Multidisciplinary Optimisation in Mission Analysis and Design Process

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1. INTRODUCTION

The aim of the study presented in this document is to identify an efficient approach to tackle conflicts at different sub-systems levels, arising in space engineering during the whole design activity. This document focuses on a typical scenario that the system engineering has to deal with and is oriented to introduce an advanced Multidisciplinary Optimisation (MDO) methodology. Main scope of the study is to illustrate the conceptual aspects of the methodology and point out the applicability of the approach to a wide class of cases arising in space engineering.

The WATS (WAter vapour and temperature in Troposphere and Stratosphere) mission has been chosen as basic case study. It is described in chapter 2, giving particular attention to the engineering point of view. This chapter has to be considered as preliminary to the whole study that focuses on a MDO methodology aimed at supporting the system engineer in facing conflicts arising during the project activities.
The case study is described in a simplified form, in order to point out the conceptual aspects of the approach proposed. Technical engineering details that are not essential to understand the methodology have been deliberately neglected. The mission analysis, the power and the propulsion sub-systems have been selected as reference disciplines to simulate a realistic (even if simplified) space engineering environment.

The proposed Multidisciplinary Optimisation approach is introduced in chapter 3. It is based on a joint use of three methodologies: Neighbourhood Search, Game Theory and Multicriteria Decision Analysis. The basic concepts of this new approach are given in section 3.1. The Neighbourhood approach aims at finding (by means of a dedicated heuristics) a set of 'paretian' (non dominated) solutions at system level. It is described in section 3.2. The total number of such solutions could be extremely high. Then it becomes necessary to have efficient methods to reduce such number to a small subset of solutions to be considered “optimal” from the point of view of conflict reduction. The methods utilised are the Game Theory and the Multicriteria Decision Analysis. The two approaches are described in sections 3.3 and 3.4, respectively. It is interesting to realise that such methods can work also without the set of paretian solutions given by the Neighbourhood approach. The input they require is simply a set of solutions, not necessary paretian, which are considered feasible by the system engineer. This is the case which happens very often in practice. For this reason, in Chapter 4, the Game Theory and the Multicriteria Analysis methods have been applied to a possible feasible set of solutions of the WATS case study, bypassing the Neighbourhood approach.

A software prototype, considering all the three methodologies, has been developed to demonstrate the efficiency of the proposed method and the possibility to develop a general framework to solve a wide class of practical cases. It is described in Appendix 2. The software prototype has been tested on a further illustrative case study, dealing with a simplified Mars mission (no three-dimensional orbital evolution is considered). The system engineering point of view is considered first. It is reported in Chapter 5. The utilisation of the software prototype is illustrated in Chapter 6. Even if the case study considered is very simple, this chapter shows that the proposed approach can be efficiently extended to a wide class of real cases and that the application of the methodology can be 'automated', by the development of such a framework.

In Appendix 1 the WATS mission analysis issue is formulated (in a simplified form) as an optimisation problem. The resulting complexity (even if the problem is formulated in a simplified form and limited to the mission analysis only) points out the practical impossibility to tackle the whole engineering problem as a single optimisation problem. The software prototype is described in Appendix 2 and the software Reference Guide is reported in Appendix 3.

2. WATS MISSION CASE STUDY

In this paragraphs the WATS mission case study is presented and it is shortly introduced in 2.1, while in 2.1.1 the reduced/tailored study logic, problem activity flow, trade-offs and conflicts of the WATS mission up to the level needed for the case study are shown.

2.1 PRELIMINARIES

The WATS mission has the aim of monitoring variations and changes in the global atmospheric water vapour distribution and winds in lower stratosphere and upper troposphere. It consists of a constellation of LEO satellites at 650 km and 850km altitude.

The following observations are performed:

- Refractivity profiles from radio occultation events exploiting the L-Band signals of the global navigation satellite system satellites.
- Refractivity and absorption profiles from LEO to LEO (Low Earth Orbit) cross-link occultation events using K-band signals emitted by each LEO for the derivation of water vapour absorption profiles

Radio occultation measurements allow the determination of transmitter to receiver ray path refraction in the atmospheric layers. Radio path refraction mainly depends on atmospheric physical properties. Due to the employment of radio frequency signals, bending angles are derived by Doppler shift in signal frequency with respect to the carrier. Refractivity of atmospheric layers can then be retrieved from the bending angle profiles. From this information, it is possible to derive pressure, temperature and humidity that are necessary for the study of water vapour distribution and winds. The measurements of radio occultation between the LEO satellites and GNSS (Global Navigation Satellite System) produce accurate information about the properties of stratosphere and external atmosphere layers. However, due to the absorption properties of lower troposphere layers, the achievable measurement results are inaccurate at the L-Band frequencies. The main problem of this zone is the dominance of oxygen absorption effect at frequencies lower than 10GHz. At the K-Band frequencies (LEO - LEO satellites occultation), the interaction between the electromagnetic field and the water vapour will be dominant, so more accurate data about lower troposphere structure and properties can be achieved.

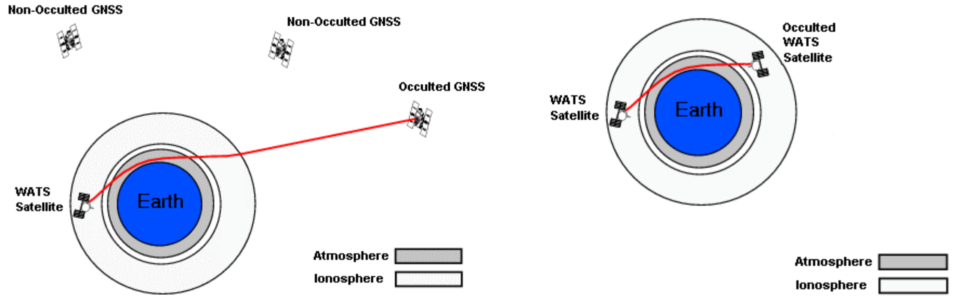


Figure 2.1-1: GNSS to LEO and LEO to LEO occultation concepts

The ESA (European Space Agency) stability and accuracy requirements in the experiment are reported in Table 2.1-1, while the ESA mission analysis requirements are reported in Table 2.1-2. Further information about WATS mission can be found in RD 1, RD 2, RD 3, RD 4 and RD5.

Data type	Value
LEO-LEO minimal vertical atmospheric domain coverage	1km÷20km
GNSS-LEO minimal vertical atmospheric domain coverage	1km÷90km
GNSS to LEO cross-link bending angles measurement accuracy (single occultation)	10^{-6}rad
LEO to LEO cross-link bending angles measurement accuracy (single occultation)	10^{-6}rad
LEO to LEO cross-link amplitude attenuation measurement stability over 60 s (single occultation)	0.025dB
Baseline frequencies	10.3, 17.2 and 22.6GHz
Additional frequencies to be assessed	27.4 and 32.9GHz

Table 2.1-1: Measurement requirements

Data Type	Value
Number of occultation	LEO - LEO cross-links: ≥ 1600 events per day GNSS - LEO: > 6500 events per day (day = 24 hours period)
Spatial distribution	As homogeneous as possible within 24 hours period (i.e. aiming at an uniform density of events per unit area over the globe)
Temporal distribution	As homogeneously as possible within 30 days period in order not to create a diurnal bias (i.e. aiming at uniform density of events per unit local time)
Timeliness	At least 30% of the data should be available in near real time (2 - 3 hours)
Maximal Horizontal Atmospheric domain to be crossed during occultation	500 km
Baseline mission life time	7 years

Table 2.1-2: Mission analysis requirements

2.1.1 WATS Mission Case Study Logic

The WATS mission case study Logic is shown in
Figure 2.1-2. Where it is shown that, as requested by ESA, Mission Analysis and two subsystems (Power and Propulsion) had been chosen for the this case study. The relations among the subsystems and the Mission Analysis, through the spacecraft (S/C) configuration and with the feedback from Launch Strategy back to Mission Analysis are shown, as well. In
Figure 2.1-2: P/L means Payload, S/S means sub-system and ΔV is the Variation of Velocity of the Satellite.

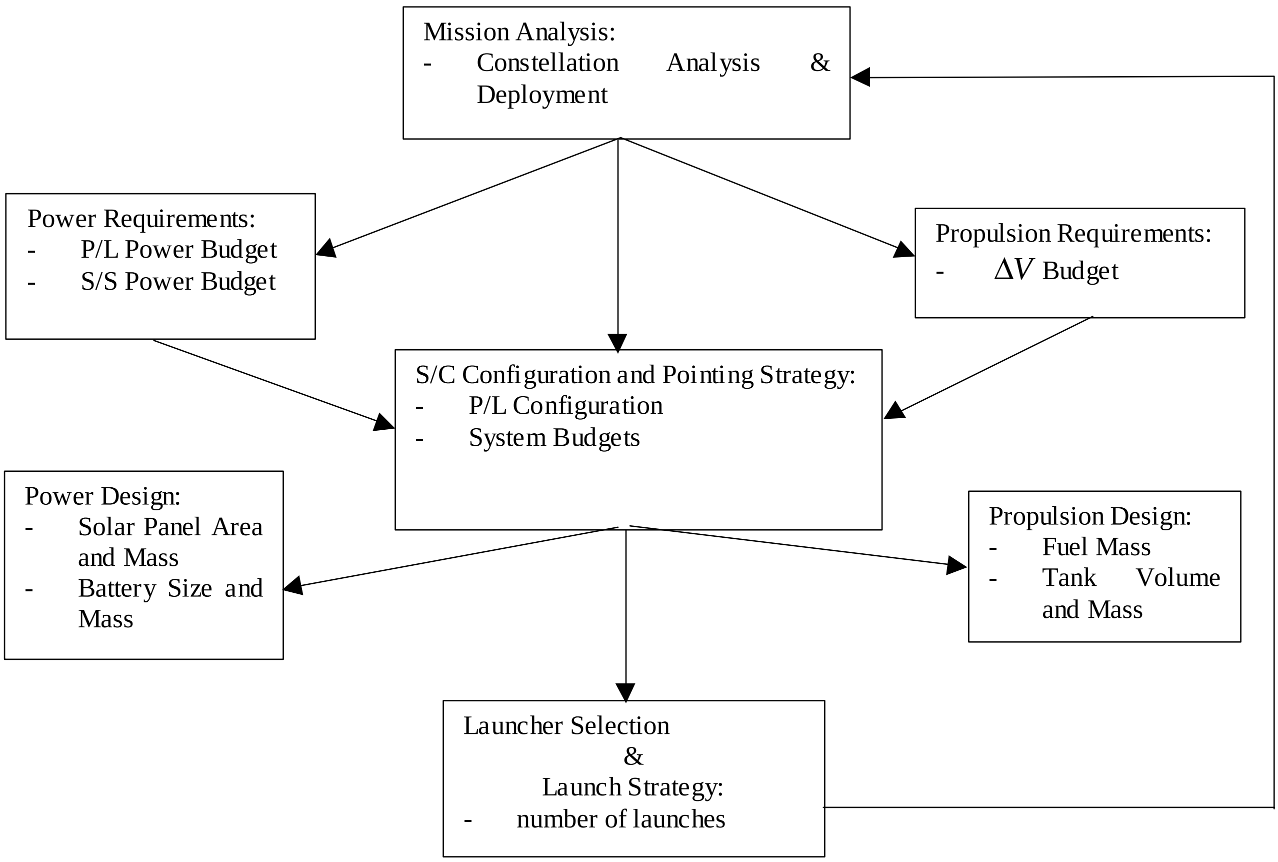


Figure 2.1-2 WATS Mission Case Study Logic

The WATS mission case study logic is a parallel representation of the WATS mission case study. In order to fully understand the activity flow related to
Figure 2.1-2, the WATS Mission Case Study Activity Flow and Trade Offs are shown, in a sequential way, in Table 2.1-3. It must be underlined that in this case study: the Event is the LEO to LEO occultation (see Figure 2.1-1). In Table 2.1-3: $\Delta\Omega$ is the Ascending Node Separation between the planes of the satellite orbits in the constellation and $\Delta\vartheta$ is the True Anomaly Separation among the satellite position on the orbits in the constellation. In
Figure 2.1-2 and in Table 2.1-3 are summarised all the Activities, Trade-offs, Constellation and Satellite Parameters, involved in the Trade-offs; as well as, Feedback check and flow that are exploited and described in 2.2 and 2.3.

- Mission Analysis
  - Constellation Analysis and Trade-offs:
    - number of Events:
      - number of Satellite
      - $\Delta\Omega$ Distribution
      - $\Delta\theta$ Distribution
  - Constellation Deployment and Trade-offs:
    - ΔV Budget:
      - Parking Orbit Analysis
      - Transfer Orbit Analysis
- S/C Configuration, Pointing Strategy and Trade-offs
  - Earth Pointing versus Sun Pointing:
    - P/L Configuration:
      - number of Antennas and of Receivers:
        - P/L Mass and Power
    - System Budgets:
      - Overall satellite Mass and Power budget:
        - Fuel Mass
        - Tank Volume and Mass
        - Solar Array Area and Mass
        - Battery Size and Mass
- Launcher Selection, Launch Strategy and Trade-offs:
    - Launcher Selection:
      - number of Launches

Table 2.1-3 WATS Mission Case Study Activity Flow and Trade - Offs

It must be stressed that the main task of Mission Analysis and System Engineering activity is to find conflicts among the parts involved in this Case Study. That is why, the overall Case Study Logic and Activity Flow and Trade-offs, given in
Figure 2.1-2 and in Table 2.1-3, are summarised with the following two main conflicts:

1. Between number of Satellite and number of Launches: in order to lower as much as possible the number of launches and to rise as much as possible the number of satellite
2. Among Payload, Power Subsystem and Propulsion Subsystem: in order to have the Payload as simpler and lighter as possible, to have the power subsystem as simpler and lighter as possible and to have to propulsion subsystem as simpler and lighter as possible.

The 1st conflict leads to minimise as much as possible the mass budget of the satellite and drives the 2nd conflict with the request to find the minimum of the sum of the Payload, Propulsion and Power masses.
The 2nd conflict is through the S/C Configuration (Antennae Layout, Solar Array and Propulsion options) and Pointing Strategy (Earth Pointing vs Sun Pointing) as explained in following table

Best	Worst
Power: Less Mass, Battery Volume and Solar Panel Area (Sun Pointing)	P/L: More Antennas and Receivers
Propulsion: Less Fuel Mass and Tank Volume and Mass (Earth Pointing without Attitude Manoeuvres)	Power: More Mass, Battery Volume and Solar Panel Area
P/L: Less Antennas and Receivers (Earth Pointing with Attitude Manoeuvres)	Propulsion: More Fuel Mass and Tank Volume and Mass

Table 2.1-4 2nd Conflict Explanation

2.2 PROCESS MODEL

The Process Model is the full set of equations, fixed parameters and input/output parameters that are needed to perform the analysis and trade off in order to manage the conflicts (see page 11) of WATS Mission Case Study and to find an optimised solution of them.

2.2.1 Mission Analysis

The scope of the mission analysis is to find the best distribution of satellite orbit parameters in order to "maximise" the number of events. A brief introduction to Occultation Theory and Characteristic is given in 2.2.1.1. Full explanation of the theory can be found in RD 6. In 2.2.1.1, all it is needed to fully understand following analysis and trade offs it is summarised for reader's convenience.

2.2.1.1 Occultation Theory and Characteristics

The occultation event is computed for two satellites with position vectors $\vec{r}_i = r_i \vec{u}_i$ and $\vec{r}_j = r_j \vec{u}_j$. The distance d_{ij} (see Figure 2.2-1) from the origin O of the reference frame (Geocentric Equatorial Frame) and the straight line joining the apex of the vector $\vec{r}_i$ and apex of the vector $\vec{r}_j$ is given by:

(1)
$$d_{ij} = \frac{r_i r_j \sqrt{1-\cos^2 \Delta_{ij}}}{\sqrt{r_i^{\,2} + r_j^{\,2} - 2 r_i r_j \cos\Delta_{ij}}}$$

while the co-ordinates of the point P_{ij} (see Figure 2.2-1) are the components of the vector $\vec{p}_{ij} = d_{ij}\vec{u}_{ij}$ (see Figure 2.2-1) from the centre of the Earth that is given by:

(2)
$$\vec{p}_{ij} = \frac{X_{ij}\vec{u}_i + \vec{u}_j}{\sqrt{1 + 2X_{ij}\cos\Delta_{ij} + X^2_{ij}}} = d_{ij}\vec{u}_{ij}$$

where $X_{ij} = \frac{r_i \cos\Delta_{ij} - r_j}{r_j \cos\Delta_{ij} - r_i}$ and $\cos\Delta_{ij} = \frac{\vec{r}_i \cdot \vec{r}_j}{r_i r_j}$. There is an occultation event when $R_E < d_{ij} < R_E + h$, where R_E is the Earth Radius and h is given by instrument requirements.

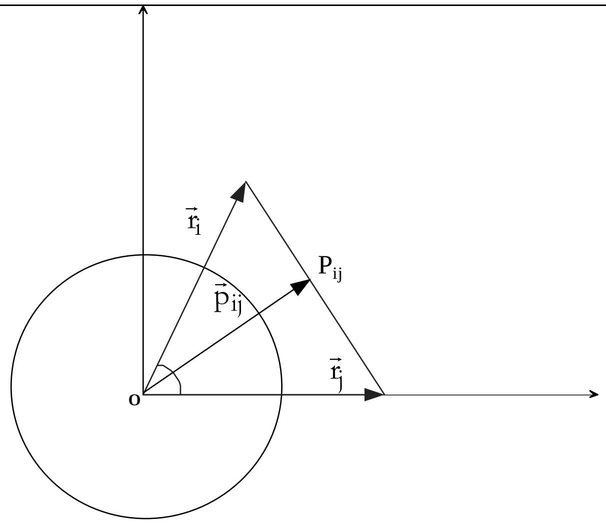


Figure 2.2-1 Geometry of the Occultation Event

Once the co-ordinate x, y and z of the point P_{ij} are known the latitude and longitude of the point event are given by:

(3)

$$Lat_{ij} = a\sin(P_{ijz})$$

$$Long_{ij} = a\tan\left(\frac{P_{ijy}}{P_{ijx}}\right) + \varpi_E (t - t_0)$$

Where ϖ_E is the Earth angular rate.

From the vector $\vec{p}_{ij}$ it is possible to calculate $\vec{p}'_{ij}$, that is the position of the point Pij with respect to satellite i in the local reference frame PQW (see RD 8) centred in satellite i. Once the co-ordinate of the vector $\vec{p}'_{ij}$ are know the azimuth and elevation of satellite j with respect to satellite i are given by:

(4)

$$\delta_{ij} = a\sin(p'_{ijp})$$

$$\alpha_{ij} = a\tan\left(\frac{p'_{ijq}}{p'_{ijw}}\right)$$

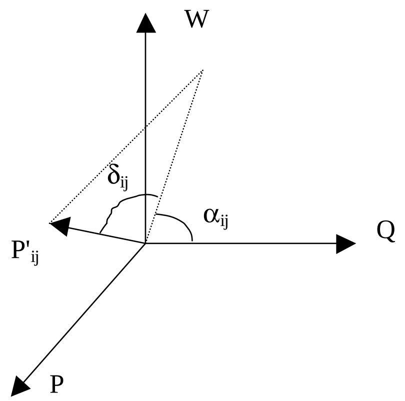


Figure 2.2-2 Azimuth and Elevation of satellite j with respect to satellite i

Equation 4 is needed in order to understand which is the statistic of the positions of the events within the satellite reference frame, this is needed to understand which is the better antennae layout of the satellite.

2.2.1.2 Constellation Trade-off

The full set of requirements, auxiliary parameters, fixed parameters and trade offs that will be used and performed for the WATS mission case study in the mission analysis are listed here below. Auxiliary parameters are parameters needed to make decision about the goodness of the constellation. Fixed parameters are parameters that had been fixed in the case study for the sake of simplicity. It must be underlined that the fixed parameters does not limit at all the reality of the found conflicts (see pag. 11).

- The requirements that must be satisfied are:
  - Number of occultations: ≥ 1600 events per day
  - Occultation duration: 60 sec
  - Spatial Occultations distribution (one day): As homogeneous as possible within 24 hours period
  - Minimal Vertical Atmospheric Domain: [1 km ÷ 20 km]
  - Maximal Horizontal Atmospheric Domain: 500 km
  - Mission Lifetime: 7 years

- The auxiliary parameters for the Constellation Trade Off are:
  - Statistic distribution of occultation events (Latitude vs. Longitude)
  - Statistic distribution of occultation events (Azimuth vs Elevation)

- The fixed parameters for the Constellation Trade-offs are:
  - Satellite Altitude (H): 650 km and 850 km
  - Satellite Inclination (I): 95° and 70°
  - Satellite Eccentricity (e): 0
  - Satellite Argument of Perigee (ω): 0

The goodness of the constellation or, in other words, the optimised constellation is the one that satisfies the number of occultation events as much as possible with the minimum number of satellites and a suitable distribution of satellite orbits ascending Node (Ω) and satellite on orbits true anomaly (ϑ) (see RD 8).

- The following options can be considered for the Constellations Trade Off:
  - Satellite number
  - Satellite Ascending Node (Ω) separation and distribution
  - Satellite True Anomaly (θ) separation and distribution

For the sake of clarity it must be stressed that some requirements during the WATS phase A study (see RD 3) had ben traslated into index that had to be made as high as possible. One of them is the number of occultations. It can be seen at page 64 figure 6.3 of RD 3 that the number of LEO-LEO occultation events is far less than 1600. So we can say that the requirement on number of occultations is not a "Must" to be reached at any cost.

2.2.1.3 Constellation Example

The following constellation parameters are of a Constellation Example. They had been taken from RD 7. This constellation example has been computed just to show how the event ground tracks distribution is in the case of a constellation of four satellites (2 + 2).

Number of Spacecraft	2	2
Number of planes	1	1
Altitude of operational orbit	650 km	850 km
Inclination of operational orbit	90 °	90 °
Orbit Eccentricity	0	0
Ascending Node of operational orbits	0 °	180 °
Ascending Node orbit plane separation	180 °	
Mean anomaly of satellite	0 °, 90 °	180 °, 270 °
Satellite Separation in Mean Anomaly	90 °	90 °

Table 2.2-1: Constellation example parameters

This constellation example has a very good spatial occultation distribution and a good number of events (≈ 200). This constellation is an example of optimised constellation. In fact, it gives as many occultations as possible with as minimum number of satellite as possible.

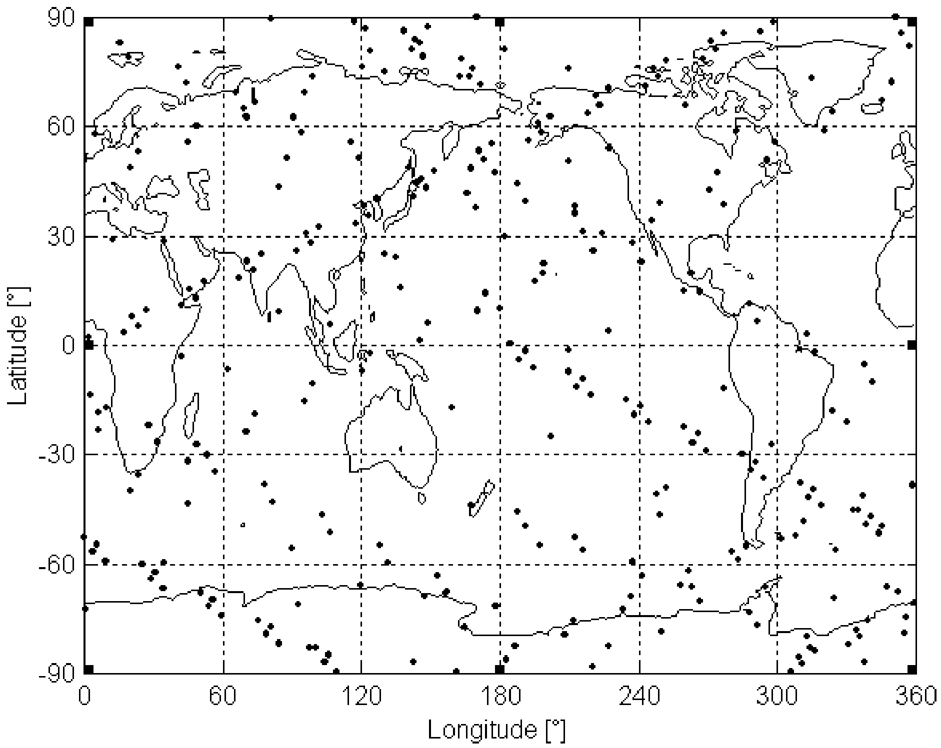


Figure 2.2-3: Event Ground Tracks for the Orbit Constellation Example

2.2.2 Power Subsystem

The scope of the Power Sub-system design is to size the solar array area and mass and to size the battery volume and mass.

2.2.2.1 Power theory and characteristics

The Power subsystem is defined by means of the following parameters and computations:

Description	Unit
Solar Array Specific Power Area	W/m²
Solar Array Specific Power Mass	W/kg
Battery Specific Energy Mass	W·h/kg
Battery Specific Energy Volume	W·h/l
Orbital Period	h
Eclipse Period	h
Day Light Period	h
Solar Aspect aNgle	°

Table 2.2-2 Power sizing parameters

- From the power budget the Power Need (*PN*) from P/L and S/S is determined: *PN* [W]
- From the Eclipse Period (*EP*) and *PN* the Battery Energy Need (*BEN*) is determined:

(5) $$BEN = PN \cdot EP \ \mathbf{[W{\cdot}h]}$$

- From Day Light Period (*DLP*) and *BEN* the Power Need for Battery Charging is determined (*PNBC*):

(6) $$PNBC = \frac{BEN}{DLP} \ \mathbf{[W]}$$

- From *PN*, *PNBC* and Solar aspect ANgle (*SAN*) the Total Power Need (*TPN*) is determined:

(7) $$TPN = \frac{PN + PNBC}{\cos\left(SAN \cdot \frac{\pi}{180}\right)} \ \mathbf{[W]}$$

- Once *TPN* and *BEN* are known, using the Specific Power and Energy parameters, the Solar Array area and mass and the Battery Volume and Energy are determined.

In following table the characteristics of some cells (solar panel and battery) are listed.

Single Junction GaAs (S_j)	180 [$W\cdot m^{-2}$]	38 [$W\cdot kg^{-1}$]	Solar Panel
Multi Junction GaAs (M_j)	250 [$W\cdot m^{-2}$]	70 [$W\cdot kg^{-1}$]	Solar Panel
NiH_2	55 [$W\cdot kg^{-1}$]	60 [$W\cdot l^{-1}$]	Battery
Li-Ion	150 [$W\cdot kg^{-1}$]	399 [$W\cdot l^{-1}$]	Battery

Table 2.2-3 Characteristics of some cells (Solar Panel & Battery)

2.2.2.2 Power Trade-offs

The following options can be considered for the Power Trade-offs:

- Option 1:
    - Solar Array Cell: Single Junction Gallium Arsenide
    - Battery Cell: Nickel hydrogen

- Option 2:
    - Solar Array Cell: Multiple-junction Gallium Arsenide
    - Battery Cell: Litium-Ion

In order to minimise the:

- The Solar Panel Area and Mass
- The Battery Volume and Mass

2.2.3 Propulsion Subsystem

The scope of the propulsion subsystem design is to size propellant mass and the propellant tank's mass and diameter.

2.2.3.1 Propulsion Theory and Characteristics

The Propulsion Subsystem is defined starting with the determination of the total variation of velocity ΔV [$m \cdot s^{-1}$]. The propellant mass m_p [kg] is computed from:

$$\textbf{(8)} \qquad m_p = m_f \cdot \left[e^{\left(\frac{\Delta V}{I_{sp} \cdot g}\right)} - 1 \right] = m_o \cdot \left[1 - e^{-\left(\frac{\Delta V}{I_{sp} \cdot g}\right)} \right]$$

where m_f [kg] is the final mass and m_o [kg] is the initial mass (w.r.t. the variation of velocity, i.e. the manoeuvre), I_{sp} [s] is the specific impulse of the propellant and g=9.80665 ms^{-2}.

Once the propellant mass has been computed the volume V_T [litres] and diameter D_T [m] of the tank can be obtained from:

- Monopropellant

$$\textbf{(9)} \qquad V_T = \frac{m_p}{\rho_p} \ \textbf{and} \ D_T = 2 \cdot \sqrt[3]{\frac{3}{4 \cdot \pi} \cdot V_T \cdot 10^{-3}}$$

where ρ_p [$g \cdot cm^{-3}$]=[$kg \cdot liter^{-1}$] is the density of the propellant.

- Bipropellant

$$\textbf{(10)} \quad V_T = \frac{m_p}{\rho_1 + \rho_2} \ \textbf{and} \ D_T = 2 \cdot \sqrt[3]{\frac{3}{4 \cdot \pi} \cdot \frac{V_T}{nT} \cdot 10^{-3}}$$

where ρ_1 and ρ_2 are the density of the fuel and of the oxidiser and nT is the number of tanks ($\geq$ 2). Previous equations are valid under the realistic assumption that the volume of the tanks is the same for both of them. In fact from $\rho_1 \cdot V_1 + \rho_2 \cdot V_2 = m_p$ with $V_1 = V_2 = V_T$ it follows **10** and that $m_1 = \rho_1 \cdot V_T$ and $m_2 = \rho_2 \cdot V_T$.

In following table the characteristics of some propellant are listed.

Type	Propellant	Isp [s]	Density [$g \cdot cm^{-3}$]
Monopropellant	N_2H_4	150-225	1.0
Bipropellant	N_2O_4 and MMH	300-340	1.43 and 0.86

Table 2.2-4 Characteristics of some propellant

The tank mass m_T [kg] can be obtained from:

$$\textbf{(11)} \qquad m_T = 0.1 \cdot m_P$$

For a complete design of the propulsion subsystem, the propellant mass m_{attman} [kg] needed for attitude manoeuvres must be computed. That is:

$$\textbf{(12)} \qquad m_{attman} = \frac{4 \cdot I_C \cdot \Theta_m}{T \cdot L_t \cdot g \cdot I_{sp}}$$

where Θ_m is the angle [radians] swept in time T [sec], I_C [kg·m²] is the Spacecraft moment of inertia about the control axis and L_t [m] the truster lever arm about this axis.

2.2.3.2 Propulsion Trade-offs

The following options can be considered for the Propulsion Trade-offs:

- Option 1:
  - Monopropellant
- Option 2:
  - Bipropellant

In order to minimise the:

- The Propellant Mass
- The Tank's Volume and Mass

2.2.4 Spacecraft Configuration and Pointing Strategy

The scope of the Spacecraft configuration and pointing strategy is to find the best layout of Satellite Sub-system and the best pointing strategy with respect to the total system resources.

The following topics are related to the S/C Configuration:

- Interplay between number of antennae and solar panel area and mass
- Interplay between number of antennae and fuel mass
- Interplay between fuel mass and solar panel area and mass
- System Budgets: Mass, Power and Volume

Two main options can be considered for Pointing Strategy:

- Option 1:
  - Earth Pointing

- Option 2:
  - Sun Pointing

In 2.2.4.1 two configurations example are shown. From Figure 2.2-4 and Figure 2.2-5 it is possible to see the interplay between the number of antenna and the solar panel area and mass. In Earth Pointing Configuration the number of antennae is minimum (6) and the number of solar panels is maximum (6); while, on the other hand in Sun Pointing Configuration the number of antennae is maximum (24) and the number of solar panels is minimum (2).

The remaining inter-plays and the System Budgets consideration can not be shown so easily with an example. They are exploited in the overall analysis and summarised in 2.3.3.

2.2.4.1 S/C Configurations Example

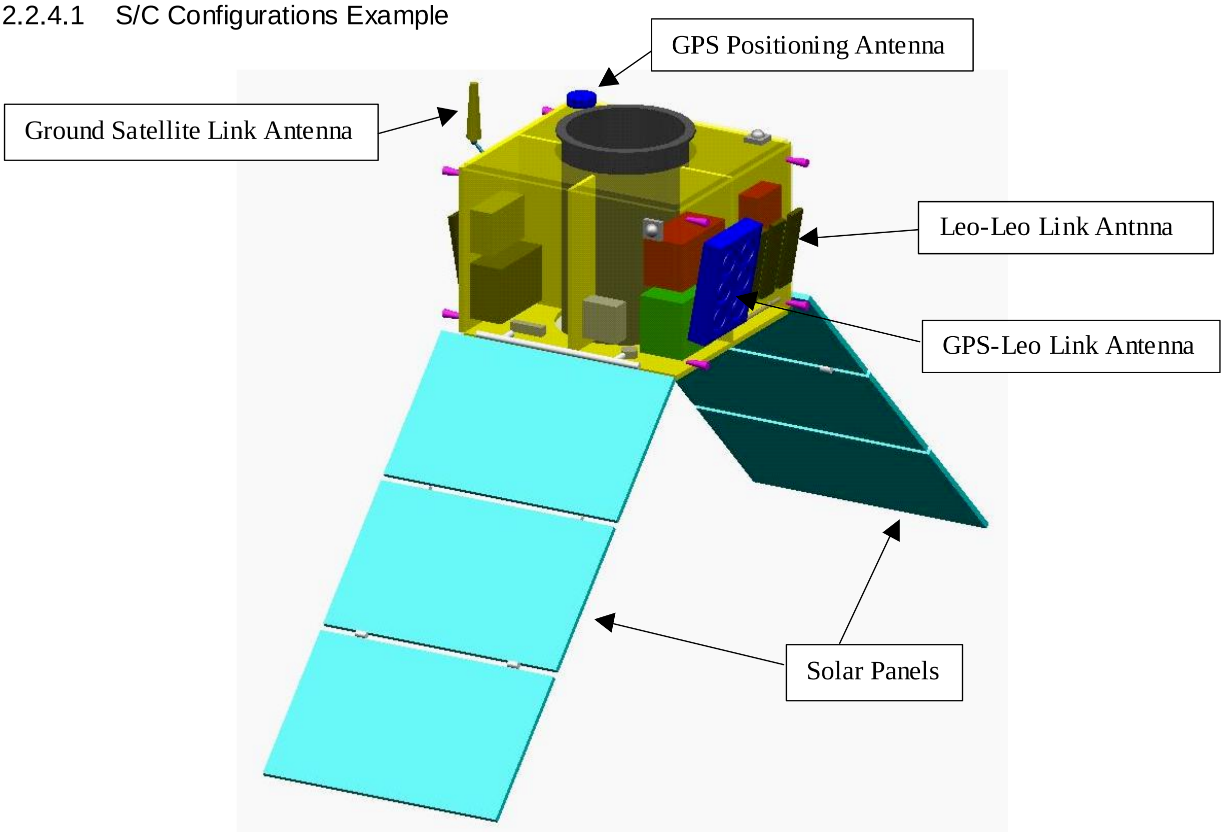


Figure 2.2-4 Earth Pointing configuration Example

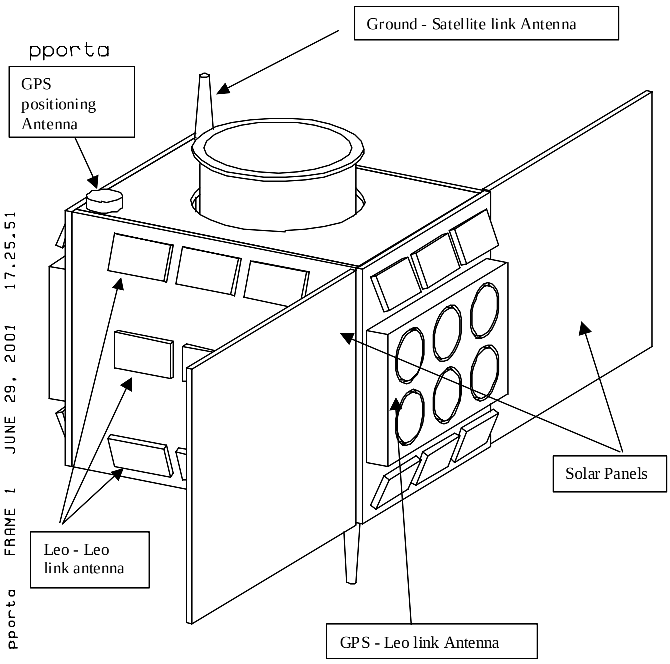


Figure 2.2-5 Sun Pointing Configuration Example

2.2.5 Launcher Selection and Launch Strategy

The scope of Launcher Selection and Launch Strategy is to find a suitable launcher in order to optimise the number of launches for the selected constellation deployment.

The following topics are related to the Launcher and Launch Strategy:

- minimum number of launches w.r.t. propellant need for constellation deployment

In order to minimise the number of launches the technique of using differential precession between orbits with different altitudes must be used for constellation deployment. This technique is used in order to phase the satellite in ascending node separation. The technique consists in launching clusters of satellite on a parking orbit. From that orbit, first of all, a satellite goes, with its own propulsion, to the nominal orbit; while, the other satellite of the cluster wait on parking orbit till the right ascending node separation had been reached. This, of course, costs because of the drag compensation needed on parking orbit. After the right ascending node separation had been reached each satellite by each goes to the nominal orbit with its own propulsion.

That is why, in order to optimise the number of launches, the time ΔT [day] needed to reach the desired Ascending Node Separation $\Delta\Omega$ [°] (see RD 8) among satellite's orbit planes has to be computed. For circular orbit (e = 0, see RD 8) it is obtained from:

(13) $$\Delta T \cong \frac{\Delta\Omega}{-2.06474\times10^{14}\cdot\left[a_P^{-\frac{7}{2}} - a_N^{-\frac{7}{2}}\right]\cdot\cos\left(I\cdot\frac{\pi}{180}\right)}$$

where a_P [km] is the positive axis of the Parking orbit, a_N [km] is the positive axis of the Nominal orbit, I [°] is the inclination of the orbit planes and $\Delta\Omega = \Omega_P - \Omega_N$ is the desired difference between the ascending node of the parking orbit and the ascending node of the nominal orbit (see RD 8). In order to compute the propellant need for constellation deployment the variation of velocity ΔV_D [km·s^{-1}] per orbit to compensate the orbit decay due to Drag force on parking orbit and the variation of velocity ΔV_T [km·s^{-1}] to reach the operational orbit had to be evaluated. They are obtained from:

(14) $$\Delta V_D = \pi\cdot\left(C_D\cdot\frac{A}{m}\right)\cdot\rho\cdot a\cdot V$$

where A [m²] is the satellite cross-sectional area, m [kg] is the satellite mass, ρ [g·m^{-3}] is the atmospheric density, a [km] is the positive axis and $V = 631.34812\cdot a^{-\frac{1}{2}}$ [km·s^{-1}] is the satellite circular velocity and

(15) $$\Delta V_T = \sqrt{\frac{\mu}{r_P}}\cdot\left[\sqrt{\frac{2\cdot\frac{r_N}{r_P}}{1+\frac{r_N}{r_P}}}\cdot\left(1-\frac{r_P}{r_N}\right)+\sqrt{\frac{r_P}{r_N}}-1\right]$$

where r_P [km] and r_N [km] are the radius of the parking and nominal circular orbit and $\mu = 3.986005\times10^{5}$ [km^3·s^{-2}] is the Earth Gravitational Parameter.

In the following table a list of possible launchers is shown.

Launcher	Fairing				Mech. requirements				P/L mass [kg] to 90° @ 850 km	P/L mass [kg] to SSO @ 850 km	Cost [M$]
					Dynamic		QSL				
	Cylind. φ [mm]	Cylind. height [mm]	Conical φup [mm]	Conical height [mm]	Lateral [Hz]	Axial [Hz]	Lateral [g]	Axial [g]			
Rockot	~ 2100	3511	410	2424	15	33	0.9	8.1	~ 800	~ 1000	14-15
Dnjepr	~ 2000	2500	410	1500	10	20	1	8.3	~ 400	TBD	10-20
Cosmos	2400	2673	316	2864	10	25	1.6	6.8	~ 700	700	9-13
Taurus XLS	2055	3310	488	2400	25	35 ÷ 45	2.5	8	~ 750	~ 700	20-25
PSLV	2900	3100	800	2700	N/A	N/A	N/A	N/A	~ 1000	TBD	20-25
Athena 2 (LMLV2)	1984	1781	909	2002	12	30	2.5	8	1100	~ 1000	22-26
Tzyklon (Cyclone)	2420	3400	400	2500	N/A	N/A	1.4	10	~ 1500	TBD	20-25

Table 2.2-5 List of Possible Launchers

- One option can be considered for Launcher Selection and Launch Strategy:
  - to lower as much as possible the number of launches and to rise as much as possible the number of satellite

2.2.5.1 Launch Configuration Example

An example of launch configuration is reported here below. Where a stack of three satellite (≈ 250 kg each) is hosted within the Eurokot fairing.

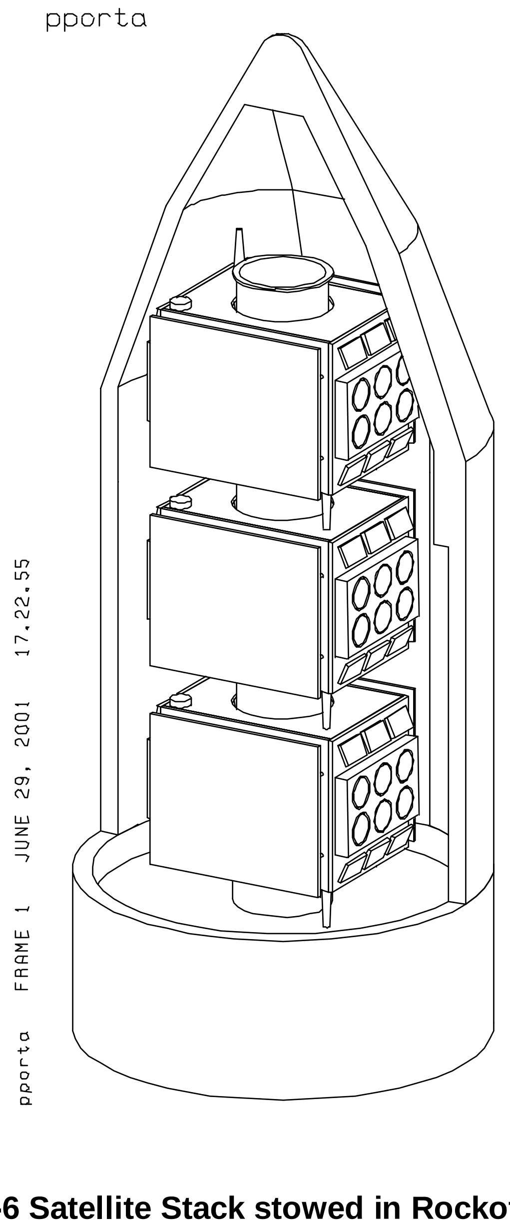


Figure 2.2-6 Satellite Stack stowed in Rockot Launcher

2.3 WORK BENCH

The Work Bench is the full set of analysis outputs (computer runs, equations calculations and budget set up) needed to support the looking for an optimised solution finding the best compromise among the conflicts listed on page 11.

2.3.1 Constellation Analysis and Trade-offs

In order to find an optimised constellation (see 2.2.1.2) a set of constellations had been studied with number of satellite starting from 4 and reaching 16, with a step of 4. For each constellation an uniform distribution of Ω and ϑ had been studied within the following interval $\Omega \in [0°, 360°]$ and $\theta \in [0°, 360°]$. As already said in 2.2.1.2 the other parameters of the constellation had been fixed for the sake of simplicity without loosing reality of the found conflicts.

The complete results of the set of constellation are in 2.3.1.1, 2.3.1.2, 2.3.1.3 and 2.3.1.4. In Table 2.3-1, it is summarised the number of events as a function of the number of satellite.

Number of events	Number of satellite
93	4
410	8
1142	12
2029	16

Table 2.3-1 Number of Events w.r.t. Number of Satellite for the set of constellation

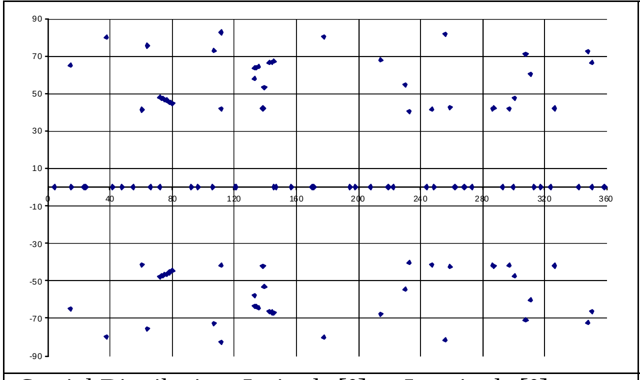
From Table 2.3-1, it is possible to see that the requirement of number of events (≥ 1600) is met for a number of satellite between 12 and 16. As we already know that it will be difficult (see 2.3.2 and 2.3.3) to deploy a constellation of more than 12 satellite both by the point of view of constellation deployment and overall mission complexity; an attempt to rise the number of events, for the constellation of 12 satellite, tuning (optimising) the Ω and ϑ distribution had been done. The complete results of this optimisation are given in 2.3.1.5. For what regarding the number of events, it had been found that with an optimised distribution of Ω and ϑ the 12 satellite constellation rises it from 1142 up to 1281. As the requirement of number of events ≥ 1600 is not a "Must" (see 2.2.1.2) to be reached at any cost, the optimised constellation of 12 satellites can be considered the baseline for the remaining trade offs to be solved at spacecraft and launcher level. What is important to be noticed, in the optimised constellation of 12 satellites, it is that $\Delta\Omega_{ij}$, between the satellite "i" and the satellite "j" with same altitude, is 30° (see 2.3.1.5).

2.3.1.1 Number of Satellite: 4

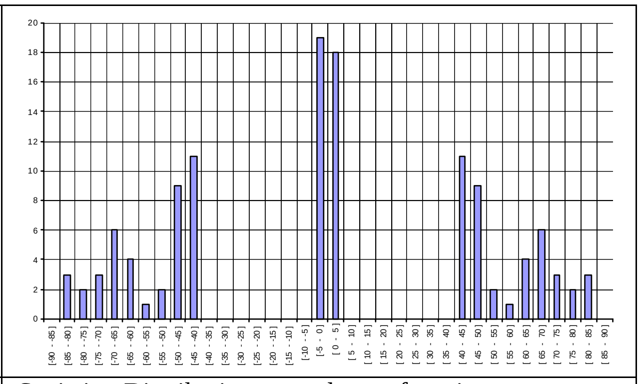
Input:

2 Satellite with following orbital parameters: H = 650 km, I = 95°: Ω = 0°, 180° and θ = 0°, 180°
2 Satellite with following orbital parameters: H = 850 km, I = 70°: Ω = 90°, 270° and θ = 90°, 270°

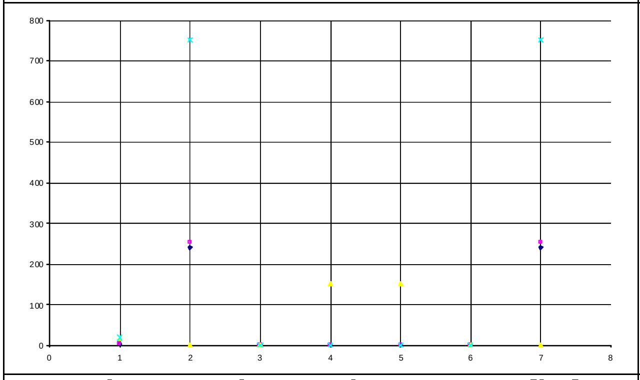
Output:



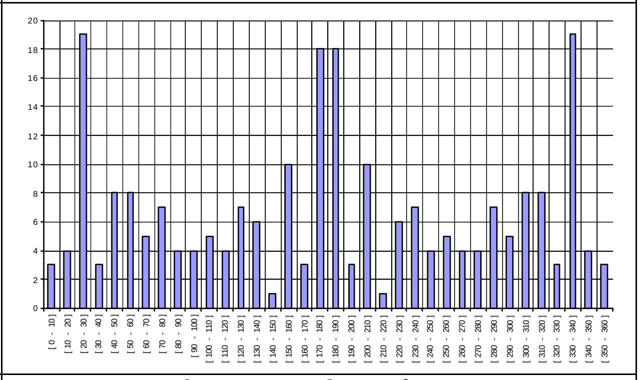
Spatial Distribution: Latitude [°] vs Longitude [°]



Statistic Distribution: number of point events vs Latitude [°]



Maximal Horizontal Atmospheric Domain [km] vs Time [hours]



Statistic Distribution: number of point events vs Azimuth [°]

Figure 2.3-1 Constellation parameter evolution for 4 satellites

number of Events: 93

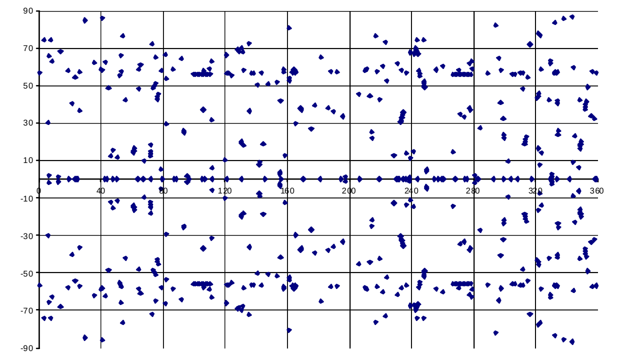
2.3.1.2 Number of Satellite: 8

Input:

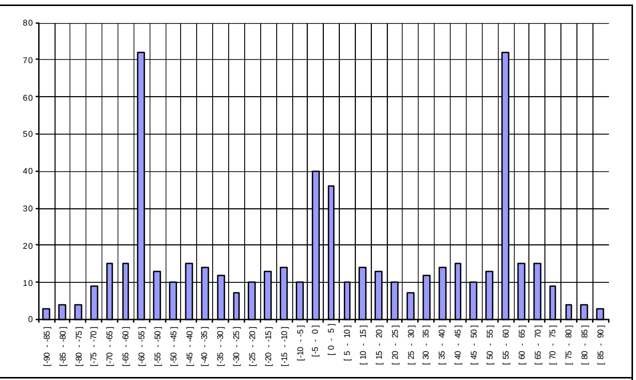
4 Satellite with following orbital parameters:
H = 650 km, I = 95°: Ω = 0°, 90°, 180°, 270° and θ = 0°, 90°, 180°, 270°

4 Satellite with following orbital parameters:
H = 850 km, I = 70°: Ω = 45°, 135°, 225°, 315° and θ = 45°, 135°, 225°, 315°

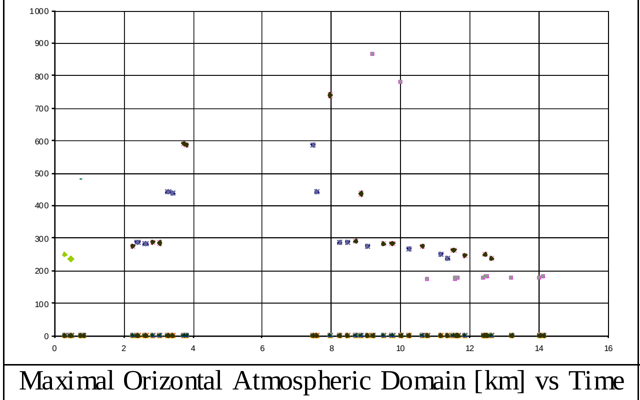
Output:



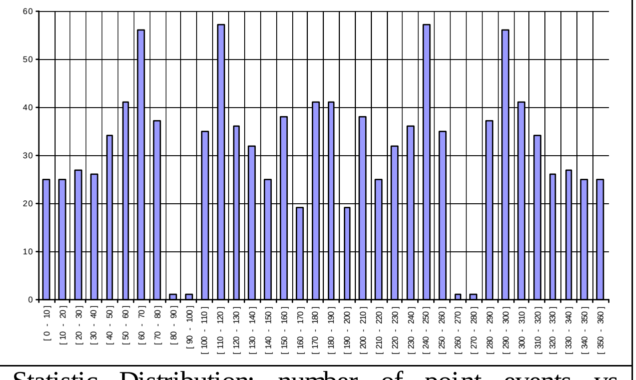
Spatial Distribution: Latitude [°] vs Longitude [°]



Statistic Distribution: number of point events vs Latitude [°]



Maximal Orizontal Atmospheric Domain [km] vs Time [hours]



Statistic Distribution: number of point events vs Azimuth [°]

Figure 2.3-2 Constellation parameter evolution for 8 satellites

number of Events: 410

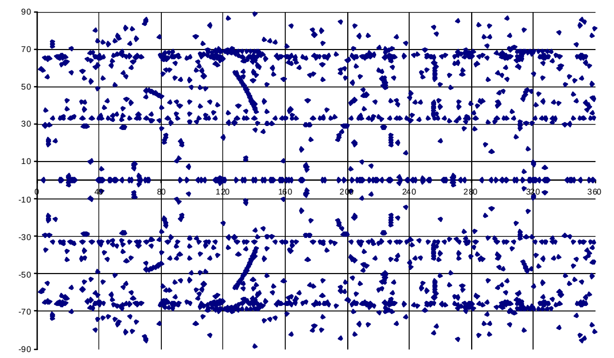
2.3.1.3 Number of Satellite: 12

Input:

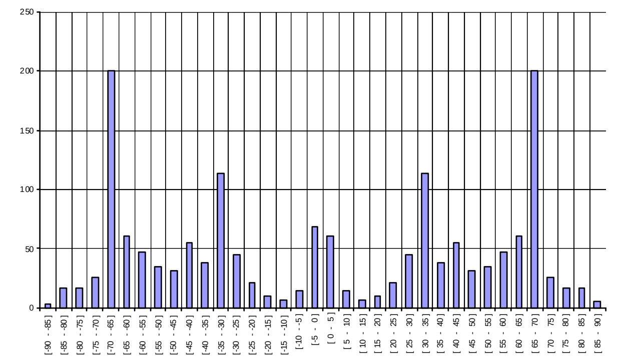
6 Satellite with following orbital parameters:
H = 650 km, I = 95°: Ω = 0°, 60°, 120°, 180°, 240°, 300° and θ = 0°, 60°, 120°, 180°, 240°, 300°

6 Satellite with following orbital parameters:
H = 850 km, I = 70°: Ω = 30°, 90°, 150°, 210°, 270°, 330° and θ = 30°, 90°, 150°, 210°, 270°, 330°

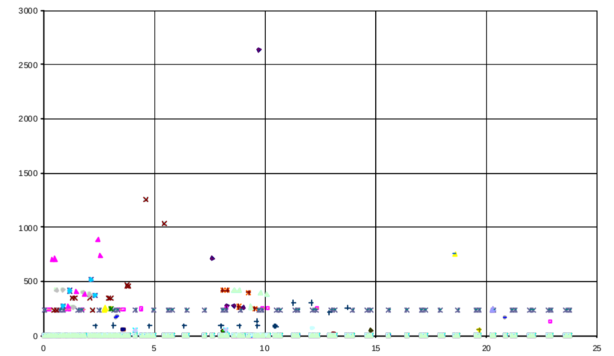
Output:



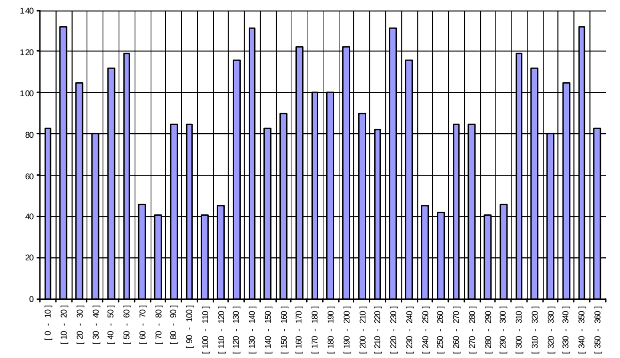
Spatial Distribution: Latitude [°] vs Longitude [°]



Statistic Distribution: number of point events vs Latitude [°]



Maximal Orizontal Atmospheric Domain [km] vs Time [hours]



Statistic Distribution: number of point events vs Azimuth [°]

Figure 2.3-3 Constellation parameter evolution for 12 satellites

number of Events: 1142

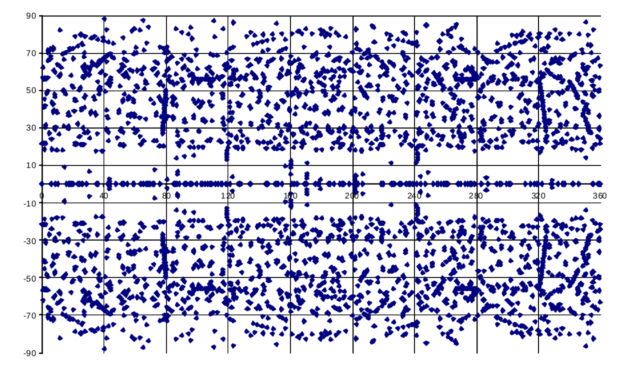
2.3.1.4 Number of Satellite: 16

Input:

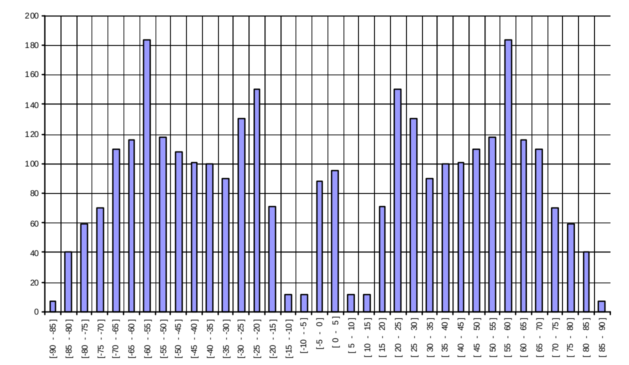
8 Satellite with following orbital parameters:
H = 650 km, I = 95°: Ω = 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° and
θ = 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°

8 Satellite with following orbital parameters:
H = 850 km, I = 70°: Ω = 22.5°, 67.5°, 112.5°, 157.5°, 202.5°, 247.5°, 292.5°, 337.5° and
θ = 22.5°, 67.5°, 112.5°, 157.5°, 202.5°, 247.5°, 292.5°, 337.5°

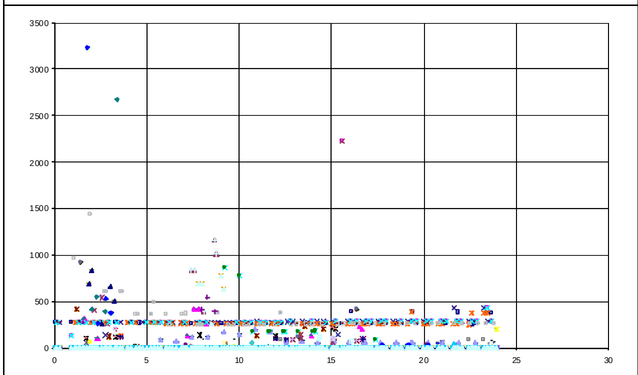
Output:



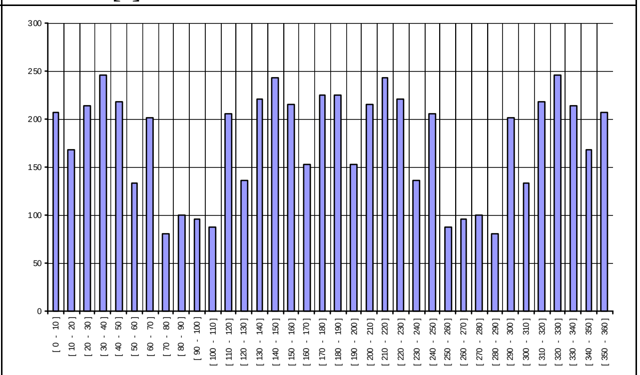
Spatial Distribution: Latitude [°] vs Longitude [°]



Statistic Distribution: number of point events vs Latitude [°]



Maximal Orizontal Atmospheric Domain [km] vs Time [hours]



Statistic Distribution: number of point events vs Azimuth [°]

Figure 2.3-4 Constellation parameter evolution for 16 satellites

number of Events: 2029

2.3.1.5 12 Satellite optimised constellation

Input:

6 Satellite with following orbital parameters:
H = 650 km, I = 95°: Ω = 0°, 30°, 60°, 90°, 120°, 150° and θ = 0°, 60°, 0°, 30°, 30°, 0°

6 Satellite with following orbital parameters:
H = 850 km, I = 70°: Ω = 15°, 45°, 75°, 105°, 135°, 165° and θ = 30°, 30°, 0°, 60°, 0°, 30°

Output:

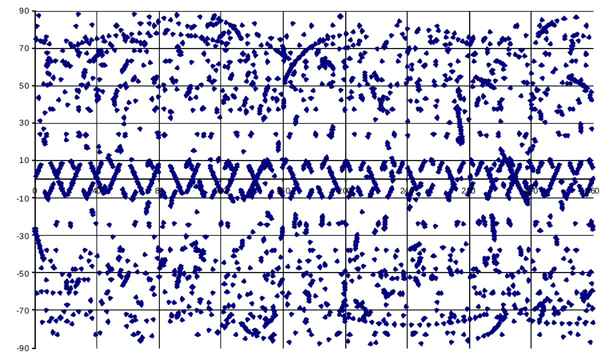
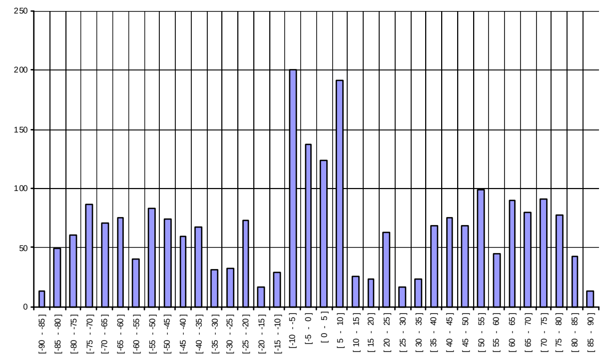
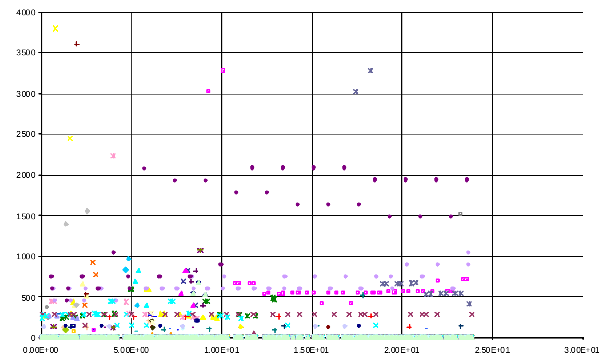
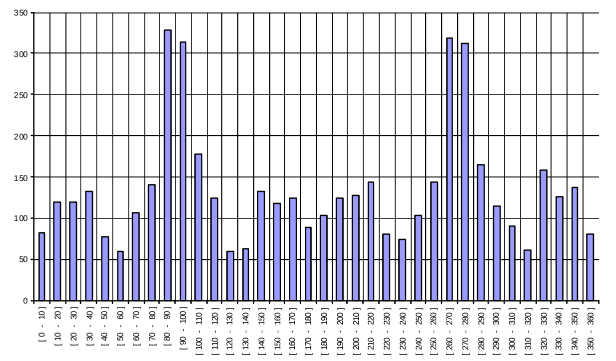
	
Spatial Distribution: Latitude [°] vs Longitude [°]	Statistic Distribution: number of point events vs Latitude [°]
	
Maximal Orizontal Atmospheric Domain [km] vs Time [hours]	Statistic Distribution: number of point events vs Azimuth [°]

Figure 2.3-5 Optimised constellation parameter evolution for 12 satellites

number of Events: 1281

2.3.2 Constellation Deployment and Trade-offs

As already explained in 2.2.5, for constellation deployment, the need of defining a parking orbit altitude arises. The parking orbit altitude should be as lower as possible with respect to the Nominal orbit altitude (H_N = 650 ÷ 850 km). This would be helpful in order to lower as much as possible the time to be waited for reaching the desired ascending node separation about orbital plane of different satellites flying at the same altitude.

In any case, the parking orbit altitude can not be too lower otherwise the fuel need to counteract drag decay can became unfeasible. It must be stressed that there is no requirement on maximum deployment time of the constellation. In any case it is wise to make it as short as possible with respect to the overall constellation deployment cost.

Two Parking orbit altitudes had been studied. Detailed results about parking orbit altitude are in 2.3.2.1 and 2.3.2.2.

Taking into account the optimised constellation in 2.3.1.5 and the desired ascending node separation among orbital planes of 30°, the parking orbit with 400 km of altitude (in 2.3.2.2) is the optimised one by the point of view of Time to wait on Parking orbit, ΔV and Propellant Mass budget. In fact with 200 km of altitude (in 2.3.2.1) the time to wait would be halved but a look at the ΔV (see
Figure 2.3-7) shows that the 200 km parking orbit is unfeasible.

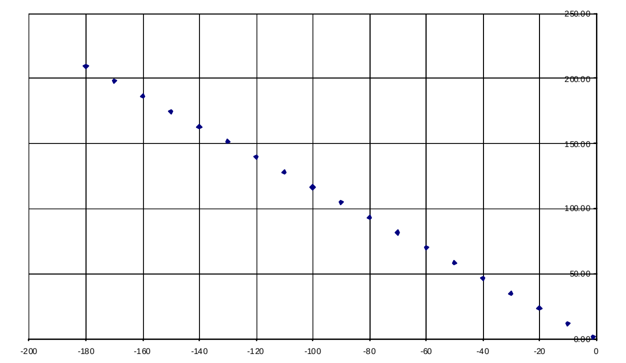
Taking into account the optimised constellation in 2.3.1.5 the desired ascending node separation among orbital planes of 30° can be reached with four launches of three satellite per launch, using an altitude of parking orbit of 400 km. In fact a waiting time of about 2 years is needed to reach an ascending node separation of 60° between the first satellite on nominal orbit and the third satellite on nominal orbit for H = 650 km & I = 95° (see Figure 2.3-10); while, the ΔV (see Figure 2.3-11) is feasible.

This, in turn, leads to either a Monopropellant mass of about 50 kg or a bipropellant mass of about 24 kg (see
Figure 2.3-12) and to either a monopropellant Tank diameter of about 46 cm or a bipropellant Tank diameter of about 21 cm (see
Figure 2.3-14).

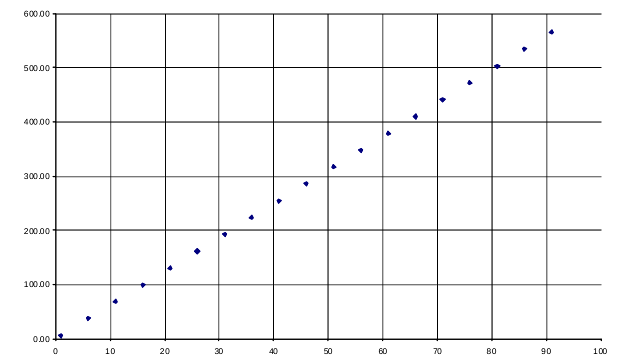
It must be underlined that the fuel mass and tank diameter, given above, take into account both the ΔV needed to reach operative orbit and ΔV for Drag compensation.

2.3.2.1 Parking Orbit Altitude: H = 200 km

$\Delta V = 0.36\ km \cdot s^{-1}$ to reach H = 850 km from parking orbit
$\Delta V = 0.25\ km \cdot s^{-1}$ to reach H = 650 km from parking orbit

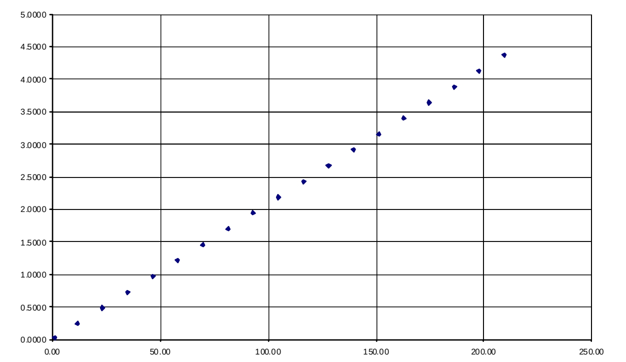


ΔT [days] vs $\Delta\Omega$ [°] for H = 850 km & I = 70 °

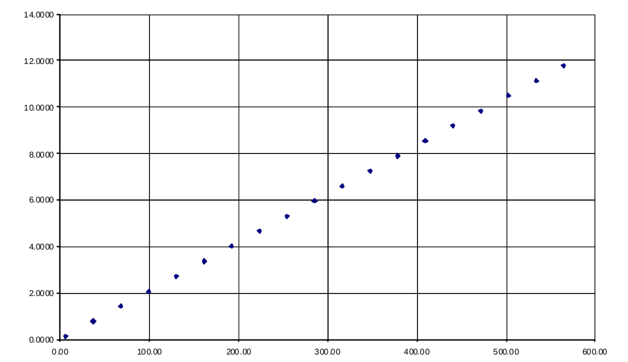


ΔT [days] vs $\Delta\Omega$ [°] for H = 650 km & I = 95 °

Figure 2.3-6 Time to wait (ΔT) to reach Ascending Node separation between Parking orbit and Nominal orbit

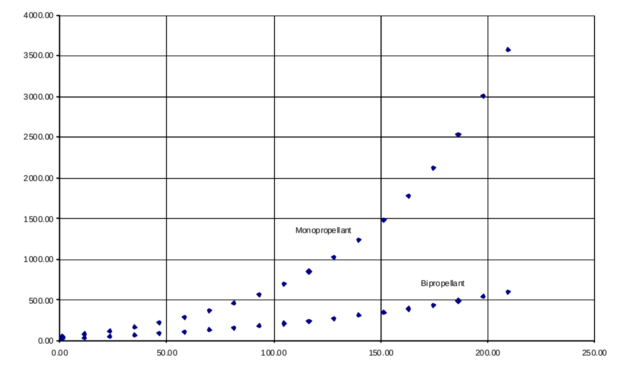


ΔV [$km \cdot s^{-1}$] vs ΔT [days] for H = 850 km & I = 70 °

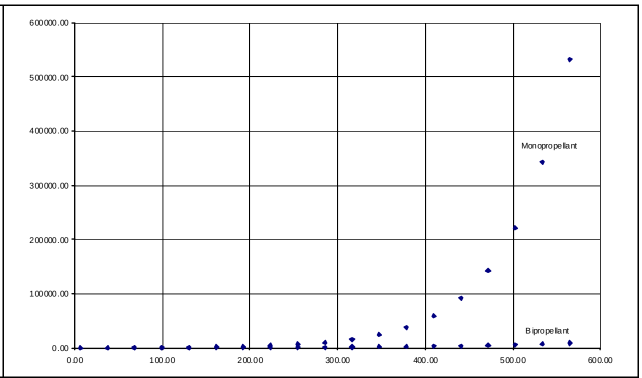


ΔV [$km \cdot s^{-1}$] vs ΔT [days] for H = 650 km & I = 95 °

Figure 2.3-7 ΔV to compensate Drag Force on Parking Orbit

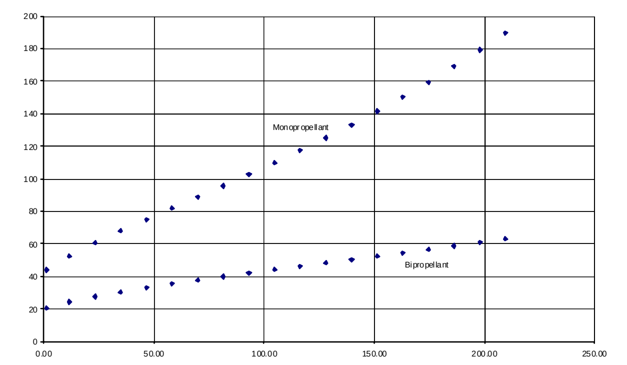


M_P [kg] vs ΔT [days] for H = 850 km & I = 70 °

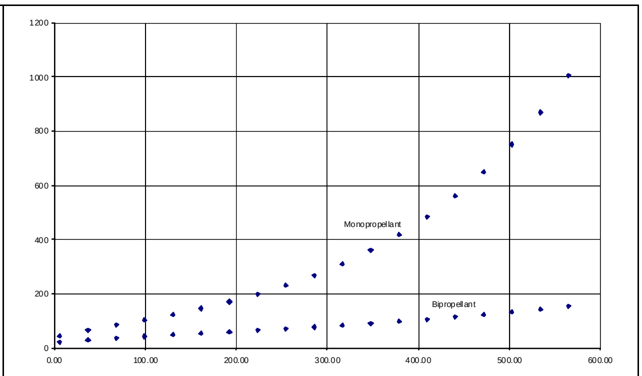


M_P [kg] vs ΔT [days] for H = 650 km & I = 95 °

Figure 2.3-8 Propellant Mass (M_P) to compensate Drag Force on Parking Orbit and to reach Nominal orbit



D_T [cm] vs ΔT [days] for H = 850 km & I = 70 °

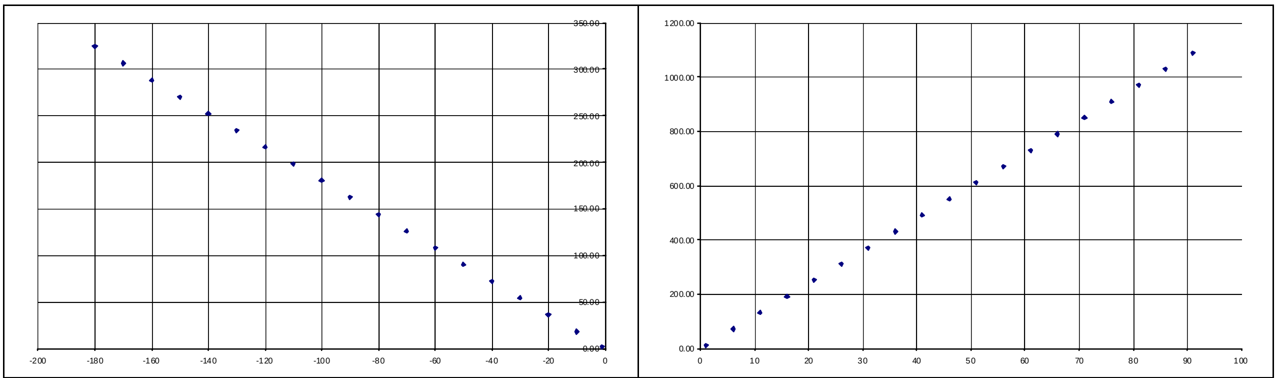


D_T [cm] vs ΔT [days] for H = 650 km & I = 95 °

Figure 2.3-9 Tank Diameter (D_T) to compensate Drag Force on Parking Orbit and to reach Nominal orbit

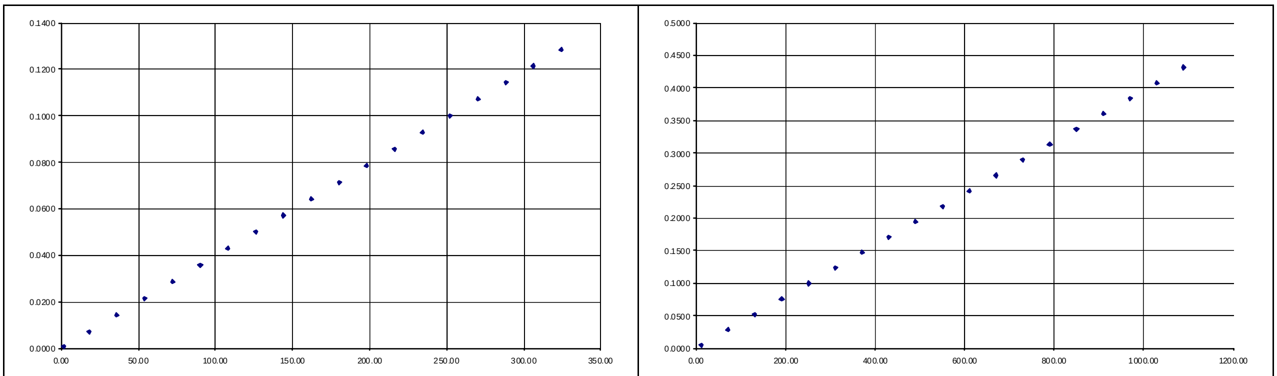
2.3.2.2 Parking Orbit Altitude: H = 400 km

$\Delta V = 0.24\ km \cdot s^{-1}$ to reach H = 850 km from parking orbit
$\Delta V = 0.14\ km \cdot s^{-1}$ to reach H = 650 km from parking orbit



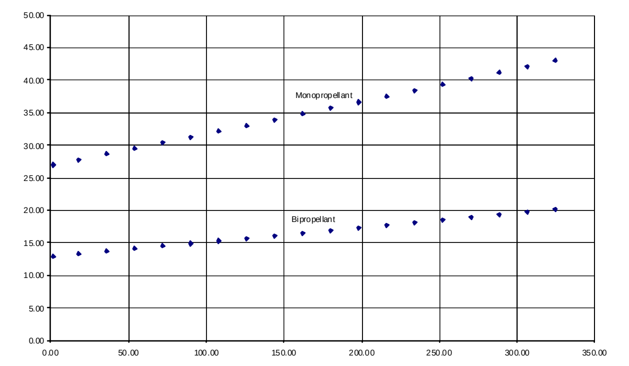
ΔT [days] vs $\Delta\Omega$ [°] for H = 850 km & I = 70 °	ΔT [days] vs $\Delta\Omega$ [°] for H = 650 km & I = 95 °

Figure 2.3-10 Time to wait (ΔT) to reach Aschending Node separation between Parking orbit and Nominal orbit

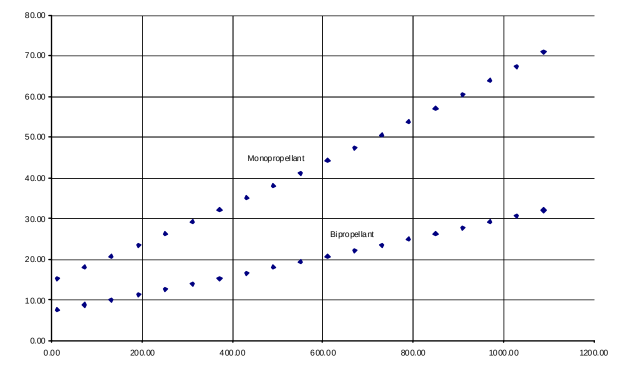


ΔV [$km \cdot s^{-1}$] vs ΔT [days] for H = 850 km & I = 70 °	ΔV [$km \cdot s^{-1}$] vs ΔT [days] for H = 650 km & I = 95 °

Figure 2.3-11 ΔV to compensate Drag Force on Parking Orbit

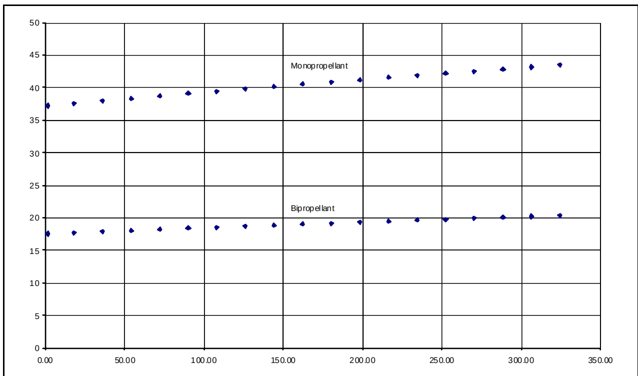


M_P [kg] vs ΔT [days] for H = 850 km & I = 70 °

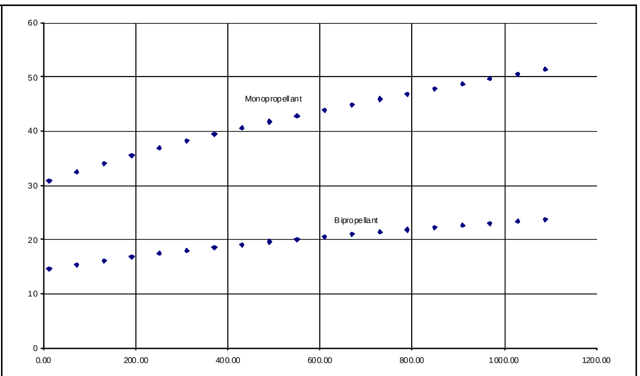


M_P [kg] vs ΔT [days] for H = 650 km & I = 95 °

Figure 2.3-12 Propellant Mass (M_P) to compensate Drag Force on Parking Orbit and to reach Nominal orbit



D_T [cm] vs ΔT [days] for H = 850 km & I = 70 °



D_T [cm] vs ΔT [days] for H = 650 km & I = 95 °

Figure 2.3-13 Tank Diameter (D_T) to compensate Drag Force on Parking Orbit and to reach Nominal orbit

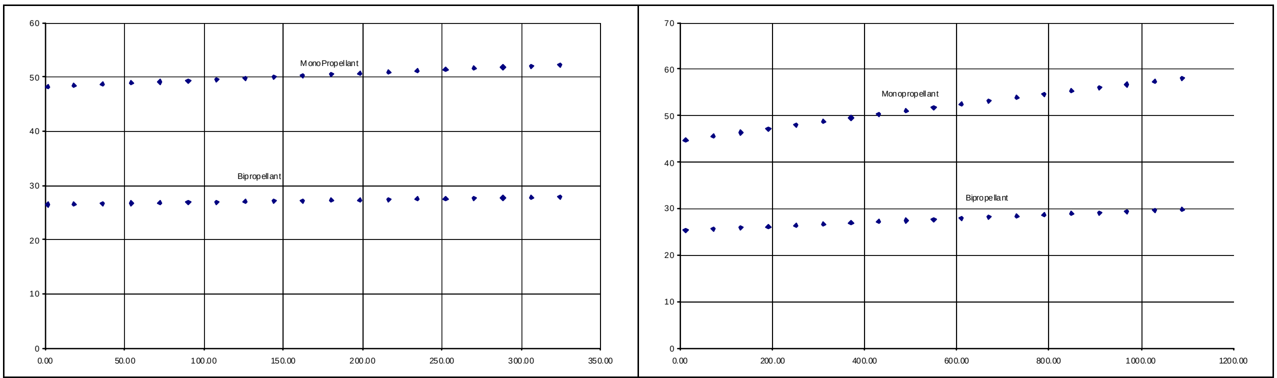
2.3.2.3 Propellant Mass for Attitude Manoeuvres

As already said in 2.2.3.1, depending on the Spacecraft configuration and pointing strategy (see 2.2.4), the need of computing the fuel mass for attitude manoeuvre can arise. In order to do this, some assumptions had to be done on the spacecraft characteristics and attitude manoeuvre characteristics.

The Propellant Mass for attitude manoeuvres with a space craft (S/C) having moment of inertia 70 kg·m², thruster lever arm 0.5 m and for 2 slew manoeuvres of 45° per orbit per 7 years of life time and lasting (2 x Start ÷ Stop) 2 x 720 sec, is:

$M_{attMan} = 31.50$ kg

The propellant mass for attitude manoeuvres has to be added to the propellant mass for orbital manoeuvres. This leads to more propellant mass to be considered in the system mass budgets and to a larger tank with the following diameter vs time to wait and for the 400 km parking orbit.



D_T [cm] vs ΔT [days] for H = 850 km & I = 70 ° | D_T [cm] vs ΔT [days] for H = 650 km & I = 95 °

Figure 2.3-14 Tank Diameter (D_T) to compensate Drag Force on Parking Orbit, to reach Nominal orbit and for Attitude manoeuvres

2.3.3 Spacecraft Configuration, Pointing Strategy and Trade-offs

Mission analysis output is that a constellation deployment with four launches of three satellite is quite feasible (see 2.3.2). This, in turn, leads to the attempt to limit the overall satellite mass either within 250 kg if a Rockot class launcher will be used or within 450 kg if a Tzyklon class launcher will be used (see Table 2.2-5). As first shot the Rockot launcher will be taken into account for the sake of lower cost. In the following trade-offs, it will exploited the attempt to have P/L, Power Subsystem and Propulsion Subsystem as simpler and as lighter as possible.

The following tasks will be considered:

- P/L:
  - (best) 1 receiver and not more than 6 antennae
  - (good) 1 receiver and 12 antennae (in order to have a 360° of azimuth coverage)
  - (worst) 3 receivers and 36 antennae (in order to have 360° of azimuth and ±90° of elevation coverage).
- Power subsystem:
  - (best) to have a Sun pointing configuration
  - (good) to have an Earth pointing configuration
  - (worst) to have an Earth pointing configuration with attitude manoeuvres.
- Propulsion Subsystem:
  - (best) to have an Earth Pointing configuration
  - (good) to have a Sun pointing configuration
  - (worst) to have an Earth pointing configuration with attitude manoeuvres.

2.3.3.1 Earth Pointing versus Sun Pointing

It must be noticed that with:

- Sun pointing configuration:
  - P/L must have 3 receivers and 36 antennae
  - Power Subsystem must cope with a higher power peak from P/L that will be charged on the battery
  - Propulsion subsystem must hold the propellant for orbital manoeuvres.
- Earth pointing configuration:
  - P/L must have 1 receiver and 12 antennae
  - Power Subsystem (Solar Array) must cope with a larger Solar aspect ANgle (SAN = 45°)
  - Propulsion subsystem must hold the propellant for orbital manoeuvres.
- Earth pointing configuration with attitude manoeuvres:
  - P/L can have just 1 receiver and 6 antennae
  - Power Subsystem must cope with a power peak from P/L and sub-systems, during the attitude manoeuvre, that will be charged on the battery
  - Propulsion Subsystem must hold the propellant for orbital and attitude manoeuvres.

2.3.3.2 System Budget

The system budgets for all the Satellite Configuration and Pointing strategy (see 2.2.4 and 2.3.3.1) taken into account are shown here below.

Pointing Strategy	Satellite Mass [kg]	Satellite Configuration	Satellite Mass [kg]	Satellite Configuration
Sun Pointing	278	S_j, N_iH_2, Biprop	267	M_j, L_i-Ion, Biprop
Earth Pointing	237	S_j, N_iH_2, N_2H_4	227	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	300	S_j, N_iH_2, N_2H_4	287	M_j, L_i-Ion, N_2H_4

Table 2.3-2 Satellite Mass Budget

Pointing Strategy	P/L Mass [kg]	Satellite Configuration	P/L Mass [kg]	Satellite Configuration
Sun Pointing	109	S_j, N_iH_2, Biprop	109	M_j, L_i-Ion, Biprop
Earth Pointing	42	S_j, N_iH_2, N_2H_4	42	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	40	S_j, N_iH_2, N_2H_4	40	M_j, L_i-Ion, N_2H_4

Table 2.3-3 P/L Mass Budget

Pointing Strategy	Propulsion Mass [kg]	Satellite Configuration	Propulsion Mass [kg]	Satellite Configuration
Sun Pointing	38	S_j, N_iH_2, Biprop	38	M_j, L_i-Ion, Biprop
Earth Pointing	74	S_j, N_iH_2, N_2H_4	74	M_j, L_i-Ion, N2H4
Earth Pointing with Attitude Manoeuvre	119	S_j, N_iH_2, N_2H_4	119	M_j, L_i-Ion, N2H4

Table 2.3-4 Propulsion Subsystem Mass Budget

Pointing Strategy	Power Mass [kg]	Satellite Configuration	Power Mass [kg]	Satellite Configuration
Sun Pointing	29	S_j, N_iH_2, Biprop	19	M_j, L_i-Ion, Biprop
Earth Pointing	28	S_j, N_iH_2, N_2H_4	18	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	35	S_j, N_iH_2, N_2H_4	21	M_j, Li-Ion, N_2H_4

Table 2.3-5 Power Subsystem Mass Budget

Having a look at
Table 2.3-2, the Earth Pointing strategy, with the S_j, N_iH_2, N_2H_4 Configuration, is the optimised solution among all that had been studied.

In fact, in this configuration the P/L is (good) (see
Table 2.3-3), Propulsion Subsystem is (best) (see
Table 2.3-4) (More mass that Sun Pointing but simpler as it is Monopropellant); while, Power Subsystem (see
Table 2.3-5) needs a bit more explanation, in fact, looking at the power subsystem budget Earth Pointing seems to be (best) for it instead of (Sun Pointing); this is not completely true.

In order to understand the situation, a look at Table 2.3-6 and

Table 2.3-7 is useful; in fact, Sun Pointing is (best) for Solar Array area and mass while, Earth Pointing is (best) for Battery volume and mass.

This means that is not possible to find a pointing strategy that is (best) for both Solar Array and Battery. In any case, as the overall policy is to find the optimised solution within the limit of overall satellite mass of 250 kg (see pag. 38), it is possible to assess that the Earth Pointing strategy, with the S_j, N_iH_2, N_2H_4 Configuration "does" is the optimised solution.

Pointing Strategy	SA Mass [kg]	Satellite Configuration	SA Mass [kg]	Satellite Configuration
Sun Pointing	10	S_j, N_iH_2, Biprop	5.5	M_j, L_i-Ion, Biprop
Earth Pointing	11	S_j, N_iH_2, N_2H_4	6.0	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manouever	14	S_j, N_iH_2, N_2H_4	8.0	M_j, L_i-Ion, N_2H_4
Pointing Strategy	SA Area [m²]	Satellite Configuration	SA Area [m²]	Satellite Configuration
Sun Pointing	2.1	S_j, N_iH_2, Biprop	1.5	M_j, L_i-Ion, Biprop
Earth Pointing	2.4	S_j, N_iH_2, N_2H_4	1.7	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manouever	3.0	S_j, N_iH_2, N_2H4	2.2	M_j, L_i-Ion, N_2H_4

Table 2.3-6 Solar Array Mass and Area Budget

Pointing Strategy	Battery Mass [kg]	Satellite Configuration	Battery Mass [kg]	Satellite Configuration
Sun Pointing	7.8	S_j, N_iH_2, Biprop	2.9	M_j, L_i-Ion, Biprop
Earth Pointing	5.7	S_j, N_iH_2, N_2H_4	2.1	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manouever	8.6	S_j, N_iH_2, N_2H4	3.2	M_j, L_i-Ion, N_2H_4
Pointing Strategy	Battery Volume [l]	Satellite Configuration	Battery Volume [l]	Satellite Configuration
Sun Pointing	7.1	S_j, N_iH_2, Biprop	1.1	M_j, L_i-Ion, Biprop
Earth Pointing	5.2	S_j, N_iH_2, N_2H_4	0.8	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manouever	7.9	S_j, N_iH_2, N_2H_4	1.2	M_j, L_i-Ion, N_2H_4

Table 2.3-7 Battery Mass and Volume Budget

2.3.3.3 Detailed System Budget

For completeness, the detailed system budget are shown here below for the Earth Pointing Configuration.

EARTH POINTING CASE	Units Number	Margin	Unitary Mass [kg]	Total Mass [kg]
Payload				**42.24**
GPS Receiver	1	5%	4.00	4.20
L band Antenna (occultation)	2	5%	2.00	4.20
L band Antenna (positioning)	1	5%	0.23	0.24
K band TX/RX (SM and TWT	1	20%	25.00	30.00
K band antenna	12	20%	0.25	3.60
AMCS				**8.48**
Coarse Sun Sensor	3	5%	0.23	0.72
Earth Sensor	1	5%	1.50	1.58
Earth Sensor Electronic	1	5%	1.00	1.05
Magnetometer	1	5%	0.23	0.24
Magnetic Rods	3	5%	0.40	1.26
Momentum Wheel	1	5%	2.55	2.68
Momentum Wheel Electronic	1	5%	0.91	0.96
OBDH				**22.00**
CDMU	1	10%	10.00	11.00
MMU	1	10%	10.00	11.00
TTC				**11.18**
S Band Transponder	2	5%	2.80	5.88
RFDU	1	5%	0.20	0.21
S Band Antenna	2	5%	0.25	0.53
L Band TX	1	20%	2.80	3.36
L Band Antenna	1	20%	1.00	1.20
Propulsion (Hydrazine)				**73.75**
Thruster	8	5%	0.30	2.52
Tank and piping	1	20%	6.36	7.63
Hydrazine	1	20%	53.00	63.60
Power (N2H4)				**28.05**
PCU	1	5%	7.00	7.35
PPDU	1	5%	2.00	2.10
Solar Array Mass (SJ)	1	10%	11.21	12.33
Battery Mass (NiH2)	1	10%	5.70	6.28
Structure				**18.57**
Thermal				**7.43**
Harness				**3.71**
System Margin				**21.54**
Earth Pointing with 45° tilted SA				
Total				**236.96**

Table 2.3-8 Earth Pointing detailed Mass Budget

	Units Number	Mean Unitary Power [W]	Mean Total Power [W]	Unitary Power [W]	Peak Total Power [Wh]	Duration [hour]
Payload			**28.00**		**47.00**	
GPS Receiver	1	14.00	14.00	38.00	26.60	0.70
L band Antenna (occultation)	2					
L band Antenna (positioning)	1					
K band TX/RX	1	14.00	14.00	68.00	20.40	0.30
K band antenna	12					
AMCS			**27.90**		**11.00**	
Coarse Sun Sensor	3					
Earth Sensor	1	8.00	8.00			
Earth Sensor Electronic	1					
Magnetometer	1	1.00	1.00			
Magnetic Rods	3	1.30	3.90			
Momentum Wheel	1	10.00	10.00			
Momentum Wheel Electronic	1	5.00	5.00	20.00	11.00	0.55
OBDH			**32.00**			
CDMU	1	20.00	20.00			
MMU	1	12.00	12.00			
TTC			**10.40**		**12.30**	
S Band Transponder	2	5.00	10.00	20.00	8.20	0.41
RFDU	1					
S Band Antenna	2					
L Band TX	1	0.40	0.40	10.00	4.10	0.41
L Band Antenna	1					
Power			**31.00**			
PCU	1	23.00	23.00			
PPDU	1	8.00	8.00			
Structure						
Thermal			**10.00**			
Harness			**5.00**			
Total (Hydrazine)			**144.30**		**70.30**	

Table 2.3-9 Earth Pointing detailed Power Budget

2.3.4 Launcher Selection, Launch Strategy and Trade-offs

Taking into account the output of the Mission Analysis (see 2.3.1), Constellation Deployment (see 2.3.2) and S/C Configuration and Pointing Strategy (see 2.3.3), it turns out that four launches with Rockot can be considered as the baseline solution.

The launch Strategy will be to wait for the right launch hour (daily launch window) in order to fix the absolute Ascending Node of the first satellite; while, the other two will stay on parking orbit up the right difference in Ascending Node had been reached.

Nevertheless a deeper look at Table 2.2-5 suggests further optimisation activity.

If it can be found a Constellation with 8 satellite giving results "as good as" the optimised Constellation with 12 satellite. A two launches strategy of four satellite with Tziklon can be considered. Of course it rises the need to wait about 3.5 years on parking orbit and the need to add more fuel for drag compensation.

3. THE PROPOSED MULTIDISCIPLINARY OPTIMISATION METHODOLOGY

3.1 BASIC CONCEPTS

This work proposes a new methodology for tackling multidisciplinary optimisation problems in space design characterised by non-collaborative entities. One of the main reasons to search for new methods and approaches to solve MDO problems is the increasing complexity of the engineering systems. Since solutions time for most analysis and optimisation algorithms increase at a super linear rate, the computational cost of MDO is usually much higher than the sum of the costs of the single disciplines represented in the MDO itself.

Several papers are available in literature dealing with MDO problems, but they are typically based on the application of particular uses of classic approaches for mono-objective problems.

Collaborative Optimisation (COLOP – see [RD 9]) is a new design architecture specifically created for large-scale distributed analysis applications, and is based on the decomposition of problems along the lines of the constituent disciplines. This method tries to solve each subsystem maintaining its independence from the others, leaving to a top level system the task of manage the interactions between the set of subsystems. It means that from the system level is deduced a simplified model for each subsystem, which involves only its variables, constraints and objectives, so COLOP seeks to solve MDO problems in a way that preserves the autonomy of the disciplinary calculation by eliminating from the system-level problem all those design variables local to individual disciplinary subsystems. Main drawback of COLOP is that it typically runs into computational difficulties when conventional non-linear programming algorithms are applied to the solution of the resulting system level.

Bi-level Integrated System Synthesis (BLISS – see [RD 10]) and its evolutions BLISS/RS and BLISS/S are recently introduced methods that use a gradient-guided path to reach the improved system design. This family is studied for maintaining multidisciplinary feasibility at the beginning of each path cycle. Starting from a best guess initial design, this method improves that design in iterative cycles, each cycle comprised of two steps. In step one, the system level variables are frozen and the improvement is achieved by separate, concurrent and autonomous optimisations in the local variable sub domains. If the starting point is feasible, then BLISS will maintain feasibility while improving the system objective. Otherwise, if the starting point is unfeasible, the constraint violations are reduced while minimizing the increase in system objective. Typical drawback of BLISS and its variants is that as they strongly exploit the use of derivatives, typically run into computational errors propagation.

To overcome the above drawbacks, in this project we propose a new method based on the joint use of three different disciplines: Combinatorial Optimisation, Game Theory and Multicriteria Decision Analysis. These disciplines are quite different and complementary to each other. Each discipline presents some advantages that make it appropriate for this study, but also some disadvantages that suggest an integration with the other ones. Here, we propose a general integrated framework in order to fill mutual deficiencies, originating a new methodology able to solve general MDO problems.

In a Combinatorial Optimisation context related to problems characterised by mathematical formulations presenting many non-linearities and then extremely complex or even impossible to be solved by means of exact approaches, heuristic approaches based on neighbourhood search techniques represent the most appropriate tool to generate good solutions. The neighbourhood search approach explores and evaluates the solutions space: actually, only a reduced subset of the solutions space is explored in order to reduce computational time, but the proposed approach typically has the ability of moving toward good solutions even evaluating few solutions, thing which is pretty important, especially in real problems like this, where the computational time required to evaluate a single solution may be significant. In spite of this, it is hard to directly and successfully apply Combinatorial Optimisation techniques to the whole problem as they are not totally suitable for multi-objective multi-disciplinary problems.

In order to overcome this issue, we make use of Game Theory and Multicriteria Decision Analysis, which constitute the most suitable approaches when dealing with problems characterised by conflictual objectives. On the other side, they base their activity on the evaluation of a set of Paretian solutions, but they are not able to generate

it, so they need a previous extern analysis. The preliminary role of Combinatorial Optimisation, which is particularly suitable for exploring the solutions space while searching for a set of Paretian solutions is clearly depicted in
Figure 3.1-1. Then, in parallel, Game Theory and Multicriteria Decision Analysis evaluate these solutions providing in output a (typically) strongly limited subset of solutions representing the best compromise for these conflicting multidisciplinary problems.

The advantage of the proposed approach, with respect to the existing conventional algorithms for MDO problems, is that it strongly reduces the probability of computational mistakes as the neighbourhood search approach is totally uncorrelated from the mathematical modelling of the problem and the only requirement is the capability of computing the values of the given solutions. Further the neighbourhood search approach allows the exploration of a quite reduced subset of the solutions space, decreasing the computational costs. This is significant since in real cases, when working on full complex problems, we typically encounter a solutions space whose size may be very large (millions of units for instance) and the time requested to compute a single solution may be not negligible. Finally, there are methods which are not able to provide solutions until the execution is ended, while in the proposed approach, several (typically good due to their Paretian peculiarity) solutions are generally available even if it is stopped in advance.

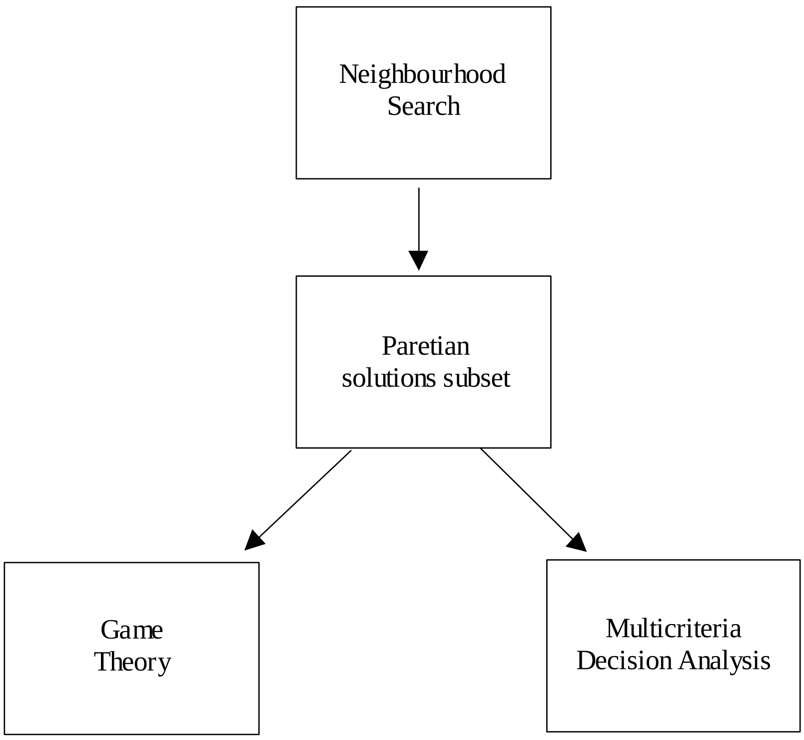


Figure 3.1-1: Disciplines interaction

3.2 NEIGHBOURHOOD SEARCH APPROACH

3.2.1 Definition of input and output parameters

The first phase of this project has been focused on the search of the input and output parameters for the considered WATS mission case study: aim of this phase is the definition of a model indicating how these parameters affect the three main subsystems (mission analysis, propulsion, power) and the corresponding objective functions.

To this aim, a network has been generated connecting the primary inputs of the general system to the outputs of the three main subsystems (mission analysis, propulsion, power), by means of several intermediate inputs and outputs specifically designed.

By analysing the characteristics of the considered system, the followings have been determined as the main input and output parameters:

Inputs	Outputs
[1] number of satellites	(10) Launchers
[2] Distribution	(11) Total mass
[3] Altitude Parking Orbit	(12) Velocity
[4] Pointing Strategy	(13) Fuel mass
[5] Solar panel kind	(14) Tank mass
[6] Fuel kind	(15) Battery mass
	(16) number of events
	(17) number of launches
	(18) Time to reach the orbit
	(19) Solar panel mass
	(30) Power cost
	(31) Propulsion cost

Table 3.2-1 Problem inputs and outputs

Notice that some of the output parameters are not comparable to each other: indeed the goal of the mission analysis is to maximise the number of relevant events, while for propulsion and power the objective is to minimise a cost function depending on the total mass and type of the components of each satellite. Hence, three different schemes were designed: a first scheme is devoted to the mission analysis where the output is then the optimal number of events, a second scheme is devoted to the propulsion where the output is the total propulsion cost and a third scheme is devoted to the power where the output is the total power cost.

In a preliminary phase, the selection (among the parameters indicated in the above table) of those parameters constituting inputs and outputs for each subsystem has been performed. The following schemes (depicted in the figures below) have been derived for Mission Analysis, Propulsion and Power, respectively.

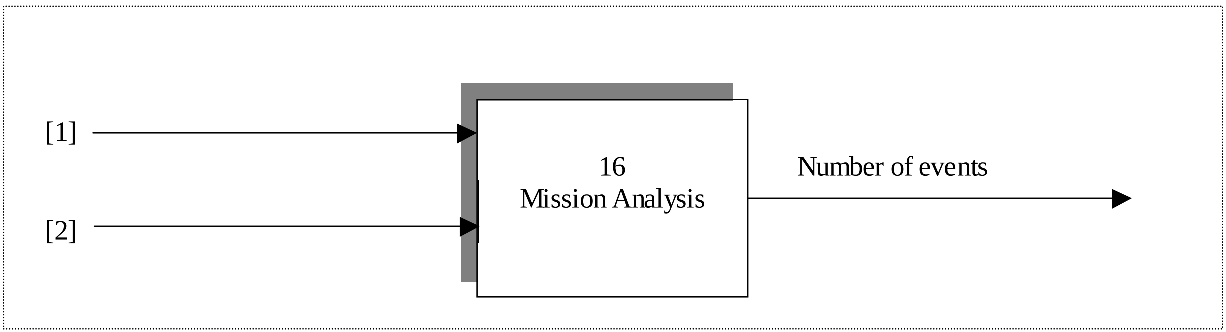


Figure 3.2-1 Mission Analysis Scheme

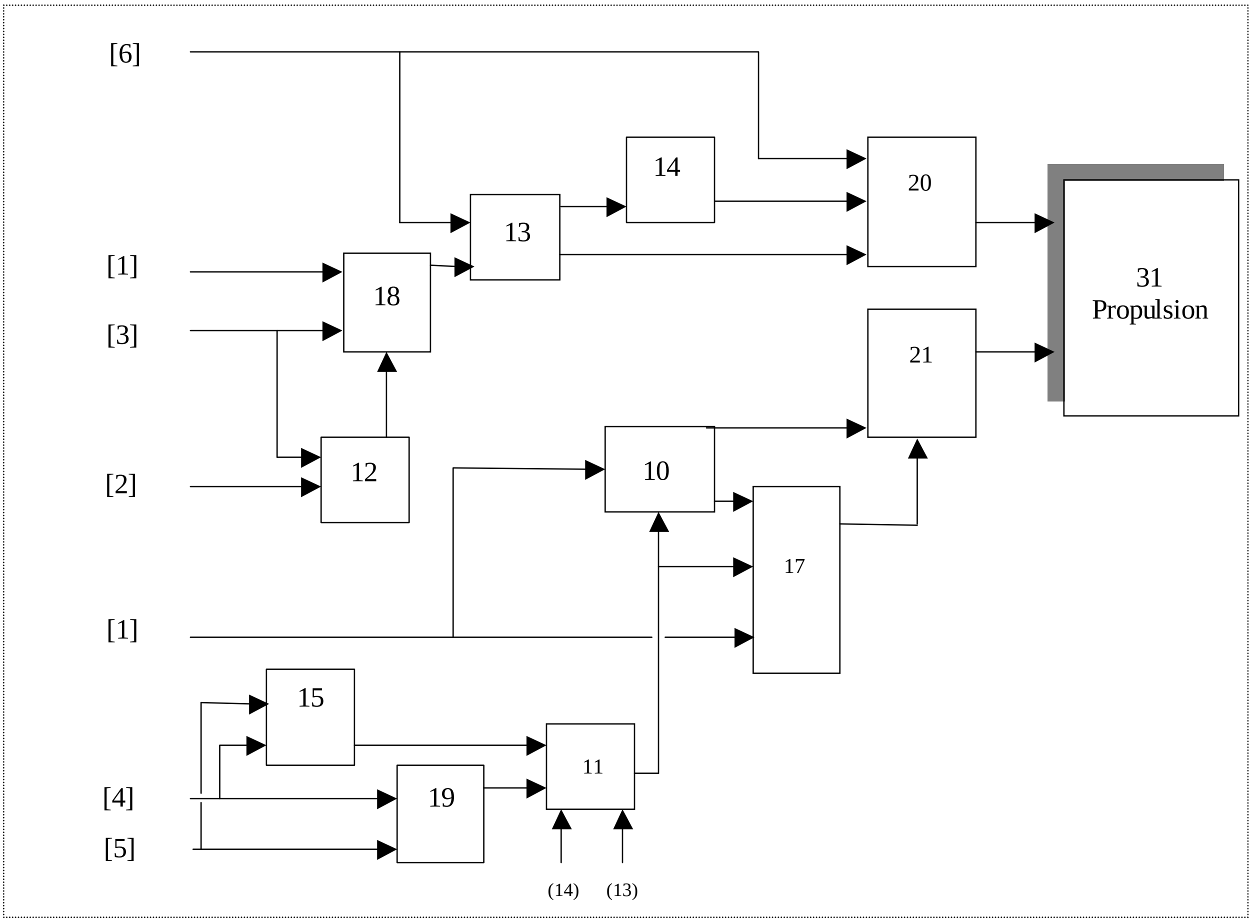


Figure 3.2-2 Propulsion Scheme

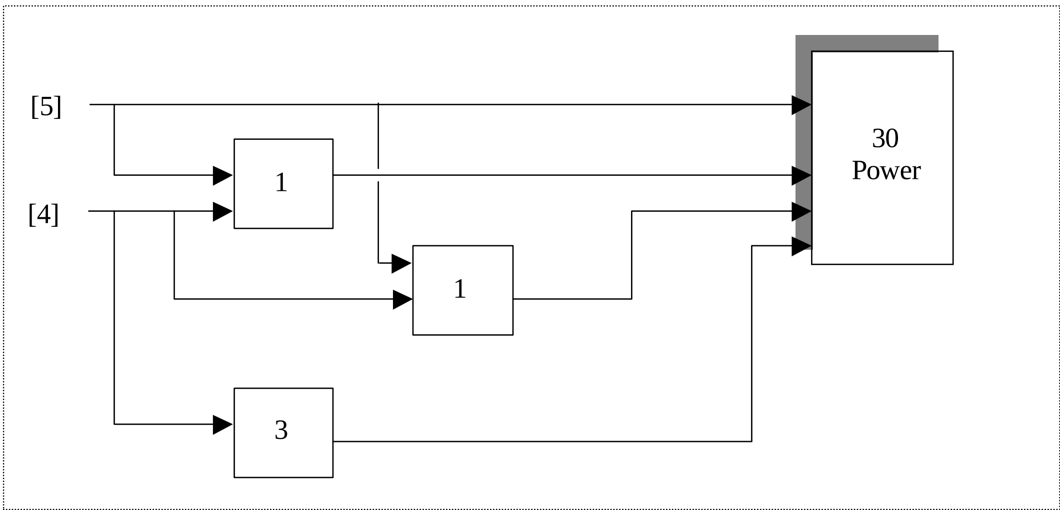


Figure 3.2-3 Power Scheme

We assume that for each considered subsystem (Mission Analysis, Power and Propulsion) there exists a local optimiser that, given a specific input configuration, is able to provide an optimal/sub-optimal solution (with respect to the considered subsystem).

It was also defined an example of values ranges for each parameter to get a rough idea of the solutions space size. With the following ranges, the solutions space would contain 30.000 units.

Parameter number	***Range***	***Notes***
[1]	4 to 16	step 2
[2]	1 to 50	Some distribution of Ω and θ
[3]	200 to 400	Step 20 km
[4]	2	Sun/earth pointing
[5]	2	$S_j + N_iH_2 / M_j + L_i$-Ion
[6]	2	Mono/Bipropellant

Table 3.2-2 Solutions Space Order of Magnitude

3.2.2 The proposed approach

Neighbourhood search is a robust way to obtain good solutions (near to optimum) in reasonable time. Though, these methods are not able to certify optimality, they tend to obtain high quality sub-optimal solutions provided that a correct neighbourhood is defined.

A neighbourhood search procedure starts from an arbitrary solution $x_1 \in X$ (X is the space of feasible solutions) and for each step i typically chooses the best solution x_{i+1} from its neighbourhood $N(x_i)$.

The main steps of such procedure are:

1. *Initialisation*: choose a feasible solution x_1 and compute its cost function;

2. *Neighbourhood generation*: select a neighbourhood $N(x_i)$ of current solution x_i;

3. *Neighbourhood evaluation*: consider neighbourhood $N(x_i)$ and select (typically) the best solution x_{i+1} in the neighbourhood;

4. *Stopping Test*: If a Stopping Criterion is true exit else go to step 2.

A neighbourhood search approach for the considered problem is proposed that works as follows:

1. An initial small set of feasible solutions (at least one) given by problem experts is required as input;

2. For each initial solution a neighbourhood step is applied to find a (heuristically) Paretian solution. Then the following steps are performed:
   a. Store the Paretian solution found;
   b. if enough Paretian solutions have been found or if the iteration number > max_iteration stop
   c. else, apply a new neighbourhood step.

Neighbourhood search takes intrinsically into account the discrete nature of the considered problem and allows in its improved versions (metaheuristics such as Tabu search, Variable Neighbourhood search, Genetic Algorithms etc. see, for instance, [RD11]) to escape from local optima and hopefully converge to a quasi-optimal solution. The typical behaviour of a neighbourhood search technique is such that, if a proper neighbourhood is defined and a starting solution is available, an initial local minimum can be reached in very few iterations, namely in very limited CPU time. Then, any improved metaheuristic approach manages to escape from that minimum to reach several other (typically) improved minima. This aspect makes neighbourhood search very appealing even in situations where a limited number of feasible solutions is available. Under a neighbourhood search context, particularly with respect to MDO and to the search of Paretian solutions as far as the various single disciplines are concerned, the Path Relinking approach (see [RD12]) appears well applicable. Path Relinking concerns the search of a path linking two given solutions S1 and S2. This path must be determined in the feasible solutions space and requires two adjacent solutions of this path to be neighbours with respect to the considered neighbourhood. Typically, the application of Path Relinking between S1 and S2 leads to discover in the path another solution S3 that often dominates both S1 and S2.

3.3 GAME THEORY

3.3.1 Proposed Approach

In the mission analysis many conflicts among different sections of the projects shows up, so that game theory results to offer interesting tools for facing and analysing them. We can just mention here number of satellites vs. number of launches, but other conflicting elements can be pointing, batteries, panels and so on.

We may suppose to consider each element as a player of a non co-operative game, whose strategies are the possible (reasonable) choices of the corresponding component; the payoff obtained by a player depends on the success of the mission (according also to the choices of the other players) and on the costs of his own choice.

Clearly some choices of the players (strategy profiles) may lead to a failure of the project: we may think to a limited amount of fuel with small size panels.

A suitable solution for this situation is the classical Nash Equilibrium (see [RD13]), that consist in a set of choices such that no player can be better off if he is the unique player that deviates.

After the analysis of the non co-operative game, it can be interesting to go further with a co-operative approach where the players may jointly decide for suitable settings of the corresponding components, such that the failure is avoided, but each player continues to be charged of his costs. This scenario corresponds to a co-operative game without transferable utility (NTU game), or more precisely to a bargaining problem (see [RD14]).

After the definition of the non co-operative game the classical approach (see [RD15]) enable us to define a bargaining problem that represents the NTU game, where the comprehensive convex hull of the payoffs of the events in the non co-operative game represents the feasible set, F, and the disagreement point, d, corresponds to the impossibility to reach a reasonable agreement on the settings of the project, in such a way that it is not carried out and the players receive a null (or perhaps negative) utility. The game theoretic literature proposes many possible solutions (Nash (N), Kalai-Smorodinsky (K), etc.), that can be selected also taking into account the underlying axiomatic characterisations. For more details on these solutions see [RD16].

We can conclude with a simple example. Consider two elements corresponding to number of satellites and number of launches; suppose that number of satellites may be 4 or 8 and number of launches may be up to 1, 2 or 3, where each launch can be used for at most 3 satellites. The non co-operative game is reported by the following table, where the payoff (f, f) represents the failure of the project.

# Lau #Sat	4	8
1	(*f*, *f*)	(*f*, *f*)
2	(1, 1)	(*f*, *f*)
3	(3, 3)	(2, 4)

Table 3.3-1 Example of non cooperative game

The bargaining problem is reported below.

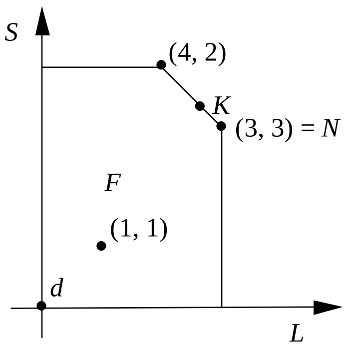


Figure 3.3-1 Bargaining Problem

3.4 MULTICRITERIA DECISION ANALYSIS

Multicriteria Decision Analysis (MCDA) can be described (see [RD17]) as a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter. Decisions matter when the level of conflict between criteria, or of conflict between different stakeholders regarding what criteria are relevant and the importance of the different criteria, assumes such proportions that intuitive ‘gut-feel’ decision-making is no longer satisfactory. This can happen even with personal decisions but becomes much more of an issue when groups are involved, such as in corporate decision making.
The concept of an optimum does not exist in a multicriteria framework and thus multicriteria analysis cannot be justified within the optimisation paradigm frequently adopted in traditional Operational Research/ Management Science. MCDA is an aid to decision-making, a process that seeks to integrate objective measurement with value judgment, and to make explicit and manage subjectivity.

A *multicriteria decision problem* is a situation in which, having defined a set A of possible actions and a consistent family F of criteria on A, one wishes ([RD18]):

- to determine a subset of actions that are considered to be the best with respect to F (choice problem),
- to divide A into subsets according to some norms (sorting problem),
- to rank the actions of A from best to worst (ranking problem).

In real-world studies, defining possible actions and coherent criteria represents the greatest part of the analyst’s work. If the nature of the actions and/or the problem statement partially or globally change(s), the criteria of the previous model have to be re-analysed because they can change nature or meaning, but are always an essential and formalised information base and enable one to move more easily towards a new coherent family of criteria.

3.4.1 Multicriteria Decision Analysis Approach to the Architecture Definition Problem and main activities

Several methodologies have been developed in the MCDA context. In relation to this specific problem an integration between two different approaches could be more appropriate. The first, the Strategic Choice Approach of [RD 19], can be used to elaborate a finite set of 'admissible' alternative solutions (or *possible actions*) and to structure the adequate multicriteria evaluation model. The second, an outranking method, compares possible actions in relation to their evaluations on the different criteria and to the decision maker's preference ([RD 18], [RD 20]).

The integration of a formal multicriteria language and way of reading the problem with an approach to coping with complexity and helping the users in "making incremental progress towards decision by focusing their attention on alternative ways of managing uncertainty" ([RD 19]) can be particularly useful. The first procedural step in multicriteria modelling is that of *problem bounding* and *alternative action definition*. The second important step is the definition of all the *problem dimensions*, i.e. all the points of view that are considered important and significant to model, and then of the coherent *criteria*, the tools which allow one to compare actions according to a particular problem dimension, the operational counterpart of a specific point of view (aspect, factor, characteristic). For each dimension one or more relevant factors could be transformed into criteria.

At this point, a method of the ELECTRE class can be used (for a ranking problem and when actions and criteria are formally defined) to compare alternatives on each criterion and to model an *outranking relation* between each pair of alternatives, by the notion of *concordance* and *discordance*. The method uses this result in the second phase, of outranking relation exploitation, to construct two *complete preorders* and a *partial preorder* of the alternative actions as the final result. In the ELECTRE class, ELECTRE III ([RD 21], [RD 22]) is proposed when some of the available data present an imprecise and uncertain nature. *Indifference and preference thresholds* are introduced in this method on the criteria used in the comparison of the actions, which then are called *pseudo-criteria*. The concept of pseudo-criterion and the use of the two thresholds allow the imprecision and uncertainty to be taken into account.

ELECTRE III starts by comparing each unit (admissible action, as it is elaborated and tested in a previous phase) to each of the others. It builds the model for the fuzzy outranking relation by the notion of concordance and discordance and the computation of a *concordance index*, a *discordance index* and an *outranking degree* (phase I of the method).

The method uses this result in the second phase of *fuzzy relation exploitation*, to construct two complete preorders through *a descending and an ascending distillation procedure*. The two complete preorders are usually not the same. When they are similar but present 'problematic actions' that do not present the same position in the two complete preorders, a partial preorder needs to be elaborated as the intersection of the two complete preorders. For details of the ELECTRE III procedures, see e.g. [RD 20] and [RD 23].

3.4.2 Application of the Strategic Choice Approach to a simplified case

Several different schemes of problem building and alternative action definition can be elaborated. A possibility is that of considering all the different involved sectors (Mission Analysis, Power subsystem, Propulsion subsystem, Configuration and Pointing subsystem, Launch Strategy) as Decision Areas, which propose a set of decision options, and of combining the different options in a finite set of alternative project typologies. A check of the mutual compatibility between each pair of options reduces the number of the possible typologies.

A second possibility is distinguishing between 'basic' project characteristics (in terms of prominent Decision Areas) and other characteristics, in terms of Decision Areas that can be examined in a second time, and developing a sequence of 'decision area shaping - design of possible solutions -comparing of options and possible solutions - choosing' which can be cyclic and aims at the elaboration of a complete set of possible solutions, the control of the uncertainties and the development of a validated evaluation model.

In this second case, a group of decision areas can be put in the focus at a specific time and, for example, the involved sectors can be:

- Launch Strategy sector that proposes, as Decision Areas, 'the type of launcher' (with a list of launchers as options), 'the number of satellites for each launch' (and the list of all the possibilities for each launcher) and 'the number of launches' (1, 2, 3,…);

- Configuration sector that proposes 'Pointing Strategy' (with Earth P., Sun P. and Earth P. + AM, as three options), 'P/L Configuration' (with three levels of configuration as options), Propellant Type' (with mono and bipropellant as two options) and 'Solar panel and battery Type' (with four combination of panels and batteries as options).

The analysis of these decision areas (with the combination of the limited set of decision options, the identification of all the incompatibility motivations and the definition and the use of some comparison areas) can allow the selection of some impossible solutions and the comparison of the others, to construct an effective multicriteria evaluation model.

4. APPLYING THE MULTIDISCIPLINARY OPTIMISATION METHODOLOGY TO THE WATS MISSION CASE STUDY

The WATS case study introduced in Chapter 2, was characterised by the presence of very complex optimisation problems, both at subsystem and at system level. Actually, all encountered optimisation issues were solved 'by hand', on the basis of the engineer expertise. In particular, no optimisation routine was available to optimise each single subsystem. The absence of such routines made inapplicable the neighbourhood search approach (for which each subsystem is a 'black box'). The implementation of these subsystem routines was however beyond the scope of this work.

For the game theoretic approach a suitable utility function was defined for the two players of the case study, depending on the number of events. The three approaches, Nash equilibrium, Nash solution and Kalai-Smorodinsky solution allow to have a first insight to their features: the Nash equilibrium and the Nash solution coincide and the corresponding point gives his maximal feasible utility to player “number of satellites”, but the other player “number of launches” cannot improve his utility without the help of the first player (Nash equilibrium) and this theoretical increase of utility is however not counterbalanced by the loss of utility of the first player (Nash solution). On the other hand the Kalai-Smorodinsky solution takes into account that it is not fair to give the maximal utility to one player, while the other is penalised with respect to his best opportunity, so reduces the utility for the player “number of satellites” and increases the utility for the player “number of launches”

The Multicriteria Decision Analysis methods work with a set of solutions, not necessary efficient in terms of Paretian solutions but feasible or admissible, in relation to the system engineer’s point of view on the decision problem. For this reason, a Multicriteria approach has been applied to the WATS case study to structure the decision problem, elaborate the reduced set of all the feasible solutions and a consistent evaluation model. This model allows the application of a Multicriteria method (such as an ELECTRE method) to the solutions to rank them and identify the best solution.

4.1 THE GAME THEORETIC APPROACH TO THE WATS MISSION CASE STUDY

We consider two elements corresponding to number of satellites and number of launches; we assume that the number of satellites may be 4, 8, 10, 12, 16 and the number of launches may be up to 1, 2, 3, 4 or 5.

The payoff are computed referring to the following hypotheses:

- A satellite weights about 350 Kg. and the cost is 17 M$
- Rockot can be used up to 3 satellites, with a cost of 15 M$.
- Tzyklon can be used up to 4 satellites, with a cost of 25 M$.
- The benefit is shared among the two players proportionally as two thirds to satellite and one third to launcher.
- The relation among benefit (B) and number of events (E) is expressed by the following relation:

$$B = 8.6\sqrt{E} + 27 \quad (16)$$

that was obtained by imposing that the benefit for 1000 events is 300 and for 1400 is 350 where the shape of formula was $B = a\sqrt{E} + b$.

For the test case we get the following table, where the data related to 10 satellites were obtained by interpolation and by formula (16).

# satellites	4	8	10	12	16
# events	93	411	720	1142	2029
Benefit (in M$)	110	201	258	318	414

Table 4.1-1 WATS mission case study data

The non cooperative game is represented by the following table, where the payoff *f* represents a negative amount corresponding to the failure of the project.

# Lau #Sat	4	8	10	12	16
1	**(12, 5)**	(*f*, *f*)	(*f*, *f*)	(*f*, *f*)	(*f*, *f*)
2	**(12, 5)**	(17, -2)	(*f*, *f*)	(*f*, *f*)	(*f*, *f*)
3	**(12, 5)**	(22, -2)	(31, 2)	(31, 8)	(*f*, *f*)
4	**(12, 5)**	(22, -2)	(31, 2)	**(46, 8)**	(38, 4)
5	**(12, 5)**	(22, -2)	(31, 2)	**(46, 8)**	(53, 4)

Table 4.1-2 WATS mission non co-operative game

If we consider the underlined payoffs as those corresponding to the best reply of each player we get the Nash equilibriums of the game (in **bold**), that correspond to the minimal configuration 4 satellites and 1 launch and to 12 satellites with 4 launches (the other Nash equilibriums are just replicas of these two).

The associated bargaining problem is represented below.

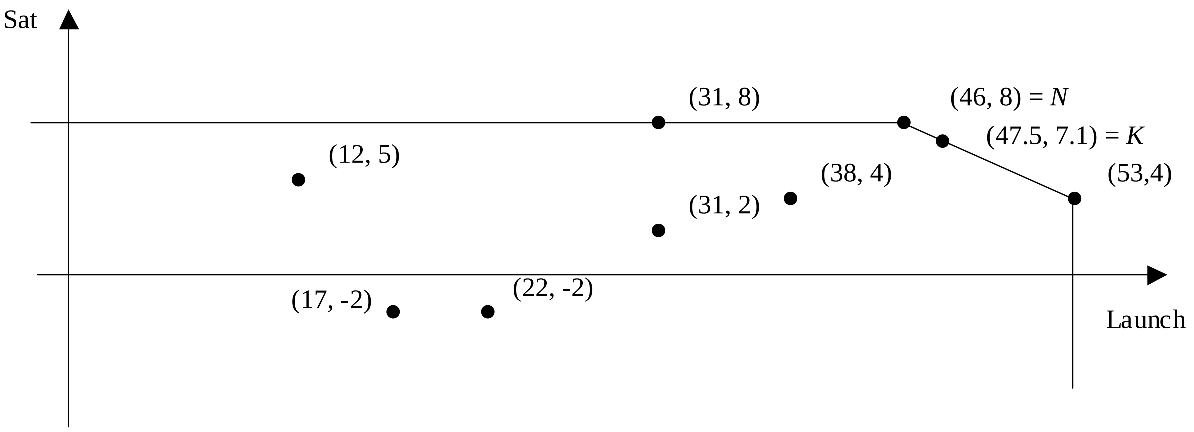


Figure 4.1-1 WATS mission associated bargaining problem

The Nash Solution coincides with the Nash Equilibrium (46, 8), while the continuum Kalai-Smorodinski Solution assigns the utilities 47.5 to the launch and 7.1 to the satellite.

4.2 A MULTICRITERIA APPROACH TO THE DEFINITION OF ALTERNATIVE SOLUTIONS AND EVALUATION CRITERIA

The decision problem, in relation to the WATS mission case study, is not enough structured for the application of a multicriteria method as ELECTRE. A set of possible solutions is not defined and therefore a consistent family of criteria cannot be yet identified and developed. The principles of the Strategic Choice Approach to planning under uncertainty (Friend, 1989) can be used to elaborate several schemes of problem shaping and design, to incrementally define a finite set of admissible alterative solutions and to support in the structuring of the multicriteria evaluation model. The Strategic Choice Approach is a methodology that can be used as a useful complement of the Multicriteria decision analysis in complex problems (see for instance [24]). It is applied to the WATS mission as an example of problem structuring that is not so different from the usual logic of an MD project co-ordination, complete, logically correct and easily documented.

Considering all the different involved sectors (Mission Analysis, Power subsystem, Propulsion subsystem, Configuration and Pointing subsystem, Launch Strategy) as interconnected *Decision Areas* (DA) is the first possibility of action. A list of *decision options* can be proposed for each area and analysed. The decision options of all the DA can be combined in a finite set of alternatives that in this case are the different project typologies. A check of the mutual compatibility between each pair of options reduces the number of the possible typologies, but if there are many DA and decision options the number of the compatible combinations is normally very high and the comparison of these typologies and the choice of the best solution may become difficult.

Strategic Choice Approach proposes a second possibility of distinguishing between 'basic' project characteristics (in terms of prominent DA) and other characteristics, in terms of decisions that can be examined in a second time, and developing a sequence of modes of activity – usually referred to as 'shaping decision areas - designing possible solutions - comparing options and global solutions - choosing'. This sequence is not linear, but normally cyclic and aims at:

- the elaboration of sequential sets of admissible solutions,
- the control of the uncertainties that make the decision difficult or impossible,
- the development of a validated evaluation model,
- the selection of the better solutions and the exclusion of the worse ones,
- the convergence towards the best solution for the decision or the use of an analytical multicriteria method to evaluate, compare and rank the set of possible solutions that the methodology produced at the end of its application.

The prominent Decision Areas, which are related to the different involved sectors, in this case could be:

- 'constellation deployment' (above all in relation to the ascending node separation);
- 'the type of launcher', 'the number of satellites for each launch' and 'the number of launches';
- 'configuration and pointing strategy', with 'propellant type' and 'solar array and battery type'.

All these DA can be represented in a graph (the problem focus) as a set of nodes, and the arcs of the graph indicate the presence of a relationship between two nodes. The analysis of these DA implies the combination of all the decision options and the identification of some motivations of the incompatibility between options, such as the limit of capacity for a specific launcher and a number of satellites for launch that is incompatible with the launcher capacity. The check on the compatibility has to be done only when two DA are related in the graph, i.e. the two decisions are interconnected. The presence of incompatibilities reduces the number of admissible combinations (global solutions) and can eliminate some decision options (which can be called fragmented solutions).

When the list of DA, decision options and compatible solutions is defined, the identification and the use of some Comparison Areas (CA) allows some fragmented or global solutions to be excluded and the list of the decision problem elements to be reduced (action of complexity limitation). A control on the discrimination potentiality of each comparison area facilitates the elaboration of an effective multicriteria evaluation model.

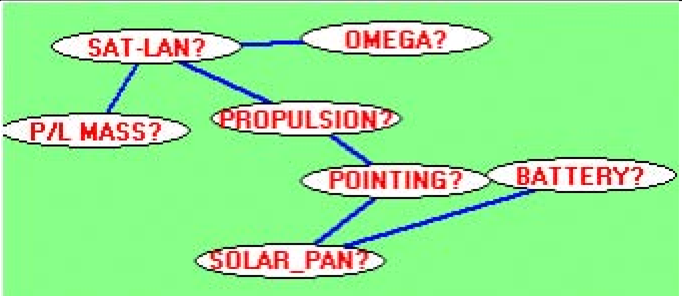


Figure 4.2-1 Decision graph

Seven Decision Areas are in focus (see the graph of figure 4.2-1) and their relationships are made evident. The DA can be examined all together or in a sequence of sub-problems that starts with the most interconnected sub-graph. The second approach is chosen; the analysed DA are described and all the possible actions are activated to reduce the complexity of the combinatorial problem. When the list of the decision options is defined, a compatibility check and several comparisons between elements of decision are developed, until the selection of the unacceptable decisions can reduce the problem to a limited and structured list of alternative solutions and consistent criteria. When all the solutions are evaluated on each criterion, an ELECTRE method can be applied to this multicriteria model.

4.2.1 Strategic Choice Approach application

P/L MASS is the DA that is connected to the 'Launcher Selection' decision. The need of reducing the number of decision options, as much as possible, suggested a set of different options that are not the launchers, but the different capacities of the launchers, which are listed in Table 2.2-5. The proposed options are 400 Kg, 800 Kg, 1100 Kg and 1500 Kg for the P/L MASS. The option 800 Kg is the intermediate value that represents the Rockot, Taurus XLS and Cosmos launchers; 1100 Kg is the capacity of Athena 2 (LMLV2) and PSLV; 400 Kg represents the Dnjepr launcher and 1500 Kg the Tzyklon.

SAT-LAN is the DA, which is connected to the 'Launch Strategy' decision (to lower as much as possible the number of launches and to rise as much as possible the number of satellites). SAT-LAN synthesises two decisions, on 'the number of satellites for each launch' and 'the number of launches'. The decision options for the SAT - LAN decision area are all the possible combinations 'number of satellites for each launch per number of launches'. They are: 2 x 3; 2 x 4, 3 x 3; 3 x 4; 3 x 6; 4 x 1; 4 x 3; 4 x 4; 5 x 2; 5 x 3.

The combinations are possible because at least one launcher is adequate, in terms sufficient capacity for the global satellite mass. The possible masses of the satellites are indicated in table 2.3-2 (in Kg) and are: 278, 237, 300, 267, 227 and 287.

The two DA P/L MASS and SAT-LAN are interconnected. This relationship is used to define the two lists of options. The different capacities have to be combined with the different options of 'satellite number per launch number'. The option of launcher capacity '400 Kg' is eliminated because the satellite minimum mass is 227 Kg and a launch with two satellites requires more capacity than 400 Kg. At this moment the two DA present only three options (the first) and ten the second, and globally thirty combinations.

OMEGA is the DA that represents the 'constellation deployment' problem, which is related to the Launch Strategy problem. The problem is defined, in 2.2.5, in these terms: 'In order to minimise the number of launches the technique of using differential precession between orbits with different altitudes must be used for constellation deployment. This technique is used in order to phase the satellite in ascending node separation. The technique consists in launching clusters of satellite on a Parking orbit and from that orbit, first of all, a satellite goes, with its own propulsion, to the Nominal orbit; while the other satellites of the cluster wait, on Parking orbit, till the right ascending node separation had been reached. This, of course, costs because of the drag compensation needed on

Parking orbit. After the right ascending node separation had been reached, each satellite by each goes to the Nominal orbit with its own propulsion'.

This DA synthesizes all the possible options of 'constellation deployment' in terms of satellite ascending node separation (total $\Delta\Omega$, i.e. the desired difference between the ascending node of the Parking orbit and the ascending node of the Nominal orbit). The waiting time, to reach a specific ascending node separation from the Parking orbit and towards the Nominal orbit can be obtained (with the diagram of figure 3.2 –5) in relation to $\Delta\Omega$. There is a limit of 1200 days as waiting time for this seven years mission. In relation to this limit, the admissible options for this DA are: 15° (for no more than six launches), 22.5° (for no more than four launches), 30° (for no more than three launches), 45° (for no more than two launches) and 90° (one launch).

The number of all the combinations, in relation to the three DA is now 150 (3x10x5) and could be reduced through the use of the 'Number of occultations' which has to be more or equal to 1600 events per day. This condition is not always satisfied. When the satellites are four, the number of events per day is 93 (see Figure 2.3-1), when they are eight the events are 410 (see Figure 2.3-2). The interpolation of the results of the figures 2.3-1 and 2.3-2 suggests that the events in relation to nine satellites are almost 600. Therefore four options of the SAT-LAN area have to be eliminated and they are 2 x 3, 2 x 4, 3 x 3 and 4x1. The other options can be conserved in this step because they are admissible or could become admissible through an action of parameter optimisation.

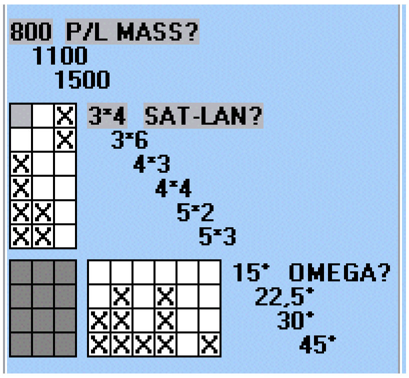


Figure 4.2-2 Compatibility analysis

The 'Number of occultations' was used as a condition but also as a Comparison Area, to limit the number of options for a specific Decision Area. As Comparison area it can be used in a future step to indicate the different preferences of the resulted best solutions. The same Comparison Area discriminates the options of the Ω area because '90°' is an option that is only connected to the situation of a single launch, with two, three, four or five satellites. None of these possibilities corresponds to an admissible number of events. Therefore also the option '90°' has to be eliminated. At this point the combinations are 74 (3x6x4) and a Compatibility analysis can still reduce their number. Some incompatibilities are indicated in figure 4.2-2, where an X symbol in a white cell corresponds to an incompatible combination of options. The motivations are different. When the option 1500 Kg is combined with the option 3x4 the incompatibility is 'waste of space', because the maximum need of space is 900 Kg (3 satellites of 300 kg). The same situation is recognised for the combination 1500 Kg with 3x6.

Another similar motivation is 'not enough space'. It is used for the combination between 800 Kg and 4x3, because the minimum requirement of space is 898 Kg (4 satellites of 227 kg), and the situation is the same for the options 4x4, 5x2 and 5x3. The combinations between 1100 Kg and 5x2 or 5x3 are incompatible for the same reason. A different motivation of incompatibility is 'time to arrive at the Nominal orbit'. The limit of time is 1200 days and the combinations between the options with three, four or six launches and the option 45° (for Ω) require more than 1200 days to arrive at the Nominal orbit. The same situation happens when the launches are six and Ω is 22,5° or 30°, or the launches are four and Ω is 30°. The shadowed area in figure 4.2-2 indicates that the DA OMEGA is not connected with the DA P/L MASS (as it is also represented in figure 4.2-1). The compatibility analysis is not applied in this case. The compatible combinations can be compared and reduced through the use of the Comparison

Areas 'Number of occultation', which was used in the previous step, Time and Costs (see Figure 4.2-3). The last CA is significant for the three DA and above all for SAT –LAN. The required time to arrive at the Nominal orbit is significant (i.e.discriminant) only for OMEGA and the number of occultation is directly significant only for SAT – LAN[1]. It means that the options of each DA can be compared and discriminated through at least one CA.

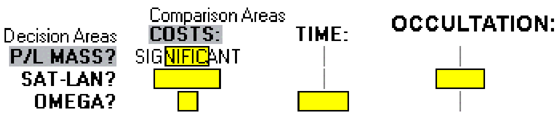


Figure 4.2-3 Different significance of the Comparison Areas

The options are compared on each criterion. The global effect of the three Comparison Areas allows the combined solution to be ranked from the best to the worst[2]. This result, which is synthesised in figure 4.2-4, presents the decision of a constellation of 12 satellites in all the first seven positions. The launcher, which is evaluated as the best, presents a capacity of 800 Kg, the second a capacity of 1100 Kg. The two options of 15° and 22,5°, for the Ω decision, are equally present in the first positions. This is not the final result because only three decision areas were analysed. When all the DA are integrated in a global scheme, a similar result will indicate the best solutions. At the present the result of

Figure 4.2-4 can be used, again, to reduce the decision problem elements. The options 45° and 30°, in the DA OMEGA, can be eliminated because they are never connected to the best solutions.

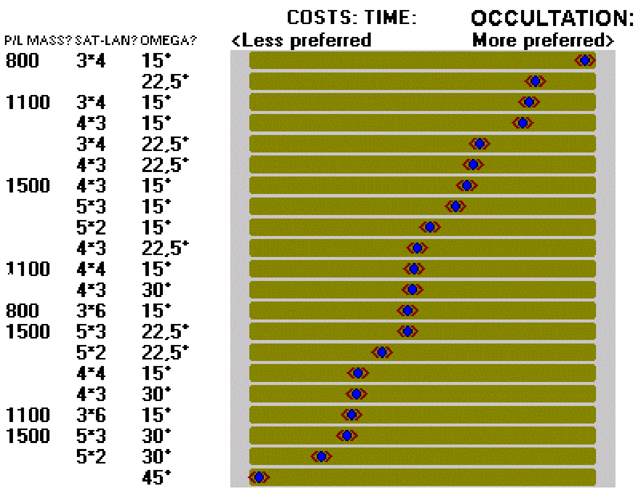


Figure 4.2-4 Result of the first step

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[1] The assumption, at this level of details, is that OMEGA does not affect the number of occultation.

[2] The Strategic Choice Approach suggests a multicriteria synthesis of the different comparisons that is more qualitative than analytical. The aim is discriminating the really different situations. An analytical comparison (for instance with ELECTRE) is required to distinguish "similar" situations.

Three of the seven DA of
Figure 4.2-1 were analysed in the firs step because they can be seen as the most interconnected sub-graph of the global graph. All the decision options were identified and some of them were excluded because not admissible or incompatible with other decision options. At this point the other four DA have to be analysed. They are relative to the Power Subsystem design (i.e. the decisions on the solar array and the battery type), to the Propulsion subsystem design (the decision on the propellant type) and to the Spacecraft configuration and pointing strategy (the decision on the pointing strategy).
Two options can be considered for the Solar Array Cell (Single Junction Gallium Arsenide or Multi Junction Gallium Arsenide) and again two options for the Battery Cell: Nickel hydrogen (NiH2) and Litium-Ion. The four combinations of these options can be analysed together. POINTING is the DA that aims at the best pointing strategy with respect to the total system resources. Two options can be considered for Pointing Strategy: Earth Pointing and Sun Pointing. Two options are possible, in terms of propellant type, to minimise the propellant mass and the tank volume and mass: mono and bipropellant. The DA is PROPULSION, which is connected both with the POINTING and the SAT – LAN.

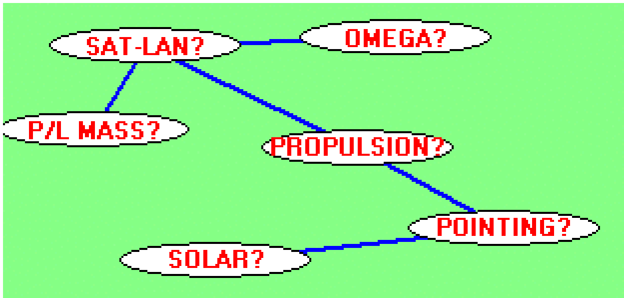
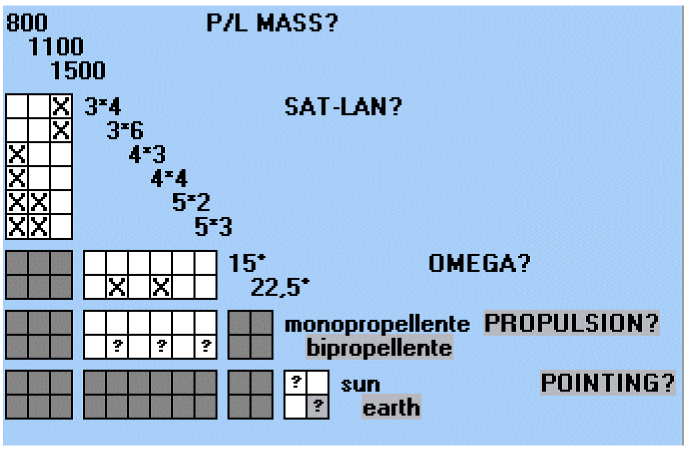


Figure 4.2-5 Six Decision Areas in focus

The analysis (Compatibility and Comparing) is developed step by step. The first step introduces only two DA and the Compatibility analysis between the options is presented in Figure 4.2-6.

The combinations between the new and the old DA are very limited (in the graph there is only the connection between PROPULSION and SAT –LAN and the relationship between the new DA). There is no one real incompatibility but some doubtful combinations that are indicated trough the question marks.



Legend: X = incompatible combination ? = doubtful compatibility
Figure 4.2-6 Compatibility analysis for five DA

The reasons are above all of economic efficiency and technical simplicity. Earth pointing needs (preferably) monopropellant and Sun pointing option does not require monopropellant. When the number of satellites is very high (15, 16 or 18) and therefore the mission is more expensive, the less expensive propellant may be more adequate[3].

With two more DA the number of combinations grows and the model evaluation is always the same. Only on of the three Comparison areas is adequate for the new PROPULSION and POINTING areas (see
Figure 4.2-7) and its discrimination is only marginal for POINTING. It means that a new CA should be identified and specifically oriented to the POINTING decision area.

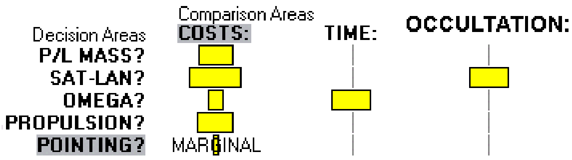


Figure 4.2-7 Significance of the CA for five DA

The results of the comparisons (see
Figure 4.2-8) are not so different from the previous ones, but the discrimination between the solutions is now more evident. The choice of 12 satellites is constant in the three first ‘blocks’ of solutions. The limitation of SAT – LAN at two options (3x4 and 4x3) can be applied in parallel to the introduction of the last decision area.

There are no more incompatibilities (see
Figure 4.2-9) and the evaluation model is always the same. It produces the result of figure 4.2-10. The solution includes a net indication of launcher capability (800 Kg) and launch strategy (3 satellites per 4 launches). The different combinations of OMEGA, PROPULSION, POINTING and SOLAR present a decreasing preference. The combination ‘monopropellant - earth pointing – single NiH2’ is preferred in terms of technical simplicity/economic efficiency. Some doubts (?) affect other combinations (sun, single-NiH2; sun, single-Li-Ion; sun, multi-NiH2; sun, multi-Li-Ion) that are therefore eliminated as too much risky or oriented to deeper studies. The two options of 15° and 22,5° are equally present and can be proposed to an optimisation of the correlated parameters.

[3] These motivations could be not so realistic. They have to be explicitly express and analyzed in the real decision process.

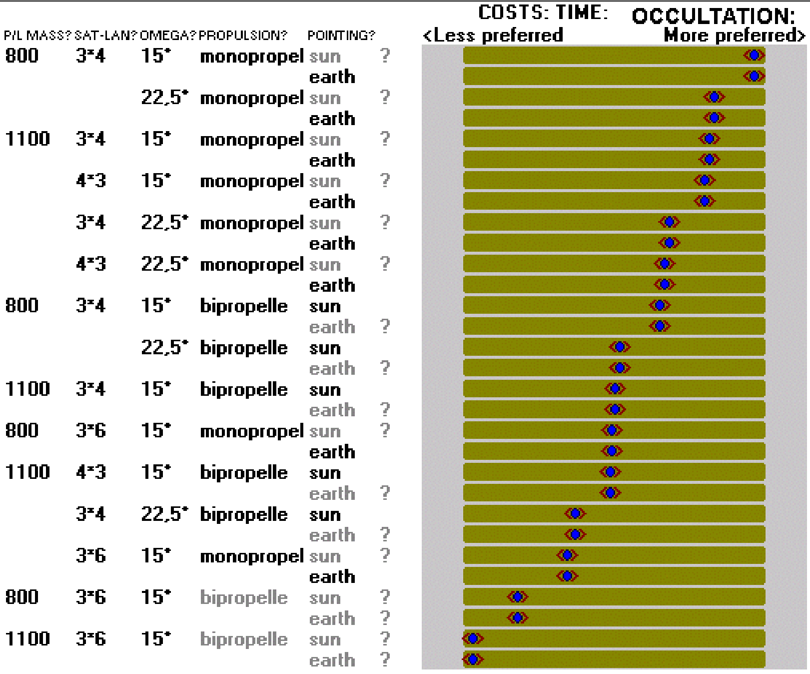
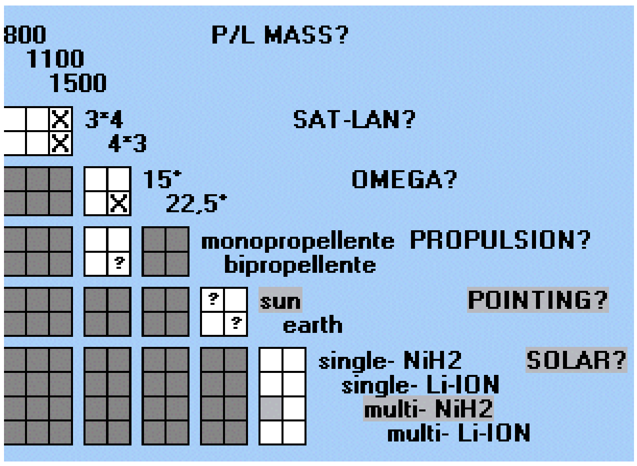


Figure 4.2-8 Result of the second step



Legend: X = incompatible combination ? = doubtful compatibility

Figure 4.2-9 Compatibility analysis for six DA

This limited set of solutions is the first result of the Strategic Choice Approach to the problem. The second is the incremental definition of an evaluation model that includes the costs, the waiting time and the number of occultation as possible criteria. A new and more oriented to the pointing strategy criterion could be useful. The set of alternatives of figure 4.2-10 should be analytically evaluated on the three (or four) criteria, after a phase of parameter optimisation, and an ELECTRE method can be used to arrive at the best solution. The application of ELECTRE to a similar model, for the MARS Mission, is presented in 6.3.

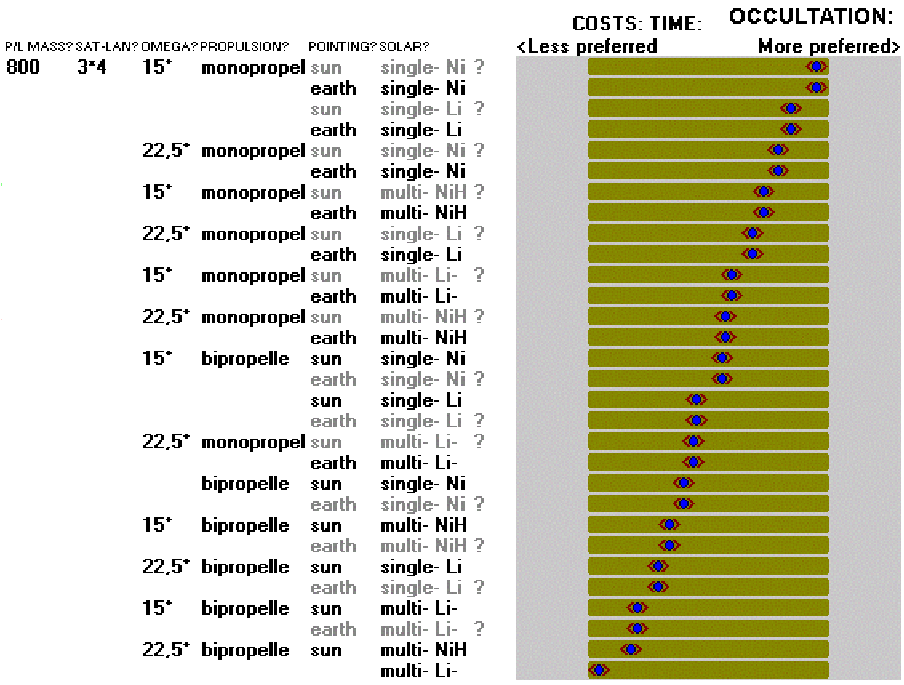


Figure 4.2-10 Result of the last step

5. MARS MISSION CASE STUDY

5.1 PRELIMINARIES

The Mars mission case study is a satellite on Mars orbit and acting as data relay antenna for a rover on Mars surface.

5.2 PROCESS MODEL

The task of the Mars mission case study is to manage the conflict between the RF subsystem of the rover and the power subsystem of the rover and to find the orbit that help to lower as much as possible the conflict between the two subsystems of the rover and that lower as much as possible the conflict between the rover it self, on one side, and the orbiter, on the other side.

The conflict between the two subsystems is:

- The rover RF subsystem wants to have the data volume per orbit as high as possible, that in turn means it wants to have RF power peak as high as possible.
- The rover power subsystem wants to have the solar panel as small as possible, that in turn means it wants to give to RF subsystems as low power peak as possible.

The conflict between the rover and the orbiter is:

- The rover RF subsystem wants to have the data volume per orbit as high as possible, that in turn means it wants to have Orbiter/Rover contact period as long as possible.
- The Orbiter, for the sake of other experiments (e.g. remote sensing), wants to have operations as simpler as possible, that in turns means the orbiter wants to stay on a circular orbit.

The example is a reduction of a real Mars missions. Where a rover needs to send data to Earth ground station via data relay orbiter.

5.2.1 Mission Analysis

In this simplified case the mission analysis gives the Orbiter/Rover contact period durations and Orbiter/Rover maximum range per contact period. The trade-off is between a circular orbit e.g. 500 x 500 km and several elliptic orbits, in order to find the best orbit that optimise the overall conflicts.

In this simplified case, instead of considering the data volume per martian day (as usual in this type of mission), we consider the data volume per overhead passage. This is not a reductive hypothesis; in fact, maximising the data volume per overhead passage gives the maximum data volume per martian day (This is only true for this "simplified case" where we just have overhead passage).

5.2.2 RF Subsystem

The RF subsystem is defined by means of the link budget equation, with all the technologic parameters taken from INTERMARSNET study (see RD 25), is:

$$P_T = \frac{d^2}{3.16 \cdot 10^{15}} \cdot R_b \qquad \textbf{(17)}$$

where P_T is the Transmitting Power [W], d is the Orbiter/Rover range [m] and R_b is the transmitting Bit Rate [bps]. The trade off is to find the Bit Rate that maximise the Data Volume [Mb] per Orbiter/Rover contact period.

5.2.3 Power Subsystem

The Power subsystem is defined by means of the equations and parameters as in 2.2.2; but, taking into account that the power P from solar array at 1.5 AU (average Sun/Mars distance) is $P=Po \cdot r^{-\alpha}$, where Po is the power from solar array at 1 AU (average Sun/Earth distance) and $\alpha=1.7$ instead of $\alpha=2$ because of the better performance of the solar cell for the major distance from the Sun, the relevant parameter for the solar array cells are as given in Table 5.2-1.

Single Junction GaAs	90 [W·m²]
Multi Junction GaAs	125 [W·m²]

Table 5.2-1 Characteristics of solar array cells at 1.5 AU

The trade off is to minimise as much as possible the solar array area for the sake of the very small room available in the Descent Module used to deliver the Rover onto the Mars Surface.

5.3 WORK BENCH

5.3.1 Mission Analysis

In following table the considered relay orbits are shown; where, hp is the perigee altitude, ha is the apogee altitude, a is the semi-major axis, e is the eccentricity, P is the period of the orbit, CT is the Orbiter/Rover ConTact period duration, Range is the maximum distance reached between the orbiter and the rover during the contact period.

hp [km]	ha [km]	a [km]	e	P [min]	CT [min]	Range [km]
500	500	3897	0.00000	123	7.5	820
500	1000	4147	0.06030	135	12.0	1252
500	2000	4647	0.16140	160	22.5	2373
500	5000	6147	0.36603	243	34.5	4164

Table 5.3-1 Relay Orbit Sizing Parameters

5.3.2 RF Subsystem

The Data Volume and the Trasmitting Power (Pt) as a function of Bit Rate (Rb) and Contact Time are given in Table 5.3-2, where the range as a function of Contact Time and the Energy, required to cope with the RF transmitting power peak, as a function of Contact Time are shown as well. Pt had been computed as explained in 5.2.2.

Contact Time [min]	range [km]	Pt [W]	Energy [Wh]	Rb [bps]
7.50	820.00	0.43	0.05	2000.00
12.00	1252.00	0.99	0.20	
22.50	2373.00	3.56	1.34	
34.50	4174.00	11.03	6.34	

Contact Time [min]	range [km]	Data Volume [Mbit]
7.50	820.00	0.90
12.00	1252.00	1.44
22.50	2373.00	2.70
34.50	4174.00	4.14

Contact Time [min]	range [km]	Pt [W]	Energy [Wh]	Rb [bps]
7.50	820.00	0.85	0.11	4000.00
12.00	1252.00	1.98	0.40	
22.50	2373.00	7.13	2.67	
34.50	4174.00	22.05	12.68	

Contact Time [min]	range [km]	Data Volume [Mbit]
7.50	820.00	1.80
12.00	1252.00	2.88
22.50	2373.00	5.40
34.50	4174.00	8.28

Contact Time [min]	range [km]	Pt [W]	Energy [Wh]	Rb [bps]
7.50	820.00	1.28	0.16	6000.00
12.00	1252.00	2.98	0.60	
22.50	2373.00	10.69	4.01	
34.50	4174.00	33.08	19.02	

Contact Time [min]	range [km]	Data Volume [Mbit]
7.50	820.00	2.70
12.00	1252.00	4.32
22.50	2373.00	8.10
34.50	4174.00	12.42

Contact Time [min]	range [km]	Pt [W]	Energy [Wh]	Rb [bps]
7.50	820.00	1.70	0.21	8000.00
12.00	1252.00	3.97	0.79	
22.50	2373.00	14.26	5.35	
34.50	4174.00	44.11	25.36	

Contact Time [min]	range [km]	Data Volume [Mbit]
7.50	820.00	3.60
12.00	1252.00	5.76
22.50	2373.00	10.80
34.50	4174.00	16.56

Contact Time [min]	range [km]	Pt [W]	Energy [Wh]	Rb [bps]
7.50	820.00	2.13	0.27	10000.00
12.00	1252.00	4.96	0.99	
22.50	2373.00	17.82	6.68	
34.50	4174.00	55.13	31.70	

Contact Time [min]	range [km]	Data Volume [Mbit]
7.50	820.00	4.50
12.00	1252.00	7.20
22.50	2373.00	13.50
34.50	4174.00	20.70

Table 5.3-2 Rover RF Subsystem Sizing Parameters

5.3.3 Power Subsystem

In order to size the Rover solar array the following assumptions, in Table 5.3-3, had been done.

	(A)	(B)	
SA specific power (area)	125.00	90.00	W/m^2
SA specific power (mass)	70.00	38.00	W/kg
Battery specific energy (mass)	150.00	55.00	Wh/kg
Battery specific enerrgy (volume)	399.00	60.00	Wh/l
Deep of discharge	0.50	0.50	
Power from SA per day to S/S	16.00		W
Night	12.00		h
Day	12.00		h
SAA angle	45.00		deg

Table 5.3-3 Rover Power Subsystem Assumptions

Further, it must be reminded that:

- The RF Power Peak is charged on the battery. This is the first thing to do in order to have solar array as small as possible, on the other hand the battery mass will be higher. A check at system level will see if battery mass is compatible with the Rover overall mass.

- The night period is equal to the day period. This is a worst condition as the Rover mission usually is during Mars summer period of the chosen hemisphere. That is day period longer than night period.

- The latitude of the Rover site on Mars surface is between 0° and 23.5°. This means that the average solar aspect angle is 45°, taking into account the daily variation SAN that is from 0° up to 90°.

In the following
Table 5.3-4 the solar array area and mass, and the battery volume and mass, for both (A) and (B) options (see Table 5.3-3), are given as a function of the energy required to cope with the RF transmitting power peak. The solar array area and mass, and battery volume and mass had been computed from the Energy from battery per night to S/S and for R/F peak, and from Total power from Solar Array as explained in 2.2.2.1 and considering
Table 5.2-1. The Energy from battery per night to S/S and for R/F peak, and from Total power from Solar Array as a function of the energy required to cope with the RF transmitting power peak are shown in
Table 5.3-4, as well.

Tx Energy [Wh]	Energy from battery per night to S/S, and for RF peak [Wh]	
0.05	12.05	
0.50	12.50	
1.00	13.00	
5.00	17.00	
10.00	22.00	
20.00	32.00	
30.00	42.00	
31.00	43.00	
Tx Energy [Wh]	Total Power from Solar Array [W]	
0.05	24.05	
0.50	24.10	
1.00	24.16	
5.00	24.63	
10.00	25.22	
20.00	26.40	
30.00	27.58	
31.00	27.70	
Tx Energy [Wh]	SA Area (A) [m²]	SA Area (B) [m²]
0.05	0.19	0.27
0.50	0.19	0.27
1.00	0.19	0.27
5.00	0.20	0.27
10.00	0.20	0.28
20.00	0.21	0.29
30.00	0.22	0.31
31.00	0.22	0.31
Tx Energy [Wh]	SA Mass (A) [kg]	SA Mass (B) [kg]
0.05	0.34	0.63
0.50	0.34	0.63
1.00	0.35	0.64
5.00	0.35	0.65
10.00	0.36	0.66
20.00	0.38	0.69
30.00	0.39	0.73
31.00	0.40	0.73
Tx Energy [Wh]	Battery Volume (A) [m^3]	Battery Volume (B) [m^3]
0.05	0.16	0.44
0.50	0.17	0.45
1.00	0.17	0.47
5.00	0.23	0.62
10.00	0.29	0.80
20.00	0.43	1.16
30.00	0.56	1.53
31.00	0.57	1.56
Tx Energy [Wh]	Battery Mass (A) [kg]	Battery Mass (B) [kg]
0.05	0.06	0.40
0.50	0.06	0.42
1.00	0.07	0.43
5.00	0.09	0.57
10.00	0.11	0.73
20.00	0.16	1.07
30.00	0.21	1.40
31.00	0.22	1.43

Table 5.3-4 Rover Power Subsystem Sizing Parameters

5.3.4 Conclusions

In order to find the optimal solution, that is the solution maximising the data volume while lowering the transmitting power (i.e. the solar array mass) and looking for an orbit as near as possible to a circular orbit (i.e. operations as simpler as possible), the definition of the I_{eff} efficiency index is very useful:

$$I_{eff} = \frac{DV}{P_T} \qquad (18)$$

where DV is Data Volume [Mb] and PT is the RF Transmitting Power Peak [W]. A look at the following Table 5.3-5 will let us find the optimal solution. The optimal solution is the one with I_{eff} as much as possible near to 1 value. The optimal solution has been found looking at the tables with the sizing parameters of the rover subsystems (see Table 5.3-2 and Table 5.3-4). For a given Solar Array Area (SAA) a Tx Energy value is fixed and all the Data Volume with Tx Energy value near by the fixed one are considered. The I_{eff} says which is the optimal solution.

SAA	0.19	m²		
Tx Energy	0.05	Wh		
Rb [bps]	Energy [Wh]	Pt [W]	DV [Mb]	Ieff
2000	0.05	0.43	0.90	2.0930
4000	0.11	0.85	1.80	2.1176
6000	0.16	1.28	2.70	2.1093
8000	0.21	1.70	3.60	2.1176
10000	0.27	2.13	4.50	2.1127

SAA	0.20	m²		
Tx Energy	5.00	Wh		
Rb [bps]	Energy [Wh]	Pt [W]	DV [Mb]	Ieff
2000	6.34	11.03	4.14	0.3753
6000	4.01	10.69	8.10	0.7577
8000	5.35	14.26	10.80	0.7574
10000	6.68	17.82	13.50	0.7575

SAA	0.22	m²		
Tx Energy	31.00	Wh		
Rb [bps]	Energy [Wh]	Pt [W]	DV [Mb]	Ieff
8000	25.36	44.11	16.56	0.3754
10000	31.70	55.13	20.70	0.3755

Table 5.3-5 Optimal Solution

It is now possible to say that the optimal solution is:

Rb = 6000 Bps, SAA = 0.20 m², Battery mass = 0.09 kg and Operative Orbit = 500 x 2000 km

This means that the orbit is not very far from the circular one, the battery mass is compatible with an overall mass of the rover equal to 16 kg (see RD 26), the solar array area is quite small compared with a maximum allowable area of 0.25 m² (see RD 26) and the data volume is very close to the 10 Mb data volume per day of INTERMARSNET mission.

6. APPLYING THE MULTIDISCIPLINARY OPTIMISATION SOFTWARE PROTOTYPE TO THE MARS MISSION CASE STUDY

6.1 MARS MISSION STRUCTURE

In order to implement the local optimisers able to compute the solutions outputs, it is useful to analyse the MARS mission structure taking also into account the conflicts described in section 5.2. This mission presents three constituent subsystems, shown in Figure 6.1-1.

- The Mission Analysis subsystem receives in input the Contact Time and returns the chosen orbit computed by means of the ha value.
- The RF subsystem, starting from the Contact Time and the Transmitting Bit Rate, returns the Data Volume sent to the Ground station.
- The Power subsystem, through Bit Rate and Contact Time input, computes the solar array dimension.

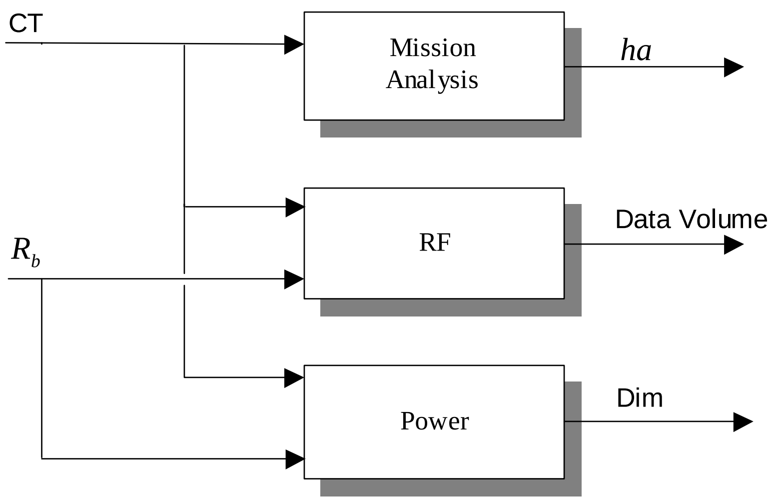


Figure 6.1-1 Subsystems structure

All the parameters can be divided into two categories:

- Input parameters:

Description	Parameter	Range
Transmitting Bit Rate	R_b	2000 ÷ 10000 W
Contact Time	CT	7.50 ÷ 34.5 min

- Output parameters:

Description	Parameter	Range
Apogee altitude	Ha	500 ÷ 5000 km
Data send to Ground station	Data Volume	5 ÷ 20 Mb
Solar array size	Dim	0.19 ÷ 0.22 m^2

6.2 NEIGHBOURHOOD SEARCH APPROACH

In order to generate the set of Paretian solutions by means of the Neighbourhood Search approach the following items must be defined:

- Starting solutions set
- Solution representation
- Neighbourhood generation
- Tabu List management
- Acceptance and stopping tests

6.2.1 Starting solution set

It includes the starting solutions set, typically composed by non dominated (Paretian) solutions, computed and analysed by space missions experts. Its minimum cardinality is two, but the algorithm can be easily conformed to more than two solutions, for instance by applying its two-cardinality version over all pairs of starting solutions. The goal of the algorithm, starting from the first solution (called 'starting solution'), is to reach the other one (called 'final solution'), moving through the current solution's neighbourhood generated each time. Among all the neighbours we select a Paretian one (or the best non Paretian if the neighbourhood contains no Paretian solutions) which is closer to the final solution than the current solution.

6.2.2 Solution representation

A generic solution is represented by the following structure:

- subsystems input values: an array sized according to the number of inputs;
- subsystems output values: a matrix whose lines correspond to the subsystems identifier numbers and whose columns correspond to its own output values;
- comparable outputs sums: an array sized according to the number of outputs.

For example, referring to the WATS mission and reminding that it is characterized by six inputs and three subsystems, each of them computing one output value, a feasible solution could assume the aspect shown in Figure 6.2-1.

Input values

14	2	200	2	1	2

Output matrix:

120	-
-	78
-	140

Comparable outputs sum

120	218

Figure 6.2-1: Solution representation

6.2.3 Neighbourhood generation

It is generated by setting each time a different input parameters configuration: possible movements for each parameter can be described as follows:

- Its value does not change (0)
- Its value decreases the distance from the final solution (+1)
- Its value increases the distance from the final solution (-1)

During each iteration, the current solution's neighbourhood is generated and the neighbour solutions are evaluated. The current solution is obtained at the end of the previous iteration by choosing the neighbour solution nearest to the final one, except for the first iteration where it coincides with the starting solution. The neighbourhood is generated by fixing the first current solution input value and its two adjacent ones, and varying the other values according to the RANGE parameter defined at the beginning.

For example, suppose that the current solution is (9 min – 2800 bps), where the Contact Time must be included in the interval 7.5 / 34.5 min with a 0.5 min step, and the Bit Rate must be included in the interval 2000 / 10000 bps with a 100 bps step. Suppose that the RANGE parameter is set to 4, the resulting neighbourhood is composed by the following solutions: (9 – 2400), (9 – 2500), (9 – 2600), (9 – 2700), (9 – 2900), (9 – 3000), (9 – 3100), (9 – 3200), (8.5 - 2400), (8.5 - 2500), (8.5 - 2600), (8.5 - 2700), (8.5 - 2800), (8.5 - 2900), (8.5 - 3000), (8.5 - 3100), (8.5 - 3200), (9.5 - 2400), (9.5 - 2500), (9.5 - 2600), (9.5 - 2700), (9.5 - 2800), (9.5 - 2900), (9.5 - 3000), (9.5 - 3100), (9.5 - 3200).

6.2.4 Tabu List management

Tabu List (TL) is a structure typical of Tabu Search algorithms allocated to avoid loop situations, in which are memorised the moves related to the last visited solutions: for instance, ($\tilde{x}$, $\hat{x}$) is the move from solution $\tilde{x}$ to solution $\hat{x}$. If the pair ($\hat{x}$, $\tilde{x}$) belongs to that list, then the procedure is not able to move from $\tilde{x}$ to $\hat{x}$ for a certain number of successive moves. TL has been implemented as a circular list, managed employing a FIFO (First In First Out) strategy. Implementing a TL strongly reduces the probability of entrapments into loops involving the revisit of solutions previously explored.

6.2.5 Acceptance and stopping tests

With reference to the set of best solutions found so far by the algorithm, for each processed solution the following three situations may occur:

- it is dominated by one of the solutions of the best solutions set;
- It is Paretian with respect to the best solutions set;
- It dominates one of the solutions of the best solutions set.

The concept of Pareto dominance is considered where different actions are to be compared on the basis of their consequences; problems with multiple objectives do not have a unique optimal solution, but a set of Pareto-optimal solutions: unfortunately, this concept almost always gives not a single solution, but rather a set of solutions called the Pareto optimal set (the above best solutions set).
Aim of the procedure is to find a set of Paretian solutions along the path (within the solutions space) connecting starting and final solution , comparing each time the current solution with the Paretian set on the basis of the previously discussed criteria.

With respect to the stopping test, it can be typically performed in many different ways:

- the algorithm's execution ends due to time limits;
- the algorithm's execution ends after N (fixed) iterations;
- the algorithm's execution ends if the number of accepted moves is smaller than a threshold for M (fixed) successive iterations;
- the algorithm's execution ends if the best solutions set did not change for P (fixed) iterations;
- the algorithm's execution ends once the final solution is reached.

The proposed stopping test is a combination of the second and the last alternatives. If the final solution has not been found after N iterations, the execution is stopped. This option guarantees that the starting and final solutions, given by space mission's experts and typically considered good ones, do still have a chance to be included in the best (Paretian) solutions set.

6.2.6 Main steps of the Neighbourhood Search algorithm for the Mars mission

1. Initialisation
   a. Define two solutions that constitute the initial best solutions set B_s.
   b. Read the input correspondence matrix.
   c. Local optimisers implementation (operation independent from the algorithm).
   d. Randomly choose starting solution x_i inside the best solutions set B_s.
   e. Assign the other solution to the final solution x_f.
   f. Assign x_i to the best solutions set B_s.
   g. Let x_i be the current solution: $\tilde{x} = x_i$.
   h. Clear TL.
2. Current solution's neighbourhood generation $N(\tilde{x})$ according to the defined rules. If $B(\tilde{x})$ represents the solutions Paretian to each other within the neighbourhood $N(\tilde{x})$. Then:
   a. If these solutions are dominated by at least one solution belonging to set B_s, then the new current solution $\tilde{x}$ is the solution in $B(\tilde{x})$ closest to x_f.
   b. If any of these solutions is Paretian with respect to B_s, then
      i. Update set B_s by inserting the new Paretian solutions.
      ii. Update TL.
      iii. The new current solution $\tilde{x}$ is the solution in $B(\tilde{x})$ closest to x_f.
   c. If any of these solutions dominates one or more solutions belonging to B_s, then
      i. Update set B_s by inserting the new Paretian solutions and deleting from B_s the dominated ones.
      ii. Update TL.
      iii. The new current solution $\tilde{x}$ is the solution in $B(\tilde{x})$ closest to x_f.
3. If $\tilde{x} = x_f$ (final solution found) STOP, else GOTO step 4.
4. If the stopping test is satisfied STOP, else GOTO step 2.

6.2.7 Computational results

We considered (Contact time: 7.5 min – Transmitting Bit Rate: 4000 bps) as starting solution and (Contact Time: 34.5 min – Transmitting Bit Rate: 8000 bps) as final solution, according to the following input parameters ranges:

- Contact Time $7.5 \div 34.5 [\mathrm{min}]$ with 0.5 min step
- Transmitting Bit Rate $2000 \div 10000 [bps]$ with 100 bps step

In the application of the procedure, the parameters discussed in sections 6.2.4 and 6.2.5 were set as follows:

- Tabu List size = 5
- RANGE = 4

Looking at the solutions generated, we notice that the same efficiency index corresponds to multiple solutions: in Table 6.2-1 is summarised the set of solutions presenting the minimum and maximum efficiency index respectively.

CT (min)	Rb (bps)	ha (km)	DV (Mb)	Dim (m^2)	Efficiency index
17,5	4800	1500	5,04	0,1931	1,036
17,5	4900	1500	5,15	0,1932	1,036
32,5	7700	4200	15,02	0,2089	0,388
33	7700	4400	15,25	0,2107	0,388
33,5	7700	4600	15,48	0,2125	0,388

Table 6.2-1 Efficiency index summary

From
Table 6.2-1 we notice that the efficiency index is not able to indicate the best solution, but it is useful to individuate a set of good solutions not so far one to another. According to the starting and final solutions defined above and the related parameters, the algorithm needs 19 iterations to produce the set of Paretian solutions depicted in Table 6.2-2.

Sol #	Ha [km]	Data Volume [Mb]	Dim [m2]	Efficiency Index
A0001	1471	5,04	0,193	1,0364
A0002	1472	5,15	0,193	1,0364
A0003	1517	5,18	0,194	1,0020
A0004	1517	5,29	0,194	1,0020
A0005	1610	5,36	0,194	0,9068
A0006	1610	5,47	0,194	0,9373
A0007	1610	5,59	0,194	0,9373
A0008	1610	5,70	0,194	0,9373
A0009	1659	5,73	0,195	0,9373
A0010	1659	5,85	0,195	0,9373
A0011	1709	5,88	0,195	0,9068
A0012	1709	6,00	0,195	0,9068
A0013	1818	6,05	0,196	0,8776
A0014	1818	6,17	0,196	0,8225
A0015	1818	6,30	0,196	0,8225
A0016	1818	6,43	0,196	0,8225
A0017	1875	6,45	0,196	0,8225
A0018	1875	6,58	0,196	0,8225
A0019	1936	6,60	0,197	0,7966
A0020	1936	6,73	0,197	0,7966
A0021	2067	6,76	0,197	0,7717
A0022	2067	6,90	0,197	0,7248
A0023	2067	7,04	0,198	0,7248
A0024	2067	7,18	0,198	0,7248
A0025	2137	7,19	0,198	0,7248
A0026	2137	7,33	0,198	0,7248
A0027	2211	7,34	0,198	0,7027
A0028	2211	7,49	0,198	0,7027
A0029	2370	7,95	0,199	0,6814
A0030	2457	8,11	0,199	0,6413
A0031	2457	8,26	0,199	0,6413
A0032	2457	8,42	0,199	0,6413
A0033	2457	8,57	0,199	0,6413
A0034	2457	8,72	0,199	0,6223
A0035	2547	8,74	0,200	0,6223
A0036	2547	8,89	0,200	0,6041
A0037	2643	8,90	0,200	0,6223
A0038	2643	9,06	0,200	0,6223
A0039	2211	7,63	0,198	0,6223
A0040	2288	7,79	0,199	0,6223
A0041	2211	7,78	0,198	0,6223
A0042	2288	7,94	0,199	0,6041
A0043	2370	8,10	0,199	0,6041
A0044	2849	9,57	0,200	0,5866
A0045	2960	9,74	0,200	0,5534
A0046	2960	9,91	0,200	0,5534
A0047	2960	10,08	0,200	0,5534
A0048	2960	10,25	0,200	0,5534

Sol #	ha [km]	Data Volume [Mb]	Dim [m2]	Efficiency Index
A0049	2960	10,42	0,200	0,5377
A0050	3077	10,43	0,200	0,5377
A0051	3077	10,60	0,201	0,5226
A0052	3200	10,61	0,201	0,5377
A0053	3200	10,79	0,201	0,5377
A0054	2643	9,22	0,200	0,5377
A0055	2743	9,40	0,200	0,5377
A0056	2643	9,38	0,200	0,5377
A0057	2743	9,56	0,200	0,5226
A0058	2849	9,74	0,200	0,5226
A0059	3463	11,34	0,201	0,5081
A0060	3605	11,53	0,202	0,4805
A0061	3605	11,71	0,202	0,4805
A0062	3605	11,90	0,202	0,4805
A0063	3605	12,08	0,202	0,4805
A0064	3605	12,26	0,202	0,4675
A0065	3753	12,28	0,203	0,4675
A0066	3753	12,46	0,203	0,4548
A0067	3908	12,47	0,203	0,4675
A0068	3908	12,66	0,203	0,4675
A0069	3200	10,96	0,201	0,4675
A0070	3328	11,15	0,201	0,4675
A0071	3200	11,14	0,201	0,4675
A0072	3328	11,33	0,201	0,4548
A0073	3463	11,52	0,201	0,4548
A0074	3908	12,85	0,204	0,4427
A0075	4071	13,06	0,205	0,4196
A0076	3908	13,04	0,204	0,4196
A0077	4071	13,25	0,205	0,4196
A0078	4603	15,28	0,212	0,4196
A0079	4797	15,50	0,214	0,4087
A0080	4071	13,63	0,205	0,4087
A0081	4071	13,82	0,206	0,3981
A0082	4241	14,04	0,207	0,4087
A0083	4071	14,02	0,206	0,4087
A0084	4241	14,24	0,207	0,4087
A0085	4797	15,71	0,214	0,4087
A0086	4797	15,91	0,215	0,4087
A0087	4797	16,12	0,215	0,3981
A0088	4797	16,32	0,216	0,3981
A0089	4998	16,35	0,217	0,3981
A0090	4998	16,56	0,218	0,3981
A0091	4241	14,63	0,208	0,3981
A0092	4241	14,82	0,209	0,3981
A0093	4418	15,05	0,210	0,3981
A0094	4241	15,02	0,209	0,3879
A0095	4418	15,25	0,211	0,3879
A0096	4603	15,48	0,213	0,3879

Table 6.2-2 Paretian solutions

6.3 THE GAME THEORETIC APPROACH FOR THE MARS MISSION

We describe the algorithms for computing the Nash equilibrium in pure strategy for the non co-operative game and the Nash solution and Kalai-Smorodinsky solution for the associated bargaining problem (co-operative game without side payments).

Nash equilibrium

We suppose that the game is represented in strategic form $(N, (\Sigma_i)_{i \in N}, (\pi_i)_{i \in N})$, where $N = \{1,...,i,...,n\}$is the set of the players, Σ_i is the set of strategies of player i, and π_i is the payoff function of player i, that assigns to each strategy profile $(\sigma_1,...,\sigma_n)$ his payoff $\pi_i(\sigma_1,...,\sigma_n)$.

For each player i, $i \in N$ consider each strategy profile of the players different from i, denoted by σ_{-i}; for each σ_{-i} determine the best reply of player i, i.e. the strategy $\sigma_i \in \Sigma_i$ with the highest payoff $\pi_i(\sigma_{-i},\sigma_i)$.

The strategy profiles containing only best replies are the Nash equilibriums of the game.

Nash solution

Taking into account the reduced size of the model (we have an approximation of the Pareto boundary made up by 96 points), which considers a small number of Pareto optimal solutions it is more efficient to use a special purpose algorithm instead of a general one.

Let $PO = \{(x^j_1,..., x^j_n)_{j = 1,..., p}\}$ be the set of Pareto optimal solutions, where in this case p assumes the value 96; for each $j = 1,..., p$ compute the Nash product $\prod_{i \in N} (x^j_i - d_i)$ and take as Nash solution the Pareto optimal point for which the value of the product is maximal. $(d_i)_{i \in N}$ is the disagreement point, that can be represented by the null solution (0, ..., 0) if nothing is done without an agreement or by the Nash solution if it is unique. Only individually rational points are considered, i.e. those points such that $x^j_i \geq d_i$ for each $i \in N$.

Kalai-Smorodinsky solution

Also in this case it is more efficient to use a special purpose algorithm instead of a general one.

Let $u_i = \max \{x^j_i, j = 1,..., p\}$ for each $i \in N$ and let $(u_1,..., u_n)$ the "utopia point". Consider the line through the disagreement point and the utopia point and compute the distance of each point in PO from this line; the Kalai-Smorodinsky solution is the nearest point.

The case study considers three players corresponding to the apogee altitude, data volume and solar array size. The data are those used in the other approaches, obtained having in input pairs of contact time and transmitting power.

In order to define the utility of each player two steps were performed:

- the utility for apogee altitude and solar array size are reversed in the sense that the lower is the value the higher is the utility;
- the utilities are normalised in the interval [0, 1000].

The computation of Nash equilibriums was omitted as starting from a set of Paretian solutions (quite) all of them result in Nash equilibriums.

For the bargaining problem, with disagreement point (0; 0; 0), the Nash solution (solution nr. A0049, see Table 6.2-2), using the algorithm presented above, corresponds to the pair (28.000; 6200.000) for contact time and transmitting power, with apogee altitude, data volume and solar array size equal to 2960, 10.42 and 0.200, respectively; the normalized utilities associated to these values are 577.983, 466.667 and 705.309. The Kalai-Smorodinsky solution (solution nr. A0071, see Table 6.2-2), using the algorithm presented above, corresponds to the pair (29.000; 6400.000) for contact time and transmitting power, with apogee altitude, data volume and solar array size equal to 3200, 11.14 and 0.201, respectively; the normalised utilities associated to these values are 510.099, 529.167 and 688.632.

6.4 THE MULTICRITERIA DECISION ANALYSIS APPLICATION TO THE MARS MISSION

The Neighbourhood generation of results for the ELECTRE application produced a matrix with alternative solutions, as rows, and evaluations of each solution on each criterion, as columns. The columns correspond to the criteria, which are a decisional expression of preference, as the relative importance of each criterion[4]. The matrix the Neighbourhood search generated presents ninety-six rows and four columns. The decisional indication is that the first three criteria have the same importance and the fourth can have the same importance of the others.

The criterion g_4 is the expression of an efficiency measurement (the ratio between the Data Volume and Transmission Power indices) that can be used as criterion with some prudence. The Data volume is another criterion (g_2) and therefore there is a correlation between these two elements of the model. Each correlation between factors has to be avoided in most Multicriteria methods. ELECTRE III, as all the other outranking methods, can accept some correlation elements because the aggregation between evaluations is not a sum of values (it can be described as a concordant synthesis of positions), but in any case this kind of criterion has to be analysed attentively.

In this case, the criterion is accepted as the expression of a risk (of choosing a not efficient solution), but its weight may be indicated as lower than the other criteria. At the same time a veto threshold is imposed to express the concept of risk more operationally in the algorithm (the veto is introduced in the outranking relation model when there is risk, in this case of choosing a very little efficient solution, comparatively with another which presents worse performances on the other criteria but a really better index of efficiency). There are two scenarios of weights, because two are the different indications of minimum weight for g_4, and a third scenario that accepts the decisional indication of four criteria all with the same weight.

Table 6.4-1 contains the details of the model for ELECTRE, in terms of criteria, thresholds and weights (or importance coefficients). The thresholds are three, two discrimination thresholds (q_j and s_j) and a veto threshold (v_j). The veto threshold is introduced only for the fourth criterion and for the first and the second scenarios. The meaning of this threshold had been explained in relation to the criterion Efficiency. The other two thresholds are connected, the first, to possible errors in the data and, the second, to a possible uncertainty in the preference expression.

	MC model	Thresholds	Weights	Weights	Thresholds	Weights
g_j	**Criteria**	**I set**	**I scenario**	**II scenario**	**II set**	**III scenario**
g_1	**Apogee altitude**	**q=0 s=100**	**0.30**	**0.27**	**q=0 s=100**	**0.25**
g_2	**Data volume**	**q=1 s=2.5**	**0.30**	**0.27**	**q=1 s=2.5**	**0.25**
g_3	**Solar array size**	**q=0 s=0.002**	**0.30**	**0.27**	**q=0 s=0.002**	**0.25**
g_4	**Efficiency**	**q=0 s=0.05 v=0.3**	**0.10**	**0.19**	**q=0 s=0.05**	**0.25**

Table 6.4-1 Three variations of the MC model

The evaluations normally present some elements of informative uncertainty and q_j, *the indifference threshold*, is introduced to avoid that two very close evaluations can be considered different, because of the uncertainty in the data, and one of them can be preferred, when they really are not different. The *preference threshold*, s_j, is introduced when the preferential uncertainty requires the indication of a minimum interval (s_j) between two evaluations to express a net (or strong) preference in favour of the better one. The formal expression of these thresholds and their use in the ELECTRE III algorithm are detailed described in (Roy, 1996; Vincke, 1992). The thresholds q_j and s_j were defined in relation to the nature of the data and the decisional indications.

[4] The importance coefficient is indicated as 'weight' in this section because this term is the more general in the Multicriteria decision analysis context

The thresholds q_j and s_j were defined in relation to the nature of the data and the decisional indications.

The application of ELECTRE III to the data of Table 6.2-2 is not possible through the demo version of the ELECTRE III that presents some severe limitations (no more than six alternatives and five criteria). Therefore the global matrix was implemented through the commercial version of the SW ELECTRE III that gave some interesting results. The final partial graphs, which resulted from the application of ELECTRE III to each variation of the model (the three different sets of thresholds and scenarios of importance coefficients of
Table 6.4-1), are very complicated. The 'head' of each graph is proposed in
Figure 6.4-1,
Figure 6.4-2 and
Figure 6.4-3. All the alternatives that are referred to in the following Figures are those listed in Table 6.2-2.

The solutions A0002, A0001 and A0004 are always in the first positions. Interesting solutions are also A0008 and, with less stability, A0003. Actually a_3 is in a different position in the second result, where it is less interesting than A0008 (unlike the other two results) and incomparable[5] with A0008 and other solutions. Other interesting solution is then A0007 and, at a secondary level, the solutions A0010, A0006, A0049 and A0083. These four solutions are present, at least two times, between the alternatives that occupy the first seven levels in the rankings, and are in a lower position the third time, at the eighth level (A0010) or in the mid ranking, the others.

This very simple analysis of the three results should be made more robust through the comparative analysis of some other results, which can be obtained by a tuning of all the model parameters.

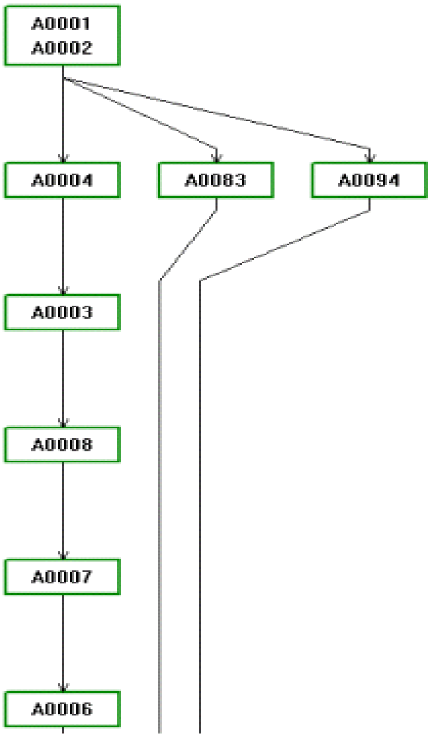


Figure 6.4-1 First result

[5] The incomparability is made evident through the presence of different paths in the partial graph. The solutions A0008 and A0003 are in the same path in
Figure 6.4-1 and
Figure 6.4-2, in two different paths in
Figure 6.4-3.

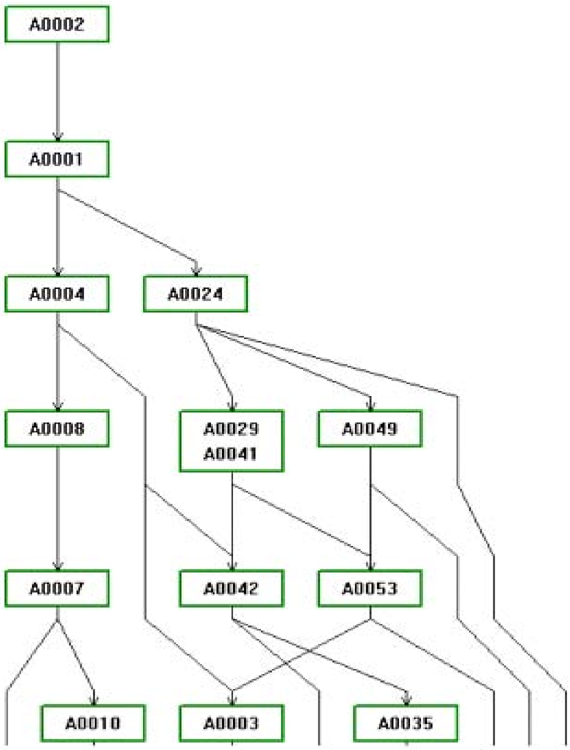


Figure 6.4-2 Second result

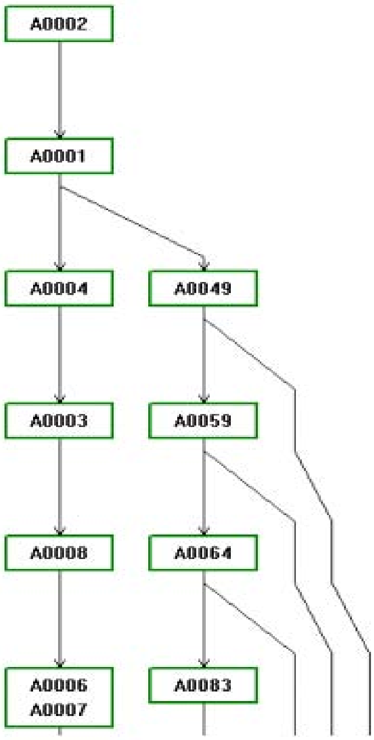


Figure 6.4-3 Third result

At this point, six solutions were chosen. They are A0002, A0004, A0008, A0024, A0029 and A0049. The demo version of ELECTRE III was used to compare these solutions. The first scenario of weights was used also in this last application, but a new set of thresholds was defined, because the informative and preferential uncertainties can be different when the solutions are only 6 of the original 96 (see

Table 6.4-2). The result, which is proposed in

Figure 6.4-4, is quite interesting. The first three solutions are not discriminated, and this is not so acceptable but the use of the other scenarios of weights can reduce this problem also this time (the first scenario resulted less discriminating than the others). Very interesting element is that now the graph is linear, without incomparability between solutions, and the ranking is consistent with the result of the global application.

MC model		Thresholds	Weights
g_j	Criteria	New set	I scenario
G_1	Apogee altitude	q=150 s=500	0.30
G_2	Data volume	q=0 s=1	0.30
G_3	Solar array size	q=0 s=0.004	0.30
G_4	Efficiency (DV/P_T)	q=0.05 s=0.10 v=0.3	0.10

Table 6.4-2 The last MC model

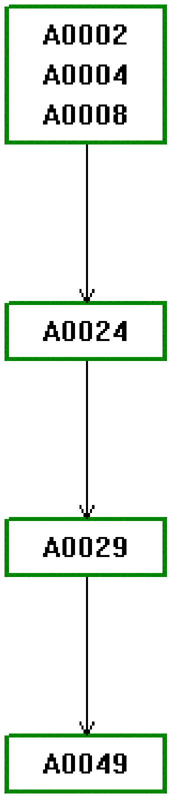


Figure 6.4-4 Result of the last model

6.5 FINAL REMARKS ON MARS MISSION

As we have seen, the Combinatorial Optimisation local search procedure based on the path re-linking strategy was able to generate from the two initial solutions provided a set of 96 Paretian solutions. This set represented then the input for the Game Theory and Multicriteria analysis approaches that evaluated these solutions and generated the related outputs.

With respect to the output generated by the Game Theory approach, it is worth to remark that the characteristic of the Nash solution (solution 49, according to Table 6.2-2) as it takes into account "what is given" to the players results also in a good quality solution for the multicriteria approach. On the other hand the Kalai-Smorodinsky solution (solution 71, according to Table 6.2-2) that consider not only "what is given" to the players but also "what they could be given" looks for a Paretian solution that leads all the players towards their maximal utility, instead to ask a small "sacrifice" to one player if the other two can greatly increase their utilities.

The Multicriteria Analysis does not propose a single solution, but a ranking of the evaluated solutions and it arrives at robust conclusions only after a robustness analysis on the model parameters. The presented result is only the first ranking and the solution 49 (Nash solution for the Game theory approach) is present in the head of the ranking, but it is not the best solution. The reason is that the multicriteria model includes four criteria and there is some discordance, for the solution 49, in relation to the last criterion Efficiency. Instead the solution 71 (the Kalai-Smorodinsky solution) is only in the mid ranking. Completing the Multicriteria Analysis application, until robust conclusions are obtained, could be interesting to analyse the final position of the solution 71 in the ranking.

7. CONCLUSIONS AND FUTURE DEVELOPMENTS

This document focuses on an advanced methodology aimed at supporting the space engineer to tackle conflicts arising in a project during its phases: subsystem targets are generally oriented differently, so that what could be optimal for a particular subsystem could be not optimal, or even unfeasible, for other subsystems.

An advanced Multidisciplinary Optimisation approach, innovative to the authors' knowledge, has been introduced, in order to provide the space engineer with a systematic methodology to face complex projects. It is based on a joint use of Combinatorial Optimisation, Game Theory and Multicriteria Analysis.

The Combinatorial Optimisation approach is oriented to look into the Paretian solutions for the whole system, on the basis of the specific target functions relative to each single subsystem. The Paretian solutions are all the non-dominated ones, i.e. the improvement of any subsystem solution implies the worsening of at least another subsystem solution. As a consequence, from the system point of view, all Paretian solutions are equivalent. Due to the complexity of the overall system, a heuristic approach based on local search techniques is applied to derive these solutions.

The Game theory and Multicriteria Analysis are introduced to compare the Paretian solutions. Game Theory search is oriented towards the 'fairness' of the solutions, Multicriteria Analysis towards a similar aim, the identification of the most robust compromise solution. In other words if a solution is very interesting according to many of the parameters (a ‘sufficient’ concordance of reasons) this will be considered very well according to multicriteria analysis, only if a very strong discordance (veto) is not present on at least one criterion. The same solution (very interesting according to many of the parameters) will results in an interesting game theoretical solution only if the other criteria (players) are not too much penalised. The proposed methodology, which elaborates and then compares Paretian solutions, is not aimed at finding the optimal solution in the absolute sense of the term, but at helping to select a solution that is beyond all criticism.

A basic scenario, relative to the WATS mission, has been selected as starting point for the whole study reported in this document. It is described in Chapter 2. This case study is considered from the engineering point of view first. The Mission Analysis, the Power and Pointing subsystems have been selected as reference disciplines. The conceptual aspects of the project are described, pointing out conflicts and trade-offs. Technical details from the engineering point of view have been purposely neglected in order to emphasise the methodological aspects.

Chapter 3 is entirely dedicated to describe the proposed methodology and Chapter 4, starting from the alternative solutions reported in Chapter 2 for the WATS case, applies the Game theory to show the philosophy of the approach. The Multicriteria Analysis (in the same Chapter 4) uses a multicriteria approach (the Strategic Choice Approach) to elaborate a complete set of admissible solutions and the criteria to evaluate the solution set.

A software prototype has been developed to illustrate the susceptibility of the proposed methodology to be extended and 'automated', giving rise to a general decisional support system applicable to a wide class of practical cases. A demonstrative case study, dealing with a simplified Mars mission, is described in Chapter 5. This case study is analysed by means of the software prototype, in Chapter 6, where a set of 96 Paretian solutions is first generated by the Combinatorial Optimisation local search procedure. This set is then evaluated by means of the Game Theory and Multicriteria analysis approaches generating in output a strongly restricted subset of solutions to be proposed to the final decision maker as viable compromise solutions (see the previous paragraph for some discussion on the characteristics of the proposed solutions)

On the basis of the analyses performed and the obtained results, the methodology proposed results in being quite promising to tackle quite complex conflicts arising in space engineering. A future activity could include further subsystems (e.g. Thermal or Structural) as well as the development of a comprehensive decision support system addressed to efficiently support the whole life cycle of complex space programs.

With respect to this latter issue, an enhancement in the integration of the considered approaches could be searched in the generation of the Paretian solutions. Indeed, the proposed local search approach, while generating non dominated solutions, moves from the initial solution to the final solution by iteratively updating the current solution where the new current solution belongs to the neighbourhood of the old one. This implies that in each iteration typically a subset of neighbour Paretian solutions (with respect to the current one) exists, but only one of these neighbours must be selected as new current solution. Indeed, this can be viewed as an evaluation process among the solutions of this subset that could be performed by means of the Game Theory / Multicriteria analysis approaches.

8. APPENDIX 1: MATH PROGRAMMING FORMULATION (MISSION ANALYSIS)

The mission analysis problem described in 2.2.1 is analysed here (in a simplified and reduced form) by a Mathematical Programming point of view.
The problem is characterised by a non-linear optimal control structure, in the presence of additional constraints.
For each satellite (i) the following state equations (motion equations) and initial conditions are set:

(19-1)

$$r'_i(t) = v_i(t)$$

(19-2)

$$v'_i(t) = G[r_i(t)]$$

(20-1)

$$r_i(0) = r_{i0}(e, i, \omega, \Omega, \alpha)$$

(20-2)

$$r'_i(0) = v_{i0}(e, i, \omega, \Omega, \alpha)$$

where:

$t \in [0,T]$ is the time;

$G[r]$ is the gravity field vector;

r_{i0} is the initial position vector, (non-linear) function of the control variables e, i, ω, Ω, α (orbital parameters for satellite i);

v_{i0} is the initial velocity vector, (non-linear) function of the control variables e, i, ω, Ω, α;

e is the eccentricity;

i is the inclination;

ω is the argument of perigee;

Ω is the longitude of the ascending node;

α is the right ascension.

For each control variable (e, i, ω, Ω, α) an admissibility range is given.

Equation 1) defines the distance $d_{ij}[r_i(t), r_j(t)]$ between satellites (i) and (j) as (non-linear) function of $r_i(t)$ and $r_i(t)$. An *occultation event* occurs at time t if and only if :

(21)

$$R_E \le d_{ij}(t) \le R_E + h$$

where R_E is the earth radius and h is given by the instrument characteristics.

Longitude and latitude of a point P on the earth surface are given by equations (2) and (3).
A longitude-latitude *grid* is considered (representing a discretisation of the earth surface); the whole time period [0,T] is partitioned into sub-periods of duration τ (e.g. one day).

The following target functions are introduced:

- maximise the total number of *occultation events* in the whole period [0,T];
- maximise the *uniformity* of the *occultation events* distribution (on the longitude-latitude *grid*), during the whole period [0,T];
- maximise the *uniformity* of the *occultation events* distribution at τ level, for all τ, during the whole period [0,T].

Remarks

The overall problem becomes of finite dimension, once equations (20) are discretised (e.g. partitioning the period [0,T] in sub-periods of duration τ);
binary variables can be introduced to identify (at each time interval) the *occultation events* (on the basis of condition 21);
to maximise the *uniformity* of the *occultation events* distribution is equivalent to minimise its standard deviation;
the problem could also include conditions on the relative azimuth and elevation between each couple of satellites (i,j) (see eqs. 4).

9. APPENDIX 2: MULTIDISCIPLINARY OPTIMISATION S/W PROTOTYPE

This document refers to the software package related to the MDO project, describes all its inner structures and its input and output files formats. It also shows the necessary steps to produce the global output.

9.1 PRELIMINARIES

This software package has been implemented in order to show the applicability of the proposed integrated approach and it has been used in the second study case (MARS). The resulting package is made of different applications integrating Neighbourhood Search, Game Theory and Multicriteria Decision Analysis algorithms proposed and discussed in chapter 3. NS software, starting from initial solutions, generates a set of Paretian solutions and corresponding input files for Multicriteria Decision Analysis and Game Theory software. In Figure 9.1-1 are shown necessary steps to produce final results.

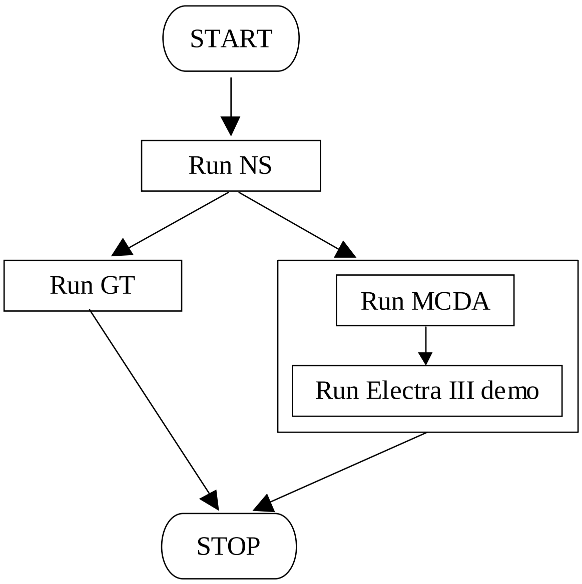


Figure 9.1-1 Steps to produce final results

9.2 INNER SOLUTIONS REPRESENTATION

A generic solution is represented by the following structure:

- subsystems input values: an array sized according to inputs number;
- subsystems output values: a matrix whose lines correspond to subsystems identifier numbers and columns to its own output values;
- comparable outputs sums: an array sized according to outputs number

For example a feasible MARS mission solution could assume the aspect shown in Figure 9.2-1.

Input values

26	5600

Output matrix:

2500	-	-
-	8.74	-
-	-	0.20

Comparable outputs sum

2500	8.74	0.20

Figure 9.2-1 Possible solution representation

9.3 FILES FORMATS

9.3.1 NS.exe

This software reads default configuration from two files, according to the formats:

File_1.txt

#inputs #outputs #subsystems
For each input:
minimum value maximum value type <# possible values > <list of possible values > <step>
type can be: 1 = value obtained using a step
2 = continuous input (each value in the range managed defining a step)

File_2.txt

in_sol.input1_value fin_sol.input1_value
....
in_sol. inputN_value fin_sol. inputN_value
in_sol output values
fin_sol output values

For more clarity we quote a possible example of the input files previously described:

file_1

2 3 3 // 2 inputs, 3 outputs for each subsystem and 3 subsystems
7.50 34.5 1 1.5 // Input1: range 7.50÷34.5, managed defining a step value of 1.5
2000 10000 2 100 // Input2: range 2000÷10000, continuous input with a step value of 100

file_2

```
7.5 16.5               // in_sol.input1=7.5     fin_sol.input1=16.5
2000 8000              // in_sol.input2=2000  fin_sol.input2=8000
500.064062 -1 –1       // in_sol subsystem1's outputs
-1 0.9 –1        // in_sol subsystem2's outputs
-1 -1 0.188622         // in_sol subsystem3's outputs
1385.666538 -1 –1      // fin_sol subsystem1's outputs
-1 7.92 –1             // fin_sol subsystem2's outputs
-1 -1 0.194508         // fin_sol subsystem3's outputs
```

NS.EXE returns as output four files: OOCIGT.TXT, OOCIMCDA.TXT and MEMO.TXT:

- OOCIGT.TXT contains input data read by Game Theory function;
- OOCIMCDA.TXT contains the Paretian solutions set according to alternatives/criteria matrix formalism;
- MEMO.TXT summarises Game Theory's results, paying particular attention to Nash and Kalai-Smorodinsky solutions found.

9.3.2 Game Theory software (GT.EXE)

It receives in input OOCIGT.TXT file generated by Neighbourhood Search software according to the following format:
- Paretian solutions number
- Inputs number
- Outputs number (it corresponds to players number)
for each player:
number of input influencing payer i and inputs list
- problems kinds (0 if minimum, 1 if maximum)
for each Paretian solution:
Input1 (CT) Input2 (R_b) Output1 (ha) Output2 (DV) Output3 (Dim)

It produces as output MEMO.TXT file, where are listed:

- Paretian solutions
for each player:
minimum and maximum value
for each player:
strategies number and list
- Nash and Kalai-Smorodinsky solutions as follows:

```
********************* Nash Solution ******************************
   28.00000   6200.00000 |  2960.19678   10.41600   0.20037 |  577.98315   466.66672   705.30939
   \_____________________/  \________________________________/  \______________________________/
        Input values                  Output values                     Players utilities

**************** Kalai-Smorodinsky Solution *****************
   29.00000   6400.00000 |  3199.58301   11.13600   0.20078 |  510.09921   529.16669   688.63159
   \_____________________/  \________________________________/  \______________________________/
        Input values                  Output values                     Players utilities
```

9.3.3 MCDA.exe output file (IN_ELE.TXT)

MCDA application aims to generate input data file for Electra III demo version, considering that it is subject to some limitations: in fact it supports no more than six alternatives and five criteria.
Electra III (without significant limitations on alternatives and criteria) is a commercial software that allows the insertion of input data from file, according to its own format described below:

- Project owner [string]
- Project description [string]
- Data set type [decimal]
  This value should be one of the following:
    1 for ELECTRE III only
    2 for ELECTRE IV only
    3 for both ELECTRE III and ELECTRE IV
    4 for matrix of degrees of credibility
- Last coefficients of distillation [2 x float] (only if 'Data set type' = 1 or 3 or 4)
- Last set of relations for ELECTRE IV [decimal] (only if 'Data set type' = 2 or 3)
  This value is compute as sum of the following values:
    1 for Quasi-dominance relation
    2 for Canonical-dominance relation
    4 for Pseudo-dominance relation
    8 for Sub-dominance relation
    16 for Veto-dominance relation
- Last used processing mode [decimal] (only if 'Data set type' = 3)
  This value should be one of following:
    1 for ELECTRE III mode
    2 for ELECTRE IV mode
- Number of criteria [decimal] (only if 'Data set type' = 2 or 3)
- Number of alternatives [decimal]

If 'Data set type' = 1 or 2 or 3
For every criterion:
- Name [string]
- Code [string]
- Weight [float] (only if 'Data set type' = 1 or 3)
- Direction of preferences [decimal]
  This value should be one of following:
    0 for decreasing
    1 for increasing
- Direction of calculation [decimal]
  This value should be one of following:
    0 for indirect
    1 for direct
- Coefficients of indifference threshold [2 x float]
- Coefficients of preference threshold [2 x float]
- Coefficients of veto threshold [2 x float or "- -" string if veto disabled]

For every alternative:
- Name [string]
- Code [string]

If 'Data set type' = 1 or 2 or 3
- Evaluation[1] [float]

....
- Evaluation[Number of criteria] [float]
If 'Data set type' = 4
- d(a[i], a[1]) [float]
....
- d(a[i], a[Number of alternatives]) [float]
<End of ASCII File>
[string] is the set of characters located in single line and limited by quotation marks (").

By default, coefficients of indifference and preference threshold and veto, described in 3.4.1, are set to 0; criteria weights, instead, are all set to 0.25.

10. APPENDIX 3: MULTIDISCIPLINARY OPTIMISATION S/W REFERENCE GUIDE

10.1 NS SOFTWARE REFERENCE GUIDE

It performs Neighbourhood Search approach, returning Paretian solutions set found.

10.1.1 Running NS

When running NS.EXE appears a menu window like the one in

Figure 10.1-1.

User can choose between two alternatives:

- *Run the software with default input data*: the software generates a Paretian solutions set starting from default input data, which are:
  Starting solution: Input 1 = 7.5 min;
  Input 2 = 2000 bps.
  Final solution: Input 1 = 16.5 min;
  Input 2 = 8000 bps.
  Relative steps are 0.5 min and 500 bps for Input 1 and Input 2 respectively.
  According to MARS mission Input 1 and Input 2 correspond respectively to Contact Time and Bit Rate.
- *Modify input data and compute solutions*: allows inserting different solutions and input data configurations from the default one.

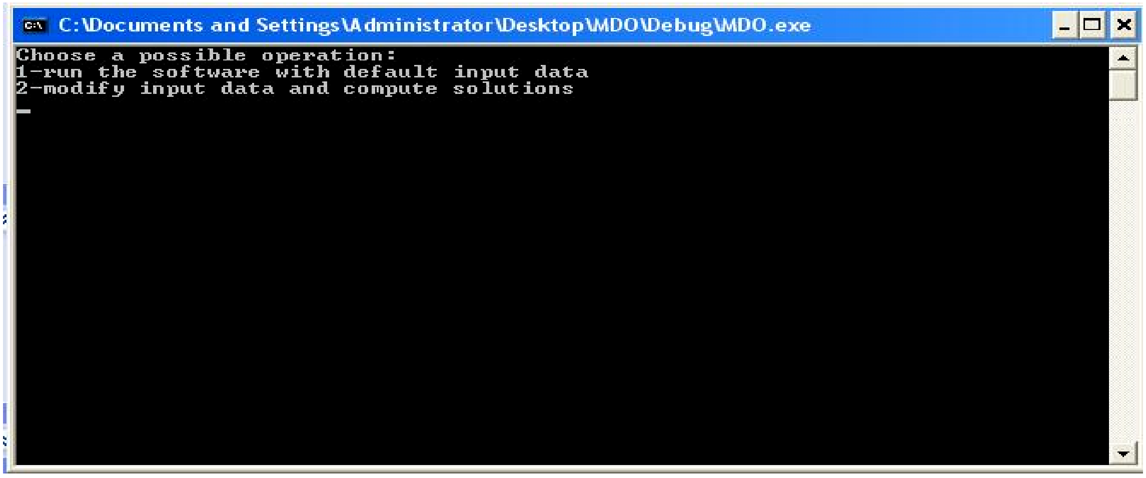


Figure 10.1-1 NS menu window

10.1.2 Output messages

NS.EXE possible output messages are:

"Final solution found after N iterations"
The final solution has been found and the Paretian solutions list is printed on file.

"The program has run for the maximum iterations number"
Final solution has not been found because there were not enough iterations, or because final solution is not reachable using step values inserted by users. In any case the Paretian solutions list found is printed on file.

"Error opening <FILE_NAME>"
Can't open a file. If it is an input file check that really exists.

10.2 GT SOFTWARE REFERENCE GUIDE

When running GT.EXE it receives in input OOCIGT.TXT file generated by Neighbourhood Search software and produces as output MEMO.TXT file.

10.3 MCDA SOFTWARE REFERENCE GUIDE

This software automatically generates Electra III demo version input files, avoiding the manually data insertion by Multicriteria Decision Analysis experts.
It is subject to Electra III demo requirements and limitations, so the output file presents no more than six alternatives and five criteria, printed according to that software input format.

10.3.1 Installation

- Copy Input for Electra 3.exe file on your desktop and run it;
- Open Input for Electra 3 folder and run MCDA.exe.

10.3.2 Options performed

MCDA software prints on screen alternatives/criteria matrix found by Neighbourhood Search software, showing how many solutions have to be deleted.
MCDA menu window appears like that shown in

Figure 10.3-1.

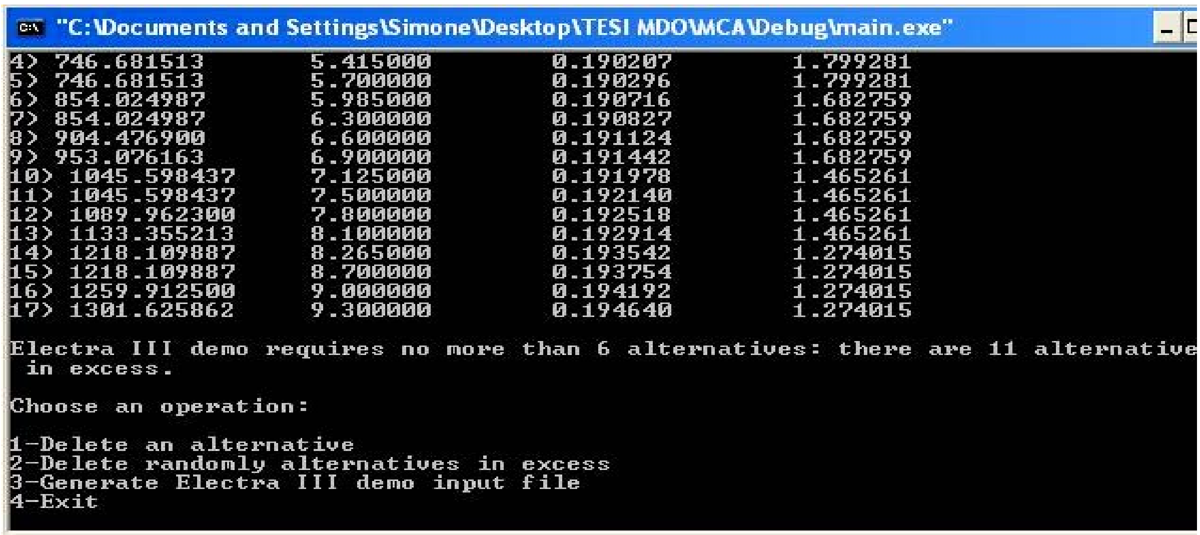


Figure 10.3-1 MCDA menu window

That menu involves the following operations performed by MCA software:

- *Delete an alternative*: allows deleting a single alternative chosen by the user;
- *Delete randomly alternatives in excess*: randomly deletes alternatives in excess in order to leave only six of them as required by Electra III demo;
- *Generate Electra III demo input file*: creates IN_ELECTRA.txt output file;
- *Exit*: stops execution.

10.4 ELECTRA III DEMO

It is the demo version of a specific software able to perform Multicriteria Decision Analysis work. It presents some limitations respect to the full version: it can handle up to six alternatives and five criteria in input, and requires printing and exporting data in/to ASCII files.

10.4.1 Running Electra III demo

In order to use this software, it is necessary to run the ELDEMO.EXE application, then choose *Import from ASCII* from *File* menu, as shown in

Figure 10.4-1, and select IN_ELE.TXT:

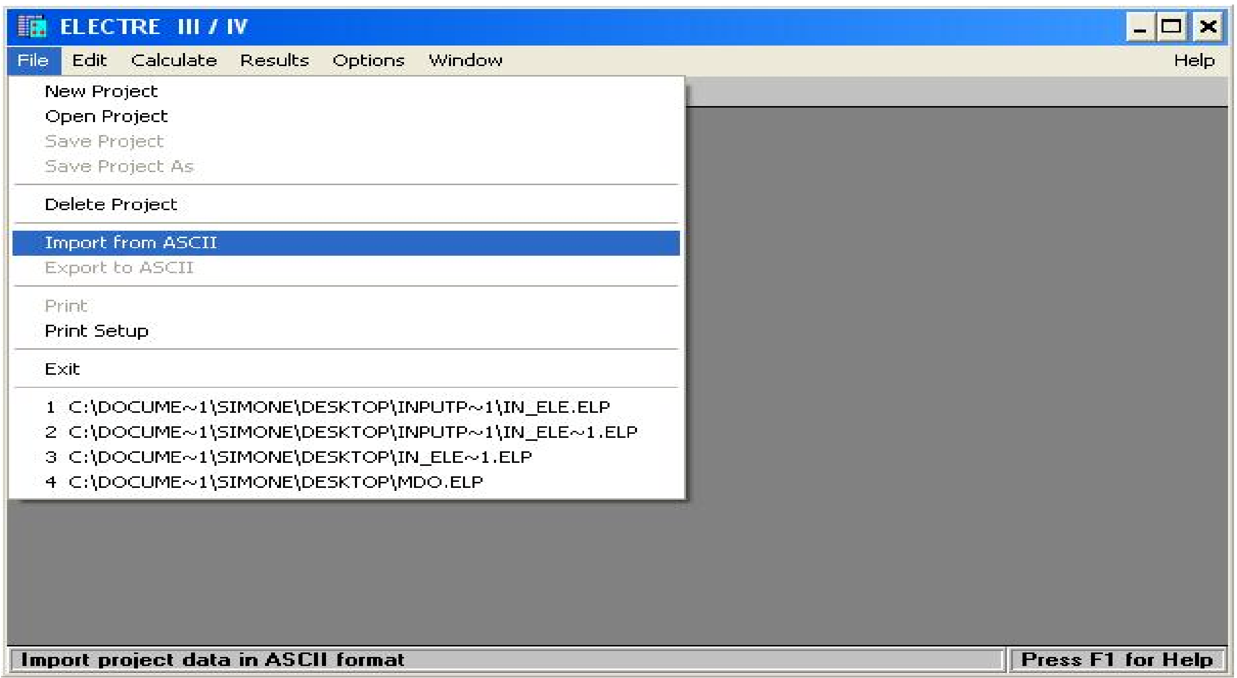


Figure 10.4-1 Electra III demo interface

Then it is ready to perform Multicriteria Decision Analysis.

In order to compute and view the results go to the *Results* menu, else open the *Edit* menu to modify default parameter values.

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12. ACRONYMS LIST

ACE+	Atmosphere and Climate Explorer Plus
AM	Attitude Manoeuvre
AMCS	Attitude Measurement Control System
ASCII	American Standard Code for Information Interchange
AU	Astronomical Unit
BEN	Battery Energy Need
BLISS	Bi-Level Integrated System Synthesis
bps	bit per second
CA	Comparison Area
COLOP	COLlaborative OPtimisation
CT	Contact Time
CDMU	Command Data Management Unit
CT	Contact Time
DA	Decision Area
Dim	solar array Dimension
DLP	Day Light Period
DV	Data Volume
ΔV	Variation of Velocity
ΔV_D	Variation of Velocity to compensate Drag decay
ΔV_T	Variation of Velocity to reach Nominal orbit from Parking orbit
$\Delta\theta$	Variation of satellite true anomaly
$\Delta\Omega$	Variation of orbit ascending node
e	Eccentricity of orbit
EP	Eclipse Period
ESA	European Space Agency
FIFO	First In First Out
g	gravity acceleration
GaAs	Gallium Arsenide
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Game Theory
H	Altitude of orbit
ha	Apogee Altitude
H_N	Altitude of Nominal Orbit
I	Inclination of orbit
I_{Eff}	Efficiency Index
I_{sp}	Specific Impulse
LEO	Low Earth Orbit
L_i-Ion	Lithium-Ion
M$	Million of Dollars
Mb	Megabit
MCDA	MultiCriteria Decision Analysis
MD	MultiDisciplinary
MDO	Multi Disciplinary Optimisation
M_j	Multy junction
MMH	Mono Methil Hydrazine
MMU	Mass Memory Unit
N/A	Not Applicable
NS	Neighbourhood Search
NTU	Non Transferable Utility
N_iH_2	Nichel Hydrogen
N_2H_4	Hydrazine

N_2O_4	Nitrogen Tetroxide
OBDH	On Board Data Handling
P	Period
PCU	Power Control Unit
Rb	transmitting Bit Rate
RFDU	Radio Frequency Distribution Unit
P/L	PayLoad
PN	Power Need
PNBC	Power Need for Battery Charging
PPDU	Power Protection Distribution Unit
Pt	Transmitting Power
QSL	Quasi Static Load
RD	Reference Document
RF	Radio Frequency
RFDU	Radio Frequency Device Unit
Rx	Receiver
SA	Solar Array
SAA	Solar Array Area
SAN	Solar aspect ANgle
SAT-LAN	number of satellites per number of launches
S/C	SpaceCraft
S_j	Single junction
S/S	SubSystem
TBD	To Be Defined
TL	Tabu List
TPN	Total Power Need
TTC	Telemetry and Tracking Communication
Tx	Transmitter
vs	versus
Wh	Watt-hour
WATS	WAter vapour and temperature in Troposphere and Stratosphere
w.r.t.	with respect to