NanoFF Mission Operations

2023 Virtual International Laser Ranging Workshop, 19.10.23

Authors: Debdeep Roychowdhury, Sascha Kapitola, Fynn Boyer & The NanoFF Team

Mission

Formation Flight Mission of two 2U-CubeSats

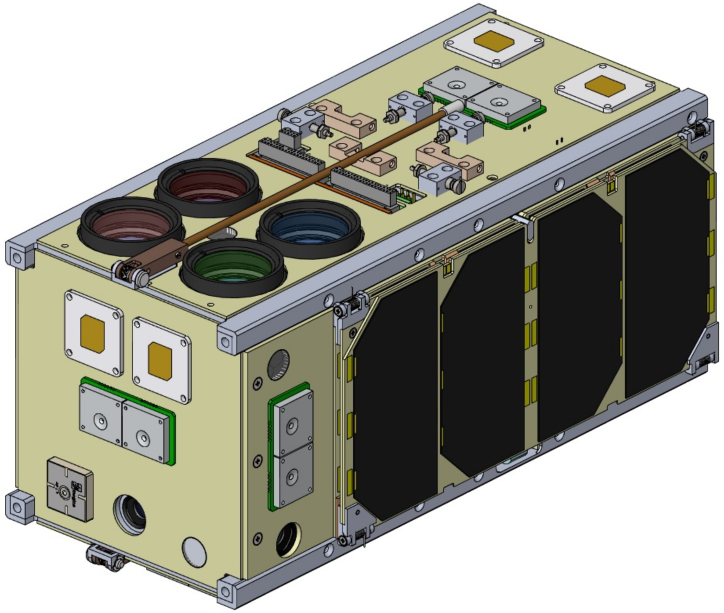
- Ground controlled Helix formation
- Autonomously controlled Helix, In-Track, Along-Track and PCO
- 300 m closest approach

Technology Demonstration

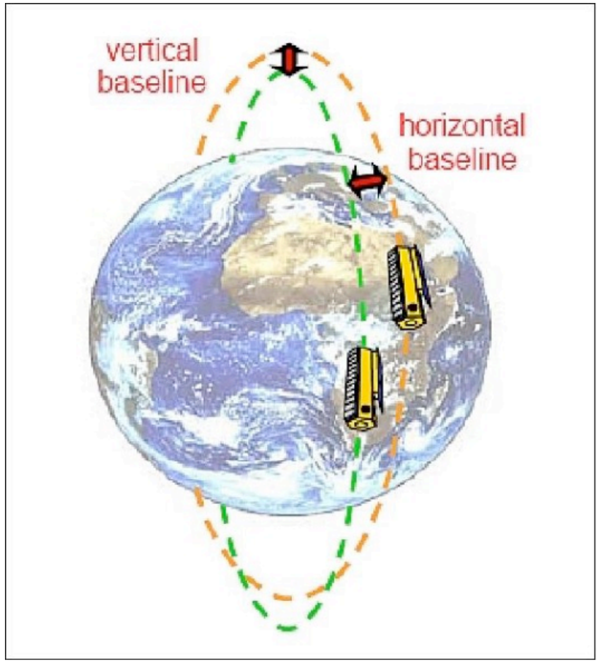
- Deployable solar panels
- Star Tracker
- S-Band Downlink

Payload

- Camera system with four spectral channels



NanoFF CAD model

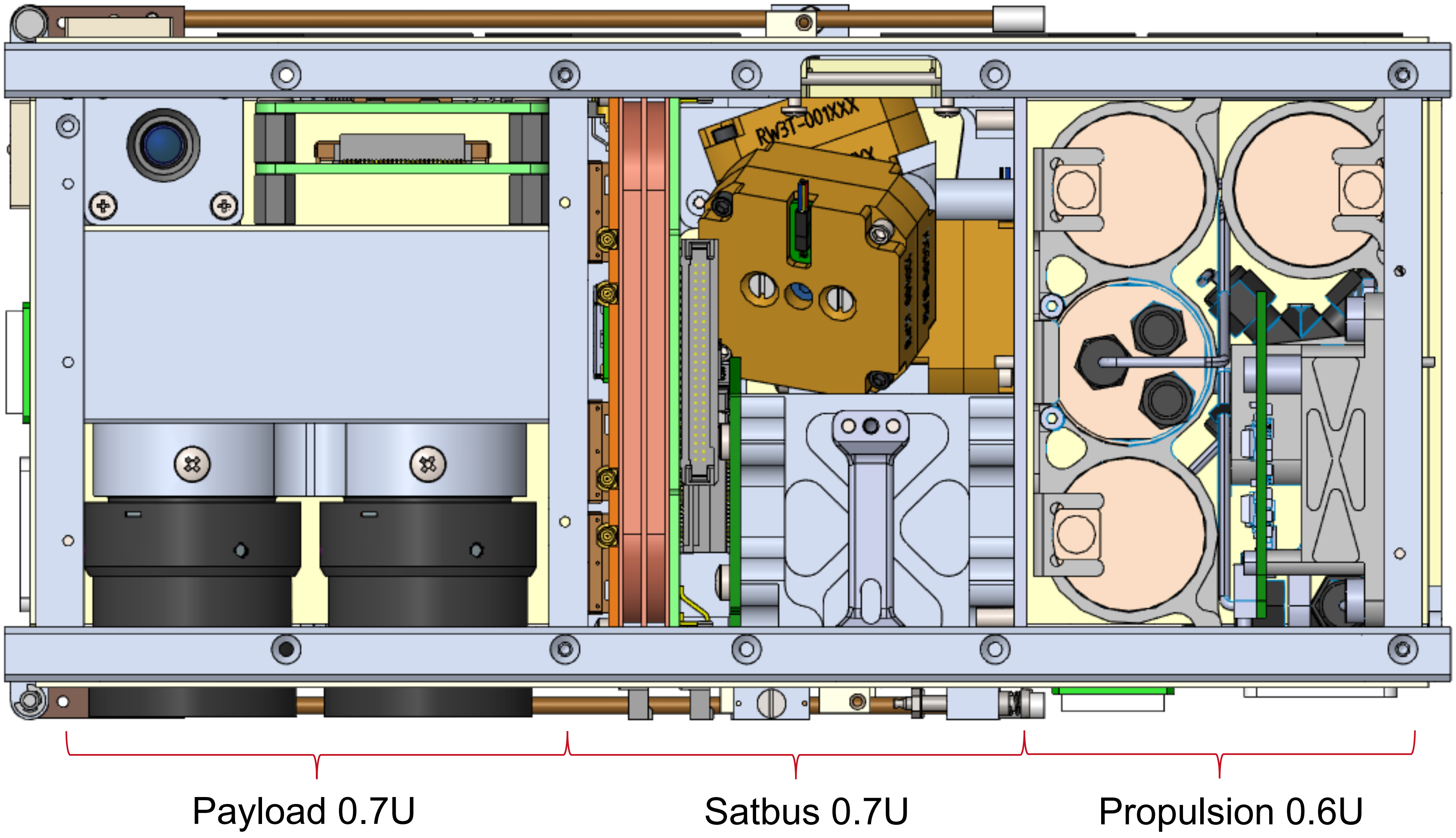


Helix Orbit [DLR]

The NanoFF Team (as of 19.10.2023)

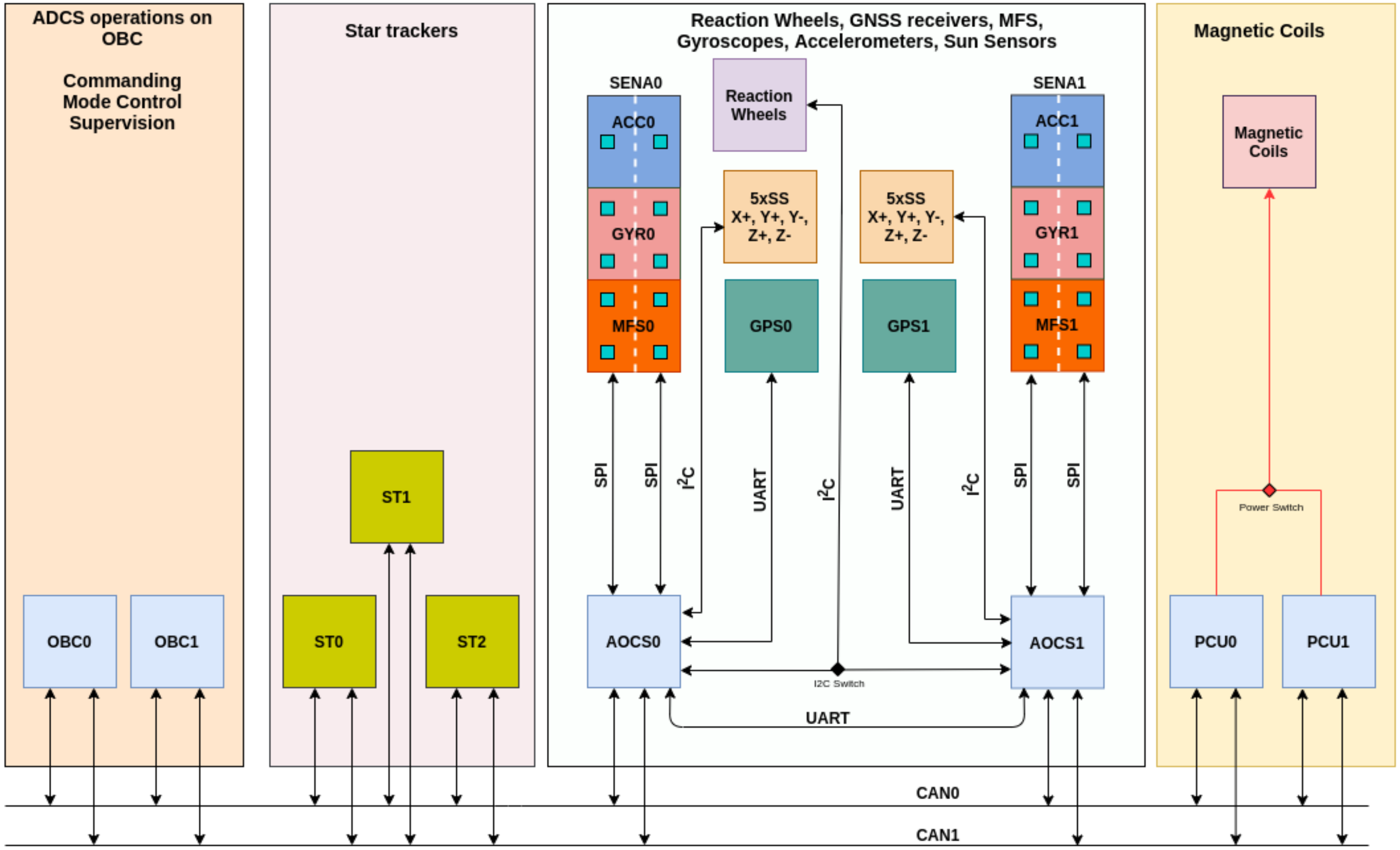
Team Member	Responsibilities
M.Sc. Jens Freymuth	Project Manager
M.Sc. Sascha Kapitola	Software, Mission Operations, Camera System
Dipl. -Ing. Frank Baumann	Hardware, Electronics, Communication System
Dipl. -Ing. Hu Quan Vu	Structure, Systems Engineering
M.Sc Felix Kübler	Software, Communication System
M.Sc Jose Diez	Software, Hardware, Electronics
M.Sc Fynn Boyer	Software, AOCS, Mission Operations
PhD Ben Palmer	Software, AOCS, Start Tracker System
B.Sc Alan Legenza	Software
M.Sc Debdeep Roychowdhury	Separation Strategy, Formation Flying, AOCS

Component Segmentation



Attitude and Orbit Control System Overview

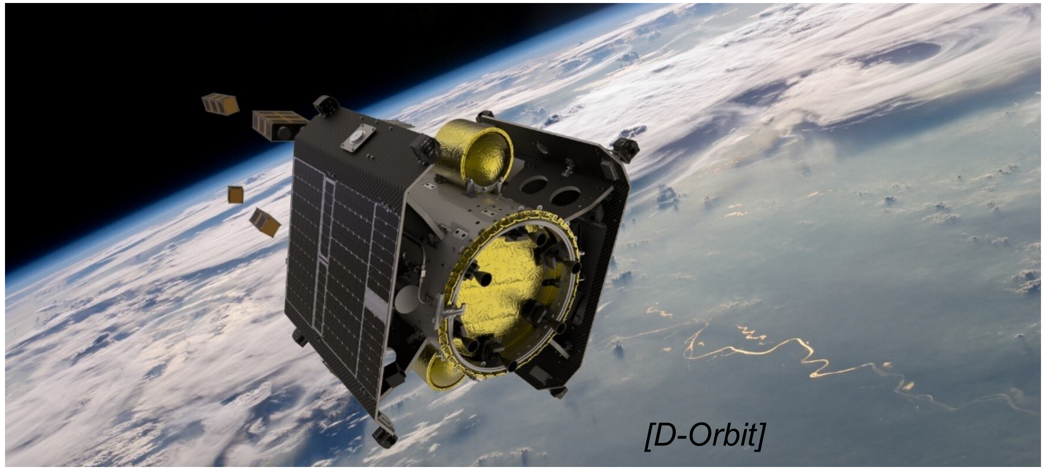
- 2 x 4 Gyroscopes
- 2 x 4 Magnetometers
- 2 x 2 Accelerometers
- 2 x 5 Sun Sensors (Side Panels)
- 4 Reaction wheels
- 3 Star Trackers

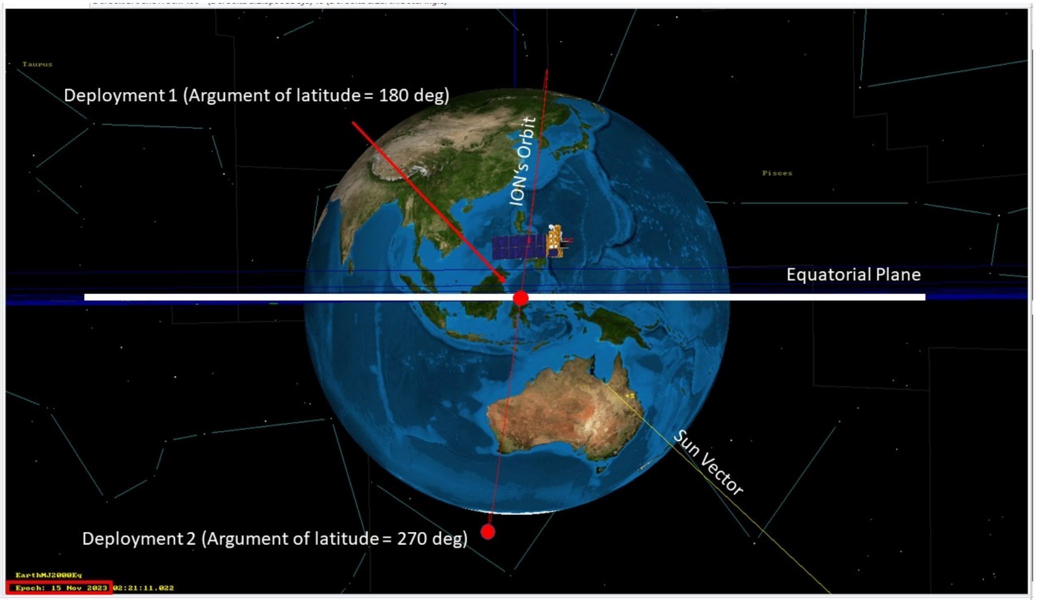


Estimated Timeline

Milestone	Approximate Timeline
Shipping of satellites and equipment	13.10.2023
On-site software updates, tests near Vandenberg SFB	26.10.2023 – 02.11.2023
Launch from Vandenberg SFB	29.11.2023
Deployment from D-Orbit ION	Launch + 2 weeks
First contact / B-Dot activation	Launch + 2 weeks
AOCS Tests (GNSS, sensors, actuators, pointing modes)	Launch + 3 weeks
Initial orbit determination	Launch + 3 weeks
Solar panel deployment	Launch + 4 weeks
AOCS + Propulsion system tests	Launch + 5 weeks
Completetion of Recovery operations (relative distance < 1 km)	Launch + 9 weeks
Preparations for close proximity operations	Launch + 10 weeks
Initiate close proximity operations	Launch + 12 weeks

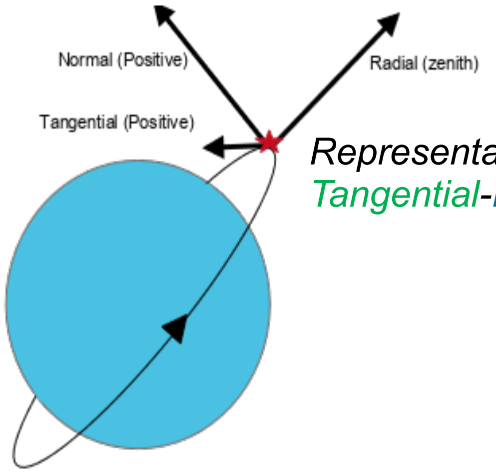
Deployment Strategy





- Using D-Orbit‘s ION satellite carrier
  - precise injection into a partial *Helix* orbit
- Deployment
  - interval 2.25 orbital periods of ION
  - in two specific directions
  - at specific locations of ION‘s orbit
- Outcome
  - minimise collision risk
  - limit along-track separation
  - Prevent formation evaporation
  - Limit delta-v usage

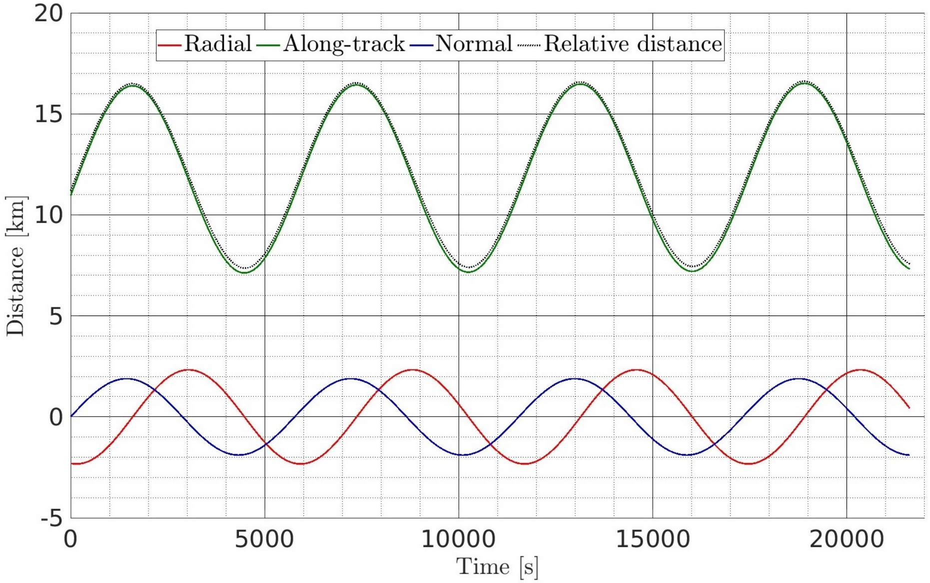
Separation Strategy



Representation of Radial-Tangential-Normal (RTN) frame

Deployment vectors in RTN frame of ION:

1st deployment: [2.0955 0.2000 0.0000] m/s; -> at the equator
2nd deployment: [0.0000 0.2000 2.0573] m/s; -> near the south pole

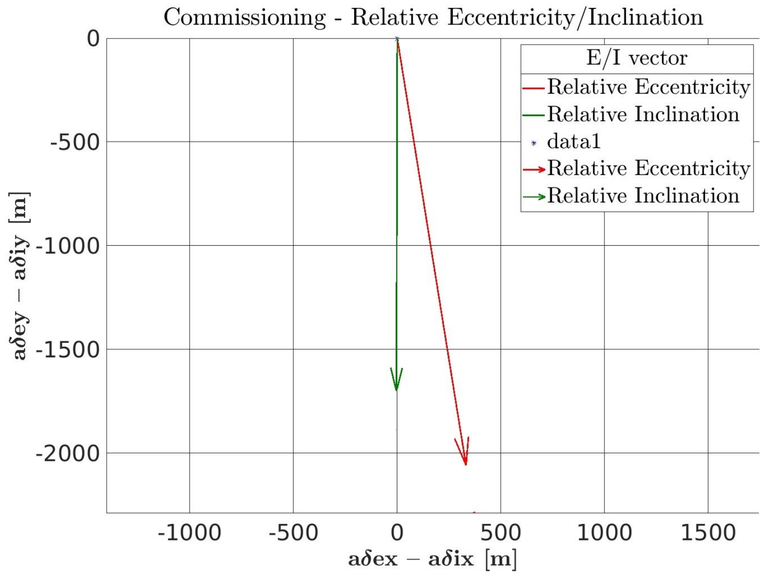


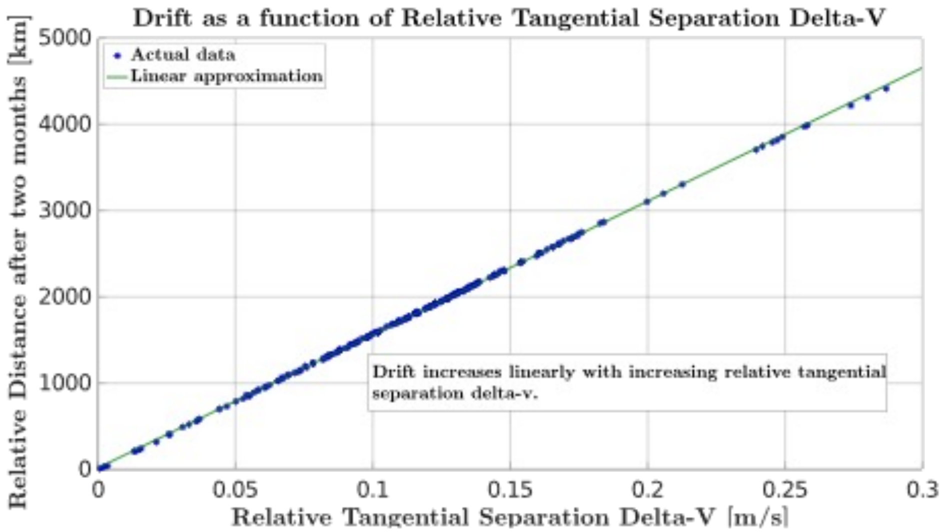
Relative Orbital Elements (ROEs):

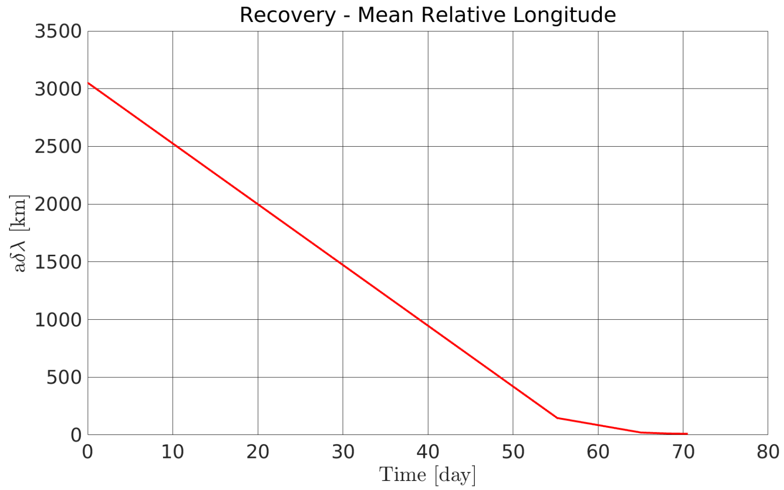
$$\delta\alpha = \begin{bmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{bmatrix} = \begin{bmatrix} (a_2 - a_1)/a_1 \\ u_2 - u_1 + (\Omega_2 - \Omega_1)\cos i_1 \\ e_2 \cos w_2 - e_1 \cos w_1 \\ e_2 \sin w_2 - e_1 \sin w_1 \\ i_2 - i_1 \\ (\Omega_2 - \Omega_1)/\sin i_1 \end{bmatrix}$$

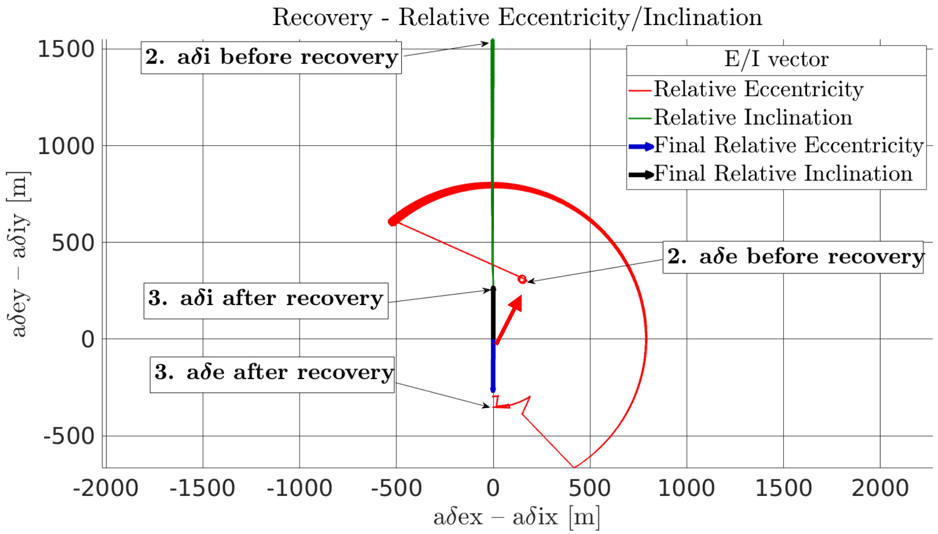
where $u = M + \omega$,
and $a, e, i, \Omega, \omega, M$ ⟶ mean Keplerian elements

Recovery Operations

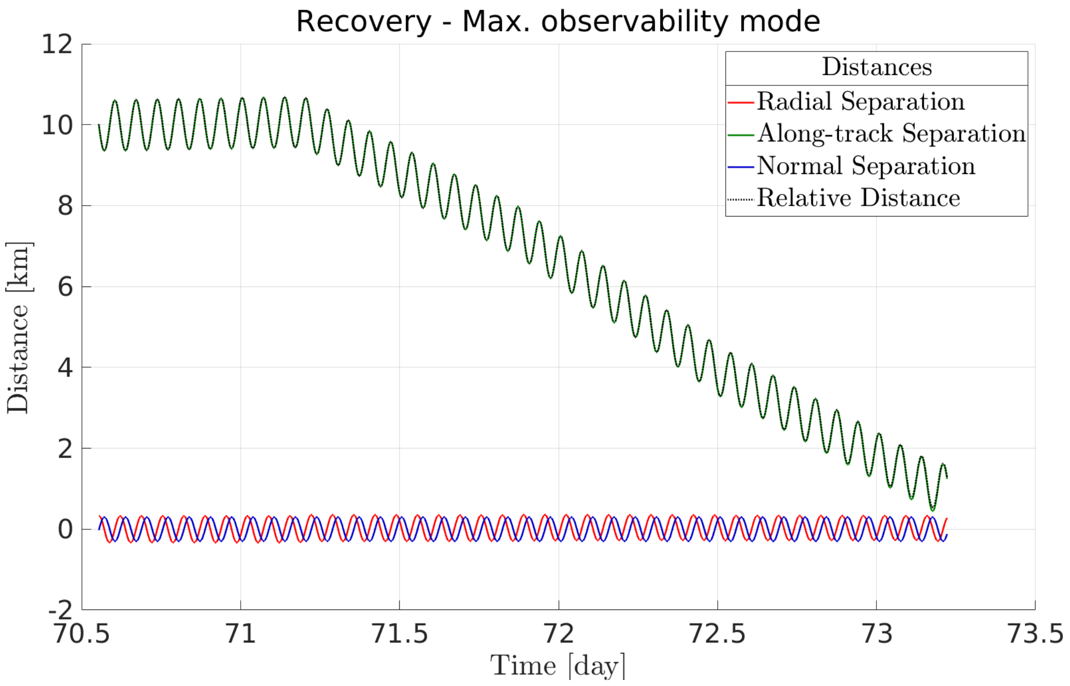


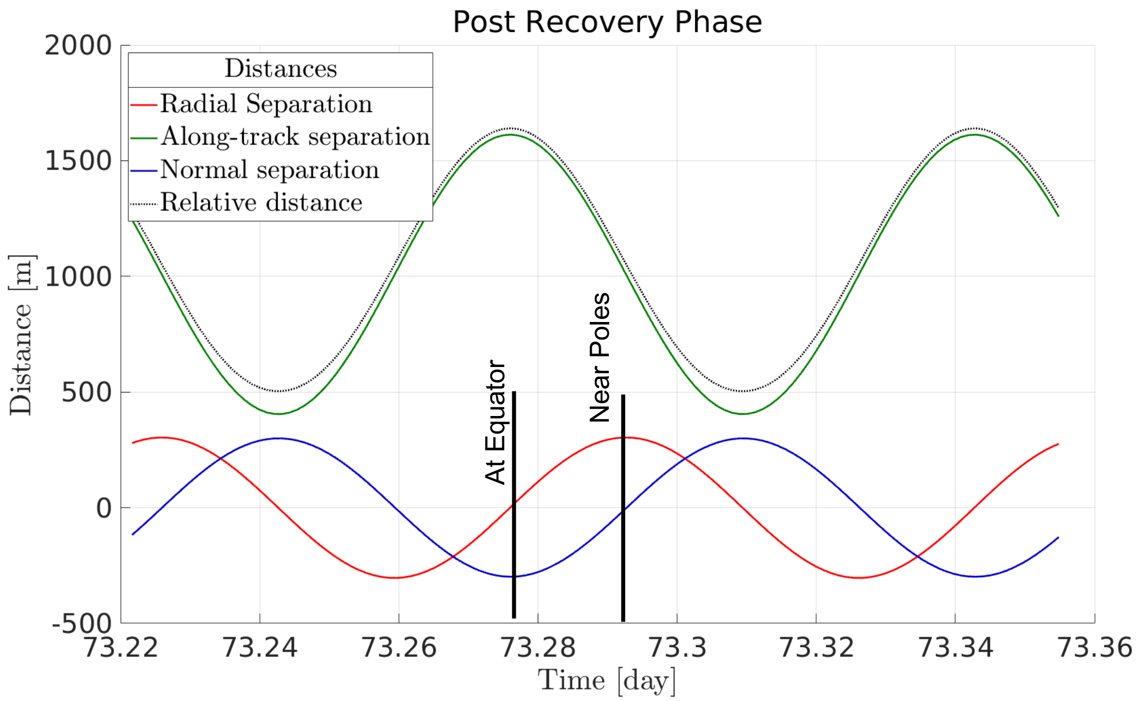






Recovery Operations: Passively Safe Helix Orbit





ROEs	$a_1\delta a$ [m]	$a_1\delta\lambda$ [m]	$a_1\delta e_x$ [m]	$a_1\delta e_y$ [m]	$a_1\delta i_x$ [m]	$a_1\delta i_y$ [m]
ROEs after commissioning	−350.4275	3046157.8753	137.6294	312.6268	−10.3324	1471.1643
Desired ROEs after recovery	0	1000	0	-300	0	300

Δv = 1.03 m/s in 1100 orbits

Technische Universität Berlin

NanoFF

Relative Navigation using GNSS Raw measurements

Objective: On-board relative position accuracy of less than 1 meter**.**

- Currently in on-board software implementation stage for two GNSS receivers: Ublox Neo M8T and SkyTraq Orion B16-C1.
- Estimate the relative position, estimate the relative velocity, propagate them during error scenarios.
- Planned order of experiments: GPS only, GPS + Galileo, GPS + Beidou, etc.

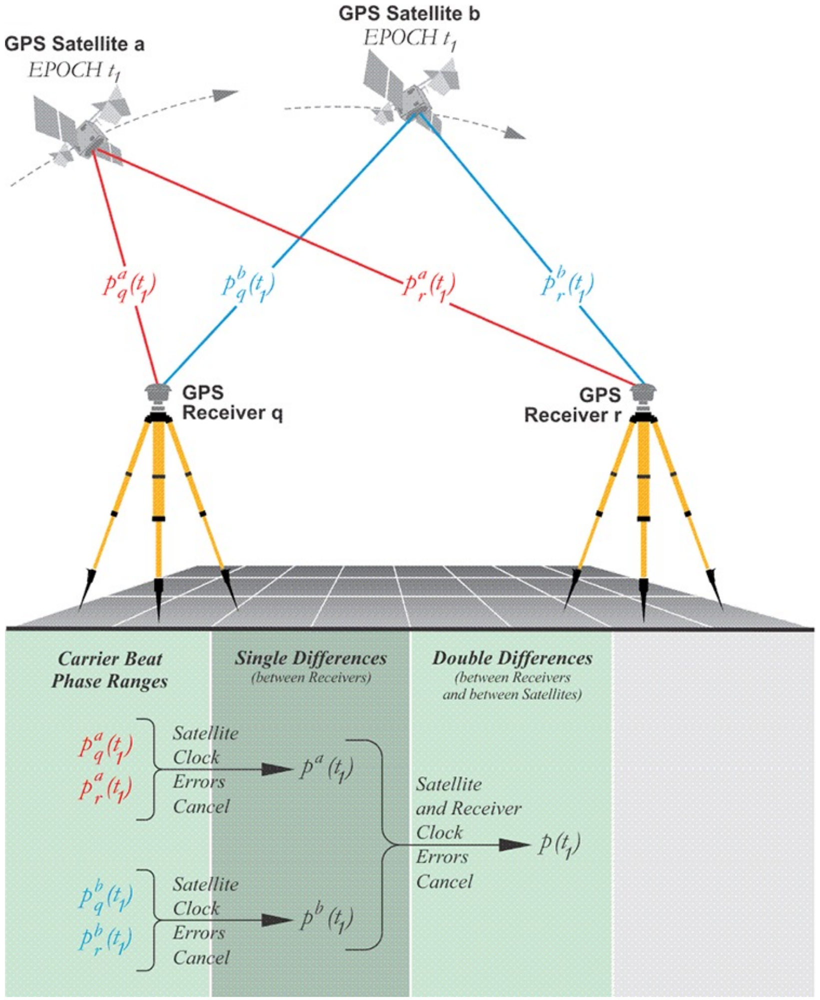
Challenges:

- UHF based Intersatellite Link (ISL) has limited bandwidth.
- The Chaser satellite has to deal with infrequent and old ISL data
- Limited on-board processing power

[u-Blox]

[Skytraq]

Double Differencing of Raw Measurements

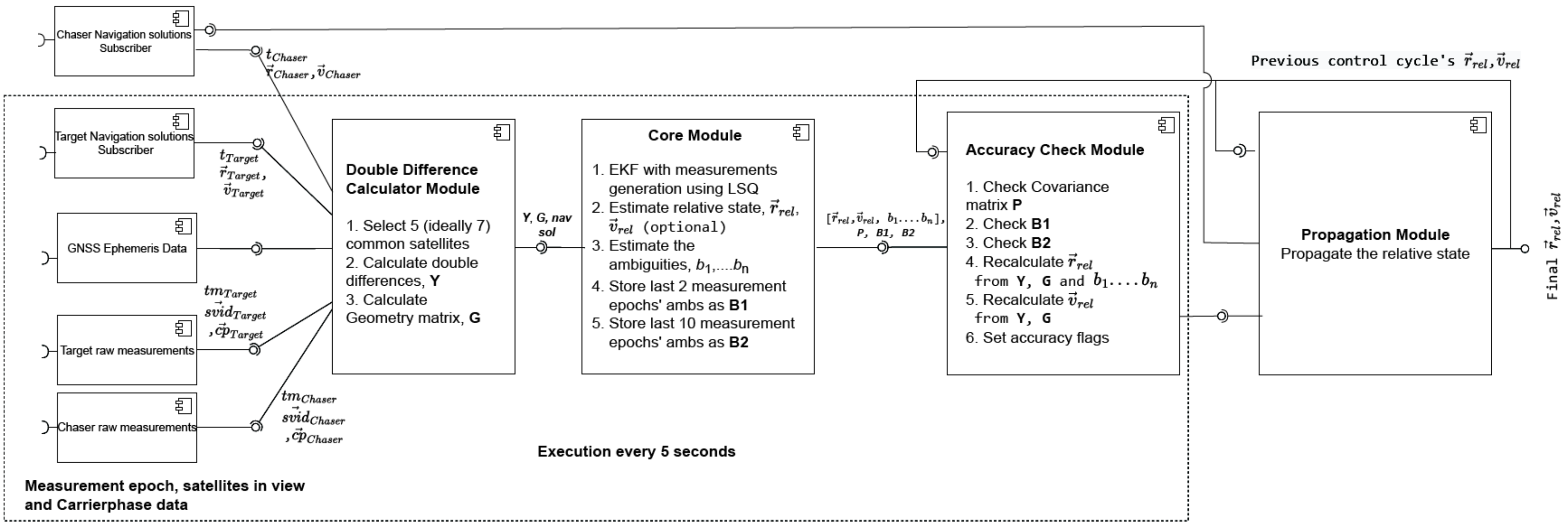


[J. Van Sickle, GPS for land surveyors. CRC press, 2008]

Error source	*Single-Difference*	*Double-Difference*
Ionosphere	Reduced, depending on the baseline length	Reduced, depending on the baseline length
Troposphere	Reduced, depending on the baseline length	Reduced, depending on the baseline length
Satellite clock	Eliminated	Eliminated
Receiver clock	Present	Eliminated
Broadcast ephemeris	Reduced, depending on the baseline length	Reduced, depending on the baseline length
Ambiguity term	Present	Present
Noise level with respect to one-way measurement	Increased by $\sqrt{2}$	Increased by 2

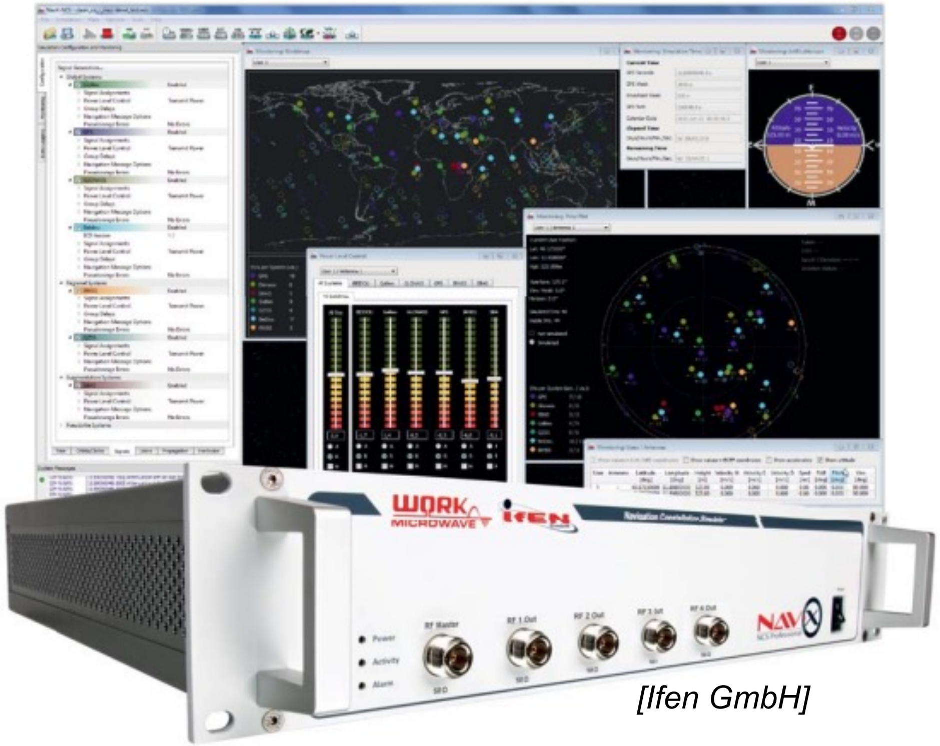
[D. Gebre-Egziabher and S. Gleason, GNSS applications and methods. Artech House, 2009]

Relative Navigation using GNSS Raw measurements



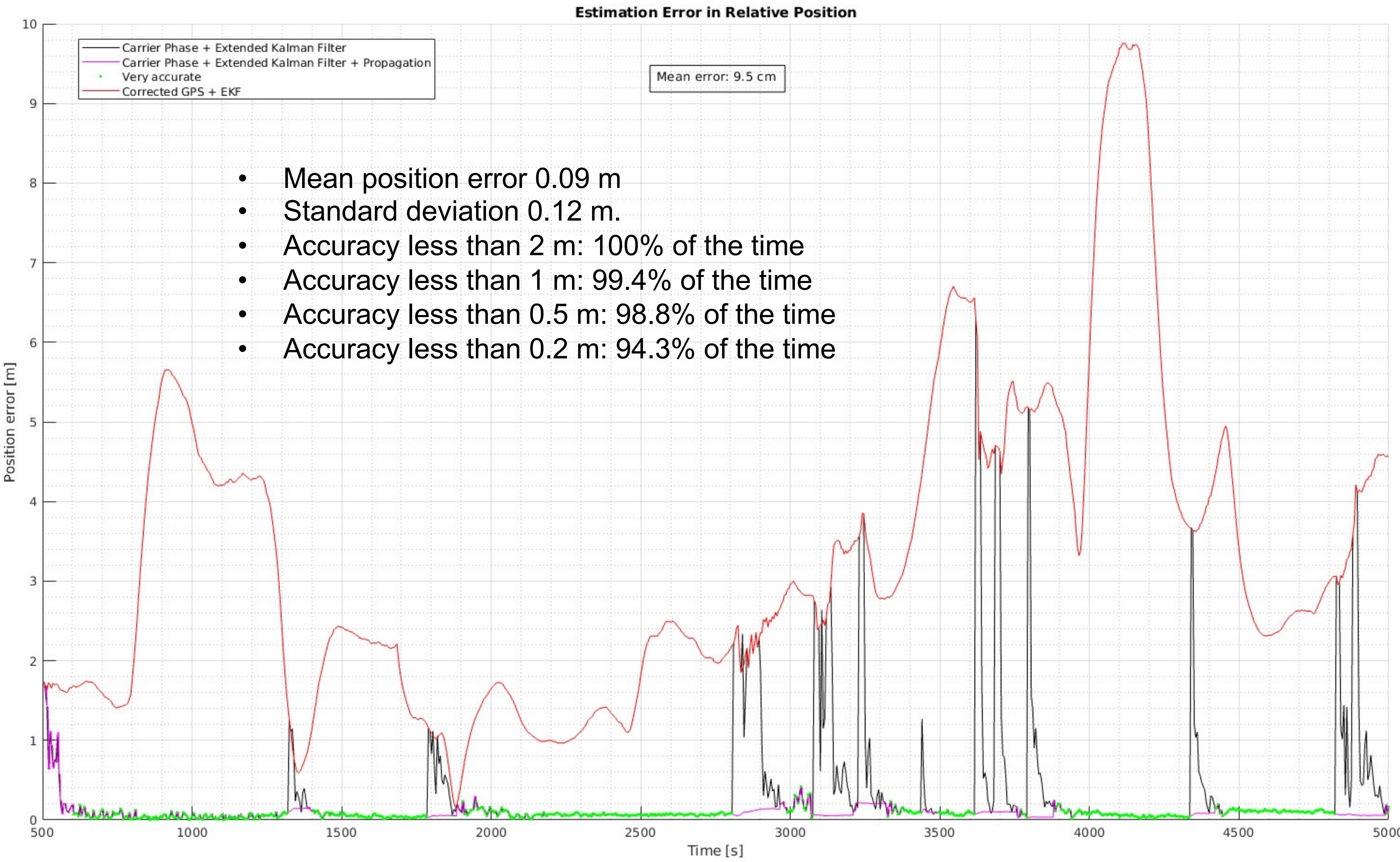
Precise Relative Navigation Test Setup and Results

- NavX-NCS GPS Simulator at L1 freqency
- Sun synchronous orbit at 550 km with ROEs:
- Input: Helix orbit with 300 m – 600 m relative distance
- Results
  - Mean position estimation error: 10 – 20 cm
  - Accuracy less than 1 m: 95% of the time
- Next steps
  - Reduce mean position error to 1 – 2 cm



[Ifen GmbH]

Relative Position Results

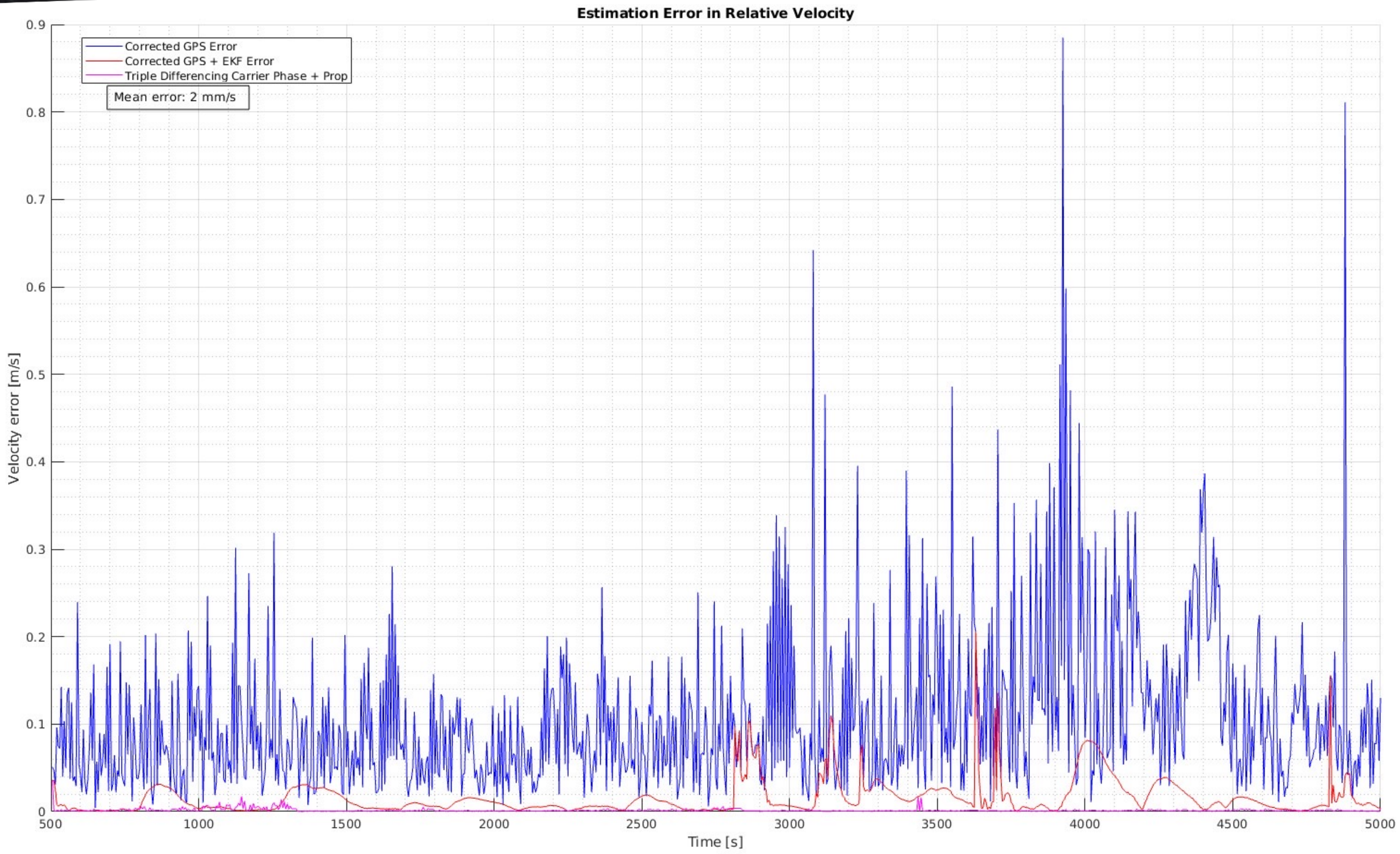


- Mean position error 0.09 m
- Standard deviation 0.12 m.
- Accuracy less than 2 m: 100% of the time
- Accuracy less than 1 m: 99.4% of the time
- Accuracy less than 0.5 m: 98.8% of the time
- Accuracy less than 0.2 m: 94.3% of the time

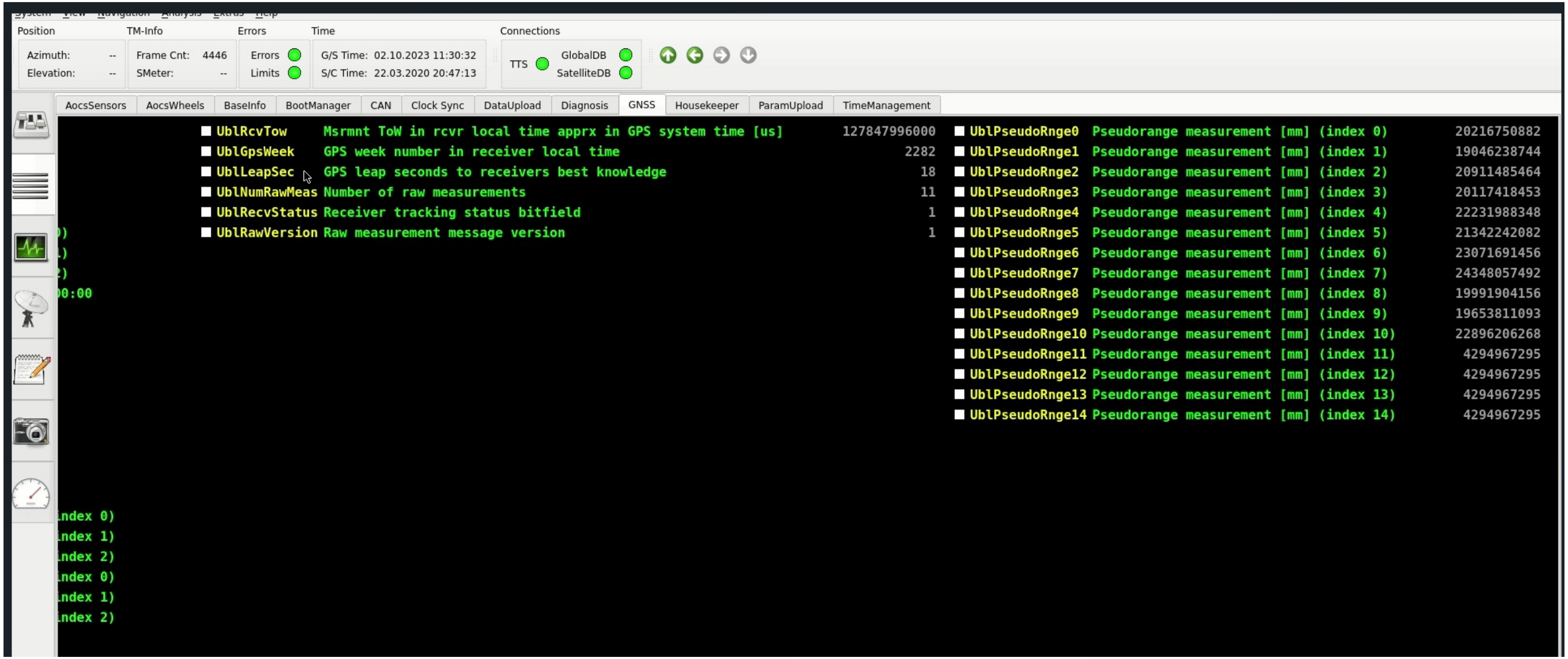
Technische Universität Berlin

NanoFF

Relative Velocity Results

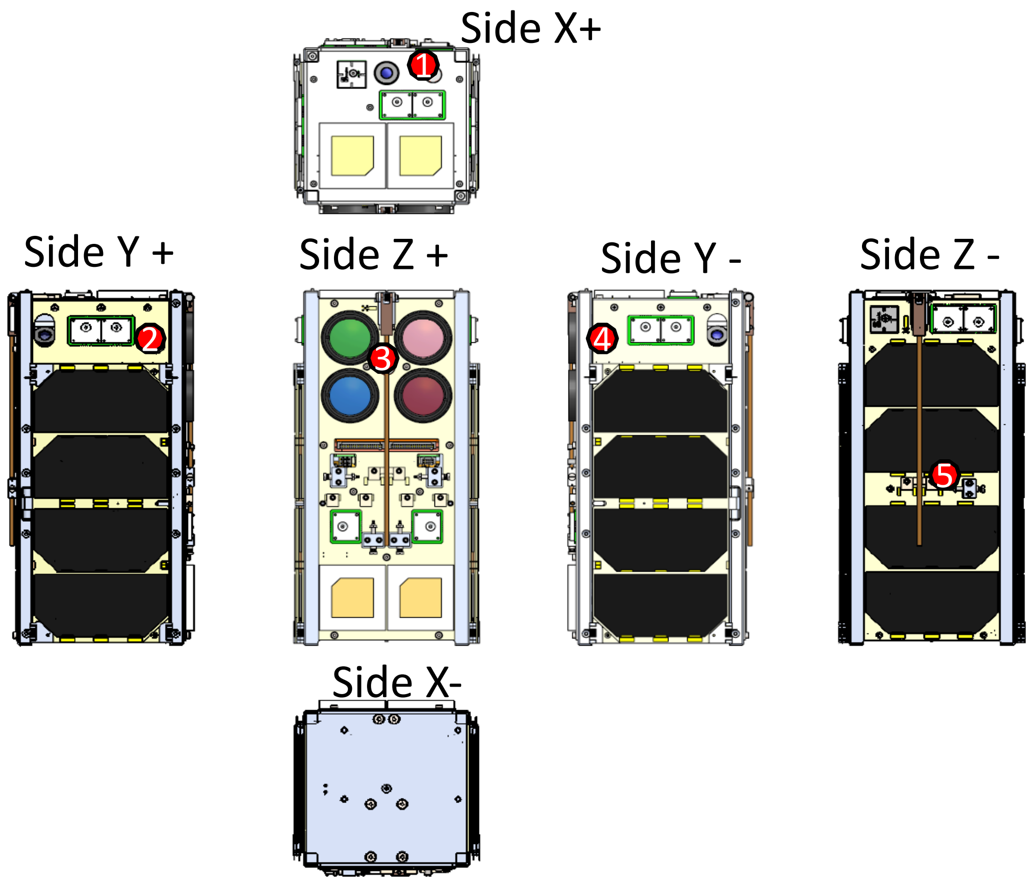


Example: GNSS Raw MeasurementsTelemetry



Satellite Laser Ranging

Objective: Compare the relative distances using SLR with those from GNSS raw measurements

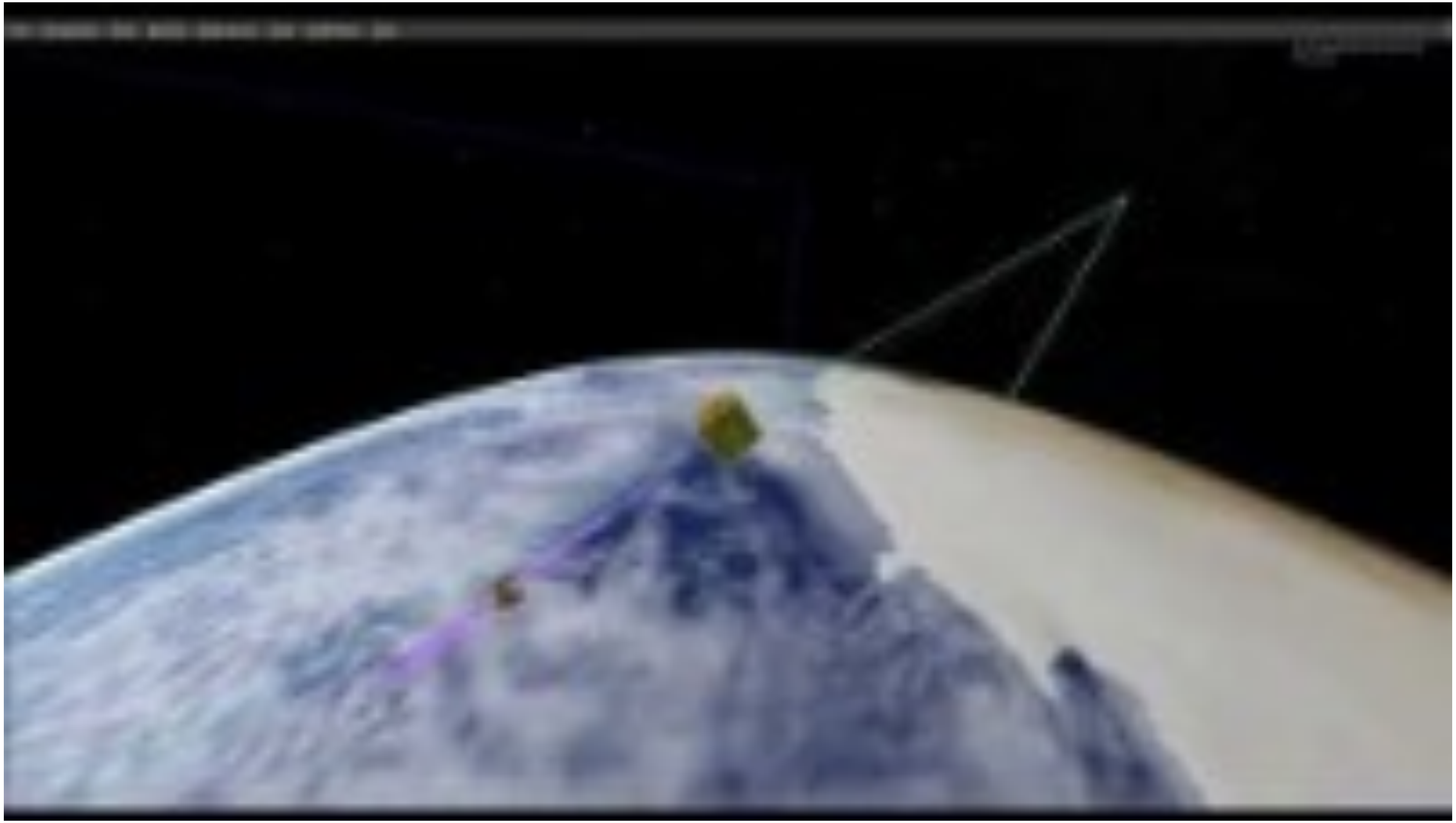


Position of the LRR surface center

No.	X [mm]	Y [mm]	Z [mm]
1	109	-28	-33
2	79	50	33
3	65	0	51
4	79	-50	33
5	-8	10	-51

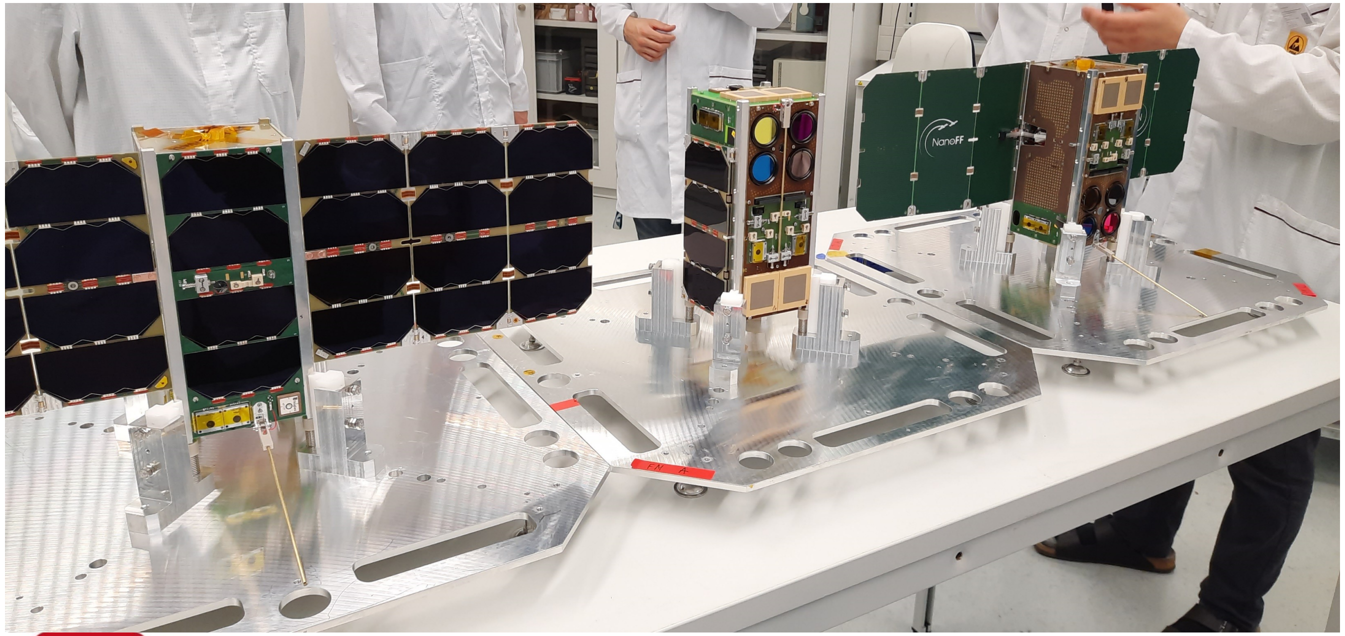
Body Fix Right Hand Geometric Centric Coordinate System (NanoFF SAT Coordinate System)

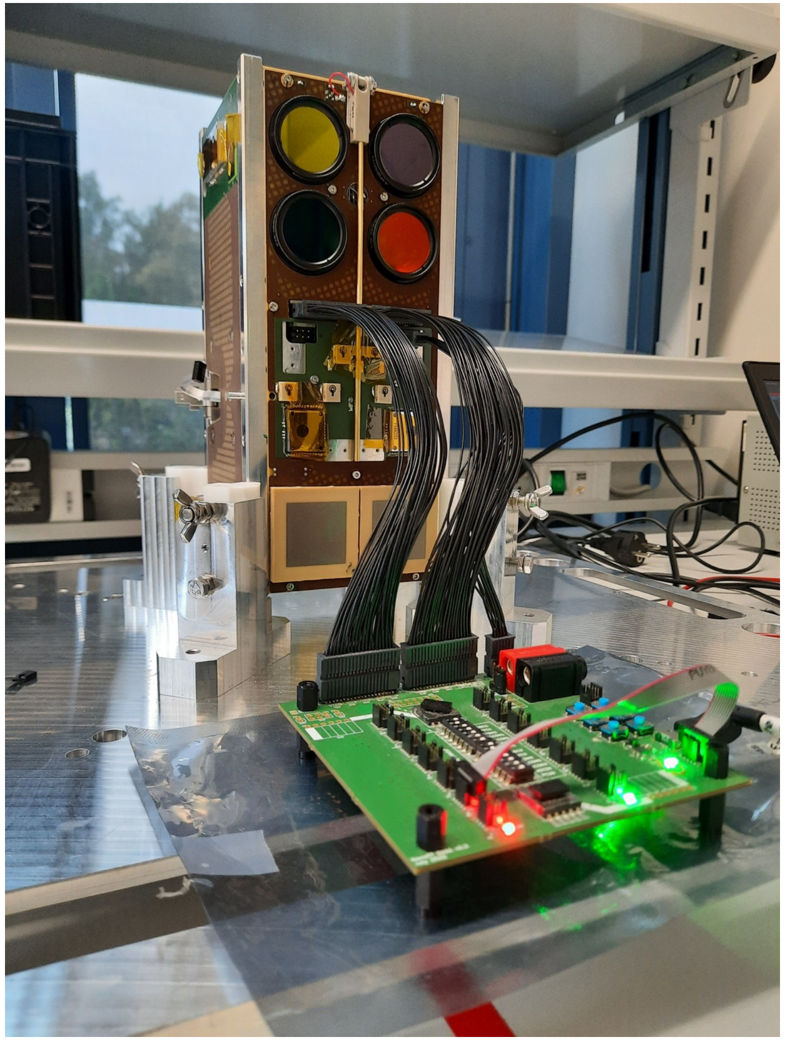
NanoFF Helix Formation



Future Work

- Gaining mission operations experience
- Developing autonomous formation flight algorithms
- Developing on-board relative position estimation algorithm using GNSS raw measurements

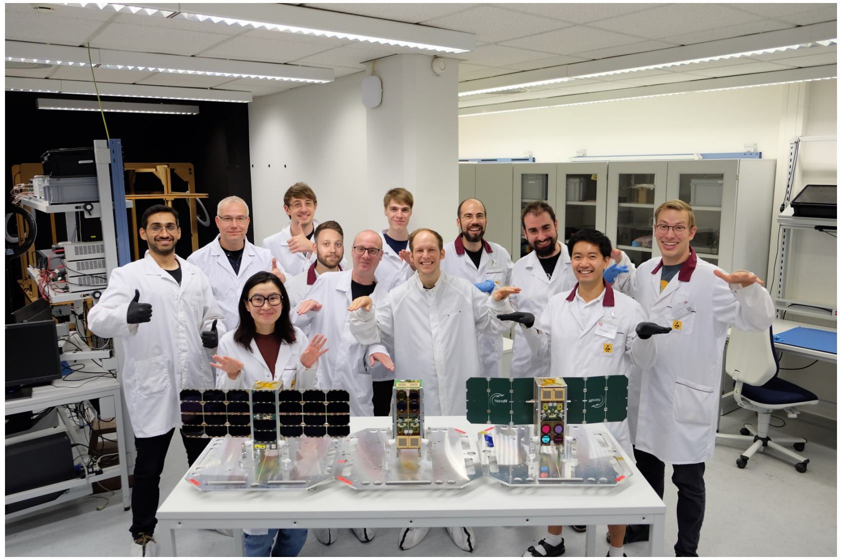




Technische Universität Berlin

NanoFF

Thank You!



Gefördert durch:

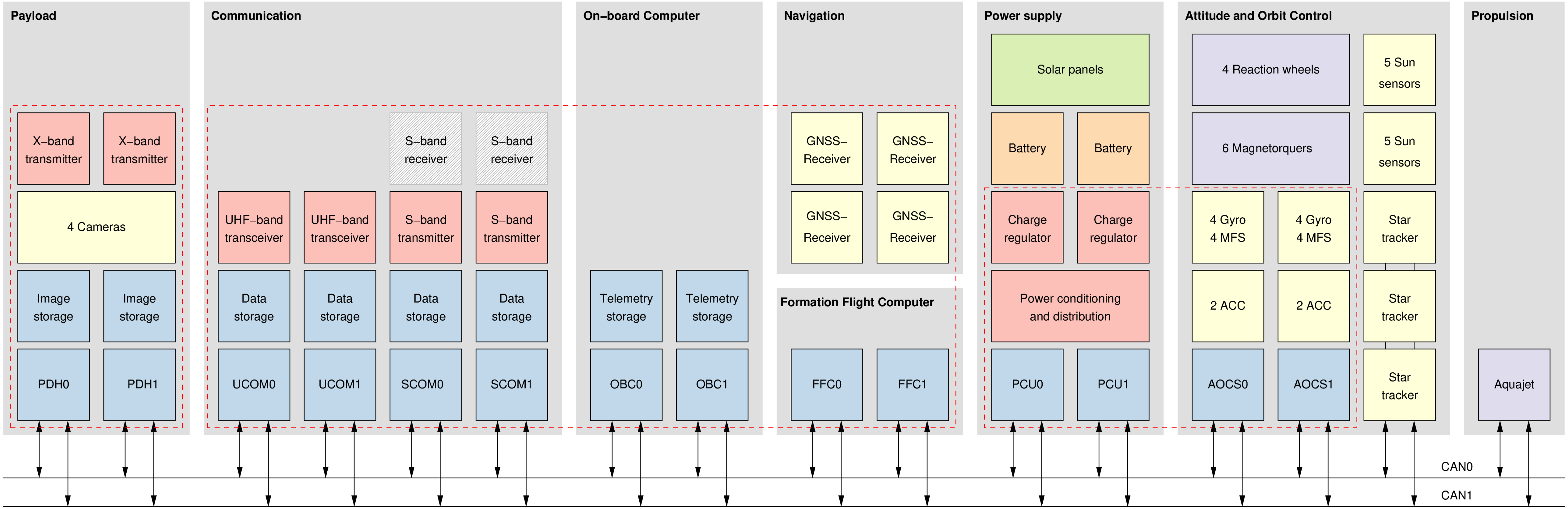
Bundesministerium
für Wirtschaft
und Technologie

aufgrund eines Beschlusses
des Deutschen Bundestages

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

DLR Grant number NanoFF: 50 RU 1803

System Overview



Technische Universität Berlin

NanoFF

Propulsion System Aquajet

AI:
Aerospace Innovation

Dimensions	**94x94x59mm3 (without connectors and cables)**
Mass	ca. 580g (incl. electronics, without connectors and cables)
Propellant mass	ca. 80g
Working fluid	Water and antifreeze
Pressure (MEOP)	ca. 5.8 bar
Vcc (nominal)	12V / 5V / 3.3V
Electric power	Max. 7W
Isp	up to 700m/s
Thrust	up to 4mN (average 1mN)
Delta v	~ 15m/s

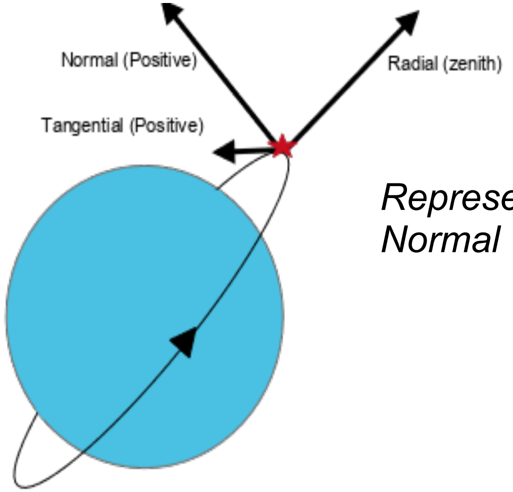
NanoFF EQM, FM1, FM2, FSM [Aerospace Innovation GmbH]

Formation Flight in NanoFF

- Use of Relative Orbital Elements

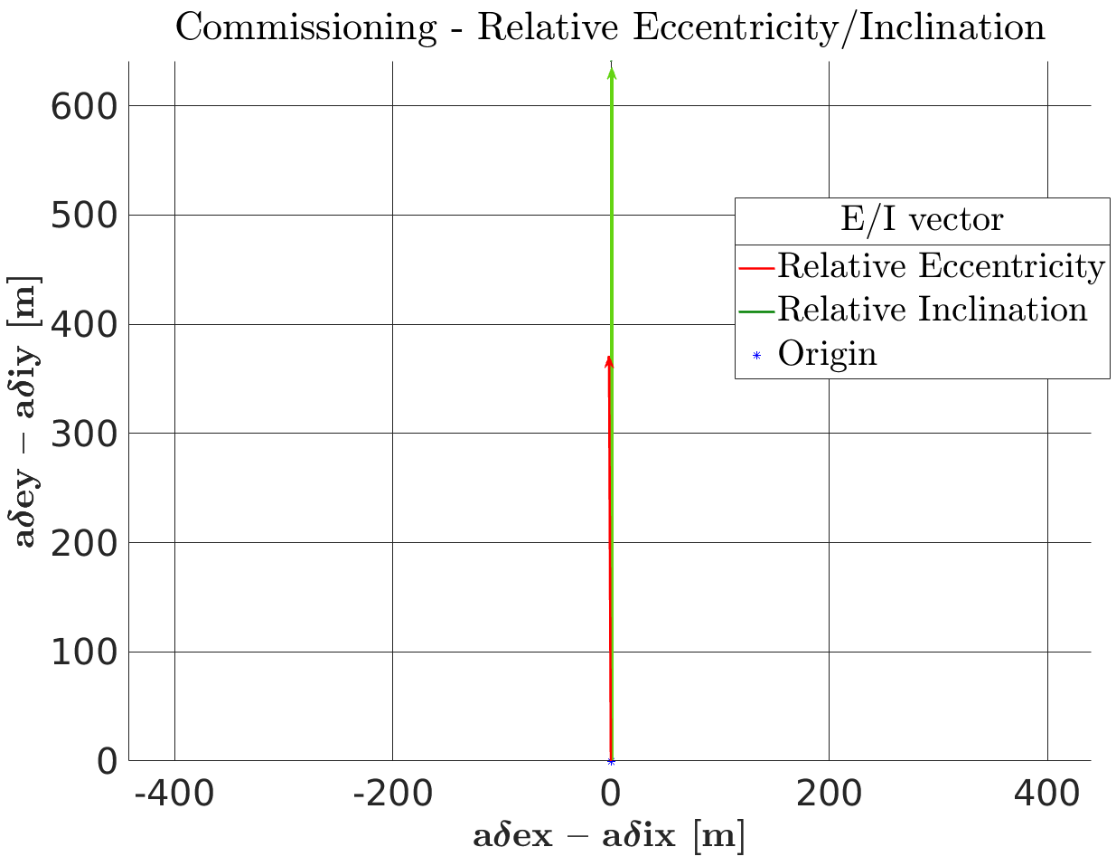
$$\delta\alpha = \begin{bmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{bmatrix} = \begin{bmatrix} (a_2 - a_1)/a_1 \\ u_2 - u_1 + (\Omega_2 - \Omega_1)\cos i_1 \\ e_2 \cos w_2 - e_1 \cos w_1 \\ e_2 \sin w_2 - e_1 \sin w_1 \\ i_2 - i_1 \\ (\Omega_2 - \Omega_1)/\sin i_1 \end{bmatrix}$$

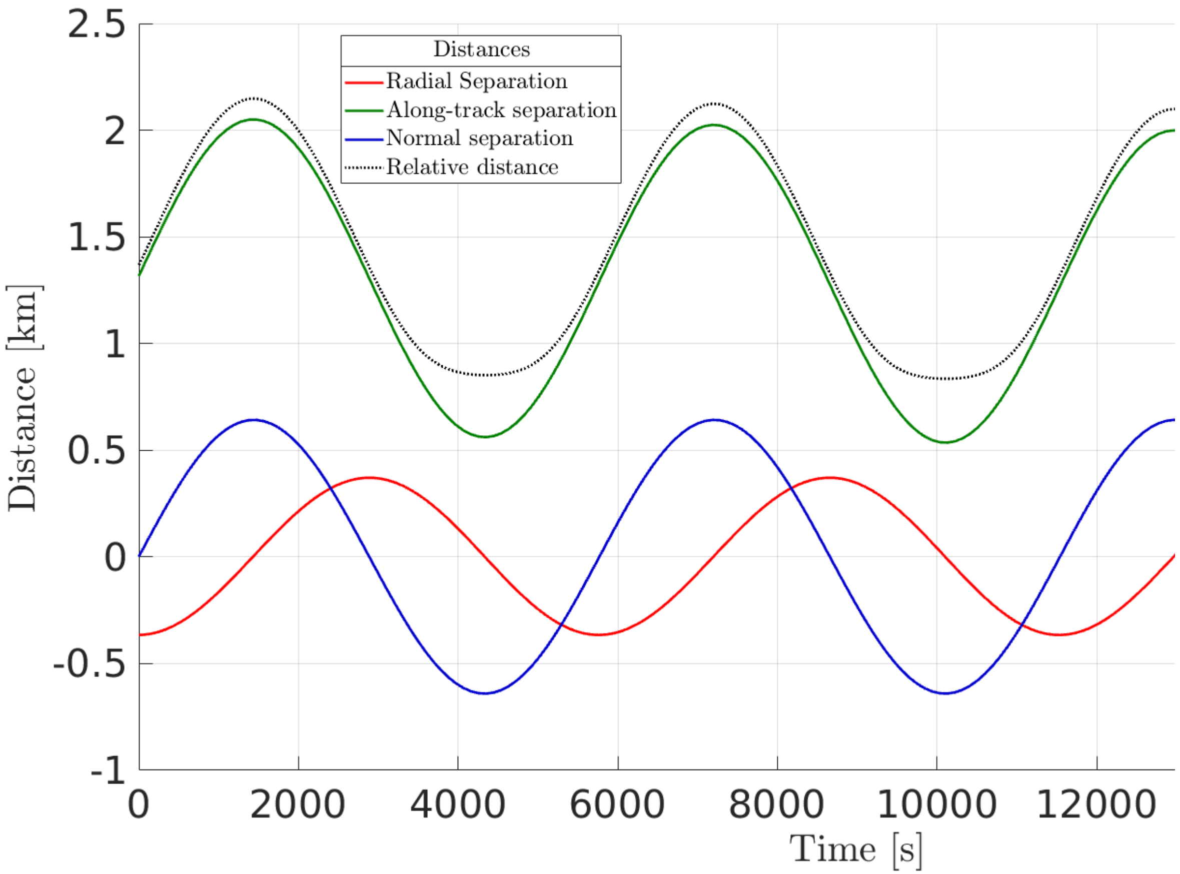
- For collision safety, $\delta e \upuparrows \delta i$ or $\delta e \uparrow\downarrow \delta i$
- Chaser satellite (the one with active control) is considered as the reference satellite.
- Based on the work and experience gained in DLR's AVANTI mission.



Representation of Radial-Tangential-Normal (RTN) frame

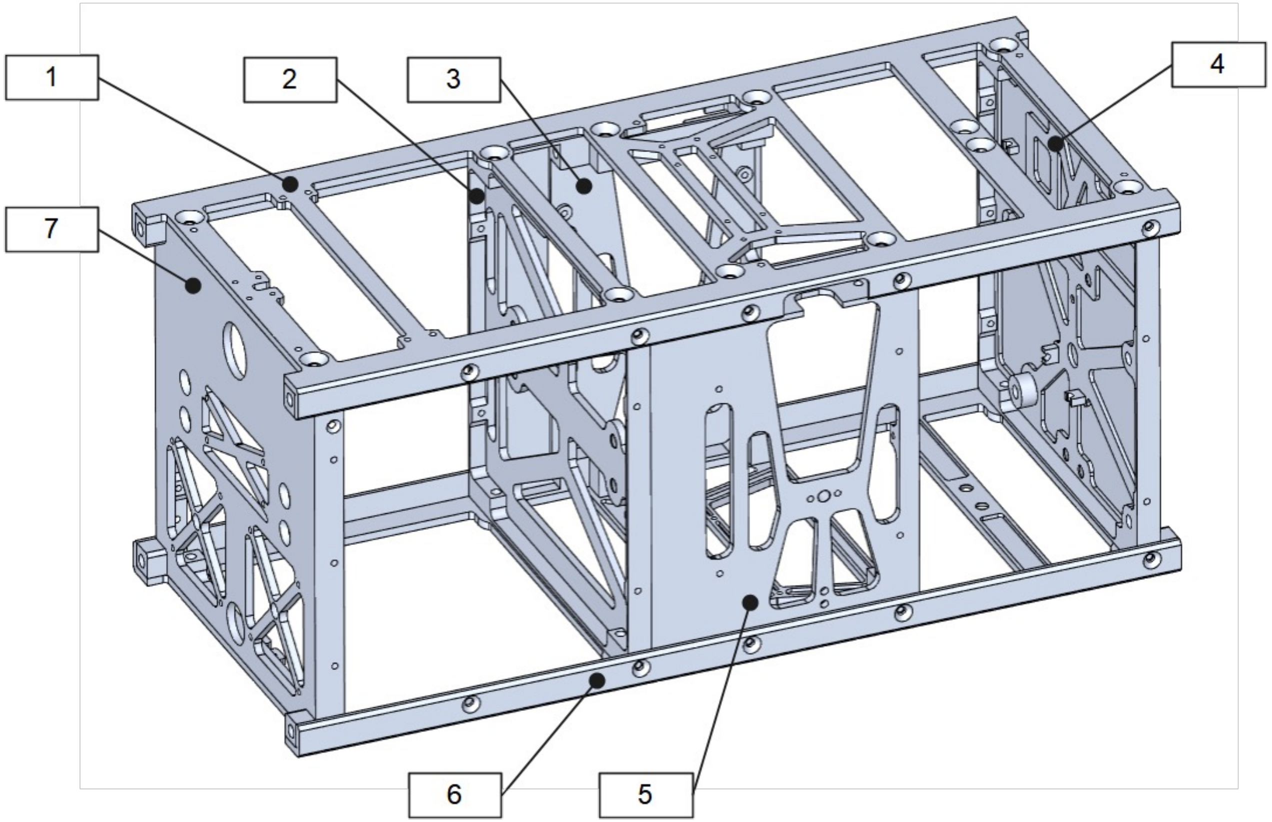
Post Deployment Relative Orbital State





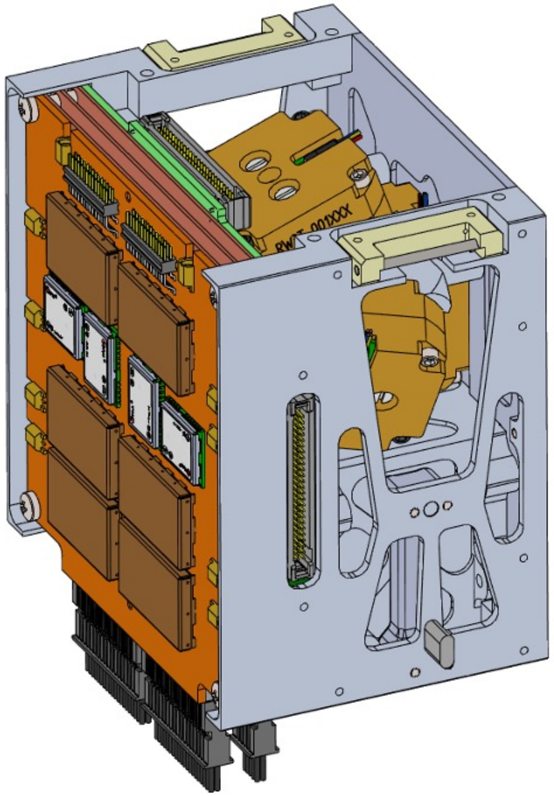
Primary structural parts

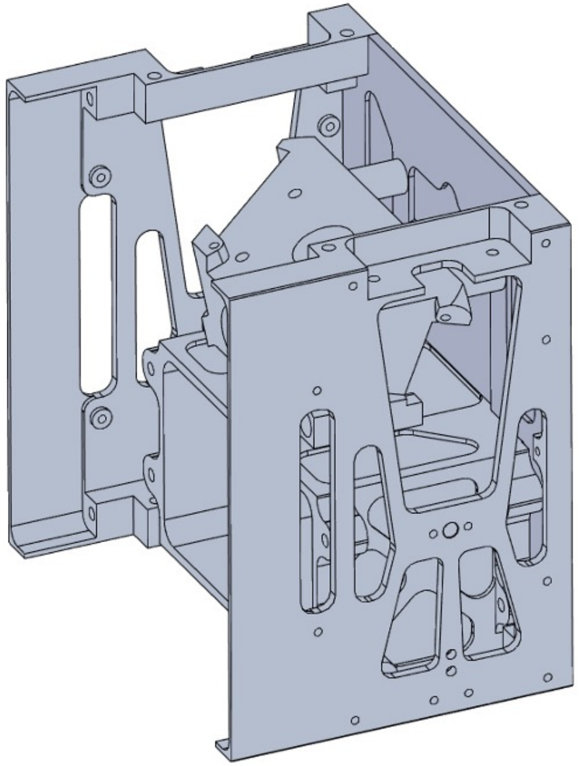
- There are seven primary structural parts
  - Two connecting structure including the rails in +Z and -Z (1 and 6)
  - The top and bottom plates (4 and 7)
  - Intermediate plate in X-Axis between the satellite bus and the payload (2)
  - Side elements of the satellite bus in +Y and –Y (3 und 5)
- The satellite bus itself has a bottom plate to be separated from the propulsion system



Satellite bus

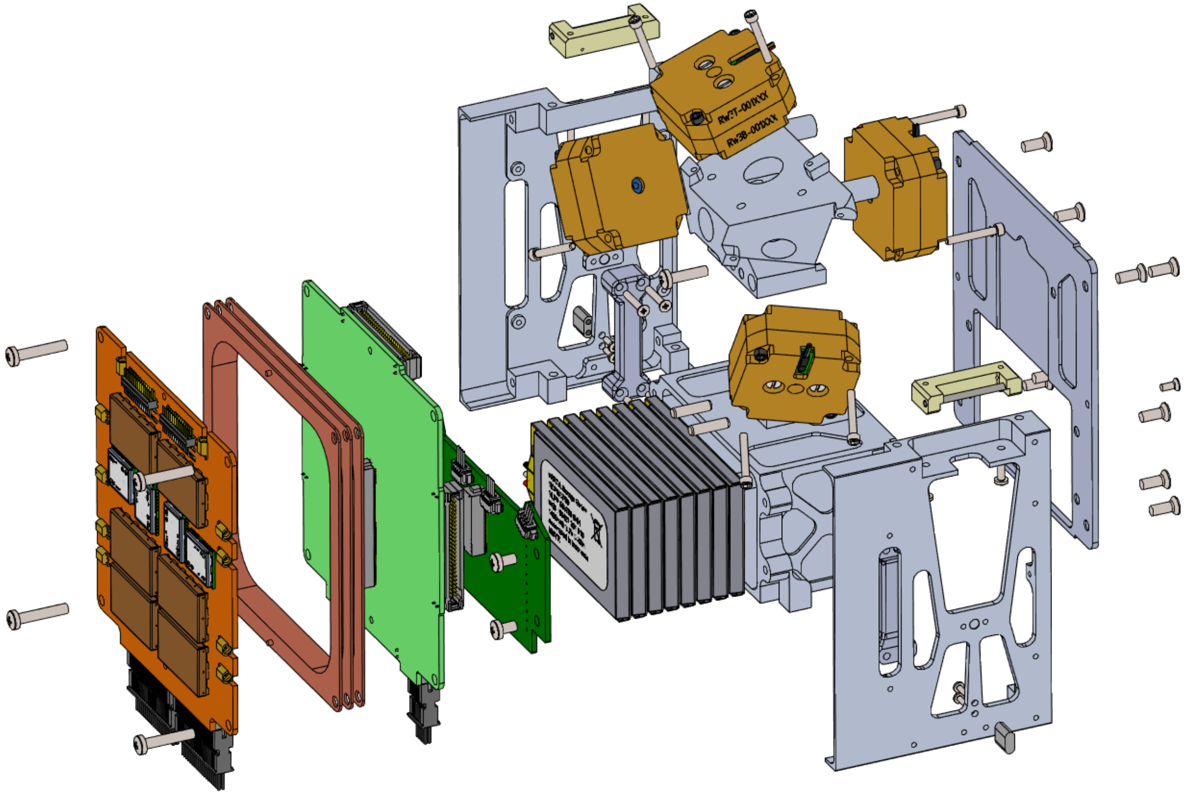
- NanoFF's satellite bus was developed as a self-contained, self-supporting, structural unit
- The complete subsystem can be integrated and tested prior to integration into the satellite
- In addition to the two primary structural elements in +Y and -Y, the subsystem has:
  - An intermediate deck in X
  - The battery housing
  - The tetrahedron structure for the reaction wheels





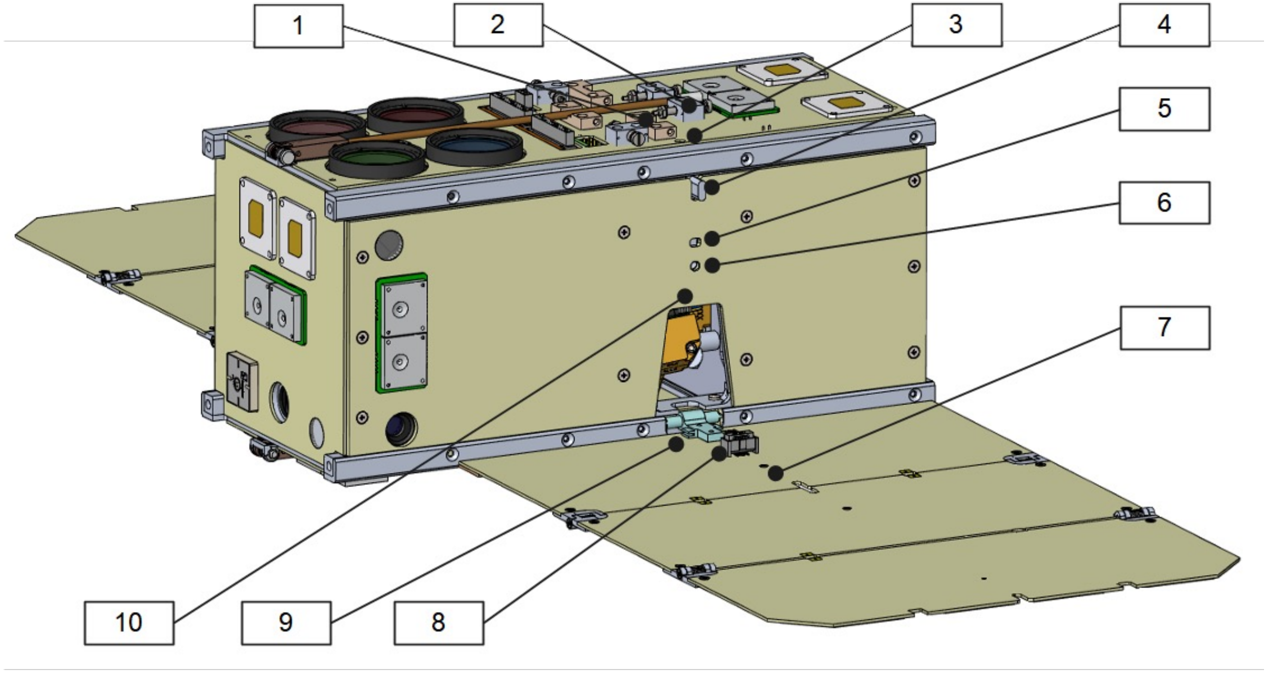
Satellite bus

- The structural elements are both screwed and secured by locating pins (between RW structure and battery compartment).
- The reaction wheels are electrically connected to the BMS via a pluggable cable connection
- The BMS, the OBC-COM-NAV board and the PCU are connected via board-to-board connectors.
- The air coil is soldered to the PCU
- The satellite bus also houses the central joint of the solar panels



Release mechanisms

- NanoFF has a total of four release mechanisms, two each for the UHF antennas and two for the solar panels
- For the UHF antennas, the release mechanism is based on the system developed during the S-NET mission
- The individual mechanisms are secured by a taut nylon thread (2)
- A redundant fusible link (1) guarantees safe triggering
- The nylon thread for the panel deployment is guided to the -Z side by means of a 3D printed guide (6) (3)



Satellite bus electronics: OBC/COM/NAV

Combined PCB with several subsystems

Communication

- 2 Transceiver in UHF-Band (UCOM)
- 2 Transmitter and 2 Receiver in S-Band (SCOM)

Data Handling

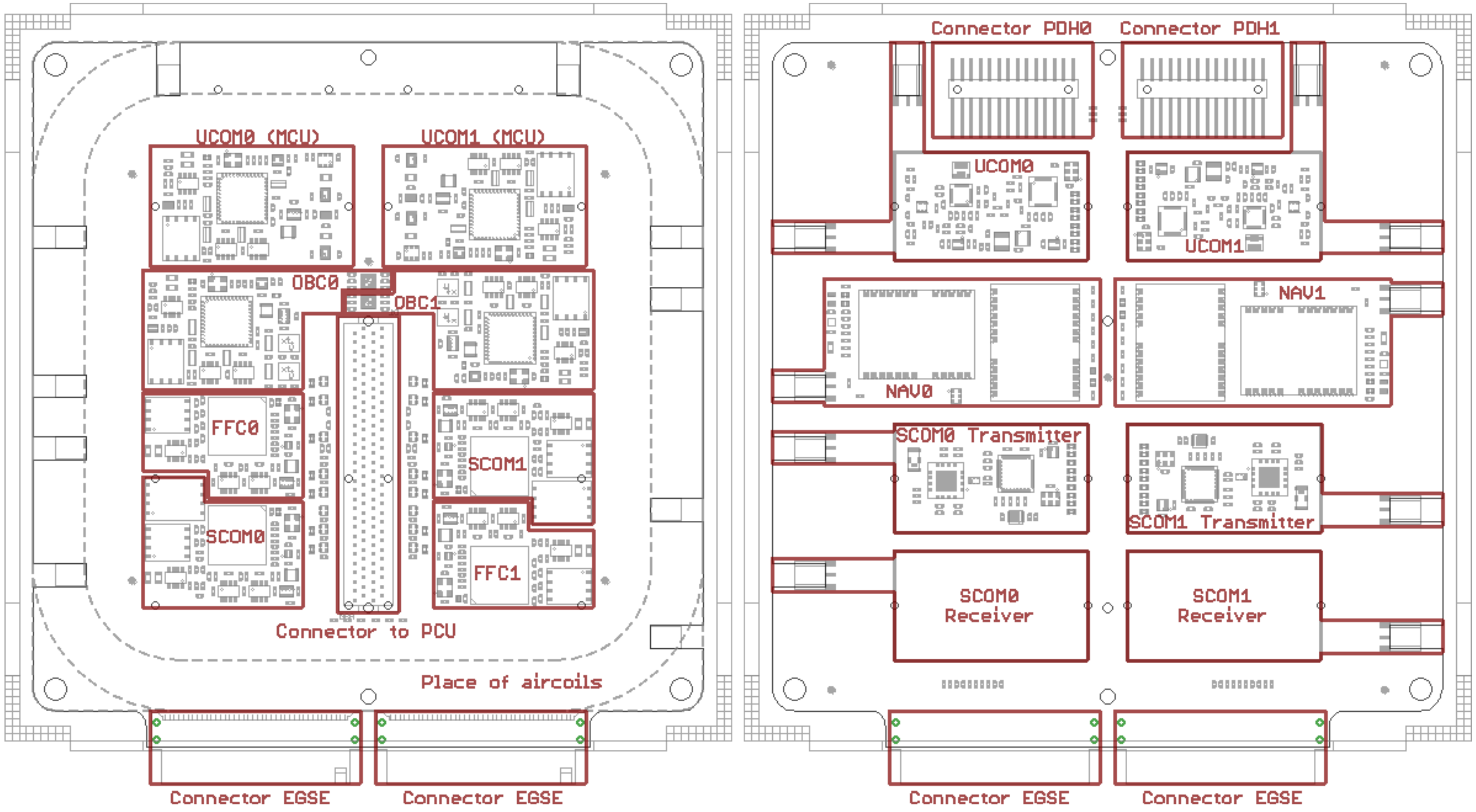
- 2 On-Board Computer (OBC)
- 2 Formation Flight Computer (FFC)

Navigation

- 4 GNSS Receiver (NAV)

EGSE

- Access to all μCs of the satellite



Satellite bus electronics: PCU/AOCS

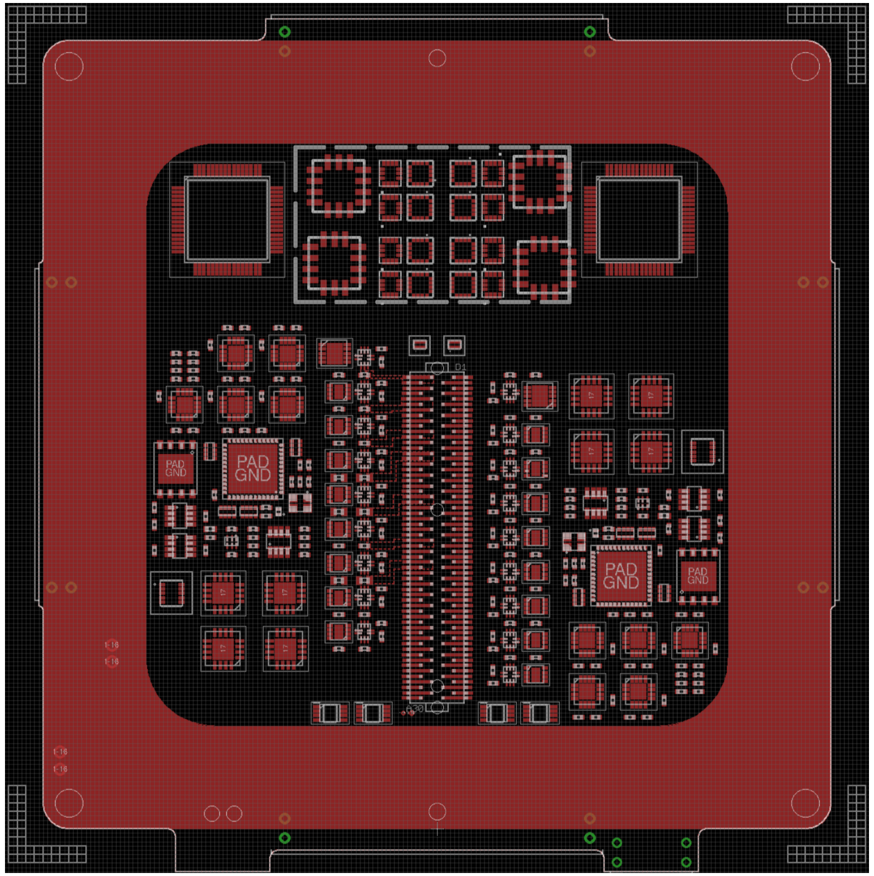
Combined PCB for PCU/AOCS

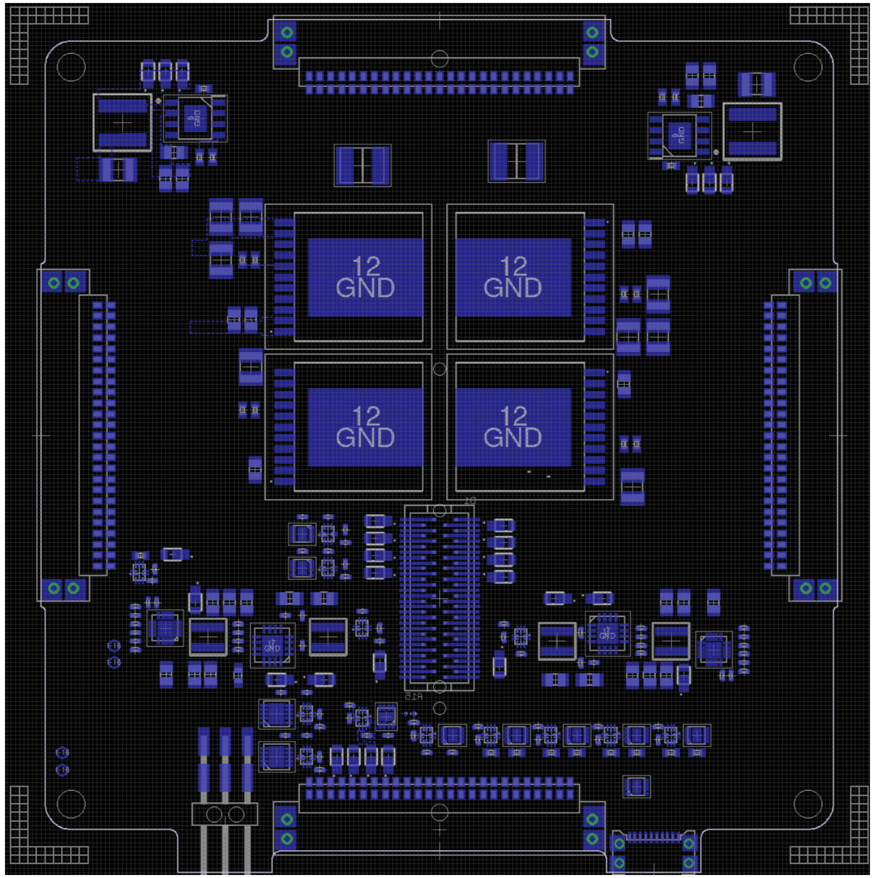
AOCS

- 2x4 Gyroscopes
- 2x4 Magnetometers
- 2x2 Accelerometers
- 2x5 Sun Sensors (Side Panels)
- 4 Reaction wheels
- 3 Star Trackers

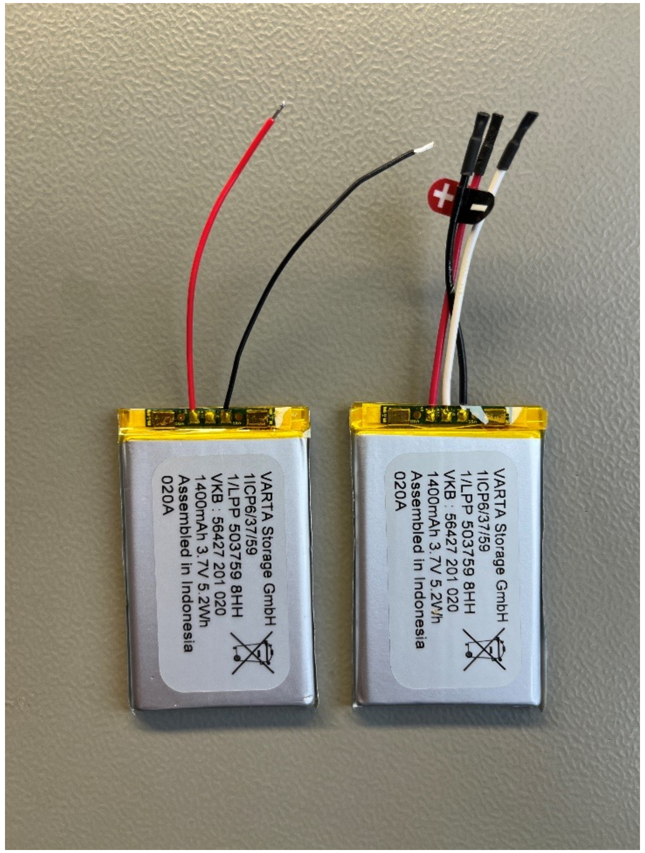
PCU

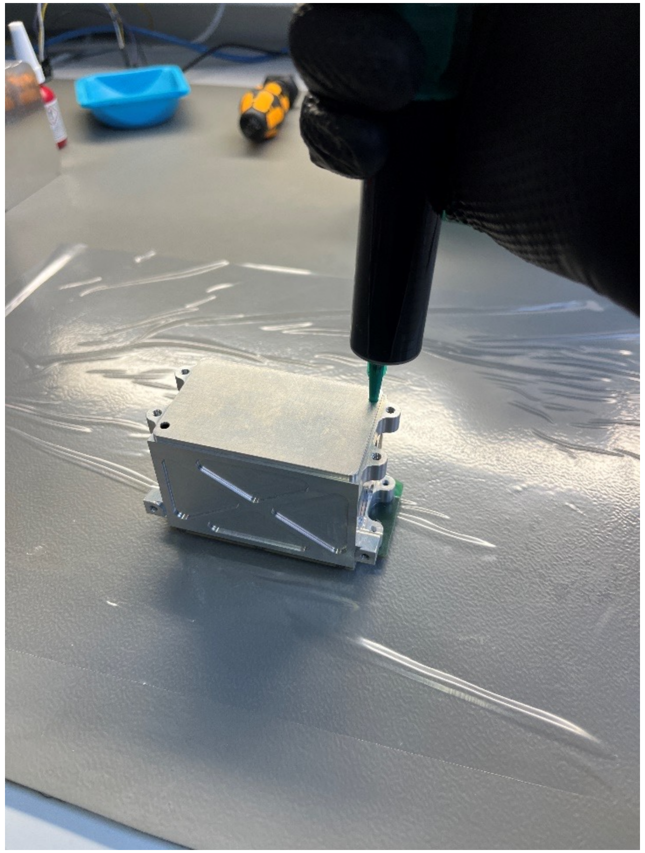
- Redundant System
- 12V, 5V, 3.3V

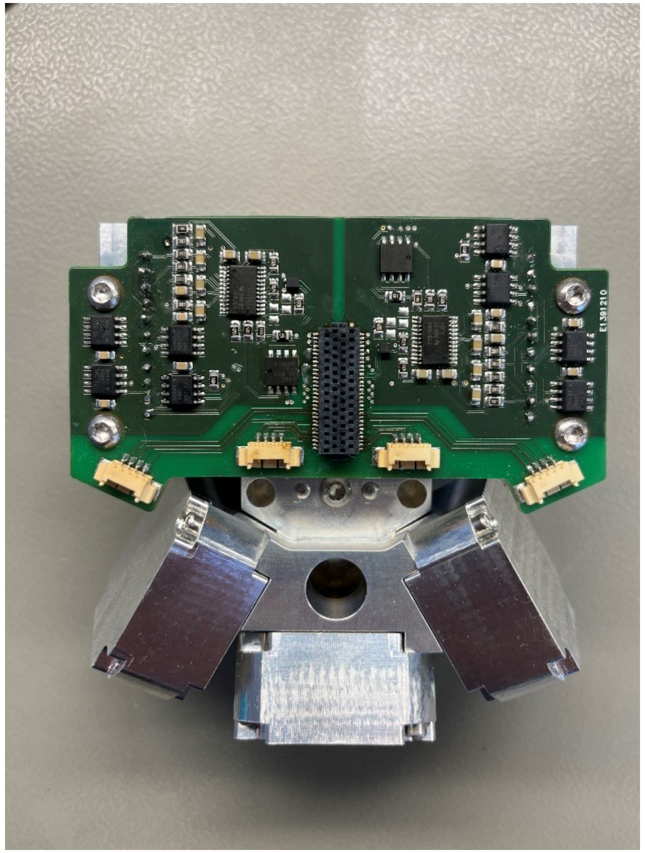




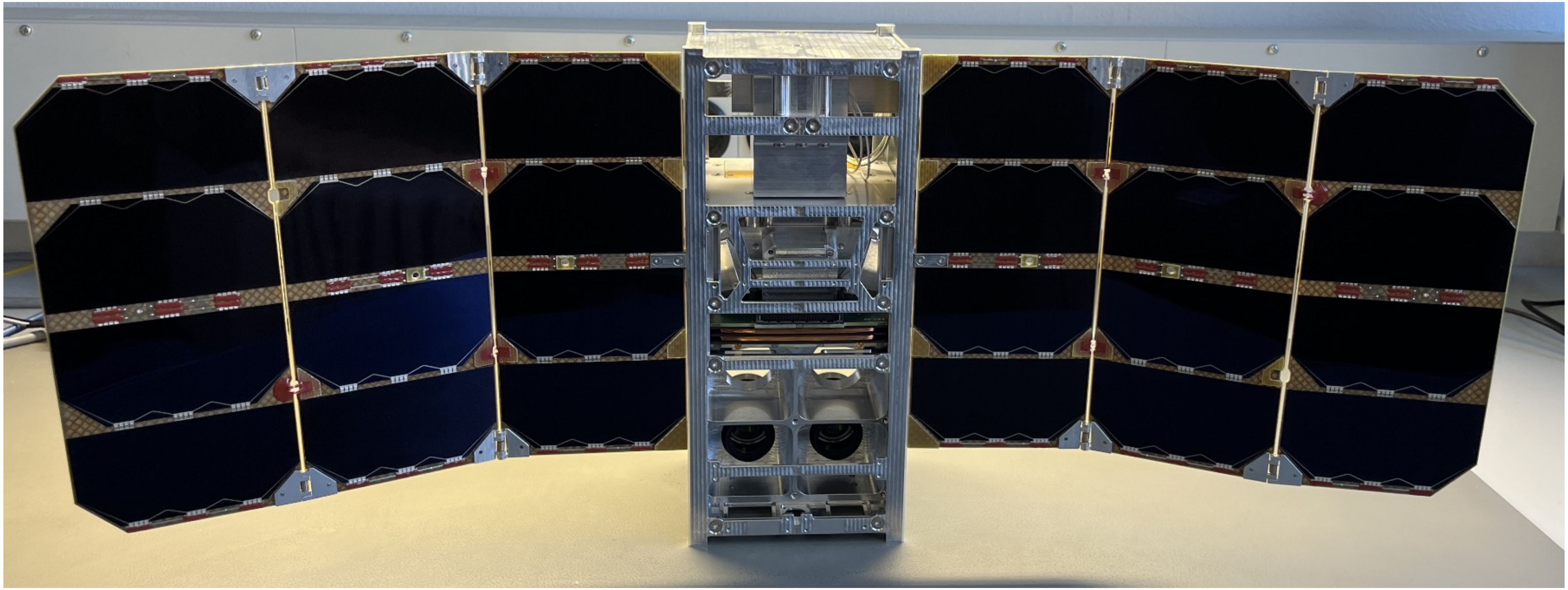
Satellite bus: EPS





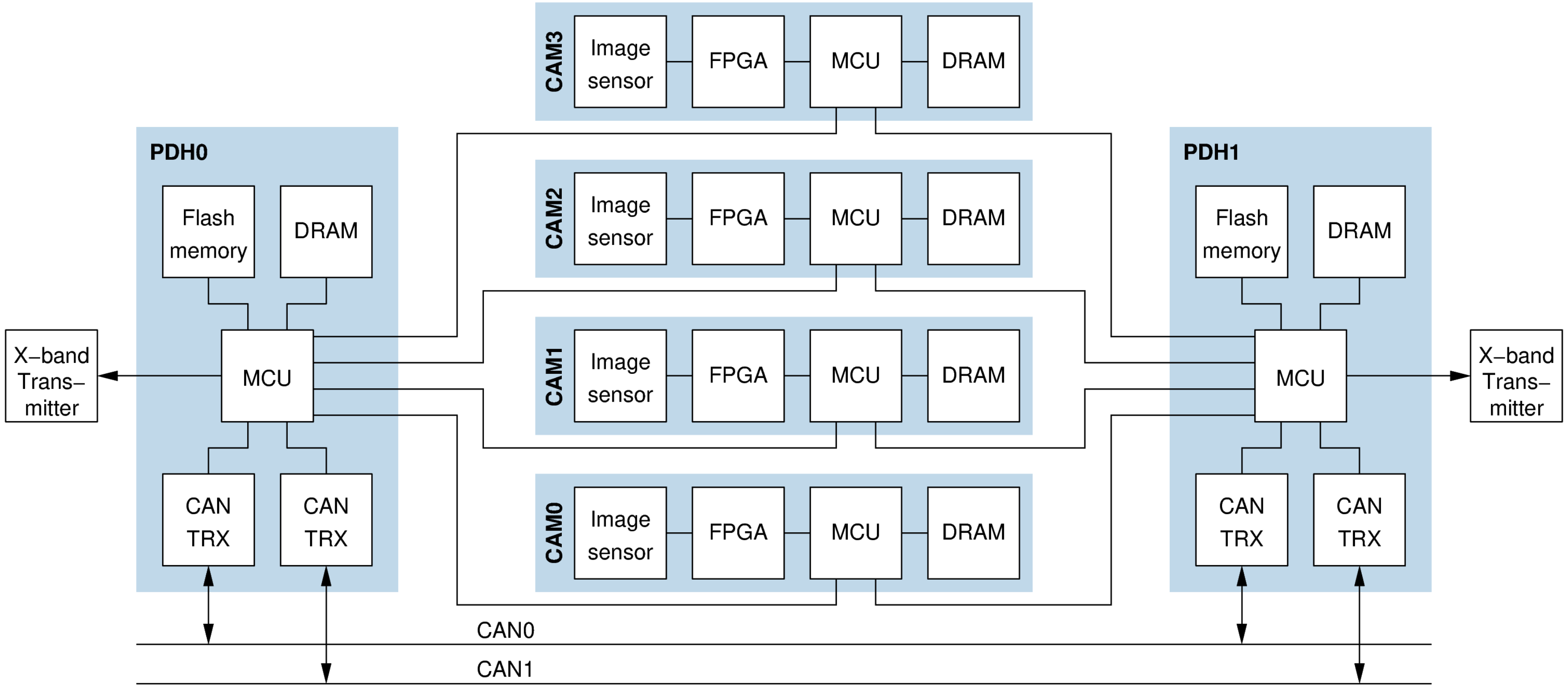


Satellite bus: EPS



Camera system

- Multispectral camera system
- Ground resolution of 30m @525km SSO
- MTF of 0.4
- Global Shutter sensor with a pixel size of 2.74µm and 12Mpx
- Swath width of 131km
  Height 96km
- Stripes of consecutive pictures
- Filters chosen with another department of TU Berlin for forest surveillance (4 red channels), other satellite RGB and near IR



Key Parameters

	2U NanoFF	3U NanoOOV
Communication		
Downlink UHF	Up to 9.6 kbit/s	Up to 9.6 kbit/s
Downlink S/X-band	Up to 4 Mbit/s	Up to 4 Mbit/s
Uplink UHF	Up to 9.6 kbit/s	Up to 9.6 kbit/s
Uplink S-Band	Up to 1 Mbit/s	Up to 1 Mbit/s
Electrical Power System		
Solarpower	36 W	55 W
Storage	47 Wh	47 Wh
AOCS		
Determination	30 arcsec	30 arcsec
Pointing	0.5°	0.5°
Position	5 m	1 m
Velocity	0.1 m/s	0.01 m/s
Propulsion	~ 15 m/s	~ 11 m/s
Payload Volume	0.7U (1.3U w/o propulsion)	1.6U (2.2U w/o propulsion)
Camera System	30m GSD	tbd