Evolution of the Launcher Market for Telecom Satellites: Impact on Mission Analysis and Flight Dynamics Operations

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DEFENCE AND SPACE

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AIRBUS

Outline

- Introduction
- Falcon 9 launch, Minimum Residual Shutdown mode and Mission Analysis
- Updating Operations
- Updating Software
- Conclusions

Introduction

Recent commercial launcher history

Main commercial launchers for large telecom satellites (~4-6 t) before 2013:

- Ariane 5: dual launch and injection on GTO
- Proton: injection on GTO or SSTO. For SSTO, a trade-off is to be done between perigee altitude increase and inclination decrease at Briz-M last burn before separation
- H-IIA: injection on GTO

Evolutions since 2013:

- Proton: decrease of Proton commercial launches, after a series of failures
- Falcon 9: new launcher, injection on sub-synchronous transfer orbits, GTO and SSTO

Airbus DS E3000 P/F evolution. From Mk1 to Mk1.5/2

- Mk1: Earth + Sun Sensor → Sun-Earth-S/C geometry constraint → limited launch window / burn attitude
- Mk1.5/2: Stellar sensor → larger launch window + unconstrained burn attitude

Introduction

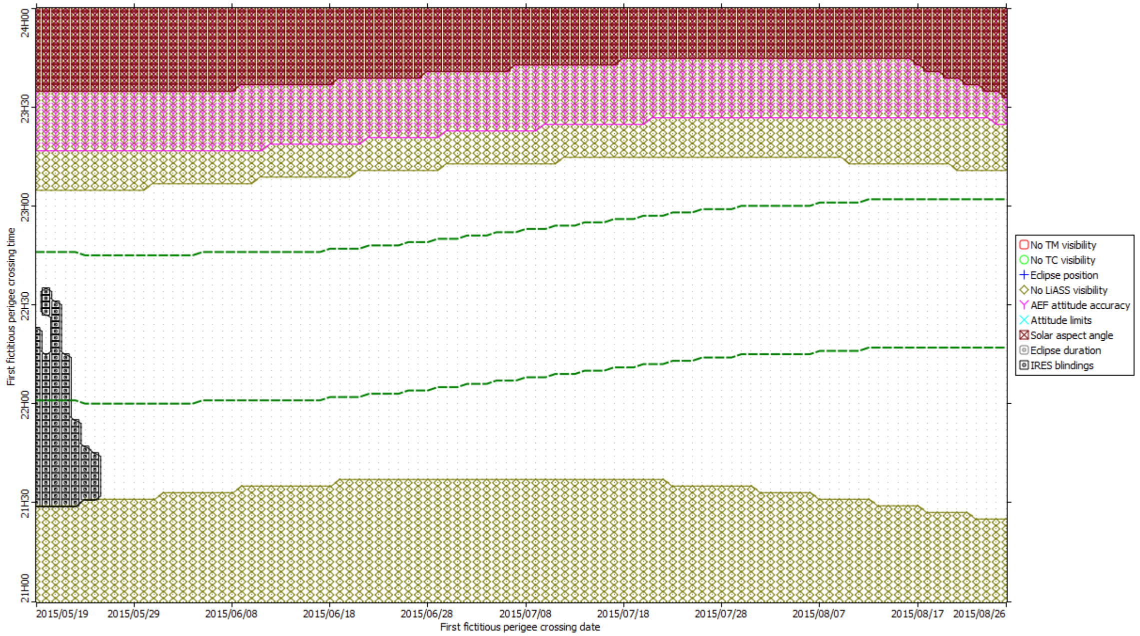
Mission analysis

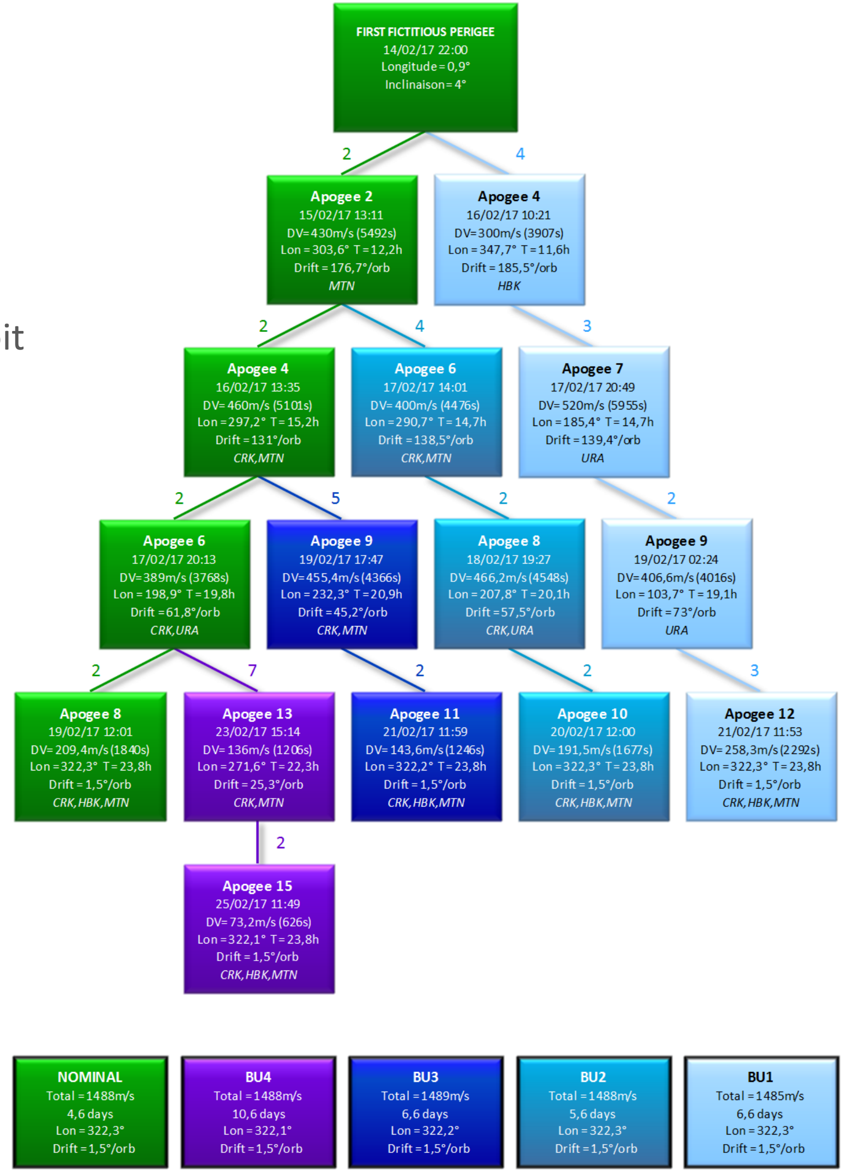
Mission Analysis planning:

- PDR (~2 years before launch): simplified mission analysis with several launchers and injection orbit
- CDR (~ 1 year before launch): full mission analysis, may still contain several launchers
- FMDR (~ 3 months before launch): full mission analysis with the final orbit

Mission Analysis content:

- First Acquisition study
- Strategy tree including launcher and satellite dispersions
- Launch window



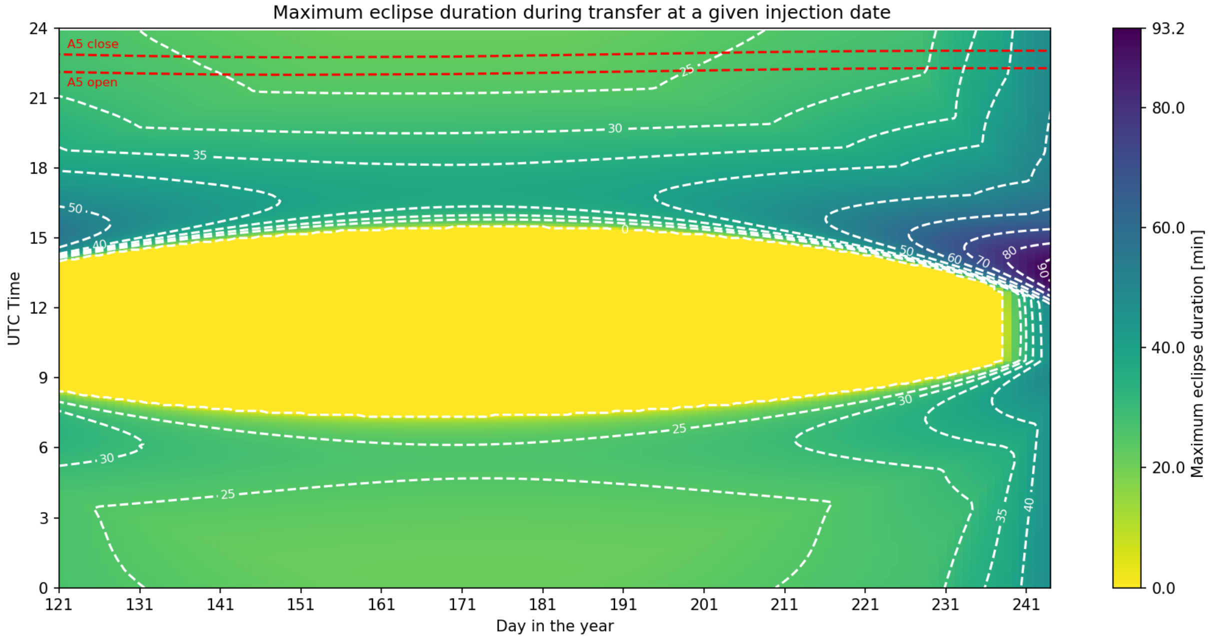


Introduction

Mission analysis

Platform evolution impact: from Mk1 with Sun and Earth sensors to Mk2 with Star Tracker

- Less constraints on the launch window → increase of the launch window size
- Generic launcher analysis only at PDR level
- Only one final full mission analysis



Introduction

Operations

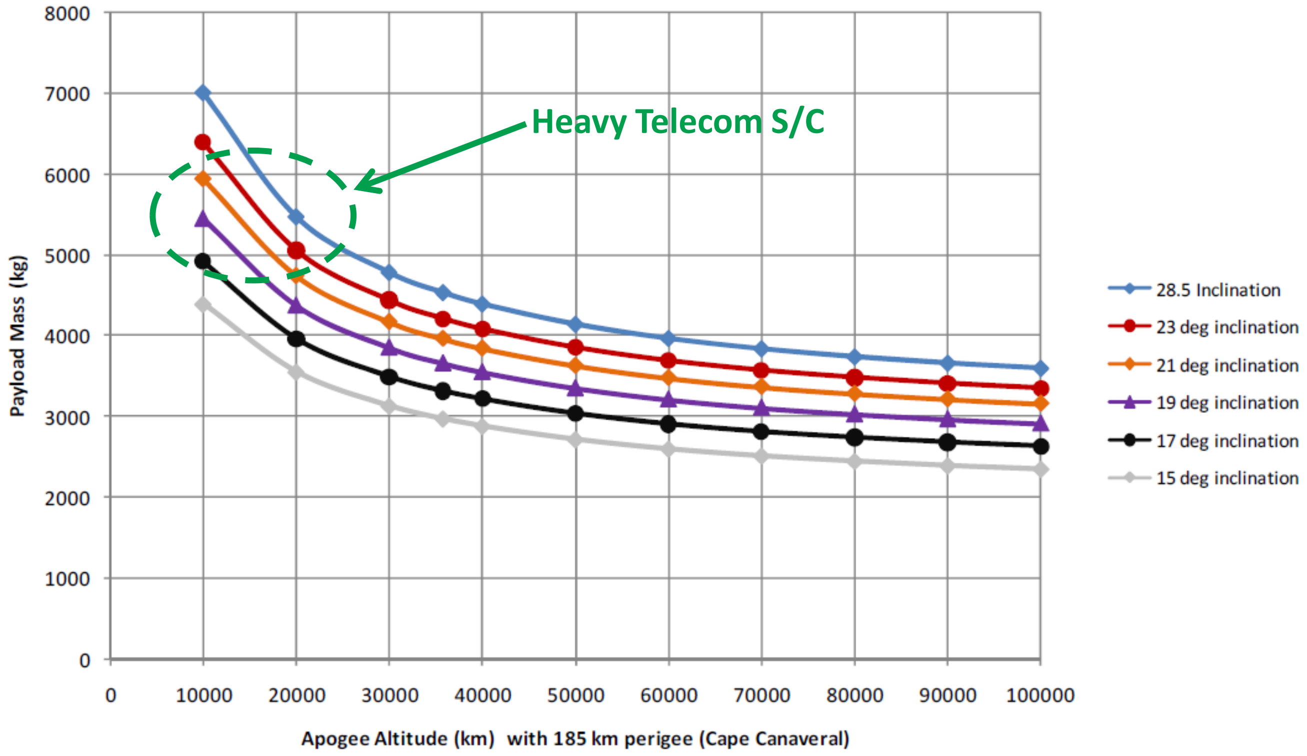
- Operations timeline and maneuvers characteristics are based on the mission analysis
- Maneuvers are optimized at each step, taking into account previous maneuvers calibration and current determined orbit. Differences are within the dispersions considered in mission analysis

- Each flight dynamics shift is done by 2 people (whole flight dynamics team is 4 people + 1 back-up)

Falcon 9, MRS and Mission Analysis

Falcon 9 Performance

- F9 performance to Geostationary Transfer Orbit (*)



(*) taken from *"SpaceX Falcon 9 Launch Vehicle Payload User's Guide – rev 1"*

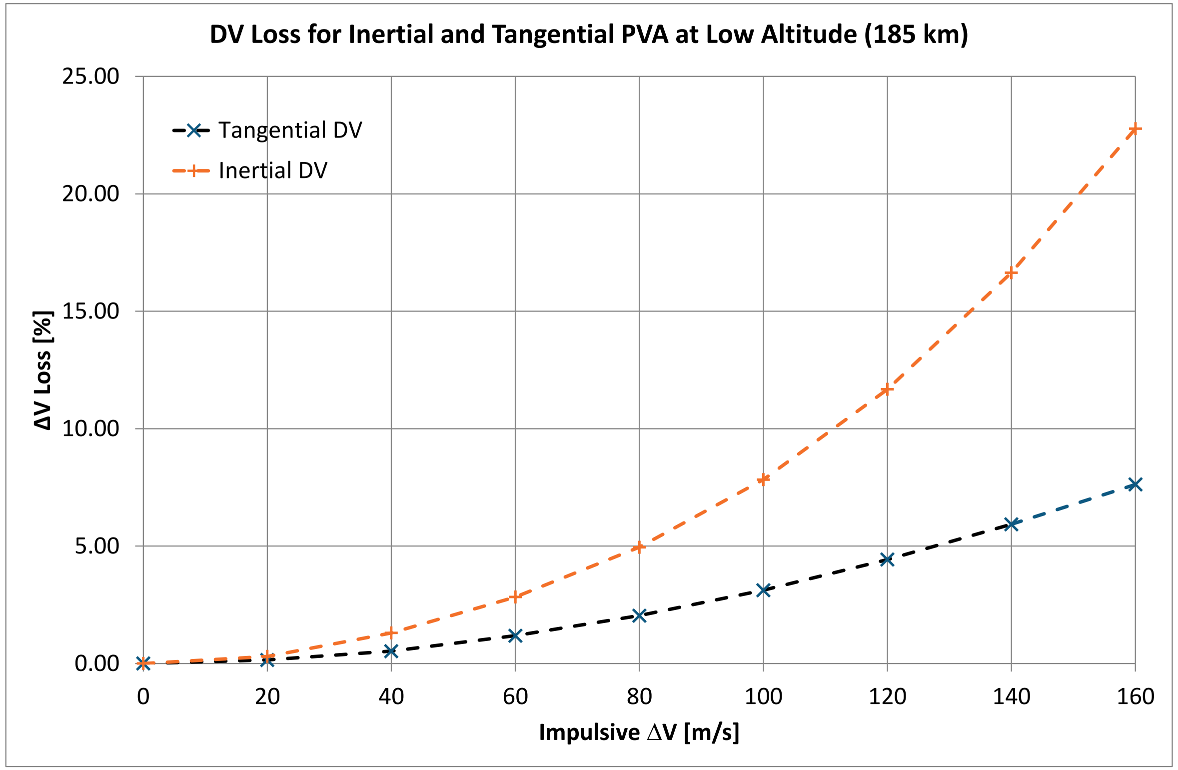
Falcon 9, MRS and Mission Analysis

Manoeuvres at Perigee

For large Telecom S/C: apogee altitude at injection in the range [10000 – 30000] km
→Requires manoeuvre(s) at perigee (PVA – Perigee Velocity Augmentation) to increase apogee altitude

Specificities related to manoeuvres at perigee:

- Manoeuvres may be performed out of visibility
- Manoeuvres may be in eclipse
- Only 1 manoeuvre may be required (no further correction)
- Manoeuvres performed at very low altitude (e.g. 185 km)
- Non-inertial manoeuvres for ΔV savings



Falcon 9, MRS and Mission Analysis

Strategy Selection - options

For low apogee altitudes: 1 or several PVA

For high apogee altitudes: 1 or several PEF (Perigee Engine Firing, manoeuvre at Perigee to decrease Apogee altitude)

For apogee altitudes around GEO arc ("near GTO orbits"):
- 1 PVA + N AEF (Apogee Engine Firing, manoeuvre at Apogee to increase Perigee altitude and correct inclination)
- N AEF → classic GTO transfer
- N AEF + 1 PEF

What if the (single) PVA/PEF duration is too short wrt minimum Liquid Apogee Engine (LAE) burn duration?
- Include burn duration constraint at optimisation level → induce ΔV overcost and transfer feasibility is not guaranteed
- Authorise the use of Reaction Control Thrusters (RCT – 10N each) instead of LAE (450 N)

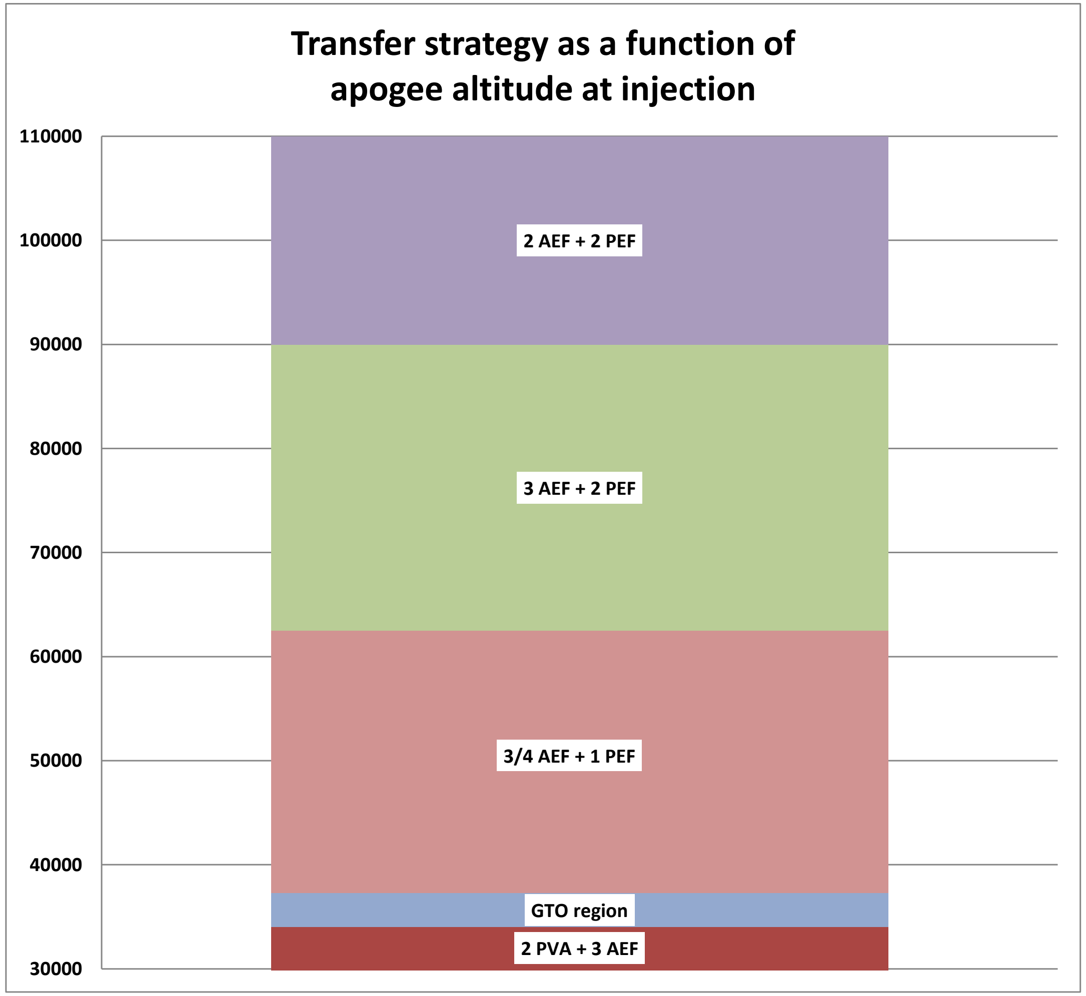
Falcon 9, MRS and Mission Analysis

Strategy Selection – Trade-off

Criteria for strategy selection:

- Constraints:
  - Minimum LAE burn duration
  - Maximum LAE burn duration
  - Minimum duration between first Acq and first burn
  - Minimum duration between 2 burns
  - Visibility during/after burns for calibration

- Objectives for the trade-off:
  - Maximise BOL mass
  - Minimise transfer duration / operational costs
  - Minimise risk of collision wrt GEO region
  - Orbit at end of transfer phase accuracy



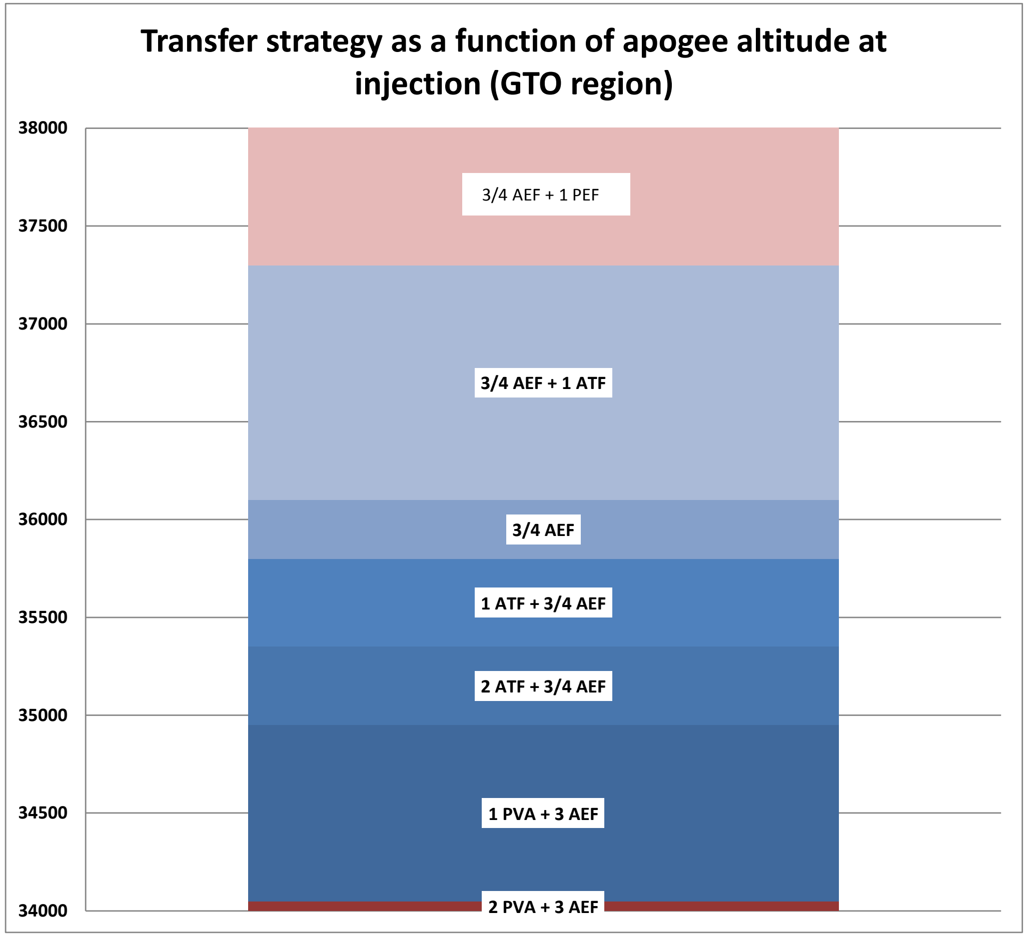
Note that transfer strategy is mission dependant

Falcon 9, MRS and Mission Analysis

Strategy Selection

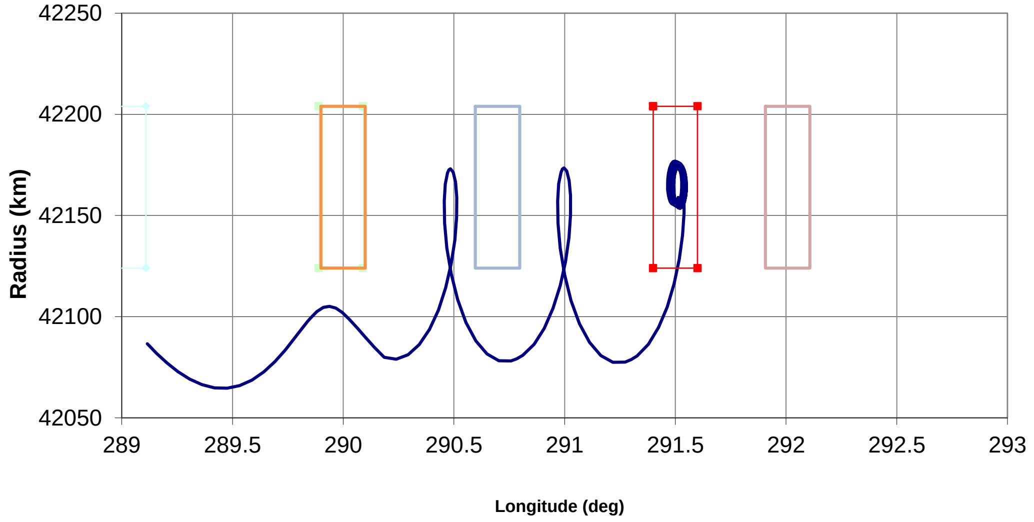
Zoom around the GTO region:

- 6 different strategies over a range of 3000 km of apogee altitudes
- Use of PVA, AEF, PEF and ATF (Attitude Thruster Firing)
- Mix of (classic) inertial and non-inertial burns



Falcon 9, MRS and Mission Analysis

Drift Phase Design



Drift phase follows the transfer phase:

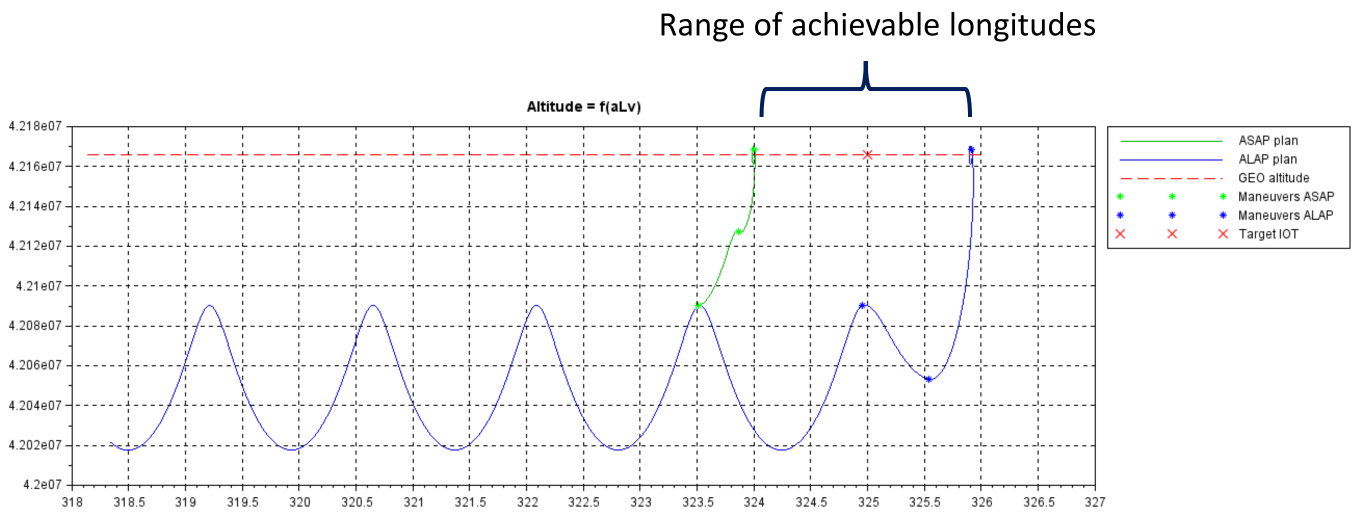
- Stop drift
- IOT Longitude insertion
- Eccentricity and inclination vector target for station-keeping initialisation

Constraints:

- Minimum duration between end of transfer phase and 1st stop drift manœuvre (Earth Acq, Solar Array & Reflector full deployment, etc …)
- Minimum duration between 2 drift stop manœuvres
- Min/Max burn duration
- Scheduled activities (e.g. Payload and Thermal IOT)

Objectives:

- Minimise ΔV
- Minimise drift phase duration
- Minimise GEO ring crossings and close approach to other S/C
- Minimise number of manœuvres/operations



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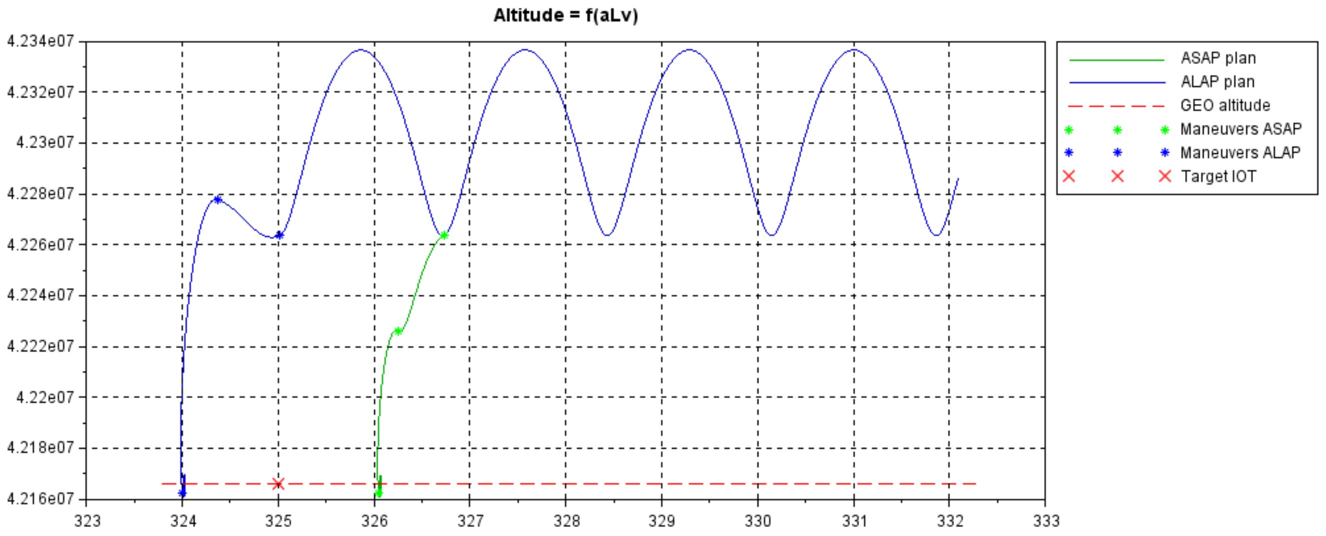
Drift Phase Design

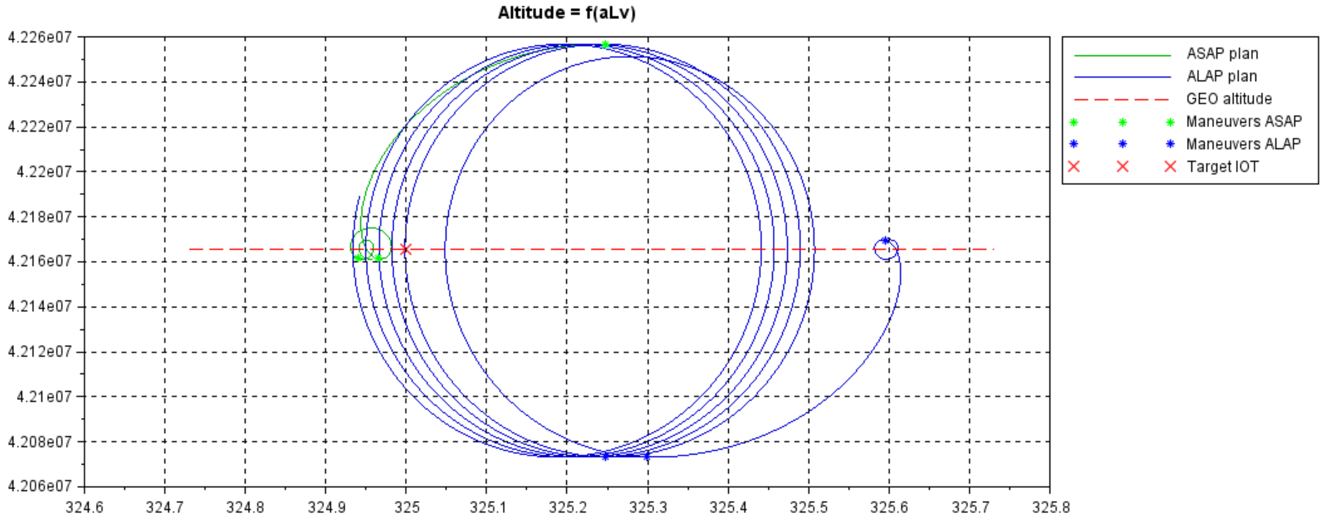
Various injection orbits:

- Apogee well below GEO arc → same drift strategy as for GTO cases (drift eastward)
- Apogee well above GEO arc (SSTO)
  - Opposite drift strategy (drift westward)
  - Direct insertion with no drift
- For apogees around the GEO arc: all strategies are possible

→trade-off between each strategies depends on:

- Engine accuracy/repetitiveness
- Transfer (last) ΔV size
- Other GEO S/C location
- Scheduled operations / staffing





Falcon 9, MRS and Mission Analysis

Minimum Residual Shutdown Mode

Minimum Residual Shutdown: instead of commanding shutdown (called guided command) → the 2nd burn of the 2nd stage is designed to run until depletion allowing the second stage to use up all its propellants with some margin for a safe engine cutoff (when low propellant alarm is triggered and the stage shuts down automatically).

Can be proposed to their client

→Allows ΔV savings for the transfer and transfer duration reduction for Electric Orbit Raising

Such strategy leads to:

- Very low dispersions on Hp, Inc, RAAN, AoP, true anomaly
- Very large dispersions on apogee altitudes (with a guaranteed minimum apogee altitude)

→ Transfer Strategy to be used is unknown before actual separation!

Table 8-3: Falcon 9 sample flight timeline—GTO mission

Mission Elapsed Time	Event
T - 3 s	Engine start sequence
T + 0	Liftoff
T + 82 s	Maximum dynamic pressure (max Q)
T + 170 s	Main engine cutoff
T + 175 s	Stage separation
T + 180 s (3.0 minutes)	Second engine start-1 (SES-1)
T + 220 s (3.7 minutes)	Fairing deploy
T + 540 s (9.0 minutes)	Second engine cutoff 1 (SECO-1)
T + 1,520 s (25.3 minutes)	Second engine start-2 (SES-2)
T + 1,585 s (26.4 minutes)	Second engine cutoff-2 (SECO-2)
T + 1,615 s (26.9 minutes)	Spacecraft separation

taken from "*SpaceX Falcon 9 Launch Vehicle Payload User's Guide – rev 2*"

Falcon 9, MRS and Mission Analysis

Argument of Perigee optimisation

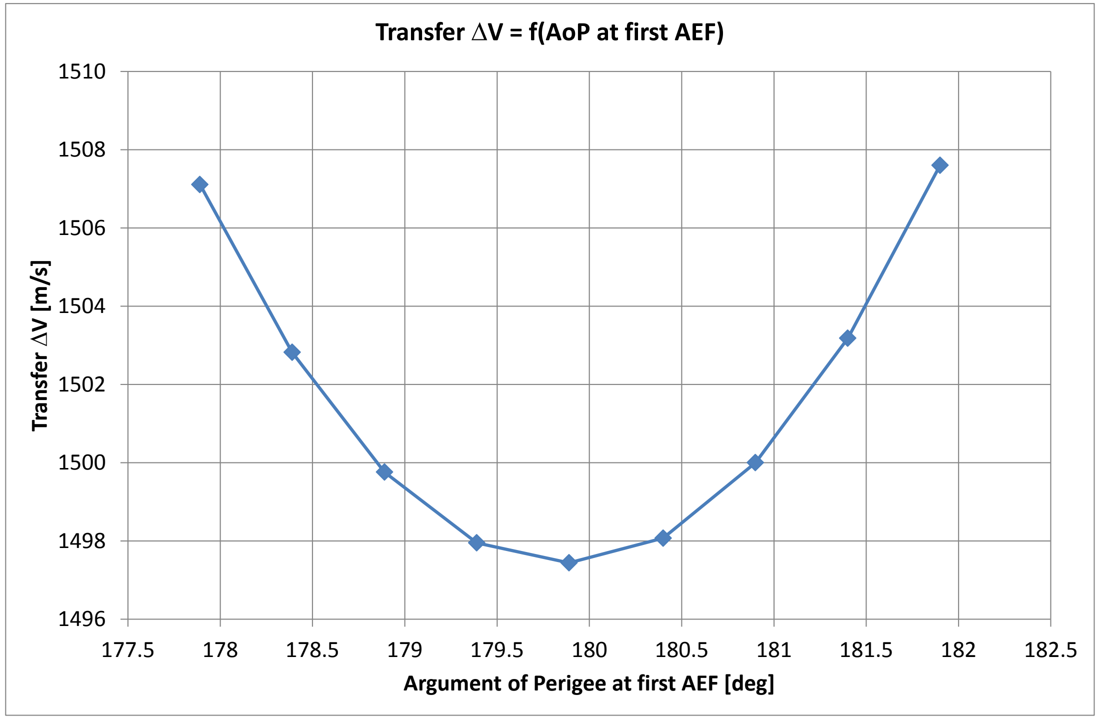
Traditionally AoP at injection is fixed by launchers: ~178 deg → value such that after 4-5 revs in GTO, the AoP is ~ 180 deg (due to J2)

→Optimum for Inc + Perigee corrections

In practice:

- Number of revs before first burn varies (tend for shorter durations)
- Various injection orbits → various AoP drift
- Various missions (chemical vs EOR) → various AoP optimum

→Possibility is offered to select AoP at injection: there is an optimum AoP considering the launcher performance

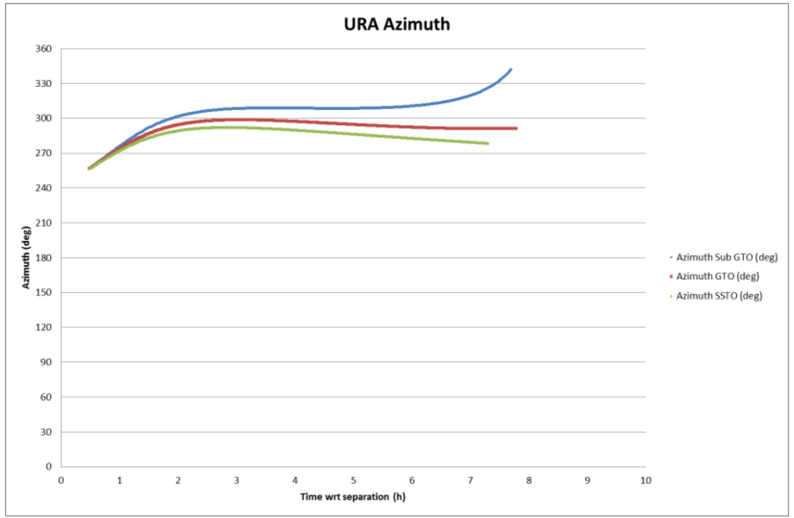


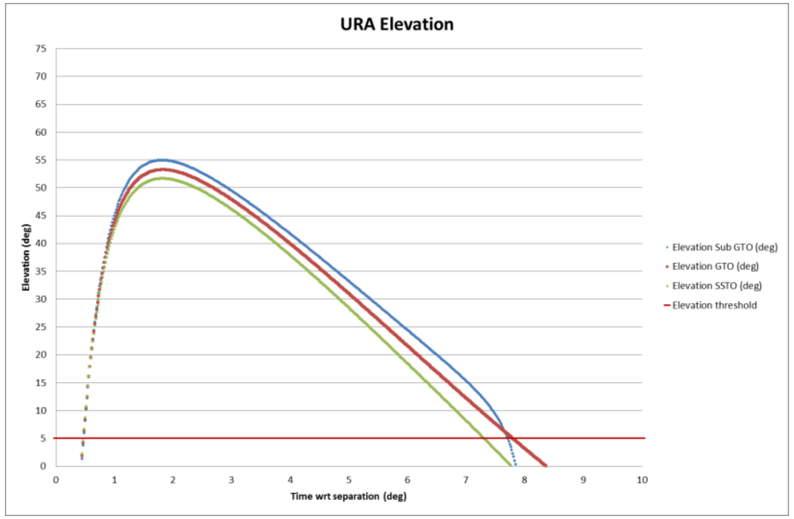
Telecom S/C Operations

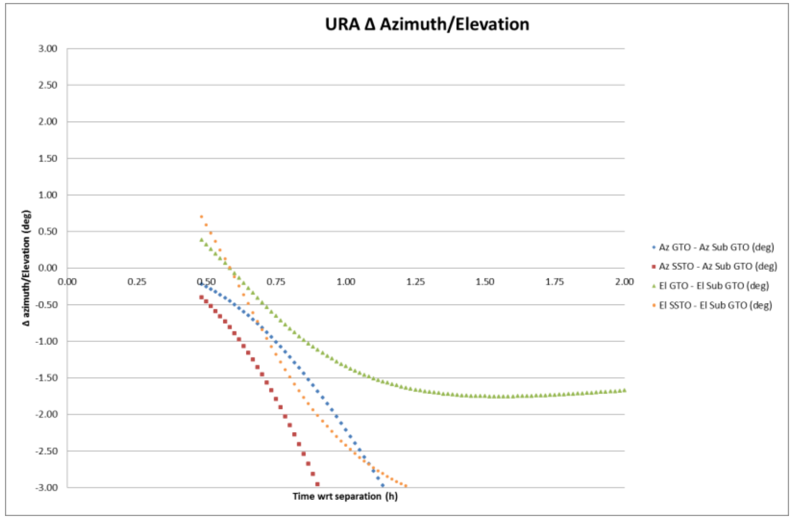
Minimum Residual Shutdown Mode

Mission Analysis:

- GCS and mean MRS cases are fully analysed in the Mission Analysis document
- Launch window opening is checked over the whole apogee altitude range
- First acquisition is critical: azimuth and elevation differences on the first acquisition stations exceed the stations beams radius after a few minutes in flight (depending on the injection apogee altitude difference)
  → Orbit at separation provided by launcher becomes critical (use of Airbus DS WALIS Network)







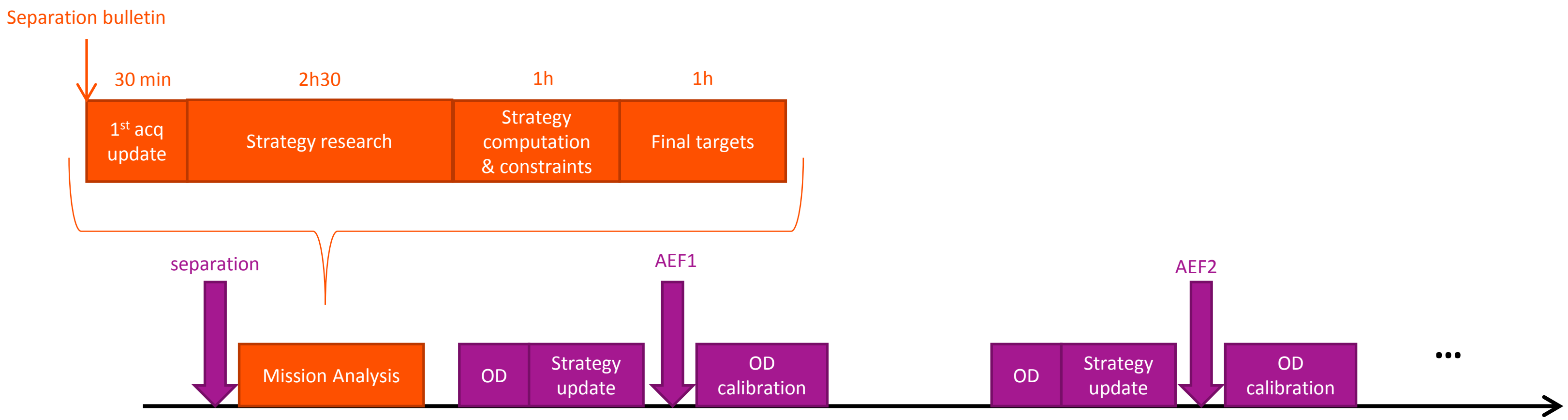
→ Stations are provided with pointing data from the mean MRS case before launch

→ Updated pointing data must be sent as soon as possible after launch

Telecom S/C Operations

Minimum Residual Shutdown Mode

- Based on the separation bulletin provided by SpaceX, the following activities are performed with a strict schedule:
  - Station data update (+ first eclipses) = time critical action (risk is loss of visibility)
  - Strategy research
  - Strategy computation and constraints checks
  - Transfer final target optimisation + drift strategy (and preliminary plan)
- Once this on-the-fly mission analysis has been run, standard operations are followed



- Output is a strategy tree with only nominal and BU1 strategies (taking into account only satellite dispersions)
- Output for Mission Manager is the Timeline → schedule operations/staffing (adapted with additionnal team to cover all cases of 1st burn date)
- Ability to find back-ups for the following burns is ensured by using only 4-5 burns strategies and by strategy design (burn balance)

Telecom S/C Operations

Minimum Residual Shutdown Mode

As the on-the-fly mission analysis is to be done under 5h, just after launch and possibly at night, the human risk factor is increased.
Risk mitigation is done with:

- Preparation
  - Computation of reference strategies across the apogee altitude distribution based on the last injection prediction from SpaceX, during the last week before launch
  - Additional training of the team
- Staffing
  - Experienced team members only
  - Team of 5 for the mission analysis shift
- Work organization
  - Computation (1st acquisition update, strategy computation and constraints, final targets) by separate people, with results consistency check
  - Separate and different strategies research, then strategy selection
- Meetings (at client request)
  - Key meetings with client FD team + Mission Managers at each step
  - Objective is to consolidate transfer strategy + final targets

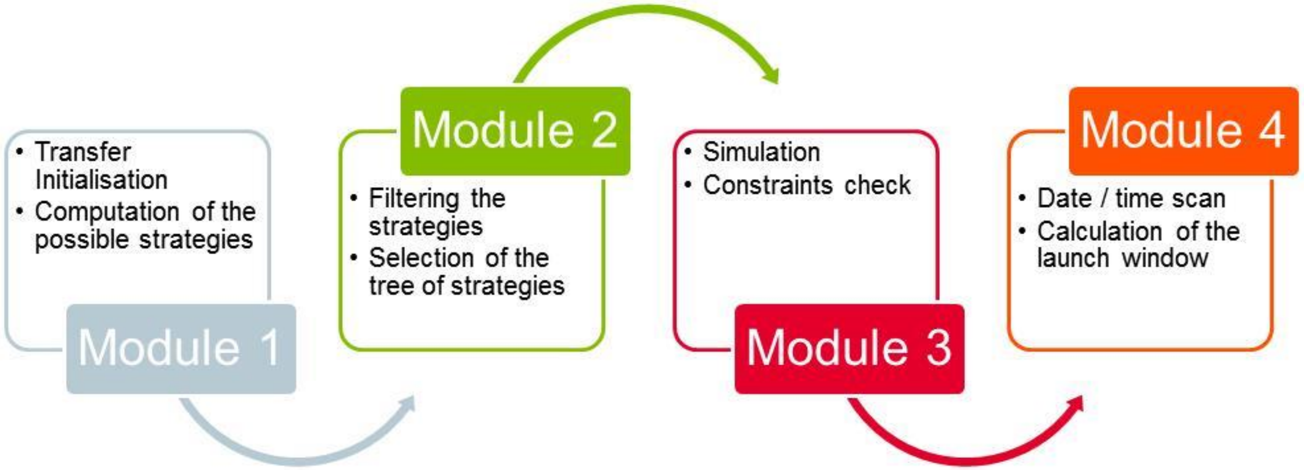
Mission Analysis and Operation Software

Mission Analysis Design: a new tool for providing transfer strategies

What for? Gathering a set of unitary legacy tools into a single one that can handle most of the injection orbit types, current and future platform and mission constraints.

How? A new software integrated in JAVA web to produce mission analysis studies for the LEOP of spacecraft with chemical propulsion:

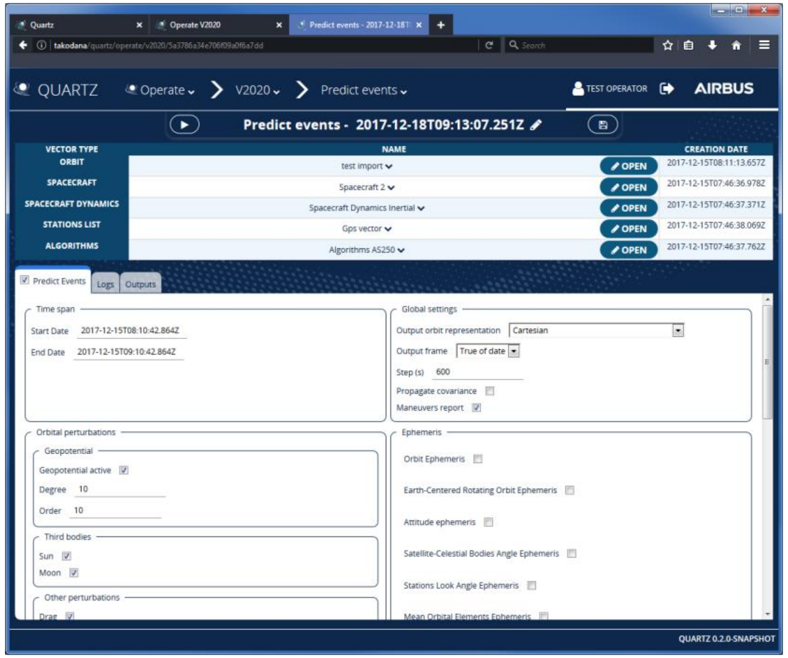
- Find a set of nominal and compatible back up strategies for chemical transfer to GEO orbit with ΔV breakdown computation.
- Handle the following initial orbits : Sub GTO, GTO & SSTO
- Compute the total propellant consumption of each strategy including the Robbin's penalty
- Handling of all the mission operational constraints
- Produce an initial guess file for each strategy that can be used to feed the optimisation software OptElec



Mission Analysis and Operation Software

Software heritage and recent developments

QUARTZ



For GTO missions, the optimisation targets at the end of transfer phase (before drift phase) are:

- Longitude + drift
- Inc + RAAN

→Use of QUARTZ software in operations for Earth bounded chemical transfer optimisation

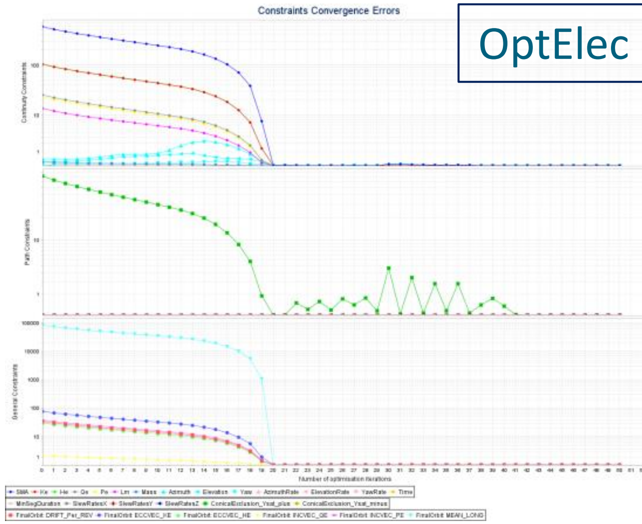
With EOR, development of Low-thrust transfer optimisation software OptElec since 2013 → used in Mission Analysis as standalone tool and embedded in QUARTZ during Operations

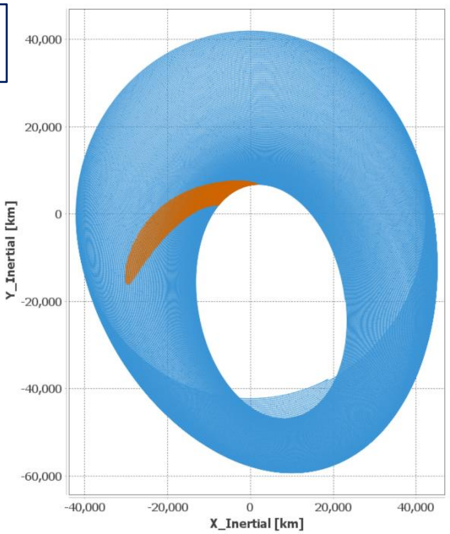
→Decision was made to make OptElec generic and treat chemical transfer optimisations and replace QUARTZ transfer optimisation module

OptElec approach:

- OptElec uses a direct optimisation approach
- Multiple Shooting (MS): discretizes the orbit transfer into segments
- Problem solved using a NLP algorithm

OptElec





Mission Analysis and Operation Software

OptElec development for chemical transfers

- Targets:
  - Keplerian: sma/drift, ecc, inc, RAAN, AoP, Anomalies
  - Equinoctial: sma/drift, ex, ey, ix, iy, longitudes (mean/true)
  - Geo longitude, **apogee/perigee altitudes**
  - Can be expressed as final targets or **intermediate** targets (before or after burn number N)
  - Can be expressed as fixed values or **max values** or **min values** (for GEO box avoidance for instance)

- Propulsion / Burns:
  - Can be used using High thrust levels (e.g. LAE), medium thrust levels (e.g. RCT) or **combination of both** (LAE + RCT or RCT + LAE)
  - Burns can be defined in Inertial Frame or LOF
  - Burns can be set **fixed** in either frame or **let free to be optimised**. This setting can be specified for each individual burn
  - Maximum and minimum burn durations can be set

- Injection parameters: can be optimised (e.g. to find optimum AoP at injection during Mission Analysis)

Mission Analysis and Operation Software

A chemical study case - assumptions

Assumptions:
- Injection orbit: Ha = 28900 km, Hp = 290 km, i = 28 deg, Ω = 170 deg, ω = 180 deg
- Mass & CPS: m = 4500 kg, F = 450N, Isp = 320s
- Perturbations: Earth potential (10x10), Sun, Moon, SRP

Targets:
- Drift = 1 deg/day, L_{geo}= 0 deg
- Maximum apogee radius: 42125 km
- i = 0.1 deg, Ω = 270 deg

P/F Constraints:
- Maximum burn duration = 2 hours & Minimum burn duration = 120 s.
- AEFs must be fixed in inertial frame while PVA may have time-varying thrust direction

Mission Analysis:
- 2 PVA must be performed, followed by 3 AEF.
- The 1st PVA occurs 5 revs after separation. The 2nd PVA occurs 3 revs after PVA1.
- The first AEF occurs 2.5 revs after the last PVA. The 2nd and 3rd AEF occurs 2 revs after the AEF before them.
- The last burn (AEF) must not exceed 350 m/s.

Mission Analysis and Operation Software

A chemical study case - results

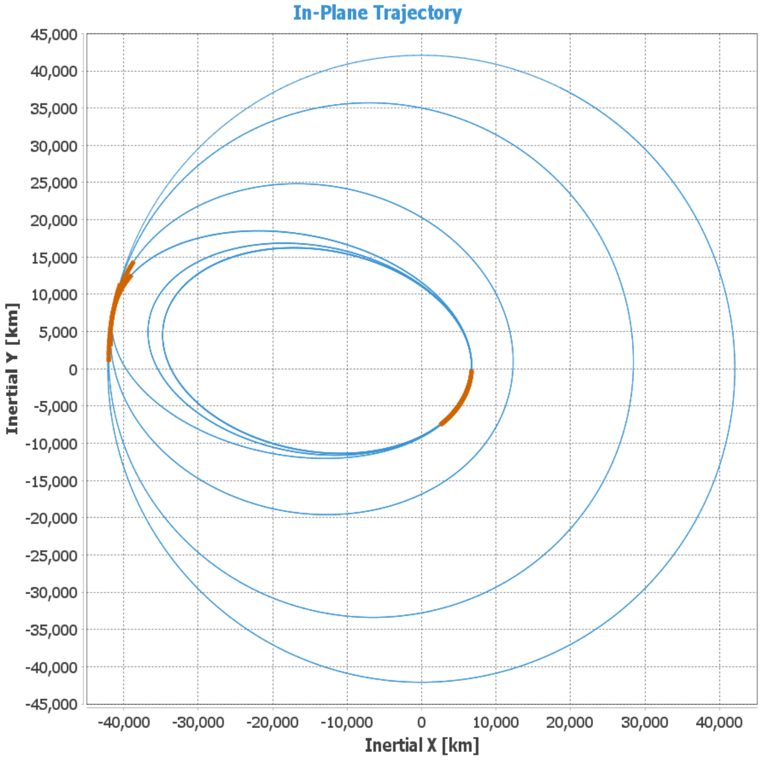
Results:

- Constraints are satisfied
- Targets are reached
- PVA1 and PVA2 are optimised (almost fixed in LOF)
- AEF1, AEF2 and AEF3 fixed in inertial frame (direction similar for all of them)

Constraint relaxation study:

- Impact of max ΔV for burn 5 constraint
- AoP at injection optimisation

Cases	AoP at injection		Last ΔV		Total ΔV [m/s]
	Status	AoP [deg]	Status	ΔV [m/s]	
C1	Fixed	180	Max	350	1974.2
C2	Fixed	180	Free	468.9	1972.3
C3	Free	176.18	Max	350	1959.2




```
INFO - TARGETS
INFO -
INFO -   Burn #5         DELTAV                 350.0 [m/s]     (max value)
INFO -
INFO -   Final Orbit     DRIFT_Per_DAY           1.00 [deg/day]
INFO -   Final Orbit     RA                   42125.0 [km]      (max value)
INFO -   Final Orbit     ix_QUARTZ              0.000 [deg]
INFO -   Final Orbit     iy_QUARTZ             -0.100 [deg]
INFO -   Final Orbit     LGEO                   0.000 [deg]
INFO -
INFO - FINAL RESULTS
INFO -
INFO -   -  Final epoch: 2016-09-09T05:00:05.064
INFO -   -  Transfer duration:                          8.208 [days]
INFO -   -  DV for transfer phase:                     1974.2 [m/s]
INFO -   -  S/C Mass at the end of transfer phase:  2398.8 [kg]
INFO -
INFO - CHEMICAL DELTA V
INFO -
INFO -   DeltaV_1 :   45.8 [m/s]   tau :   454.3 [s]   az_start :    4.24 [deg]   az_end :    6.46 [deg]   el_start :   -6.36 [deg]   el_end :   -9.81 [deg]   Frame : LOF
INFO -   DeltaV_2 :   98.6 [m/s]   tau :   956.7 [s]   az_start :    4.94 [deg]   az_end :    3.03 [deg]   el_start :   -6.65 [deg]   el_end :   -5.83 [deg]   Frame : LOF
INFO -   DeltaV_3 :  645.0 [m/s]   tau :  5567.8 [s]   az_start :  -97.58 [deg]   az_end :  -97.58 [deg]   el_start :  -24.79 [deg]   el_end :  -24.79 [deg]   Frame : IN
INFO -   DeltaV_4 :  834.9 [m/s]   tau :  5700.7 [s]   az_start :  -97.61 [deg]   az_end :  -97.61 [deg]   el_start :  -24.53 [deg]   el_end :  -24.53 [deg]   Frame : IN
INFO -   DeltaV_5 :  350.0 [m/s]   tau :  1973.7 [s]   az_start :  -97.62 [deg]   az_end :  -97.62 [deg]   el_start :  -23.95 [deg]   el_end :  -23.95 [deg]   Frame : IN
INFO -
INFO - INTERMEDIATE ORBITS
INFO -
INFO -   Initial State : 2016-09-01T00:00:00.000  sma: 20973.1  ecc: 0.68206  ra: 35278.1  rp:  6668.1  inc:  28.00  RAAN:  170.00  AoP:  180.00  trueAno:   20.00  Lgeo:   27.23
INFO -
INFO -   Before DV1    : 2016-09-02T17:35:06.263  sma: 20946.2  ecc: 0.68161  ra: 35223.5  rp:  6669.0  inc:  27.99  RAAN:  169.18  AoP:  181.25  trueAno:  313.50  Lgeo:   61.42
INFO -   After  DV1    : 2016-09-02T17:42:40.557  sma: 21991.5  ecc: 0.69648  ra: 37308.3  rp:  6674.8  inc:  27.97  RAAN:  169.20  AoP:  180.83  trueAno:  348.65  Lgeo:   91.93
INFO -
INFO -   Before DV2    : 2016-09-03T20:25:32.502  sma: 21939.6  ecc: 0.69570  ra: 37203.1  rp:  6676.1  inc:  27.96  RAAN:  168.74  AoP:  181.58  trueAno:  296.88  Lgeo:    0.49
INFO -   After  DV2    : 2016-09-03T20:41:29.219  sma: 24518.6  ecc: 0.72696  ra: 42342.7  rp:  6694.5  inc:  27.90  RAAN:  168.80  AoP:  180.67  trueAno:    8.17  Lgeo:   62.85
INFO -
INFO -   Before DV3    : 2016-09-04T22:03:13.372  sma: 24433.5  ecc: 0.72590  ra: 42169.8  rp:  6697.3  inc:  27.89  RAAN:  168.40  AoP:  181.30  trueAno:  171.94  Lgeo: -152.83
INFO -   After  DV3    : 2016-09-04T23:36:01.184  sma: 27175.9  ecc: 0.55096  ra: 42148.6  rp: 12203.2  inc:  13.61  RAAN:  168.74  AoP:  181.11  trueAno:  185.81  Lgeo: -163.05
INFO -
INFO -   Before DV4    : 2016-09-05T22:47:16.834  sma: 27175.9  ecc: 0.55096  ra: 42148.6  rp: 12203.2  inc:  13.61  RAAN:  168.61  AoP:  181.36  trueAno:  169.70  Lgeo: -167.37
INFO -   After  DV4    : 2016-09-06T00:22:17.514  sma: 35245.7  ecc: 0.19528  ra: 42128.4  rp: 28363.0  inc:   2.93  RAAN:  170.31  AoP:  179.93  trueAno:  188.15  Lgeo: -172.72
INFO -
INFO -   Before DV5    : 2016-09-07T11:55:50.302  sma: 35245.7  ecc: 0.19528  ra: 42128.4  rp: 28363.0  inc:   2.93  RAAN:  170.27  AoP:  180.02  trueAno:  174.29  Lgeo:   -1.37
INFO -   After  DV5    : 2016-09-07T12:28:43.979  sma: 42087.9  ecc: 0.00083  ra: 42122.8  rp: 42052.9  inc:   0.10  RAAN:  270.02  AoP:   85.40  trueAno:  176.98  Lgeo:   -1.79
INFO -
INFO -   Units : sma:[km], ecc:[-], ra:[km], rp:[km], inc:[deg], RAAN:[deg], AoP:[deg], trueAno:[deg], Lgeo:[deg]
```

Conclusions

- Adaptation of Telecom Satellite market to this new offer

- Lower orbits at injection:
  →PVA at low perigee (without visibility)
  →Use of RCTs made possible

- Unknown orbits at injection (MRS):
  →The type of strategy is designed before launch
  →But the actual strategy is computed after separation
  →Requires flexibility in Operations and made possible with new P/F (Mk 1.5/2)
  →Extra training to cover all potential cases

- New developments: OptElec has been updated and is used at Mission Analysis level and in Operations

- 2 MRS transfer performed so far for chemical transfers (with Mk1.5 P/F)

Evolution of the Launcher Market for Telecom Satellites: Impact on Mission Analysis and Flight Dynamics Operations

COMET-ORB Low Cost Launcher Services and their Impact, CNES, Toulouse – 04th April 2019

DEFENCE AND SPACE

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