 perigee altitude of the phasing orbit is given as a function of θ_h. Fig. 22 gives the total time from first descending node passage to arrival in geostationary orbit as a function of satellite longitude, split in waiting time in base orbit, transfer orbit time and phasing orbit time. For the points indicated with 2D, 3D, etc. and 2A, 3A, etc. no phasing is necessary and the total time is the sum of base orbit waiting time and transfer orbit time.

The same phasing problems arise on the return flight since a transfer orbit from geostationary orbit to base orbit can only be initiated on the nodal line passages. So, when the Tug arrives at base orbit the Shuttle will not be in the neighbourhood in general. For this problem two solutions have been considered:

1. <u>Tug phasing</u>
   As the Tug arrives at base orbit altitude it is not decelerated to base orbit velocity but to a somewhat higher velocity. The Tug will then describe a phasing orbit. If the period of this phasing orbit is chosen well, Shuttle and Tug will have the same earth longitude after completion of one revolution in the phasing orbit. The Tug then enters base orbit and rendez-vous with the Shuttle can take place.

2. <u>Shuttle phasing</u>

Immediately after Tug deployment, the Shuttle enters an eccentric rendez-vous orbit with perigee at base orbit altitude and in that node where the Tug will return. The period of this rendez-vous orbit must be such that when the Tug returns at base orbit altitude the Shuttle will have completed an entire number of revolutions in this rendez-vous orbit and will be at the same earth longitude as the Tug.

Fig. 23 and 24 give the required period of the Shuttle rendez-vous orbit as a function of the time between Tug deployment and Tug return at base orbit altitude. It is assumed that the Shuttle enters the rendez-vous orbit in the first ascending node or first descending node passage immediately after Tug deployment. Fig. 25 gives the required impulsive ΔV to enter the rendez-vous orbit as a function of the period of the orbit. The period is given by $P = \alpha P_o$, where P_o is the period of base orbit. Fig. 26 shows the corresponding apogee altitude of the rendez-vous orbit.

In Fig. 27 the longitude of the nodes is given as a function of time after first descending node passage. This Figure can be used to determine the departure time of the Tug from geostationary orbit, for it is only on the nodal line that this departure can be initiated.

Combining the above mentioned possibilities for ascent phasing and descent phasing, four main strategies can be defined. These strategies can be subdivided dependent on how some small impulses are given (by main engine or by APS). For placement and retrieval six different strategies have been considered while for the roundtrip mission ten strategies have been compared.

These strategies will be described in the following.

6.3. Strategies

Strategy 1 (A, B). Low-altitude phasing (Fig. 28)

1. Tug and payload are kept in Shuttle until one revolution before the chosen node is reached. Maximum waiting time is 11.75 h (Fig. 18).

   Deployment and check-out of Tug: 1.47 h.

   The Tug burns at the chosen node of base orbit such that a phasing orbit is entered with the correct period (dependent on longitude of station in target orbit) and such that the inclination change from base orbit to phasing orbit is optimal (Fig. 14-18).

Impulsive ΔV_1		0 - 1342.864 m/s
Inclination change	$-\Delta i_1$	0 - 1°313
Period		1.469 - 2.938 h
Apogee altitude		185.2 - 7892.652 km

   Tug then coasts one revolution in this phasing orbit (1.469 - 2.938 h)

2. Tug burns at perigee of phasing orbit such that a transfer orbit is entered with an apogee altitude of 35788.8 km and such that the inclination change is optimal (Table 8).

Impulsive ΔV_2		2482.691 - 1139.827 m/s
Inclination change	$-\Delta i_2$	2°16 - 0°847
Period		10.512 h
Inclination		26°34

   Tug then coasts half a revolution in transfer orbit (5.256 h)

3. Tug burns in apogee of transfer orbit such that the target orbit is entered.

Impulsive ΔV_3		1790.658 m/s
Inclination change	$-\Delta i_3$	26°34

   Total time to reach target orbit is maximal 20.9 h.

   Placement of payload (placement or roundtrip mission) or capture of payload (retrieval mission) : 3 h.

5* Only in case of roundtrip mission (Fig. 7):

1A: thrusting phase with main engine

1B: thrusting phase with APS.

This thrusting phase must be such that a drift orbit is entered. The period of this drift orbit has to be such that after one (or more) revolutions a drift of 15° has taken place (Table 6).

The required impulsive ΔV's are:

15°E drift in 1 rev.: ΔV_5 = 44.567 m/s; t = 22.94 h

15°W drift in 1 rev.: ΔV_5 = 40.988 m/s; t = 24.93 h

15°E drift in 2 revs.: ΔV_5 = 21.807 m/s; t = 46.87 h

15°W drift in 2 revs.: ΔV_5 = 20.905 m/s; t = 48.87 h

The Tug then coasts for one (or more) revolution(s) in drift orbit.

6* In apogee (easterly drift) or perigee (westerly drift) of drift orbit thrusting phase such that target orbit is entered again:

1A: thrusting phase with main engine

1B: thrusting phase with APS.

Required impulsive $\Delta V_6 = \Delta V_5$.

Fine rendez-vous and capture of payload: 3 h.

Tug stays in target orbit until nodal line passage; maximum waiting time is 12 h (Fig. 27).

7. Thrusting phase in node such that transfer orbit is entered with perigee altitude 185.2 km.

Required impulsive $\Delta V_7 = \Delta V_3$

Inclination change $\Delta i_7 = -\Delta i_3$

Tug then coasts half a revolution in transfer orbit: 5.256 h.

8. In perigee of transfer orbit a thrusting phase such that a phasing orbit is entered. The period of this phasing orbit must be such that after one revolution Tug and Shuttle are at the same earth longitude.

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* This phase occurs only in a roundtrip mission.

Impulsive ΔV_8 2482.691 - 1139.827 m/s
Inclination change Δi_8 2°16 - 0°847
Tug then coasts one revolution in this phasing orbit.

9. Tug burns in perigee of phasing orbit such that base orbit is entered. Shuttle will then be in the neighbourhood of Tug.
Impulsive ΔV_9 0 - 1342.864 m/s
Inclination change Δi_9 0 - 1°313
Rendez-vous with Shuttle.
Total time until this rendez-vous (1 rev. in D.O) $\approx$ 72 h.

Strategy 2 (A, B). Low-altitude phasing (Fig. 29)
This strategy is almost identical with Strategy 1 with the exception that directly after Tug deployment the Shuttle enters an eccentric orbit with perigee at 185.2 km and in the node where the Tug will return. The period of this orbit has to be such that at the return of the Tug at base orbit altitude the Shuttle will be at the same altitude and the same longitude (Fig. 23, 24, 25).
The phases 8 and 9 of strategy 1 are then not necessary any more, while phase 8 changes in:

8. Thrusting phase in perigee of T.O. such that the Shuttle orbit is entered.
Required impulsive $\Delta V_8 \leq$ 2482.691 m/s
Inclination change Δi_8 2°16

Strategy 3 (A, B, C). High-altitude phasing (Fig. 30)
1. Tug and payload are kept in Shuttle until one revolution before the chosen node is reached (Fig. 22).
Maximum waiting time: 11.75 h.
Tug deployment and check-out: 1.47 h.

2. The Tug then burns at the chosen node of base orbit such that the transfer orbit is entered (Table 8).

Impulsive ΔV_2 2482.691 m/s
Inclination change Δi_2 $-2^{\circ}.16$
Tug then coasts half a revolution in this transfer orbit (5.256 h).

3. On arrival at apogee of transfer orbit a thrusting phase commences such that a phasing orbit is entered. The period of this phasing orbit has to be such that after one revolution an easterly drift has taken place such that the Tug is at the prescribed longitude (Fig. 20, 21).
Required impulsive ΔV_3 1790.658 - 1729.287 m/s
Inclination change Δi_3 $-26^{\circ}.34$
Period of phasing orbit 23.934 - 22.465 h
Perigee altitude of P.O. 35788.8 - 32280 km
The Tug then coasts one revolution in this phasing orbit (23.934 - 22.465 h).

4. 3A, 3B: Thrusting phase with main engine
3C: Thrusting phase with APS
The thrusting phase has to be such that target orbit is entered.
Required impulsive ΔV_4 0 - 67.037 m/s
Inclination change Δi_4 0°
Total time to reach prescribed station in target orbit is maximal 42 h.
Placement of payload (placement or roundtrip mission) or capture of payload (retrieval mission): 3 h.

5* In case of roundtrip mission (Fig. 7):
3A : thrusting phase with main engine
3B, 3C: thrusting phase with APS.
This thrusting phase has to be such that a drift orbit is entered, with a period such that after one (or more) revolutions of the Tug in this drift orbit a drift of 15° has taken place (Table 6).
The required impulsive ΔV's are:

* This phase occurs only in a roundtrip mission.

$15^{o}E$ drift in 1 rev.: ΔV_5 = 44.567 m/s; t = 22.94 h
$15^{o}W$ drift in 1 rev.: ΔV_5 = 40.988 m/s; t = 24.93 h
$15^{o}E$ drift in 2 rev^{s}.: ΔV_5 = 21.807 m/s; t = 46.87 h
$15^{o}W$ drift in 2 rev^{s}.: ΔV_5 = 20.905 m/s; t = 48.87 h
The Tug then coasts one (or more) revolution(s) in this drift orbit.

6[x] In apogee (easterly drift) or perigee (westerly drift) of drift orbit a thrusting phase such that target orbit is entered.
3A : thrusting phase with main engine
3B, 3C: thrusting phase with APS.
Required impulsive $\Delta V_6 = \Delta V_5$
Rendez-vous and capture of payload.
Tug stays in target orbit until nodal line passage. Maximum waiting time is 12 h (Fig. 27).

7. Thrusting phase in node such that transfer orbit is entered with perigee altitude of 185.2 km.
Impulsive ΔV_7 1790.658 m/s
Inclination change Δi_7 $26^{o}.34$
Tug coasts half a revolution in transfer orbit: 5.256 h.

8. In perigee of transfer orbit thrusting phase such that a phasing orbit is entered with correct period, in connection with the rendez-vous with the Shuttle.
Impulsive ΔV_8 2482.691 - 1139.827 m/s
Inclination change Δi_8 $2^{o}.16$ - $0^{o}.847$
Tug then coasts one revolution in this phasing orbit (1.469 - 2.938 h).

9. Tug burns in perigee of phasing orbit and enters base orbit.
Impulsive ΔV_9 0 - 1342.864 m/s
Inclination change Δi_9 0 - $1^{o}.313$
Rendez-vous with Shuttle. Total time by 1 rev. in D.O. $\approx$ 92 h.

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x This phase occurs only in a roundtrip mission.

Strategy 4 (A, B, C). High-altitude phasing (Fig. 31)
This strategy is almost identical with Strategy 3. Only here, as in Strategy 2, the Shuttle enters an eccentric orbit with perigee at base orbit altitude and in the node where the Tug will return. The period of this rendez-vous orbit must be such that the total mission time of the Tug (i.e. time of departure from base orbit until return to base orbit altitude) is a multiple of this period (or a multiple and a half, depending on the node of departure and return) (Fig. 23, 24, 25).
In this case no descending phasing orbit will be necessary and phase 8 changes in:

8. Thrusting phase in perigee of transfer orbit such that the Shuttle orbit is entered.
   Impulsive ΔV_8 $\leq$ 2482.691 m/s
   Inclination change Δi_8 $2^\circ.16$

6.4. Cases selected for performance calculations

For this type of mission the placement, retrieval and roundtrip payload capabilities have been calculated for all the different strategies.
Since the payload capability is dependent on the phasing angles three cases have been considered for every mission and strategy:

1. No phasing. So only the stations indicated as 2D, 3D, etc, and 2A, 3A, etc, in geostationary orbit can be reached, while the total mission time must be such that at the return of the Tug at base orbit altitude the Shuttle is at the same altitude and longitude.

2. Worst case of phasing. This is the case where the ascent phasing angle is a maximum and the descent phasing angle is a minimum.

3. Best case of phasing. The ascent phasing angle then is minimal and the descent phasing angle is a maximum.

The cases 2 and 3 require two extra burning phases compared to case 1 using the strategies 1 or 3, while one extra burning phase is required using the strategies 2 or 4, for in these strategies the descent phasing is done by the Shuttle.

In this manner payload mass as a function of Tug initial mass is obtained as a curve in the no phasing case and as an area, lieing between the curves for the worst phasing and the best phasing case, in case of phasing.

For the strategies 2 and 4 (the strategies where the Shuttle enters a rendez-vous orbit) the ΔV required to inject the Tug into the rendez-vous orbit is taken equal to the required ΔV to enter base orbit. Although in general the first ΔV will be smaller and thus the payload capability of the Tug will be larger, it is quite dependent on the Shuttle rendez-vous orbit and thus on the total mission time. So the exact value of ΔV can only be calculated if the mission is completely specified. However, even then it is questionable whether it is realistic to use this smaller value of ΔV for in that case a part of the Tug mission is performed by the Shuttle and a "fair" comparison between the strategies is not possible any more (Strategy 2 or 4 will then be best).

6.5. Losses due to finite thrust

These losses where calculated for this mission in the manner as described in section 5. Here too non-negligible losses appeared only at the transition from base orbit to phasing orbit and at the transition from phasing orbit to transfer orbit. Since the losses are dependent on the initial conditions (orbital velocity and mass) calculations were made for two cases:

1. Losses at departure from base orbit as a function of the required impulsive ΔV, for different initial masses (Fig. 4).

2. Losses at departure from perigee of the phasing orbit which gives maximum phasing angle, as a function of impulsive ΔV (Fig. 32).

These Figures then were used in the following manner:

1. In the case of no phasing, departure from base orbit takes place by an impuls ΔV_i = 2482.691 m/s, so for this case ΔV_{loss} is only a function of the Tug initial mass (Fig. 33).

2. In the worst case of phasing first losses appear at the transition from base orbit to phasing orbit. The required ΔV for this transition is 1342.864 m/s so from Fig. 4 ΔV_{loss} follows as a function of Tug initial mass at this impulsive ΔV. The result is given in Fig. 34.
   The injection from phasing orbit into transfer orbit requires an impulsive ΔV of 1139.827 m/s. So at this value of ΔV_i a cross-plot from Fig. 32 is made which results in ΔV_{loss} as a function of initial mass at departure from phasing orbit to geostationary altitude (Fig. 35).

3. In the best case of phasing the phasing orbit is identical with the base orbit so ΔV_1 = 0, and consequently the losses are zero, while at the departure from phasing orbit (base orbit) into transfer orbit ΔV_i = 2482.691 m/s and consequently the losses are the same function of M_o as in the no phasing case (Fig. 33).

6.6. Results

The results are presented in Fig. 36 - 65 and in Table 9 - 12.

Placement

Fig. 36 - 41 give the payload mass as a function of the Tug initial mass for the six strategies considered. In all strategies payload capability is restricted by maximum useful propellant mass.
In Fig. 58 Tug initial mass is given for a 1000 kg payload for the different strategies. For all strategies the Tug initial mass is the same in the case of no phasing which is evident. From this Figure it can be concluded that strategy 2 is the best one since the mean initial mass is a mimimum.
Fig. 59 gives the maximum payload mass that can be placed in geostationary orbit. Also with respect to this maximum, strategy 2 is the best one.
Table 9 finally, gives the Tug mass distribution for maximum payload.

Retrieval

Fig. 42 - 47 give the payload mass as a function of Tug initial mass for the six strategies which are considered. Here too, maximum payload is restricted by maximum useful propellant.
Fig. 60 gives the Tug initial mass for the various strategies for a payload of 400 kg. Here too, of course, in case of no phasing the Tug initial mass is not dependent on the strategy. For retrieval strategy 2 is also the best one. In this strategy the difference between the worst case of phasing and the best case of phasing is only 1 kg payload mass. This is a result of the fact that in the worst phasing case the total losses due to finite thrust are less then the losses in the best phasing case.
Fig. 61 presents the maximum payload mass that can be retrieved from geostationary orbit. Here too strategy 2 is the best one. Table 10 gives the mass distribution of the Tug for maximum payload mass.

Roundtrip

Roundtrip payload capability is calculated for the case in which the payload that is to be retrieved is situated 15^{o} west of the station where the first payload is placed. So a westerly drift will be necessary after placing the first payload. For an easterly drift the ΔV requirement will be somewhat larger resulting in a decrease of payload mass for the same Tug initial mass. This decrease however will be small (< 10 kg).

A westerly drift can be obtained by a drift orbit in which the Tug completes one or more revolutions. In the present report calculations are made for two cases, one in which the 15^{o} drift is obtained by 1 revolution in drift orbit and one where the 15^{o} drift is obtained by 2 revolutions in drift orbit. The increase in payload mass by applying 2 revolutions is about 10%; the increase in total mission time, however, is about 25% - 50%.

For all the calculations a constant boil-off of 10 kg per coasting phase is used; in reality however, the boil-off will be lineair dependent on time. So exact figures for boil-off rate are needed to decide how many revolutions in drift orbit are optimal.

Again, maximum payload is restricted by the maximum useful propellant mass.

Fig. 62 gives initial mass for a roundtrip with a 200 kg payload, where the 15^{o} W drift is obtained by one revolution in drift orbit. Fig. 63 and 64 give the maximum payload roundtrip capability for the various mission strategies for one revolution, respectively two revolutions in drift orbit. From these Figures it can be concluded that strategy 2B is the best one.

The Tables 11 and 12, finally, show the mass distribution of the Tug for the roundtrip mission.

6.7. Conclusions

For placement, retrieval as well as for roundtrip, the maximum performance of the Tug is obtained by applying mission strategy 2B.

Thus low-altitude phasing during ascent, while in the descent phase the phasing is done by the Shuttle.
For the roundtrip the drift orbit necessary to obtain a 15^o drift in geostationary orbit is to be initiated by the APS. Due to the start losses of the main engine this is better then using the main engine to initiate the drift orbit although the specific impulse of the APS is less the half the main engine specific impuls.

The maximum payload masses are:

Placement	1960 - 1989 kg
Retrieval	759 - 760 kg
Roundtrip	440 - 446 kg (1 rev. in D.O)
	490 - 497 kg (2 rev^s. in D.O)

Since in all cases the maximum payload is a result of the maximum useful propellant of the Tug a heavier Tug could be used. Especially the retrieval and roundtrip capability could be enlarged considerably in this way. The Tug initial mass for the retrieval mission is only about 26.9 ton, while the initial mass for the roundtrip mission is about 27.5 ton. The Shuttle performance limit is 29.5 ton for this mission.

In Fig. 65 the maximum payload masses for placement, retrieval and roundtrip to geostationary orbit are compared to these maxima for a mission to the same altitude but without plane changes (this mission was discussed in section 5). From this Figure it is clear that inclination changes reduce the maximum payload mass drastically.

In the next section examples are given of a placement, a retrieval and two roundtrip missions. The figures between parenthesis apply to the case where the Tug enters the Shuttle rendez-vous orbit and docks there with the Shuttle, thus requiring less ΔV then in the case of entering base orbit directly. The figures for the used propellant mass include 68 kg of engine start losses for every main engine burning phase.

6.8. Examples

6.8.1. Placement of a 1989 kg (2307 kg) payload in geostationary orbit at an earth longitude of 20°W.

Payload mass	1989 kg	(2307 kg)
Tug net mass	3162.3 kg	(3162.3 kg)
Reserve propellant	46 kg	(46 kg)
Propellant losses	380 kg	(380 kg)
Useful propellant	23000.3 kg	(22998.3 kg)
Usable hydrazine	270	(270 kg)
Tug initial mass	28847.6 kg	(29163.6 kg)
Tug empty mass	3208.3 kg	(3208.3 kg)

Strategy 2

1. t = 0

   Shuttle in base orbit (185.2/185.2 km, 28.°5 inclination) passes first descending node at earth longitude Λ = 10°E.
   Tug is kept in Shuttle until 4th descending node passage occurring at t = 15865.4 s = 4.407 h.
   Earth longitude is then 56.° 29 W.

   t = 15865.4 s = 4.407 h ; Λ = 56.° 29 W
   Tug deployment and check-out during one revolution in base orbit.
   APS uses 54 kg of hydrazine to align Tug for first burning phase.

Initial mass	28847.6 kg	(29163.6 kg)
Final mass	28793.6 kg	(29109.6 kg)

S. t = 18509.6 s = 5.1416 h ; Λ = 112.°67 E
   Shuttle reaches 4th A.N. and enters a rendez-vous orbit with an altitude of 185.2 - 557.6 km, a period of 5515.176 s and a perigee velocity of 7901.486 m/s.
   The required impulsive ΔV for this manoeuvre is 106.824 m/s.

t = 21153.8 s = 5.876 h; Λ = 78°.39 E.

Tug reaches 5th descending node and burns for 364.4 s (368.4 s) providing a ΔV_1 of 1320.081 m/s (1320.209 m/s), consisting of an impulsive ΔV of 1289.112 m/s, losses due to finite thrust of 5.085 m/s (5.211 m/s) and a 2% contingency.

Initial mass	28793.6 kg	(29109.6 kg)
Propellant used	7355.4 kg	(7436.1 kg)
Final mass	21438.2 kg	(21673.5 kg)

A low phasing orbit is then entered:

Apogee altitude	7379 km
Inclination	27°.23
Period	10187.9 s

The Tug then coasts one revolution in this phasing orbit (2.83 h) and uses 54 kg of hydrazine to align for next burn while 10 kg of propellant is lost by boil-off.

2. t = 31341.7 s = 8.706 h; Λ = 120°.95 E.

Tug reaches perigee of phasing orbit and burns for 252.9 s (255.7 s) providing a ΔV_2 of 1222.515 m/s (1222.653 m/s) consisting of an impulsive ΔV of 1193.578 m/s finite thrust losses of 4.965 m/s (5.101 m/s) and a 2% contingency ΔV.

Initial mass	21374.2 kg	(21609.5 kg)
Propellant used	5125.5 kg	(5181.9 kg)
Final mass	16248.7 kg	(16427.6 kg)

A transfer orbit is then entered:

Apogee altitude	35788.8 km
Inclination	26°.34
Period	37843.4 s

Tug then coasts half a revolution (18921.7 s = 5.256 h) in transfer orbit and uses 54 kg of hydrazine to align for next burn, while 10 kg of propellant is boiled-off.

3. t = 50263.5 s = 13.962 h; Λ = 20°W.

Tug reaches apogee of transfer orbit at geostationary altitude and earth longitude of 20°W and burns for 268.3 s (271.3 s) providing an impulsive ΔV_3 of 1790.658 m/s plus a 2% contingency ΔV.

Initial mass	16184.7 kg	(16363.6 kg)
Propellant used	5434.1 kg	(5493.6 kg)
Final mass	10750.6 kg	(10870.0 kg)

The geostationary orbit is then entered and the payload is placed at exactly 20°W. This requires 3 h.

Thereafter, the Tug stays in geostationary orbit during 32282.6 s = 8.9674 h until descending node is at 20°W. APS uses 54 kg of hydrazine and 10 kg of propellant is boiled-off.

7. t = 93346.1 s = 25.9298 h; Λ = 20°W.

   Descending node is at 20°W and Tug burns for 143.7 s (140.4 s) providing an impulsive ΔV_7 of 1790.658 m/s plus a 2% contingency.

Initial mass	8697.6 kg	(8499.0 kg)
Propellant used	2941.2 kg	(2875.1 kg)
Final mass	5756.4 kg	(5623.9 kg)

   Transfer orbit is then entered:

Perigee altitude	185.2 km
Inclination	26°.34
Period	37843.4 s

   Tug then coasts half a revolution in this transfer orbit (5.256 h). APS uses 54 kg of hydrazine and 10 kg of propellant is lost by boil-off.

8. t = 112267.8 s = 31.1855 h; Λ = 80°.95 E.

   Time after separation from Shuttle is 26.7785 h. Tug reaches perigee of transfer orbit and burns for 120.8 s (114.2 s) providing a ΔV_8 of 2482.691 m/s (2377.228 m/s) plus 2%.

Initial mass	5692.4 kg	(5559.9 kg)
Propellant used	2484.1 kg	(2351.6 kg)
Final mass	3208.3 kg	(3208.3 kg)

By this manoeuvre base orbit (Shuttle rendez-vous orbit) is entered. At the same time the Shuttle has completed 17 revolutions in rendez-vous orbit and is also at longitude 80.95 E.
Rendez-vous with Shuttle and return to earth.

6.8.2. <u>Retrieval of a 760 kg (917 kg) payload from geostationary orbit at earth longitude of 20°W.</u>

Payload mass	760 kg	(917 kg)
Tug net mass	3162.3 kg	(3162.3 kg)
Reserve propellant	46 kg	(46 kg)
Propellant losses	380 kg	(380 kg)
Useful propellant	23000.6 kg	(23000.9 kg)
Usable hydrazine	270 kg	(270 kg)
Tug initial mass	26858.9 kg	(26859.2 kg)
Tug empty mass	3968.3	(4125.3 kg)

<u>Strategy 2</u>

1. t = 0 ; Λ = 10°E

Shuttle in base orbit (185.2/185.2 km, 28°.5 inclination) passes first descending node at earth longitude 10°E.
Tug is kept in Shuttle until 4th descending node passage occurring at t = 15865.4 s = 4.407 h.

t = 15865.4 s = 4.407 h ; Λ = 56°.29 W.
Tug deployment and check-out during one revolution in base orbit.
APS uses 54 kg of hydrazine to align Tug for the first burn.

Initial mass	26858.9 kg	(26859.2 kg)
Final mass	26804.9 kg	(26805.2 kg)

S. t = 18509.6 s = 5.1416 h ; Λ = 112°.67 E.

Shuttle reaches 4th ascending node and enters a rendez-vous orbit at an altitude of 185.2 - 557.6 km, with an inclination of 28°.5, a period of 5515.176 s and a perigee velocity of 7901.486 m/s.

The required impulsive ΔV for this manoeuvre is 106.824 m/s.

t = 21153.8 s = 5.876 h ; Λ = 78°.39 E.

Tug reaches 5th descending node and burns for 339.0 s (339.0 s) providing a ΔV_1 of 1319.341 m/s (impulsive ΔV = 1289.112 m/s, ΔV_{loss} = 4.360 m/s, 2% contingency).

Initial mass	26804.9 kg	(26805.2 kg)
Propellant used	6847.7 kg	(6847.7 kg)
Final mass	19957.2 kg	(19957.5 kg)

A low phasing orbit is then entered:

Apogee altitude	7379 km
Inclination	27°.23
Period	10187.9 s

Tug then coasts one revolution (2.830 h) in this phasing orbit and uses 54 kg of hydrazine for alignment while 10 kg of propellant is lost by boil-off.

2. t = 31341.7 s = 8.706 h ; Λ = 120°.95 E.

   Tug reaches perigee of phasing orbit and burns 235.2 s (235.2 s) providing a ΔV_2 of 1221.704 m/s (impulsive ΔV = 1193.579 m/s. ΔV_{loss} = 4.170 m/s, 2% contingency).

Initial mass	19893.2 kg	(19893.5 kg)
Propellant used	4771.3 kg	(4771.4 kg)
Final mass	15121.9 kg	(15122.1 kg)

   Transfer orbit is then entered:

Apogee altitude	35788.8 km
Inclination	26°.34
Period	37843.4 s

   Tug then coasts half a revolution in transfer orbit (5.256 h) and uses 54 kg of hydrazine; 10 kg of propellant is lost by boil-off.

3. t = 50263.5 s = 13.962 h ; Λ = 20°W.

   Tug reaches apogee of transfer orbit at geostationary altitude and earth longitude of 20°W and burns for 249.5 s (249.5 s) providing an impulsive ΔV_3 of 1790.658 m/s plus 2% contingency.

Initial mass	15057.9 kg	(15058.1 kg)
Propellant used	5058.9 kg	(5059.0 kg)
Final mass	9999.0 kg	(9999.1 kg)

The geostationary orbit is then entered and the payload is captured, taking 3 h.

Tug stays in geostationary orbit until descending node is at 20°W (waiting time is 8.9674 h). APS uses 54 kg of hydrazine; 10 kg of propellant is boiled-off.

7. t = 93346.1 s = 25.9298 h ; $\Lambda = 20^{\circ}$W.

   Descending node is at 20°W and Tug burns for 176.9 s (179.5 s), providing a ΔV_7 of 1790.658 m/s plus 2% contingency.

Initial mass	10695.0 kg	(10852.1 kg)
Propellant used	3606.3 kg	(3658.6 kg)
Final mass	7088.7 kg	(7193.5 kg)

   Transfer orbit is entered by this manoeuvre.

   The Tug coasts half a revolution in this transfer orbit. APS uses 54 kg of hydrazine to align Tug and again 10 kg of propellant is boiled-off.

8. t = 112267.8 s = 31.1855 h ; $\Lambda = 80\overset{\circ}{.}95$ E.

   Time after separation from Shuttle 26.7785 h.

   Tug reaches perigee of transfer orbit and burns for 149.4 s (146.8 s) providing a ΔV_8 of 2482.691 m/s (2377.228 m/s) plus 2% contingency.

Initial mass	7024.7 kg	(7129.5 kg)
Propellant used	3056.4 kg	(3004.2 kg)
Final mass	3968.3 kg	(4125.3 kg)

   Base orbit (Shuttle rendez-vous orbit) is then entered at the same earth longitude as the Shuttle, which has completed 17 revolutions in this rendez-vous orbit.

   Rendez-vous with the Shuttle and return to earth.

5.8.3. Roundtrip with a 446 kg (497 kg) payload to geostationary orbit. Placement at 20^{o}W, retrieval from 35^{o}W.

15^{o}W drift by one revolution in drift orbit.

Payload mass	446 kg	(497 kg)
Tug net mass	3162.3 kg	(3162.3 kg)
Reserve propellant	46 kg	(46 kg)
Propellant losses	380 kg	(380 kg)
Useful propellant	22998.8 kg	(23000.5 kg)
Usable hydrazine	644.9 kg	(643.7 kg)
Tug initial mass	27678.0 kg	(27729.5 kg)
Tug empty mass	3654.3 kg	(3705.3 kg)

Strategy 2B

1. t = 0 ; Λ = 10^{o}E.

   Shuttle in base orbit (185.2/185.2 km, $28^{o}.5$ inclination) passes first descending node.

   Tug is kept in Shuttle until 4^{th} descending node passage occurring at t = 15865.4 s = 4.407 h.

   t = 15865.4 s = 4.407 h ; Λ = $56^{o}.29$ W.

   Tug deployment and check-out during one revolution in base orbit. APS uses 54 kg of hydrazine to align Tug.

Initial mass	27678.0 kg	(27729.5 kg)
Final mass	27624.0 kg	(27675.5 kg)

S. t = 18509.6 s = 5.1416 h ; Λ = $112^{o}.67$ E.

   Shuttle reaches 4^{th} ascending node an enters a rendez-vous orbit with an altitude of 185.2 - 364.7 km, an inclination of $28^{o}.5$, a period of 5397.4 s and a perigee velocity of 7847.096 m/s.

The required impulsive ΔV for this manoeuvre is 52.433 m/s.

t = 21153.8 s = 5.876 h ; Λ = 78°39 E.
Tug reaches 5^{th} descending node and burns for 349.4 s (350.1 s) providing a ΔV_1 of 1319.632 m/s (impulsive ΔV = 1289.112 m/s, ΔV_{loss} = 4.645 m/s, contingency of 2%).

Initial mass	27624.0 kg	(27675.5 kg)
Propellant used	7056.7 kg	(7069.8 kg)
Final mass	20567.3 kg	(20605.7 kg)

A low phasing orbit is then entered:

Apogee altitude	7379 km
Inclination	27°23
Period	10187.9 s

Tug then coasts for one revolution (2.830 h) in this phasing orbit and uses 54 kg of hydrazine, while 10 kg of propellant is lost by boil-off.

2. t = 31341.7 s = 8.706 h ; Λ = 120°95 E.
Tug reaches perigee of phasing orbit and burns 242.5 s (242.9 s) providing a ΔV_2 of 1222.024 m/s (impulsive ΔV = 1193.579 m/s, ΔV_{loss} = 4.484 m/s)

Initial mass	20503.3 kg	(20541.7 kg)
Propellant used	4917.1 kg	(4926.3 kg)
Final mass	15586.2 kg	(15615.4 kg)

Transfer orbit/is then entered:

Apogee altitude	35788.8 km
Inclination	26°34
Period	37843.4 s

Tug coasts half a revolution in this transfer orbit and uses 54 kg of hydrazine and loses 10 kg of propellant.

3. t = 50263.5 s = 13.962 h ; Λ = 20°W.
Tug reaches apogee of transfer orbit at geostationary altitude

and earth longitude of 20°W and burns for 257.3 s (257.8 s) providing a ΔV_3 of 1790.658 m/s plus a 2% contingency ΔV.

Initial mass	15522.2 kg	(15551.4 kg)
Propellant used	5213.5 kg	(5223.2 kg)
Final mass	10308.7 kg	(10328.2 kg)

The geostationary orbit is then entered and the payload is placed, requiring 3 h.

5. t = 61063.5 s = 16.962 h ; Λ = 20°W;

Thrusting phase with APS such that a drift orbit is entered:

Apogee altitude	38114.6 km
Inclination	0°
Period	89754.2 s

Required ΔV_5 = 40.988 m/s

Initial mass	9862.7 kg	(9831.2 kg)
Hydrazine used	189.0 kg	(188.6 kg)
Final mass	9673.7 kg	(9642.6 kg)

Tug then coasts one revolution in drift orbit (24.932 h).

6. t = 150817.7 s = 41.8938 h ; Λ = 35°W

Tug reaches perigee of drift orbit at earth longitude of 35°W. Thrusting phase with APS such that geostationary orbit is entered again.

Required ΔV_6 = 40.988 m/s.

Initial mass	9673.7 kg	(9642.6 kg)
Hydrazine used	185.9 kg	(185.1 kg)
Final mass	9487.8 kg	(9457.5 kg)

Tug rendez-vous and captures second payload requiring 3 h. Tug then waits in geostationary orbit until descending node is at 35°W (waiting time is 5.9669 h). APS uses 54 kg of hydrazine and 10 kg of propellant is lost by boil-off.

7. t = 183098.5 s = 50.8607 h ; $\Lambda = 35^\circ$ W.
Descending node is at 35° W and Tug burns for 163.2 s (163.5 s) providing ΔV_7 of 1790.658 m/s plus 2% contingency.

Initial mass	9869.8 kg	(9890.5 kg)
Propellant used	3331.5 kg	(3338.4 kg)
Final mass	6538.3 kg	(6552.1 kg)

Transfer orbit is entered by this manoeuvre.
Tug coasts half a revolution in this transfer orbit. APS uses 54 kg; 10 kg propellant is boiled-off.

8. t = 202020.2 s = 56.1167 h ; $\Lambda = 65^\circ.95$ E.
Time after separation from Shuttle is 51.7097 h.
Tug reaches perigee of transfer orbit with a velocity of 10254.373 m/s and burns for 137.6 s (135.7 s) providing a ΔV_8 of 2482.691 m/s (2430.911 m/s) plus 2% contingency.

Initial mass	6474.3 kg	(6488.1 kg)
Propellant used	2820.0 kg	(2782.8 kg)
Final mass	3654.3 kg	(3705.3 kg)

Base orbit (Shuttle rendez-vous orbit) is entered by this manoeuvre. At this time the Shuttle has completed 34 revolutions in the rendez-vous orbit and is at the same earth longitude ($65^\circ.95$ E).
Rendez-vous with Shuttle and return to earth.

6.8.4. Roundtrip with a 497 kg (547 kg) payload to geostationary orbit. Placement at 20° W, retrieval from 35° W.

15° W drift by two revolutions in drift orbit.

Payload mass	497 kg	(547 kg)
Tug net mass	3162.3 kg	(3162.3 kg)
Reserve propellant	46 kg	(46 kg)
Propellant losses	380 kg	(380 kg)

Useful propellant	22999.8 kg	(23001.3 kg)
Usable hydrazine	461.1 kg	(460.5 kg)
Tug initial mass	27546.2 kg	(27597.1 kg)
Tug empty mass	3705.3 kg	(3755.3 kg)

Strategy 2B

1. t = 0 ; Λ = 10° E.

   Shuttle in base orbit (185.2/185.2 km, 28°.5 inclination) passes first descending node.
   Tug is kept in Shuttle until 4th descending node passage occurring at t = 15865.4 s = 4.407 h.

   t = 15865.4 s = 4.4070 h ; Λ = 56°.29 W.
   Tug deployment and check-out during one revolution in base orbit.
   APS uses 54 kg of hydrazine to align Tug.

Initial mass	27546.2 kg	(27597.1 kg)
Final mass	27492.2 kg	(27543.1 kg)

S. t = 18509.6 s = 5.1416 h ; Λ = 112°.67 E.

   Shuttle reaches 4th ascending node and enters a rendez-vous orbit with an altitude of 185.2 - 359.5 km, an inclination of 28°.5, a period of 5393.5 s and a perigee velocity of 7845.576 m/s.
   The required impulsive ΔV for this manoeuvre is 50.913 m/s.

   t = 21153.8 s = 5.876 h ; Λ = 78°.39 E.
   Tug reaches 5th descending node and burns for 347.8 s (348.4 s) providing a ΔV_1 of 1319.583 m/s (impulsive ΔV = 1289.112 m/s, ΔV_{loss} = 4.598 m/s, 2% contingency ΔV).

Initial mass	27492.2 kg	(27543.1 kg)
Propellant used	7023.0 kg	(7036.0 kg)
Final mass	20469.2 kg	(20507.1 kg)

A low phasing orbit is then entered:

Apogee altitude	7379 km.
Inclination	27°.23
Period	10187.9 s

The Tug then coasts one revolution (2.830 h) in this phasing orbit; 54 kg of hydrazine is used for alignment, 10 kg of propellant is boiled-off.

2. t = 31341.7 s = 8.7060 h ; Λ = 120°.95 E.

Tug reaches perigee of phasing orbit and burns 241.3 s (241.7 s) providing a ΔV_2 of 1221.971 m/s (impulsive ΔV = 1193.579 m/s, ΔV_{loss} = 4.432 m/s).

Initial mass	20405.2 kg	(20443.1 kg)
Propellant used	4893.6 kg	(4902.7 kg)
Final mass	15511.6 kg	(15540.4 kg)

Transfer orbit is then entered:

Apogee altitude	35788.8 km
Inclination	26°.34
Period	37843.4 s

Tug coasts half a revolution in this transfer orbit and uses 54 kg of hydrazine to align for next burn, while 10 kg of propellant is lost by boil-off.

3. t = 50263.5 s = 13.9621 h ; Λ = 20° W.

The Tug reaches apogee of transfer orbit at geostationary altitude and longitude 20° W, and burns for 256.0 s (256.5 s) providing a ΔV of 1790.658 m/s plus 2%.

Initial mass	15447.6 kg	(15476.4 kg)
Propellant used	5188.6 kg	(5198.2 kg)
Final mass	10259.0 kg	(10278.2 kg)

The geostationary orbit is then entered and the payload is placed at exactly 20°W. This takes 3 h.

5. t = 61063.5 s = 16.9621 h ; Λ = 20° W.

Thrusting phase with APS such that drift orbit is entered:

Apogee altitude	36955.3 km	
Inclination	0°	
Period	87959.1 s	
Required ΔV_5 = 20.905 m/s		
Initial mass	9762.0 kg	(9731.2 kg)
Hydrazine used	96.0 kg	(95.7 kg)
Final mass	9666.0 kg	(9635.5 kg)

The Tug then coasts two revolutions in this drift orbit (48.866 h).

6. t = 236981.7 s = 65.8283 h ; Λ = 35° W.

Tug reaches for second time perigee of drift orbit at earth longitude of 35° W.

Thrusting phase with APS such that geostationary orbit is entered again.

Required ΔV_6 = 20.905 m/s.

Initial mass	9666.0 kg	(9635.5 kg)
Hydrazine used	95.1 kg	(94.8 kg)
Final mass	9570.9 kg	(9540.7 kg)

Tug captures second payload (3 h) and waits 5.9669 h. in the geostationary orbit until the descending node is at longitude of 35° W. APS uses 54 kg of hydrazine for alignment of Tug and 10 kg of propellant is lost by boil-off.

7. t = 269262.5 s = 74.7951 h ; Λ = 35° W.

Descending node is at 35° W and Tug burns for 165.4 s (165.7 s) providing a ΔV_7 of 1790.658 m/s plus 2% contingency.

Initial mass	10003.9 kg	(10023.7 kg)
Propellant used	3376.1 kg	(3382.8 kg)
Final mass	6627.8 kg	(6640.9 kg)

Tug is injected into transfer orbit by this manoeuvre wherein it coasts half a revolution using 54 kg of hydrazine for alignment and losing 10 kg of propellant.

8. t = 288184.2 s = 80.0512 h ; $\Lambda = 65\overset{\circ}{.}95$ E.
Time after separation from Shuttle is 75.6442 h.
Tug reaches perigee of transfer orbit with a velocity of 10254.373 m/s and burns for 139.5 s (137.7 s) providing a ΔV_8 of 2482.691 m/s (2432.412 m/s) plus a 2% contingency ΔV.

Initial mass	6563.8 kg	(6576.9 kg)
Propellant used	2858.5 kg	(2821.6 kg)
Final mass	3705.3 kg	(3755.3 kg)

Tug then enters base orbit (Shuttle rendez-vous orbit). At this time the Shuttle has completed 50 revolutions in the rendez-vous orbit and is at the same earth longitude as the Tug.
Rendez-vous with Shuttle and return to earth.

7. Conclusions

1. Gravity losses at the transition from transfer orbit to target orbit and vice versa, as well as the losses at transition from transfer orbit to base orbit are negligible.

2. The maximum payload mass that can be placed in a geosynchronous orbit with 28.5° inclination is 3762 kg. The payload mass is restricted by the maximum Tug initial mass of 29.5 ton (Shuttle performance limit). For retrieval and roundtrip missions the maximum payload mass is constrained by the useful propellant capacity of the Tug (23 ton). The maximum payload masses are:

retrieval	1837 kg
roundtrip	1185 kg (15° W drift in 1 rev.)
	1241 kg (15° W drift in 2 revs.)

3. For a roundtrip mission to a 28.5° inclination geosynchronous

orbit with maximum payload, the transition from target orbit into drift orbit and vice versa has to be executed by the APS and not by the main engine.

4. For geostationary missions the optimal plane change at base orbit altitude is -2.16^{o}, leaving a total plane change of -26.34^{o} at geosynchronous altitude.

5. When impulses are given only at the nodes and the nodes are the apses of the transfer orbit, only a discrete number of stations in geostationary orbit can be reached in a direct transfer. Other stations can be reached when phasing orbits are included in the mission.

6. In the ascent flight phasing can be accomplished both by low-altitude phasing (perigee of phasing orbit at base orbit altitude) and high-altitude phasing (apogee of phasing orbit at geosynchronous altitude).
   When using low-altitude phasing any station in geostationary orbit can be reached within 21 h. after arrival in base orbit of the Shuttle/Tug combination. With high-altitude phasing any station can be reached within 42 h.
   In the return flight from geostationary orbit a low-altitude phasing orbit for the Tug or a low-altitude Shuttle phasing orbit can be used. This orbit has to be selected such that a rendez-vous between Tug and Shuttle can be accomplished.

7. High-altitude phasing is performed most economically when the phasing orbit period is slightly less than the period of the geostationary orbit, corresponding to an easterly drift of the Tug.

8. For geostationary placement, retrieval and roundtrip missions the payload capability is a maximum when in the ascent flight a low-

altitude phasing orbit is applied, while in the return flight the phasing is done by the Shuttle.

In the roundtrip mission the transition from geostationary orbit to drift orbit and vice versa is performed most economically by the APS.

Depending on the location of the stations in geostationary orbit which have to be reached, the maximum payload masses are:

placement	1960-1989 kg
retrieval	759- 760 kg
roundtrip	440- 446 kg (15° W drift in 1 rev.)
	490- 497 kg (15° W drift in 2 revs.)

In all cases the maximum payload is restricted by the maximum useful propellant of the Tug.

9. Since in most missions the total Tug mass at maximum payload is less than the Shuttle performance limit of 29.5 ton, a heavier Tug could be used for these missions. In particular the retrieval and roundtrip payload capability could be enlarged considerably in this way.

8. References

1. Anon. Phase A Space Tug Study. Guidelines for study's 1st part. STS (72) NT6; Feb. 1972.

2. Anon. ELDO Tug Candidates. HSD EST 192; 1972.

Table 1: Tug mass data (RTS-23)

H_2 in start tank	1.8	
unburnable prop. and resid. gases	169.0	
fuel-cell reactants	30.0	
residual hydrazine and helium	20.0	
fluorine in start tank	1.5	
Total		222.3
nominal usable hydrazine		216
nominal useful propellant mass		23000
precool propellant	208	
engine start losses	7	
boil-off	30	
press. and boost pump bleed	57	
Total nominal prop. losses		302
reserve propellant		46
dry structure mass		2940
Nominal total stage mass		26726.3
Tug net mass		3162.3
Nominal usable propellant		23302
Total miscellaneous fluids		438.3
Engine firing propellant losses	68 kg/start	
Propellant boil-off	10 kg/coast*	
Misc. fluid fixed loss rate	54 kg/coast	

* excludes coast prior to 1st burn

All masses in kg.

Table 2: Tug performance data (RTS-23)

Main engine		
specific impuls	(s)	460
exhaust velocity	(m/s)	4511
mass flow rate	(kg/s)	20
thrust	(N)	90221.2
APS		
specific impuls	(s)	220
exhaust velocity	(m/s)	2157.5

Table 3: Geophysical constants and base orbit data

Geophysical constants		
Mean earth's radius	(m)	6375438
Earth's gravitational const.	(m^3/s^2)	398603.2 10^9
Base orbit data		
Altitude	(m)	185200
Radius	(m)	6560638
Velocity	(m/s)	7794.663
Angular velocity	(^{o}/s)	0.068073
Period	(s)	5288.453
	(min)	88.141
	(h)	1.469

Table 4: Geosynchronous orbit data

Inclination	(^{o})	28.5
Altitude	(m)	35788799
Radius	(m)	42164237
Velocity	(m/s)	3074.668
Angular velocity	(^{o}/s)	0.004178
Period	(s)	86164
	(h)	23.934

Table 5: Data on transfer orbit in geosynchronous missions

Inclination	(°)	28.5
Perigee altitude	(m)	185200
Apogee altitude	(m)	35788799
Perigee velocity	(m/s)	10254.373
Apogee velocity	(m/s)	1595.552
Req. ΔV to leave base orbit	(m/s)	2459.710
Req. ΔV to enter target orbit	(m/s)	1479.116
Period	(s)	37843.438
	(h)	10.512

Table 6a: Drift orbit data for drift of 15°W

15°W drift in 1 rev.		
Perigee altitude	(m)	35788799
Apogee altitude	(m)	38114599
Perigee velocity	(m/s)	3115.656
Req. ΔV to enter drift orbit	(m/s)	40.988
Period	(s)	89754.2
	(h)	24.932
15°W drift in 2 rev.s		
Perigee altitude	(m)	35788799
Apogee altitude	(m)	36955309
Perigee velocity	(m/s)	3095.573
Req. ΔV to enter drift orbit	(m/s)	20.905
Period	(s)	87959.1
	(h)	24.433

Table 6b: Drift orbit data for drift of 15° E

15° E drift in 1 rev.		
Perigee altitude	(m)	33429765
Apogee altitude	(m)	35788799
Apogee velocity	(m/s)	3030.102
Req. ΔV to enter drift orbit	(m/s)	44.567
Period	(s)	82573.8
	(h)	22.937
15° E drift in 2 rev.s		
Perigee altitude	(m)	34613465
Apogee altitude	(m)	35788799
Apogee velocity	(m/s)	3052.861
Req. ΔV to enter drift orbit	(m/s)	21.807
Period	(s)	84368.9
	(h)	23.436

Table 7: Geostationary orbit data

Inclination	(°)	0
Altitude	(m)	35788799
Radius	(m)	42164237
Velocity	(m/s)	3074.668
Angular velocity	(°/s)	0.004178
Period	(s)	86164
	(h)	23.934

Table 8: Data on transfer orbit in geostationary missions

Inclination	(°)	26.34
Perigee altitude	(m)	185200
Apogee altitude	(m)	35788799
Perigee velocity	(m/s)	10254.373
Apogee velocity	(m/s)	1595.552
Req. ΔV to leave base orbit	(m/s)	2482.691
Req. ΔV to enter target orbit	(m/s)	1790.658
Optimal inclination change at base orbit	(°)	- 2.16
Optimal inclination change at target orbit	(°)	-26.34
Period	(s)	37843.438
	(h)	10.512

Table 9: Mass distribution for geostationary placement mission

strategy	phasing mode	M_u	M_o	M_{pl}	M_p	M_{fu}	M_{f1}	M_f
1	n.p.	1960	28686	302	23302	0	216	216
	b.p.	1630	28620	458	23458	0	324	324
	w.p.	1510	28500	458	23458	0	324	324
2	n.p.	1960	28686	302	23302	0	216	216
	b.p.	1989	28848	380	23380	0	270	270
	w.p.	1960	28818	380	23380	0	270	270
3A, B	n.p.	1960	28686	302	23302	0	216	216
	b.p.	1498	28488	458	23458	0	324	324
	w.p.	1334	28324	458	23458	0	324	324
3C	n.p.	1960	28686	302	23302	0	216	216
	b.p.	1629	28487	380	23380	0	270	270
	w.p.	1385	28581	380	23380	338	270	608
4A, B	n.p.	1960	28686	302	23302	0	216	216
	b.p.	1829	28687	380	23380	0	270	270
	w.p.	1810	28668	380	23380	0	270	270
4C	n.p.	1960	28686	302	23302	0	216	216
	b.p.	1960	28686	302	23302	0	216	216
	w.p.	1859	28927	302	23302	342	216	558

for explanation of symbols see page 64

Table 10: Mass distribution for geostationary retrieval mission

strategy	phasing mode	M_u	M_o	M_{pl}	M_p	M_{fu}	M_{f1}	M_f
1	n.p.	752	26726	302	23302	0	216	216
	b.p.	626	26990	458	23458	0	324	324
	w.p.	577	26990	458	23458	0	324	324
2	n.p.	752	26726	302	23302	0	216	216
	b.p.	760	26858	380	23380	0	270	270
	w.p.	759	26858	380	23380	0	270	270
3A, B	n.p.	752	26726	302	23302	0	216	216
	b.p.	575	26990	458	23458	0	324	324
	w.p.	512	26990	458	23458	0	324	324
3C	n.p.	752	26726	302	23302	0	216	216
	b.p.	626	26858	380	23380	0	270	270
	w.p.	534	27179	380	23380	321	270	591
4A, B	n.p.	752	26726	302	23302	0	216	216
	b.p.	702	26858	380	23380	0	270	270
	w.p.	695	26858	380	23380	0	270	270
4C	n.p.	752	26726	302	23302	0	216	216
	b.p.	752	26726	302	23302	0	216	216
	w.p.	717	27046	302	23302	320	216	536

for explanation of symbols see page 64

Table 11: Mass distribution for geostationary roundtrip mission

15^{o} W drift by 1 rev. in drift orbit.

strategy	phasing mode	M_u	M_o	M_{pl}	M_p	M_{fu}	M_{f1}	M_f
1A	n.p.	392	27382	458	23458	0	324	324
	b.p.	300	27554	614	23614	0	432	432
	w.p.	262	27516	614	23614	0	432	432
1B	n.p.	440	27540	302	23302	374	216	590
	b.p.	347	27716	458	23458	379	324	703
	w.p.	310	27680	458	23458	380	324	704
2A	n.p.	392	27382	458	23458	0	324	324
	b.p.	399	27521	536	23536	0	378	378
	w.p.	398	27520	536	23536	0	378	378
2B	n.p.	440	27540	302	23302	374	216	590
	b.p.	446	27677	380	23380	373	270	643
	w.p.	440	27671	380	23380	373	270	643
3A	n.p.	392	27382	458	23458	0	324	324
	b.p.	266	27520	614	23614	0	432	432
	w.p.	220	27474	614	23614	0	432	432
3B	n.p.	440	27540	302	23302	374	216	590
	b.p.	311	27678	458	23458	377	324	701
	w.p.	265	27632	458	23458	377	324	701
3C	n.p.	440	27540	302	23302	374	216	590
	b.p.	347	27584	380	23380	379	270	649
	w.p.	280	27845	380	23380	707	270	977
4A	n.p.	392	27382	458	23458	0	324	324
	b.p.	357	27479	536	23536	0	378	378
	w.p.	352	27474	536	23536	0	378	378
4B	n.p.	440	27540	302	23302	374	216	590
	b.p.	404	27634	380	23380	372	270	642
	w.p.	399	27629	380	23380	372	270	642
4C	n.p.	440	27540	302	23302	374	216	590
	b.p.	440	27540	302	23302	374	216	590
	w.p.	414	27842	302	23302	702	216	918

for explanation of symbols see page 64

Table 12: Mass distribution for geostationary roundtrip mission

15^{o} W drift by 2 rev.^{s} in drift orbit.

strategy	phasing mode	M_u	M_o	M_{pl}	M_p	M_{fu}	M_{fl}	M_f
1A	n.p.	430	27420	458	23458	0	324	324
	b.p.	338	27592	614	23614	0	432	432
	w.p.	300	27554	614	23614	0	432	432
1B	n.p.	490	27407	302	23302	191	216	407
	b.p.	400	27583	458	23458	192	324	517
	w.p.	362	27545	458	23458	193	324	517
2A	n.p.	430	27420	458	23458	0	324	324
	b.p.	434	27556	536	23536	0	378	378
	w.p.	433	27555	536	23536	0	378	378
2B	n.p.	490	27407	302	23302	191	216	407
	b.p.	497	27546	380	23380	191	270	461
	w.p.	490	27539	380	23380	191	270	461
3A	n.p.	430	27420	458	23458	0	324	324
	b.p.	297	27551	614	23614	0	432	432
	w.p.	257	27511	614	23614	0	432	432
3B	n.p.	490	27407	302	23302	191	216	407
	b.p.	362	27543	458	23458	191	324	515
	w.p.	317	27499	458	23458	192	324	516
3C	n.p.	490	27407	302	23302	191	216	407
	b.p.	399	27450	380	23380	193	270	463
	w.p.	332	27709	380	23380	519	270	789
4A	n.p.	430	27420	458	23458	0	324	324
	b.p.	395	27517	536	23536	0	378	378
	w.p.	390	27512	536	23536	0	378	378
4B	n.p.	490	27407	302	23302	191	216	407
	b.p.	455	27502	380	23380	189	270	459
	w.p.	450	27497	380	23380	189	270	459
4C	n.p.	490	27407	302	23302	191	216	407
	b.p.	490	27407	302	23302	191	216	407
	w.p.	465	27709	302	23302	518	216	734

for explanation of symbols see page 64

Explanation of Tables 9, 10, 11 and 12

These Tables give the mass distribution of the Tug for the geostationary placement, retrieval and roundtrip missions with maximum payload mass for the various mission strategies as defined in section 6.

For every mission strategy 3 mass distributions are given dependent on the phasing mode:

- n.p.: no phasing necessary
- b.p.: best case of phasing (ascent phasing angle minimal, descent phasing angle maximal)
- w.p.: worst case of phasing (ascent phasing angle maximal, descent phasing angle minimal)

In general the mass distribution will lie somewhere between the distribution given by b.p. and w.p.

M_u payload mass

M_{pl} propellant losses (engine start losses and boil-off)

M_p usable propellant mass

M_{fu} hydrazine used for orbital manoeuvres

M_{fl} hydrazine used for attitude control (alignment of Tug)

M_f usable hydrazine

The usable propellant mass is found as $M_p = M_{pl} + M_{pu}$ where M_{pu} is the useful propellant mass which is a maximum (23000 kg) for the in the Tables given missions.

M_f is defined by $M_f = M_{fl} + M_{fu}$

The Tug initial mass M_o is found from:

$$M_o = M_c + M_{pr} + M_u + M_p + M_f$$

for the placement and roundtrip missions, and from:

$$M_o = M_c + M_{pr} + M_p + M_f$$

for the retrieval missions, where M_c = 3162.3 kg (Tug net mass) and M_{pr} = 46 kg (Reserve propellant mass).

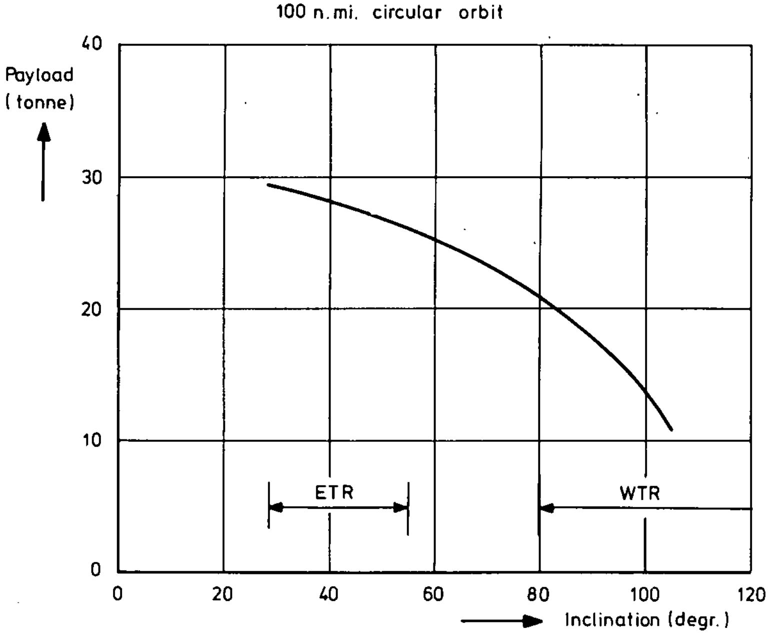


Fig.1: Space Shuttle payload capability as a function of inclination.

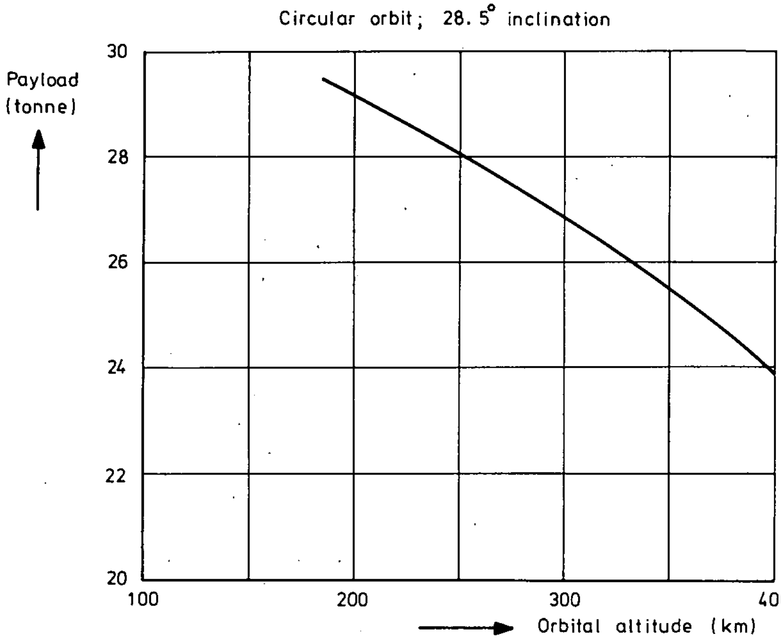


Fig. 2: Space Shuttle payload capability as a function of altitude.

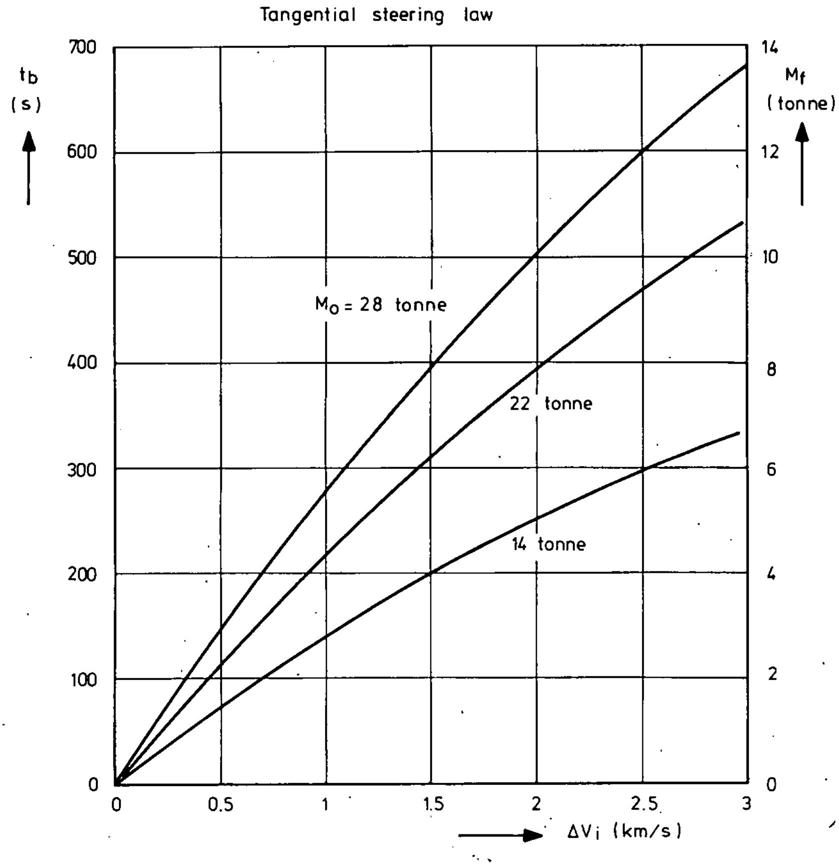


Fig. 3: Engine burning time for a required impulsive ΔV at departure from base orbit.

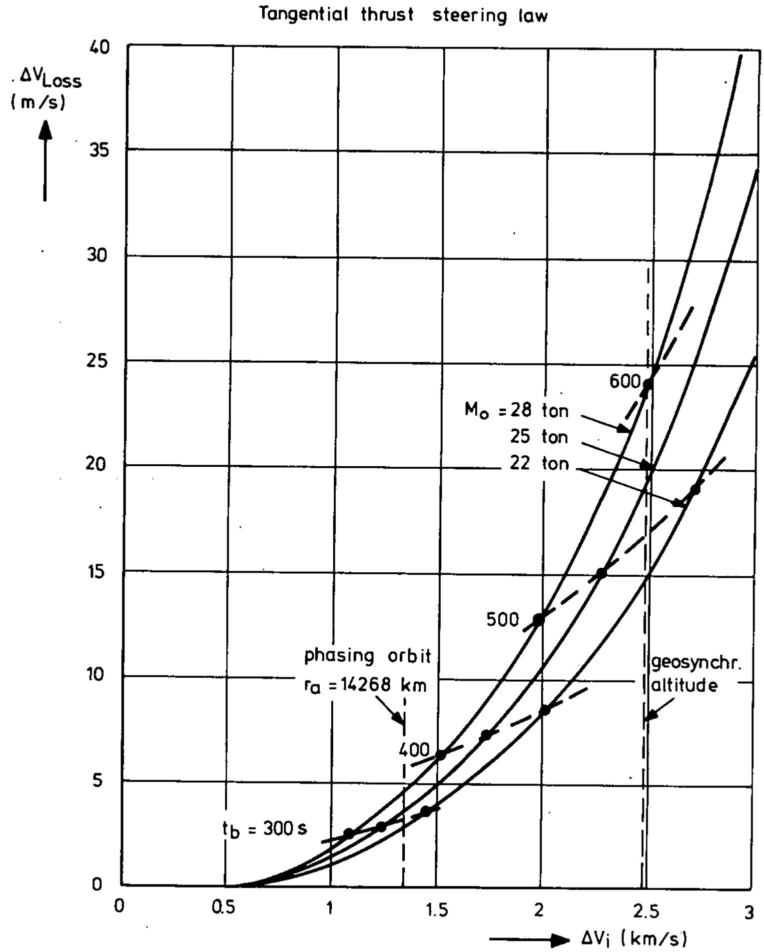


Fig.4: Non-impulsive ΔV loss at departure from base orbit as a function of the impulsive ΔV.

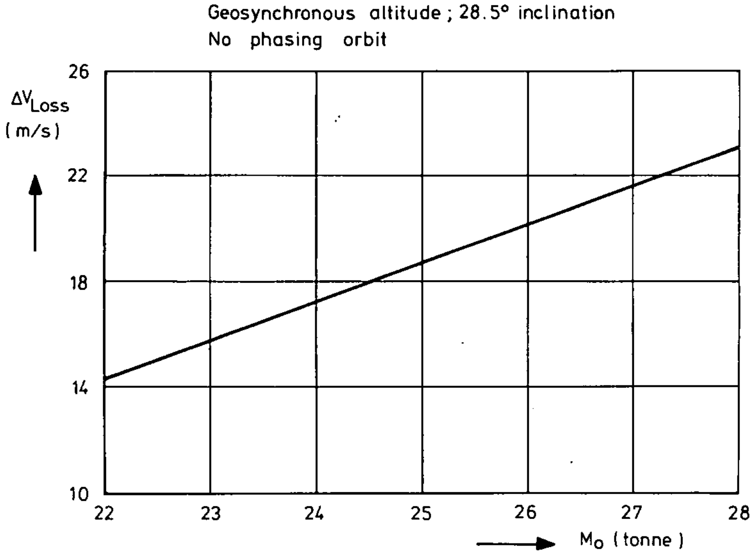


Fig. 5: Non-impulsive losses at departure from base orbit to geosynchronous altitude ($\Delta V_i = 2459.710$ m/s)

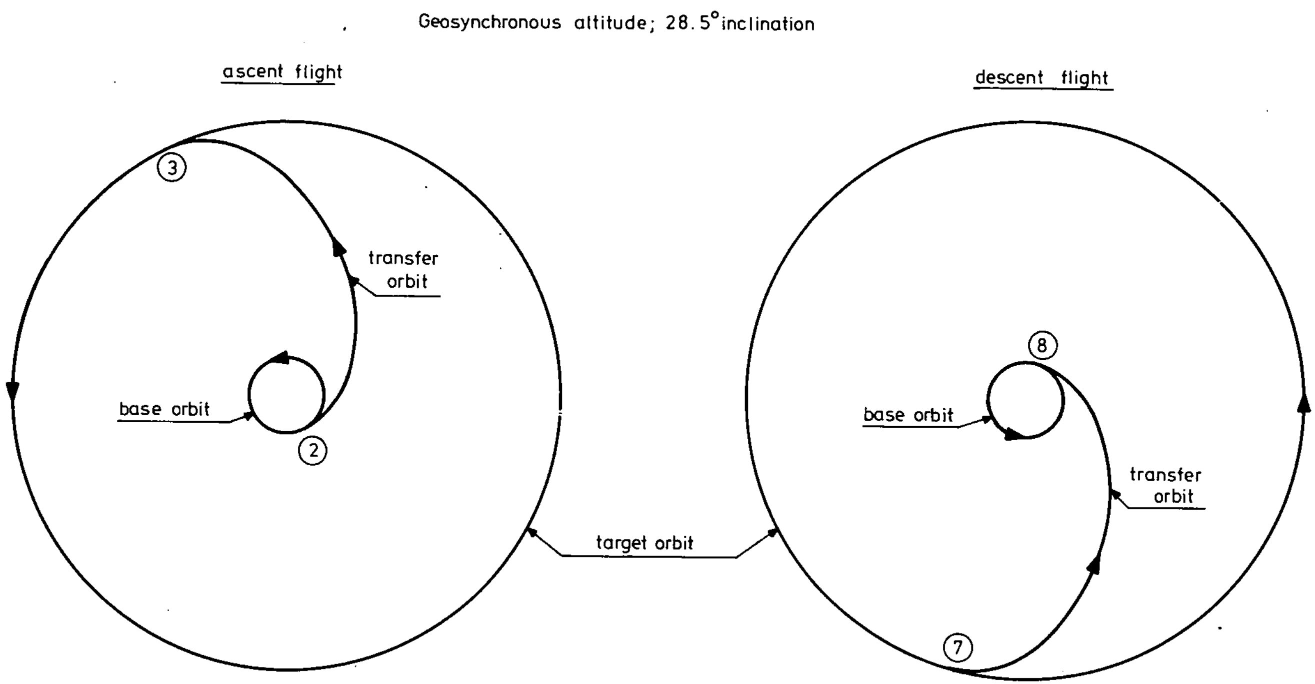


Fig. 6: Strategy 1. Mission to geosynchronous altitude. No plane changes.

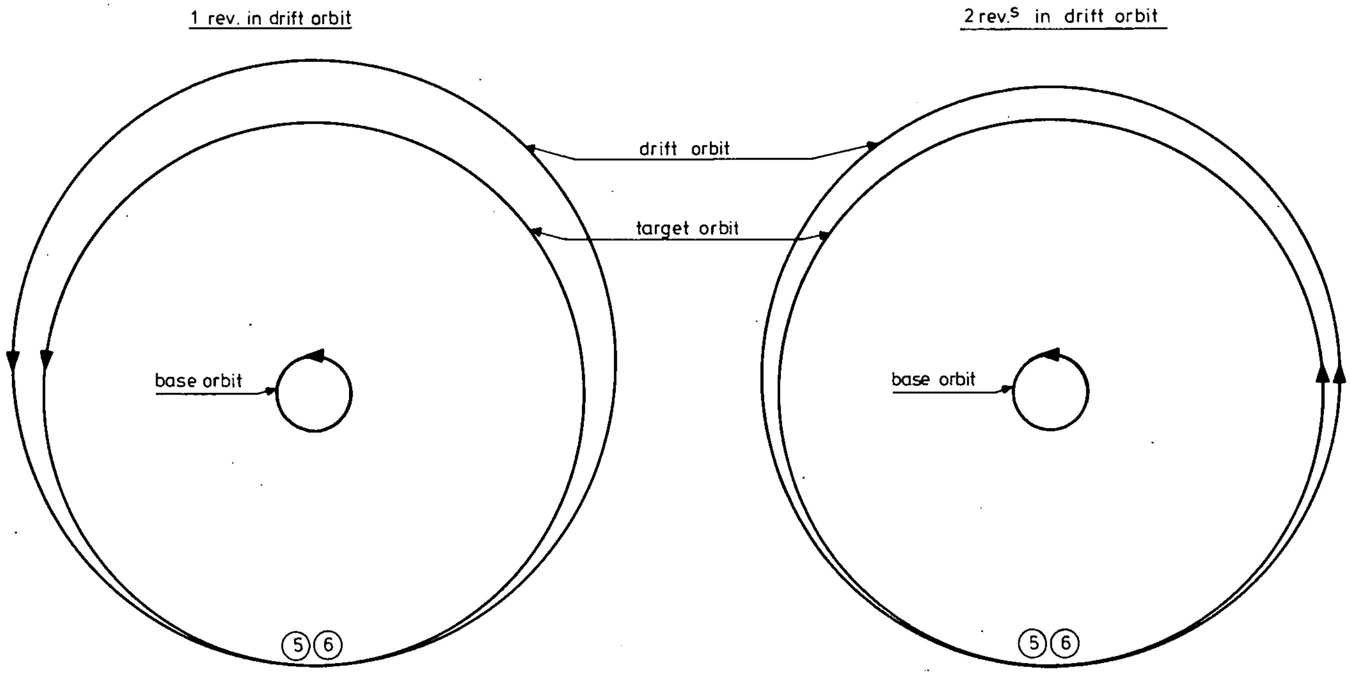


Fig.7: 15° Westerly drift in target orbit.

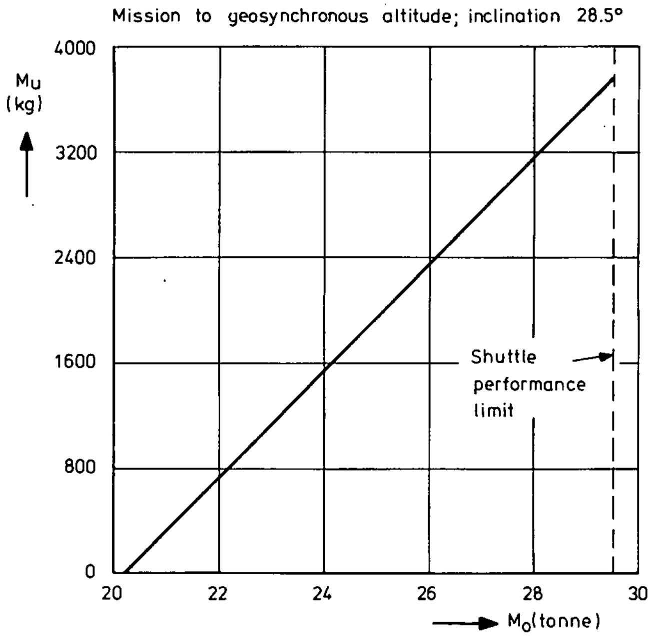


Fig. 8: Payload placement capability.

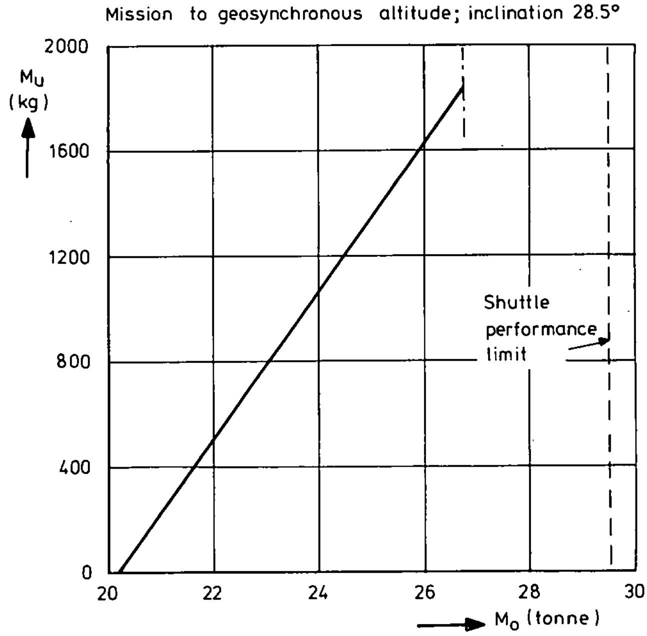


Fig. 9: Payload retrieval capabilility.

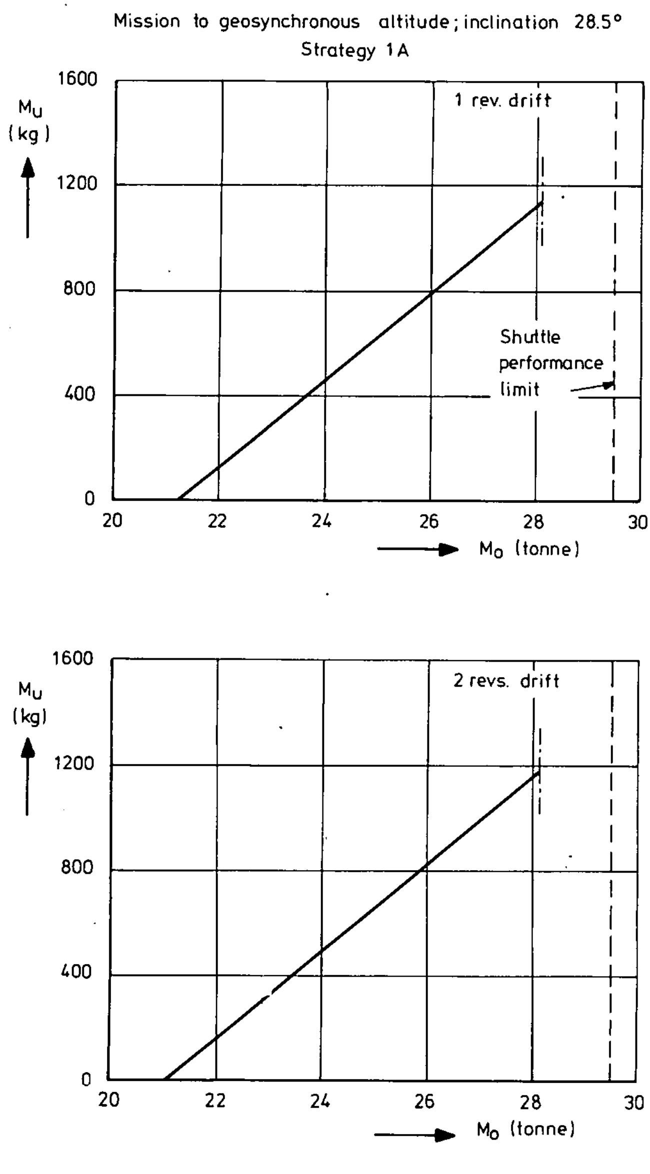


Fig. 10: Payload roundtrip capability.

Mission to geosynchronous altitude; inclination 28.5°
Strategy 1 B

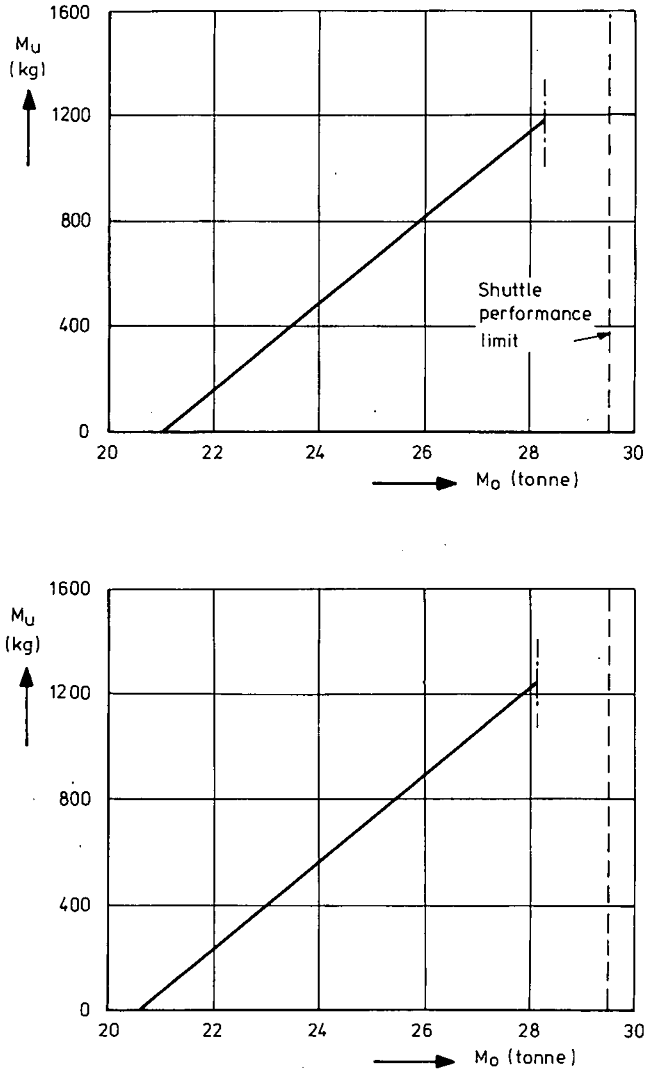


Fig. 11 : Payload roundtrip capability.

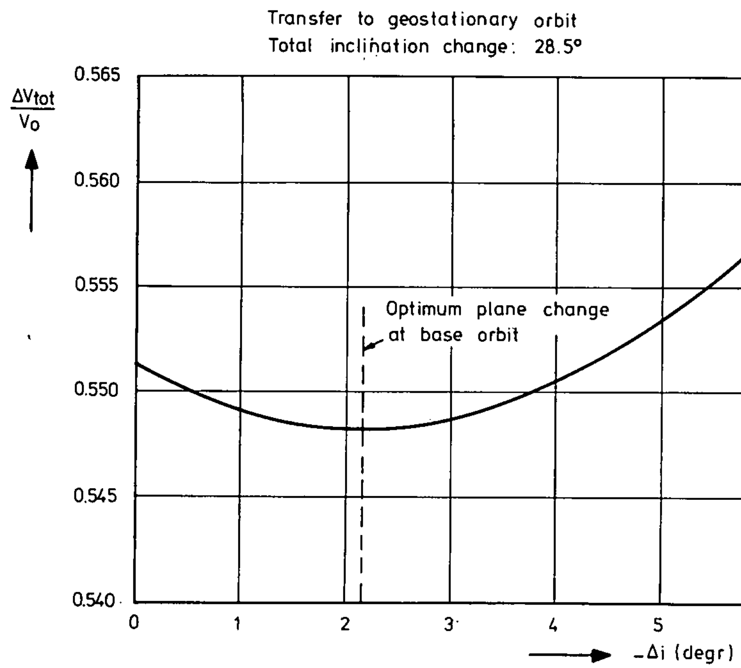


Fig.12: Total ΔV as a function of total plane change at low altitude (185 km).

Geostationary mission

t = 0

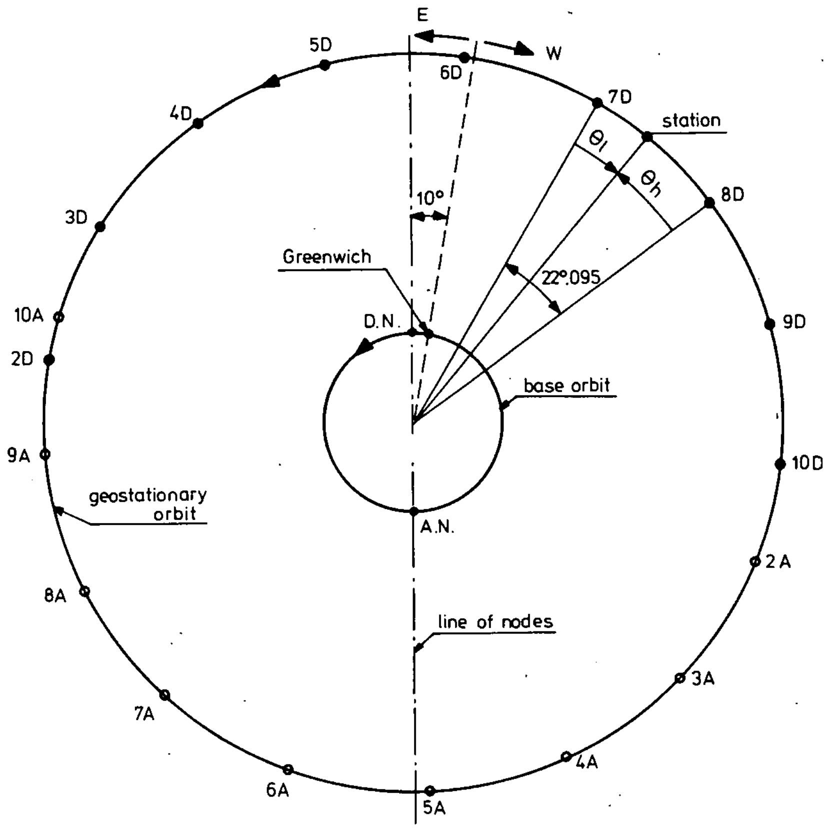
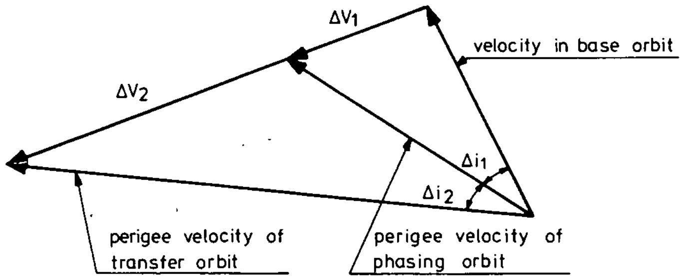
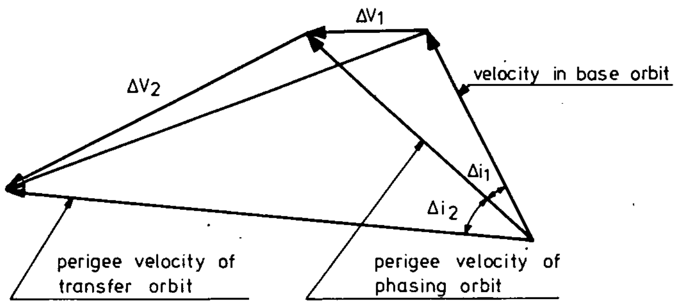


Fig. 13: Stations in geostationary orbit that can be reached without phasing.

Geostationary mission
low-altitude phasing



<u>Optimal</u> $\Delta i_1 + \Delta i_2 = -2°16$; $\Delta V_1 + \Delta V_2 = 2482.691$ m/s



<u>Non Optimal</u> $\Delta i_1 + \Delta i_2 = -2°16$; $\Delta V_1 + \Delta V_2 > 2482.691$ m/s

Fig. 14: Velocity diagrams for the transition from base orbit to transfer orbit via a phasing orbit.

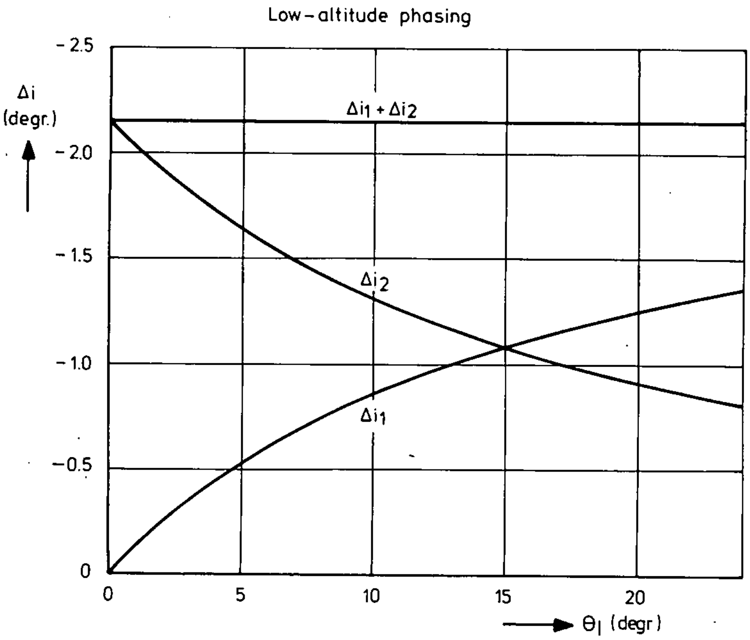


Fig.15: Optimal split in total plane change at base orbit altitude.

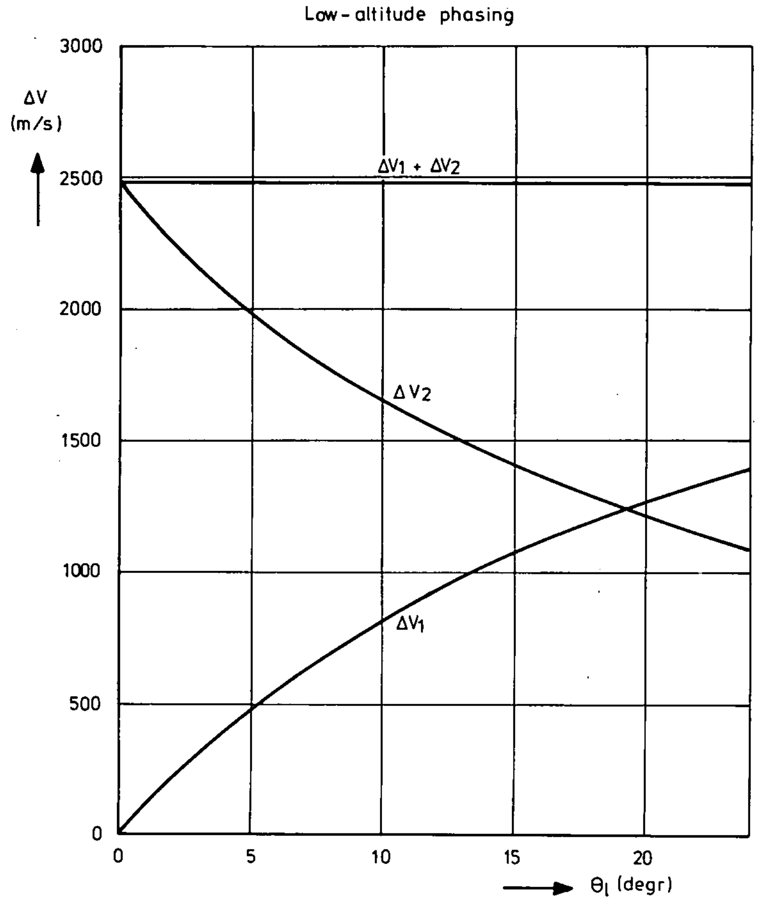


Fig. 16: Split in ΔV at base orbit altitude as a function of the drift angle.

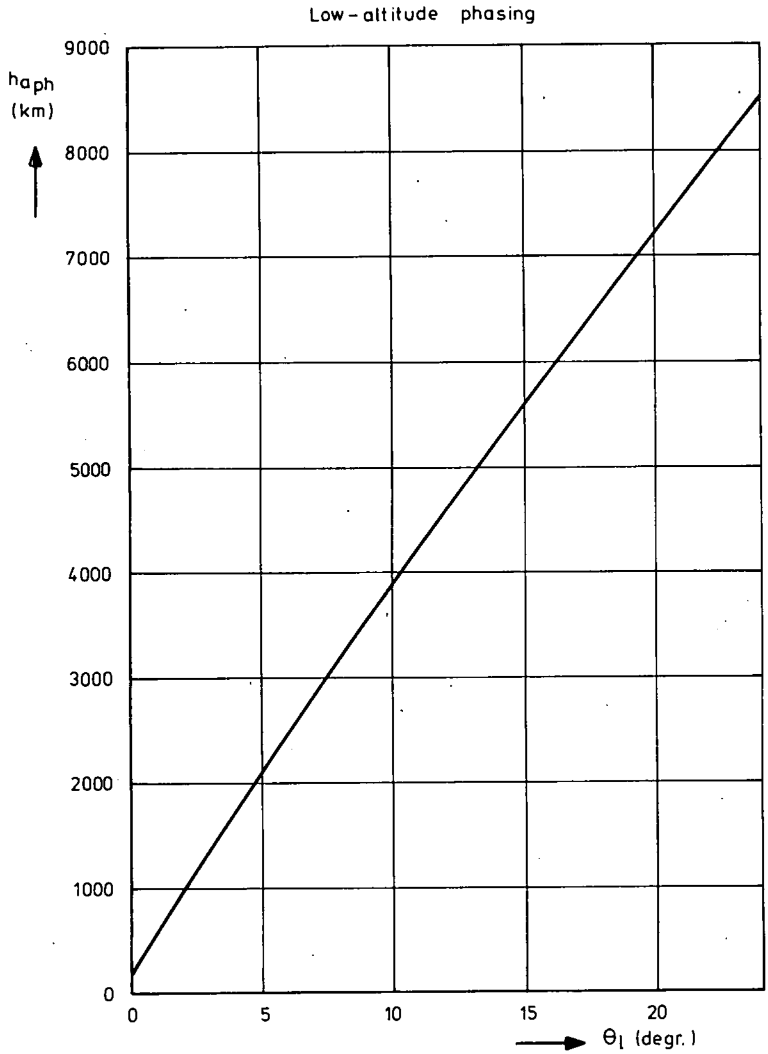


Fig.17: Apogee height of phasing orbit as a function of the drift angle.

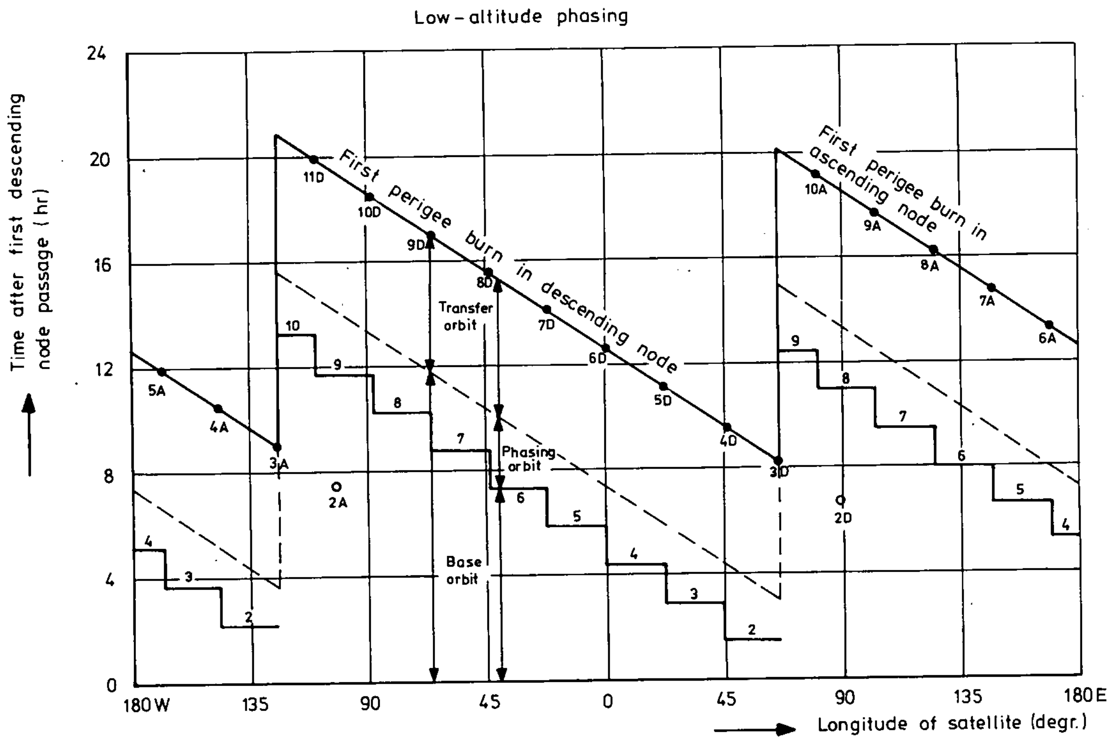
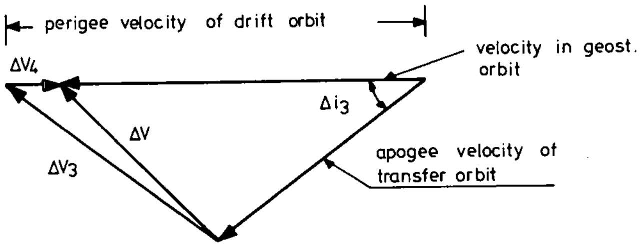
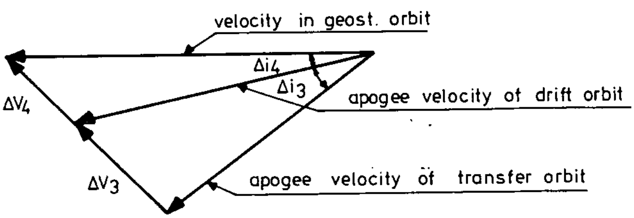


Fig. 18: Time from first descending node passage of Shuttle to arrival in geostationary orbit as a function of satellite longitude.

Geostationary mission
High-altitude phasing



a. Westerly drift : $\Delta V3 + \Delta V4 > \Delta V = 1790.658$ m/s
$\Delta i3 = -26°34$



b. Easterly drift : $\Delta V3 + \Delta V4 = \Delta V = 1790.658$ m/s
$\Delta i3 + \Delta i4 = -26°34$

Fig. 19: Velocity diagrams for the transition from transfer orbit to geostationary orbit via a phasing orbit.

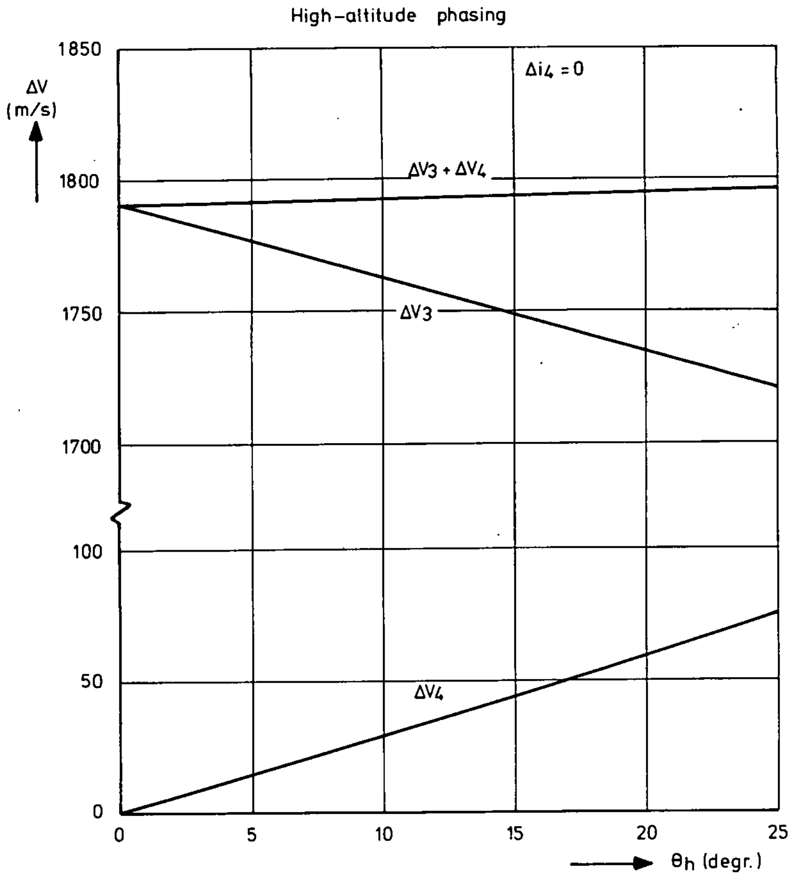


Fig. 20: Split in ΔV at geostationary altitude as a function of the drift angle

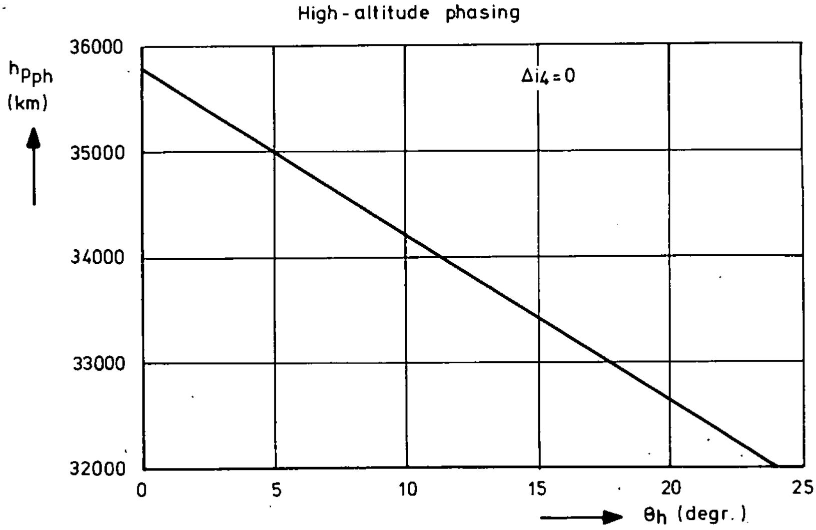


Fig. 21: Perigee height of phasing orbit as a function of the drift angle.

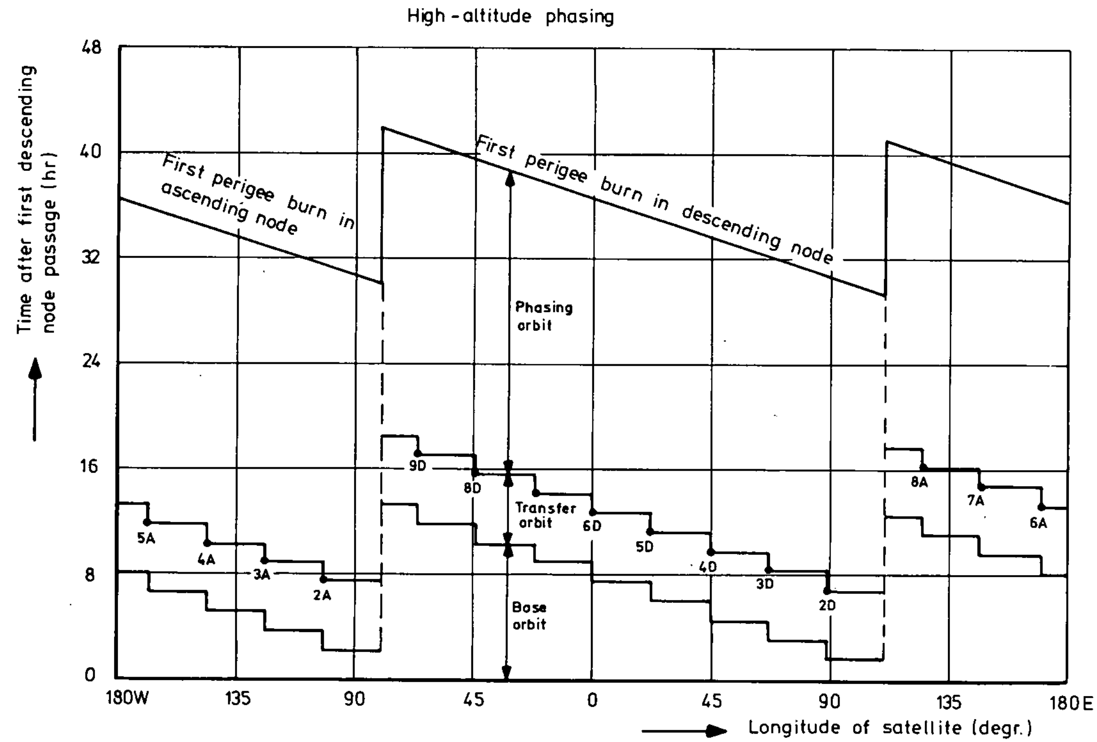


Fig. 22: Time from first descending node passage of Shuttle to arrival in geostationary orbit as a function of satellite longitude.

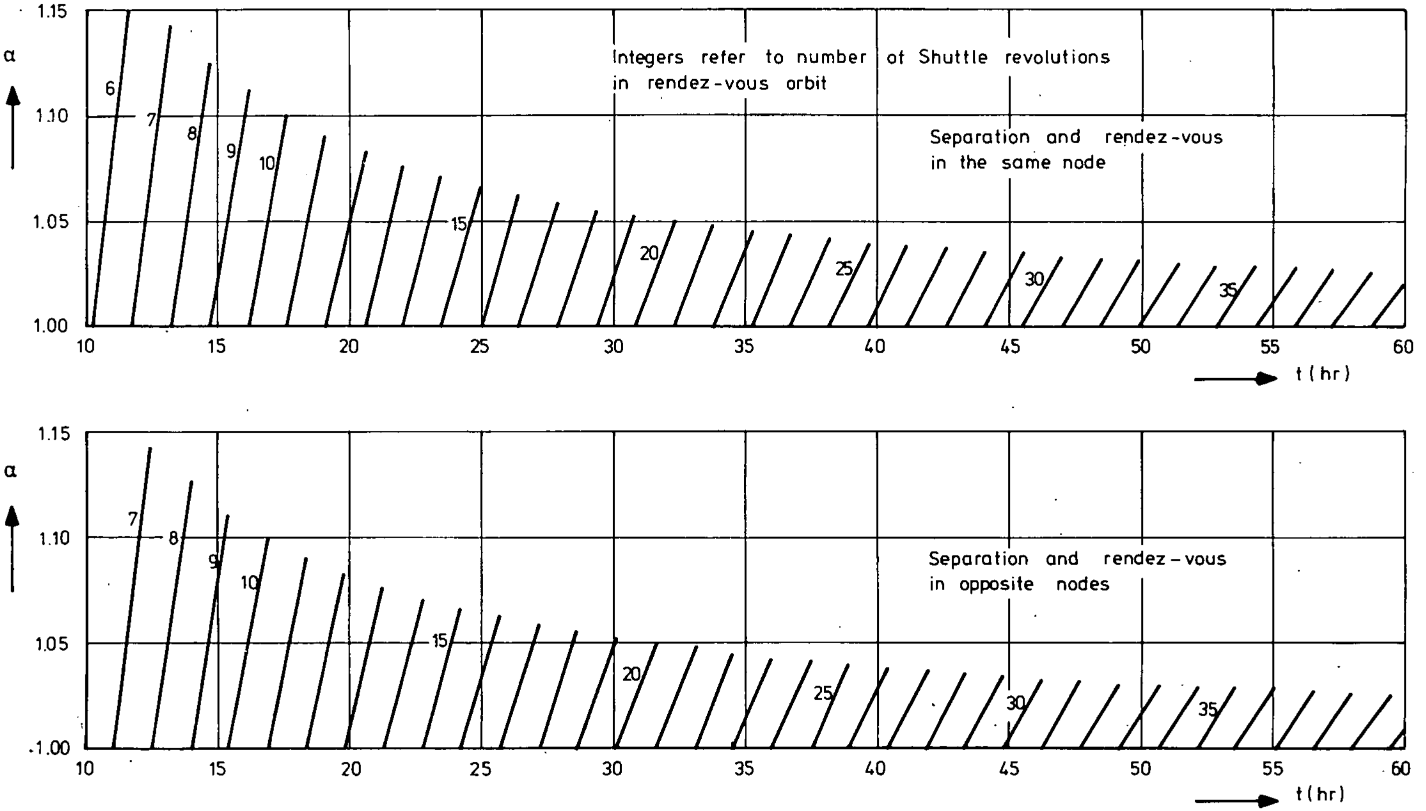
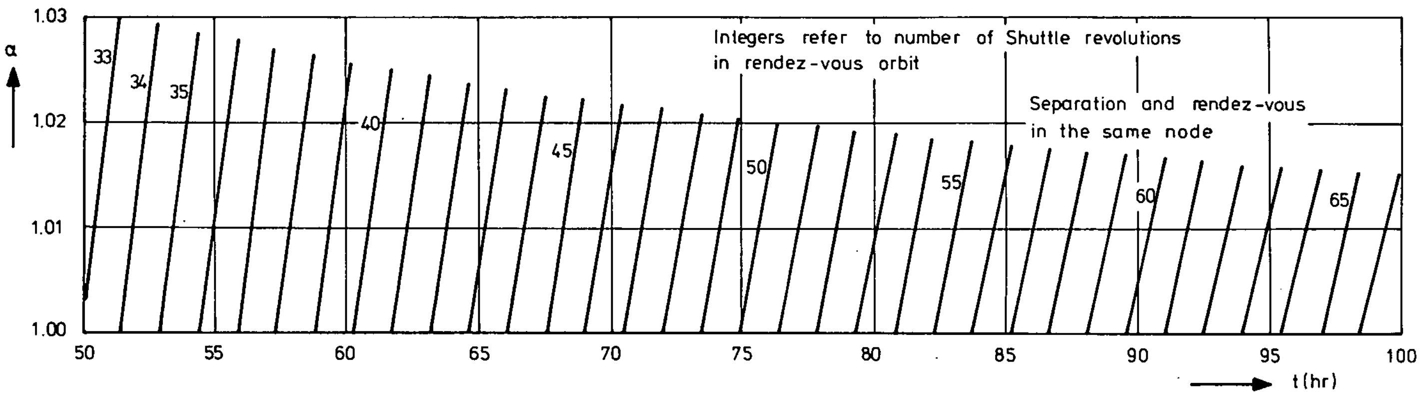


Fig. 23: Required period of Shuttle rendez-vous orbit ($P = \alpha P_o$).



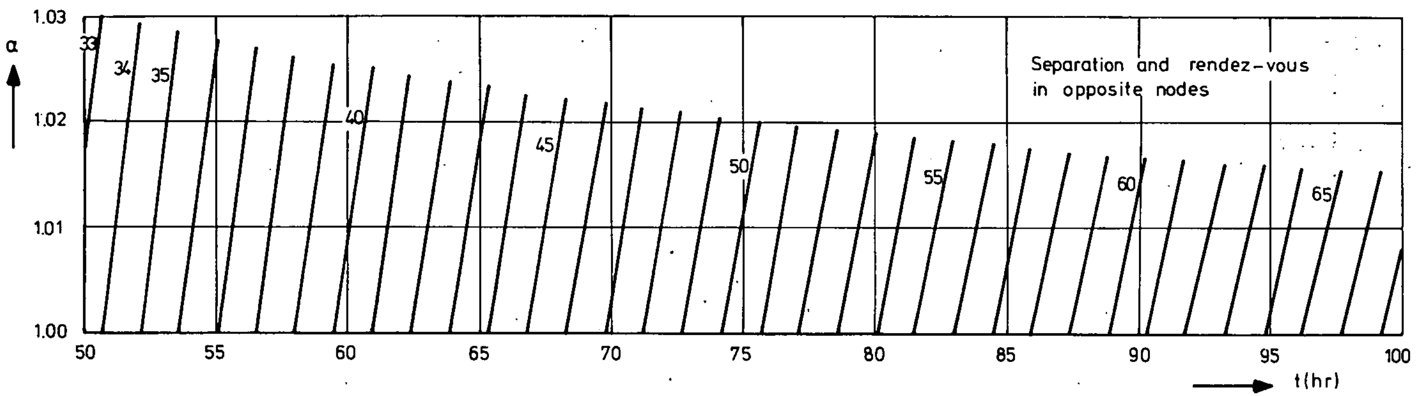


Fig. 24: Required period of Shuttle rendez-vous orbit ($P = \alpha P_o$).

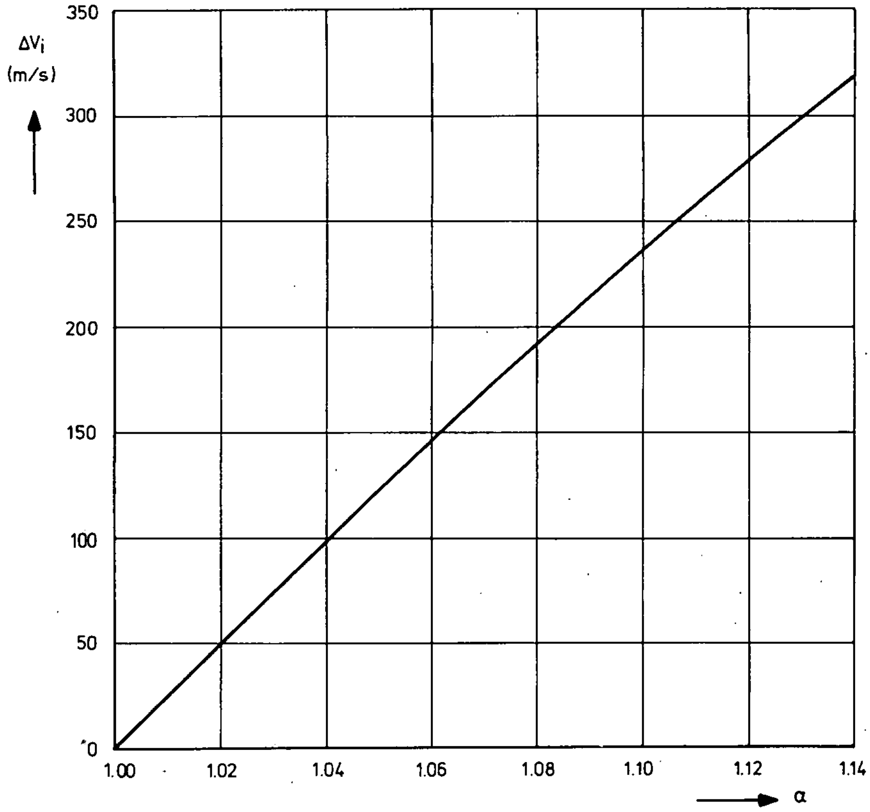


Fig. 25: Impulsive ΔV required to inject Shuttle in rendez-vous orbit.

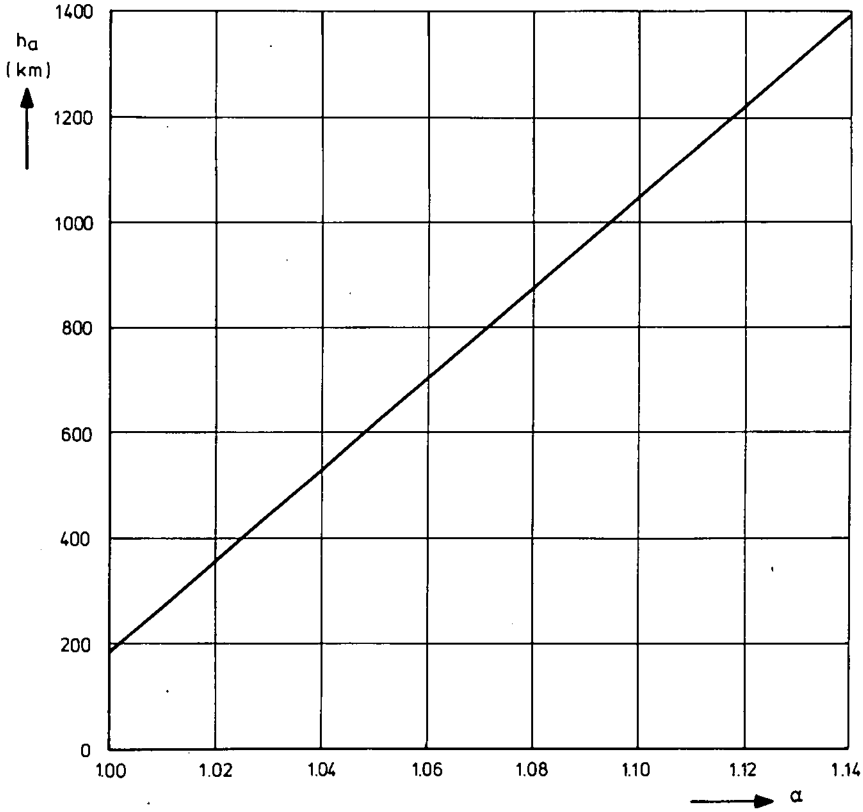


Fig. 26: Apogee altitude of Shuttle rendez-vous orbit.

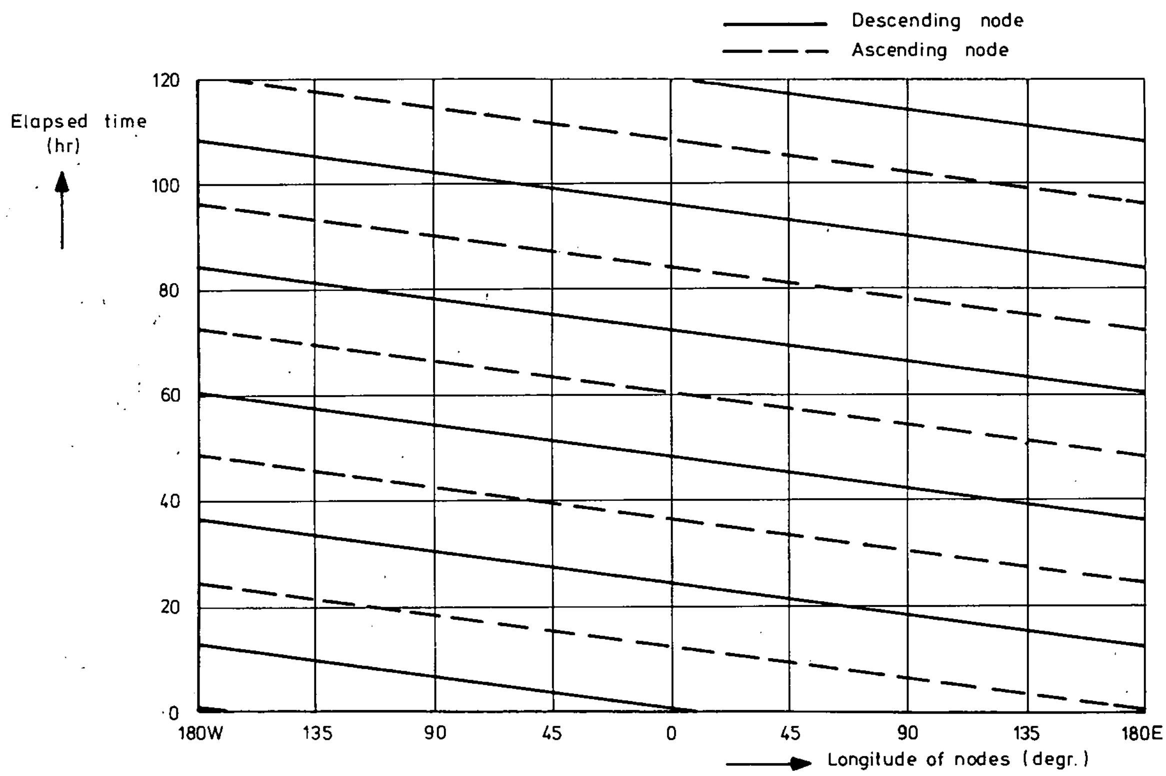


Fig. 27: Earth longitude of nodes as a function of time after first descending node passage of Shuttle.

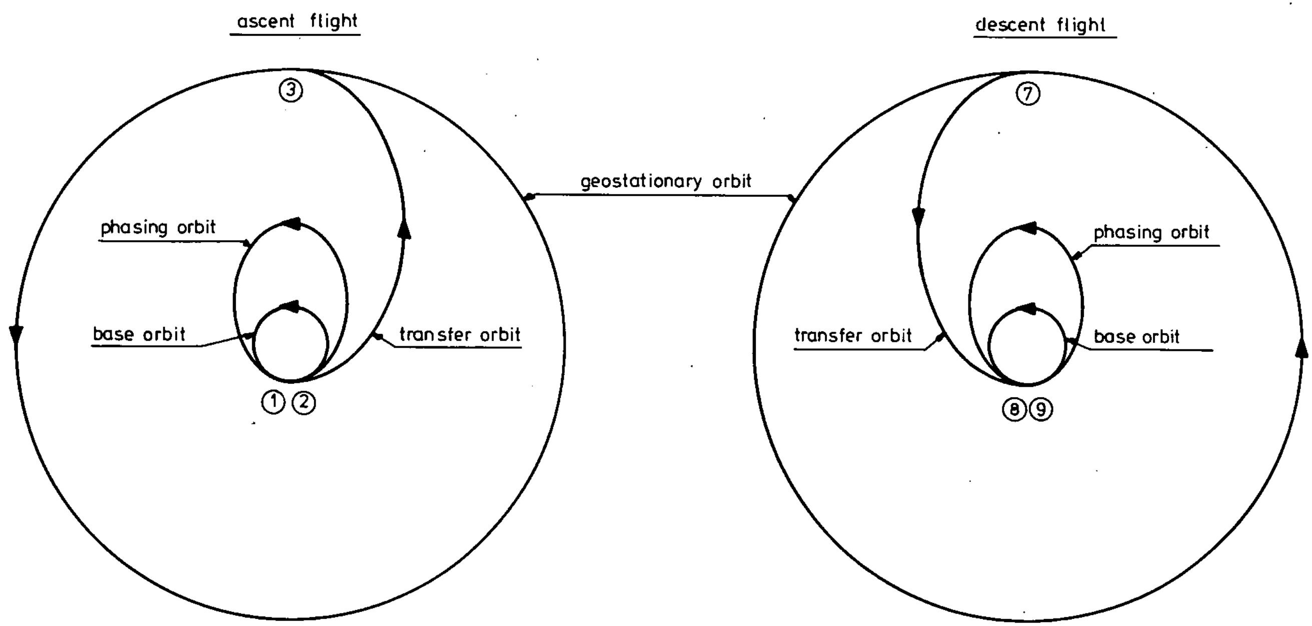


Fig. 28: Geostationary mission. Strategy 1.

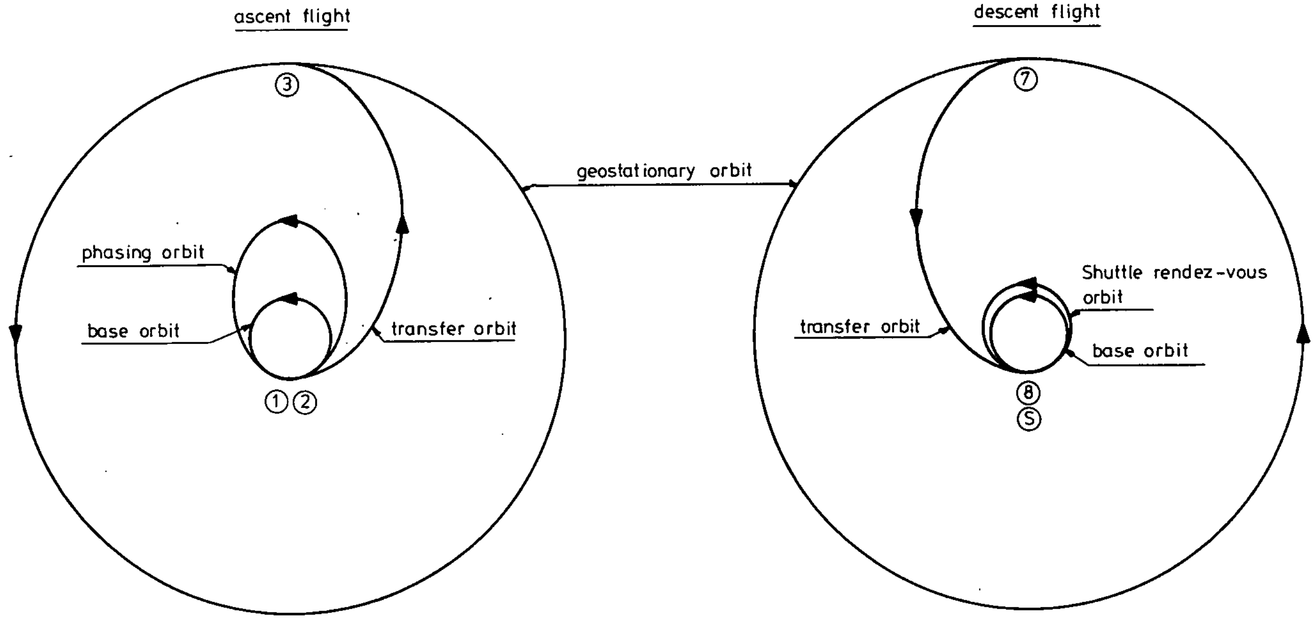


Fig. 29: Geostationary mission. Strategy 2.

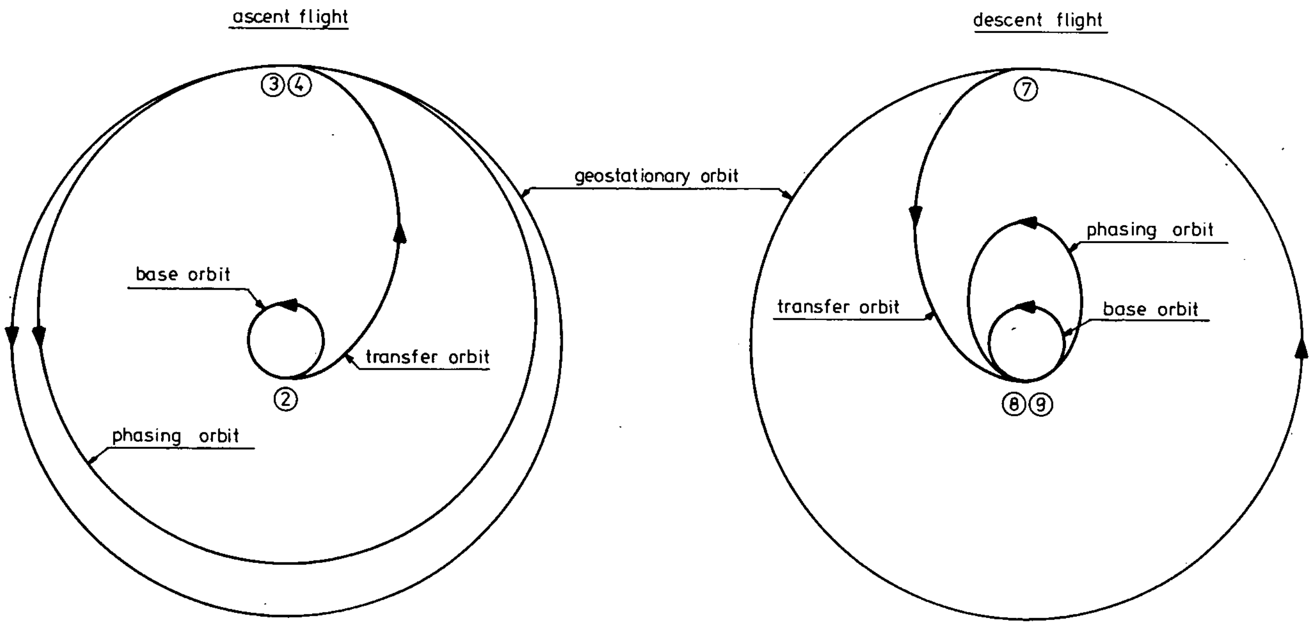


Fig. 30: Geostationary mission. Strategy 3.

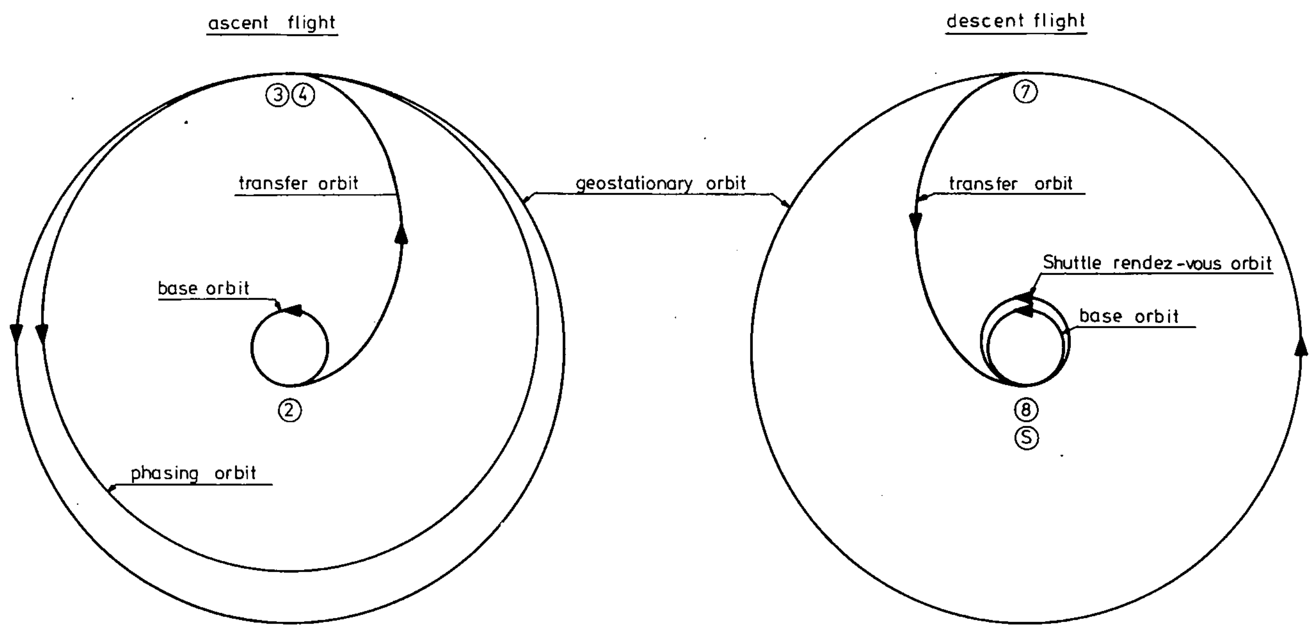


Fig. 31: Geostationary mission. Strategy 4.

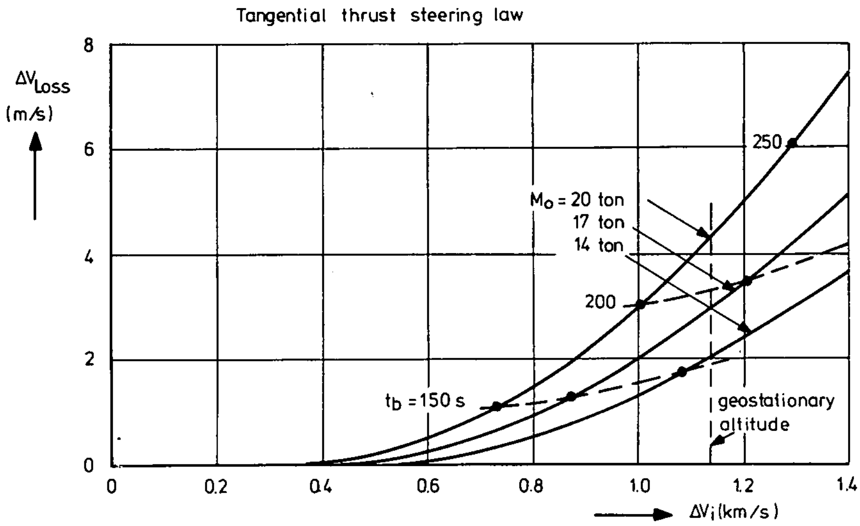


Fig. 32: Non-impulsive ΔV loss at departure from perigee of phasing orbit (r_a = 14268 km) as a function of the impulsive ΔV.

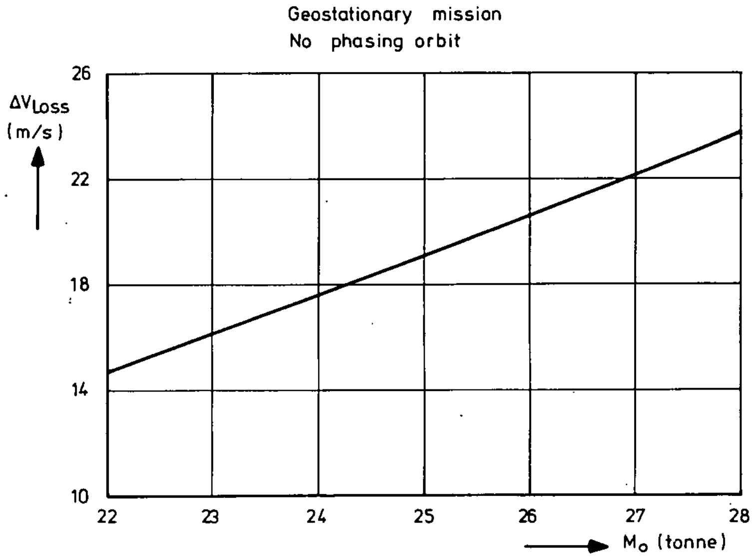


Fig. 33: Non-impulsive losses at departure from base orbit to geostationary altitude (ΔV_i = 2482.691 m/s)

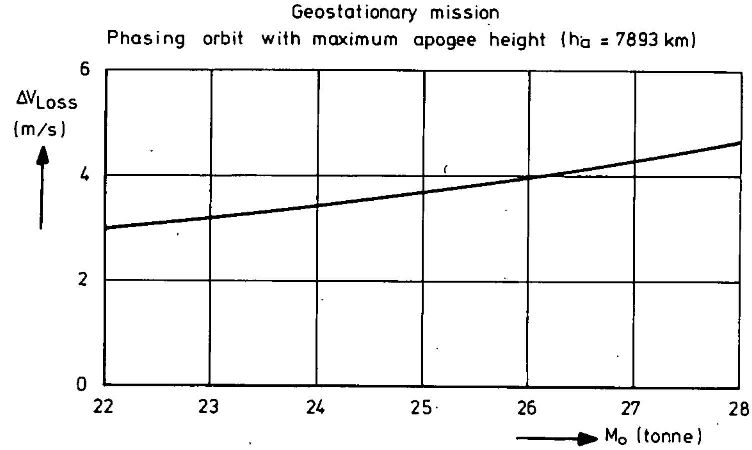


Fig.34: Non-impulsive ΔV loss at departure from base orbit into phasing orbit (ΔV_i = 1342.864 m/s).

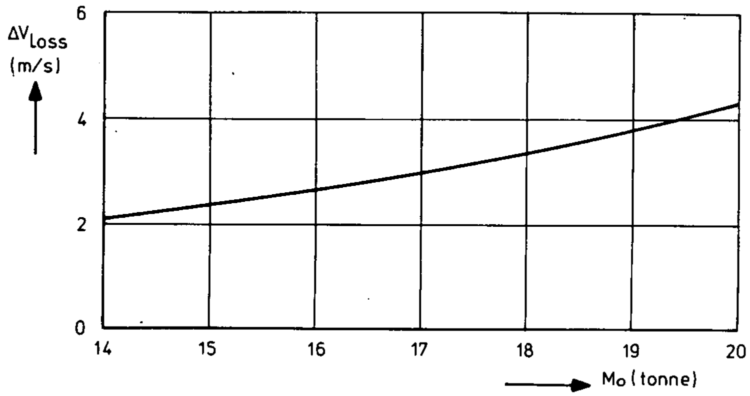


Fig. 35: Non–impulsive ΔV loss at departure from perigee of phasing orbit to geostationary altitude (ΔV_i = 1139.827 m/s).

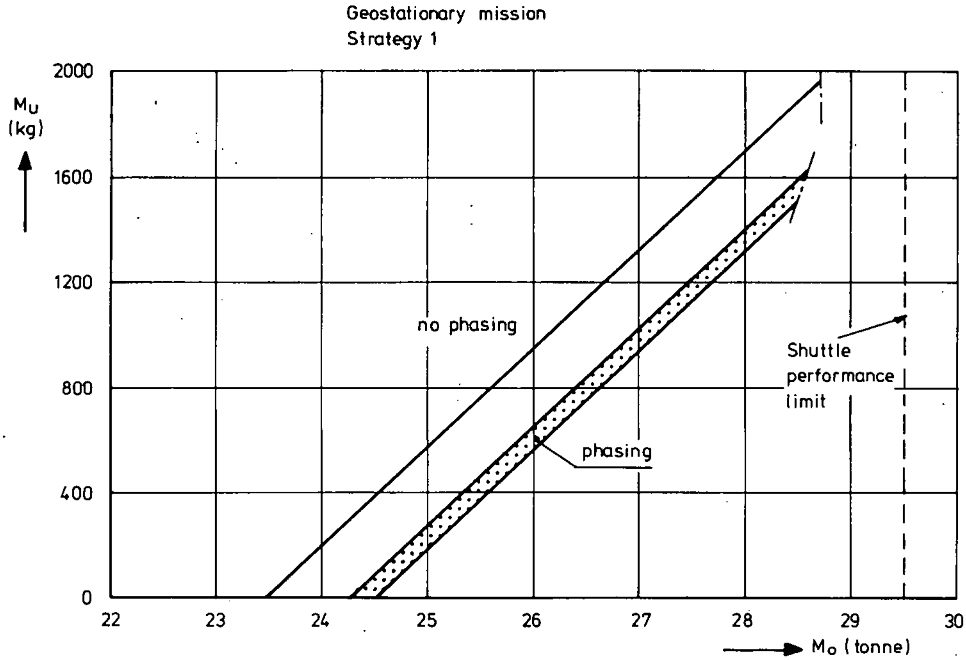


Fig. 36: Payload placement capability.

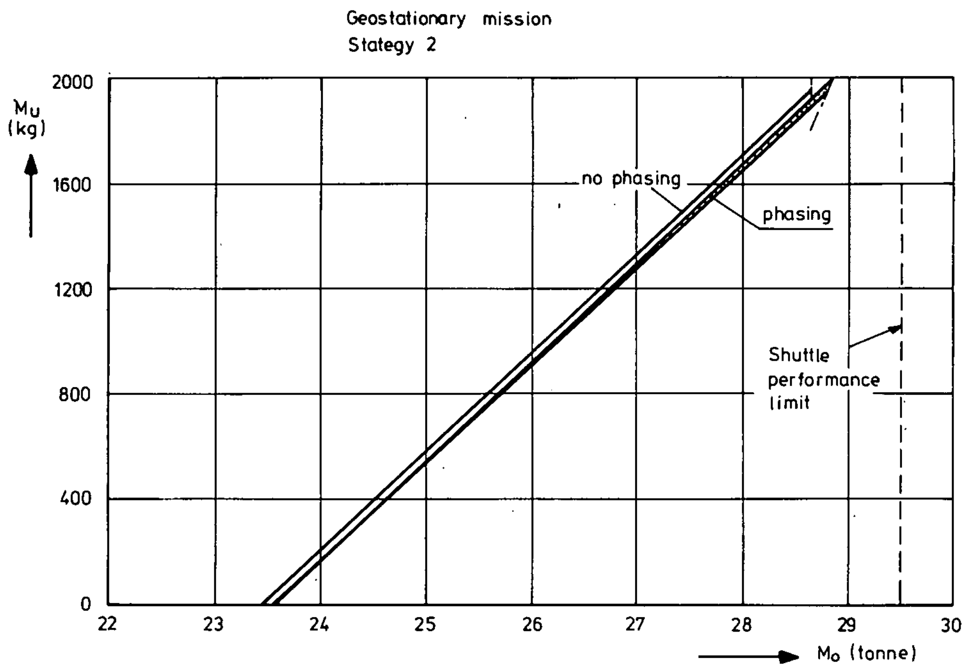


Fig. 37: Payload placement capability.

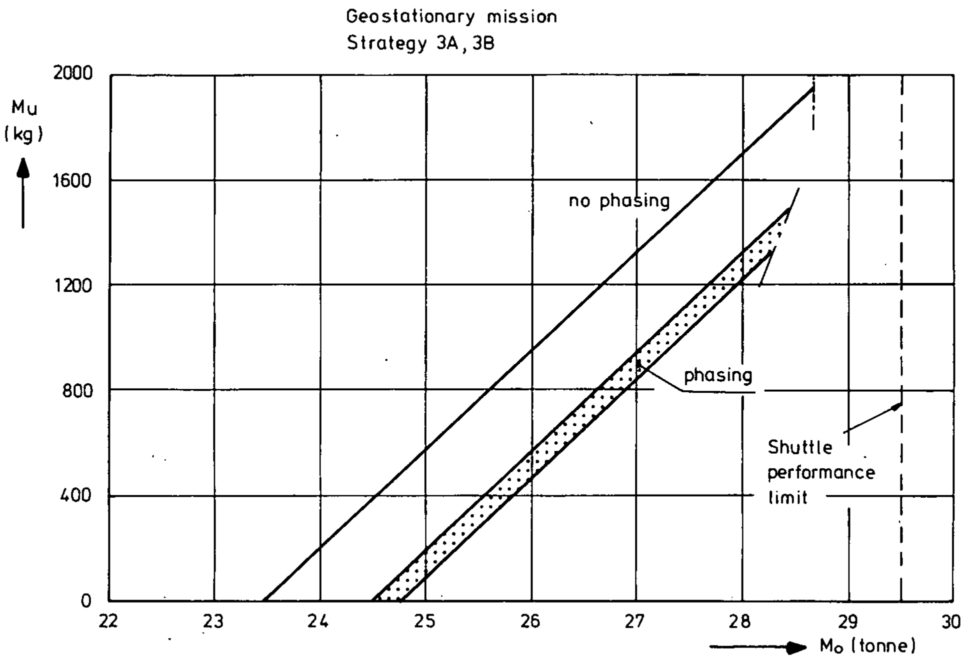


Fig. 38: Payload placement capability.

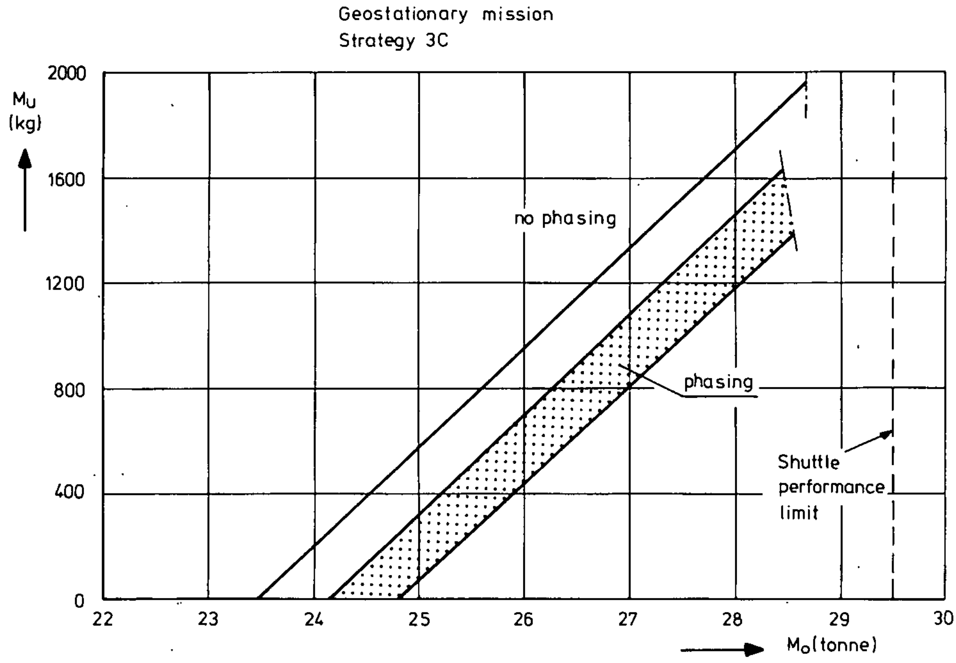


Fig. 39: Payload placement capability.

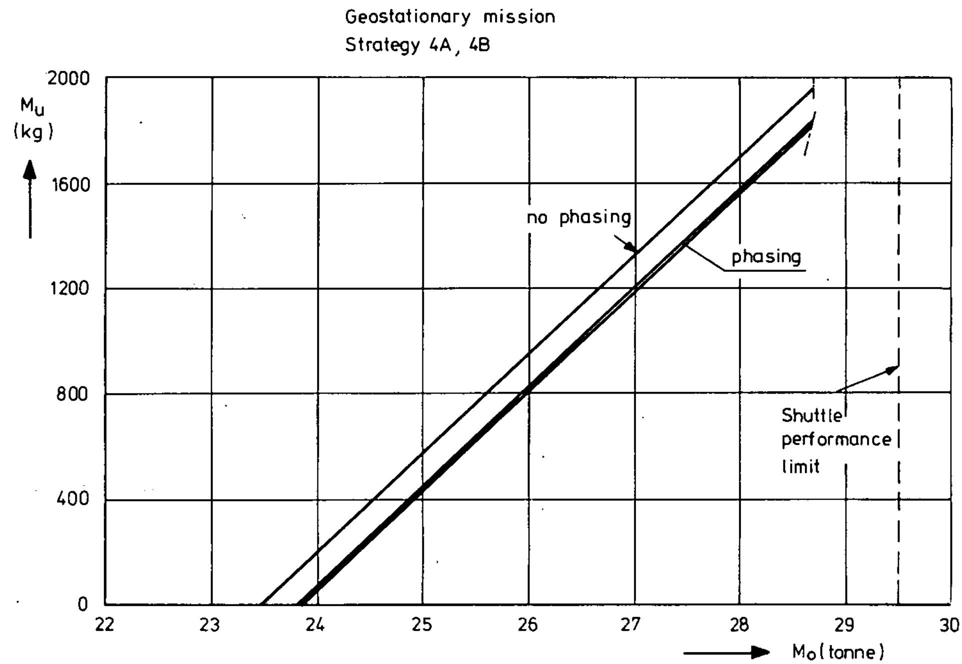


Fig. 40: Payload placement capability.

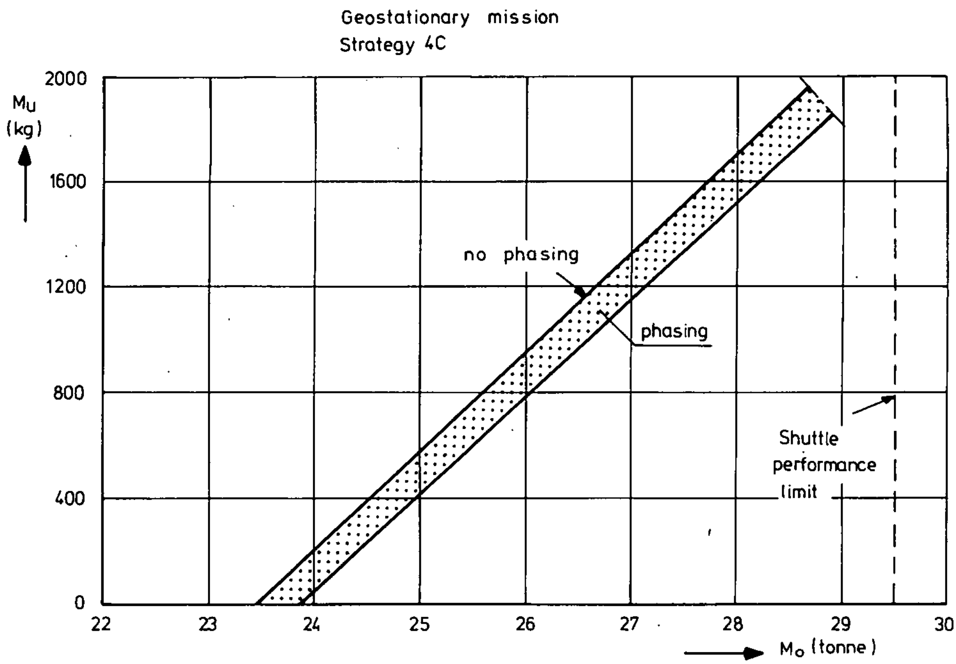


Fig. 41: Payload placement capability.

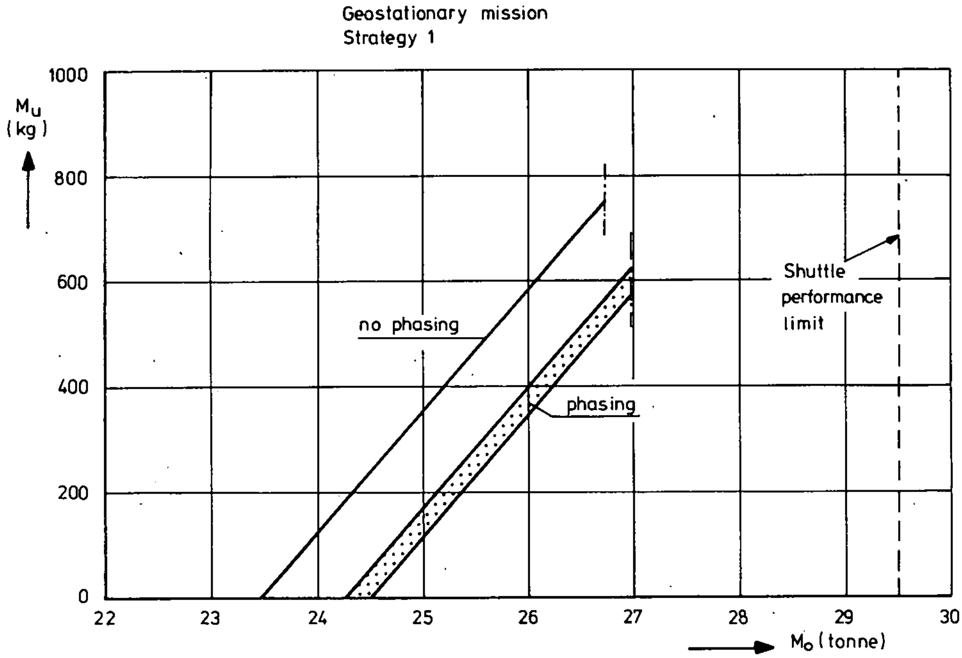


Fig. 42: Payload retrieval capability.

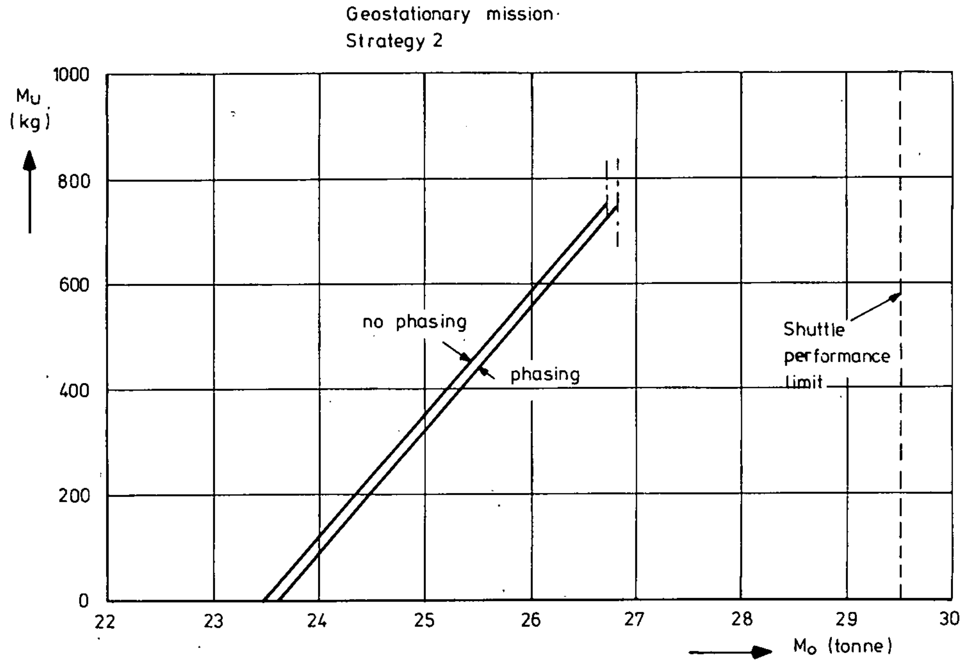


Fig. 43: Payload retrieval capability.

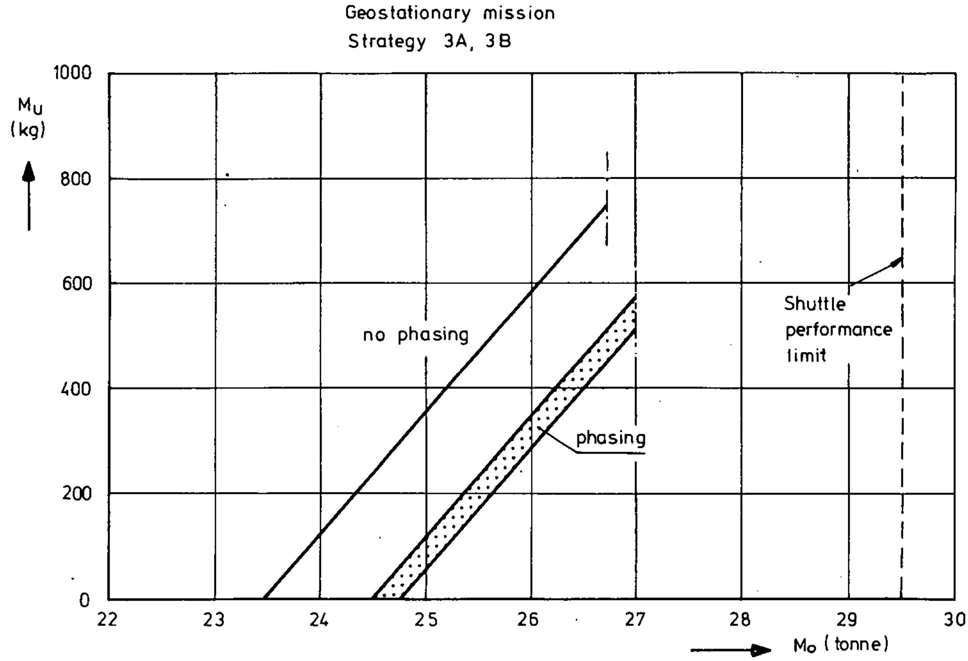


Fig. 44: Payload retrieval capability.

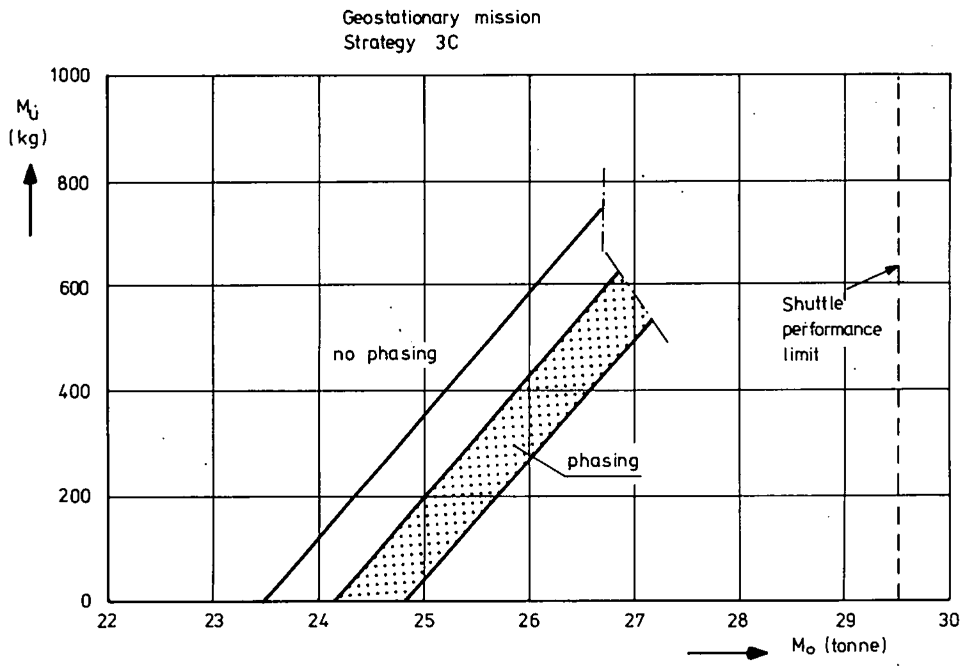


Fig. 45 : Payload retrieval capability.

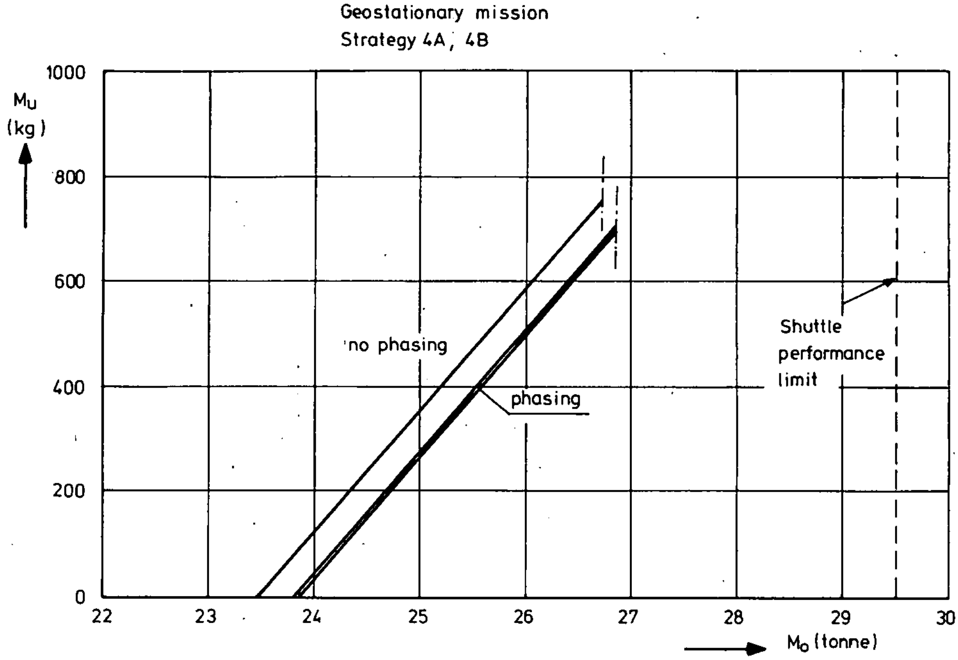


Fig. 46: Payload retrieval capability.

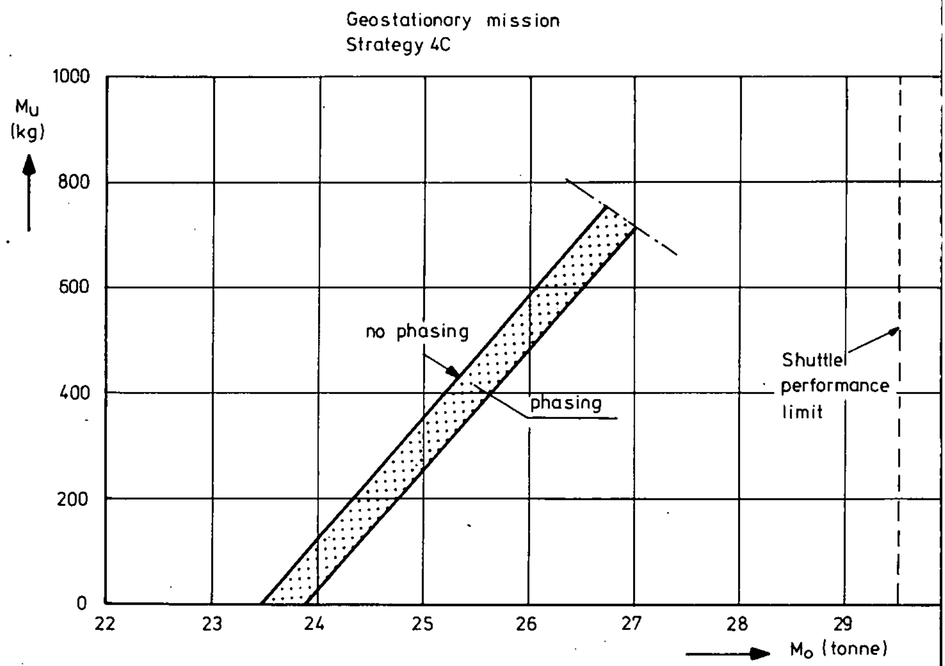


Fig.47: Payload retrieval capability.

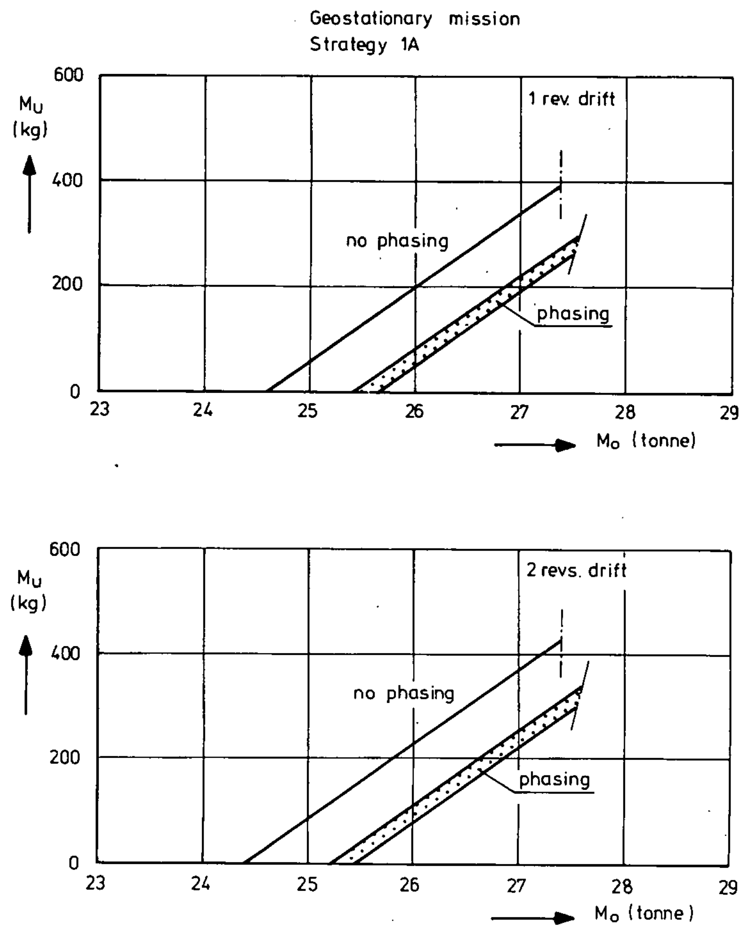


Fig. 48: Payload roundtrip capability.

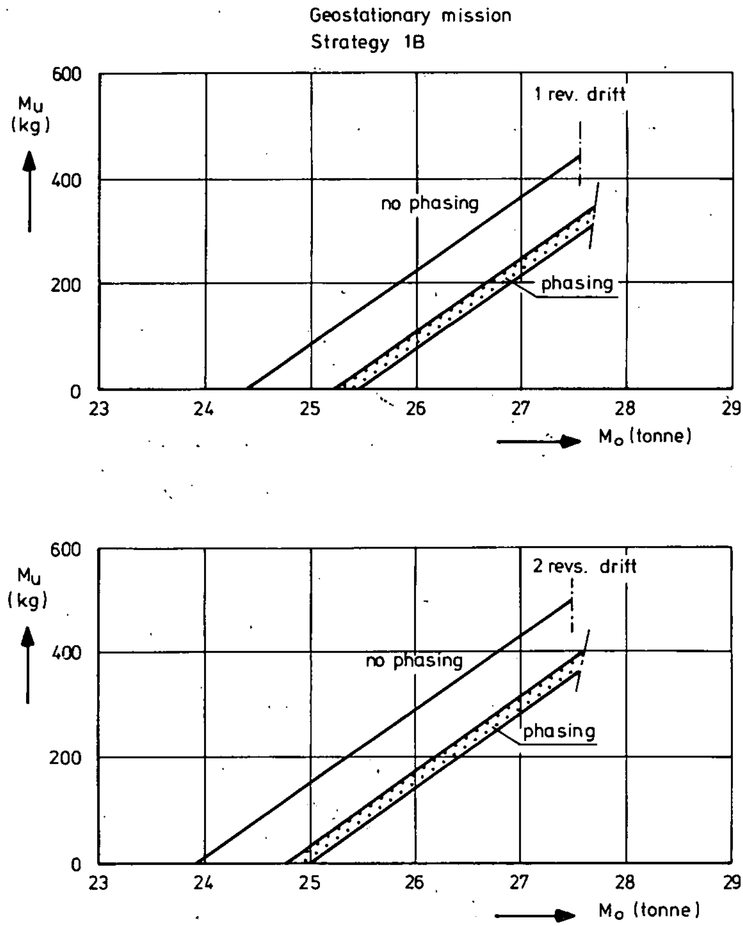


Fig. 49: Payload roundtrip capability.

Geostationary mission
Strategy 2A

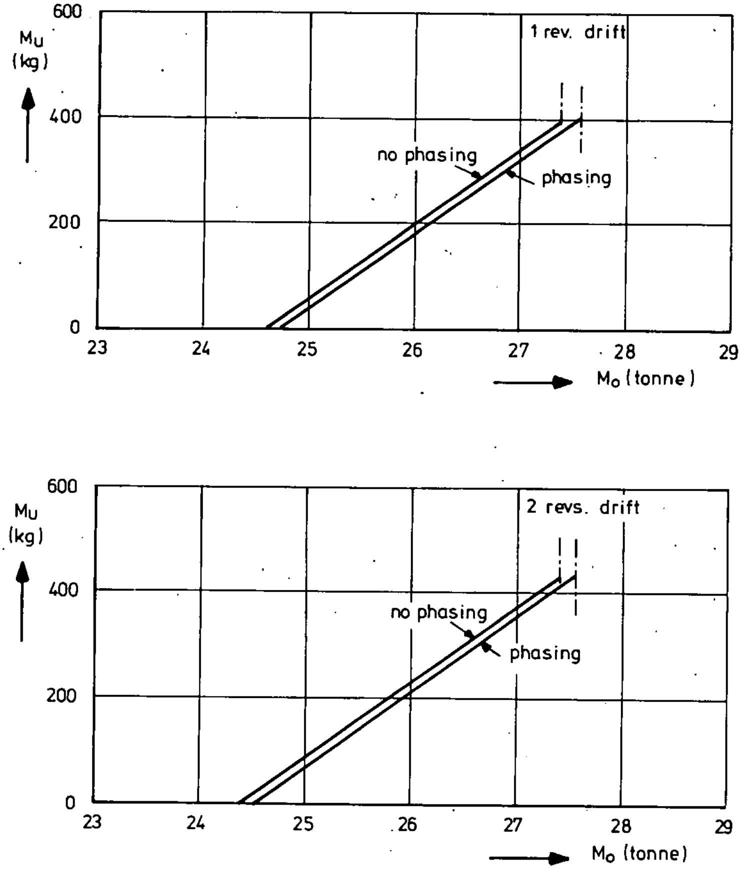


Fig. 50: Payload roundtrip capability.

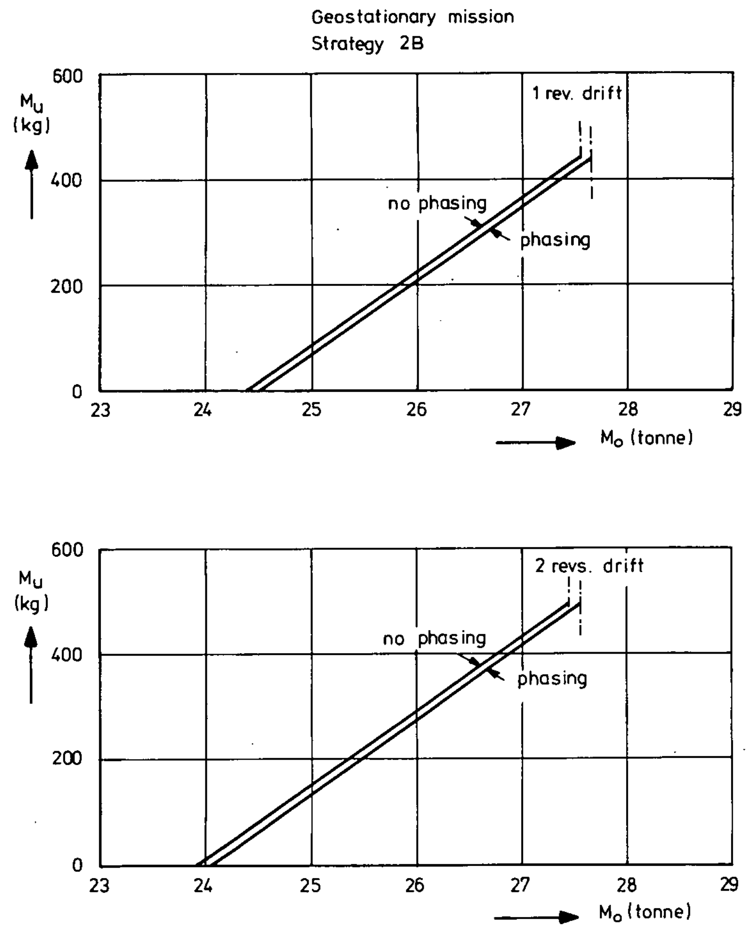


Fig: 51: Payload roundtrip capability.

Geostationary mission
Strategy 3A

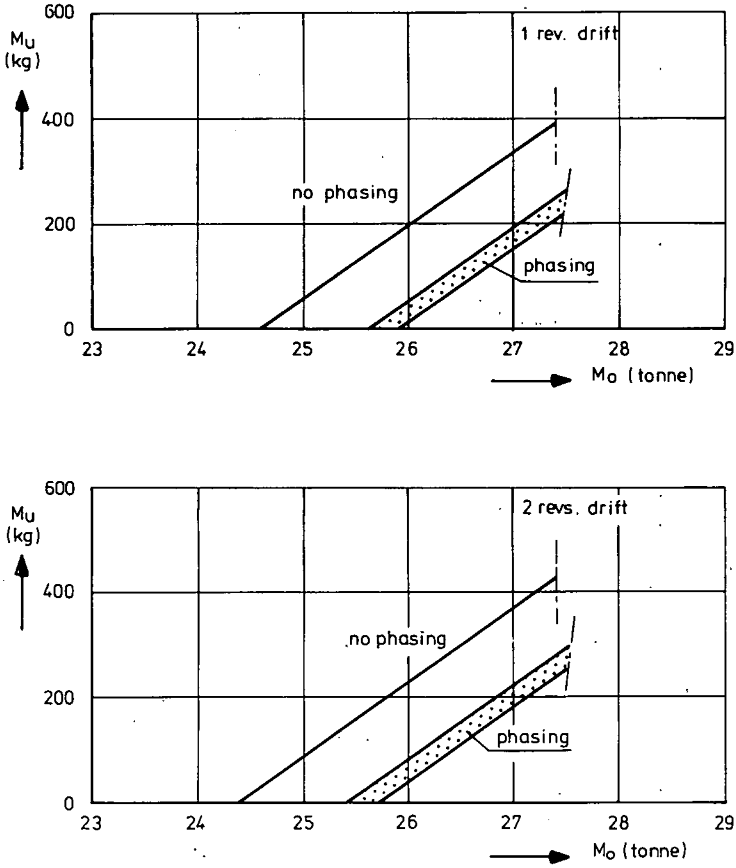


Fig. 52: Payload roundtrip capability.

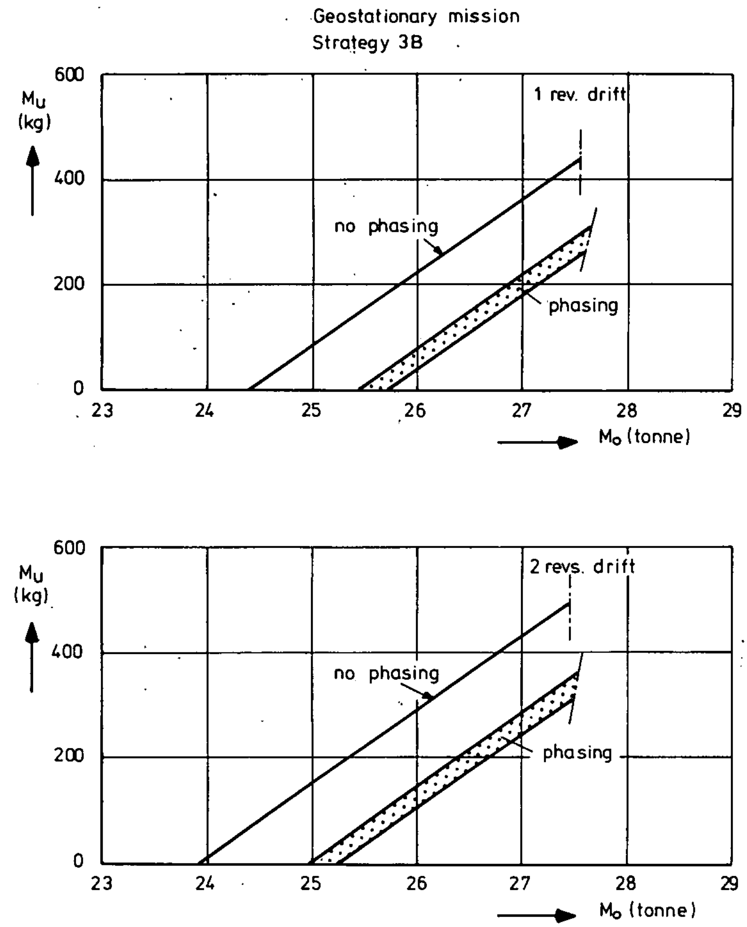


Fig. 53: Payload roundtrip capability.

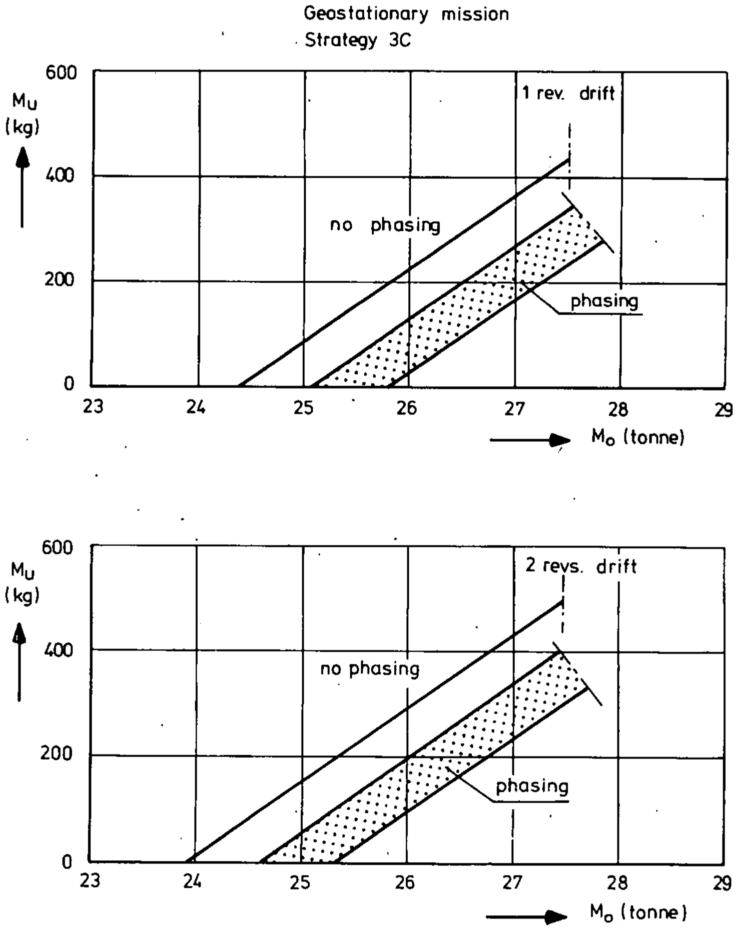


Fig. 54: Payload roundtrip capability.

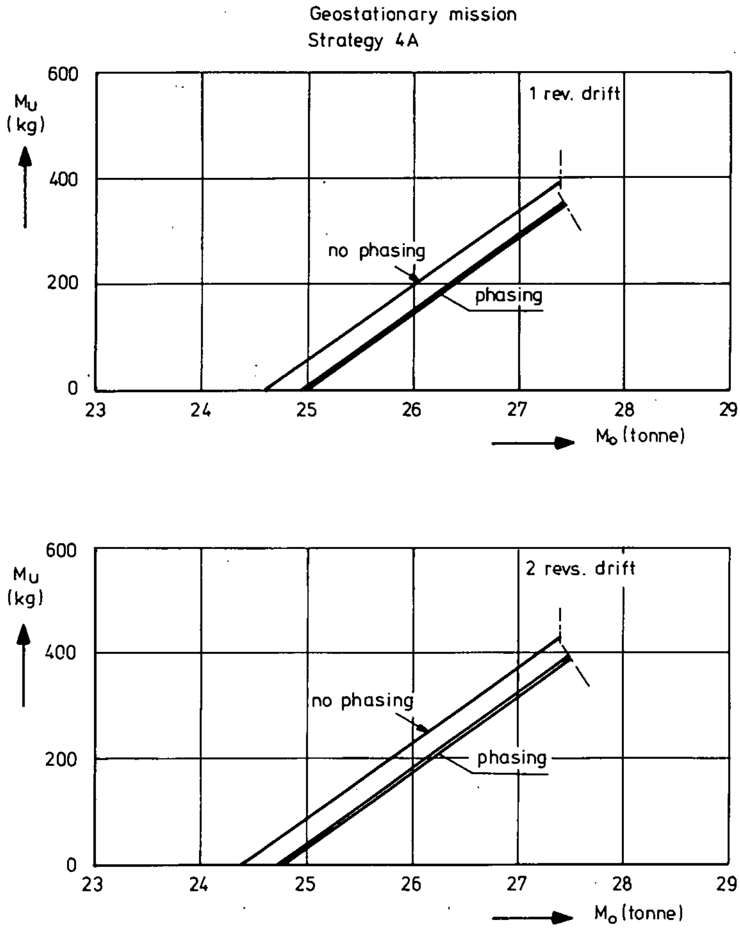


Fig. 55: Payload roundtrip capability.

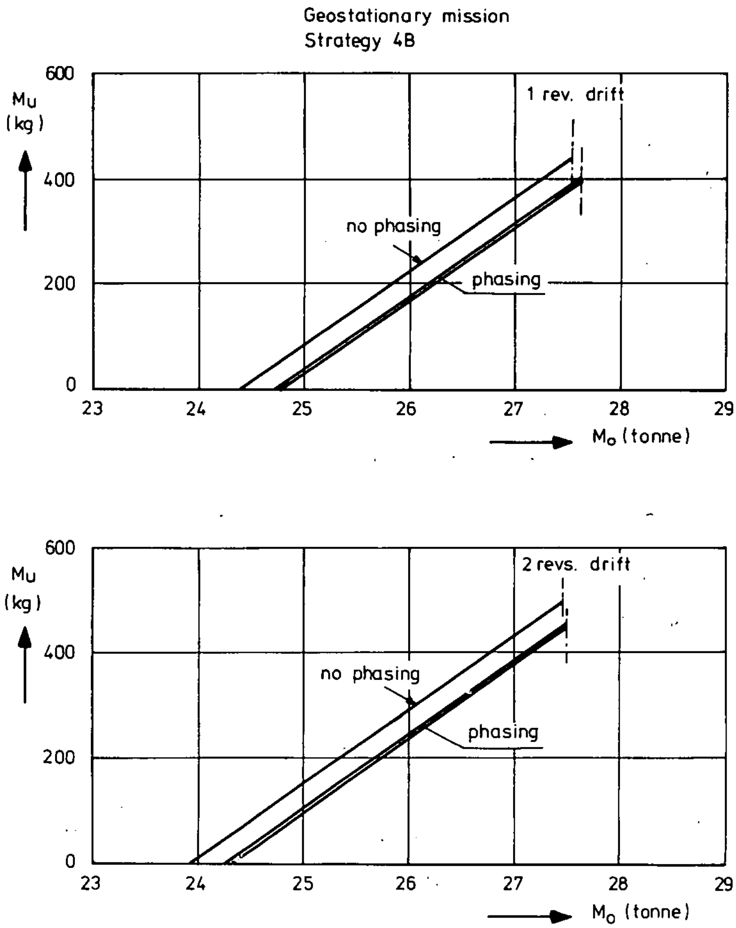


Fig. 56: Payload roundtrip capability.

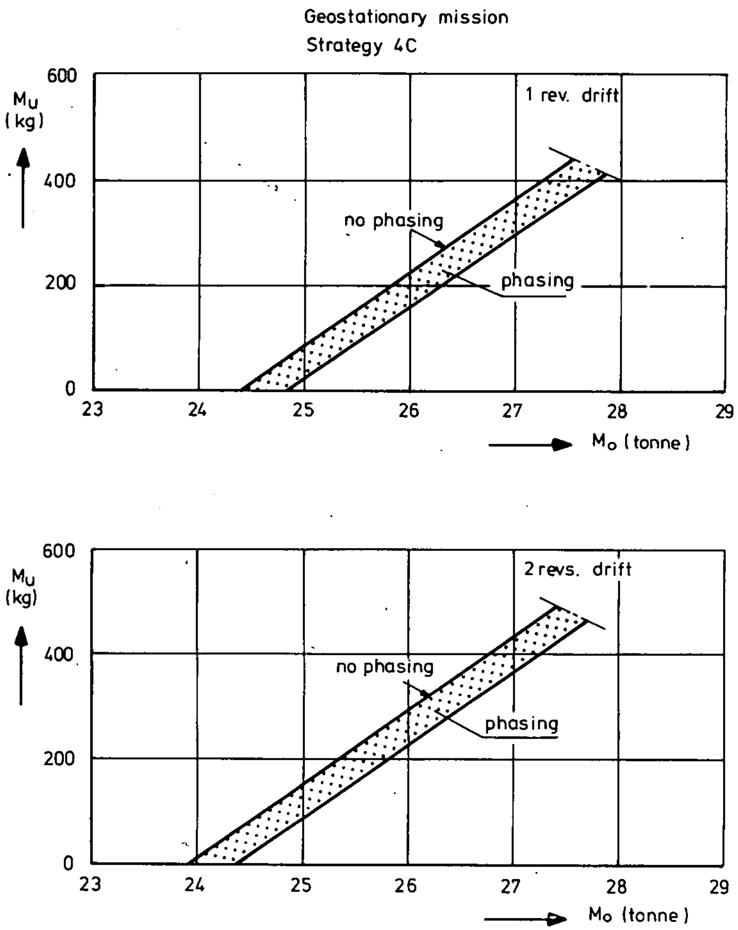


Fig. 57: Payload roundtrip capability.

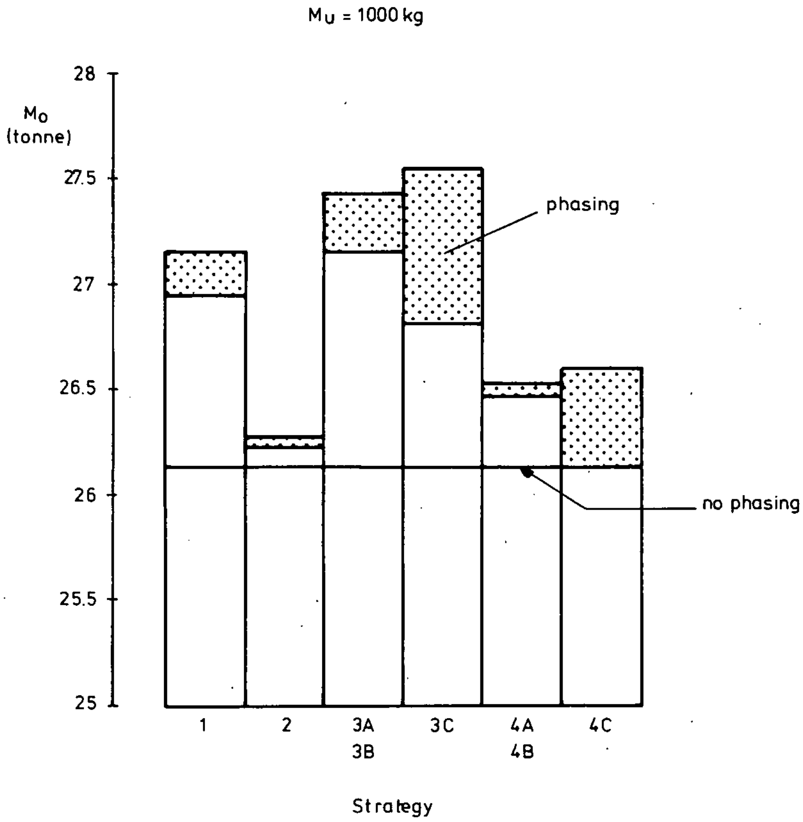


Fig. 58: Total Tug mass for placement of a 1000 kg payload in geostationary orbit for various mission strategies.

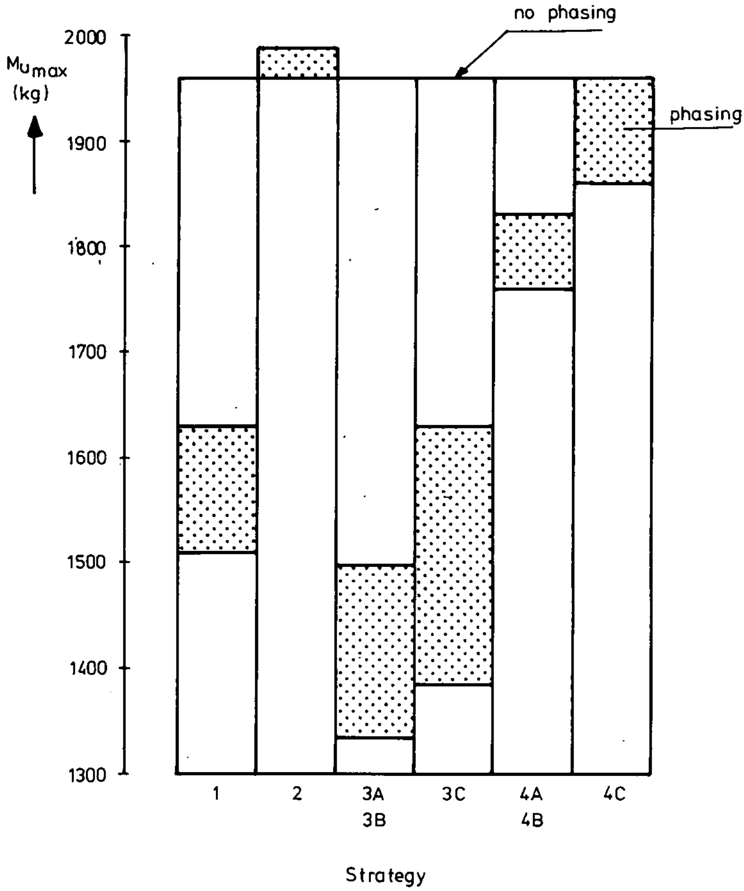


Fig. 59: Maximum geostationary placement capability for various strategies.

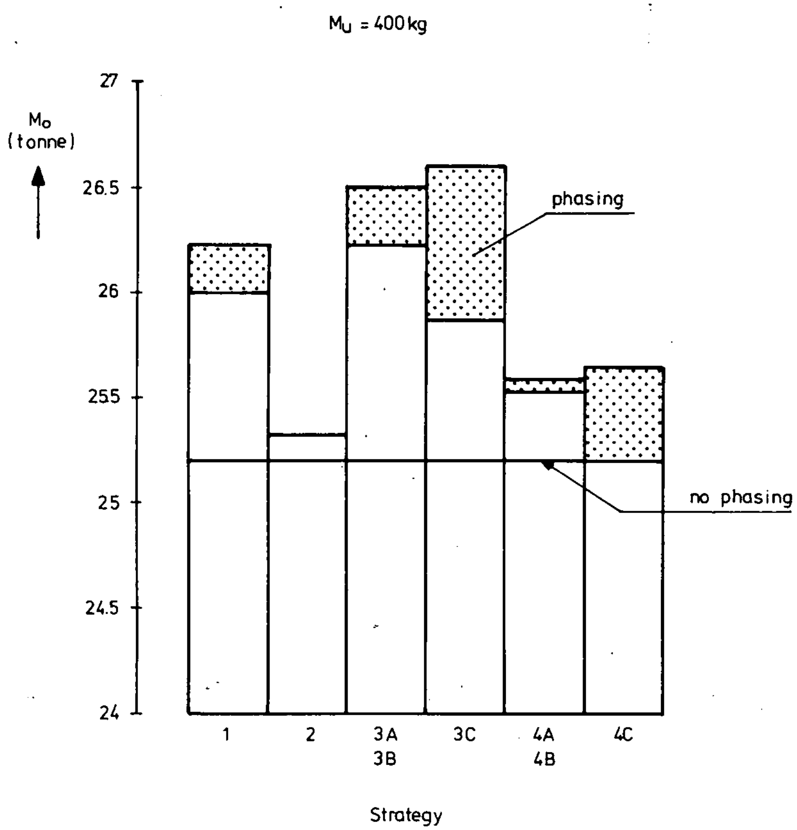


Fig. 60: Total Tug mass for retrieval of a 400 kg payload from geostationary orbit for various mission strategies.

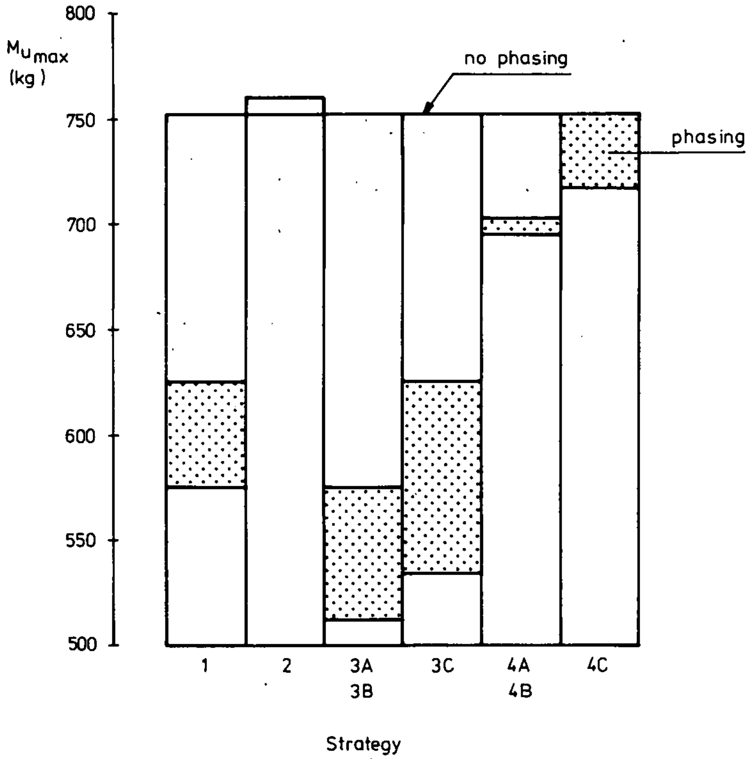


Fig. 61: Maximum geostationary retrieval capability for various strategies.

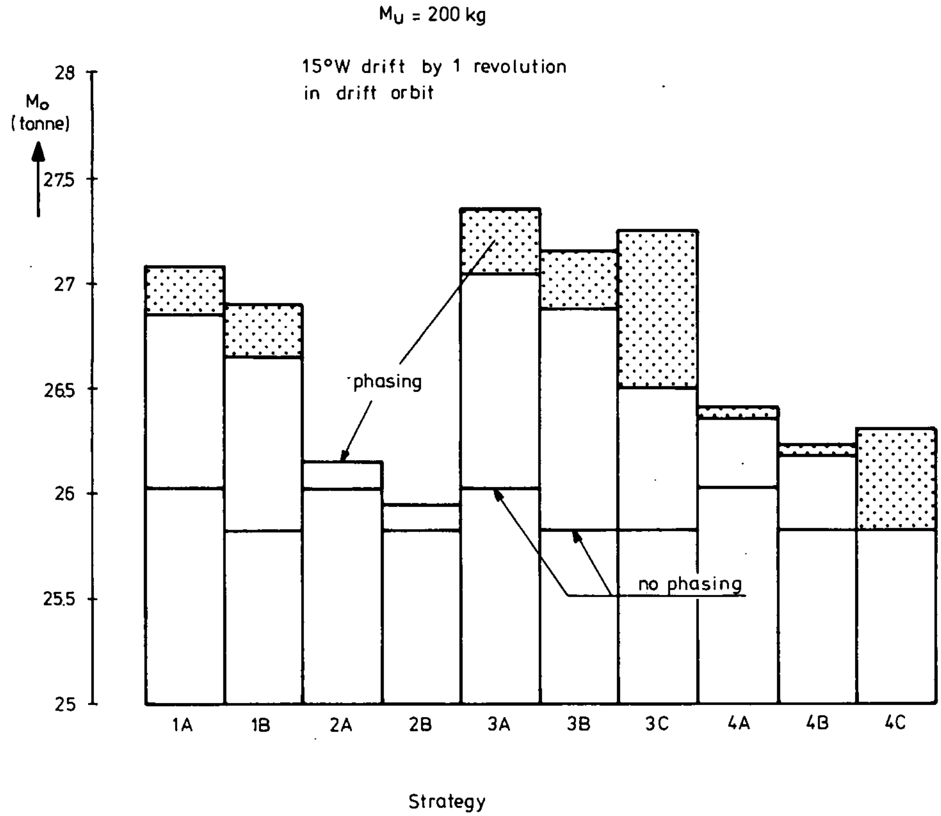


Fig. 62: Total Tug mass for a roundtrip with a 200kg payload to geostationary orbit for various mission strategies.

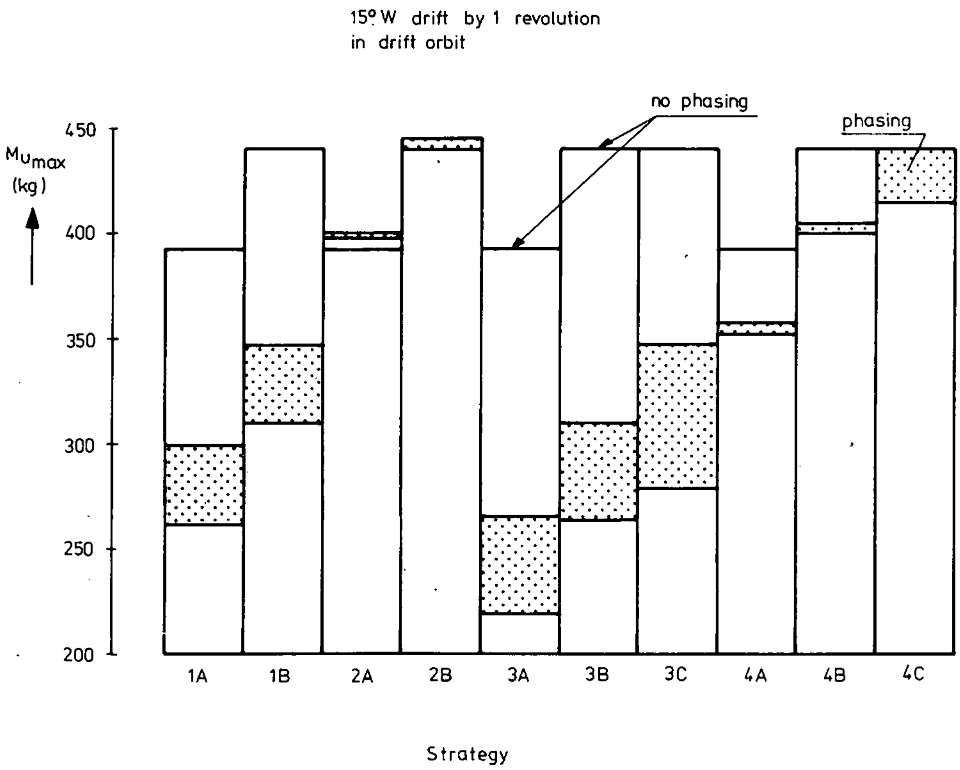


Fig. 63: Maximum geostationary roundtrip capability for various strategies.

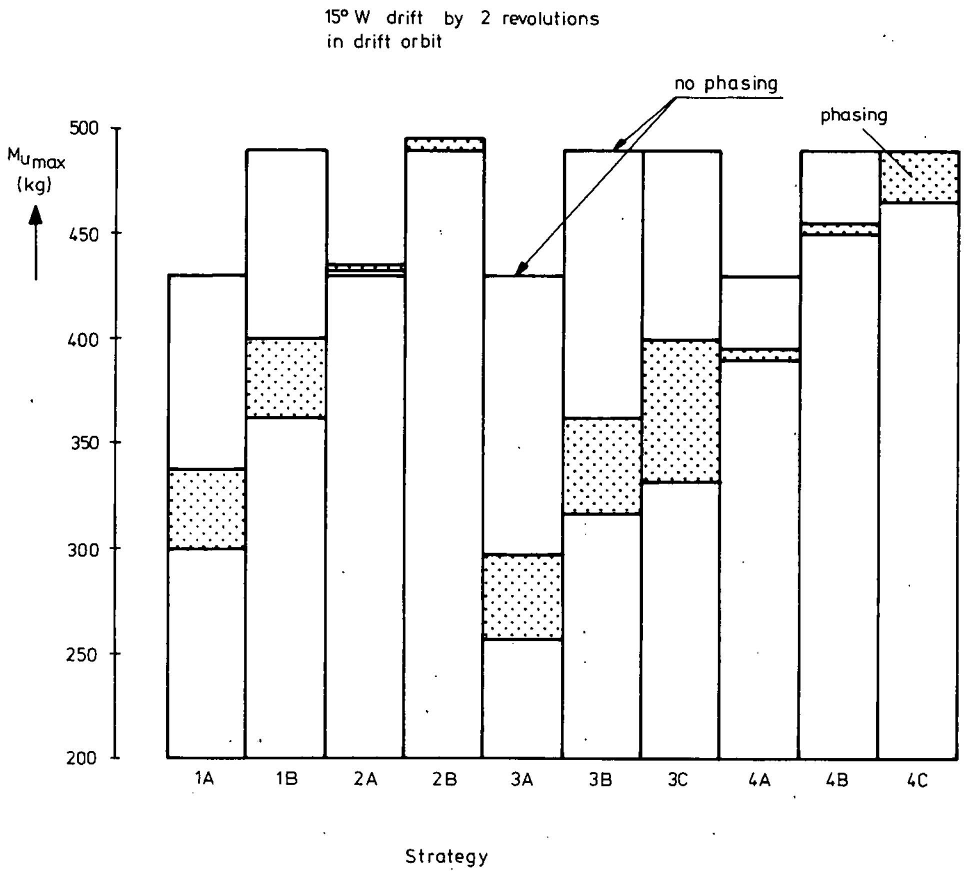


Fig. 64: Maximum geostationary roundtrip capability for various strategies.

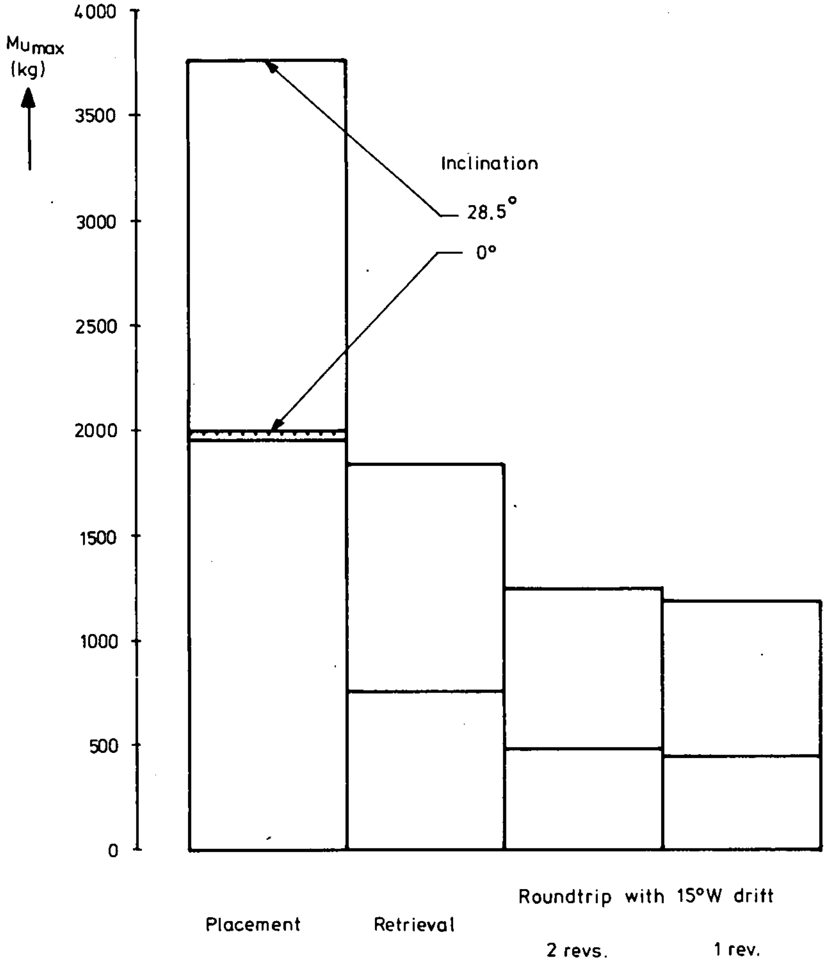


Fig. 65: Payload capability for missions to geosynchronous altitude