Recent Advances and Low cost concept for the Gamma-Ray Lens Project MAX

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Introduction

- Alcatel Alenia Space has been studying Formation Flying based missions since 1999 with the highly challenging DARWIN mission:
  - Expertise enriched by recent merge of French and Italian R&Ts.
- Alcatel Alenia Space has since contributed to identify several science mission with high science return increase thanks to formation flying:
  - Preliminary assessment of these missions has been performed internally to assess feasibility, technical challenges and formation flying performance classes
- Based on the identified technical challenges, Key technologies have been the object of internal and institutional (ESA and CNES) R&T:
  - Formation Control Techniques
  - Optical and RF Metrology
  - Command / Control and Avionics architecture
  - System architecture and redundancy approach
- MAX Mission is one of these studies:
  - Key functions (Mechanical and thermal, Avionics and control, Power) have been analyzed by Alcatel Alenia Space

Formation Flying goal

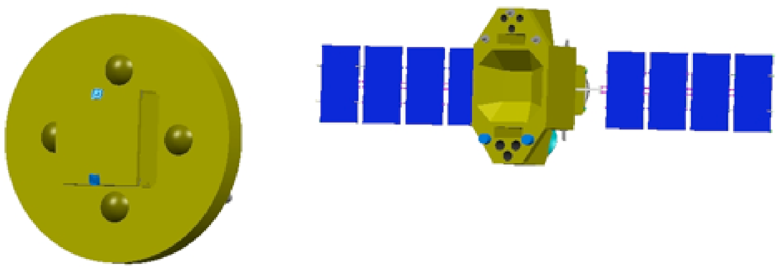
- Scientific missions in Space are today limited by Instrument size:
  - Performances are straightly proportional to size of optics, focal length & base-line,
  - Instrument sizes are restricted by platform and launchers capabilities.
- The idea is to distribute the instrument functions over several spacecrafts:
  - Instrument size limitations are roll back,
  - The S/C formation is then the space system. There are no more individual S/C but fullness formation function and performance.
- The major constraint for formation is to keep the geometric stiffness inter S/C:
  - The formation shall hold an unique Kinematics,
  - The relative dynamics between S/C shall be minimized (position & attitude).
- The means for the goal:
  - use of dedicated **position** and **attitude sensors**: the FF metrology,
  - use of dedicated **actuators**: FEEPS, gold gas,
  - use of new **Command/Control concepts**: collision avoidance, centralized/non-centralized/hybrid,
  - use of new **orbit maintenance** and **deployment strategies**,
  - use of dedicated **GNC architecture** and **control laws**,
  - define dedicated **test-bench** and validation approach.

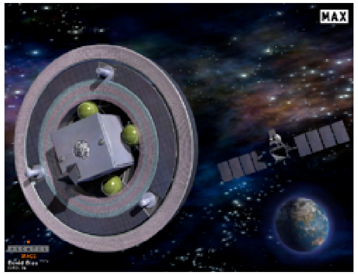
Two classes of performances (1/2)

Today, the scientific goals of the missions requesting a Formation Flying system show two different class of performances for the satellites, in particular for the Guidance Navigation Control System.

1/ The millimeter class

Satellite number	inter-satellites distance	Longitudinal positioning	Lateral positioning	Lateral positioning knowledge	Pointing accuracy
2	30 to 100m	few cm to tens of cm	In the cm	In the mm	Tens of arcsecond





- **ASPICS** (CNES): Coronagraphic mission,
- Main objective : imaging of the internal corona of Sun,
- Using 2 S/C: 1 occultor satellite & 1 detector satellite,
- Inter S/C distance = [100 ; 150] m.

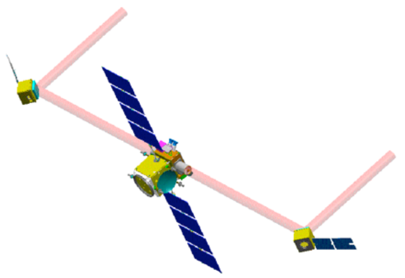
- **MAX** (CNES): Gamma spectroscopy mission
- Main objective: supernovae, pulsar, black holes,
- using 2 satellites : 1 'lens' & 1 'detector',
- Inter S/C distance = 86 m.

Two classes of performances (2/2)

2/ The micro-nanometer class:

Final performances are several order of magnitude more stringent than the millimeter class. The target missions are mainly the space interferometry missions.

Satellite number	Base - inter-satellites distance	Lateral positioning	inter-satellites stability	Absolute Pointing accuracy	inter-S/C relative pointing	Optical Path difference control
At least 3	50 to 500m	In the mm	1 to 10 μm/s	1 to Tens of arc-second	Tens of milli arc-second	few nm



- **PEGASE** (CNES): IR interferometry mission,

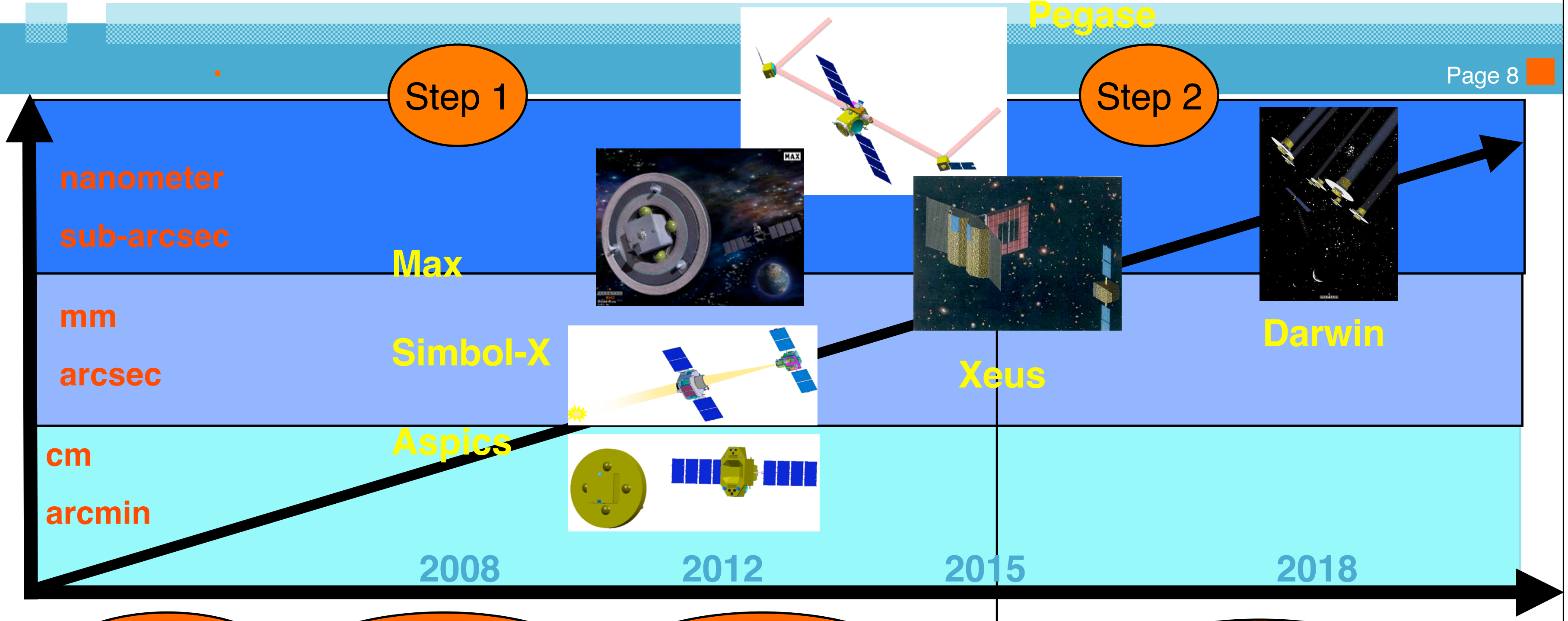
- Main objective : Detection of Earth-like planets, formation of planetary systems,
- Formation of 3 S/C: 2 free-flyer housing the mirrors and one central combiner
- Inter S/C distance = 25 to 250 m.

- **DARWIN** (ESA): Space Interferometer:

-Main objective:
-1/ finding and characterizing Earth-like planets orbiting other stars than the sun (nulling technics)
-2/ high resolution astrophysical imaging.
- Formation of 4 S/C: : 3 telescopes or collectors & 1 Beam Combiner.
- Distance inter S/C = 8 m to 170 m.

- Multiple degree of freedom (dof) to control:
  - Formation with 2 S/C: 3Translations +2x3Rotations = 9 dof,
  - Formation with 4 S/C: 3x3T +4x3R = 21 dof,
  - coupling between dof due to Dynamics (COG), sensors measure equation.
- Very accurate performances to reach:
  - Technological step in sensor performances:
    - attitude ->sub- arcsec, position -> sub-mm.
  - Technological step in actuators performances: Thruster from few mN --> μN,
  - External disturbance: need to consider the today neglected disturbances:
    - Differential Solar Pressure, differential gravity acceleration between spacecrafts,
    - Micro-meteorites.
- Orbit formation maintenance:
  - deployment: using dedicated vehicle, as a composite, separate transfer then RdV,
  - orbit maintenance, resizing: acceleration gradient (differential gravity effect) --> optimal control to minimize fuel consumption, or time maneuver,
  - collision avoidance & escape avoidance strategies.
- New Command/Control services:
  - need different level of architecture of computation resources,
  - need dialogue inter S/C.

The steps of technology acquisition



Technos to develop

- RF metrology (level 1)
- Optical metrology (level 2)
- Improved attitude Sensor
- Cold gas THR
- Micro-propulsion
- Deployment
- Fine GNC resizing, rotation
- FDIR collision avoidance

→

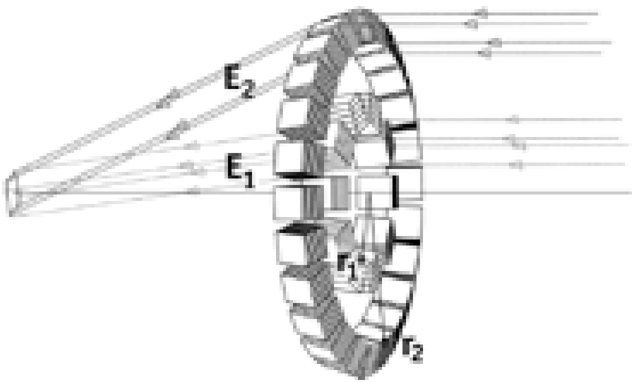
- Optical metrology (level 2')
- Fringe Tracker (level 3)
- Attitude Sensor Fine Relative
- Optical Delay Line
- Nanometer GNC

The origin of the MAX twin satellites concept (1/2)

- For Nuclear astrophysics missions “bigger is not necessarily better”, because:
  - sensitivity is proportional to the square root of the detector surface, but
  - background noise is roughly proportional to the volume of the detector.
- INTEGRAL probably is the pinnacle of what is possible with current technologies.
- Detector system based on Gamma-rays phase information is a very promising concept that can allow steps ahead with respect the current technologies:
  - Gamma-ray can interact coherently inside a crystal lattice (Bragg difraction) provided that angles of incidence very small,
  - After coherent interaction the gamma-ray are scattered inside well defined angle, allowing, with appropriate crystal geometry, gamma ray focusing,
  - This concept separate the collecting area (the lens) from the detector volume ,
  - Typical gamma-ray energy of interest for Nuclear astrophysics drive the selection of a lens Bragg-difraction in Laue geometry for scattering.

The origin of the MAX twin satellites concept (2/2)

- CLAIRE experiment demonstrated the validity of such a concept in a narrow bandpass:
  - by laboratory testing,
  - by observation of Crab Nebula photons (june 2001) during the CLAIRE flight on-board balloon.
- MAX configuration has been defined on the basis of this new concept, considering broad bandpass Laue lens (Crystal plus Cu rings) covering two wide energy bands of high relevance for nuclear astrophysics.
- The Laue lens for MAX mission implies a focal length of 86 meter: consequently the MAX mission is composed of two satellites in formation flying: one dedicated to the detector the second dedicated to the Laue lens.



The basic design of a crystal diffraction lens in Lue geometry for MAX Mission

The scientific mission in short

An innovative measurement technique:

- take advantage of the phase information of the photons,
- focus γ-rays from the large collecting area of a crystal diffraction lens onto a very small detector volume.

Supported by an innovative space approach:

Use two satellites flying in formation composed of:

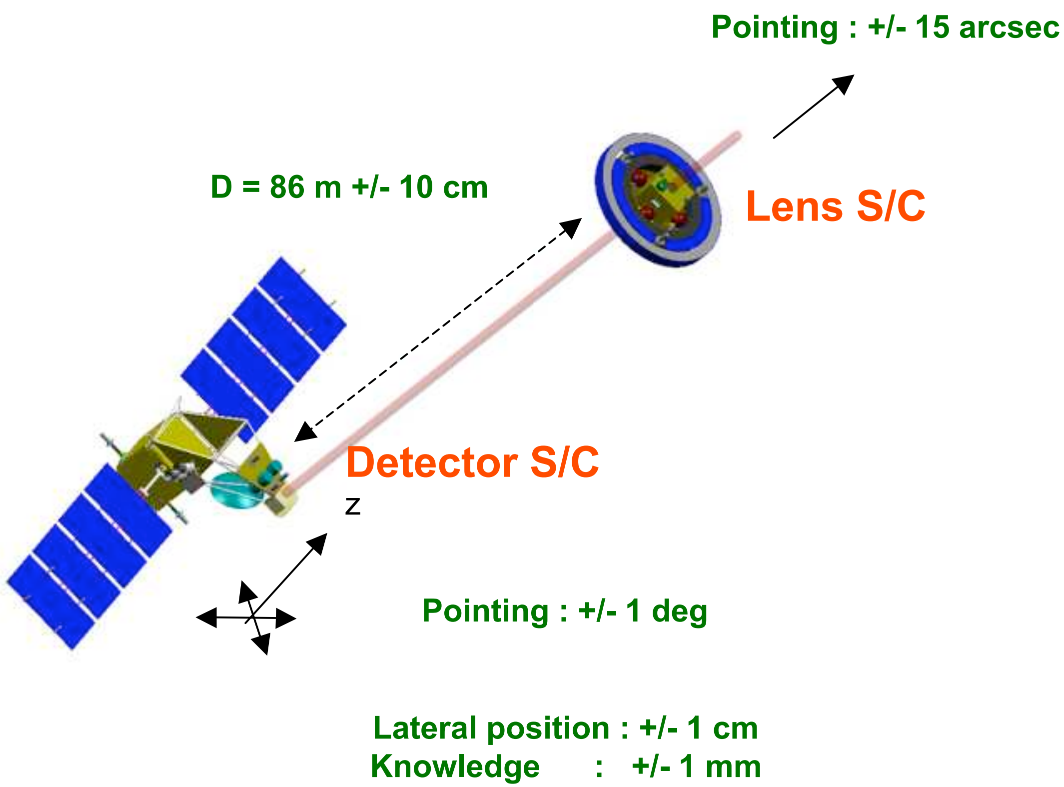
- a stabilized S/C equipped with a Laue lens able to simultaneously focus two γ-rays energy pass bands (800 - 900 keV & 450 - 530 keV)
- a 3-axes stabilized S/C equipped with a small array of germanium detectors

To achieve primary scientific objectives of measuring:

- intensities, shift & shapes of Supernovae type Ia nuclear gamma-ray lines,
- electron-positron annihilation (511 keV emission) from the Galactic Center
- size, shape and age of the Universe.

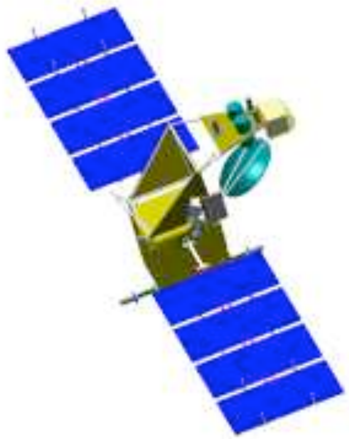
Max Spacecraft requirements

- Mission duration = 2 years min, 50 targets,
- Observations out of radiation belts,
- Instrument focal length = Distance inter S/Cs,
- Observation time ≈ 12 days/target,
- Pointing an relative position in a medium demanding class for Formation Flying,
- Payload data downlink ≈ 400Mbits/day



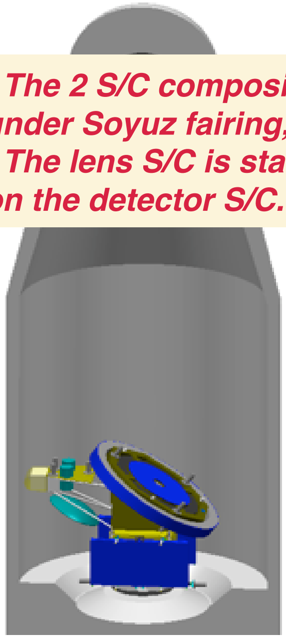
The development strategy for MAX:

- The key constraint of the space programs for the new century:
  - is to lead spacecraft development for high interest scientific missions in a context of limited funding and reduced budget.
- One possible approach to reduce the overall cost:
  - is to lead an evolution of existing LEO scientific platforms,
  - mainly in the Guidance Navigation Control and Command/Control fields,
  - the detector satellite is based on the new generation of Alcatel-Alenia Space 500Kg range scientific platform,
  - the lens satellite is an evolution of French micro-sat family,



Allocation of functions over the both S/C of formation

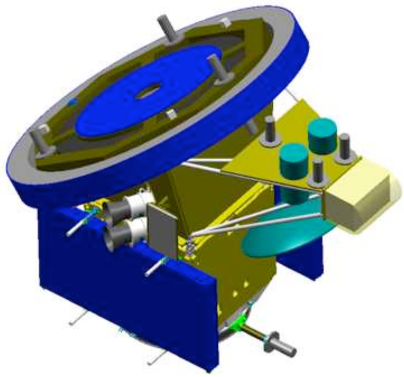
- The **Detector** satellite will be:
  - the leader of the formation,
  - the Pilot of the Composite up to the operational orbit,
  - the link with Ground,
  - the Data Processing and Storage Centre.



- The 2 S/C composite under Soyuz fairing,
- The lens S/C is stacked on the detector S/C.

- The **lens** satellite will be:
  - separated from leader housing, only on operational orbit position,
  - the only TM/TC link is with the leader, using the RF position metrology also as a communication link,
  - have no Data storage. Command/control is performed by the leader, except for the collision avoidance function that is implemented on both S/C.

- The 2 S/C composite after launcher separation,
- Power generation and Guidance-Navigation- Control are assured by the detector S/C.



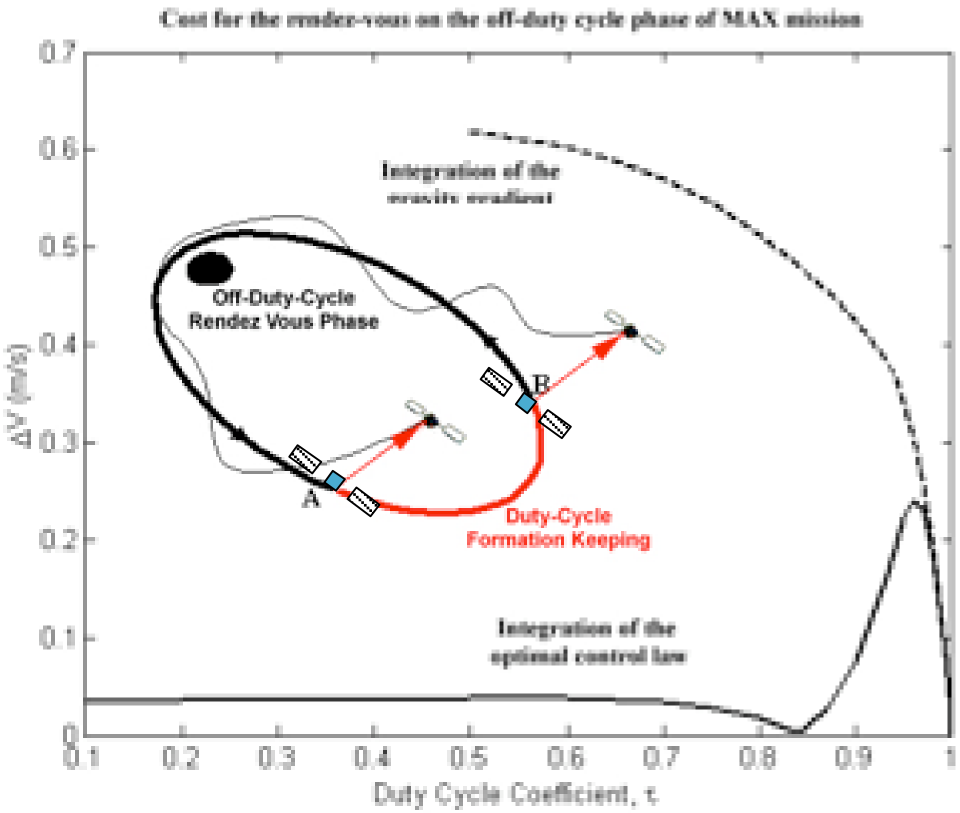
Orbit selection

Choice of orbits is driven by a lot of constraints:

- enough high altitudes to minimize forces & torques during observations,
- ground stations visibility,
- fuel consumption for in orbit injection and maintenance.

Evolution of the choices:

- GTO: apogee out of Van Allen belts
  - exists optimal Formation RdV & maintenance strategies for min. ΔV
  - but lose of mission at perigee $\Rightarrow$
- HEO: 46000-72000/235000km
  - key driver: mass of both S/C + launcher interface w.r.t launcher capabilities



← Solutions under study

Typical relative disturbance accelerations for [300,500] Kg S/C formation

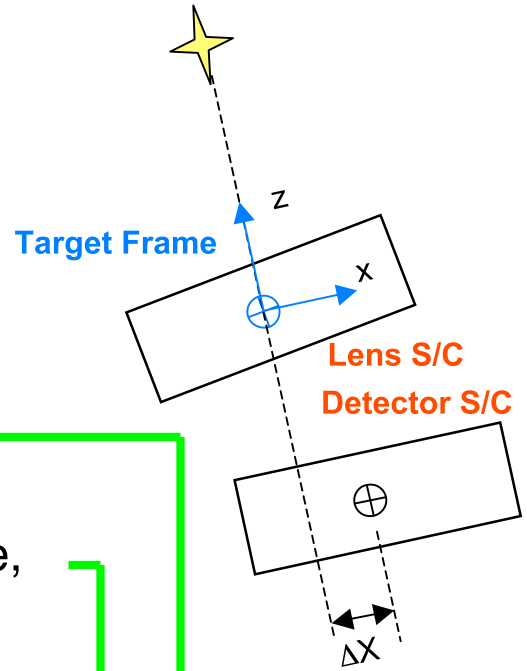
	$\Delta\gamma$: differential of linear acceleration	$\Delta\dot{\omega}$: differential of angular acceleration
Differential Gravity contribution Altitude = 200000km Altitude = 85000km Altitude = 40000km	0.01 μm/s² 0.1 μm/s² 1 μm/s²	0.01 μrd/s² 0.1 μrd/s² 1 μrd/s²
Differential Solar Pressure	0.02 μm/s²	0.1 μrd/s²

9 degrees of freedom to control

- $(\theta_{x\_L}, \theta_{y\_L}, \theta_{z\_L})$ inertial attitude of Lens S/C,
- $(\theta_{x\_D}, \theta_{y\_D}, \theta_{z\_D})$ inertial attitude of Detector S/C,
- $(\Delta X, \Delta Y, \Delta Z)$ relative position of Detector/target frame,

- for ΔZ: **relative longitudinal sensor ≈ few centimeters**
- for ΔX, ΔY: **relative lateral sensor ≈ 1 arcsec**

A fine Star Tracker on each S/C ≈ 1 arcsec

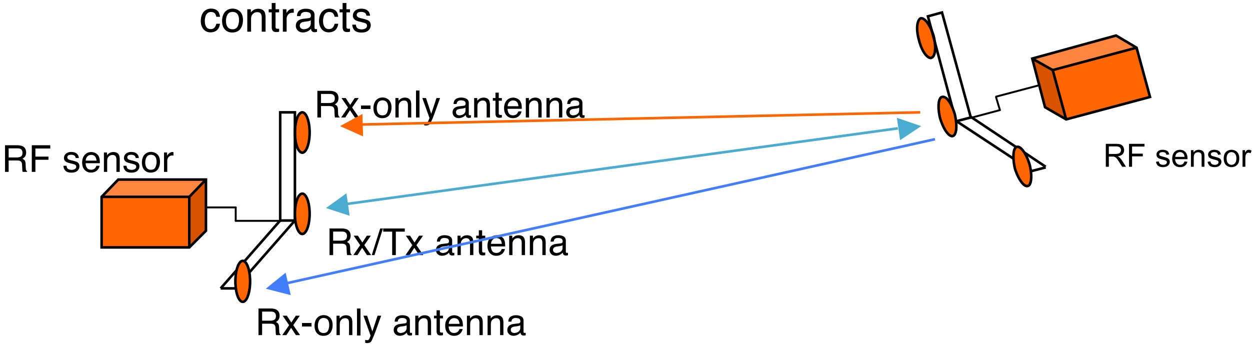


Metrology/ control/actuation (1/2)

Longitudinal sensor for MAX

- RF sensor performances are enough to control the inter S/C distance: accuracy = 2 cm (3σ) for D < 100m,

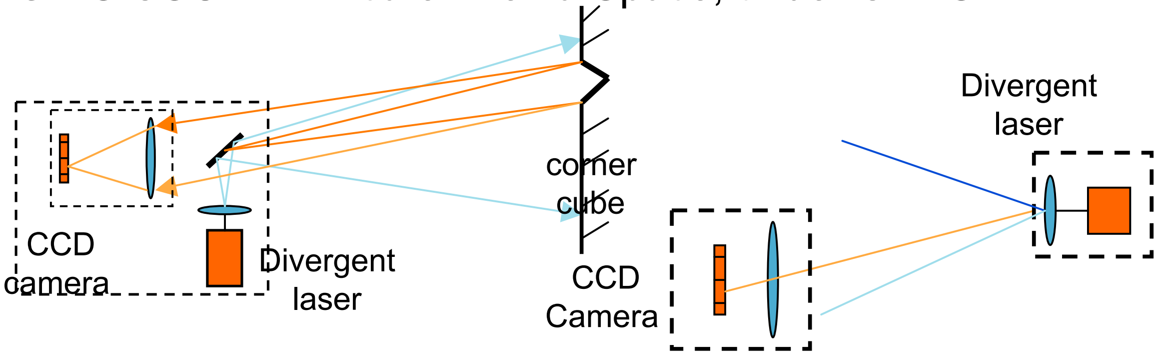
  bread-board developed in frame of ESA & CNES contracts



If finest mission accuracy is requested then a dedicated longitudinal sensor will be used: development is leaded by SAGEIS CSO with Alcatel Alenia Space, under CNES contract.

Lateral sensor for MAX

- Several concepts are possibles, derived from Star Tracker technologies



Metrology/ control/actuation (2/2)

Coupling of measurement equations

- Metrology data are strongly coupled with attitude of each S/C,
- Specification of metrology sensors are not independent of attitude sensor selected and lay-out on satellite.
- For control of these multiple coupled degrees of freedom several strategies are under studies:
  - separation of bandwidth,
  - multi-variable optimal control, etc ….

$$\begin{bmatrix}\delta X\\ \delta Y\\ \delta Z\end{bmatrix} = \begin{bmatrix}\delta X_m\\ \delta Y_m\\ \delta Z_m\end{bmatrix} + [S_1]\begin{bmatrix}\theta_{X1}\\ \theta_{Y1}\\ \theta_{Z1}\end{bmatrix} + [S_2]\begin{bmatrix}\theta_{X2}\\ \theta_{Y2}\\ \theta_{Z2}\end{bmatrix}$$

Attitude of Lens S/C

Attitude of Detector S/C

Metrology measurements

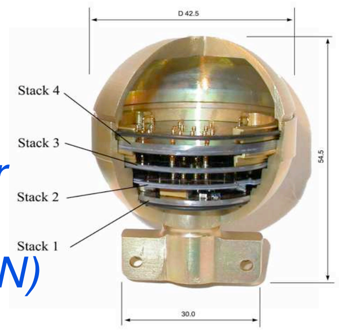
True Detector position

Actuation

Cold gas technology: Nitrogen

- ON/OFF trust control: range [0.2 ; 10] mN,
- or fine cold gas technology: Nitrogen, range: 0.2 μN to 5 mN,
- drawbacks: low Isp= 60s. Limited cycles number (few 100 000)

microthruster
Nanospace
(0.5 μN to 5 mN)



Conclusion

- In a design to cost approach the mission goals are matched by the increase of functions and performances of current science platforms systems:
  - Hardware: Related position sensors, Micro-propulsion,
  - SW functions: Relevant control stages, Operation modes and FDIR
- Alcatel Alenia Space is developing the Formation Flying technologies required for different missions, in particularly in the field of GNC and sensors.
- First step (millimeter class) performances, corresponding to the MAX mission, can be achieved in a near future, compatible with start of phase A in 2006 and launch in 2011.
- Alcatel Alenia Space is eager to start the development of the first formation flying mission.

MAX Formation Video of deployment