Università degli Studi di Napoli Federico II

Dipartimento di Ingegneria Industriale

"La partecipazione degli studenti di Space Mission Design al congresso AIDAA 2019"

RUDOLPH PROJECT

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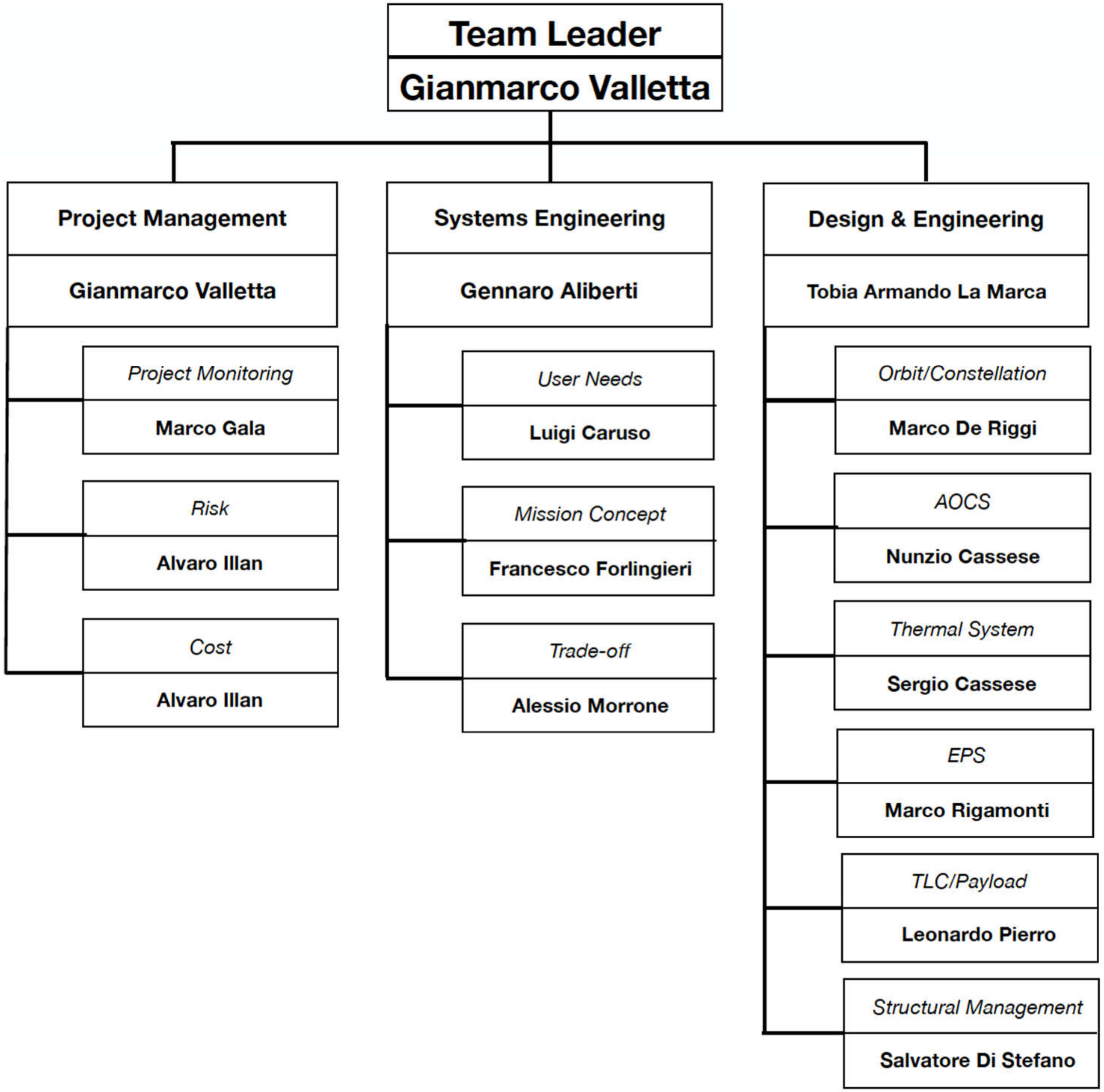
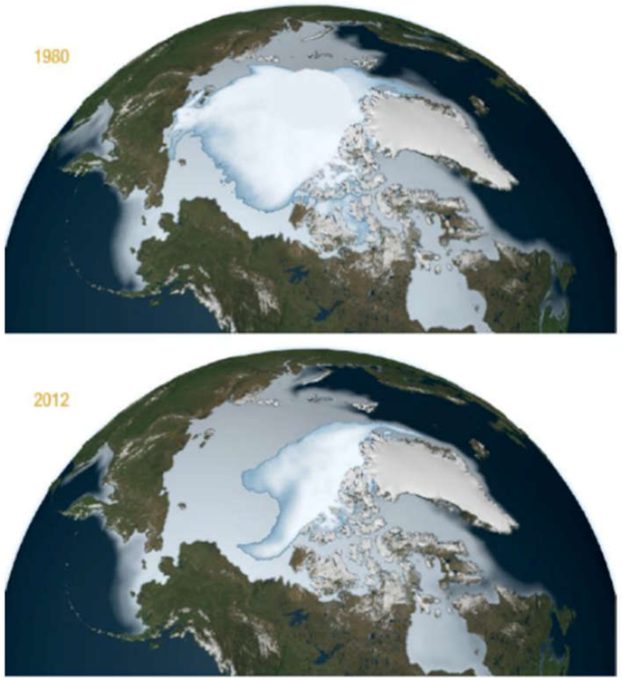
Reliable Unbiased Determination Of user Location in Polar and High latitude arctic areas

RUDOLPH Group



Why?



The reduction of arctic ice has become more and more evident in the last years. The melting of Arctic sea, mainly due to climate changes, is expected to lead to potential industrial boom for the Arctic regions, both in terms of energy production and good transportation.
The interest, both political and economical of nations, linked to the lack of reliability and accuracy of the current GNSS (Global Navigation Satellite Systems), such as GPS or Galileo, and of the Geostationary Augmentation Satellites, within EGNOS and WAAS Program, it gave birth to RUDOLPH Project.

FUNCTIONAL REQUIREMENTS	
AVAILABILITY	➢ 99,8% per 30 days.
ACCURACY	➢ Horizontal accuracy of 10 m
INTEGRITY	➢ Alert limit: 25 m. ➢ Time to Alert: 10 s. ➢ Integrity risk: per 3 hours.
CONTINUITY	➢ 99,97% over 3 hours.

OPERATIONAL REQUIREMENTS	
COVERAGE	➢ Arctic areas (beyond latitude 67°).
SURVIVABILITY	➢ The system must survive in LEO/HEO conditions.
MISSION DESIGN LIFE	➢ 15 years.

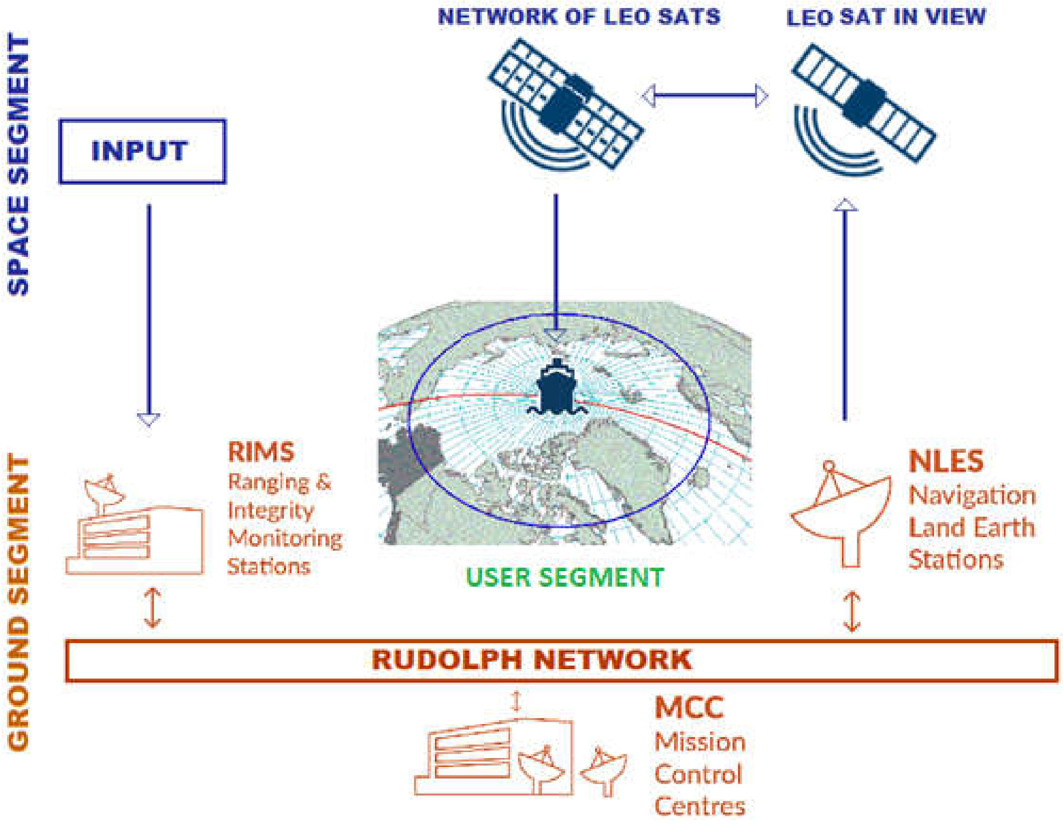
Constraints

CONSTRAINTS	
DEVELOPMENT CONSTRAINTS	➢ Must use all European components and existing equipment.
ENVIRONMENT	➢ Natural (i.e. ionospheric effects).
POLITICAL	➢ Governments request to sail in these areas for public and private purposes. ➢ The launcher shall be a european/russian one.
COST	➢ 50% of EGNOS production cost which is around €2.2 billions in total (about $2.5 billions).
SCHEDULE	➢ Operational within 4 years (lower time with respect to EGNOS).

Based on a preliminary analysis of Needs, Constraints and Requirements two main architectures have been considered and investigated.

MOLNIYA SATS

LEO SATS

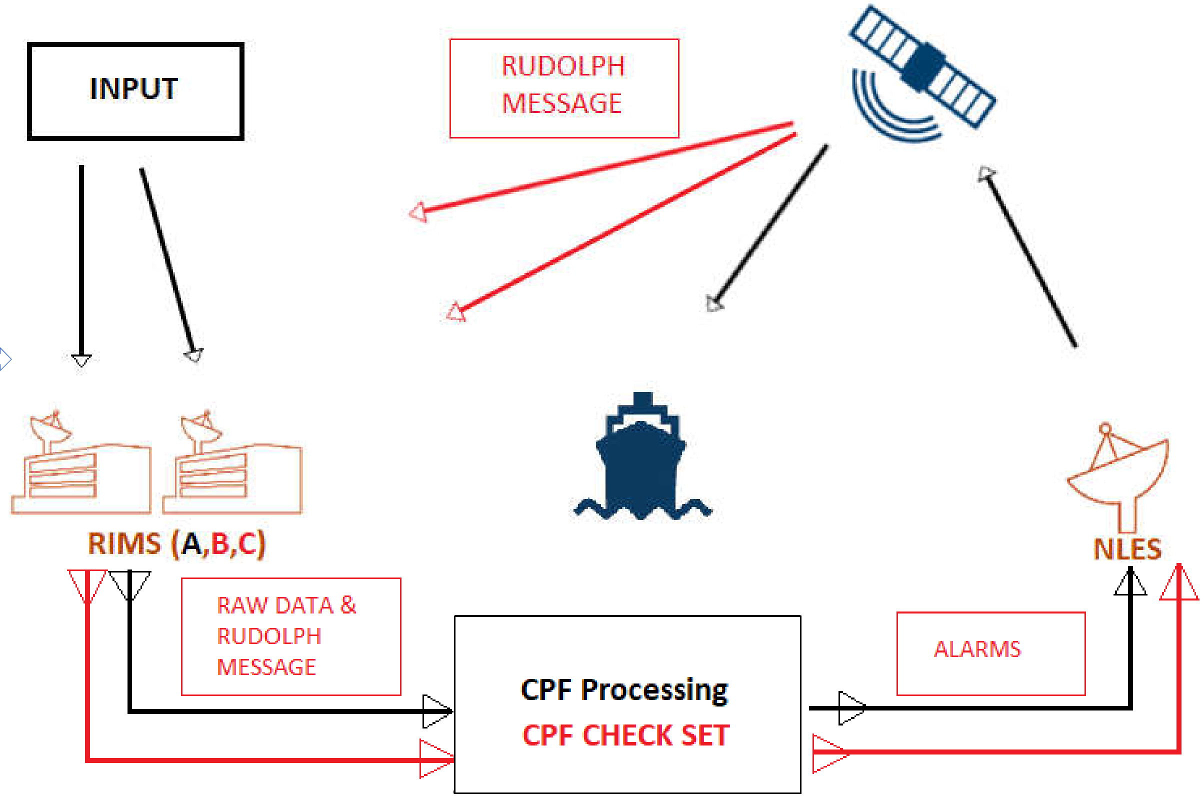


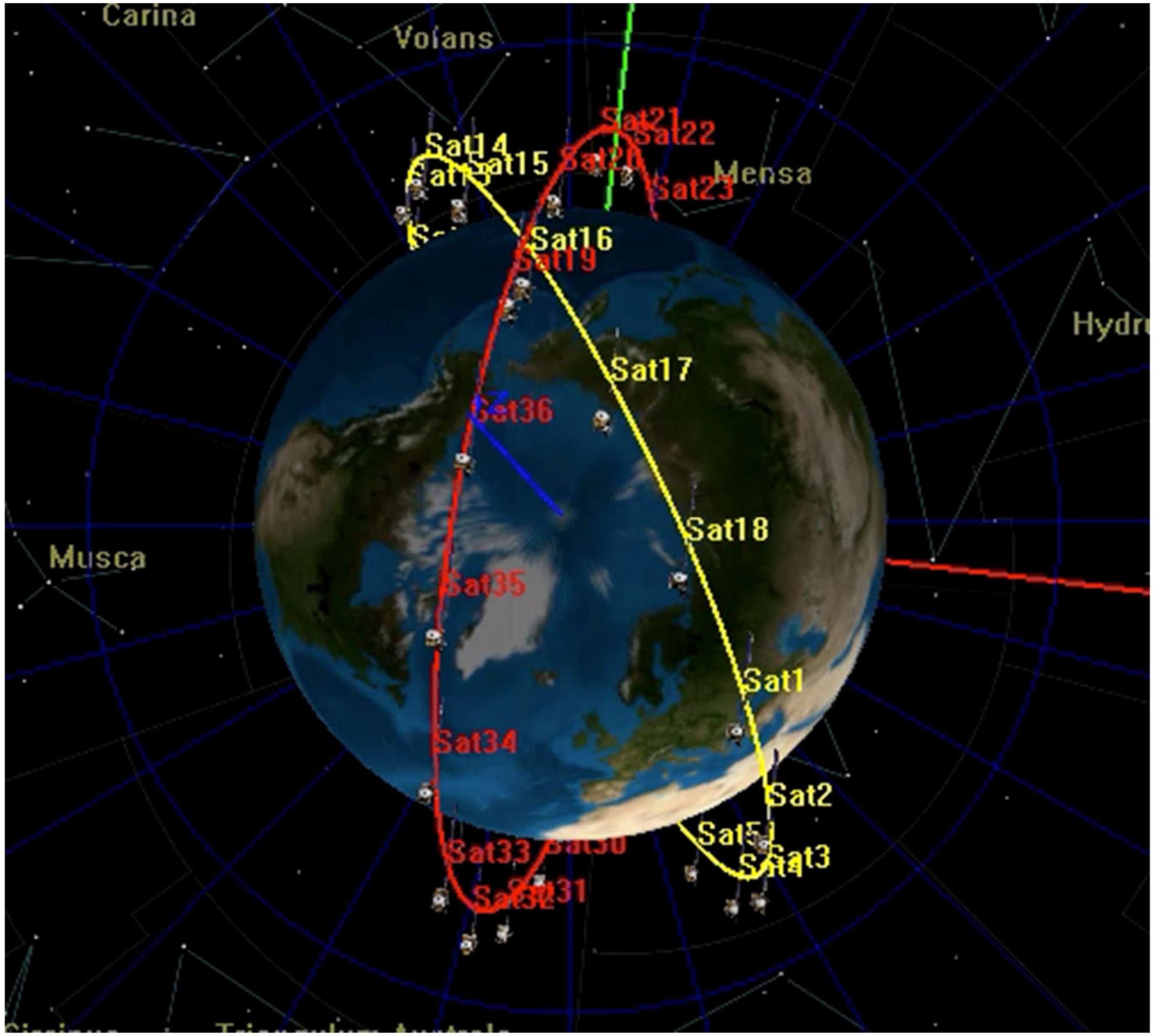
- This kind of configuration uses a network of LEO satellites which are linked together, meaning that they communicate each other all the information about the status of the system.

- It's not necessary that a particular sat is in view both of the ground station and the user.

The RUDOLPH MOLNIYA SATS data flow is separated in two cycles:

- ❑ PROCESSING CYCLE
- ❑ CHECK CYCLE



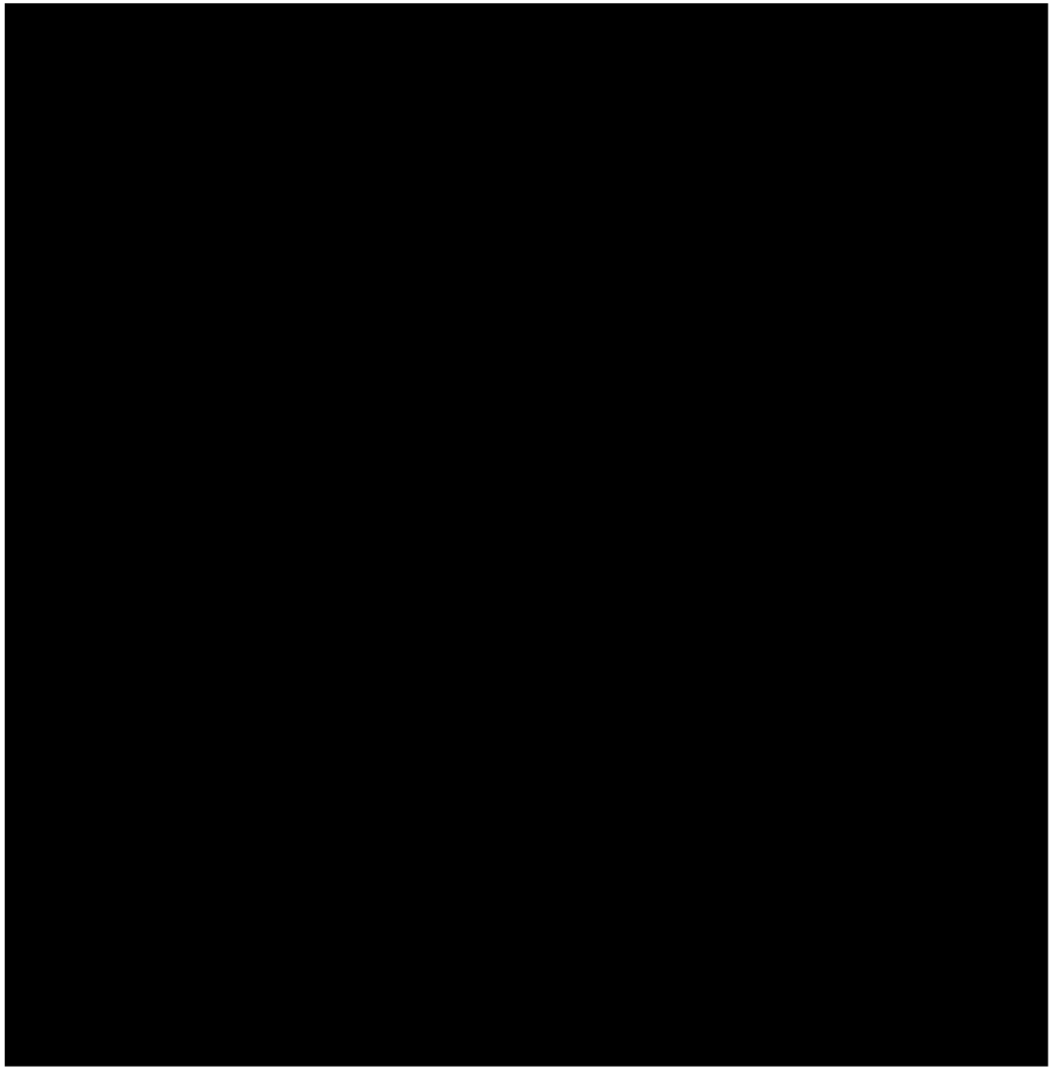


The nominal LEO configuration consists of 2 different orbits, 18 satellites per orbit for a total of 36 satellites.

Satellites per orbit	18
Semi - Major Axis	7876Km
Altitude	1498 km
Eccentricty	0.001
Inclination	102°
Argument Of Perigee	10°
Right Ascension of the Ascending Node	122°(267°)
Difference in Right Ascension between the two orbits	145°

- Sun – Synchronous nearly - polar orbit

Coverage Area



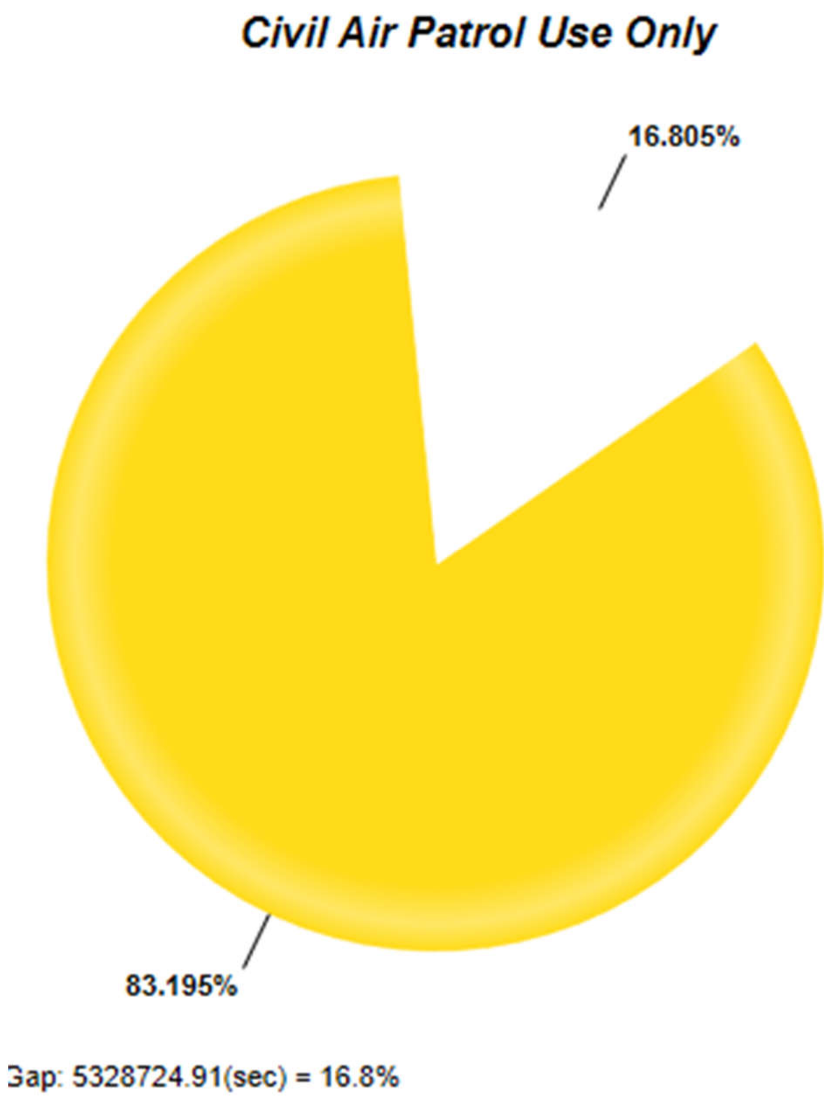
- Coverage area on the Arctic zone provided by the LEO constellation : the entire Arctic area is continuously covered.

- The propagation of the orbit was carried out in order to analyze the trend of the orbital parameters. It was found that this strategy does not need any orbital control maneuver during the whole lifetime of the satellite.

- When the nominal orbit is reached, rendez-vous maneuvers are required in order to separate the satellites in True Anomaly with respect to the first one.

- The Analysis have been completed assuming Impulsive Maneuvers and zero positional errors at the end of the launch phase. The calculations have been completed considering the worst case.

- At the end of the mission, the satellites can be transferred on a circular orbit at an altitude of 500 km to guarantee that the orbit decay will cause its burn and destruction in a period of 25 years : one Hohmannian maneuver is needed.



- Maximum eclipse period of 30 minutes
- Primary Source : solar panels
- Secondary Source : lithium batteries

- The RF band used for TT&C is S-band. The frequency used for downlink is 2.2 GHz, for uplink is 2 GHz. The antenna used both for downlink and uplink is a fixed, nadir-pointing conical log spiral antenna.

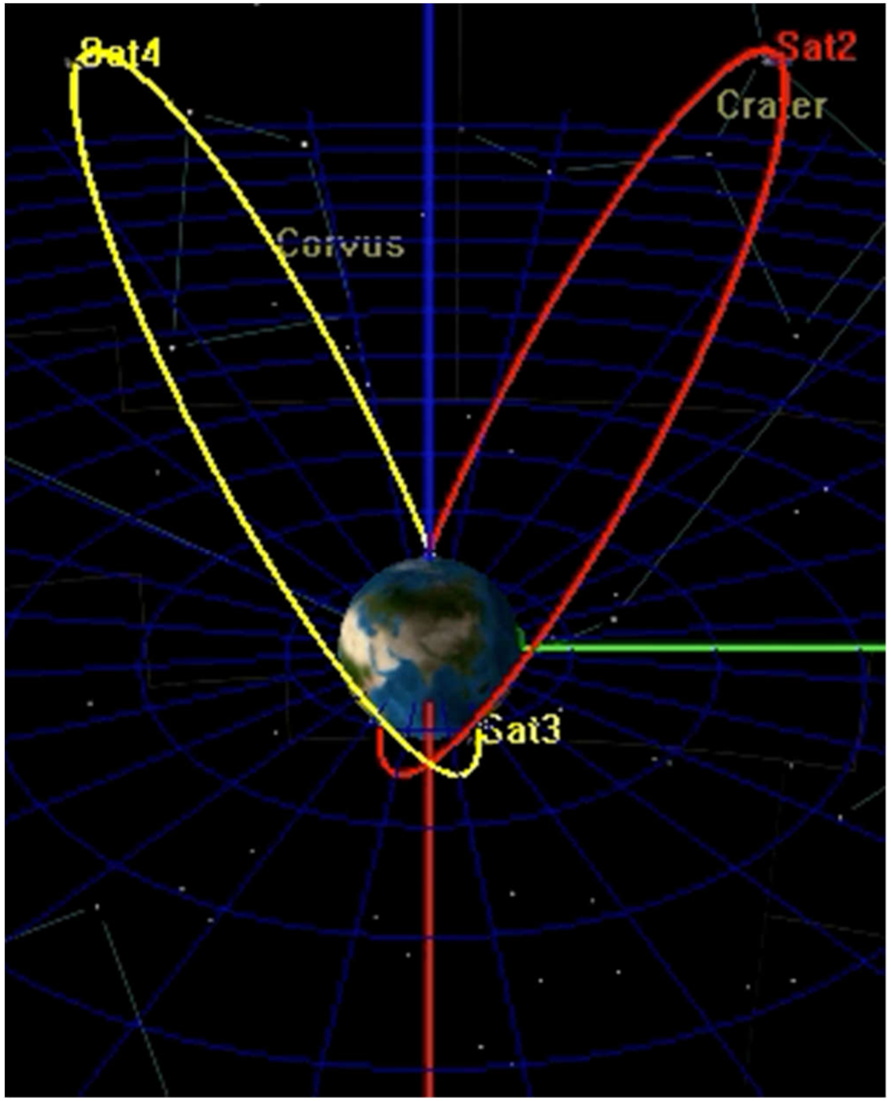
- A phased array antenna (45 beams) is employed for the payload data trasmission.

- Crosslink allows each satellite in view of the GS to communicate payload data (250 bit/s) to other satellites in the same orbital plane.

- The use of two parabolic antennas is needed, each one communicating with adjacent satellites in an orbit plane, front and back in the sense of the motion of the satellite.

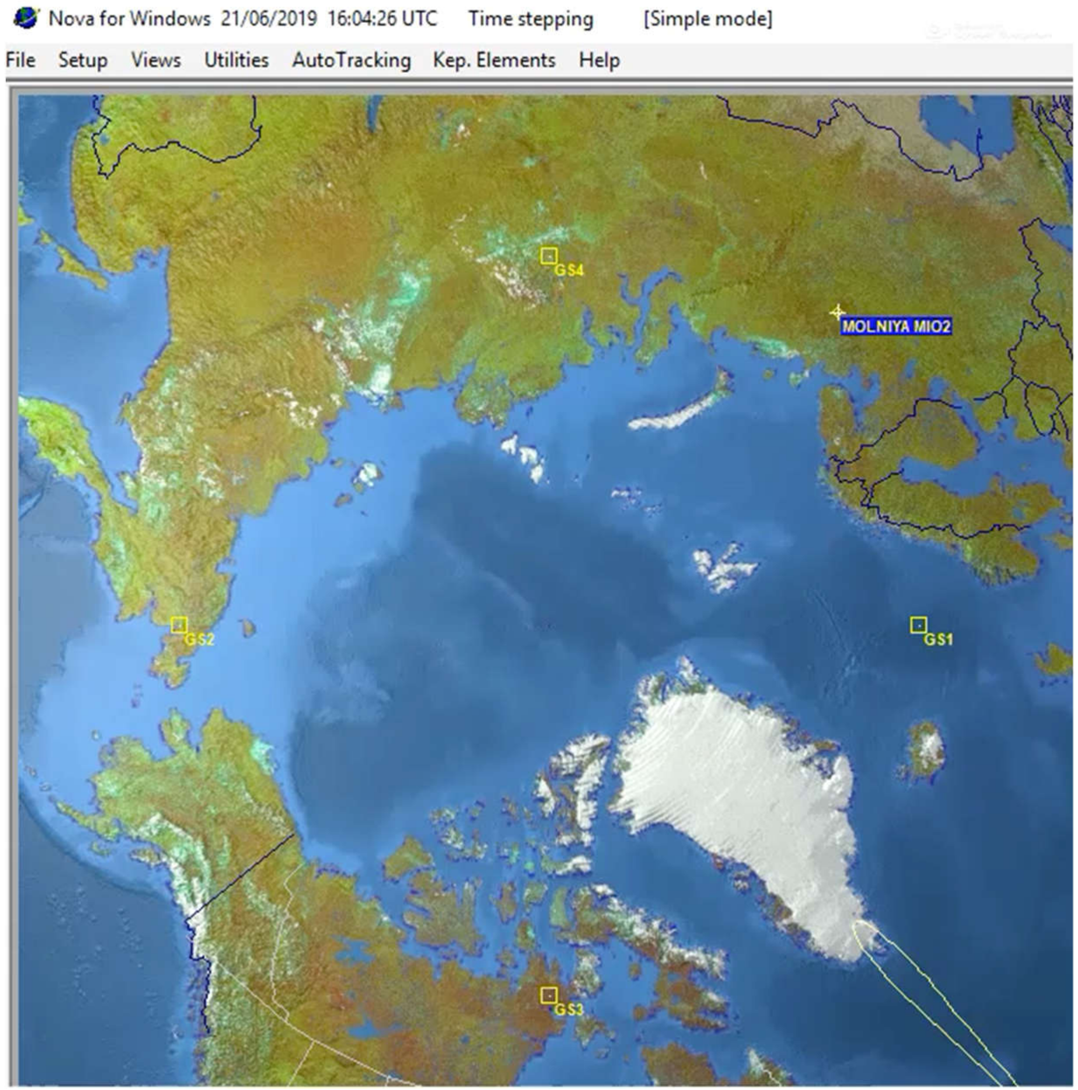
- Pointing mechanisms are required.

- The RF band is S-band.



- The Nominal Molniya Strategy consists of 2 different orbits, 2 satellites per orbit for a total of 4 satellites.

Satellites per Orbit	2
Semi – Major Axis	26553Km
Eccentricty	0.7
Inclination	63.43°
Argument of Perigee	270°
Right Ascension of the Ascending Node	0°(180°)



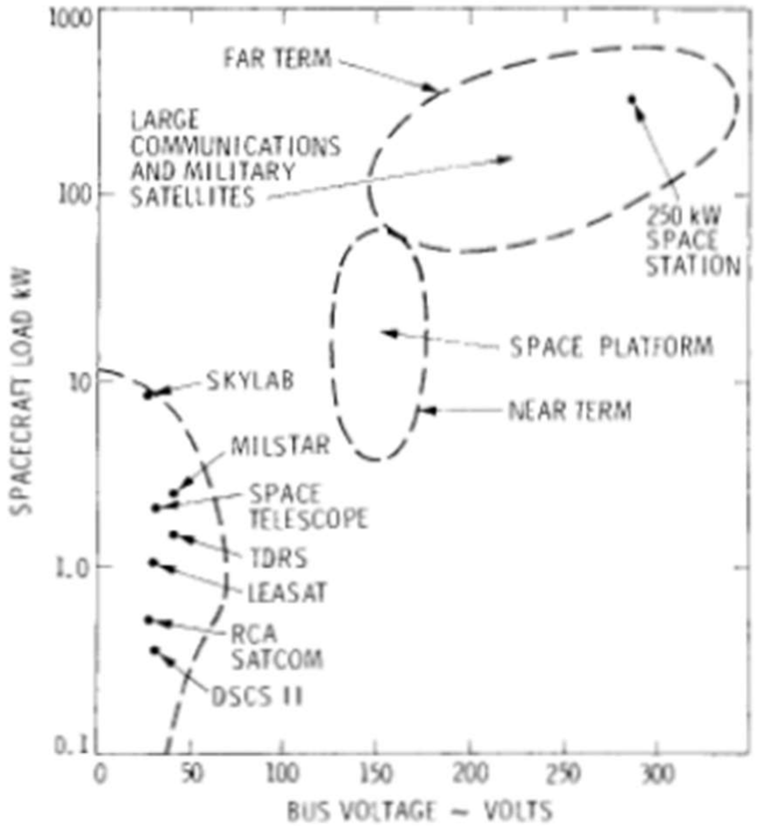
- Coverage area on the Arctic zone provided by the Molniya constellation: the entire Arctic Area is continuosly covered

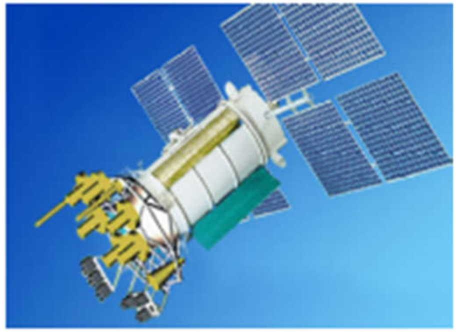
- The propagation of the orbit was carried out in order to analyze the trend of the orbital parameters. This strategy does not need any orbital control maneuver during the whole lifetime of the satellite.

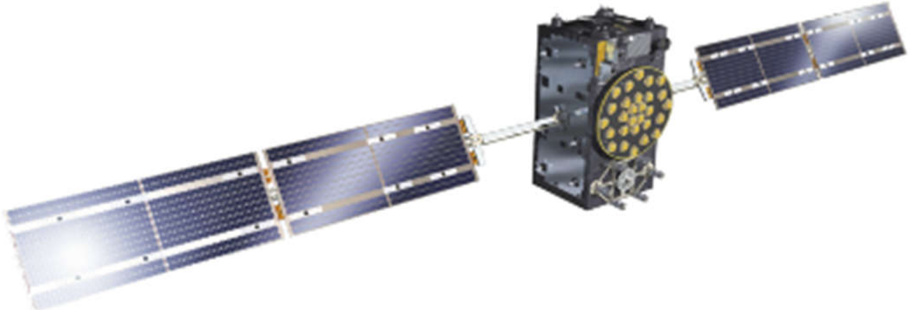
- When the nominal orbit is reached, rendez-vous maneuvers are required in order to separate one of the two satellite in True Anomaly ($\Delta = 180°$) with respect to the other one.

- The Analysis have been completed assuming Impulsive Maneuvers and zero positional errors at the end of the launch phase and considering the worst case.

- At the end of the mission, the satellites will be transferred on a disposal circular orbit with the same inclination but with SMA of 42457 km. Two impulsive maneuvers are required.

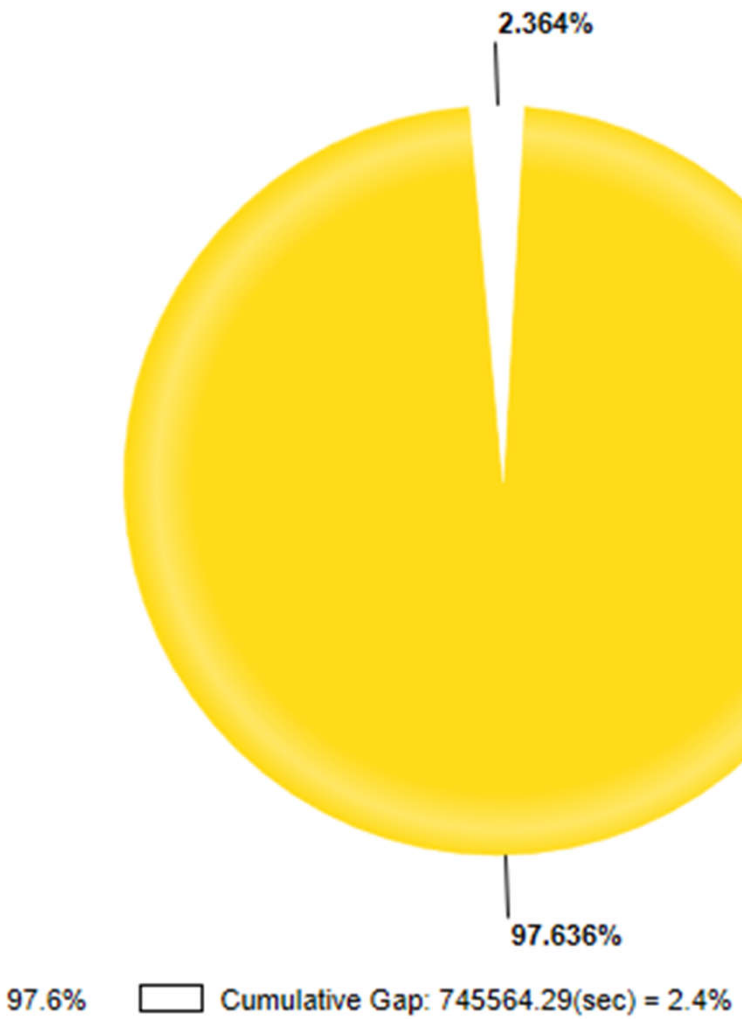




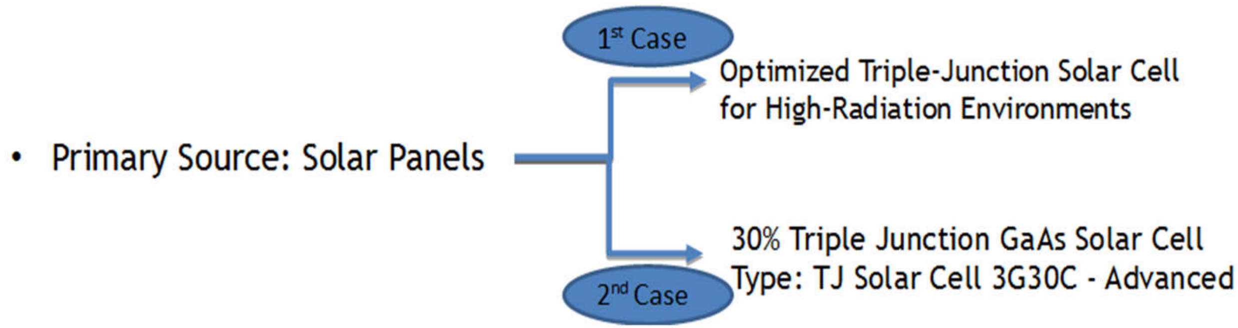


Initial Estimate for Power Consumption:

1.6 kW



- The maximum eclipse period is about 45 minutes



- Secondary Source : Lithium battery

Energy Density	113.1 Wh/Kg
DOD	80 %
Number of Cells	14
V bus	50.4 V
Total Mass	24 Kg (x2)

- Lithium Battery and Solar cells characteristics.
- Need of a 2 D.o.F solar arrays or an oversized subsystem with a periodical yaw steering maneuver

Case 1 / Case 2	
Efficiency	29.4% / 29.8 %
Solar Cell's Area	60 cm^2/30*50 cm^2
Number of Cells	1962 / 3542 cells
Total Area	12.5 m^2 / 12.2 m^2
Solar Panel Weight	50 Kg / 48.8 Kg
Solar Array's Total Mass	141 Kg / 110 kg
Solar Array's Dimensions	4 Solar Panels (two per side)
Solar Array's Deployment Mechanism	Rigid Solar Panel

Sun-Tracking error 40 °

Total Area	19 m^2
Solar Panel Weight	76 Kg
Solar Array's Total Mass	141 Kg

- The RF band used for TT&C is C-band. The frequency used for downlink is 4 GHz, for uplink is 6 GHz. The antenna used both for downlink and uplink is a fixed, nadir-pointing horn antenna.

- The frequency used for downlink is L1 (1575.42 MHz).

- For payload data transmission, an L-Band Helical Array with 19 individual helix antennas, arranged in an outer ring (12 elements), an inner ring (6 elements) and a central element, is used.

- The advantages of this arrangement are that one array can produce a large number of beams simultaneously and these can be steered electronically over a rather large angular range without the need for mechanical pointing systems (high reliability).

For what concerns solar panels, the analysis show :

- Tmax=330.53 K;
- Tmin=86.53 K.

So, considering that the operational temperature is from 173 K to 373 K, we can use:

- Heaters
- Coatings

In the case of satellite it is obtained:

- Tmax=292.44 K;
- Tmin=193.98 K.

The most stringent temperatures are given by the batteries, so T must stay beetween 278 K and 293 K. The operating temperature range is of 15°K.

- Heaters
- Radiators:
- Coatings
- Multilayer Insulation

Structure and Weights distribution

Starting from the Payload mass knowledge, the following results have been obtained through a bottom – up strategy (launch mass 1751 kg):

Propellant (kg)	990
LVA (kg)	151
Payload (kg)	110
Total dry on orbit (kg) [5.55 times PL]	610
Bus dry (kg)	500
Margin (kg) [15 % for AIAA rule]	65
Bus without Margin (kg)	435
Total dry [including PL] (kg)	545

	Rodolph masses	Percentages of overall
Subsystems overall (kg)	435	
Structure (kg)	126	29 %
Thermal (kg)	28	6.5 %
ACS (kg)	42	9.5 %
POW (kg)	159	36.5 %
CAB (kg)	16	3.5 %
Propulsion (kg)	38	9 %
TLC (kg)	110 (payload)	
CDS (kg)	26	6 %

ARIANE 5
HEAVY

Main applications: telecommunications, navigation, scientific Missions, Earth observation

GTO >10 MT

LEO 20 MT

SSO >10 MT

79 successes in a row since 2002

Max volume of fairing (m³)	123(config.1 with Selda coverage) 203 (config.2)
Max N multiple spacecrafts in volume (with volume margin percentages)	4 Molnija in congif.1 (30%) 7 max Molnija in congif.2 (30%)
COST per launch (US$ million)	178 in average
Molnija-cost for launches: (LM: 1751 kg) (2 orbits- 2x3 sats)	2 GTO (1 launch by 3 sats per orbit) 330 Million 2 Zenithal incline Orbit (the same price)

The reliability of a **medium satellite** for a lifetime of 15 years is 96.2%

↓

For a "m+1 out of n" fail

$$R_S = \left(\sum_{k=m}^{n} \frac{n!}{k!\,(n-k)!} R^k (1-R)^{n-k} \right)^2 = 95.60\%^*$$

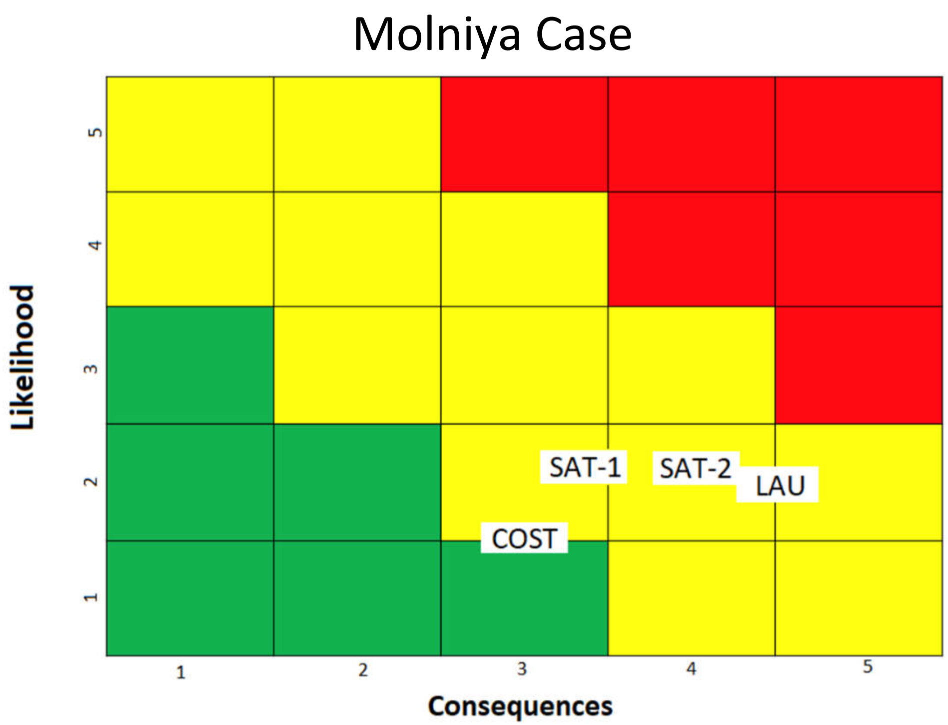
* Being R_S the reliability of the system and R the reliability of a satellite.

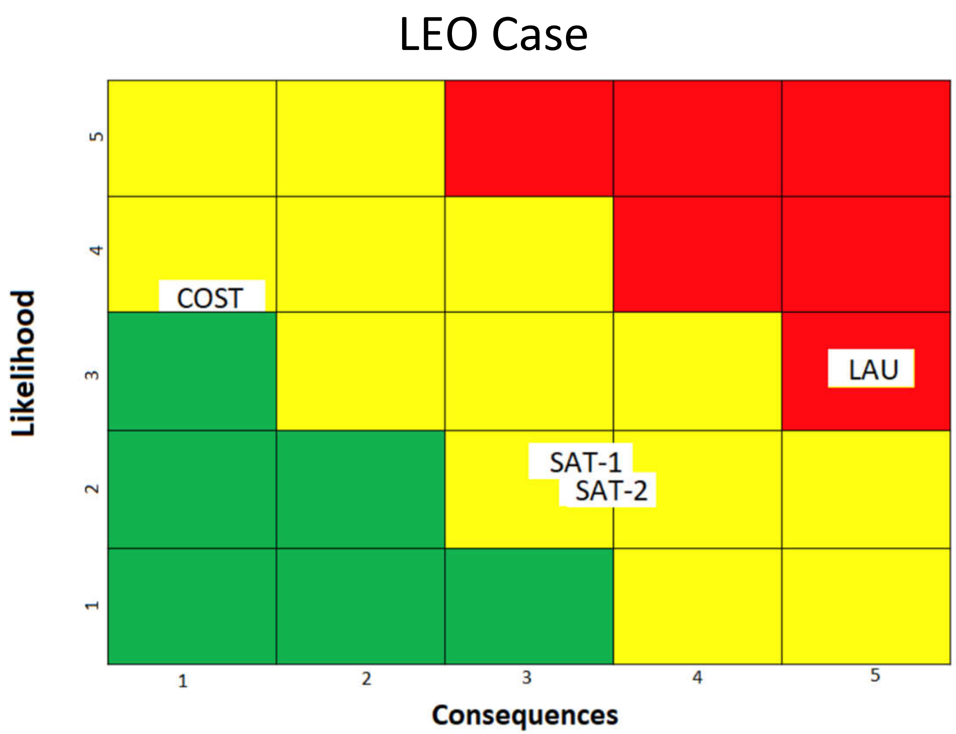
The reliability of a **large satellite** for a lifetime of 15 years is 85.25%

For a "m+1 out of n" fail

$$R_S = \left(\sum_{k=m}^{n} \frac{n!}{k!\,(n-k)!} R^k (1-R)^{n-k} \right)^2 = 99.43\%^{*}$$

* Being R_S the reliability of the system and R the reliability of a satellite.





Risk category	Call sign	Mission risk
Satellite	SAT-1	Failure of any satellite
Satellite	SAT-2	Being unable to meet accuracy and integrity requirements
Launcher	LAU	Failure to launch any of the satellites
Cost	COST	Mission cost too overwhelming to continue

To provide a more accurate picture (considering production, operating, launches and maintenance cost, with relative error) it is provided a division from Best case and Worst case:

Best Case (LEO): $Totalcost_{LEO} = 24297M\$$

Worst Case (LEO): $Totalcost_{LEO} = 30077M\$$

Best Case (Molniya): $Totalcost_{Molniya} = 3105M\$$

Worst Case (Molniya): $Totalcost_{Molniya} = 4335M\$$

RUDOLPH - Trade off - Performance

KEY PARAMETERS	MOLNIYA SOLUTION	LEO SOLUTION
COVERAGE	Beyond 67° Guaranteed by 4 sats	Beyond 67° Guaranteed by 36 sats
HORIZONTAL ACCURACY	(99% as maximum value) **σ_h = 8,56 m**	(99% as maximum value) **σ_h = 9,40 m**
MIN/MAX NUMBER OF SATELLITES IN VIEW	RUDOLPH + GPS **7/13**	RUDOLPH + GPS **6/14**
INTEGRITY	Guaranteed	Guaranteed

RUDOLPH - Trade off - Management

KEY PARAMETERS	MOLNIYA SOLUTION	LEO SOLUTION
RELIABILITY	**99,43%**	**95,60%**
NUMBER OF LAUNCHES	(ARIANE 5) **2 LAUNCHES** (1 BY 3 SATS PER ORBIT) **TOTAL SATELLITES = 6**	(SOYUZ ST) **8 LAUNCHES** (4 BY 6 SATS PER ORBIT) **TOTAL SATELLITES = 48**
RISK	**NO RELEVANT RISK**	**HIGH LAU RISK**
COST WORST CASE ($)	**4335 MILLIONS**	**30077 MILLIONS**
COST BEST CASE ($)	**3105 MILLIONS**	**24297 MILLIONS**

A constellation of 6 Molniya satellites, arranged in two different orbital planes, guarantees the delivery of SBAS services for safe maritime navigation at latitudes higher than 67° in the northern hemisphere. The system is completed by a suitable network of ground station, i.e. RIMS, NLES, and MCC. Preliminary mission budgets were derived supporting the idea that the proposed solution is feasible and can cost less than currently operational augmentation systems serving mid-/low-latitude users.

THANKS FOR THE ATTENTION!