DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

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Università degli Studi di Padova – Dipartimento di Ingegneria Industriale

Corso di Laurea in Ingegneria Aerospaziale

Relazione per la prova finale
«Retrospective proposals for the orbital correction of GSAT0201 & GSAT0202»

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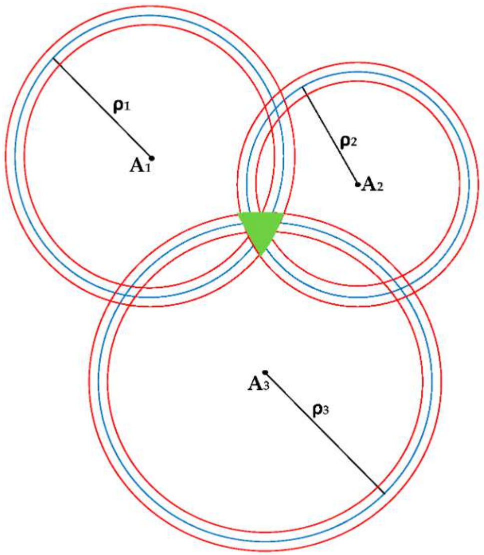
INTRODUCTION

Galileo is the European GNSS (*Global Navigation Satellite System*) which provides free and precise position and timing services all over the world.

Launch VS09, which was transporting the 5^{th} and 6^{th} satellites of the constellation, failed during the injection procedures. The final orbit was degraded and many subsystems on board ceased to function. Orbit nominality couldn't be reached: the programmed schedule had to be aborted.

In this presentation, after a discussion about the Galileo system, the VS09 launch and the subsystem recovery operations, some possible drivers and orbits for the correction will be proposed and analised. A comparison with the actual recovery orbits will be made at the end.

True range multilateration



MUST KNOW:

- Position in space and time of satellites *(navigation data)*;
- Models to reduce error.

Pseudorange *(with PRN)*

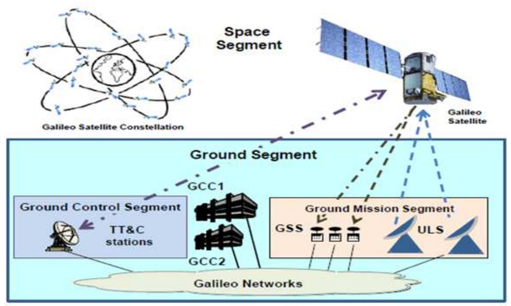
$$meas_{rec}^{sat} = \rho_{rec}^{sat} + c \cdot (dt_{rec} - dt_{sat}) + \varepsilon_{mod} + \varepsilon_{unmod}$$

Multilateration solution

$$\begin{bmatrix} prefit^1 \\ prefit^2 \\ \vdots \\ prefit^n \end{bmatrix} = \begin{bmatrix} \frac{x_{i,rec}-x^{sat_1}}{\rho_{i,rec}^{sat_1}} & \frac{y_{i,rec}-x^{sat_1}}{\rho_{i,rec}^{sat_1}} & \frac{z_{i,rec}-z^{sat_1}}{\rho_{i,rec}^{sat_1}} & 1 \\ \frac{x_{i,rec}-x^{sat_2}}{\rho_{i,rec}^{sat_2}} & \frac{y_{i,rec}-x^{sat_2}}{\rho_{i,rec}^{sat_2}} & \frac{z_{i,rec}-z^{sat_1}}{\rho_{i,rec}^{sat_2}} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \frac{x_{i,rec}-x^{sat_n}}{\rho_{i,rec}^{sat_n}} & \frac{y_{i,rec}-x^{sat_n}}{\rho_{i,rec}^{sat_n}} & \frac{z_{i,rec}-z^{sat_1}}{\rho_{i,rec}^{sat_n}} & 1 \end{bmatrix} \begin{bmatrix} \Delta x_{rec} \\ \Delta y_{rec} \\ \Delta z_{rec} \\ c \cdot dt_{rec} \end{bmatrix}$$

where $prefit^k = meas_{rec}^{sat_k} - \rho_{i,rec}^{sat_k} + c \cdot dt_{sat_k} - \varepsilon_{mod,k}$

GNSS architecture



- Space segment
- Ground segment
- User segment

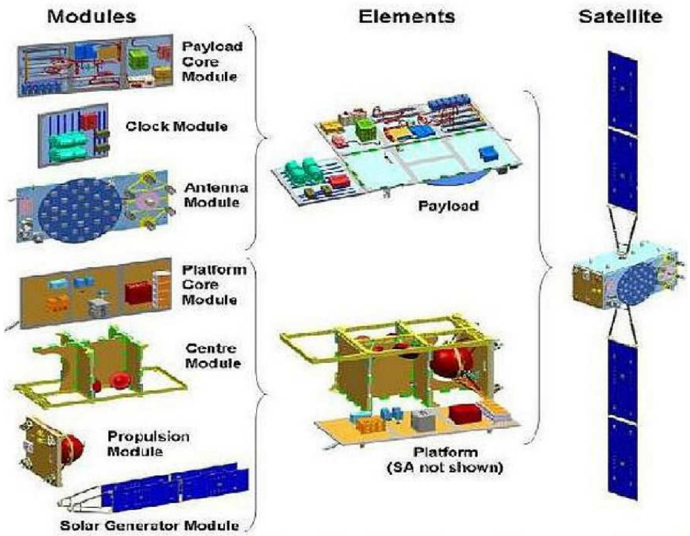
Sources: [15], [16]

GALILEO SPACE SEGMENT AND FOC SATELLITE

The aim of the space segment is to generate and transmit code and carrier signals and to brodcast the navigation message.

Orbit SMA a [m]	29599801	Reference RAAN Ω_0 [deg]	77.632
Orbital period T	14h 4min 42s	Reference AOP ω_0 [deg]	0
Orbit ECC e	0	Reference MA M_0 [deg]	15.153
Orbit INC i [deg]	56	Reference epoch T_0	2016/11/21, 21:00:00 UTC
Satellites in plane N_s	8	Orbital planes N_p	3

$\Longrightarrow$ **34 orbits every 20 days**



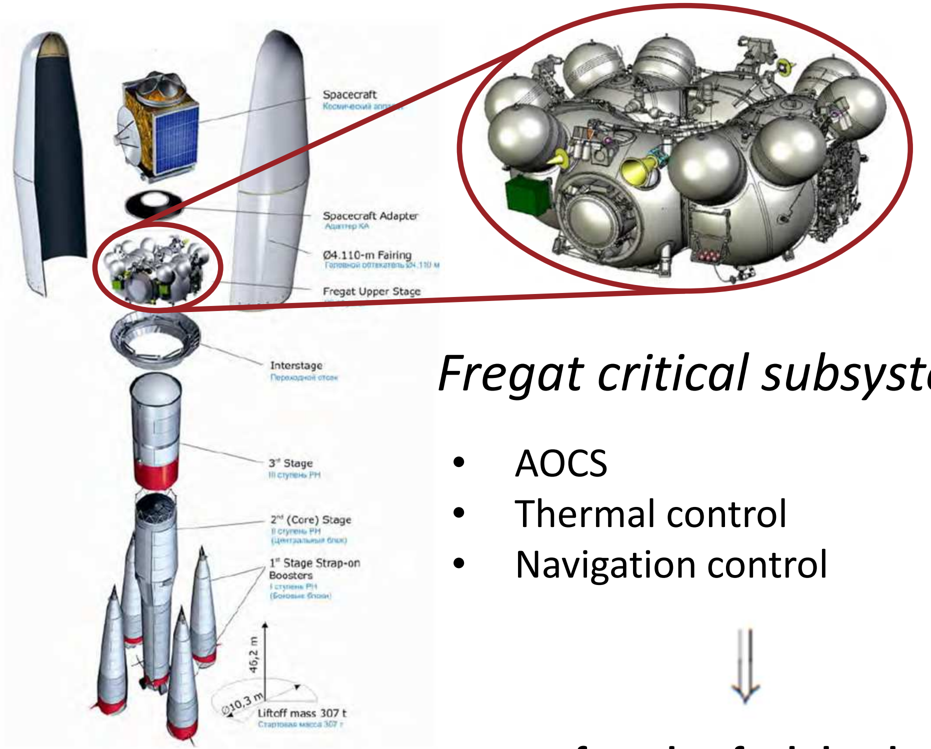
FOC satellite critical subsystems

- *Earth sensors:* Minimum altitude: 15331 km
- *Solar arrays:* Deployment with thermal knives
- *Gyroscopes:* Software valid only for circular orbits
- *Hydrazine thrusters and tanks:*

$$\begin{cases} m_{struc} = 732.8kg \\ m_{fuel} = 68kg \\ I_{sp_{N_2H_4}} = 220s \\ g_{sl} = 9.80665\frac{m}{s^2} \end{cases} \Longrightarrow \Delta v_{max} = g_{sl} I_{sp_{N_2H_4}} ln\left(1 + \frac{m_{fuel}}{m_{struc}}\right) = 191.45\frac{m}{s}$$

Sources: [1], [3], [11], [12], [13], [14]

Soyuz ST-B and Fregat



Success rate at ELS: 96.3%
(one failure in 27)

Fregat critical subsystems

- AOCS
- Thermal control
- Navigation control

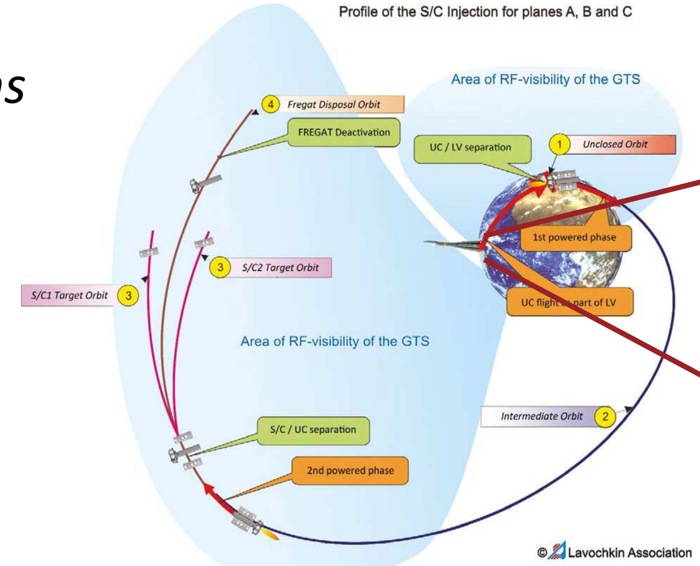
⇓

found at fault by the Arianespace Inquiry Board for VS09 launch failure

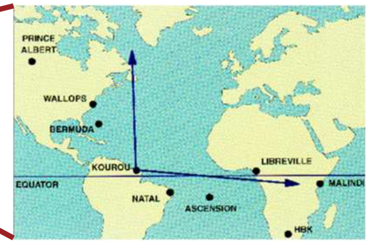
Typical MEO mission profile

1. Ascent of the three-stages Soyuz;
2. First Fregat burn to intermediate orbit;
3. Coast phase of variable duration;
4. Second Fregat burn to reach the final orbit.

Duration: ~ 3h 50 min



ELS position

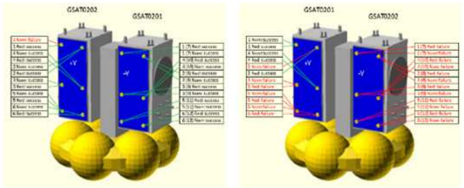


Sources: [3], [4], [5], [7], [19]

LAUNCH AND INJECTION FAILURE

- Lift-off: 22/08/2014, 12:27:11 UTC
- Acquisition of Signal: 22/08/2014, 16:15:08 UTC

⟹ After solving **Low downlink signal** **Error in antenna pointing** Discovery of… ⟹ **PANELS NOT DEPLOYED**



Recovery done exposing thermal knives to the Sun through gap between S/C and wing

⇓

WRONG ORBIT

Orbit assessment (at AoS)

GSAT0201	a [km]	e	i [deg]	Ω [deg]	ω [deg]	$u = \theta + \omega$ [deg]
Observed	26197.6	0.232	49.77	87.47	24.73	249.04
Δ wrt target	-3715	0.23	-5.35	-13.19	/	7.79
σs of error	111	698	134	330	/	/

GSAT0202	a [km]	e	i [deg]	Ω [deg]	ω [deg]	$u = \theta + \omega$ [deg]
Observed	26181.3	0.233	49.77	87.48	24.88	249.76
Δ wrt target	-3706	0.23	-5.35	-13.18	/	7.78
σs of error	111	698	134	329	/	/

Causes (according to Arianespace Inquiry Board)

- Poorly placed helium lines on Fregat
- ⇓ Hydrazine freezing in conducts
- ⇓ Interruption of fuel flow to AOC thruster
- ⇓ Nav. System out of inertial system limits
- ⇓ Wrong orientation at injection

Injection error (in RSW coord.)

	Nominal	Actual	Abs. error
Radial [m/s]	-28	-663	635
Along [m/s]	1456	1135	321
Cross [m/s]	108	637	529
Magnitude [m/s]	1459	1460	1

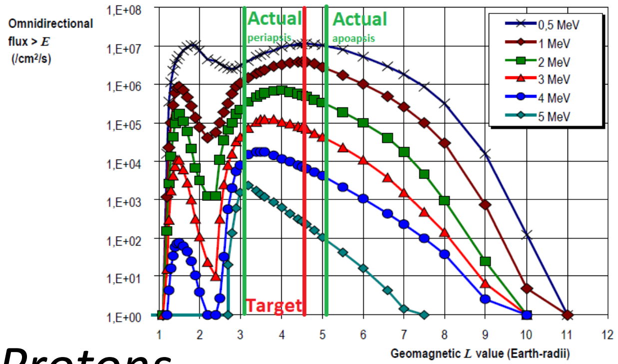
⟹ 35.34° away from nominal direction

Sources: [3], [5], [6]

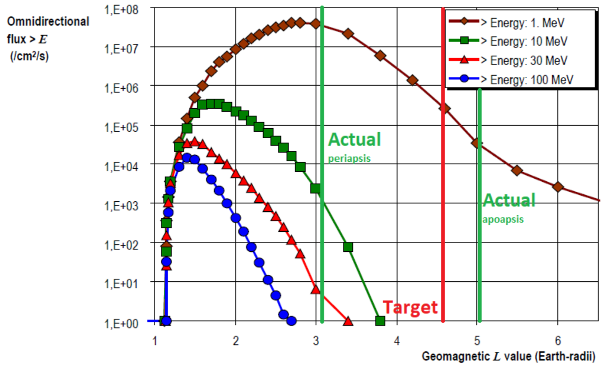
ORBIT-CAUSED PROBLEMS

Radiation protection

Electrons

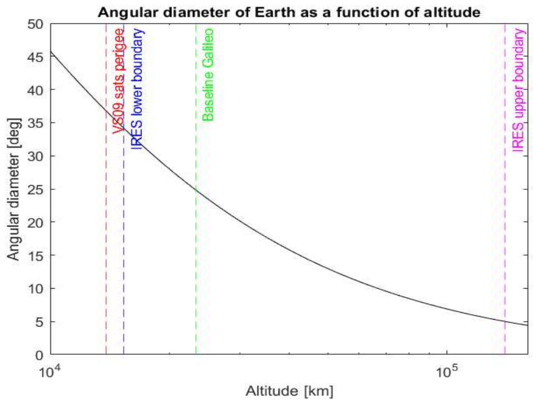


Protons



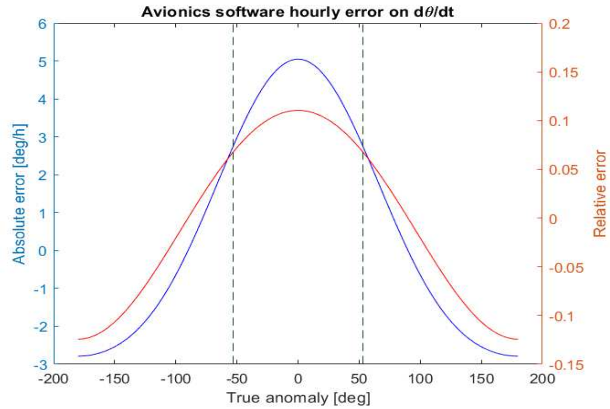
$r \in [3.1, 5.1]\ R_{Earth}$

Earth sensor



unusable for $|\theta| < 53°$
(18.8 % orb. period)

Gyroscopes



up to 5°/h of error
at perigee

Other

- *Wider range of Doppler shift;*
- *Presence of lower-than-normal visibility periods*
- *Grav. redshift on payload clocks*

⟹ **SATELLITES NOT FIT FOR GALILEO OPERATIONS**

Sources: [17], [18]

PROPOSED RECOVERY DRIVERS

I. Reserve enough fuel for collision avoidance with other orbiting bodies and for attitude control;
II. Reduce the harmful radiation dose on the spacecrafts and their degradation rate;
III. Allow for baseline operations of all attitude and orbit control system sensors;
IV. Reduce the operational burden on the satellites communications system;
V. Insert the satellites into orbits with a certain ground track repeatability, similar to the one of the Galileo constellation;
VI. Reduce secular drifts due to Earth oblateness;
VII. Insert the probes into specific orbital planes.

Numerical estimation for orb. parameters

$\Longrightarrow$

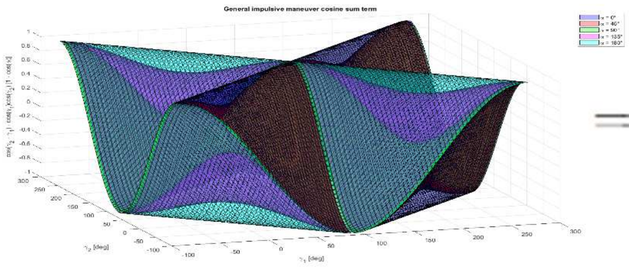
1. Increase of the semimajor axis a up to a specific value;
2. Reduction of orbit eccentricity e as much as possible;
3. Change of i and Ω to fit into Galileo constellation planes

$$\begin{cases} a(1-e) > 21704km \\ e \to 0 \\ \sqrt{\frac{4\pi^2}{\mu}a^3} \begin{cases} \to \frac{10}{17}d \\ = \frac{20}{n}d, n \in \mathbb{N} \end{cases} \\ a \to \infty \\ (i, \Omega) \to (i_{nom}, \Omega_{nom}) \end{cases}$$

Impulsive maneuver general equation

$$\Delta v = \sqrt{v_1^2 + v_2^2 - 2v_1 v_2 \left[\cos(\gamma_2 - \gamma_1) - \cos(\gamma_1)\cos(\gamma_2)(1 - \cos(\alpha))\right]}$$

⟹ Δv is at its minimum when cos(γ2 − γ1) − cos(γ1) cos(γ2)[1 − cos(α)] is at its maximum ⟹



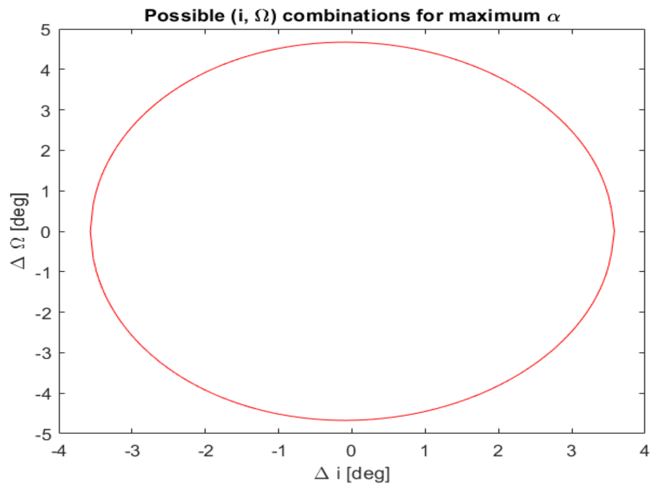
⟹ $\vec{v}_1, \vec{v}_2$ and $\Delta\vec{v}$ have to lie on the same direction $(\gamma_1 = \gamma_2)$

Pure plane rotation ($\Delta v \neq \min$)

$$\begin{cases} \alpha = 2\arcsin\left(\dfrac{\Delta v}{2v_1\cos(\gamma)}\right) \\ \cos(\alpha) = \cos(\Omega_2 - \Omega_1)\sin(i_1)\sin(i_2) + \cos(i_1)\cos(i_2) \end{cases}$$

	Max Δ wrt actual [deg]	Min Δ wrt nominal [deg]	$\Delta_{nominal}/\sigma$
Pure i change	± 3.57	2.66	66.5
Pure Ω change	± 4.67	8.51	127.65

$(a = 26200 \text{ km}, \; e = 0.233, \Delta v = 0.192\ km/s)$



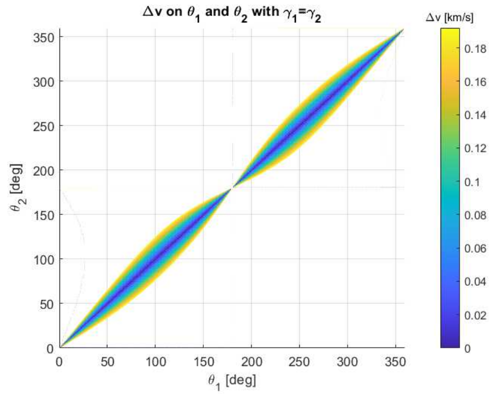
Sources: [8]

IMPULSIVE MANEUVERS SELECTION

General in-plane maneuver with $\gamma_1 = \gamma_2$ $(\Delta \mathrm{v} = \min)$

$$\Delta v = \sqrt{\mu}\left(\sqrt{\frac{(1+e_2^2+2e_2\cos\theta_2)}{a_2(1-e_2^2)}} - \sqrt{\frac{(1+e_1^2+2e_1\cos\theta_1)}{a_1(1-e_1^2)}}\right)$$

$$\Longrightarrow \begin{aligned} e_2 &= \frac{\tan(\gamma_1)}{\sin(\theta_2)-\cos(\theta_2)\tan(\gamma_1)} \\ a_2 &= \frac{1+e_2\cos(\theta_2)}{1+e_1\cos(\theta_1)}\frac{1-e_1^2}{1-e_2^2}a_1 \end{aligned} \Longrightarrow \Delta v = f(\theta_1, \theta_2)$$

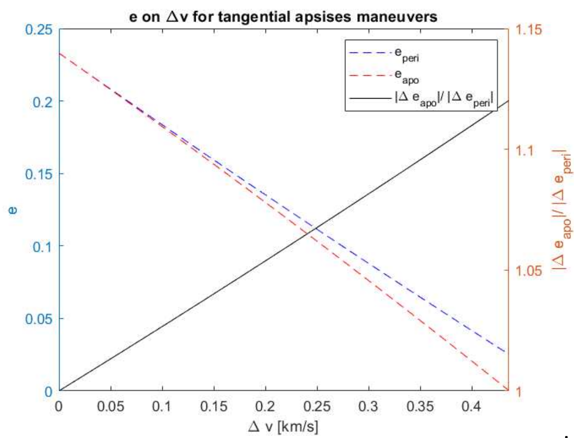


$\Longrightarrow$ Part of Δv wasted in the rotation of apsis line if maneuver performed outside of apsides

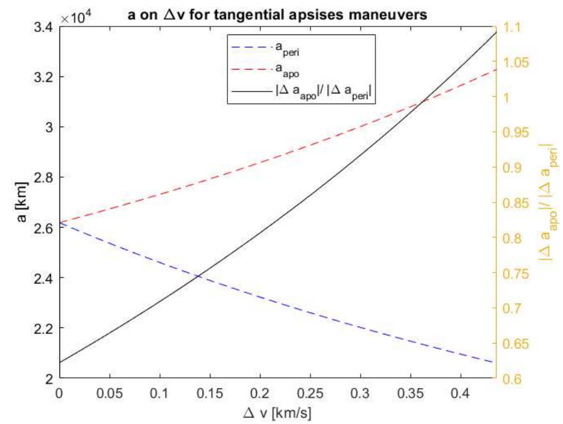
Tangential maneuver at apsises $(\gamma_1 = \gamma_2 = 0°, \sin(\theta) = 0, \Delta \mathrm{v} = \min)$ $(\mathrm{a} = 26200\ \mathrm{km},\ \mathrm{e} = 0.233)$

$$\Delta v_{apsis} = \sqrt{\frac{\mu}{a_{fin}}\frac{1 \pm e_{fin}}{1 \mp e_{fin}}} - \sqrt{\frac{\mu}{a_{in}}\frac{1 \pm e_{in}}{1 \mp e_{in}}}$$

$$\Longrightarrow \begin{aligned} e_{fin} &= \pm\left(\Delta v\sqrt{\frac{a_{in}(1 \mp e_{in})}{\mu}} + \sqrt{1 \pm e_{in}}\right)^2 \mp 1 \\ a_{fin} &= a_{in}\frac{1 \mp e_{in}}{1 \mp \left[\left(\Delta v\sqrt{\frac{a_{in}(1 \mp e_{in})}{\mu}} + \sqrt{1 \pm e_{in}}\right)^2 \mp 1\right]} \end{aligned}$$



e decreases more if the same $|\Delta v|$ is applied at the apocenter

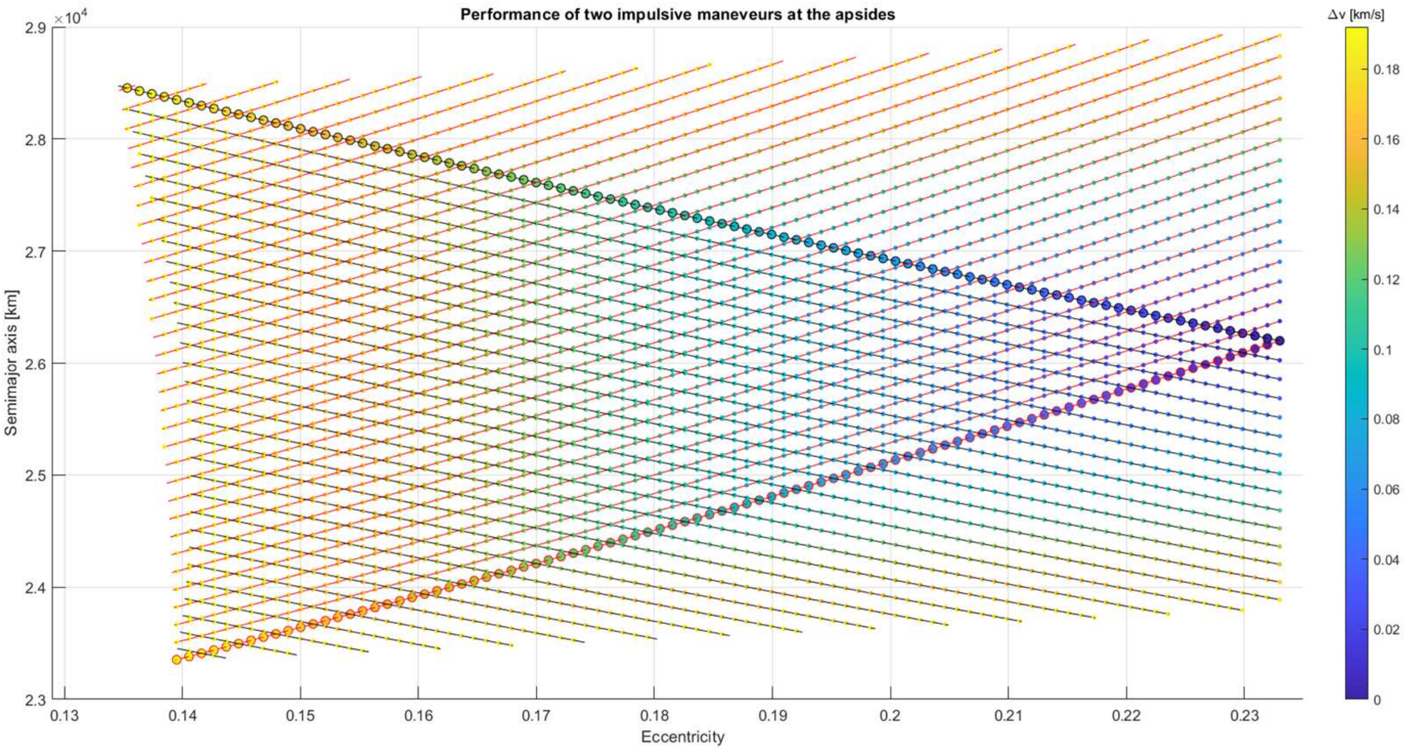


$|\Delta a|$ increases more if the same $|\Delta v|$ is applied at the perigee, for $\Delta v \in [0, \sim 0.35]$ km/s

Sources: [8]

Combination of tangential maneuver at apsides

a_{fin} is independent of e_{fin}. When performing multiple circularising maneuvers, Δv is lower if the first burn is at apogee for a certain (a_{fin}, e_{fin}).



$(a = 26200 \text{ km},\ e = 0.233)$

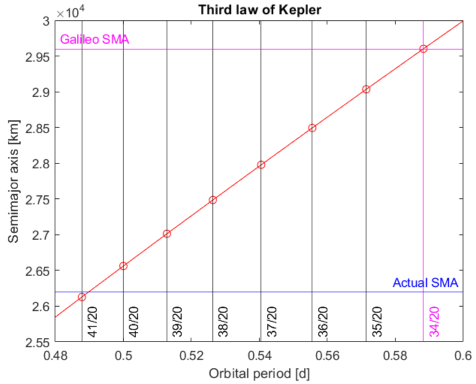
Sources: [3], [8]

Δv budget

Accounting for necessary savings and non-impulsive man. inefficiencies:

	GSAT0201	GSAT0202
Δv [km/s]	0.160	0.160

Ground track repeatability (most stringent driver)



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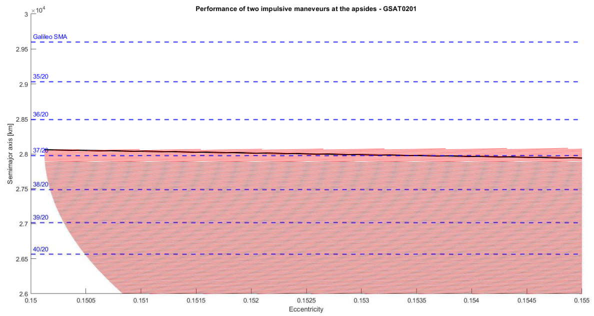
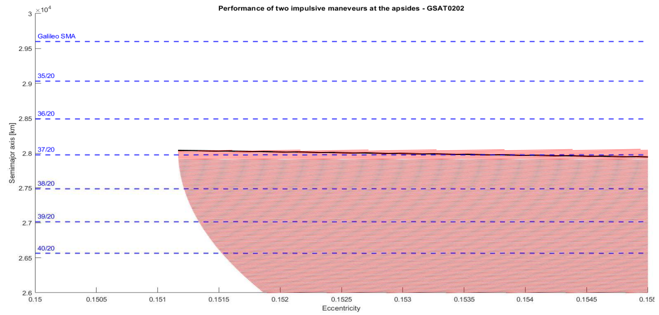


$(a = 26197.8 \text{ km}, \ e = 0.232)$



$(a = 26181.7 \text{ km}, \ e = 0.233)$

Orbit proposals

GSAT0201

T [d]	a [km]	e	Δv_{apo} [km/s]	Δv_{peri} [km/s]	m_{apo} [kg]	m_{peri} [kg]	m_{rem} [kg]
20/37	27978.7	0.15015	0.1572	0.0027	56.27	1.03	10.70
20/38	27485.7	0.15019	0.1406	0.0194	50.51	7.17	10.32
20/39	27013.8	0.15036	0.1252	0.0358	45.14	12.82	10.04
20/40	26561.7	0.15053	0.1081	0.0519	39.17	18.98	9.85

GSAT0202

T [d]	a [km]	e	Δv_{apo} [km/s]	Δv_{peri} [km/s]	m_{apo} [kg]	m_{peri} [kg]	m_{rem} [kg]
20/37	27978.7	0.15119	0.1578	0.0022	56.50	0.78	10.72
20/38	27485.7	0.15124	0.1412	0.0188	50.74	6.92	10.34
20/39	27013.8	0.15136	0.1249	0.0351	45.04	12.92	10.04
20/40	26561.7	0.15155	0.1088	0.0512	39.40	18.75	9.85

Drivers satisfaction

	I	II	III	IV	V	VI	VII
20/37	1^{st}	1^{st}	✓	1^{st}	✓	1^{st}	/
20/38	2^{nd}	2^{nd}	✓	2^{nd}	✓	2^{nd}	/
20/39	3^{rd}	3^{rd}	✓	3^{rd}	✓	3^{rd}	/
20/40	4^{th}	4^{th}	✓	4^{th}	✓	4^{th}	/

BEST ORBITS AND TIMING

To reduce differences, GSAT0201 will be inserted at (a, e) of GSAT0202 20/37 orbit.

Time independent parameters and man. data

	GSAT0201	GSAT0202
a [km]	27978.7	27978.7
e	0.15119	0.15119
i [deg]	49.77	49.77
Δv_{apo} [km/s]	0.1561	0.1578
Δv_{peri} [km/s]	0.0019	0.0022
m_{rem} [kg]	11.41	10.72

Time dependent parameters (on 15/11/14, 04:27:12 UTC)

	GSAT0201	GSAT0202
Ω [deg]	83.21	84.31
ω [deg]	28.31	27.54
$\nu = \theta + \omega$ [deg]	210.31	27.54

Timetable for correction

Starting epoch t_0	22/08/14, 16:15:08 UTC
GSAT0202 apo. man.	$t_0 + 0.399$ d
GSAT0202 peri. man.	$t_0 + 0.668$ d
GSAT0201 apo. man.	$t_0 + 84.239$ d
GSAT0201 peri. man.	$t_0 + 84.504$ d

⇓

$\Delta\theta$ oscillates between 170° and 184°

REAL RECOVERY ORBITS AND COMPARISON

Recovery drivers

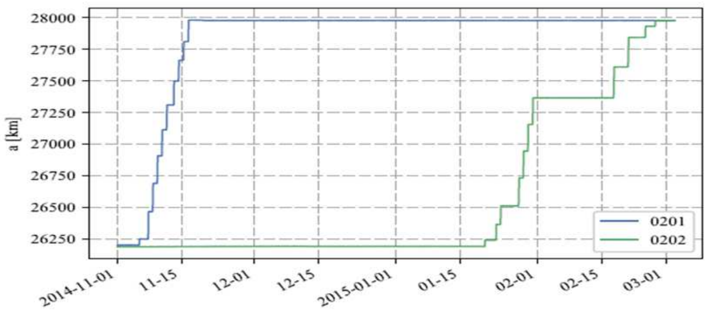
- Reduction of operational burden on AOCS system;
- Reduction of the exposure to Van Allen belts;
- Reduction of eccentricity;
- Improvement of the Galileo constellation performance

GSAT0201 corr. (9 apo, 1 peri, 5-19/11/14)

GSAT0201	a [km]	e	i [deg]	Ω [deg]	ω [deg]	θ [deg]
Observed	27979.043	0.156	49.776	82.692	28.927	0

GSAT0202 corr. (10 apo, 1 peri, 22/1-2/3/15)

GSAT0201	a [km]	e	i [deg]	Ω [deg]	ω [deg]	θ [deg]
Observed	27978.585	0.156	49.875	77.52	34.35	0

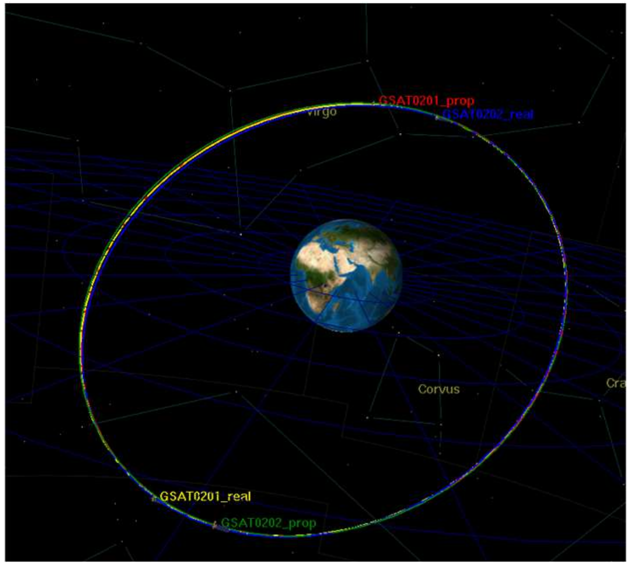


Sources: [1], [2]

Comparison

- $e_{real} > e_{retro}$
- $(i_{real}, \Omega_{real}, \omega_{real}) \neq (i_{retro}, \Omega_{retro}, \omega_{retro})$
- Non-impulsive man. mean more burns for better efficiency

	a [km]	e	i [deg]	Ω [deg]	ω [deg]	$\nu = \theta + \omega$ [deg]
GSAT0201 - proposed	27978.7	0.15119	49.77	79.01	31.84	55.11
GSAT0202 - proposed	27978.7	0.15119	49.77	80.10	31.07	224.99
GSAT0201 - real	27979.0	0.15600	49.78	78.74	32.24	212.65
GSAT0202 - real	27978.5	0.15600	49.88	77.52	34.35	34.35



Insertion in constellation:
GSAT0201: 19/12/14
GSAT0202: 25/3/15

CONCLUSIONS

The failure in the injection procedures in flight VS09 left the first two FOC Galileo satellites in non-nominal orbits. An improvement of the trajectory was possible, which could enable the probes to use their GNSS payload.

We concluded the best orbits have a resonance of 37 orbits every 20 days, achieved performing one main maneuver at apogee and one fine positioning burn at perigee. The timing was also considered, to allow for the quasi-alternability of the satellites.

This retrospective proposal can solve many of the orbit-related problems affecting the probes, allowing for testing into the Galileo GNSS. The quality of finding is corroborated by the fact it’s a better version than the one the Galileo team implemented, since it possesses lower eccentricity.

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