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Group of Astrodynamics for the Use of Space Systems

G.A.U.S.S. ACTIVITIES ON ATTITUDE AND ORBITAL CONTROL SYSTEMS

4th IAA DyCoSS, CHANGSHA, China, 21-23 May 2018

Agenda

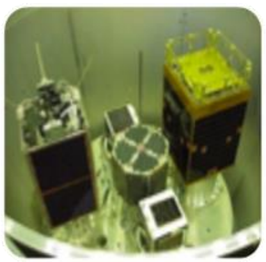
This presentation will track the following topics:

- Introduction about G.A.U.S.S.
- Orbital Control
- Attitude Control

These three elements share a common focus, represented by *microsatellites*.

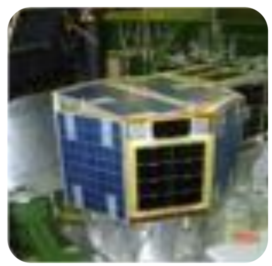
GAUSS SRL

- The company name is an acronym for "**Group of Astrodynamics for the Use of Space Systems**".
- As a laboratory group of Astrodynamics at *Sapienza* University of Rome, we have launched six microsatellites.



UNISAT 2000

UNISAT-2 2002



UNISAT-3 2004

UNISAT-4 2006

EDUSAT 2011

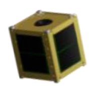
UniCubeSat-GG 2012

- Then, on 2012, GAUSS became a limited liability company…

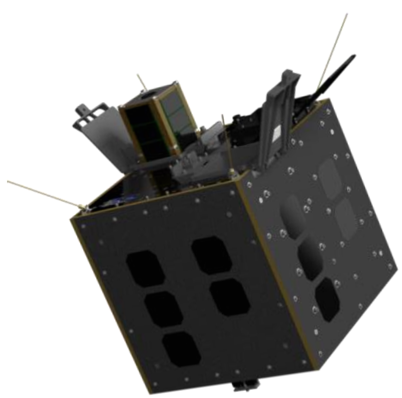
GAUSS SRL

- As a private company (2012 on), we have successfully launched three small satellites, UniSat-5 (2013), UniSat-6 (2014) and TuPOD (2017). UniSat-7 will be launched in 2019.
- GAUSS small satellites are used also as launch platforms for third-party satellites.

UNISAT-5 2013

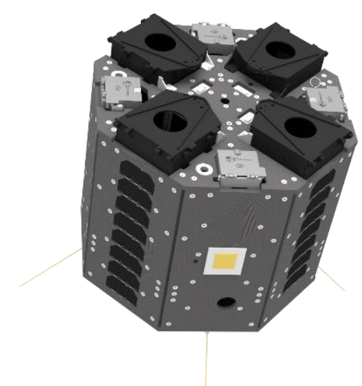


UNISAT-6 2014



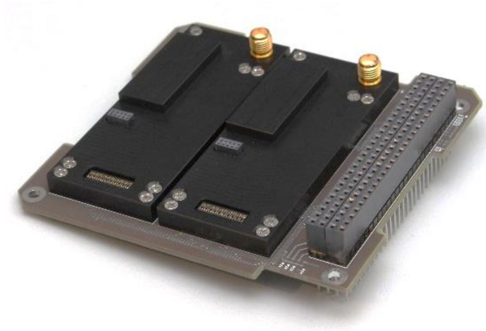
TUPOD 2017

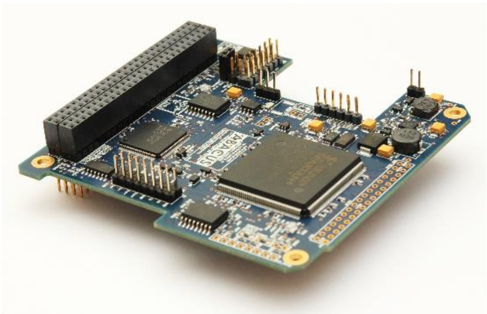
UNISAT-7 to be launched in 2019



GAUSS SRL

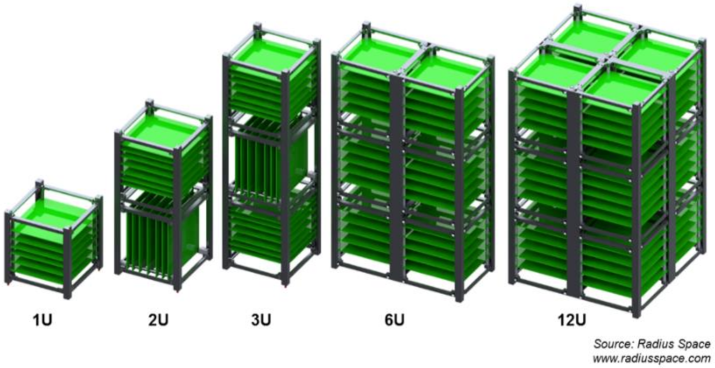
- GAUSS Srl activities include:
  - NanoSatellite launch provider
  - Personalized Satellite bus for payloads
  - Mission analysis
  - Ground station services
  - Satellite subsystems:
    - OnBoard computers
    - Radio subsystem for TT&C
    - Power susbystem EPS





What’s a Micro & Nano Satellite?

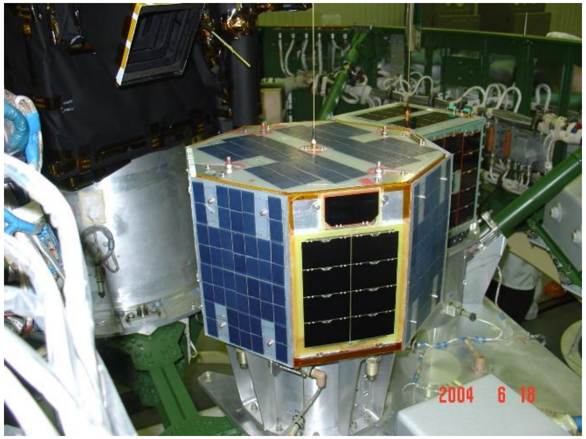
- Pico, Micro & Nano Satellites:
  - MicroSatellite: 10-100kg
  - NanoSatellite: 1-10kg
  - PicoSatellite: 0.1-1kg
  - Femto: 1-100g

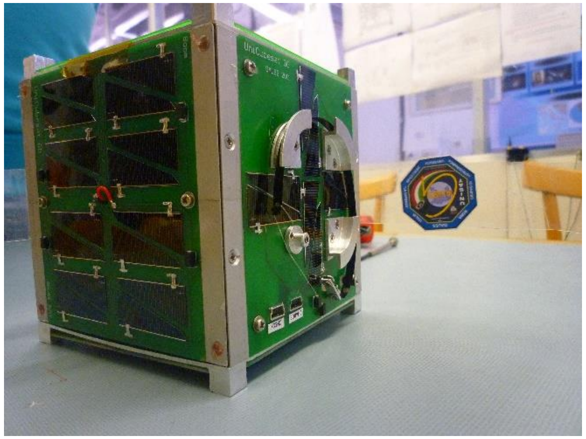


- What’s a CubeSat?
  - It is a nanosatellite obeying to a specific standard, with cubic shape of 10x10x10cm (1l) and a maximum mass of 1.33kg *also called a CubeSat 1U*.
  - In recent years other dimensions have become popular:
    - CubeSat 3U: 10x10x30cm, 4kg
    - CubeSat 6U: 10x20x30cm, 8kg

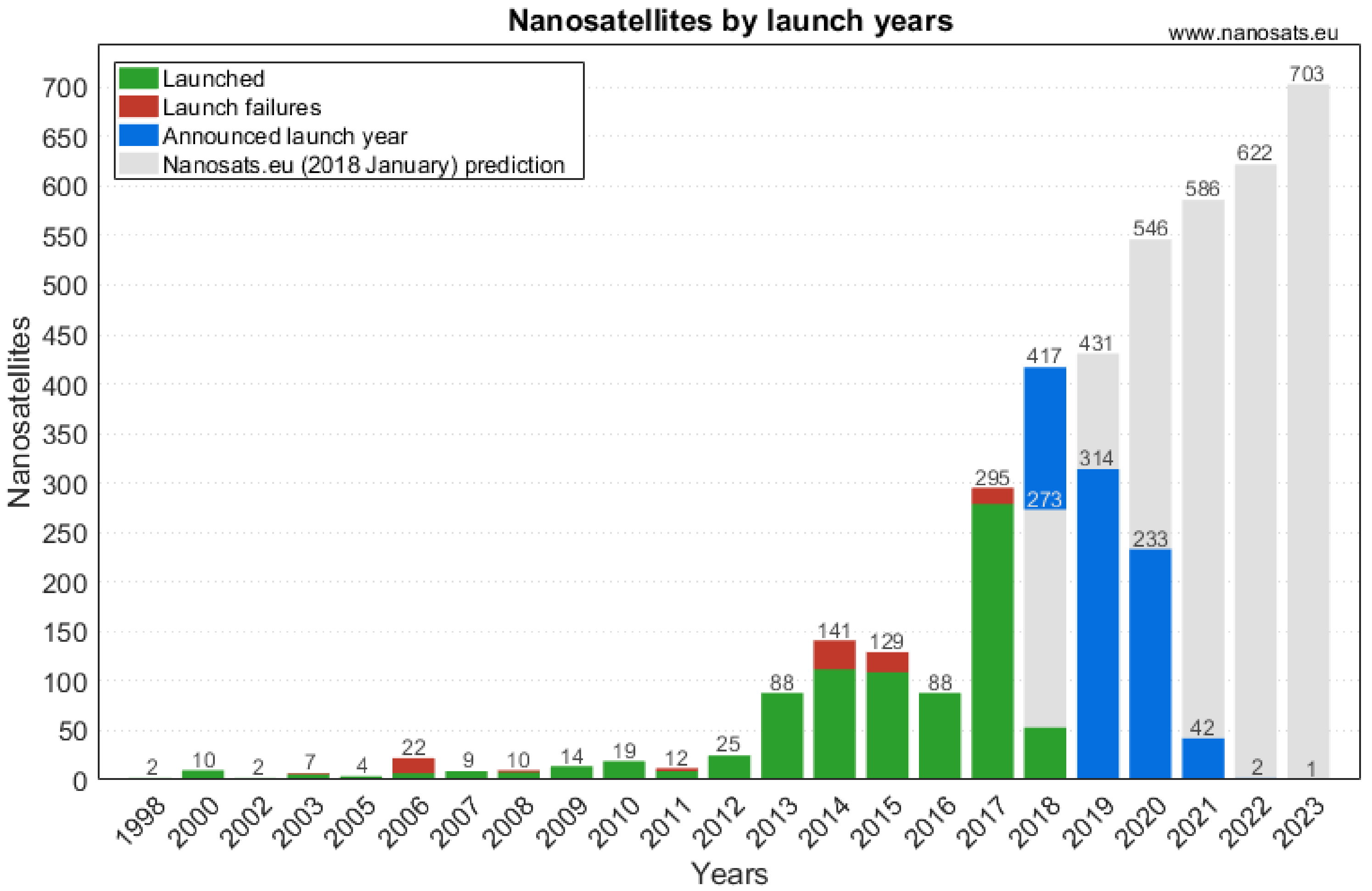
History of Microsatellites

- Educational purpose:
  - CubeSats: Proposed by professors Bob Twiggs and Jordi Puig-Suari in 1999. Launched already more than 500 CubeSats.
  - GAUSS Lab from the School of Aerospace Engineering of La Sapienza and later as a private company launched
    - Eight satellites (EduSat, UniSat,Tupod)
    - One Nanosatellite: 1u CubeSat



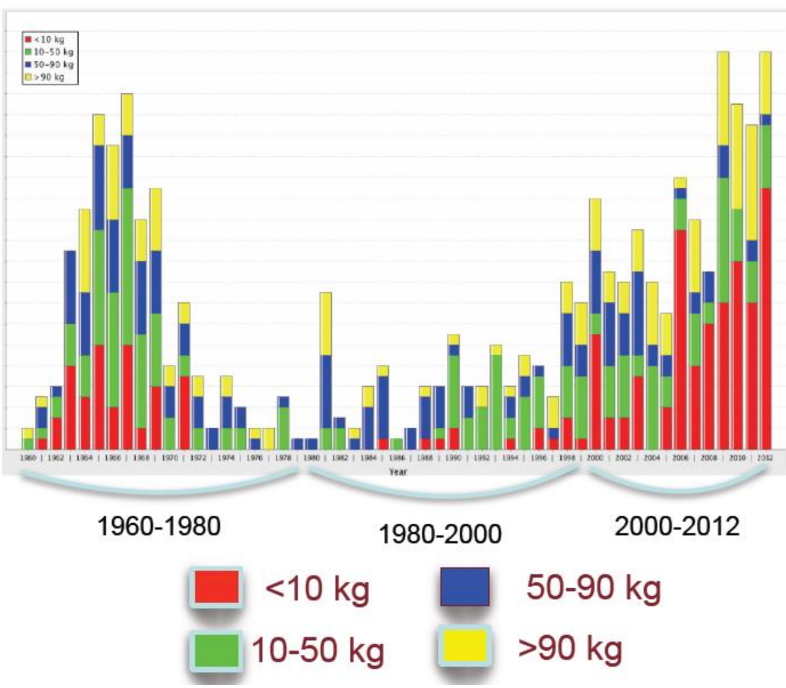


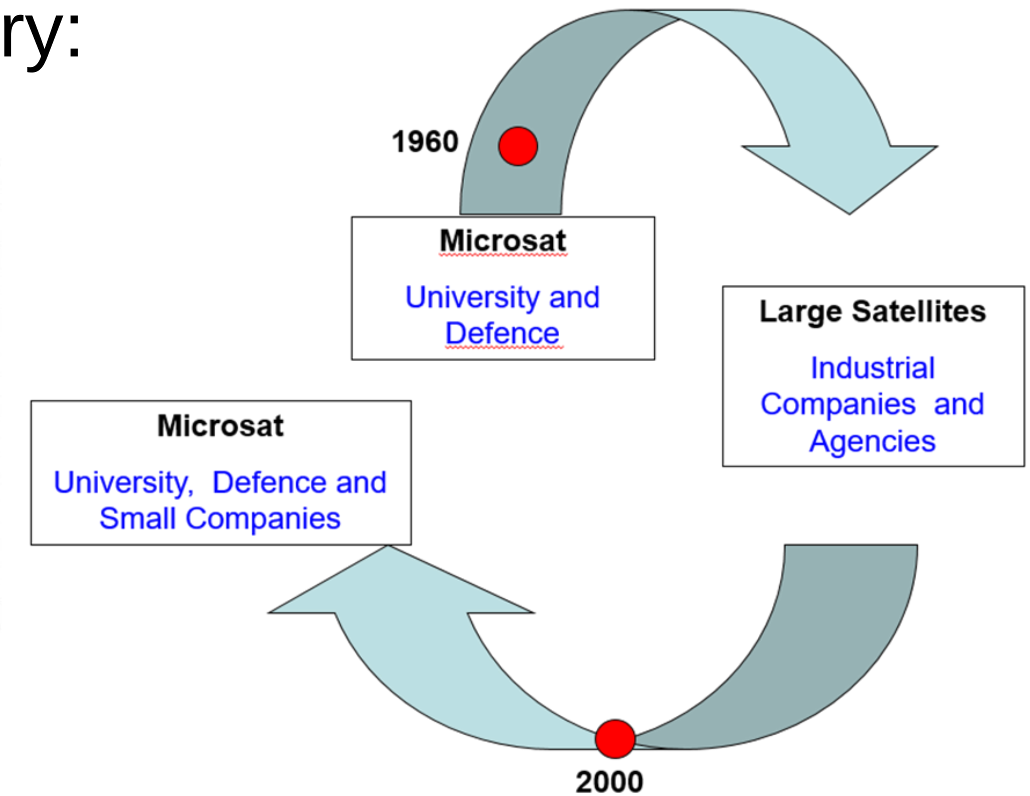
Nanosatellite History



Reasons for Micro/Nanosatellites revenge

- Actually, the previous bar-chart is part of a longer history:



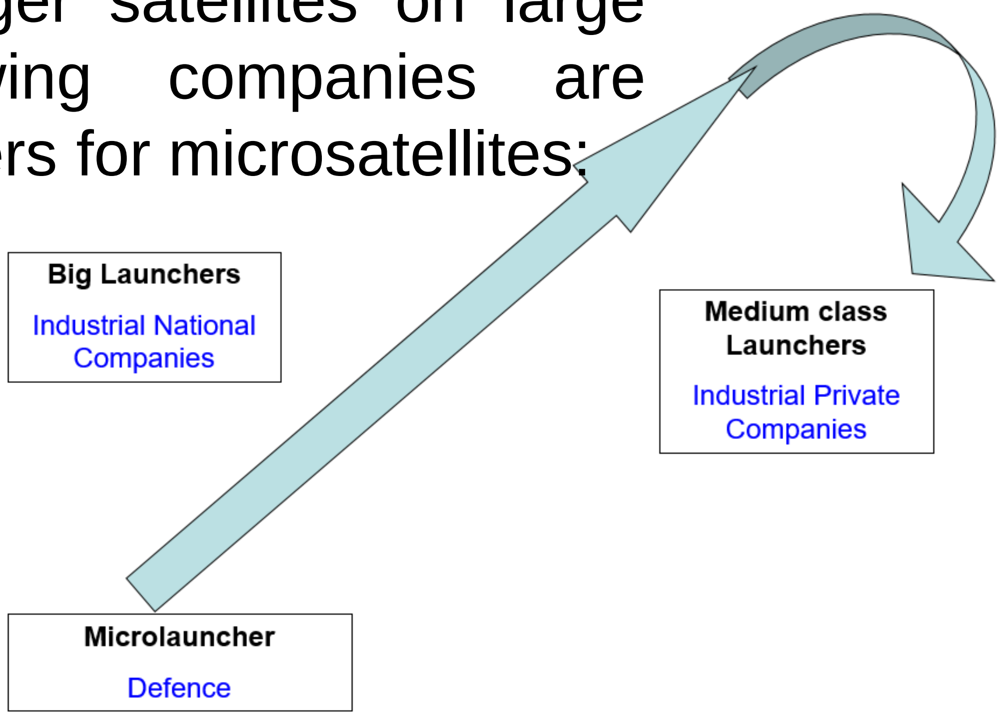


Why back to Microsatellites?

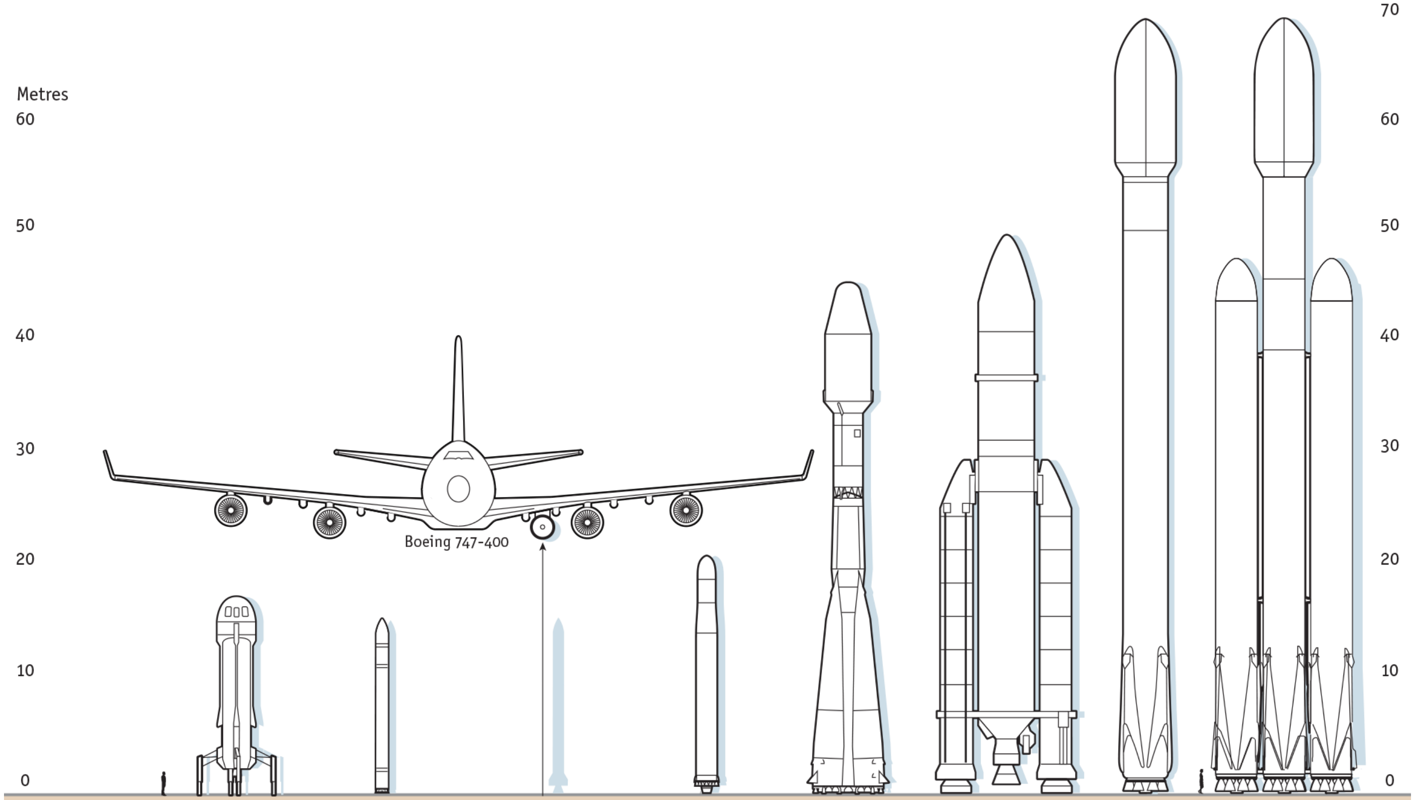
- **Miniaturization** of electronics has allowed developing high performance subsystems. (On board and payload computers, Radio, ADCS, Propulsion)
- **Reduced costs**: Mostly use of COTS electronics. Use of standards allow for a very fast construction.
- **Acceptable increased risk** of the mission: Losing one microsatellite will no longer geopardize the mission.
- Very **fast** reaction construction
- **Responsive space**, design and construction of microsatellites can be very fast and cheap in comparison with bigger satellites.

One more reason (for µsats bright future)

- Small launchers are back. There is a new chance to launch smaller satellites without being piggyback of bigger satellites on large launchers. The following companies are developing small launchers for microsatellites:
  - RocketLabs
  - PLD Space
  - Virgin Orbit
  - Vector Space Systems
  - Super Strypi
  - Vega
  - Land Space



Small launchers are back

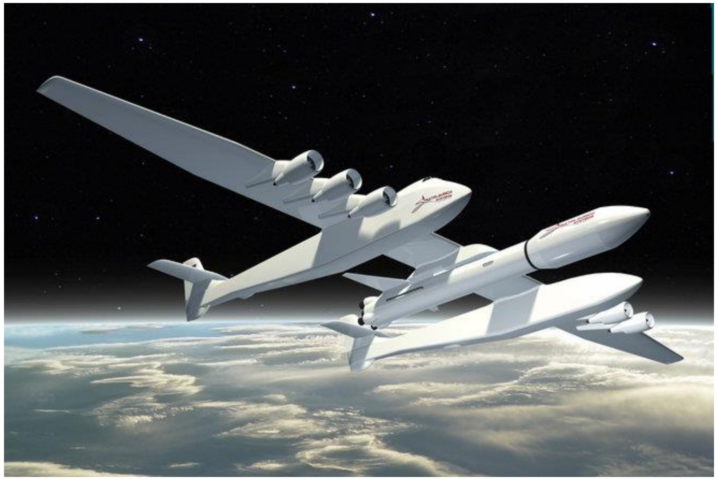


Carrier rocket / Organisation	New Shepard / Blue Origin	Electron / Rocket Lab	LauncherOne / Virgin Galactic	Alpha / Firefly	Soyuz-2.1a / Russia	Ariane 5 / ArianeSpace	Falcon 9 / SpaceX	Falcon Heavy / SpaceX
Height, metres	18.0*	16.0	16.0*	21.6*	46.1	50.5	70.0	70.0
Payload to LEO†, kg	n/a	150	500	200	7,800	20,000	22,800	54,400

*Estimated †Low-Earth orbit

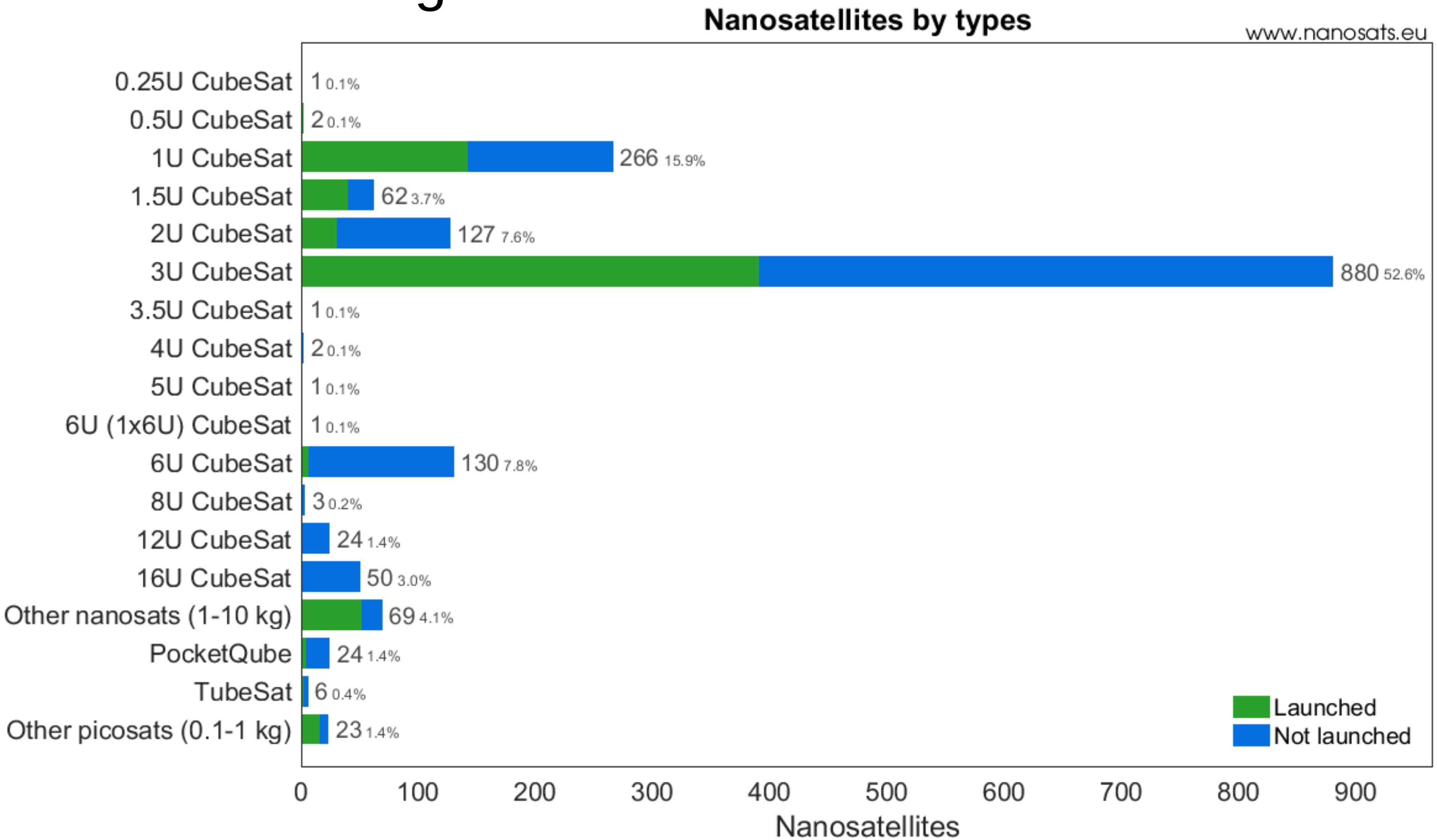
Small launchers are back

- Air-launched rockets are back into business:
  - LauncherOne by Virgin Orbit
  - StratoLauncher by Scaled Composites
  - GOLauncher by Generation Orbit
- Readiness to launch on demand



Microsatellites

- 1U and 3U CubeSats are the most popular sizes while the 6U is increasing in interest:

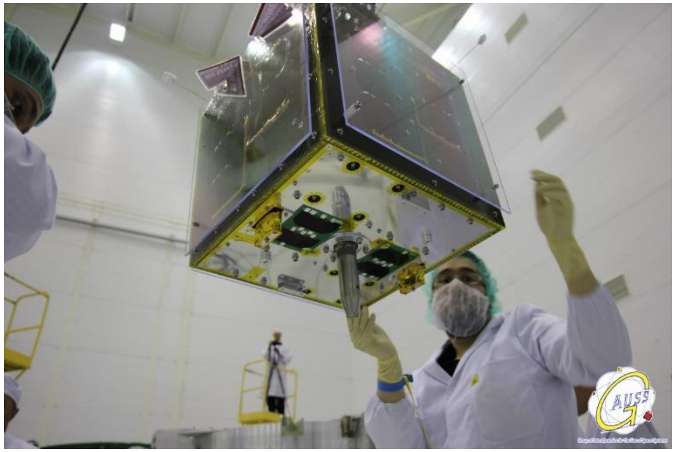


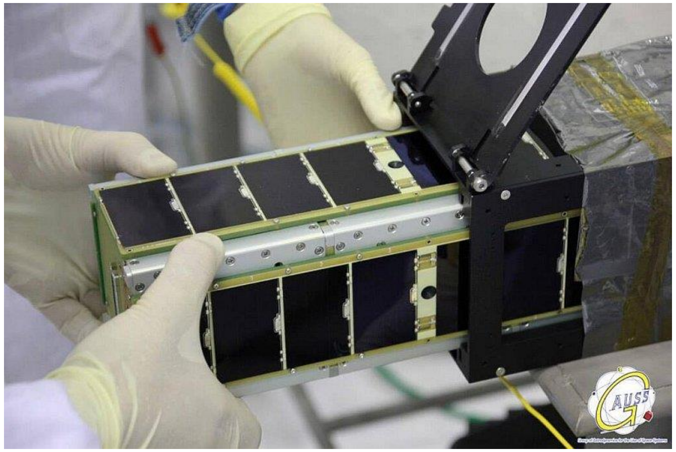
Our background

- **GAUSS Lab**, at the School of Aerospace Engineering, launched:
  - Five microsatellites
  - One Nanosatellite

- Technology test: **UniSat-5** and **UniSat-6** , launched in 2014 currently operational, developed by **GAUSS Srl** and used for testing new electronics in orbit.

- Educational: **Tigrisat,** launched in 2014 and still operative, a satellite built by the School of Aerospace Engineering with students from Iraq to train young engineers. Mission goal is to observe dust storms over Iraq.



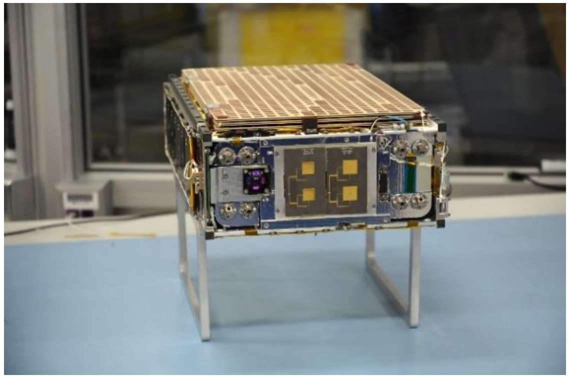


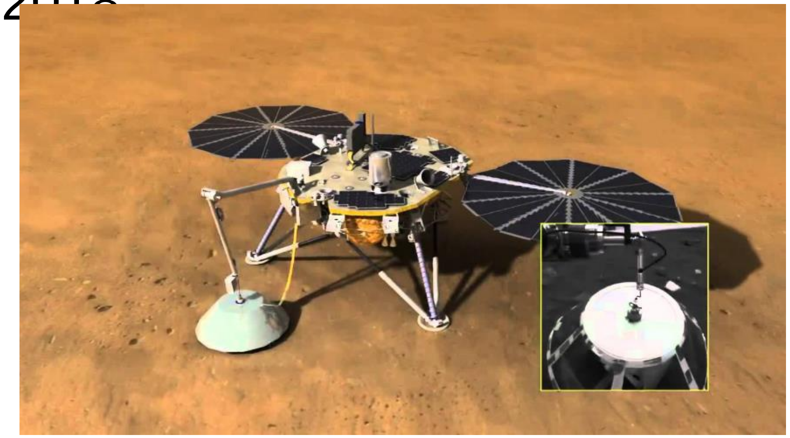
Many Microsatellites operating together?

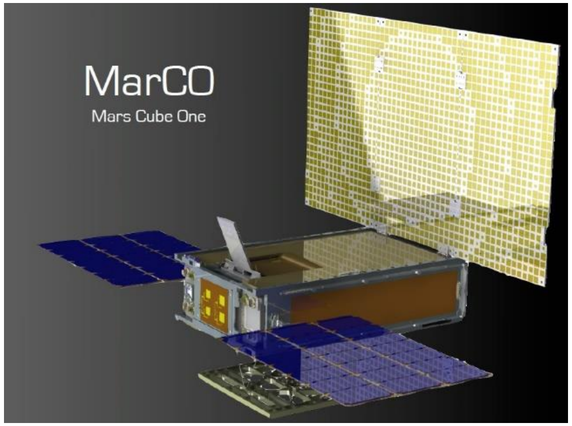
- Microsatellites' Constellations are an emerging, effective and economically quite interesting application:
  - **Planet**: Earth Observation constellation with a 10 to 15m resolution. Launched more than 150 satellites.
  - **Spire**: Weather monitoring using the GPS signals. Launched more than 40 satellites.

Microsatellites in Deep Space missions

- **MarCO**: (Mars Cube One) Developed and built by NASA. MarCO is composed by a couple of 6U Cubesats that will provide both UHF and X-band functions capable of immediately relaying information received over UHF during the EDL of the NASA's Insight lander mission in 2018.

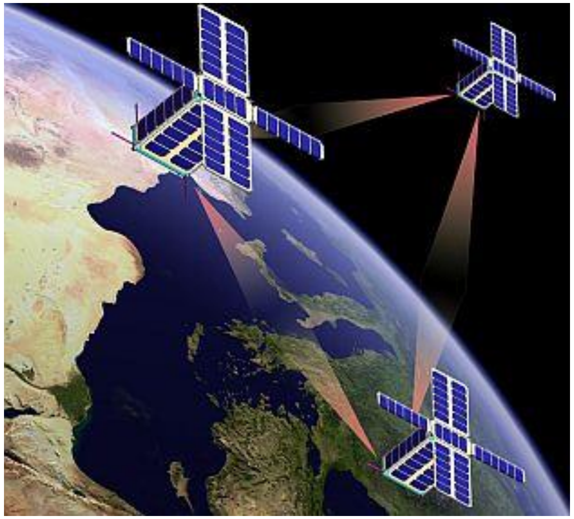


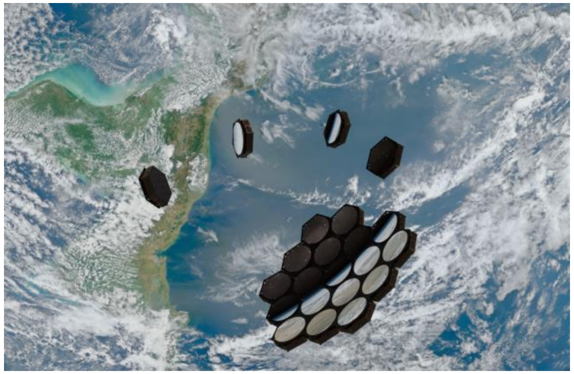




Future of Microsatellites

- Formation flying:
  - It will allow emulating bigger SAR antennas, having greater resolution than its big counterparts.
  - It will allow continuous coverage of a target on ground from LEO orbits.
  - Multiple small satellites will allow the construction of gigantic, reconfigurable structures, telescopes and radiotelescopes (ie AAReST from SSC).





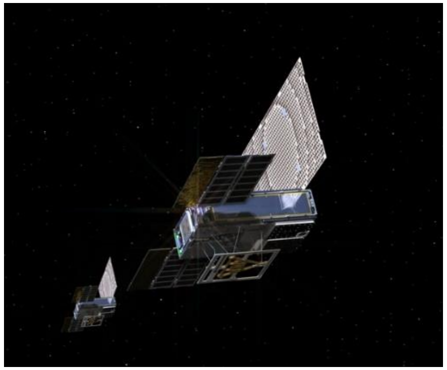
Future of Microsatellites

- Microsatellites might never fully replace bigger satellites, but they will offer **new services** or **increase their capabilities** when used in coordination.
- Microsatellites also allow for a very **responsive** access to space.
- Microsatellites are the **future** in both commercial and science missions.

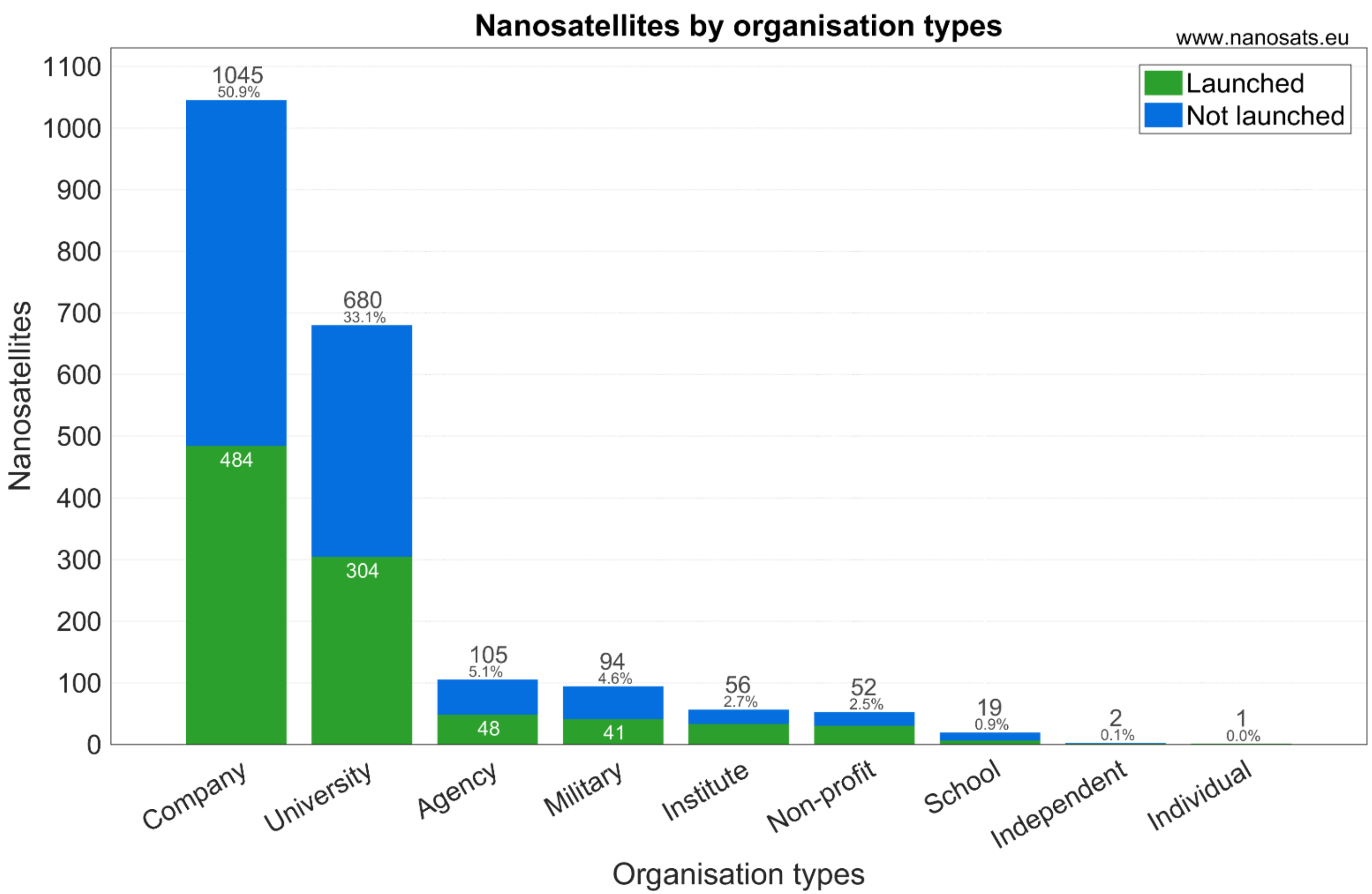
A recap

- CubeSats encompass a quite limited history (international standard first proposed in 1999 by Bob Twiggs and Jordi Puig-Suari).
- However, they can rely on a significant flight heritage already.
- Even more important, they are becoming more sophisticated, do have an extended lifetime, and are even bound for other planets (May 4th, 2018, successful launch of NASA's MarCO A & B, now in commissioning phase, headed to Mars).

In short, they are now a suitable platform for both scientific experiments and commercial services.



Nanosatellites by organisation types



Rationale

- Opposite to educational ventures, these advanced missions usually involve a strict trajectory's and operations' design, to be exactly followed.
- We can translate such a constraint as the capability – for the CubeSat – to command its kinematic state:

$$\vec{x} = \begin{bmatrix} \vec{x} & \vec{v} & \vec{q} & \dot{\vec{q}} \end{bmatrix}^T$$

The following slides will consider the exploitation of this control capability, divided in a part about orbit control and a part about attitude control.

Available technologies for Orbital Control (onboard CubeSats)

CubeSat Propulsion System	Size (U)	End/Cener Mount	Propellants	Thruster type	Thrusters	Nominal Thrust (mN)	Total Impulse (N-s)
PUC	0.14U-1U	End	R236FA/ SO2	Warm Gas	1	5.4	595
CPOD	1U	Center	R134a/ R236FA	Cold Gas	8	25	186
MarCO	2U	End	R236FA	Cold Gas	8	50	755
Green Mono Prop System	0.5-1U+	End	ADN/AF-M315E	Mono-Prop	4	400	3320
End mounted standard	0.25-1U	End	R134a/ R236FA	Cold Gas	5	10	312
Hybrid Green Monoprop	0.5-1U+	End	ADN/AF-M315E	Mono-Prop	1 Hot, 4 Cold	100	783
Standard	0.3-1U	End	R134a/ R236FA	Cold Gas	5	10	250
MEPSI	0.25U	End	Isobutane	Cold Gas	5	53	23
Palomar	1U	Center	Isobutane	Cold Gas	8	35	85

From wacco.com, NASA heritage

Towards an effective control capability

- Obviously, the allowed thrust is very low.

- Even such a low thrust could be exploited only for short times, because the amount of propellant stored onboard is quite limited (hot / cold gas thrusters), or

because the power available onboard a CubeSat is also limited, and thruster switch-on requires to charge the batteries.

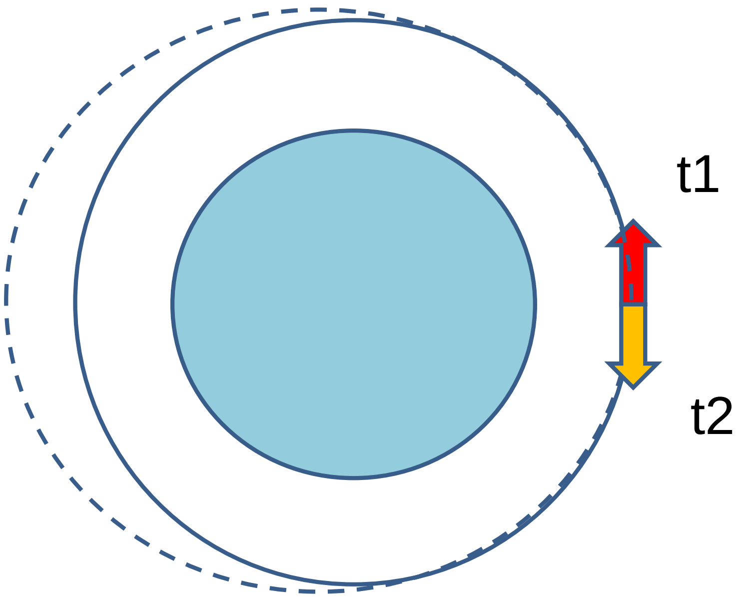
- The resulting orbit correction will be certainly small, both in the case of **in-plane** or **out-of-plane** maneuvers:

$$\Delta v = \frac{\mu}{2 v a^2} \Delta a$$

$$\Delta v = 2\, v \sin\frac{\Delta i}{2}$$

In-plane maneuvers - Rephasing

- The limited effect of the correction performed by onboard thrust can be magnified by extending the duration of the maneuver!
- In fact, the shift at time t1 to a even slightly different orbit can attain – in time, due to the different period – the desired amount of rephasing, to finally come back to the original and desired altittude at time t2.



In such a way, the increased lifetime of modern cubesats will be fruitfully exploited.

Out-of-plane maneuvers

- The very same approach applies to the more expensive out-of-plane maneuvers.

- By shifting the CubeSat on a sligthly different semiaxis orbit (by means of an **in-plane maneuver**) we will wait for the oblatenss to attain the change in the node, and then we will be back to the correct altitude.

- The nodal drift, in a time equal to one orbital period, is for each orbit equal to

$$\Delta\Omega_{2\pi} = -3\pi J_2 \left(\frac{R_\oplus}{p}\right)^2 \cos i$$

by comparing this relation evaluated for the original and the shift orbits (same i as copalanar, different p) we get the relative drift.

Orbital planes separation by in-plane maneuvers

- In-plane maneuvers to increase the semimajor axis
- Orbital node drift due to J2 perturbation effect

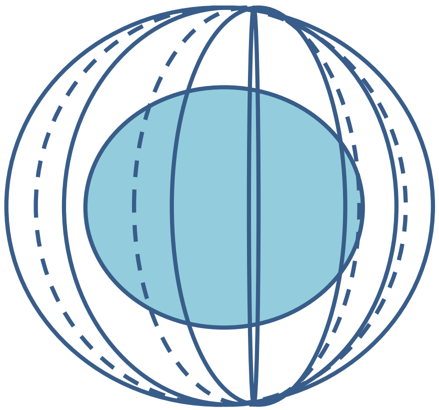
$$\langle \Delta\Omega \rangle = \frac{21}{4} \cdot J_2 \cdot R_E^2 \cdot \sqrt{\mu} \cdot T \cdot a^{-9/2} \cdot \cos(i) \cdot \Delta a$$

- In-plane maneuver to come back to the initial semimajor axis

The separation of orbital planes is achieved only by in-plane maneuvers by exploiting the Earth oblateness perturbation.

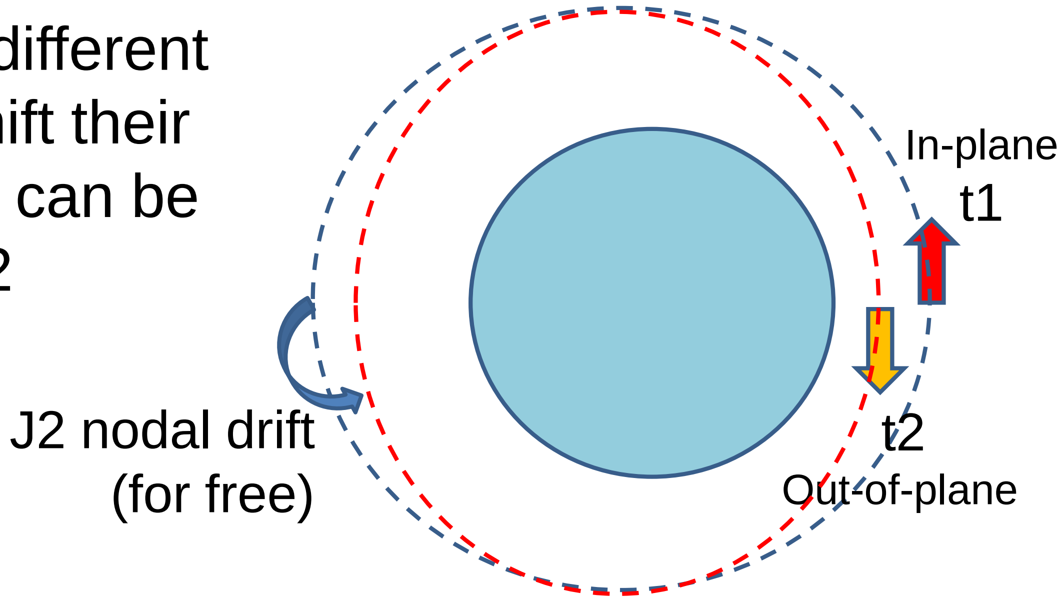
Out-of-plane maneuvers: J2 trick

- Constellations are based on the distribution of the satellites among several orbital planes, having the same inclination but equally spaced in node. We need to achieve these nodes...



! Polar orbits are only used to simplify the representatio n

- Satellites are injected into an initial orbit. Then cluster aiming at different planes are commanded to shift their orbits. The two thrust actions can be spaced in time to have the J2 providing the required nodal correction.



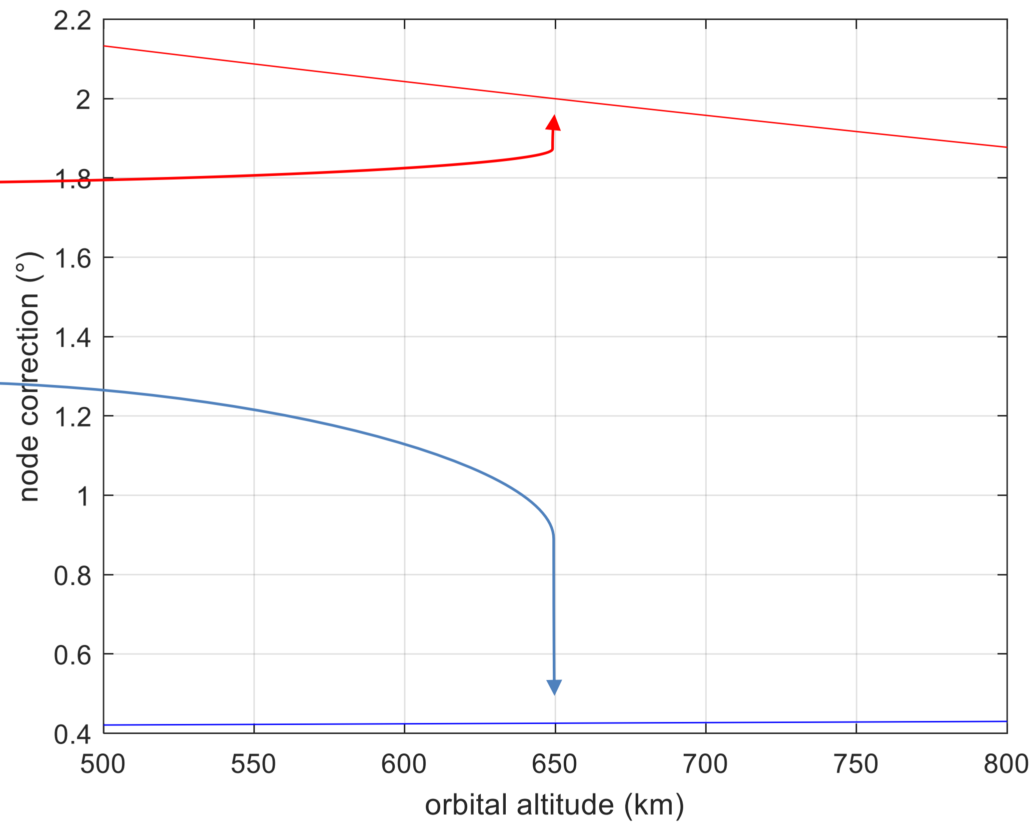
J2 trick - example

- Considering as (a very simplified) example the total impulse available to MarCO as fully used for a nodal correction in LEO

Nodal spacing achievable in 30 days exploiting J2

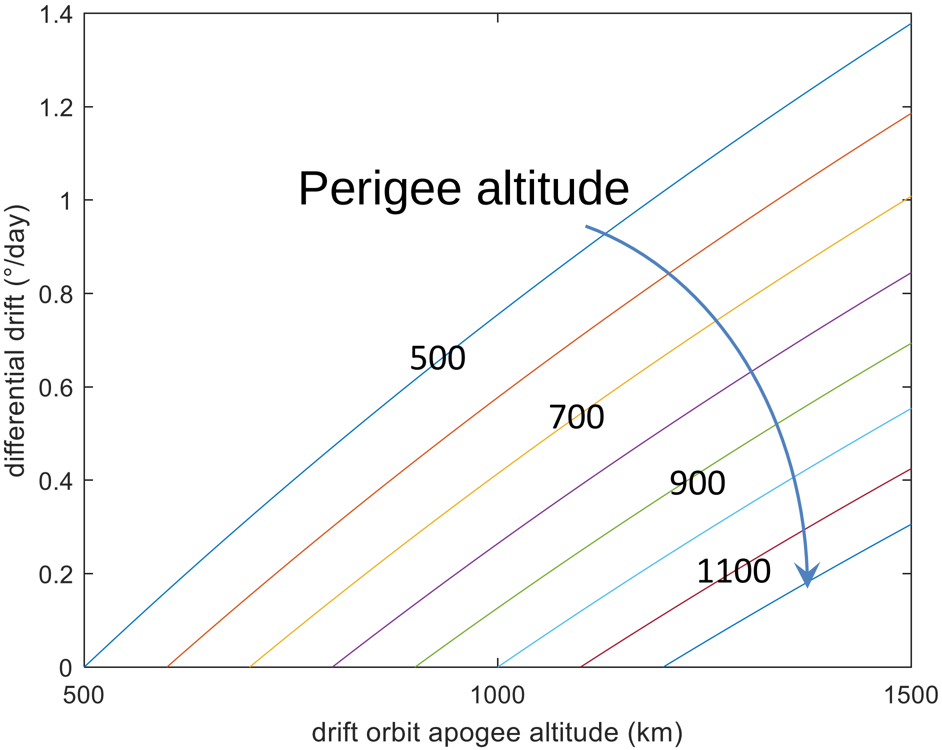
Nodal spacing attained with the single out-of-plane maneuvre

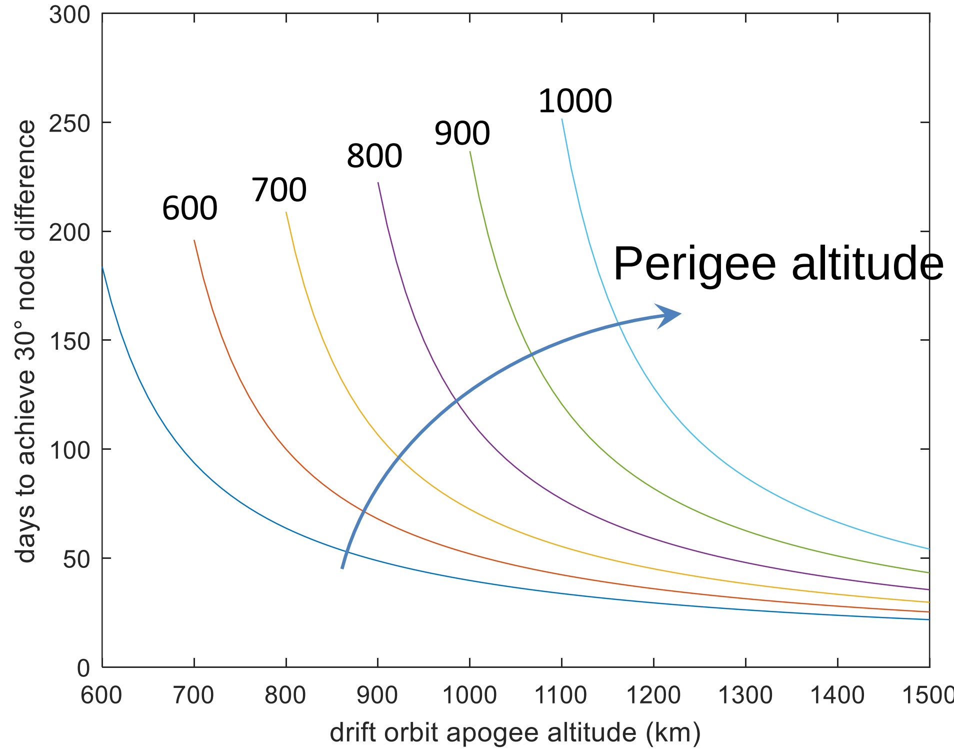
! A remarkable 5-times increase, to be augmented at will by waiting longer



J2 trick

- Again, limited performance of propulsion onboard microsatellites will allow small corrections and indeed small effects, but by exploiting extended lifetime of current Microsats, some tradeoff can be accomplished.



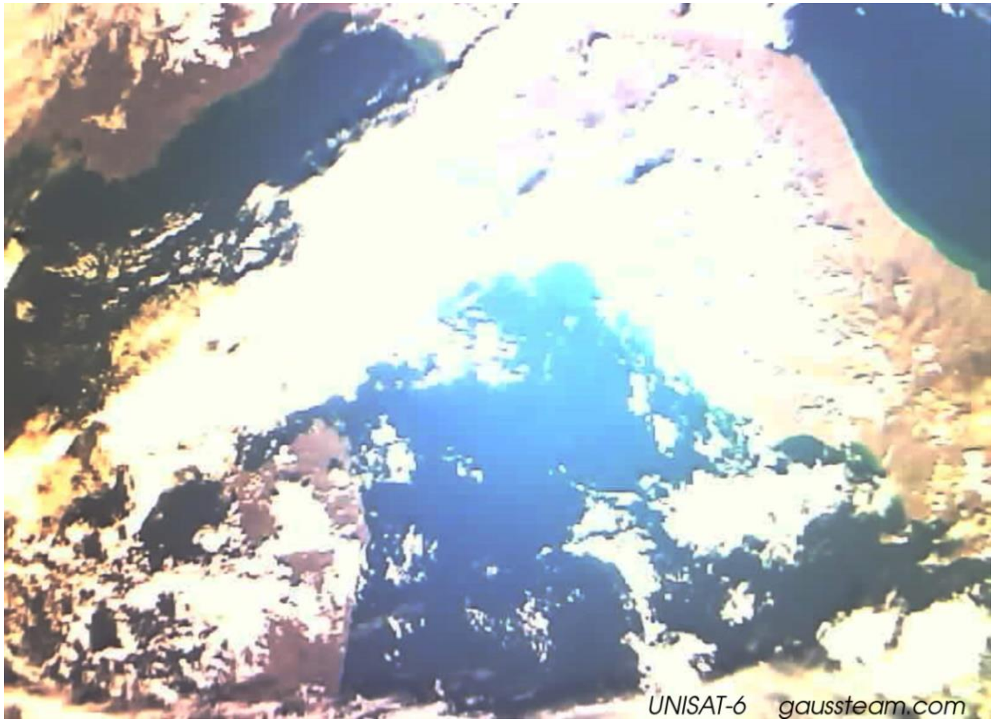


Attitude Control (motivation)

- Current scientific and commercial interest is related to remote sensing missions, either looking at the Earth (look at the picture of Italy by UniSat-6) or at a celestial body.

- Remote sensing / observation require accurate pointing.

- Accurate pointing requires attitude control technique **suitable for microsatellites** (as magnetic and wheels).



Attitude Control - Magnetic

- The most common attitude control technique for microsatellites exploits the Earth magnetic field, convenient due to size of actuators and power reqs, i.e.

$$\frac{d\vec{\Gamma}}{dt} = \dot{\vec{\Gamma}} + \vec{\omega} \times \vec{\Gamma} = \vec{M} \qquad \text{with} \qquad \vec{M} = \vec{m} \times \vec{B}$$

Considering $\vec{m}$ the control variable, we can choose $\vec{m} = \vec{\varepsilon} \times \vec{B}$ to have $\vec{B}$ always normal to $\vec{m}$ and indeed the maximum efficiency.

Considering $\vec{\varepsilon}$ the attitude error, we find the two possibilities of

detumbling and of ***nadir pointing*** ($\hat{r}_o$ local vertical, $\hat{k}$ body axis)

$$\vec{\varepsilon} = \vec{\omega}$$

$$\vec{\varepsilon} = \hat{r}_o \times \hat{k}$$

Magnetic Control - Detumbling

- Implementation of detumbling requires the output from a gyro to compute $\vec{\varepsilon} = \vec{\omega}$ and then $\vec{m} = \vec{\omega} \times \vec{B}$
- Alternatively we have the approximate solution of the «poor man» using

$$0 \approx \frac{d\vec{B}}{dt} = \dot{\vec{B}} + \vec{\omega} \times \vec{B}$$

to evaluate

$$\vec{\omega} \times \vec{B} \cong -\dot{\vec{B}} = \vec{m}$$

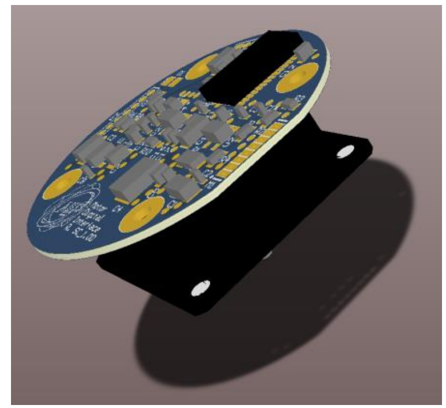
that **better fits microsatellite's approach to limited hardware requirements**.

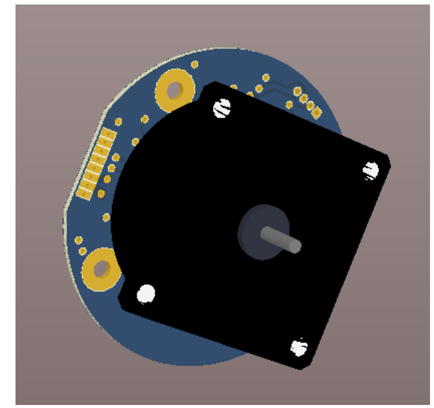
GAUSS Reaction wheels

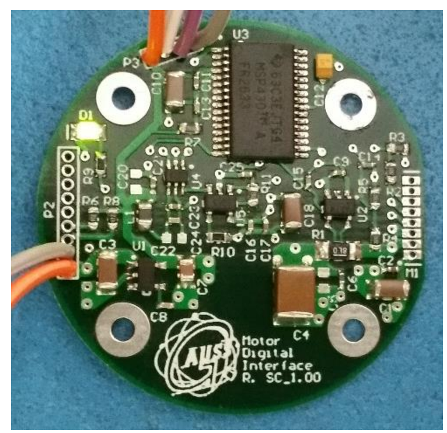
- Reaction wheels are an accurate yet sophisticated alternative – some data from a **GAUSS prototype design**

- Electronics coupled with the wheel's motor to save space
  - Microcontroller using radiation tolerant memory (FRAM)
  - 5V Single Power Supply
  - Temp. range -40°C to +85°C

- Brushless Motor features:
  - Speed 5000 rpm
  - Max Torque 3.7 mN m
  - Bearing lubrication for vacuum (10^{-7} Torr @ 20°C)
  - Temp. range -40°C to +85°C







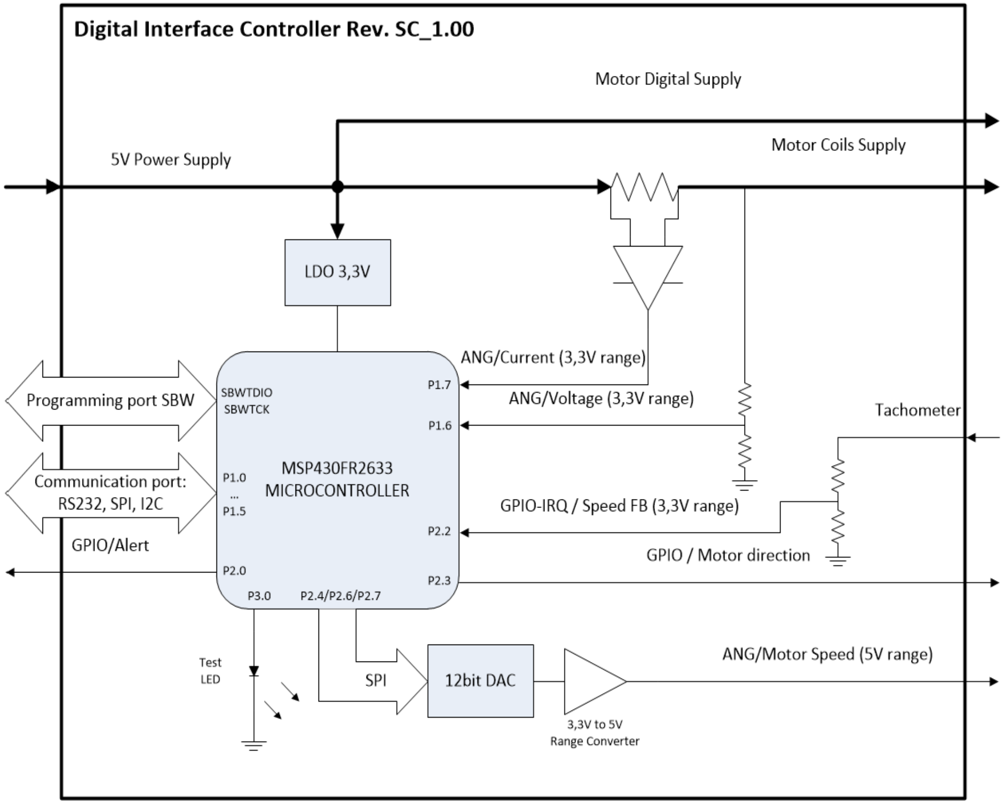
GAUSS Reaction wheels

- Brass Wheel features:
  - Mass 96.8 g
  - Inertia $32*10^{-6}$ kg m^2
  - Momentum 23.4 mN m s

- Total dimension including wheel:
  - Diameter 44 mm
  - Height 21mm
  - Total mass 130 g

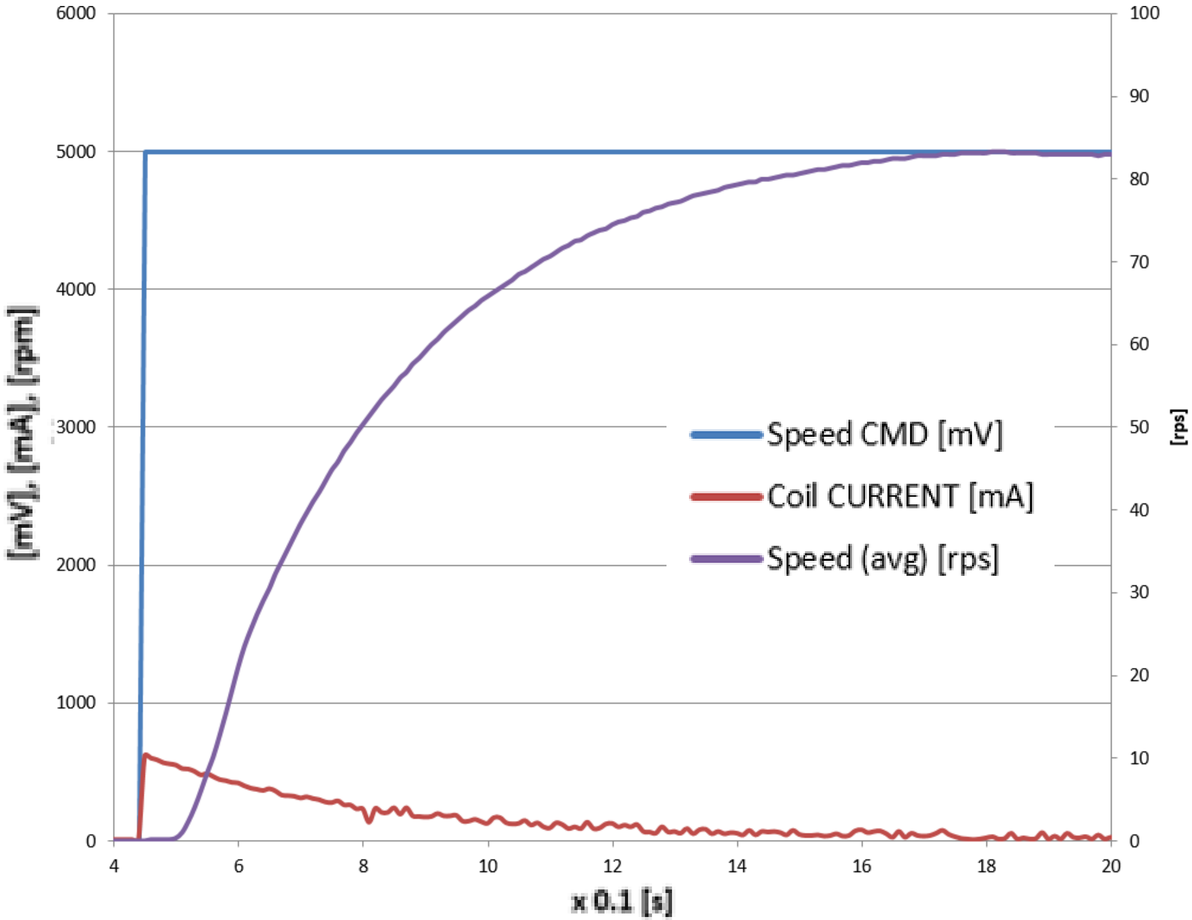
GAUSS: Reaction wheel prototype

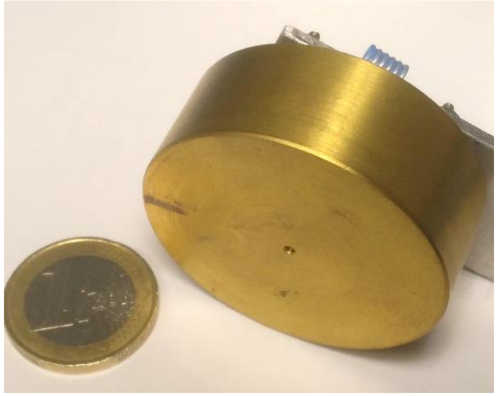
- Digital Interface Controller
  - designed to drive a digitally speed controlled brushless motor
  - allows users to drive the motor using serial communication protocols as SPI, I2C or RS232
  - further releases will provide also CAN and RS422/485 ports
- Other Controller features:
  - Coils Voltage monitor
  - Coils Current monitor
  - PCB Temperature monitor
  - LED for test purposes

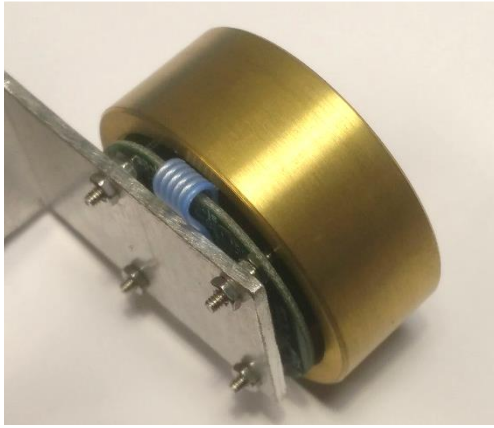


GAUSS Reaction wheels prototype

- Realization & impulse response







Thank you

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