EXOHALO L2

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MISSION DESIGN

1 Mission Design

5 ways to find a planet

Radial velocity

Direct imaging

Gravitational microlensing

Transit

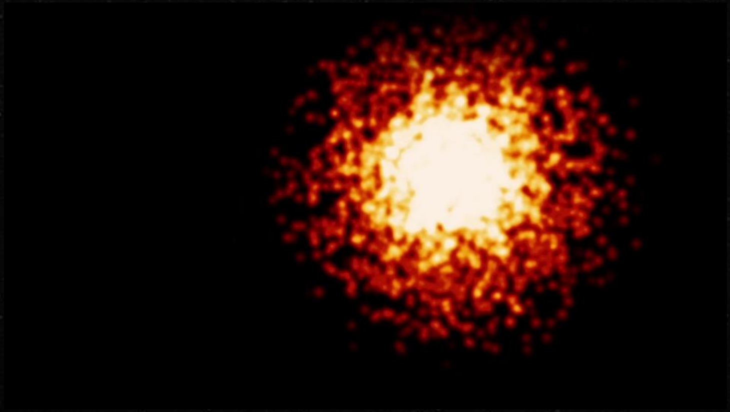
Astrometry

Source:
Brennan, Pat et al. (2020). EXOPLANET EXPLORATION Planets Beyond Our Solar System. NASA

1 Mission Design

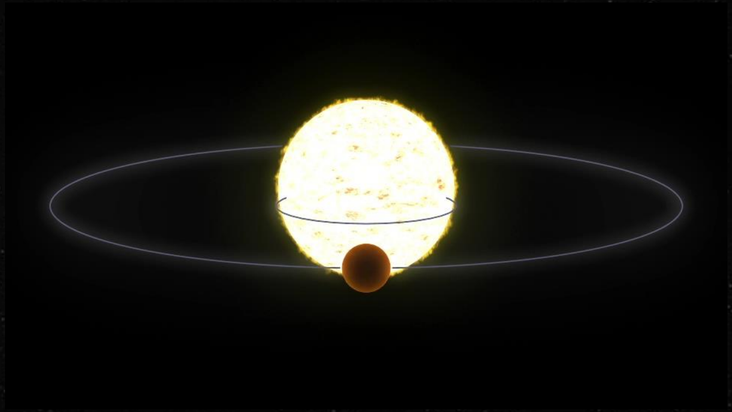
Radial Velocity →

Transit ←



Astrometry →

Direct imaging ←



Source:
Brennan, Pat et al. (2020). EXOPLANET EXPLORATION Planets Beyond Our Solar System. NASA

1.1 Mission objectives

1. Determine with high precision the bulk properties of exoplanets in a wide range of systems and inferring the presence or absence of a significant atmospheric envelope

2. Analyse exoplanets in the size range of super-Earths and mini-Neptunes located in the habitable zone of solar-like stars

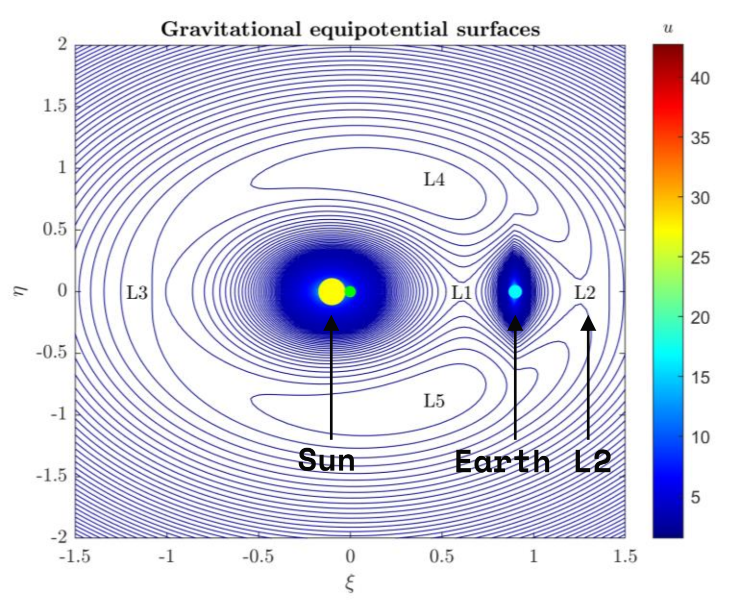
3. Study the atmospheric composition, i. e. to study the physical and chemical properties of a large and diverse sample of uncovered exoplanets and, through those, understand how planets form and evolve in this galaxy and whether they can harbour carbon based life or not

02

ORBITAL MECHANICS

2.1 Lagrange points

Sun-Earth Lagrange points

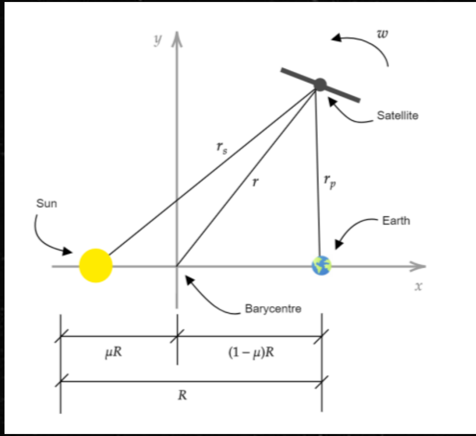


Gravitational equipotential surfaces of Sun-Earth system and Lagrange points in a rotating system coordinates. Source: Own.

Why L2 ?

Stable environment
Absence of eclipses
Thermal stability
Low radiation

- Non-inertial reference frame
- Restricted three-body problem



Three body problem rotating reference frame. Source: Own.

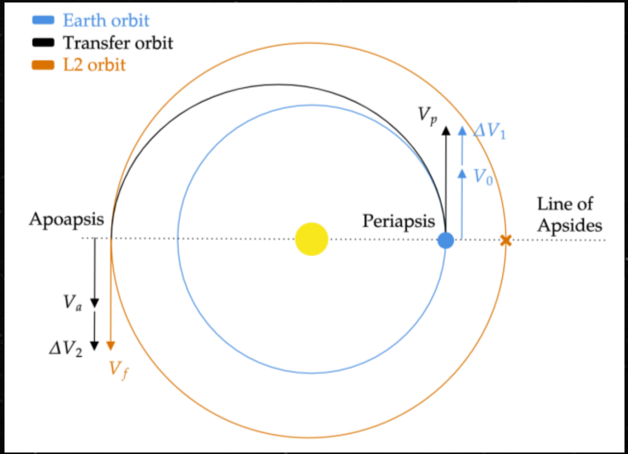
Source: MIT (2008). *Exploring the Neighbourhood: the Restricted Three-Body Problem*. Dynamics.

2.2 Orbital transfer

Orbital transfers candidates

Orbit transfer type	Advantages	Disadvantages
Hohmann	High efficiency (low ΔV)	High elapsed time Circular rendezvous phasing required to L2
High energy Lambert transfer	Low elapsed time Direct injection to L2 rendezvous	High ΔV budget required Higher accel. (rough environment)

Sun-Earth system's L2 Hohmann transfer



Earth-L2 Hohmann transfer. Source: Own.

Transfer performance

- Elapsed time: t = 184.0 days (6.1 months)
- Budget: $\Delta V = 147.8\ m/s$
- Propellant mass:

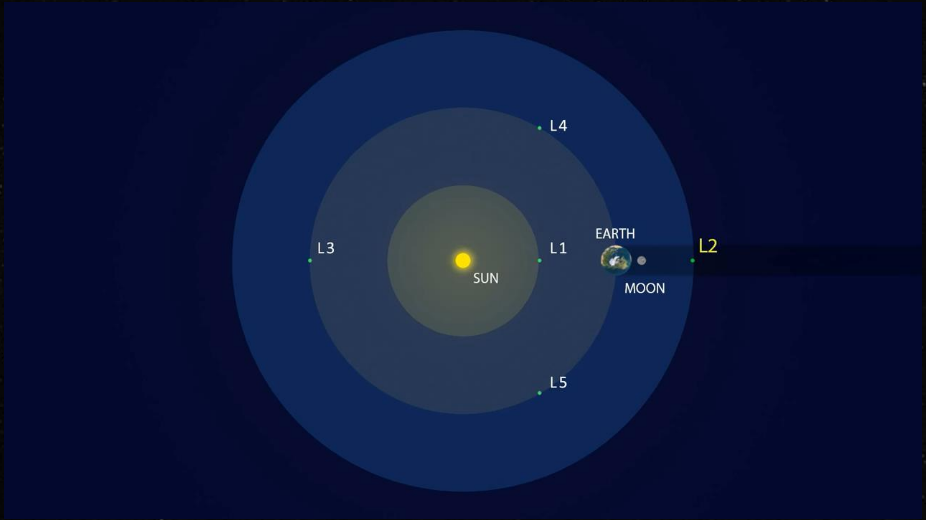
$$\frac{\Delta m_p}{m_0} = 0.0444$$

$$\Delta m_p = 426.6 \text{ kg}$$

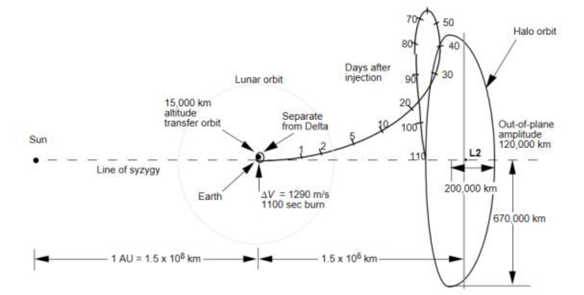
Optimization ≫ Less fuel load
High energy transfer

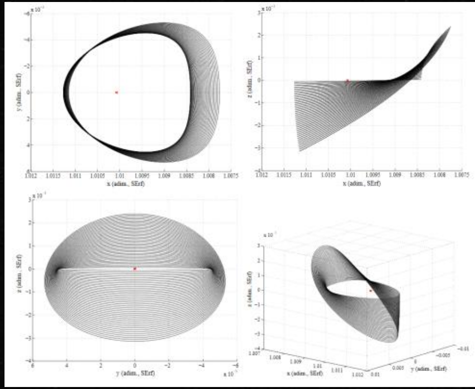
2.3 Halo orbit around L2

- Oscillating 3D Orbit
- Out-of-plane motion (avoids eclipses)



Visual representation of a Halo Orbit





Source:
Figure 2.9. Bernelli, Franco et al. (2020). Assessment of Mission Design Including Utilization of Libration Points and Weak Stability Boundaries. Politecnico di Milano
Figure 5. Miers, Tom. (1996). *System design of a mission to detect Earth-sized planets in the inner orbits of solar-like stars*. Journal of Geophysical Research.
Video animation. Lamid. https://www.youtube.com/watch?v=IyyQqaF4tNY&ab_channel=lamid

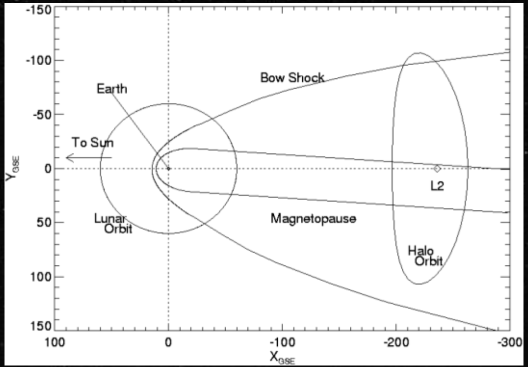
03

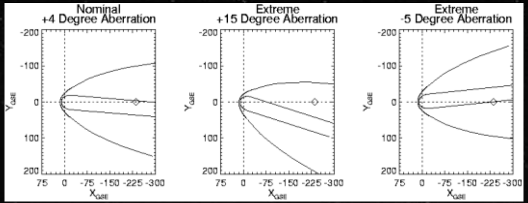
SPACE ENVIRONMENT

3. Space environment

- Halo orbits lead to interference with:
  - Solar wind
  - Magnetotail
  - Magnetosheath

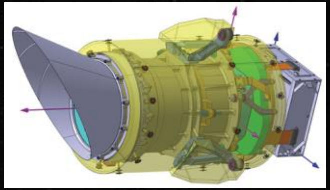
- Consequences:
  - Spacecraft charging
  - Surface ablation
  - Deviation due to solar pressure
  - Ionizing doses
  - Single Event Effects: solar flares





- Suggested protections:
  - 5-10 mm Pyrex glass sheet

  - Camera multi-layer insulation (MLI)



- Metoroid background is sporadic. ⟹ Conditioned only by meteor streams (e.g. Perseids and Leonids).
- Strong ionizing radiation background can be only avoided by selecting a low solar activity period for the mission.

Source: Figure 4.6 & 4.8. Evans, S.W. (2003). *Natural environment near the Sun/Earth-Moon L2 libration point*. Marshall Space Flight Center.
Figure 4.3. Conny, A. et al (2017). *PLATO definition study report*. ESA-SCI(2017).1
Figure 4.6. Vanderspek, Roland et al. (2018). *Tess Instrument Handbook*.
Ambrosi, R.M. et al. (2005). The effect of the prompt particle environment at L2 on optical CCDs for astronomy and astrophysics. *Planetary and Space Science*. Volume 53. Issues 14–15. Pages 1449-1465, ISSN 0032-0633

04

LAUNCH CONSIDERATIONS

4.1 Launcher selection

Selection criteria

Criteria		Soyuz 2-1b Fregat	Ariane 5	Ariane 6-62
Performance	Weight capability to L2 (kg)	2165	6600	3500
	Insertion accuracy ($\pm 3\sigma$)	a: ±12km e: $\pm 1.20 \cdot 10^{-3}$	a: ±7.5km e: $\pm 1.05 \cdot 10^{-3}$	
Availability	Attempts per day	>2 (33min launch window)	>2 (45min launch window)	
	Launch site	Kourou, French Guiana		
Payload adapter compatibility		ASAP-S (<400kg as minisatellite piggyback)	Dual launch	MLS (<400kg as piggyback)
Costs	Specific cost (k$/kg)	27.8*	23.4	-
	Launch cost (M$)	37.5	165.0	-
Reliability (%)		98.40	94.85	-

* Lower cost only if the piggyback option is considered in comparison with an Ariane 5 dual launch payload configuration

Selected launcher

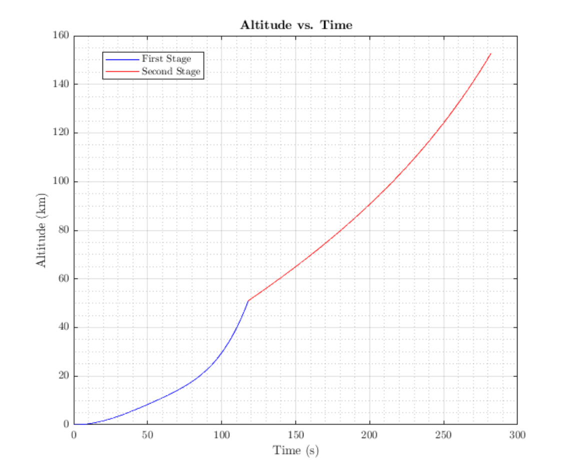
Soyuz 2-1b Fregat

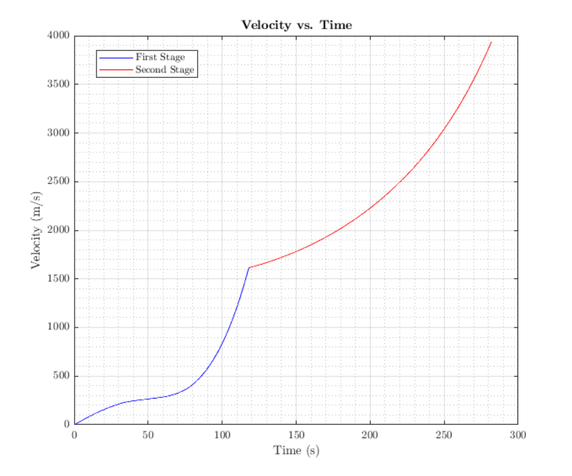
Source: ESA. (2017a). PLATO Denition Study Report (tech. rep.). ESA.
Space, A. (2019a). Technical overview Soyuz. Ariane Group.
ESA. (2017b). ARIEL Denition Study Report (tech. rep.).
ESA. Space, A. (2019b). Technical overview Ariane 6. Ariane Group.

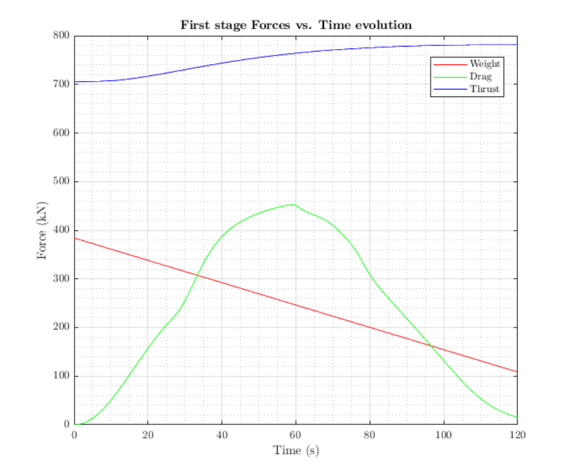
4.2 Launch dynamics

First and second stages ascent dynamics study

- Constant pitch angle considered:
  - First stage = 90º
  - Second stage = 45º
- No pitch maneuver considered, therefore 3r stage don't give realistic results
- Considerable drag effects during first stage ascent



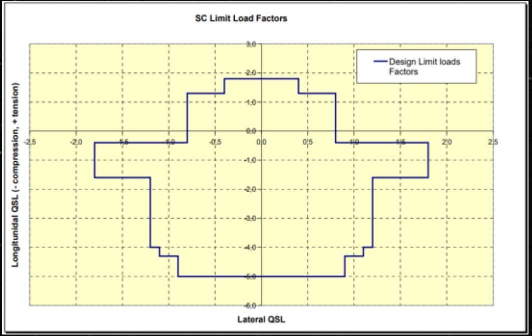


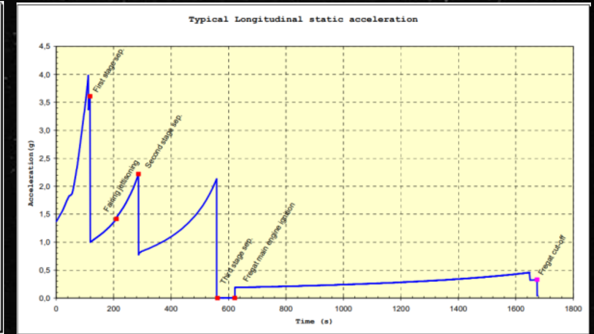


4.3 Launch environment

Accelerations

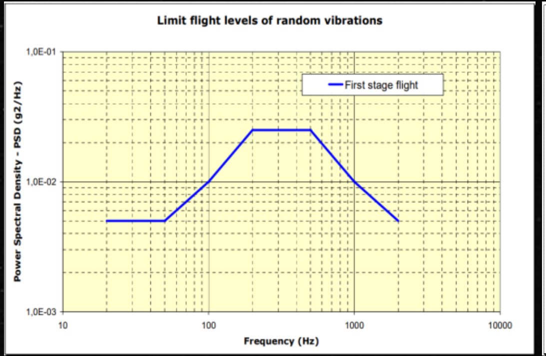
Maximum steady-state acceleration	
Longitudinal [g]	Lateral [g]
First stage cut-off engine	Max. dynamic pressure
4.1	0.4

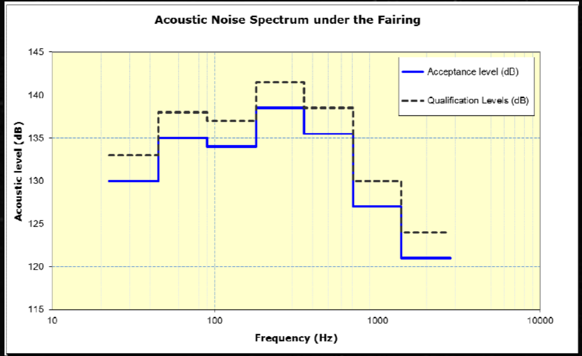




Vibrations

Low frequency sinusoidal vibrations		
Direction	Frequency band [Hz]	Maximum sine amplitude [g]
Longitudinal	10-30	0.8
Lateral	5-20	0.4





Acoustic Environment

Highest Flight limit level [dB]
137.5

Source: Figure 3.2.1 a “Soyuz Users’ Mannual” issue2 Revision1 (May 2018)
Figure 3.2.5 a “Soyuz Users’ Mannual” issue2 Revision1 (May 2018)
Figure 4.3.3.3 a “Soyuz Auiliary Passengers Users’ Mannual” issue1 Revision0 (June 2017)

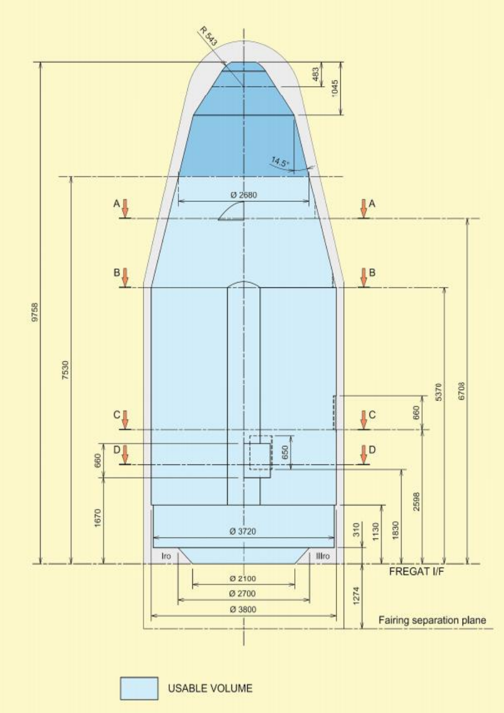
4.4 Payload protection

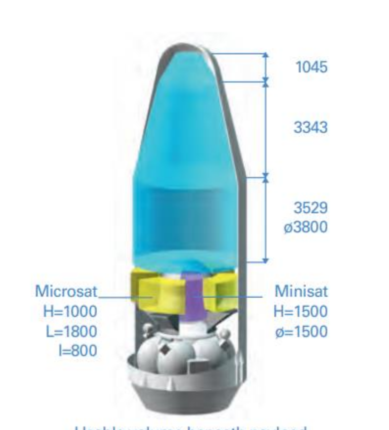
Fairing

- ST Fairing
- Two-half-shell carbon-fiber reinforced plastic (CFRP)
- Approximated total thickness of 25 mm
- Payload usable volumen definition

Safety factors

SC tests	Safety Factors	Tests duration
Static Accelerations	1.25	N/A
Sinusoidal Vibrations	1.25	0.5 oct/min
Random Vibrations	2.25	240 s
Acoustics	+3 dB	120 s





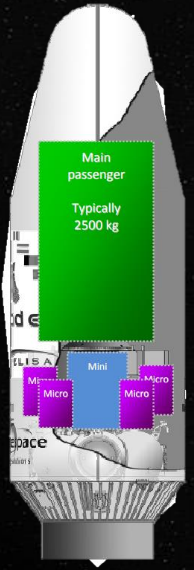
Usable volume beneath payload fairing and ASAP-S (Arianespace System for Auxiliary Payloads)

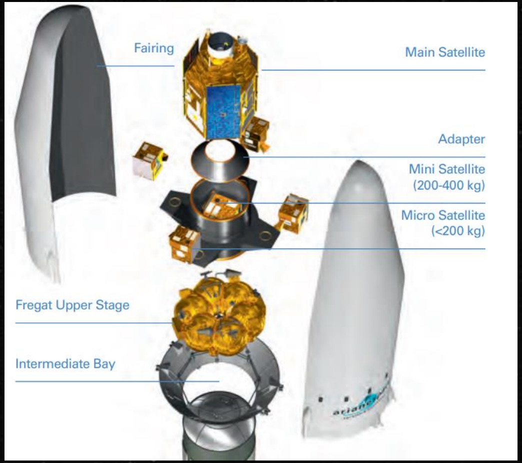
Source: Figure 5.3.1 a “Soyuz Users’ Mannual” issue2 Revision1 (May 2018)
“Soyuz Brochure” (October 2015)

4.5 Payload emplacement

Piggyback

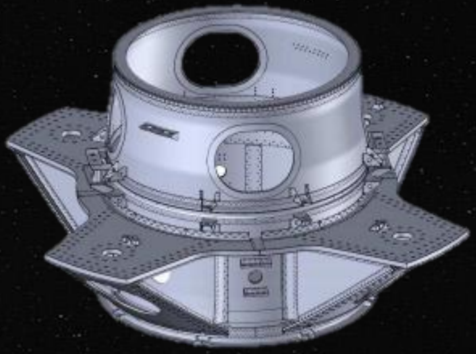
- Shared Soyuz launcher with any other primary mission going to L2
- ASAP-S Mini-satellite piggyback
- Considerable lower launch costs

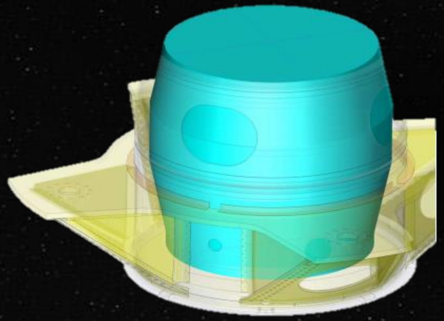




Launch Vehicle Adapter

- ASAP-S system allowing multiple launch configurations
- Specialized adapted ring
- Total mass: 425 kg
- Total heigh: 1841 mm





Source: Figure 1.2.2 ; 1.6.2a ; 2.3.2.3 b "Soyuz Auxiliary Passengers Users' Mannual" issue1 Revision0 (June 2017)

4.6 Propulsion

Launcher's propulsion system

ASCENT TO LEO | ASCENT TO L2

Criteria	Soyuz 2-1b Fregat			
Stage	1st	2nd	3rd	Fregat upper stage
Propellants (kg)	27 900kg LOX 11 260kg Kerosene	63 800kg LOX 26 300kg Kerosene	17 800kg LOX 7 600kg Kerosene	6638kg N_2O_4/UDMH
Engine	RD-107A	RD-108A	RD-0124	S5.92
Isp (s)	262 SL (319 vac.)	255 SL (319 vac.)	359 vac.	332 vac.
Attitude control				Pitch, yaw, roll: 50N hydrazine thrusters

Fregat upper stage

Justification

ALL STAGES

Liquid bi-propellant
Orbit insertion
Orbit maintenance and maneuvering
Attitude control

FREGAT UPPER STAGE

Storable propellant
Interplanetary stage
Liquid at room T
No tank venting needed

Fuel budget (kg)	
Injection	426.6
Attitude control & residual	29.9
Margin	64.0
Total	**520.5**

520.5 → < Fregat's maximum fuel load (6638kg)

Source: Space, A. (2019a). Technical overview Soyuz. Ariane Group.

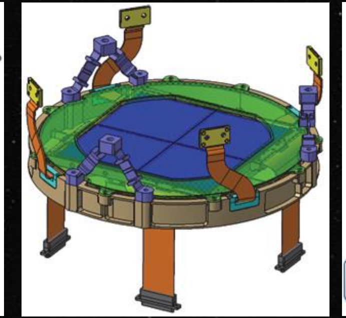
05

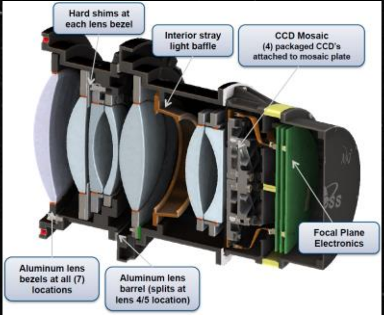
SPACECRAFT DEFINITION

5.1 Payload

Camera

- 4-camera configuration

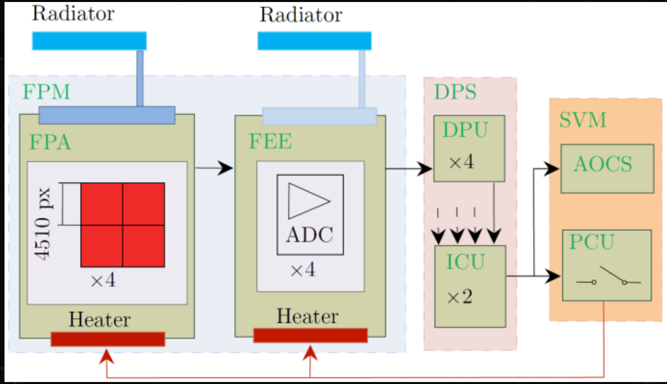




Optics overview	
Number of cameras	4
Wavelength range	400 – 1000 nm
Camera focal plane layout	4 e2v CCD 270 4510 px.^{2} 18 µm
Camera field of view	625°
Exposure time	~10 s

Optics electronics

- FPM: Focal plane module
  - FPA: Focal Plane Assembly
  - FEE: Front End Electronics
- DPS: Data Processing Subsystem
  - DPU: Data Processing Unit
  - ICU: Instrument Control Unit
- SVM: Service Module
  - AOCS: Attitude and Orientation Control Subsystem
  - PCU: Power Control Unit

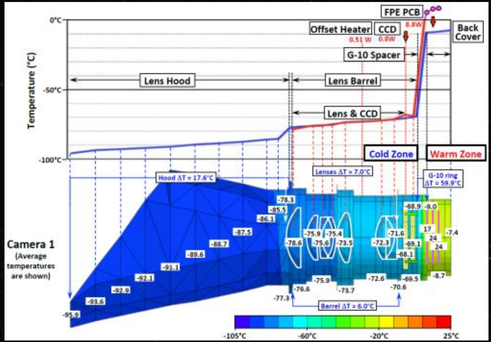


Source:
Figure 2 & 4. Ricker, G. et al. (2014). *The Transiting Exoplanet Survey Satellite*. Journal of Astronomical Telescopes, Instruments, and Systems.
Figure 4.6. Conny, A. et al (2017). *PLATO definition study report*. ESA-SCI(2017).1
Endicott, J. et al. (2012). *Charged-Coupled Devices for the ESA PLATO M-class Mission*. SPIE Astronomical Telescopes and Instrumentation.

5.2 Service module

Thermal subsystem

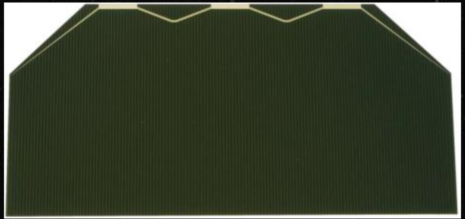
- CCD heat extracted through copper straps.
- Lens hood serves as a heat sink and radiator.



Copper strap

Power subsystem

- Estimated consumption of 250 W (based on CHEOPS and TESS).
- Azur Space quadruple junction GaAs solar cells $\eta \approx 32\ \%$.
- Cell surface=30 cm^2. Around 300 cells required.
- Auxiliary 40 Ah lithium battery.



Attitude and orientation subsystem

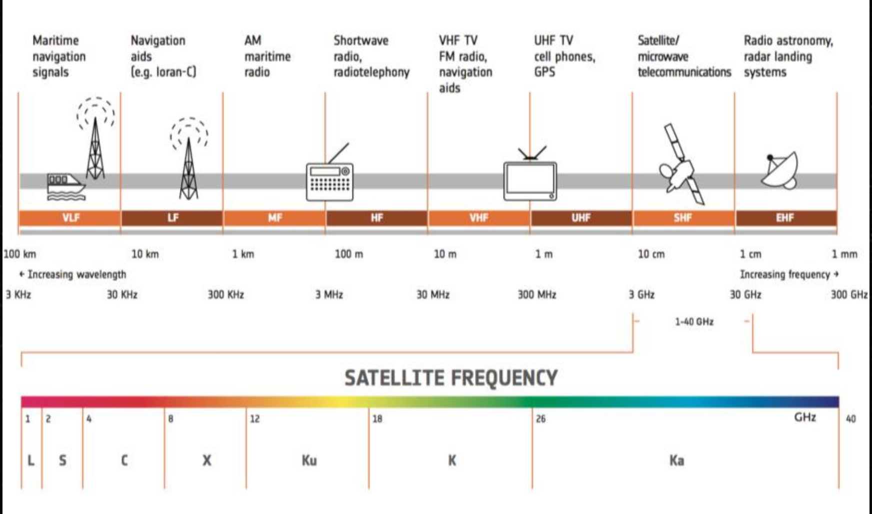
- Honeywell reaction wheels for precise attitude control.
- 3 sets are implemented (1 for redundancy).

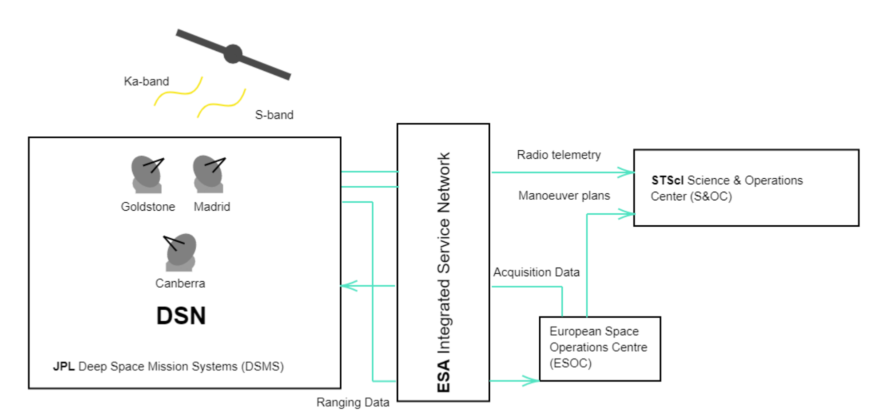
VACCO Cold Gas Thruster Triad

- 3 thrusters along x, y, z.
- Thrust: 8.9 N (2.0 lbf).
- Operating pressure: 1.8 MPa (260 psi).

Source: Figure 4.8. Vanderspek, Roland et al. (2018). *Tess Instrument Handbook*.
Figure 4.7. Conny, A. et al. (2017). *PLATO definition study report*. ESA-SCI(2017).1
VACCO Industries. (2004). *VACCO Space Products*.
Azur Space. (2019). *32% Quadruple Junction GaAs Solar Cell*.
Honeywell Aerospace (2020). *HR04 Reaction Wheel Assembly (RWA)*.

5.3. Mission operation & communication subsystem





- Ka-band: High rate downlink for satellites
- S-band: Command uplink, low rate telemetry downlink

- Deep Space Network (DSN)
- ESA Integrated Services Network
- European Space Operations Center (ESOC)
- Science and Operations Center (S&OC)

Source:
NASA (2020) 020c). *James Webb Space Telescope (JWST) Project Overview*. An overview of the JWST
European Space Agency (2020). *Satellite frequency bands*. Journal of Astronomical Telescopes, Instruments, and Systems.