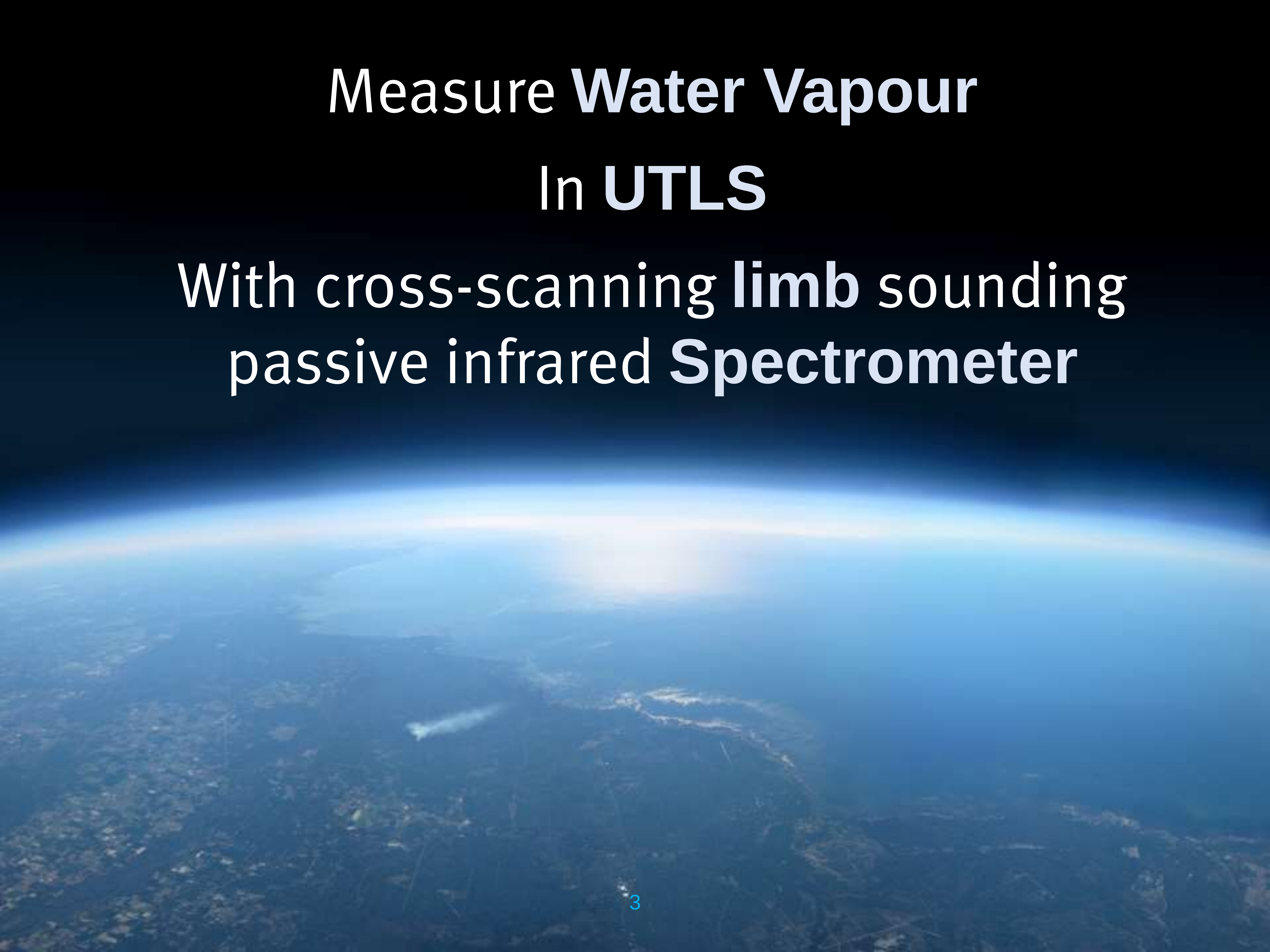
# WAVE-E

## WAter Vapour European-Explorer

**Team Green**

Summer School Alpbach 2016


Measure **Water Vapour**
In **UTLS**
With cross-scanning **limb** sounding passive infrared **Spectrometer**

# Outline

## 1 Science Case

Reasoning, Objectives and Requirements

## 2 Payload Design

Measurement principle and Instrument description

## 3 Mission Design

From Launcher to Ground Segment

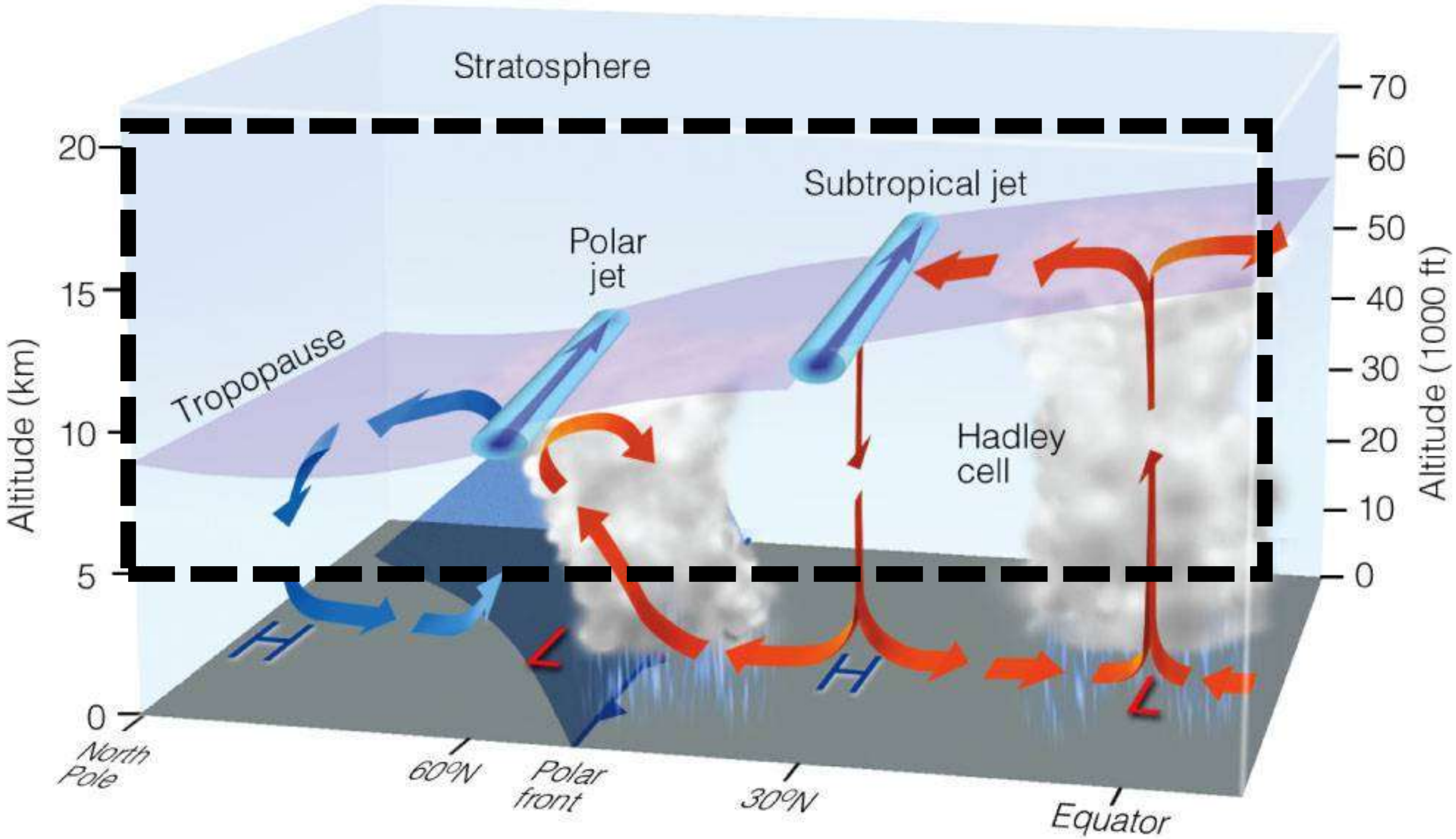
Risks, costs and alternatives

# WAVE-E

## Science Case

# Stratosphere-Troposphere Interactions

WATER VAPOUR



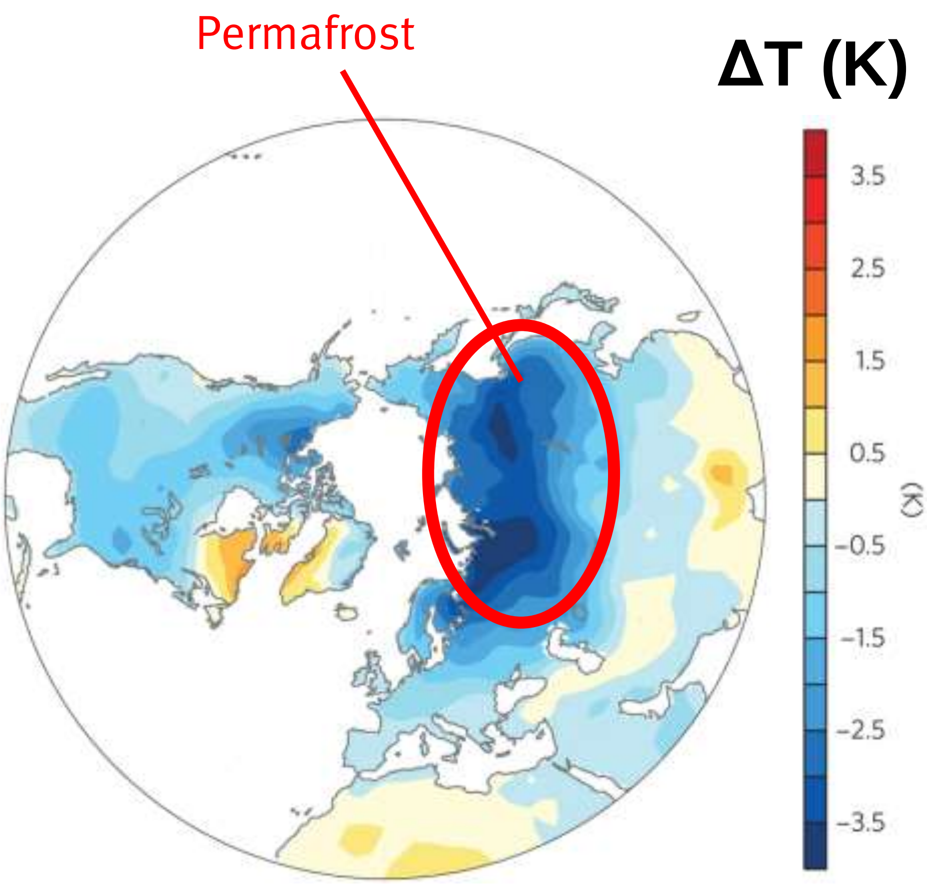

JCB, 2011

**WATER CYCLE**

# UTLS and Water Cycle Surface Parameters

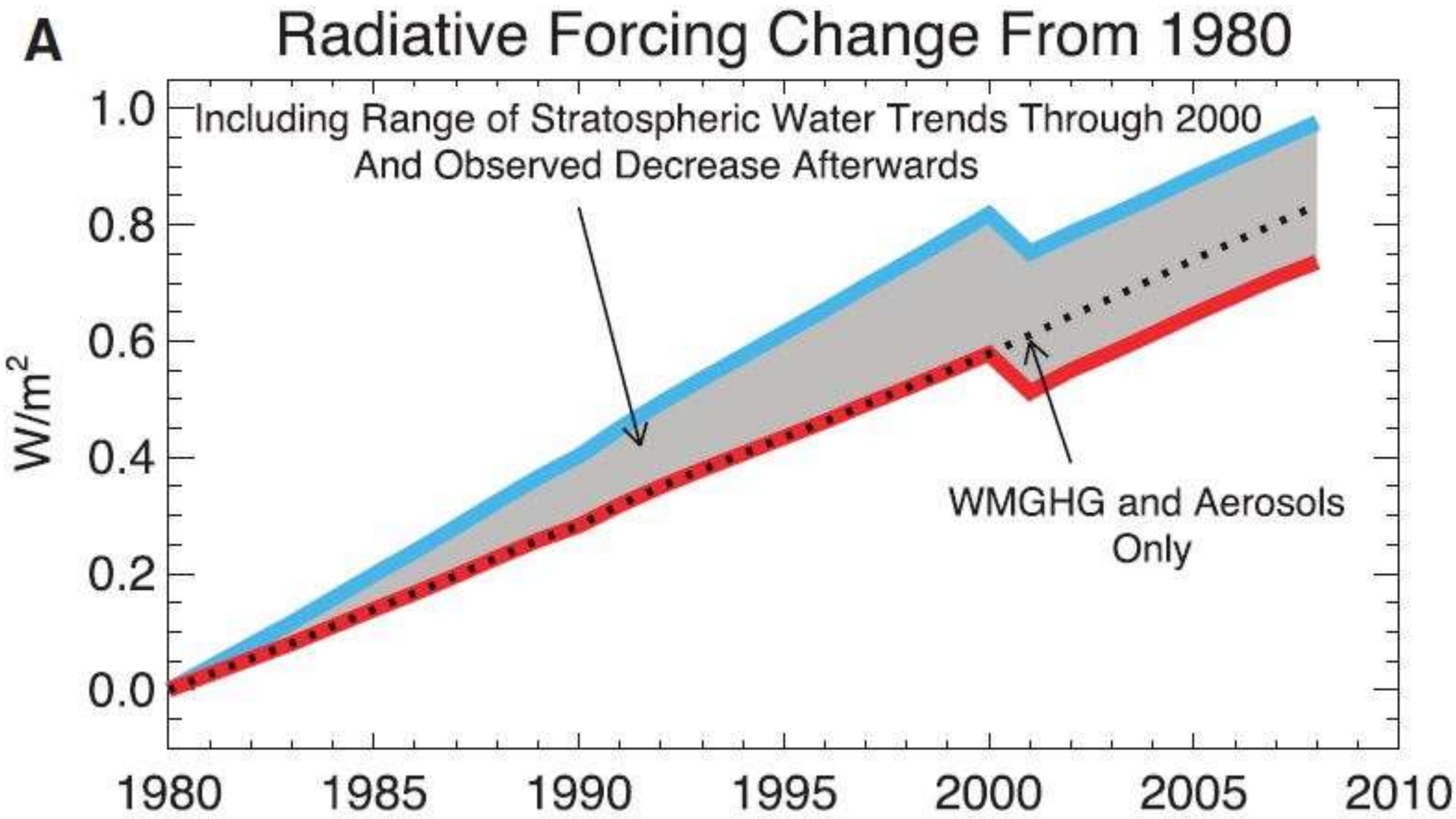
Strong **polar vortex** in the mid-stratosphere

→ Great impact on surface temperature




Kidston et al., Nature Geoscience, 2015

# UTLS and Water Cycle and Energy Budget




Solomon, et al., Science, 2010

# Societal impacts of the mission

Working towards better predictions for...

**Floods/ Monsoons**

During monsoon events, 75% of the water vapor exchange takes place in the UT

[Gettelmann, et al., 2004]

**Cyclones**

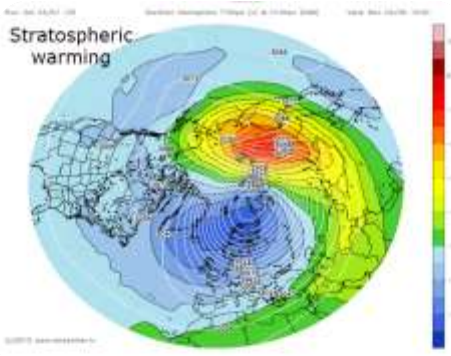
Cyclone development in most cases is initiated by dynamical processes in the UT (“top-down”)

[Wallace & Hobbs, 2006]

**El-Niño/ La-Niña**

Responses of ENSO on surface pressure systems have biases of up to 9 hPa without resolved UTLS

[Ineson and Scaife, Nature, 2009]




**SSW**

Impacts of SSW on surface temperatures are captured 4 days ear-lier using highly resolved stratosphere

[Marshall & Scaife, 2010]

# Water Vapour in the UTLS identified as a High Priority

Global Climate Observing System, **ECV** (Essential Climate Variable), 2010

ESA-GEWEX October, 2015 (EO and **water cycle science priorities**)

**WATER VAPOUR in UTLS**

**"Theory of stratosphere-troposphere coupling"**
Kidston et al., Nature, 2015
Muller et al., 2016
Salomon et al., Science, 2010

**IPCC** , WG1
Water vapour feedback

FFG esa …

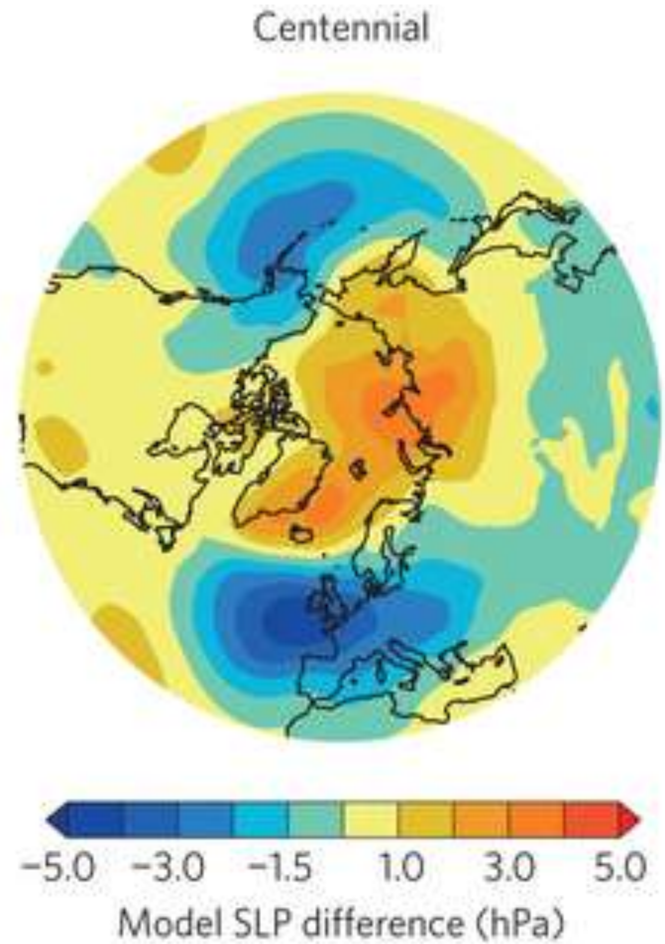
# UTLS Water Vapour Observations?

| Platform/ Mission | Instrume nt | Technique | Vertical constraints | Spatial coverage |
|---|---|---|---|---|
| **Aura, 2004-2016 (ongoing)** | TES Nadir | **Cross-nadir** scanning infrared sounder | **Troposphere only** | **Global coverage in 16 days** |
| **Metop SG 2021 (planned)** | IASI - NG | **Cross-nadir** scanning infrared sounder | **Troposphere only** & Coarse vertical resolution above | Near-global coverage twice/day |
| **Sentinel 5-P 2016 (planned)** | TROPOMI | **Cross-nadir** scanning **short-wave** sounder | **Troposphere only** | Global coverage in 1 day |
| **ISS, 2016 (planned)** | SAGE-III | Limb-scanning sounder | **Stratosphere only** | **Limited to latitudes above approx. 50 degrees** |
| **PREMIER 2004 (proposed)** | IRLS | Infrared Limb-scanning sounder | UTLS region | **Global coverage in 4 days** |

⇨ **The need for a dedicated mission for UTLS Water Vapor is evident!**

# Need for vertically resolved measurements

**Enhancement** of stratospheric **vertical resolution** (3.8 km to 2.5 km) has huge impact on **surface pressure predictions**




Kidston et al., Nature Geoscience, 2015; after Scaife et al., 2011

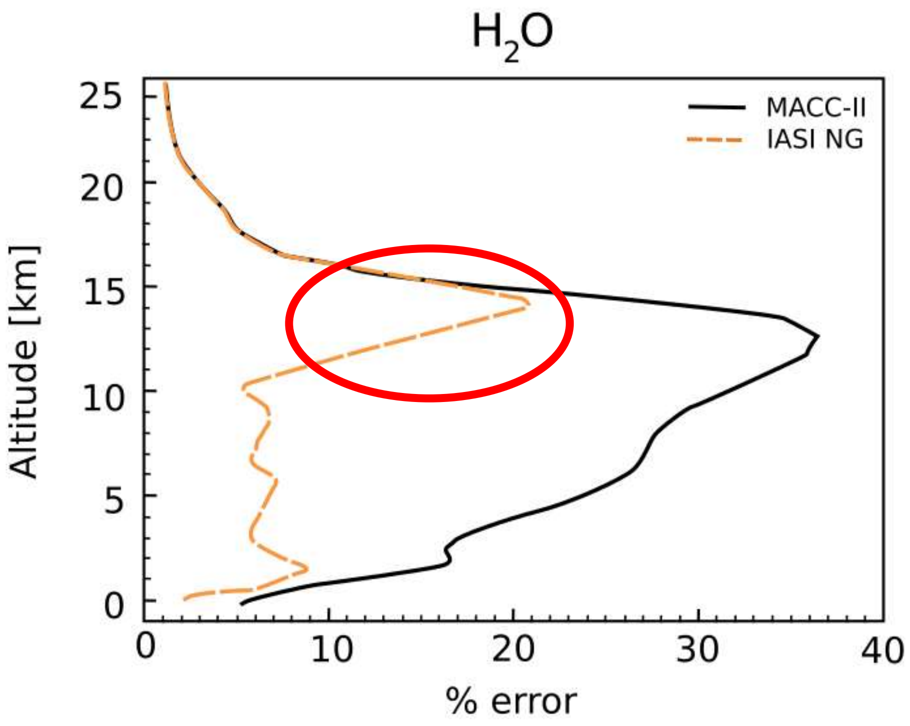
**Scientific Community:**
Everything better than **2 km** is **"extremely valuable"**
(Mueller et al., 2016)

**Operational NWPs:**
**ECMWF** short and medium range forecast models run with **300-500 m** resolution

# Measurement Uncertainty

**$H^2O$-errors** for atmospheric models like MACC-II (ECMWF) are **significantly high in the UTLS**

**Nadir-sounding instruments** like IASI **fail to reduce the errors** particularly in the boundary layer




→ we aim for **<10 % uncertainty** in order to significantly improve our understanding

[Adapted from A. Waterfall]

# Traceability Matrix – Primary Scientific Objectives

| Objectives | Measurement Requirements | References |
|---|---|---|
| **PSO 1** Monitor water vapour profiles in the UTLS region at the vertical resolution required to **improve knowledge on short-term weather phenomena** (SSW, Extreme Rainfall Events) | **SR 1.1** Significantly less than 2 km vertical resolution | ESA-GEWEX October, 2015<br>Mueller et al., 2016 |
| | **SR 1.2** 9 - 36 km horizontal resolution | ECMWF HRES / ENS / ENS-Extended |
| | **SR 1.3** <6 h temporal resolution | Mueller et al., 2016<br>ECMWF HRES / ENS |
| | **SR 1.4** Uncertainty <10 % (ppm) | Waterfall A., 2012 |
| **PSO 2** Monitor water vapour profiles in the UTLS region at the vertical resolution required to **improve knowledge on mid-term & seasonal weather phenomena** (ENSO, Monsoon, NAO) | **SR 2.1** 12 h temporal resolution | Marshall & Scaife, 2010<br>ECMWF 4D-VAR |

# Traceability Matrix – Secondary Scientific Objectives

| Objectives | Measurement Requirements | References |
| --- | --- | --- |
| **SSO 1** Obtain a long-term dataset of vertically resolved UTLS water vapour to understand the impact of UTLS water vapour **on the radiative budget of the Earth** | **SG 1.1** 11 years mission duration (duration of Solar Cycle) | ECV essential climate variables<br>IPCC report |
| **SSO 2** Development of a coherent **theory of stratosphere-troposphere coupling** | **SG 2.1** Long term mission duration | Kidston et al., Nature, 2015<br>Muller et al., 2016<br>Salomon et al., Science, 2010 |

# Key Science and Mission requirements

| | |
|---|---|
| Vertical Resolution | 1 km |
| Horizontal Resolution | 9 - 36 km |
| Temporal Resolution | <6 h / 12 h |
| Uncertainty (ppm) | <10 % |

# WAVE-E

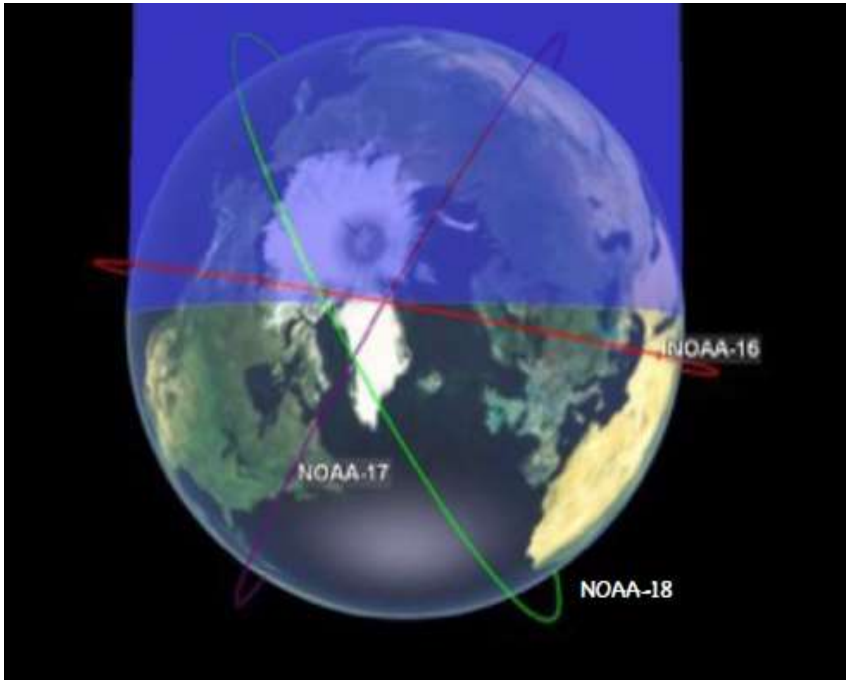
## Payload Design

# Observation Strategy (I)

Three satellites that are launched by **two** separate launch systems (and times) in **SSO, 817 km**

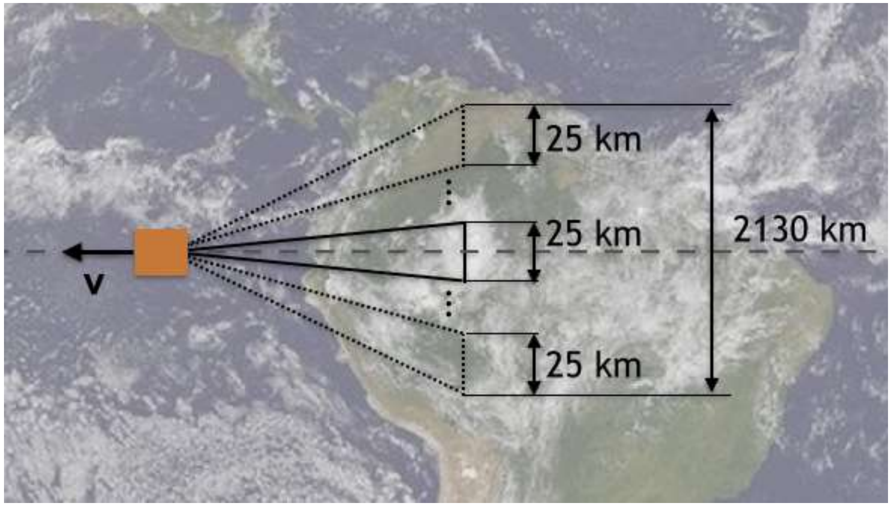
Temporal Resolution 4h

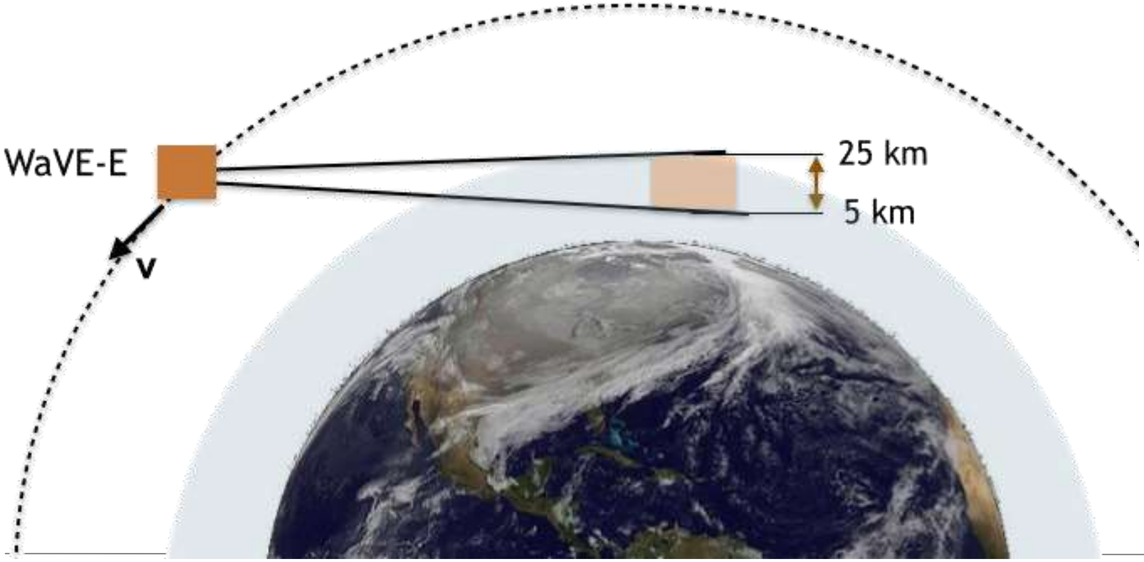
(SR 1.3)




Courtesy: Space Systems Synthesis, by M. Aguirre

# Observation Strategy (II)

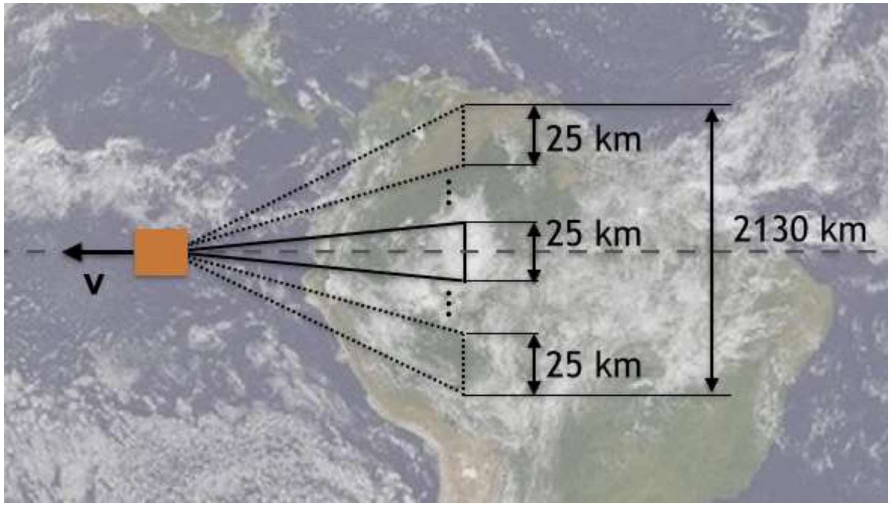


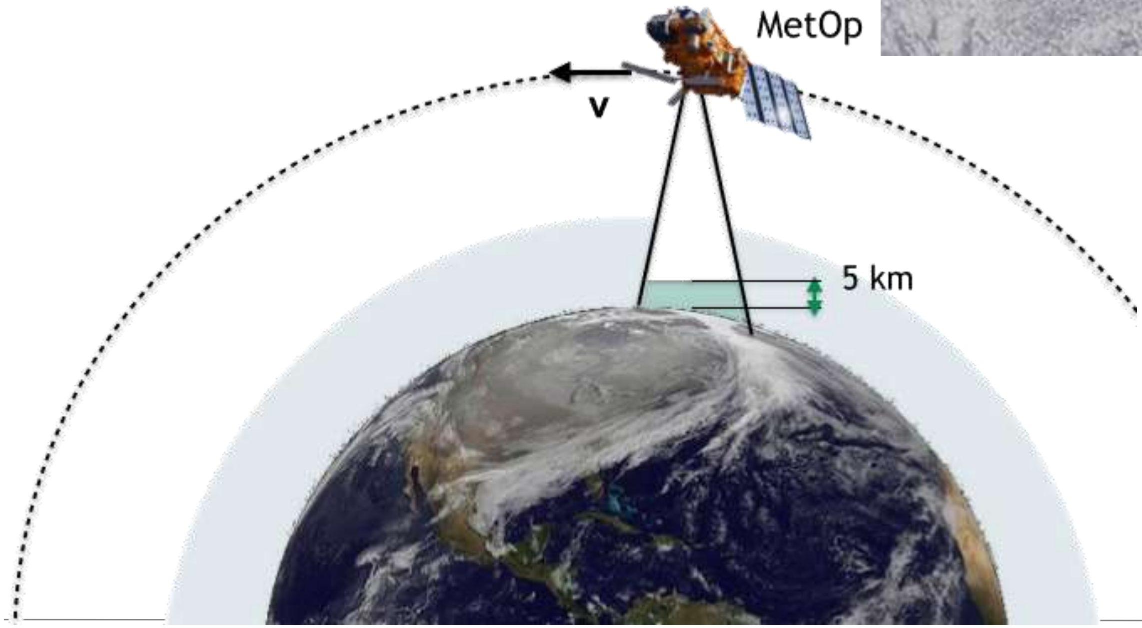




**Resolution:**

Vertical: 1 km (SR1.1)
Horizontal: 25 km (SR1.2)

# Observation Strategy (II)

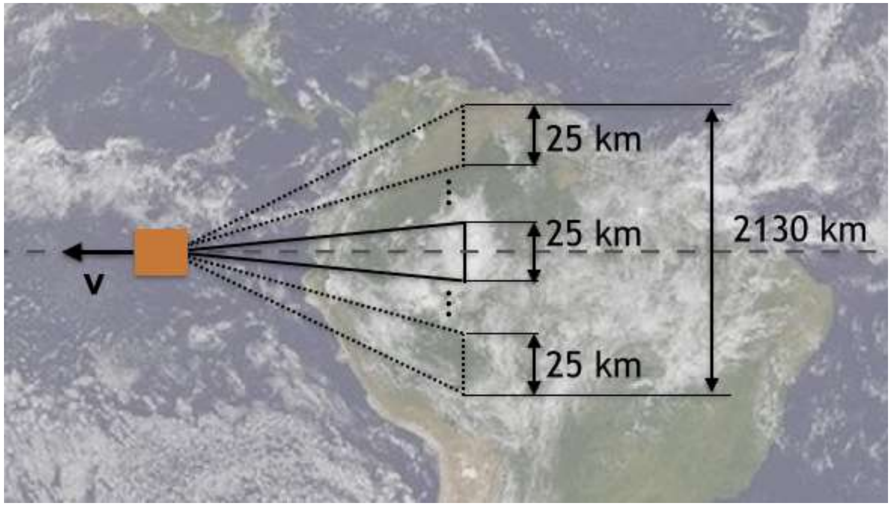


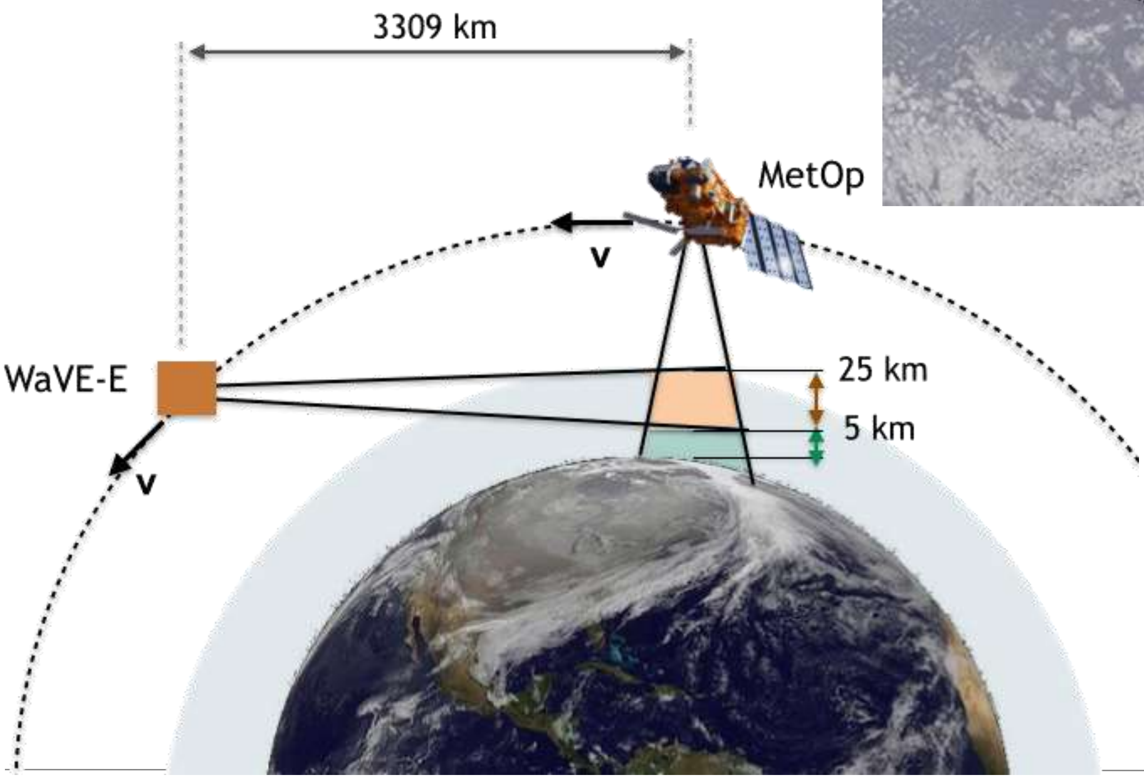




**Resolution:**

Vertical: 1 km (SR1.1)
Horizontal: 25 km (SR1.2)

# Observation Strategy (II)



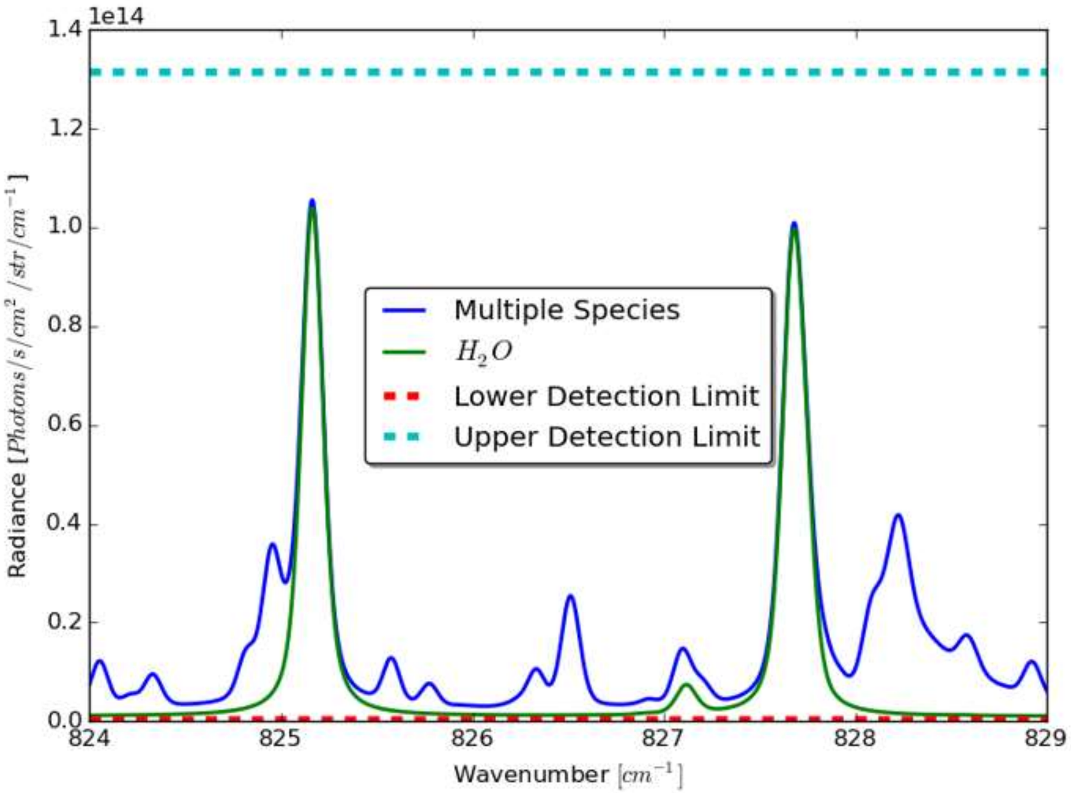

**Resolution:**

Vertical: 1 km (SR1.1)
Horizontal: 25 km (SR1.2)

# Measurement principle (I)

Requirement:

Instrument uncertainty less than 5% (SR 1.4, 5% retrieval uncertainty)




**Spectral Bandwidth**: 824 - 829 cm$^{-1}$

**Spectral Resolution:** 0.08 cm$^{-1}$

**Species considered:** H2O, O3, CO2, N2O, O2, CH4

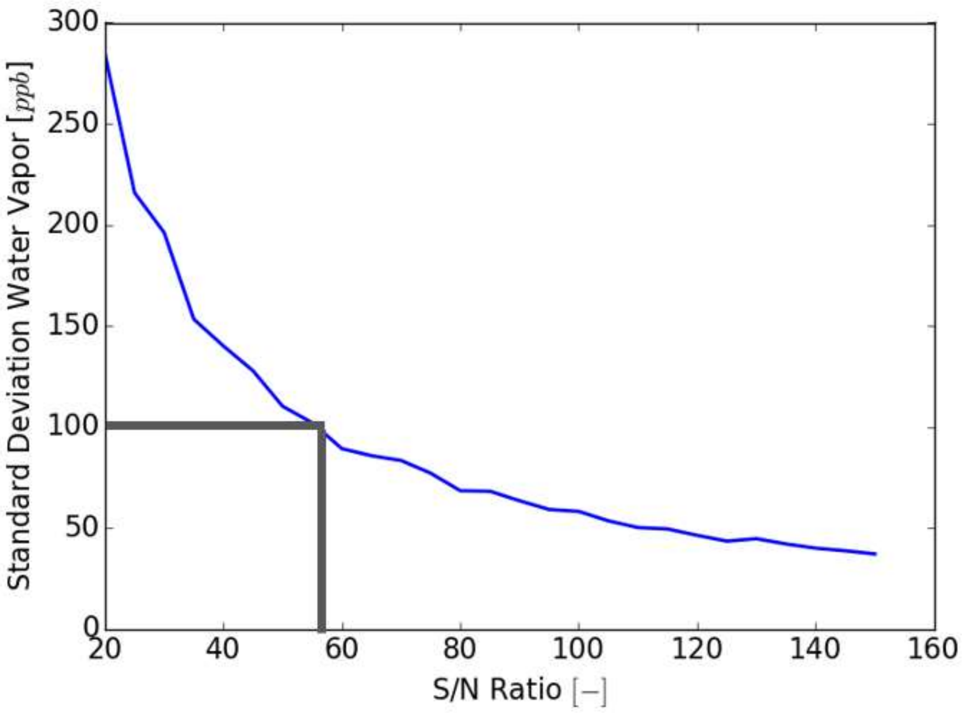
**Apparent Tangent Height:** 10 km

**Refracted Tangent Height:** 9,37 km

**Model Atmosphere:** US Standard Atmosphere

**Spectral Database:** Hitran 2012

# Measurement principle (II)




**Monte Carlo Simulation:** 1000 samples

**Water Vapor:** 70 ppm

**Multiplicative Noise:** 50%

**Additive Noise:** 50%

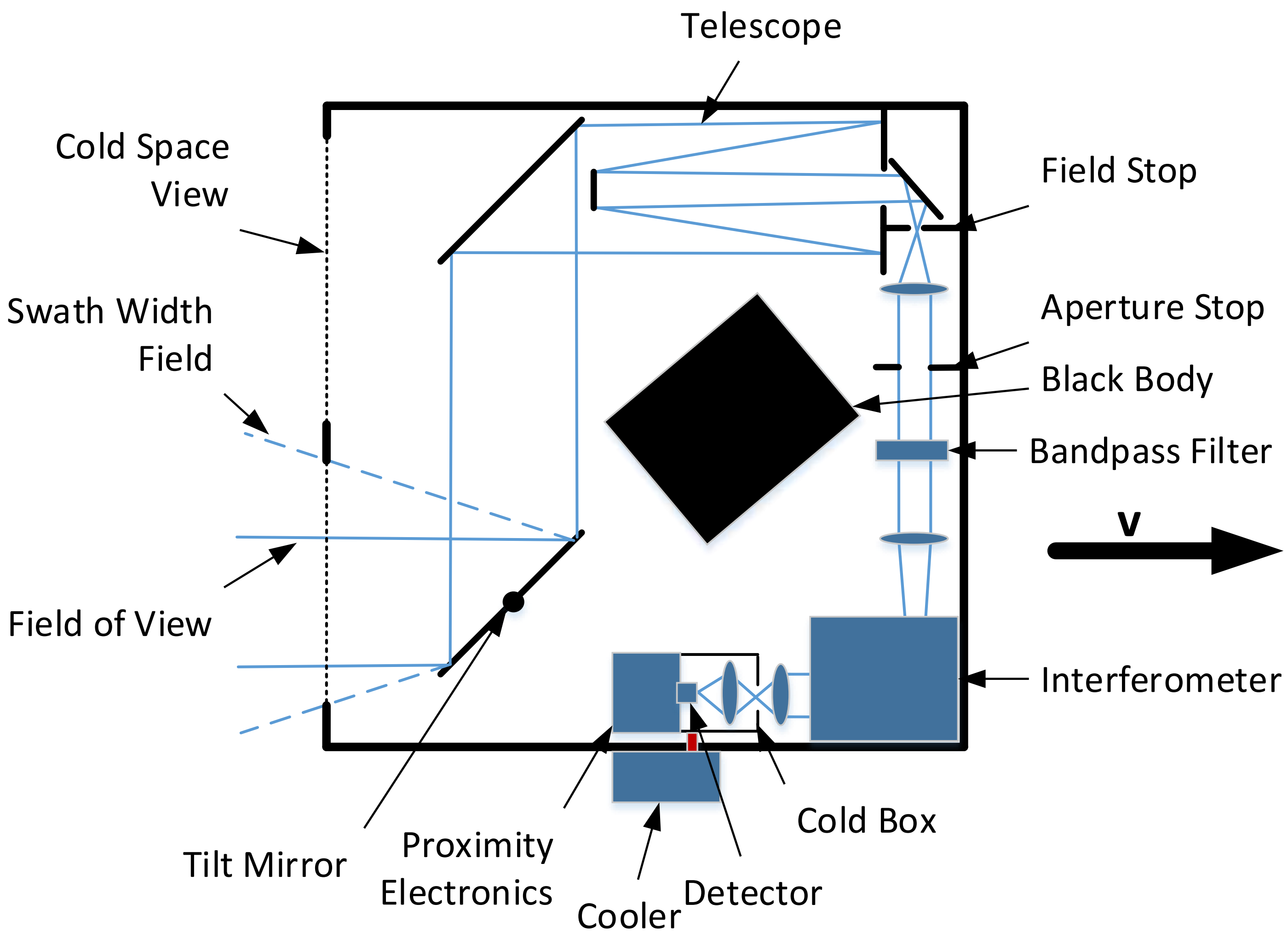
**Retrieval Variable:** Water Vapor

**Assumption:** Linear relation between water vapor and radiance

# Signal-to-Noise Ratio Analysis (S/N-Analysis)

| **Spectral Flux** | **1,22E-06** | **W/cm^2/str** | **Total H2O Flux** |
|---|---|---|---|
| **Factor of Safety** | **10** | - | |
| Spectral Flux | 1,31E+10 | photons/s | Etendue Pixel Row: 1,62E-03 $cm^{-2}$ str |
| Total Signal | 6,83E+06 | electrons/s | Quantum Efficiency: 80%<br>Transmissivity: 40% |
| Signal per Pixel row | 1,71E+04 | electrons/s | Interferogram Samples: 400 |
| Integrated Signal | 5,12E+03 | electrons | Integration Time: 0.3s |
| Other emission lines | **60** | electrons | 1.17% of H2O Peak |
| Calibration Error | **51** | electrons | Absolute Calibration Accuracy: 1% |
| Readout Noise | **100** | erms | |
| Dark Current | **0,4** | e/s | |
| Shot Noise | **72** | erms | |
| **S/N** | **70** | - | |

# Instrument - Schematics



# Instrument - Budgets

| Mass | kg |
|---|---|
| Instrument | 59 |
| Maturity Factor | 1.35 |
| **TOTAL** | **79** |

| Power | W |
|---|---|
| Instrument | 68 |
| Maturity Factor | 1.35 |
| **TOTAL** | **92** |

**Volume**: 0.8 x 0.8 x 0.3 m

**Datarate: 940 kbit/s**

# Instrument - Telescope

**Type**: **Ritchey-Chretien telescope**

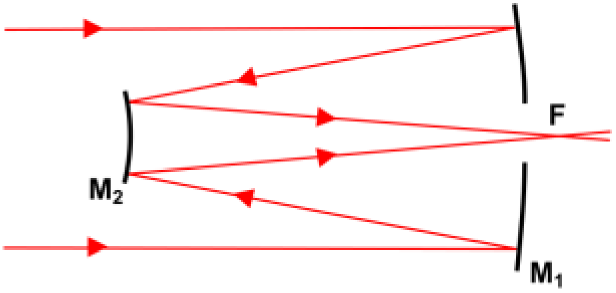
Hyperbolic mirrors

**Aperture**:

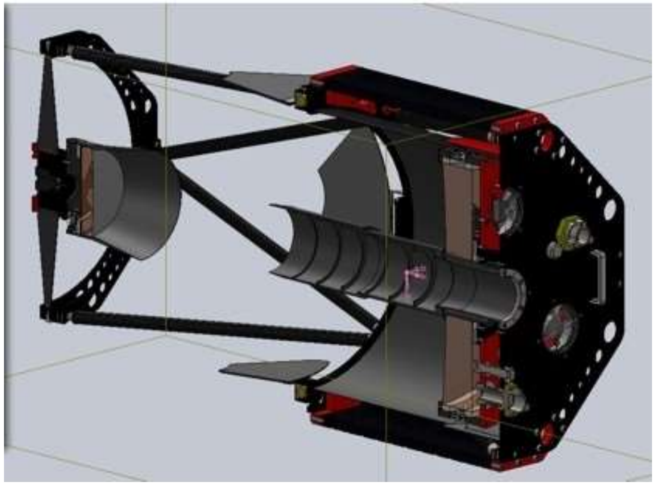
Input - 150 mm

Output - 40 mm

**Distance between mirrors**: 300 mm




Ritchey-Chrétien



https://www.optcorp.com/

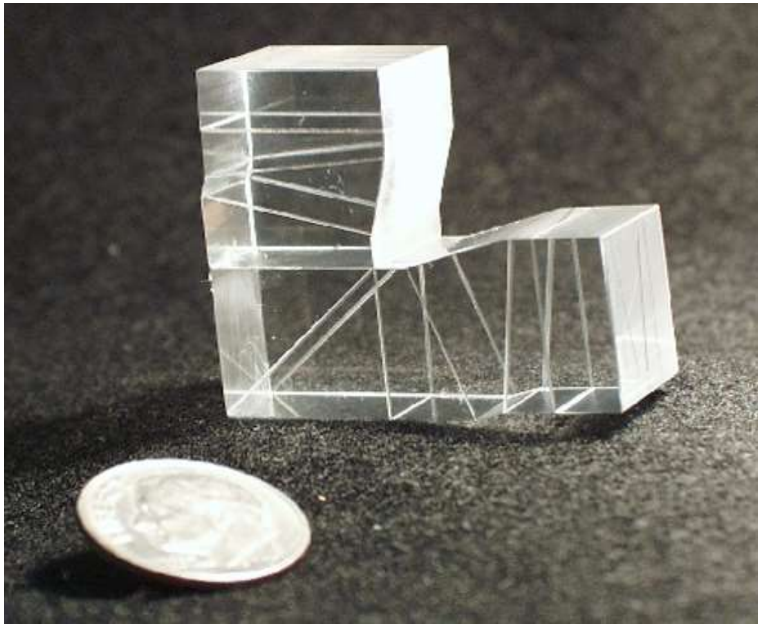
# Instrument - Spectrometer

Type: **Spatial Heterodyne Spectrometer**

**Advantages:**

- Field-widening possible
- Rigid design
- High spectral resolution
- Less sensitive to vibrations
- No moveable parts

| | |
|---|---|
| Spectral Resolution | 0.07 $cm^{-1}$ |
| Resolving Power | 12 000 |
| Field of View | 1.3 º |
| Aperture Diameter | 4 cm |
| Etendué | 0.00163 $cm^{-2}$ str |



[Doe, 2011]

# Instrument - IR Detector

HgCdTe-detector

Cooled to ~ 80 K with COTS cryocooler

**Resolution** **400 x 25 pixels**

**Readout noise** < 100 $e^-$

**Dark current** < ~ 0.4 $e^-$/s

**Quantum Efficiency** > 80%

[sofradir.com]

# Instrument - Cooling

Detector and cold box around it need to be cooled to **80 K**

**Active** cooling with **Stirling-type cryocooler**

- Better efficiency
- Small and light COTS widely available
- Vibrations don't affect the spectrometer performance of SHS spectrometer

Cooling power: 850 mW

[Mai, 2011]

➢ Reduced volume & visibility constraints (compatible with Soyouz launch)

➢ Good confidence as already flying in Sentinel's, Envisat...

# Instrument - Calibration

## Hot Black Body at 293 K
## Cold Black Body : Deep space at 3 K

| | |
|---|---|
| Aperture | 15 cm |
| Size | 20x20x25 $cm^3$ |
| Absolute temperature knowledge | ‹ 0.1 K |
| Cavity spectral emissivity | 0.998 |
| Temperature stability | ‹ 25 mK/min |

[Olschewski, 2013]
Personal communication

# WAVE-E

## Mission Design

# Launch strategy & Orbit Parameters

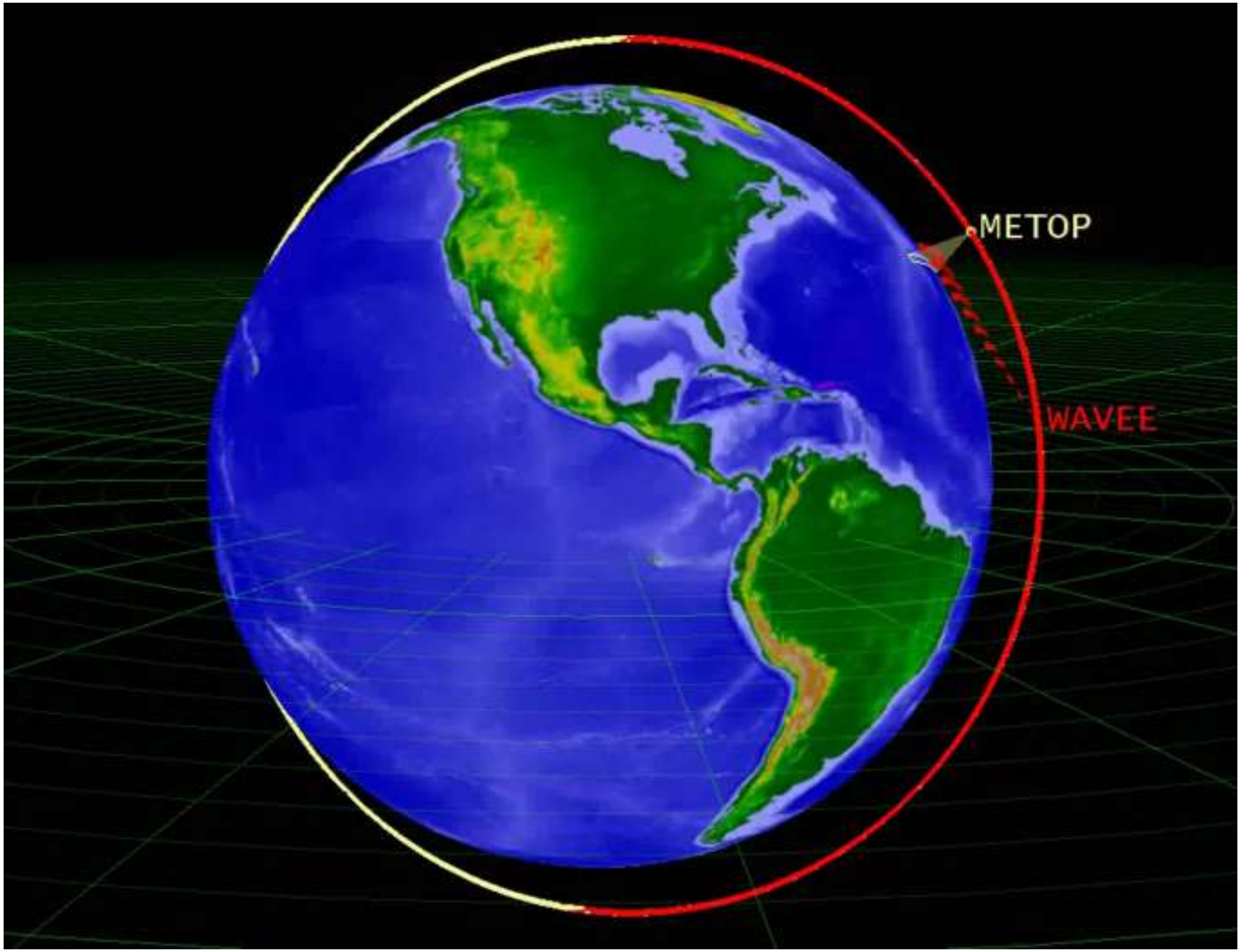
- **3 WaVE-E satellite** constellation; revisit time of **4 hours**.
- **Baseline mission objective:**
  - **1 WaVE-E launched independetly + 2 WaVE-E launched together later**

**Orbit**

- **LEO**: SSO 817 km, 98.7° (**period**: 101 min, eclipse: 32 min/orbit).
- **Coverage**: 98 % in 1 day (2130 km swath)

| | S/C 1 | S/C 2 | S/C 3 |
|---|---|---|---|
| RAAN [deg] | 63.8 | 123.8 | 183.8 |

# Launch S/C 1



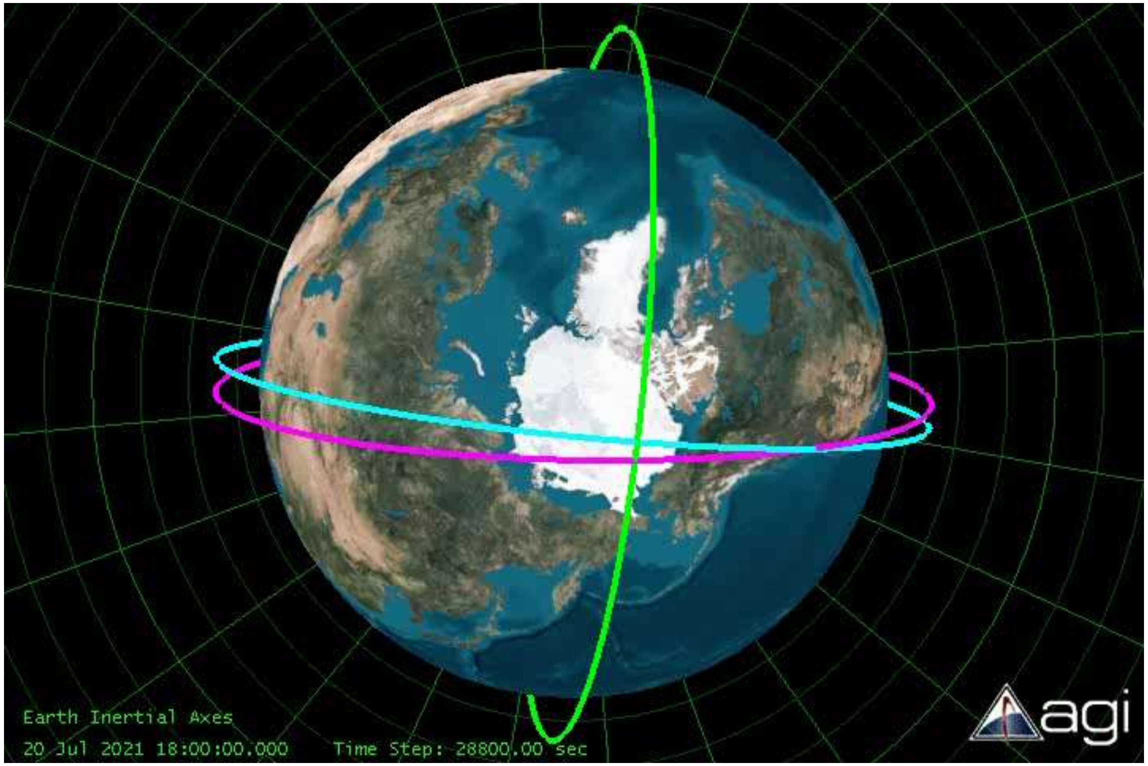
# Launch S/C 2, 3

**Maneuvers**

- Vega insertion
  → Intermediate orbit
- Inclination change: **1.5°**
- **J2** natural drift
- Change inclination back
- Total maneuver**:**
  **6 months**

**Result**

- Each satellites positioned 60° from each other



# Mass budget

| | Mass w/o Margin [kg] | Margin [%] | Margin [kg] | Total [kg] | Check [%] |
|---|---|---|---|---|---|
| Payload | 79.2 | 30% | 23.8 | 103.0 | 33% |
| Structure | 40.3 | 25% | 10.1 | 50.4 | 16% |
| Harnessing | 14.1 | 25% | 3.5 | 17.6 | 6% |
| Thermal | 6.9 | 25% | 1.7 | 8.6 | 3% |
| EPS | 28.9 | 10% | 2.9 | 31.8 | 10% |
| Comms | 9.0 | 10% | 0.9 | 9.9 | 3% |
| OBDH | 30.0 | 10% | 3.0 | 33.0 | 11% |
| ADCS | 17.3 | 10% | 1.7 | 19.0 | 6% |
| Propulsion | 32.6 | 10% | 3.3 | 35.8 | 12% |
| Total | 258.4 | | | 309.3 | 100% |
| System margin | | 20% | 61.9 | | |
| **Dry Mass** | | | | **371.2** | |

| | S/C 1 | S/C 2 | S/C 3 |
|---|---|---|---|
| Propellant [kg] | 67.5 | 109 | 109 |
| **Total Launch Mass [kg]** | **438** | **480** | **480** |

→ **SMALL SATELLITE**

# ΔV Budget

| | Delta V w/o Margin [m/s] | Margin | Delta V [m/s] |
|---|---|---|---|
| Launcher Dispersion | 27.3 | 5% | 28.6 |
| Initial Detumbling | 10.0 | 100% | 20.0 |
| Orbital transfers | 0.0 | 5% | 0.0 |
| Drag maintenance | 10.9 | 5% | 11.4 |
| | | | |
| Attitude control (3-axis) | 44.0 | 100% | 88.0 |
| M. wheel unloading | 44.0 | 100% | 88.0 |
| Deorbit EoL | 90.0 | 5% | 94.5 |
| Collision avoidance | 44.0 | 5% | 46.2 |

| | **S/C 1** | **S/C 2,3** |
|---|---|---|
| **Total [m/s]** | **376.8** | **581.4** |
| **$M_{prop}$ [kg]** | **67.5** | **109.1** |
| Volume [L] | **89.1** | **144.1** |

# Propulsion System

| | Mass [kg] | Notes |
|---|---|---|
| Tank | 13.5 | 600 x 896 mm (ø, height). Capacity: 170 kg Volume margin for boil-off, ullage, traped liquid. |
| Presurrant Tank | 5.4 | Ø = 310 mm |
| Presurrant Gas | 6.5 | Helium |
| Thruster | 3.5 | 12x (4 redundancy) |
| Valves | 3.2 | 12 main valves, 8 safety valves |
| Pipes | 0.5 | 7.50% of tank mass |
| **Total System Mass** | **32.6** | |

| | S/C 1 | S/C 2,3 |
|---|---|---|
| $M_{prop}$ [kg] | **67.5** | **109.1** |

# Data Budget

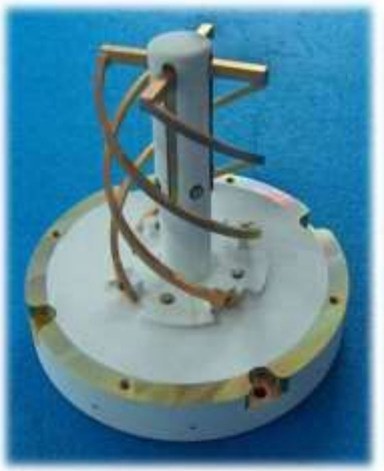
| TM production datarates | |
|---|---|
| Bus housekeeping [bit/s] | 10 000 |
| Instrument datarate [bit/s] | 1 152 000 |
| Instrument housekeeping [bit/s] | 20 000 |
| Instrument compression rate | 20% |
| Total [bit/s] | 931 600 |

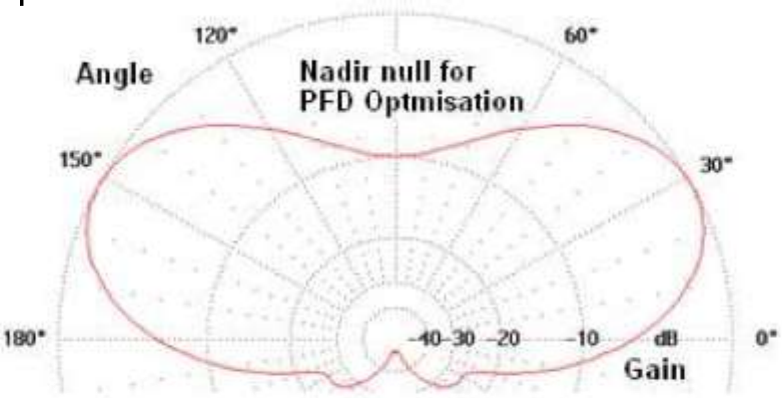
| | per orbit | per day |
|---|---|---|
| Total data [Mbytes] | 674 | 9 595 |
| Link time [min] | 13 | 179 |

| | Access Time in one day [min] |
|---|---|
| **Kiruna** | 116,76 |
| **Svalbard** | 157,36 |

# Telemetry, Tracking & Commanding

- **S-band** Transceiver
  - Uplink: 2 025 – 2 110 MHz
  - Downlink: 2 200 – 2 290 MHz
- **Data rate**: 10Mbit/s
- Modulation: QPSK
- Concated Forward Error Coding
  - Half rate convolutional coding (viterbi) + Reed Solomon
- TX power: 10 Watts
- Antenna: Nadir pointing helix
- Total transmission losses: 170dB



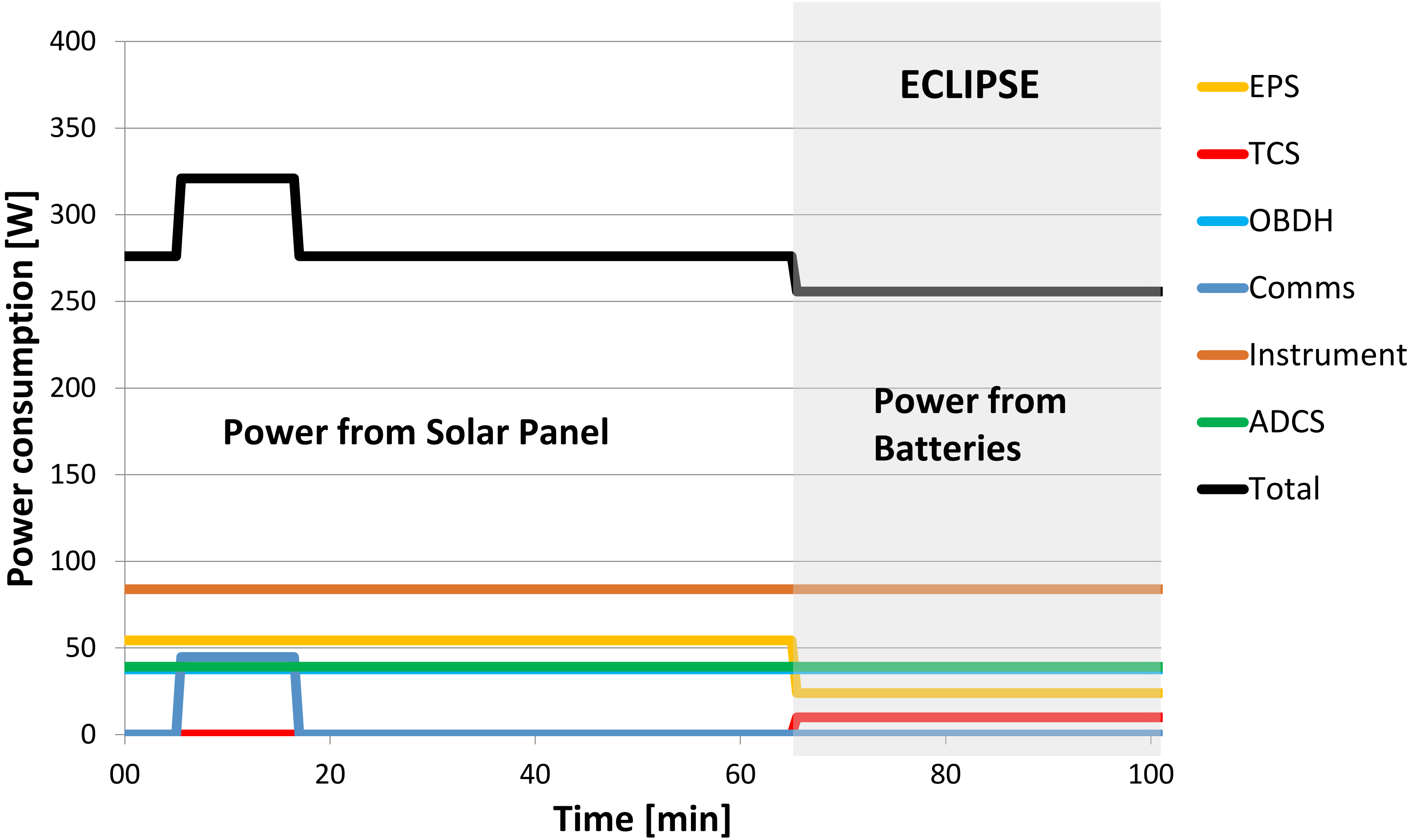


# Power Budget

| | Power [W] | Margin [%] | Power w/ margin [W] |
|---|---|---|---|
| Instrument | 91.8 | 20% | 110.2 |
| Structure | 2.72 | 20% | 3.3 |
| Thermal | 29.35 | 20% | 35.2 |
| EPS | 23.48 | 20% | 28.2 |
| Comms | 31.3 | 20% | 37.6 |
| OBDH | 26 | 20% | 31.2 |
| Attitude control | 26.09 | 20% | 31.3 |
| Propulsion | 10 | 20% | 12.0 |

| | |
|---|---|
| Sum | 289.0 |
| System margin | 20% |
| Total Power [W] | 346.7 |

# Power Management



# Electrical power system

**Primary power system - Solar array sizing**

- NeXt Triple Junction Solar Cells (**24%)**
- Full onboard power generation & battery charging

  (**960 W BoL, 650 W EoL**)
- 1200 cells in a **3.2 $m^2$** solar array

**Secondary power system - Battery dimensioning**

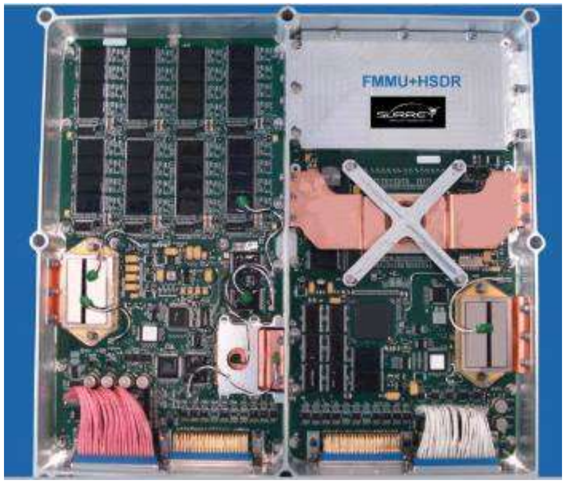
- 2 Li-Ion batteries (1568 Whr), 35% DOD

# Thermal Control

| | Mass [kg] | Power [W] |
|---|---|---|
| MLI | 2.4 | - |
| Black paint | 0.5 | - |
| Heat pipes, base plates | 1 | - |
| Heaters | 2 | 30 |
| Passive Radiator | 1.5 | - |
| Total | **6.9** | **2** |

# OBDH

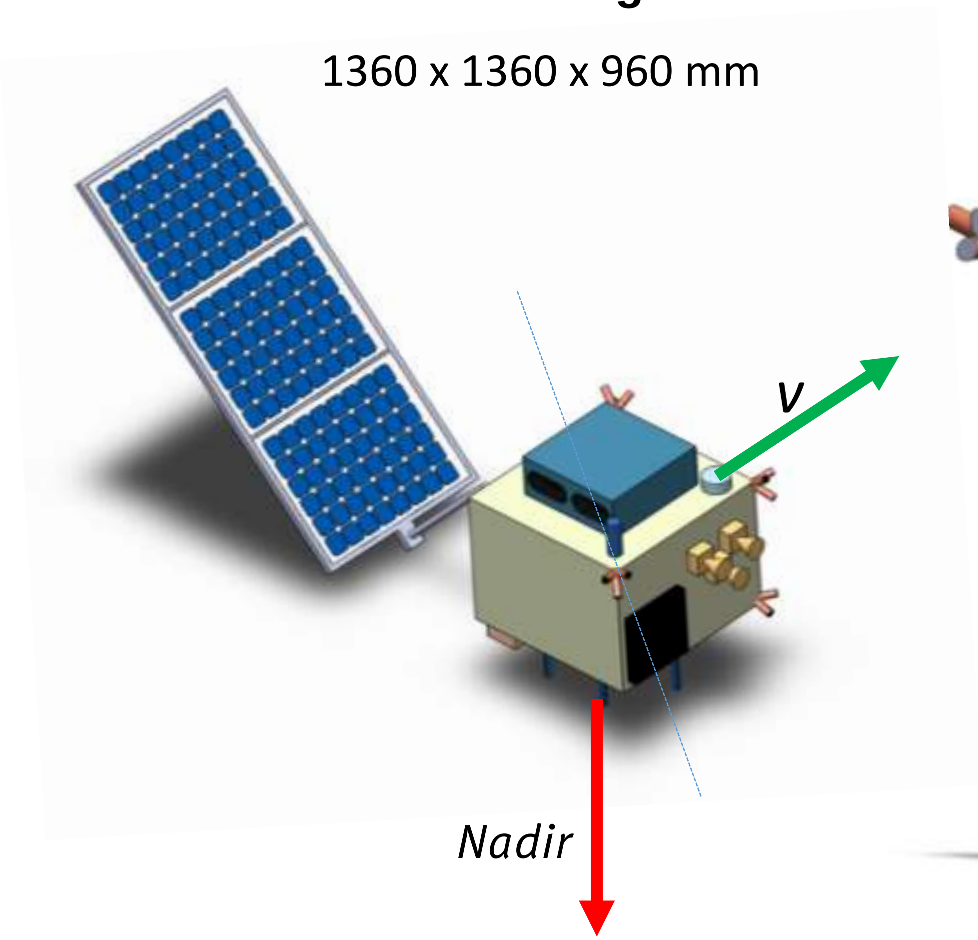
| | Amount | Mass [kg/unit] | Power [W/unit] |
|---|---|---|---|
| Mass Memory Unit (256Gb) | 2 | 2.5 | 3 standby, 20 active |
| Panther processor Board | 2 | 1.3 | 6 |
| SpaceWire cable | 15 m | 1.5 | 0 |
| System Total | - | **30** | **26** |



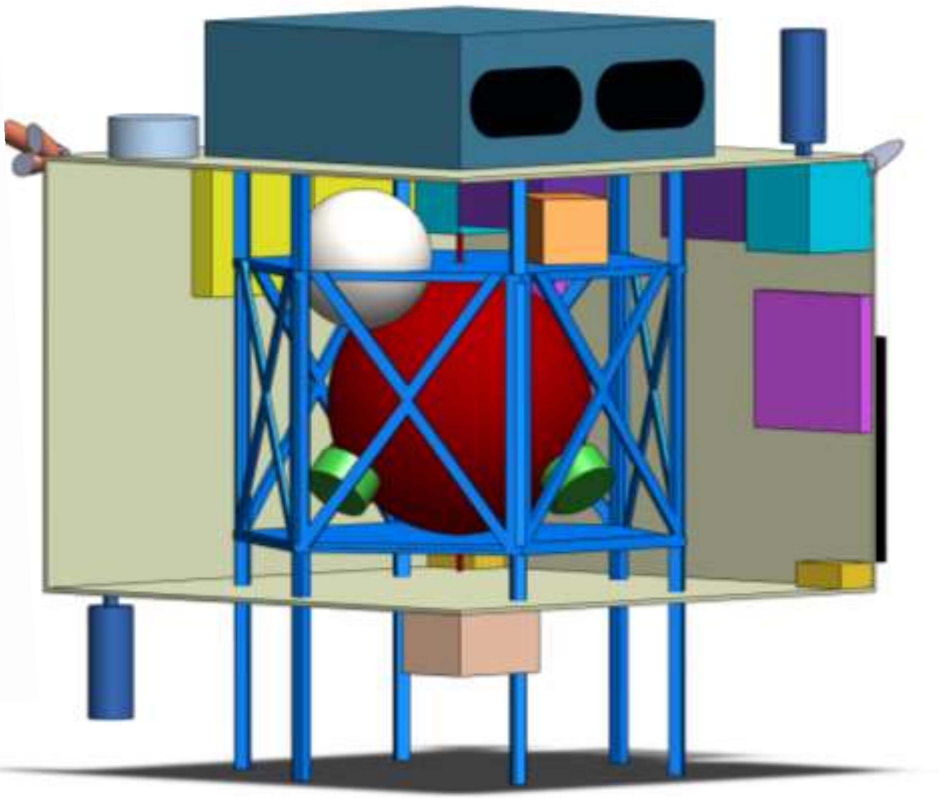
# Conceptual Configuration

**External Configuration**

1360 x 1360 x 960 mm



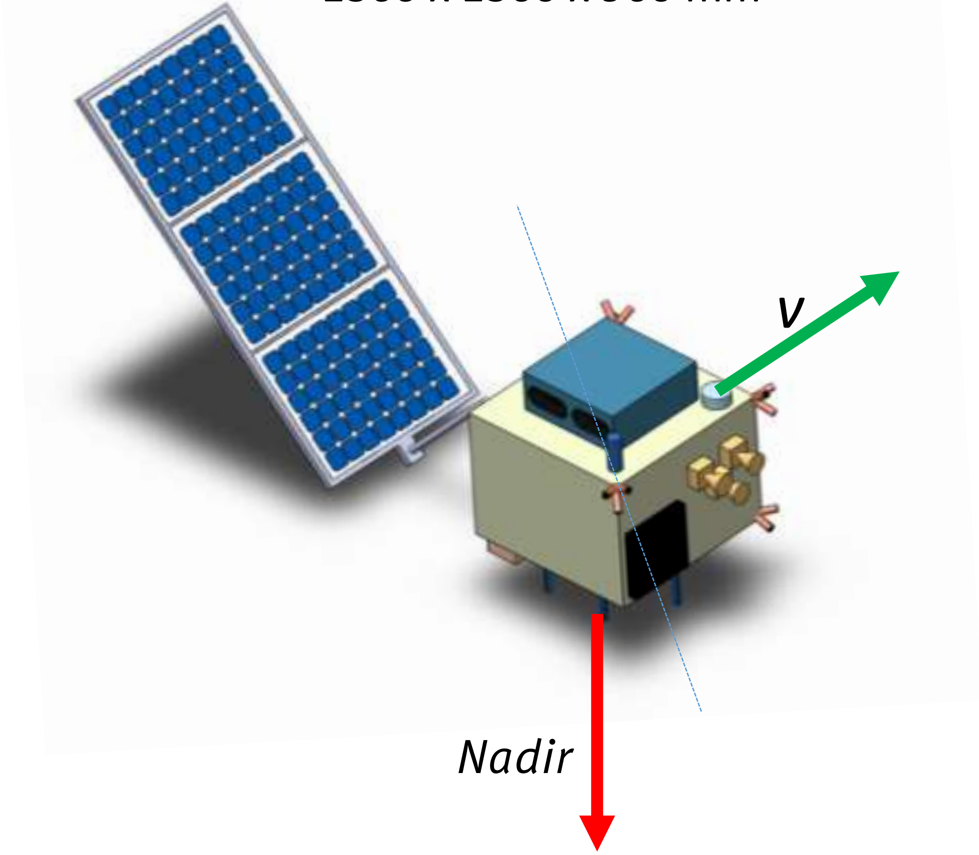

**Internal Configuration**



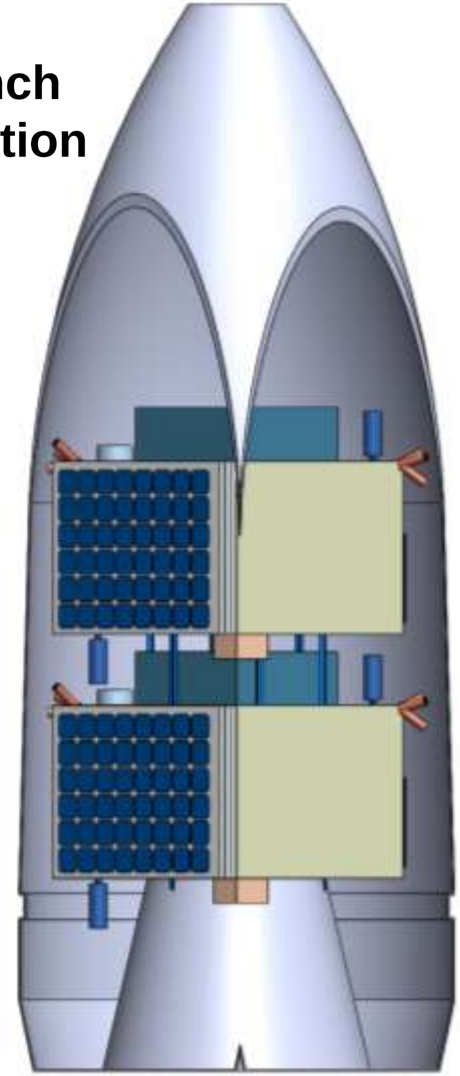
# Conceptual Configuration

**External Configuration**

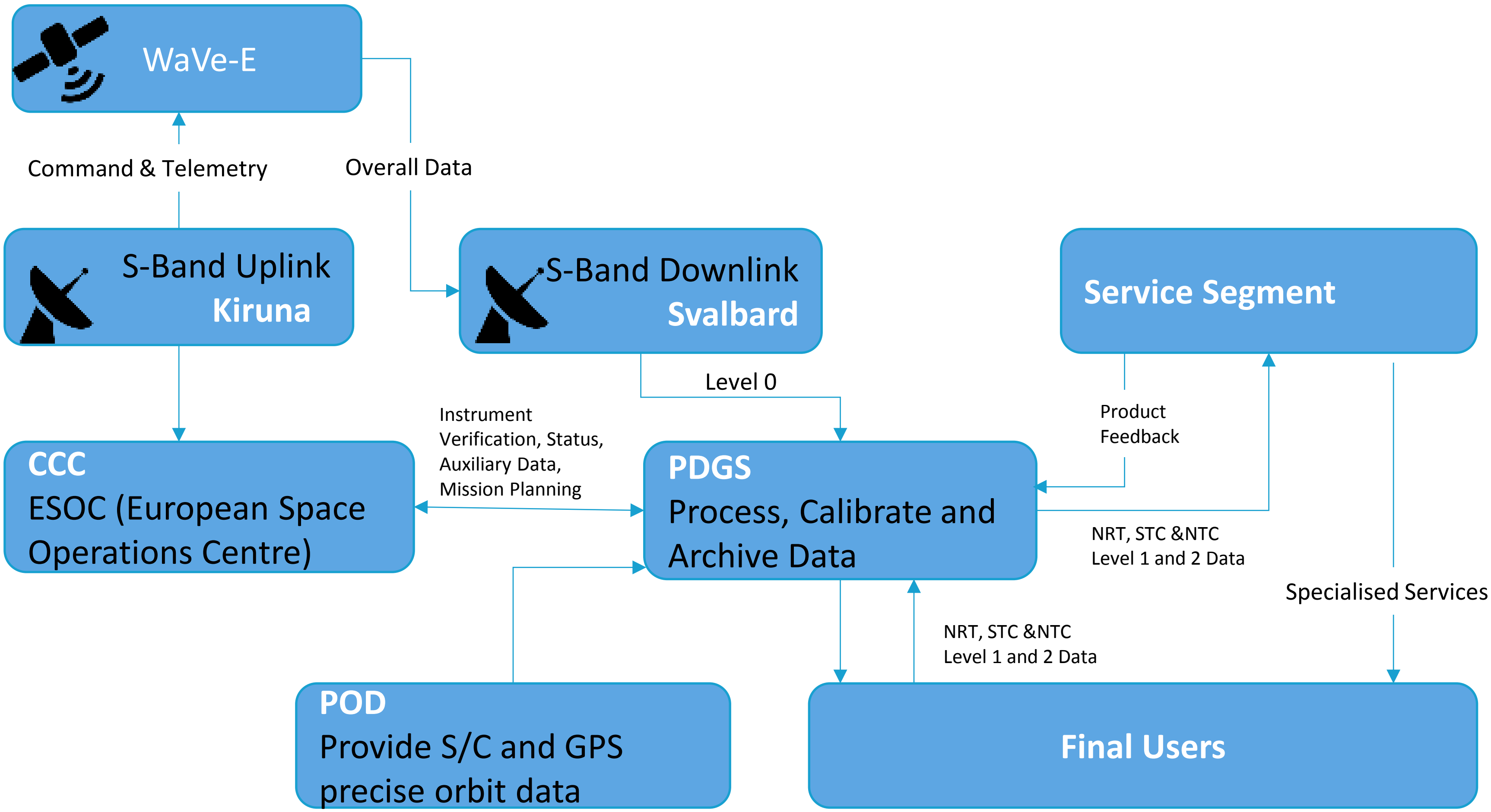
1360 x 1360 x 960 mm




**Dual Launch Configuration**



# Ground Segment



# Ground Segment

| | Description | Units | Res. Vert. | Res. Horz. |
|---|---|---|---|---|
| L0 | Raw data | 16bit voltages | - | -- |
| L1C | Radiances with associated accuracies | W/cm² str $cm^{-1}$ | 1 km | 25 km |
| L2 | UTLS Water vapour profiles | ppm | 1 km | 25 km |
| L3 | UTLS Monthly water vapour profiles | ppm | 1 km | 25 km |
| L4 | Water vapor profile from 0-25 km | ppm | 0.5 km | 25 km |

METOP DATA

Service Segment

**CCC**
ESOC (European Space Operations Centre)

**PDGS**
Process, Calibrate and Archive Data

Specialised Services

**POD**
Provide S/C and GPS precise orbit data

**Final Users**

# Risk assessment

| Event | Risk | Impact | Mitigation |
|---|---|---|---|
| Orbital injection failure | 1 | 4 | extra fuel |
| ADCS failure | 2 | 5 | redundancy |
| Thruster malfunction | 3 | 5 | redundancy |
| Computer processor failure | 2 | 5 | redundancy |
| Structure failure | 1 | 5 | pre-flight testing |
| Star trackers failure | 2 | 4 | redundancy |
| Software failure | 3 | 4 | pre-flight testing redundancy |
| Solar flare damages critical component | 2 | 5 | redundancy |

# Technology readiness level

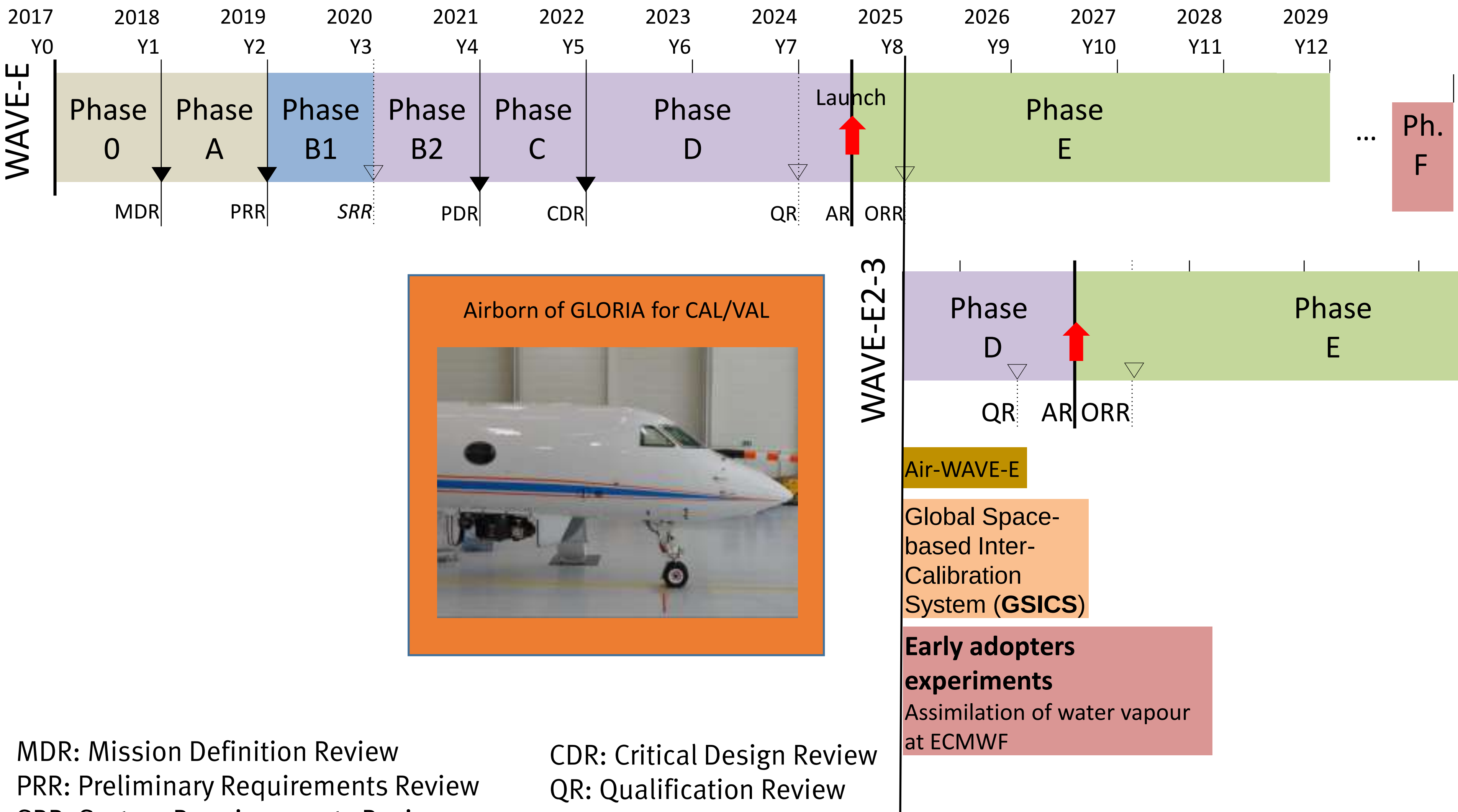
| Subsystem | Component | Component TRL | Subsystem TRL | TRL Comments |
|---|---|---|---|---|
| Payload | SHS | 3 | 3 | Components have not been tested in this configuration |
| | Telescope | 4 | | |
| | Blackbody | 4 | | |
| | Mirror | 4 | | |
| | Detector | 4 | | |
| EPS | Solar cells | 7 | 7 | Flight-proven but unconventional design required |
| | Li-Ion batteries | 8 | | |
| C&DH | Panther | 6 | 6 | Flight-proven, but changes necessary |
| | Mass memory | 6 | | |
| ADCS | ASTRIX 120 IMU | 7 | 6 | Flight-proven |
| | RUAG GPSR | 7 | | |
| | Star tracker | 7 | | |
| | M/W | 6 | | |
| Propulsion | Propellant tank | 8 | 8 | Flight-proven |
| | Engines | 8 | | |
| | Propellant | 9 | | |

# ROM – Initial Costing

| Item | Approximation | Cost [€] |
|---|---|---|
| Project Team | ~10% of 2, 3, 4 | 50.000.000 |
| Industrial Cost with Instrument | ~60% Total | 300,000,000 (x 3 S/C) |
| Mission Operations | ~15% Total | 75.000.000 |
| Science Operations | | |
| Contingency | ~15% | 75,000,000 |
| | **Total ROM [€]** | ~ 500.000.000 |
| Launcher (2 Vega) | - | 80,000,000 |
| | **Total ROM [€]** | ~ 580.000.000 |

*Note: Payload cost is approximated using €1M per kg payload (each payload is approx. 80kg from Mass Budget)*

# Programmatics




MDR: Mission Definition Review
PRR: Preliminary Requirements Review
SRR: System Requierements Review
PDR: Preliminary Design Review

CDR: Critical Design Review
QR: Qualification Review
AR: Acceptence Review
ORR: Operational Readiness Review


# WAVE-E

# WAVE-E

## Additional Slides

# Science References

[ Kidston, et al., Nature Geoscience, 2015 ]
[ Thompson et al., J Climate 2002 ]
[ Muller et al., 2016 ]

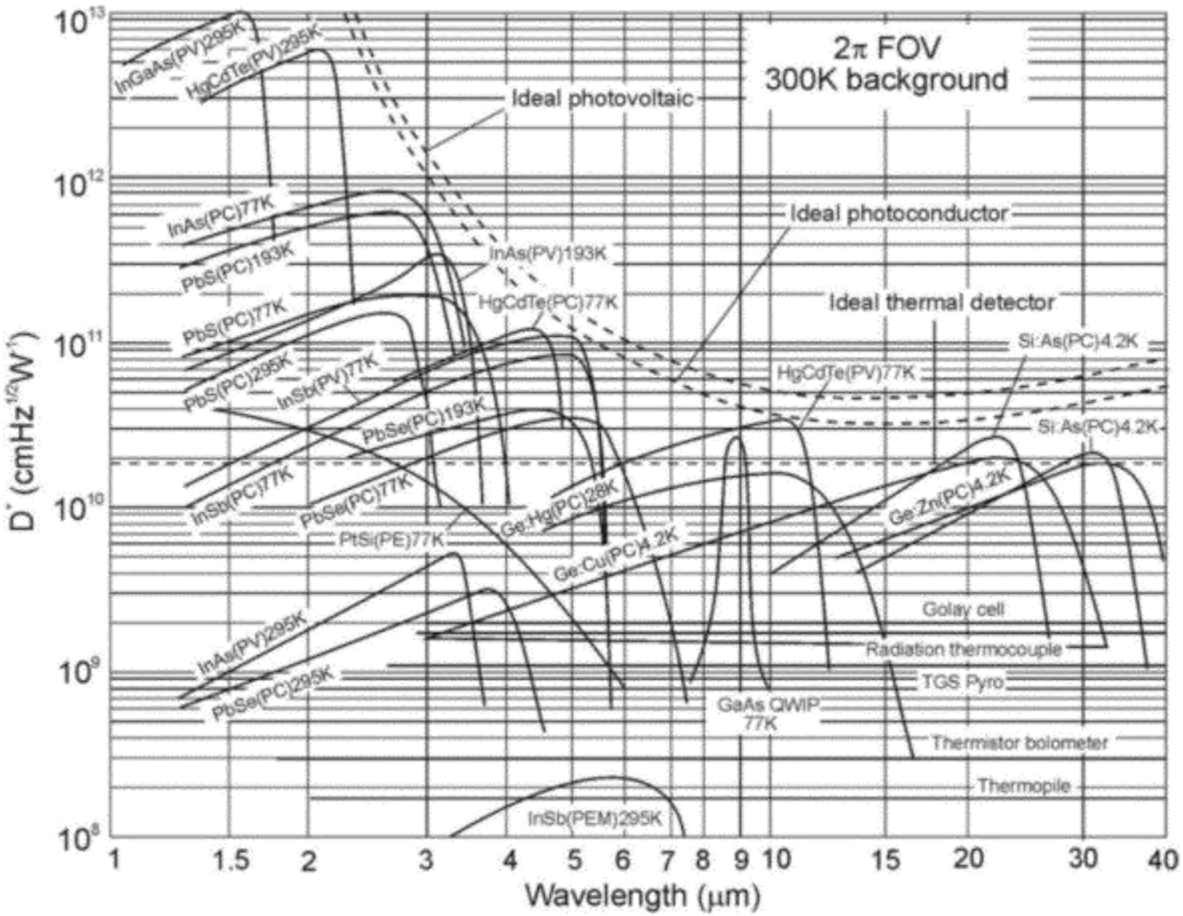
**CONCLUSION**

We propose an Earth explorer mission for water vapour in the UTLS region which may lay the path for a future monitoring mission.

# UTLS Water Vapour Observations?

| Platform/ Mission | Instrume nt | Technique | Temporal Constraints | Vertical constraints | Spatial coverage |
|---|---|---|---|---|---|
| **Aura, 2004-2016 (ongoing)** | TES Nadir | **Cross-nadir** scanning infrared sounder | **Clouds** | **Troposphere only** | **Global coverage in 16 days** |
| **Metop SG 2021 (planned)** | IASI - NG | **Cross-nadir** scanning infrared sounder | **Clouds** | **Troposphere only** & Coarse vertical resolution above | Near-global coverage twice/day |
| **Sentinel 5-P 2016 (planned)** | TROPOMI | **Cross-nadir** scanning **short-wave** sounder | **Daylight Measurements only** | **Troposphere only** | Global coverage in 1 day |
| **ISS, 2016 (planned)** | SAGE-III | Limb-scanning sounder | | **Stratosphere only** | **Limited to latitudes above approx. 50 degrees** |
| **PREMIER 2004 (proposed & rejected)** | IRLS | Infrared Limb-scanning sounder | | UTLS region | **Global coverage in 4 days** |

# Detector Selection

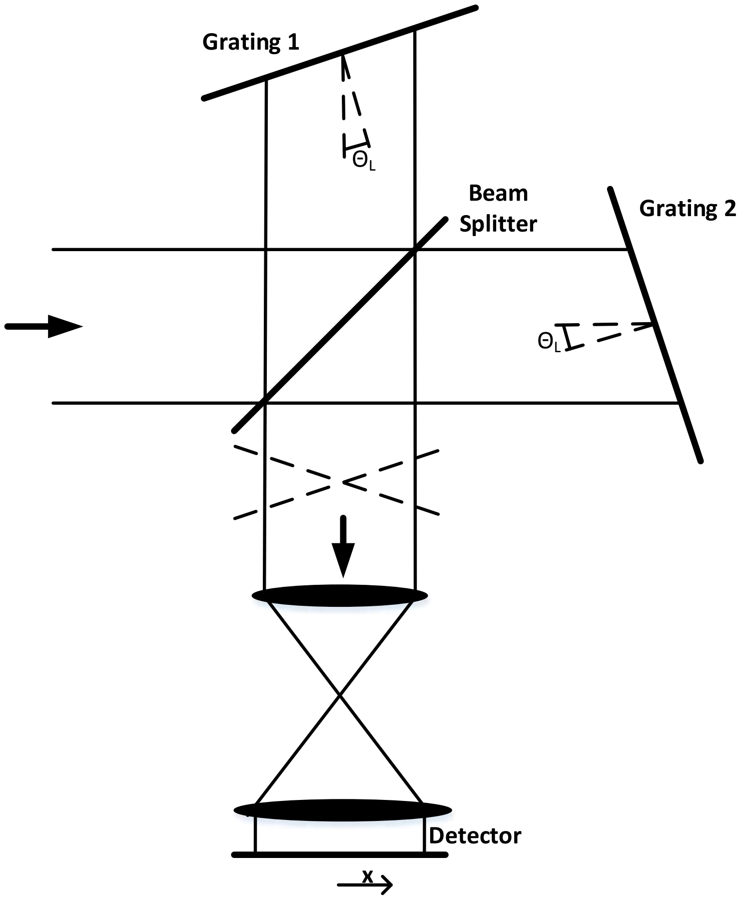


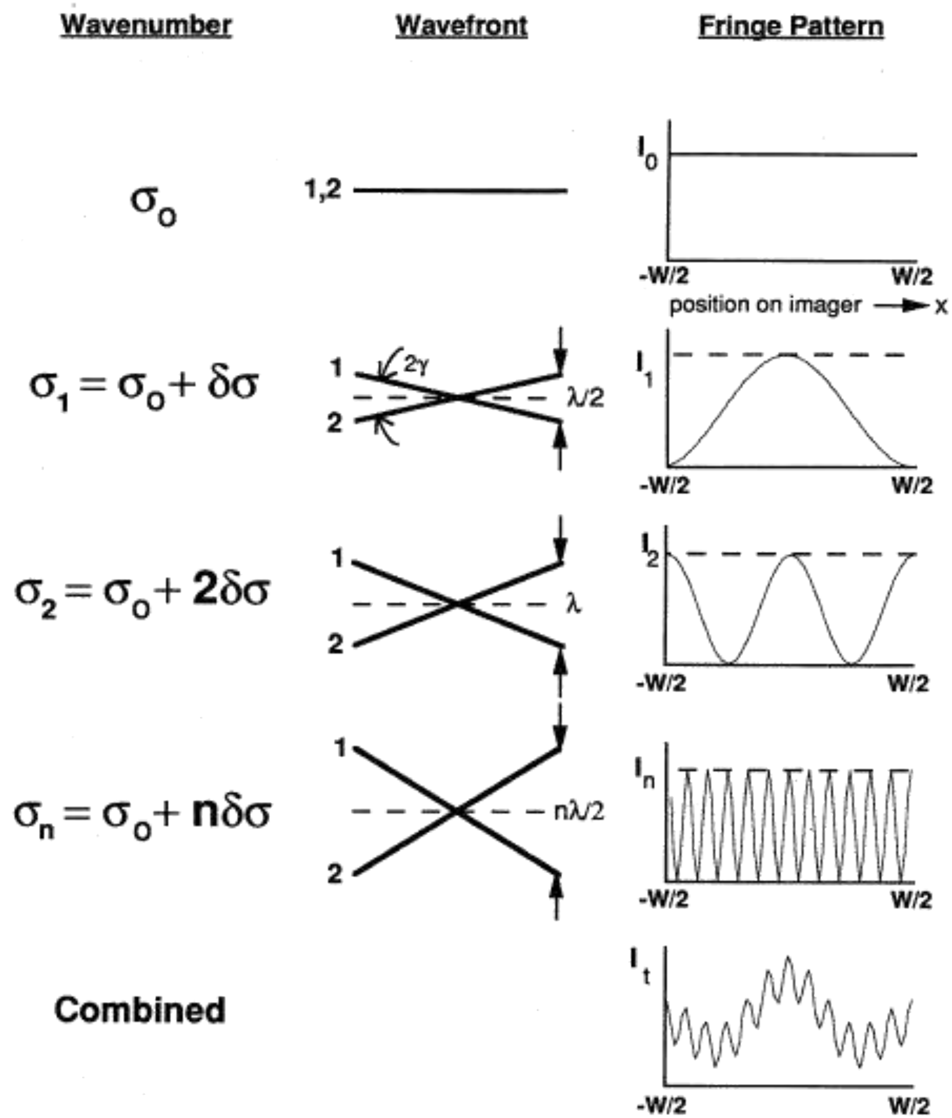

[Rogalski, 2005]

# Observation Geometry

| | | |
|---|---|---|
| Orbit Altitude | 817 | km |
| Earth Radius | 6371 | km |
| Earth Gravity Constant | 3,99E+14 | m^3/s^2 |
| Orbit Velocity | 7,45 | km/s |
| Observation Altitude | 10 | km |
| Footprint Limb Vertical | 25 | km |
| Footprint Limb Horizontal | 25 | km |
| Spatial Resolution Limb Vertical | 1 | km |
| Field of View Spectrometer | 0,1691 | str |
| Etendue Vertical Bin | 0,00121 | cm^2str |
| Etendue Safety Factor | 1,35 | - |
| Effective Etendue Vertical Pixel Row | 0,00163 | cm^2str |
| Slant Range | 3309 | km |
| Limb Angle Field of View Horizontal | 0,433 | ° |
| Limb Angle Field of View Vertical TOTAL | 0,433 | ° |
| Limb Angle Field of View Vertical Bin | 0,017 | ° |
| Field of View TOTAL | 2,28E-04 | str |
| Field of View Vertical Bin | 9,13E-06 | str |
| Aperture Area Limb | 1,79E+02 | cm^2 |
| Entrance Pupil Aperture Diameter | 15 | cm |

# SHS Principle




(Harlander,1992)

# Mass Budget

| | Mass Budget | | | | |
|---|---|---|---|---|---|
| | Mass w/o Margin [kg] | Margin [%] | Margin [kg] | Total [kg] | Check [%] |
| Instrument | 79 | 30% | 24 | 103 | 33% |
| Structure | 40 | 25% | 10 | 50 | 16% |
| Harnessing | 14 | 25% | 4 | 18 | 6% |
| Thermal | 13 | 25% | 3 | 16 | 5% |
| EPS | 35 | 10% | 4 | 39 | 12% |
| Comms | 5 | 10% | 1 | 6 | 2% |
| OBDH | 30 | 10% | 3 | 33 | 11% |
| ADCS | 17 | 10% | 2 | 19 | 6% |
| Propulsion | 26 | 10% | 3 | 29 | 9% |
| Total | 260 | | | 312 | 100% |
| System margin | | 20% | 62 | | |
| **Dry Mass** | | | | **375** | |

| S/C 1 | |
|---|---|
| Propellant [kg] | 79 |
| **Total Launch Mass [kg]** | **454** |

| S/C 2, 3 | |
|---|---|
| Propellant [kg] | 115 |
| **Total Launch Mass [kg]** | **490** |

# Power Modi

| | | Instrument | Thermal | AOCS | Comms | Propulsion | OBDH | EPS | Mech. | Harness excl. PSS | SUM | Margin [%] | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Launch Mode | Max | 0.0 | 0.0 | 6.0 | 1.0 | 0.0 | 26.0 | 24.0 | 0.0 | 1.0 | 58.0 | 20% | 69.6 |
| | Nom | 0.0 | 0.0 | 4.0 | 1.0 | 0.0 | 26.0 | 24.0 | 0.0 | 1.0 | 56.0 | 20% | 67.2 |
| | Min | 0.0 | 0.0 | 3.0 | 1.0 | 0.0 | 26.0 | 24.0 | 0.0 | 1.0 | 55.0 | 20% | 66.0 |
| Initialization Mode | Max | 0.0 | 0.0 | 27.0 | 9.6 | 9.6 | 26.0 | 24.0 | 3.0 | 2.3 | 101.5 | 30% | 132.0 |
| | Nom | 0.0 | 0.0 | 25.9 | 8.6 | 8.0 | 26.0 | 24.0 | 2.0 | 1.9 | 96.4 | 30% | 125.4 |
| | Min | 0.0 | 0.0 | 13.5 | 7.7 | 6.4 | 26.0 | 24.0 | 0.5 | 1.6 | 79.7 | 30% | 103.6 |
| Operational Mode | Max | 91.8 | 0.0 | 27.0 | 32.0 | 0.0 | 26.0 | 24.0 | 3.0 | 2.3 | 206.1 | 40% | **288.6** |
| | Nom | 57.9 | 0.0 | 23.3 | 17.6 | 0.0 | 26.0 | 24.0 | 2.0 | 1.9 | 152.6 | 40% | 213.7 |
| | Min | 46.3 | 0.0 | 13.5 | 4.8 | 0.0 | 26.0 | 24.0 | 0.5 | 1.6 | 116.7 | 40% | 163.4 |
| Eclipse Mode | Max | 91.8 | 10.0 | 27.0 | 32.0 | 0.0 | 26.0 | 24.0 | 3.0 | 4.7 | 218.5 | 50% | **327.7** |
| | Nom | 57.9 | 9.0 | 23.3 | 17.6 | 0.0 | 26.0 | 24.0 | 2.0 | 2.3 | 162.1 | 50% | 243.2 |
| | Min | 46.3 | 8.1 | 13.5 | 4.8 | 0.0 | 26.0 | 24.0 | 0.5 | 2.1 | 125.3 | 50% | 187.9 |
| Safe Mode | Max | 0.0 | 0.0 | 6.0 | 9.6 | 0.0 | 26.0 | 24.0 | 3.0 | 2.3 | 70.9 | 30% | 92.2 |
| | Nom | 0.0 | 0.0 | 4.0 | 8.6 | 0.0 | 26.0 | 24.0 | 2.0 | 1.9 | 66.5 | 30% | 86.5 |
| | Min | 0.0 | 0.0 | 3.0 | 7.7 | 0.0 | 26.0 | 24.0 | 0.5 | 1.6 | 62.8 | 30% | 81.7 |
| Orbit Maintenance Mode | Max | 91.8 | 0.0 | 27.0 | 32.0 | 9.6 | 26.0 | 24.0 | 3.0 | 2.3 | 215.7 | 30% | **280.5** |
| | Nom | 57.9 | 0.0 | 23.3 | 17.6 | 8.0 | 26.0 | 24.0 | 2.0 | 1.9 | 160.6 | 30% | 208.8 |
| | Min | 46.3 | 0.0 | 13.5 | 4.8 | 6.4 | 26.0 | 24.0 | 0.5 | 1.6 | 123.1 | 30% | 160.0 |
| De-orbiting Mode | Max | 0.0 | 0.0 | 27.0 | 9.6 | 9.6 | 26.0 | 24.0 | 3.0 | 2.3 | 101.5 | 20% | 121.8 |
| | Nom | 0.0 | 0.0 | 23.3 | 8.6 | 8.0 | 26.0 | 24.0 | 2.0 | 1.9 | 93.8 | 20% | 112.6 |
| | Min | 0.0 | 0.0 | 13.5 | 7.7 | 6.4 | 26.0 | 24.0 | 0.5 | 1.6 | 79.7 | 20% | 95.7 |

# Alternative design options


| Mission Compatibility | |
|---|---|
| Orbit Average Payload Power | 140W (180W peak) EOL |
| Maximum Payload Mass | 150kg |
| Bus Dry Mass | 218 kg without payload |
| Science Data Downlink | 105 Mbps, X-Band |
| Science Data Storage | 16 Gbytes capacity, dual-redundant mass memory |
| Pointing Knowledge | 72 arcsec (1 sigma) all 3 axes |
| Pointing Control | 360 arcsec (1 sigma) all 3 axes |
| Pointing Stability (Jitter) | 2 arcsec/sec |
| Slewrate | 0.75 deg/sec |
| Position Knowledge | 10m |
| Mission Design Life | 7 years, Ps= 92% |
| Compatible Launch Vehicles | Falcon 1e, Atlas, Delta, Athena and other launchers |
| Types of Orbits Available | LEO 400km to 2000km, any inclination |
| External Payload Volume | 730mm x 455mm x 1000mm |
| Internal Payload Volume | 279.5mm x 231.5mm x 252.5mm |
| **Bus Description** | |
| Attitude Control System | 3-axis control with reaction wheels and magnetorquers |
| Batteries | Li-ion cells providing 15 Ah capacity |
| Solar Arrays | Triple-junction GaAs cells, total area 2.44m$^2$ |
| Main Bus Voltage Range | 28V-33V range |
| C&DH Bus Architecture | Dual-redundant Controller Area Network (CAN) bus |
| Communication Up\Downlink Band | S-Band uplink/S-Band downlink |
| Structure | Aluminum and aluminum-skinned honeycomb panels |
| Propulsion | Hot gas Xenon resistojet |
| Delta V | 15m/s |
| Thermal Control | Primarily passive, plus limited use of heaters |