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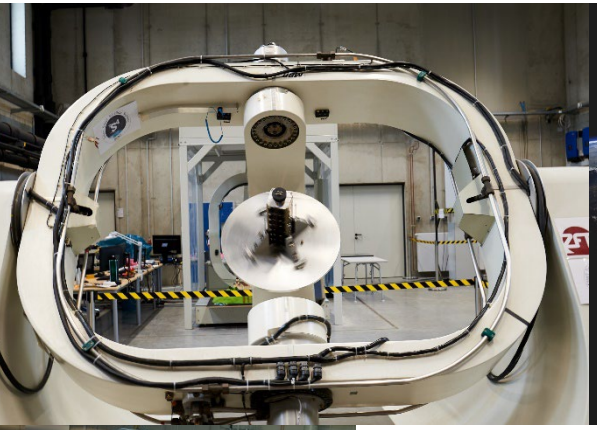
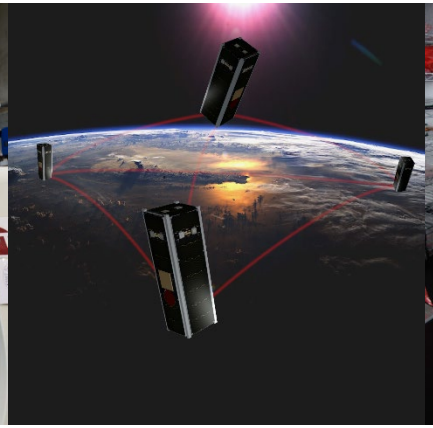


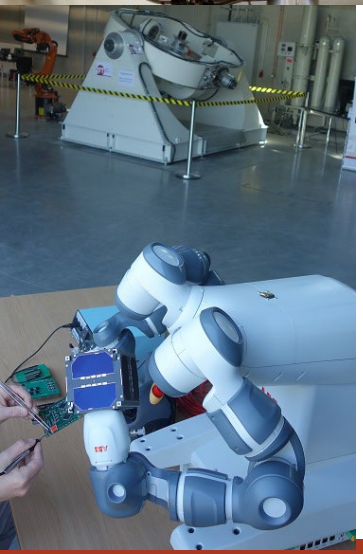

Perspectives in S^5: Small, Smart, Self-organizing, Satellite Systems for IoT

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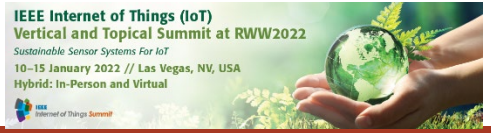

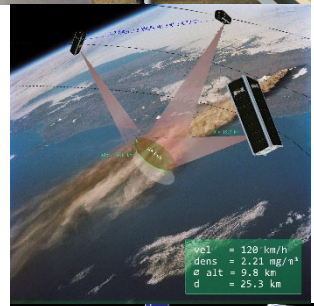

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Space Technology is today in a Disruptive Phase !

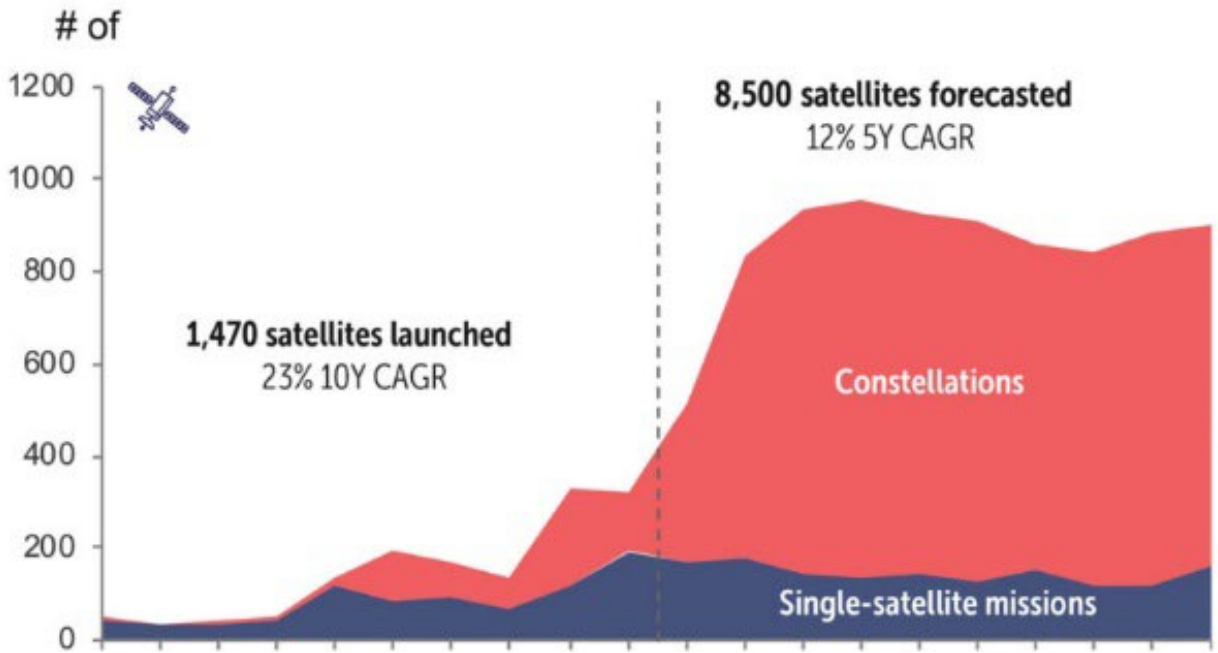
- one company alone (Starlink) placed more than 1700 satellites in orbit during the last 2 years
  before 2010 we had worldwide typically about 50 satellites per year

- satellites benefit from miniaturization to much more cost-efficiently provide same functionalities in orbit
  launcher costs scale with mass and production of larger quantities reduces costs, too

- trends are observed to move from traditional multi-functional large spacecraft to distributed, networked systems of smart small satellites
  similar to information processing, which moved during the last 50 years from mainframe computers to cloud computing, making by example the information already available at internet connected smart phones

The next challenge: Small Satellite Formations

Some 8,500 satellites with a launch mass of 500 kilograms or less stand to launch between 2019 and 2028, according to Paris-based Euroconsult.

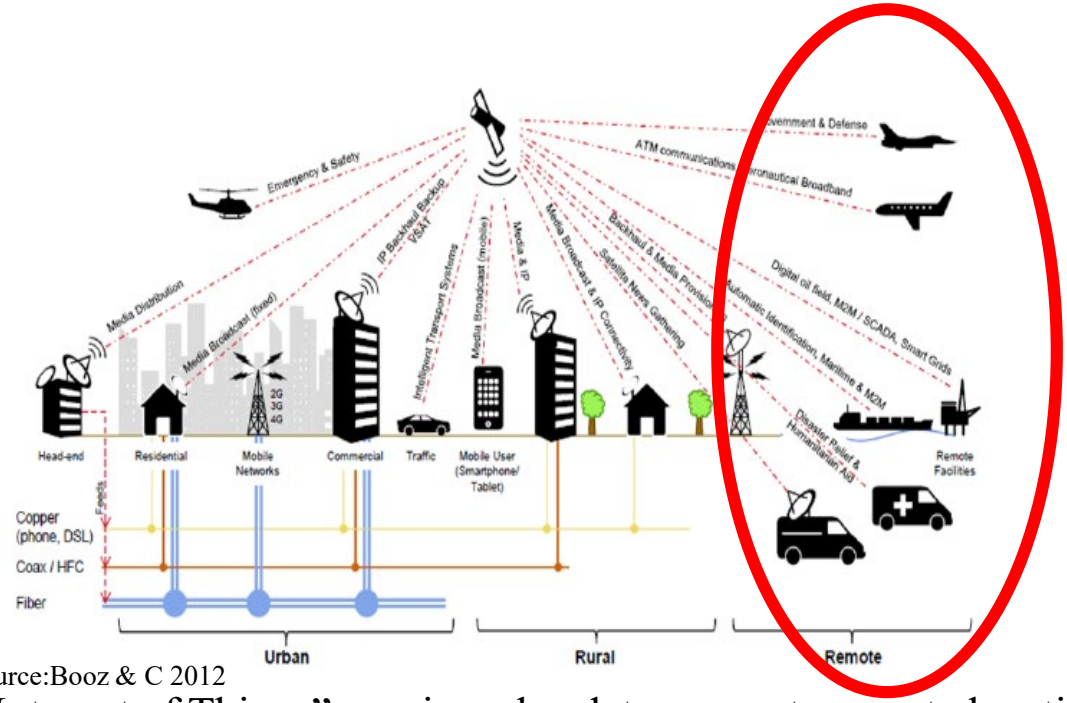


"23 % compound annual growth rate (CAGR) from 2009 to 2018. Even greater expansion is expected between 2019 and 2024 … five-year growth rate for smallsats to peak at 48% in 2024"

Source: EuroConsult / SpaceNews 6.8.2019

Application Perspectives of Nano-Satellite Formations

Internet of Things (IoT) is expected to connect until 2020 more than 25 billion devices.



Source:Booz & C 2012

Internet of Space

"Internet of Things" requires also data access to remote locations (by example oil platforms in deep sea, mines in mountains,…) and to mobile systems (trains crossing deserts, transport drones, autonomous cars, airplanes over the oceans, ships on sea, ….)

WWW becomes worldwide: Planned Mega-Constellations of Satellites

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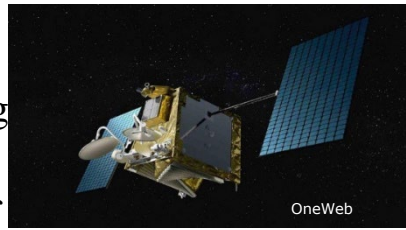
Earlier approaches for global telecommunication networks in LEO:

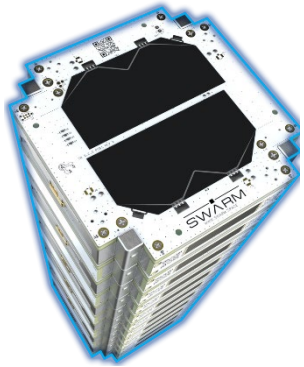
- **Iridium, GlobalStar**, … currently upgrade to a 2nd generation

Recent developments:

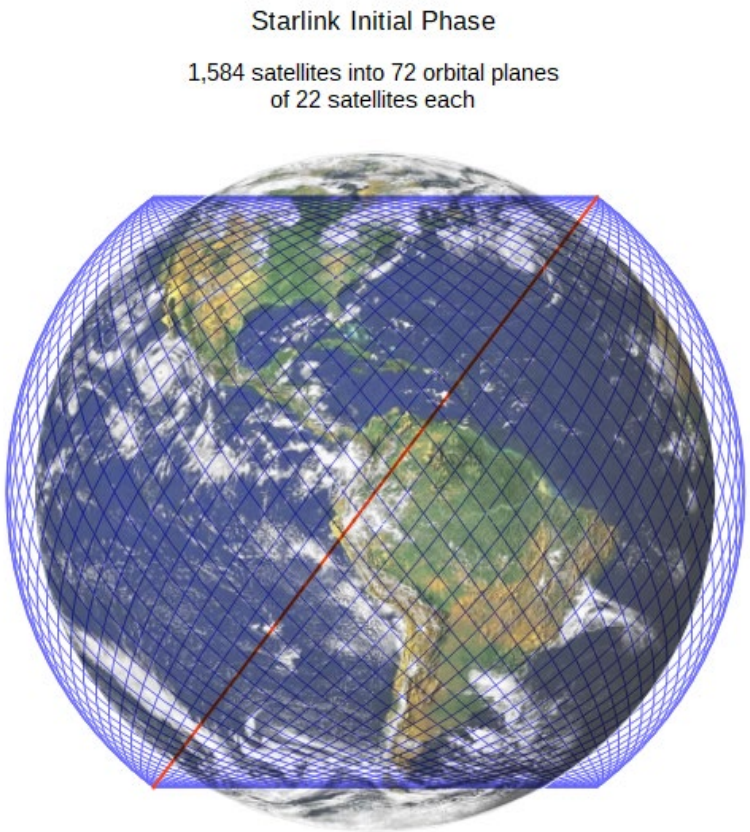
- **SpaceX**, launched **1791** "**Starlink**" satellites with 227 kg between **2019 and end of 2021** at an operational altitude of 550 km. Since 2021 with laser inter-satellite link. Planned constellation in V-band composed of **7.518** satellites, following the earlier proposed **4.425** satellites in Ka- and Ku-Band
- **OneWeb** launched first 6 satellites **26.2.2019,** has **358 satellites** with a mass of 147.5 kg in orbit. It plans for **648** in LEO and **1.280** in Medium Earth Orbit (MEO).



- **SWARM** operates more than 100 very small satellites (mass 400 g, 0.25 U CubeSat) of planned 150 in orbit for continuous low bandwith communication links
- **Amazon**, "Project Kuiper" got ITU-approval of 784 sats at 590 km orbit, 1.296 sats at 610 km and 1.156 sats in 630 km.
- **other companies (OrbCom, TeleSat, Samsung, Boeing, ...)** announced further LEO-constellations
- China claimed at ITU frequencies for a total of 12,992 satellites (GW-A59 and GW-2"), involved are CASIC and CASC, as well as companies like LinkSure and Galaxy Space



Starlink communication satellite network

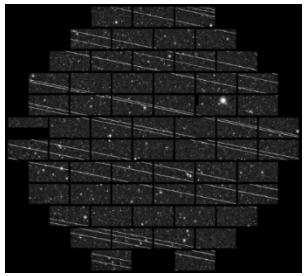


As end of 2021, SpaceX has launched 1 792 Starlink satellites

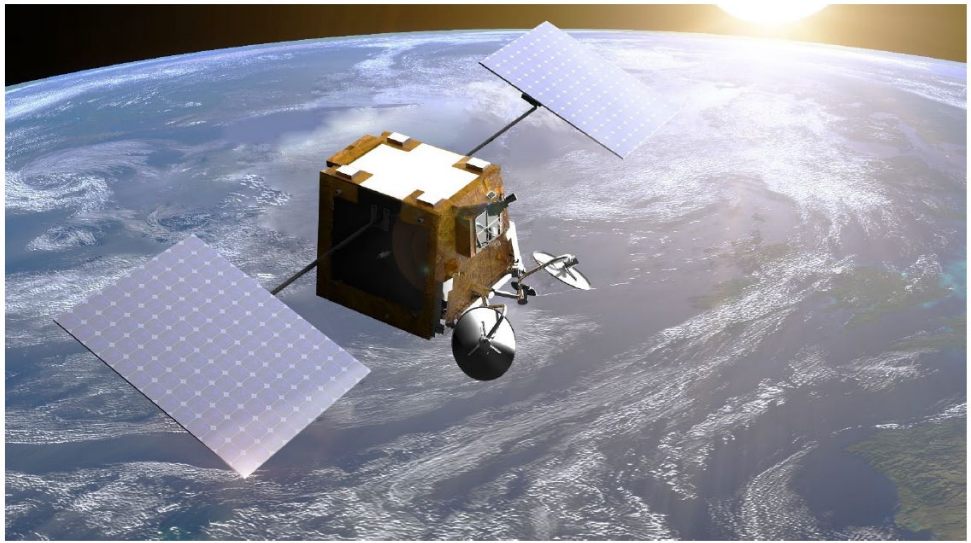
Current FCC application:

- First shell: 1,440 in a 550 km altitude shell at 53.0º inclination.
- Second shell: 1,440 in a 540 km shell at 53.2º inclination.
- Third shell: 720 in a 570 km shell at 70º inclination.
- Fourth shell: 336 in a 560 km shell at 97.6º.
- Fifth shell: 172 satellites in a 560 km shell at 97.6º.

Pollution of night sky

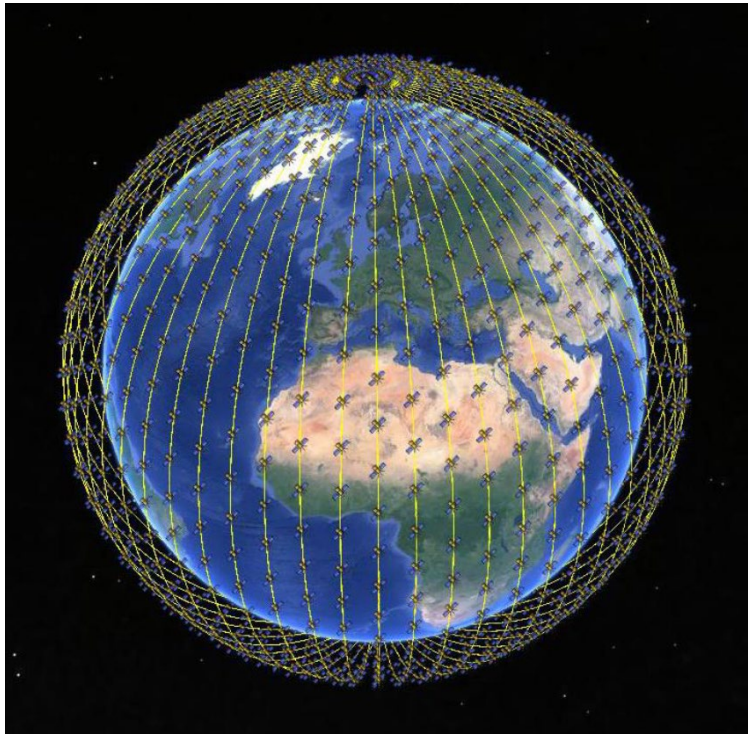


ONEWEB SATELLITES



CUSTOMER	OneWeb
MANUFACTURER	OneWeb Satellites (Florida factory)
MISSION	Global connectivity
OPERATIONAL ORBIT	Low Earth orbit, at 1,200 km. altitude and 87.4° inclination
PLATFORM	Specific
PROPULSION	Electric (Xenon HET)
BATTERY	Li-ion
ANTENNAS	Two TTC omni antennas; two Ku-band antennas; two Ka-band antennas
STABILIZATION MODE	3-axis stabilized
COVERAGE	Global

Currently 12 orbital planes with 49 satellites, leading to 588 operational satellites plus 60 on-orbit spares.



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Arguments for satellite based IoT

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1. **Coverage** of large areas and remote sites
2. **Reliability**, with advantages for scalable availability, for overload situations, as redundant chanel
3. **Long life duration** infrastructure (life cycle of satellite networks ca. 20 years, longer duration than mobile radio networks (2G GSM 1996, 3G UMTS 2004, 4G LTE 2010, 5G LTE Slicing 2020))
4. **No local infrastructure** needed, similar equipment worldwide used
5. **Isolation** (higher safety and reliability as closed system, proprietary satellite IoT-network)
6. **Multicasting**

Key Technology Development Areas for Science: National Academy of Science Recommendations

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“ Constellations of 10 to 100 science spacecraft would have the **potential to enable critical measurements** for space science and related space weather, weather and climate, as well as some astrophysics and planetary science topics. Therefore NASA should develop the capability to implement **large-scale constellation missions** taking advantage of **CubeSat**s or **CubeSat derived technology** and a philosophy of evolutionary development.

NASA and other relevant agencies should invest in technology development programs in four areas that the committee believes will have the largest impact on science missions:

- high bandwidth communications,
- precision attitude control,
- propulsion and
- the development of miniaturized instrument technology.”

(source: NAS report “Achieving Science with CubeSats”, 2016)

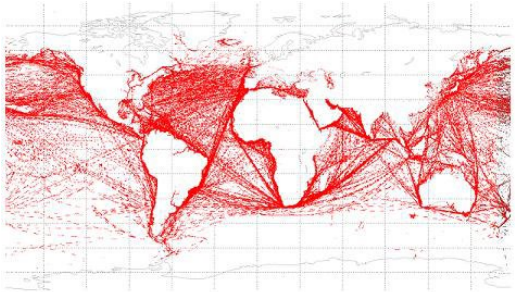
Small Satellite IoT Applications

By using very small satellites a space based communication system can provide the following properties

- global availability
- 24/7 h service
- low cost implementation opportunities
- support of energy-autonomous sensor systems
- safe and high availability data transfer for IoT (monitoring, process management and control, ...)
- low latency in LEO

→ Pico- and Nano-satellites support paradigm change in space technology towards "faster – less expensive – high commercialization potential"

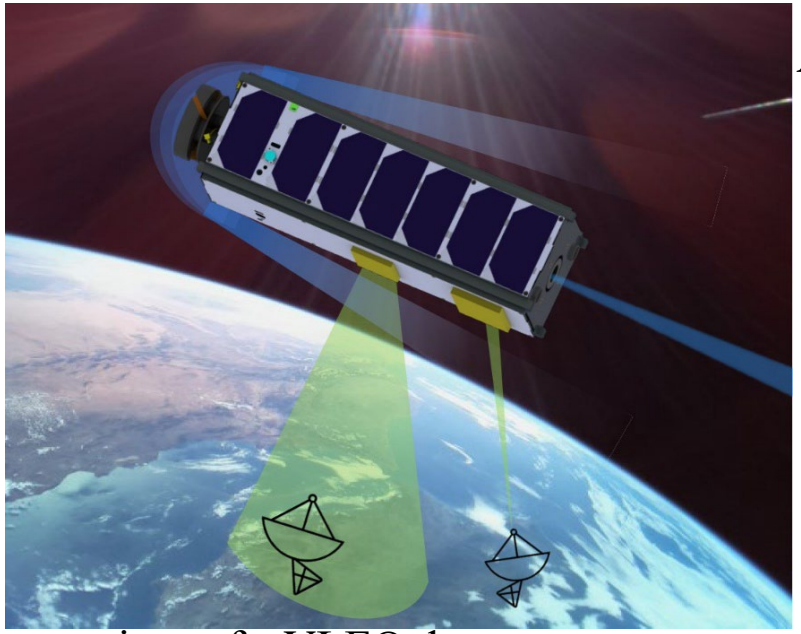
IoT Application: Automatic Identification System (AIS) for Railway Transport Tracking



90 % of worldwide transports are done by ships. The Automatic Identification System (AIS) is used to avoid collisions. The first AIS data from AISSat-1 (a 20 cm cube). The yellow and orange symbols show the new AIS data that the satellite gives in addition to the data from the land-based network shown in turquoise symbols. (credits: FFI)

IoT Feature on Low Latency :

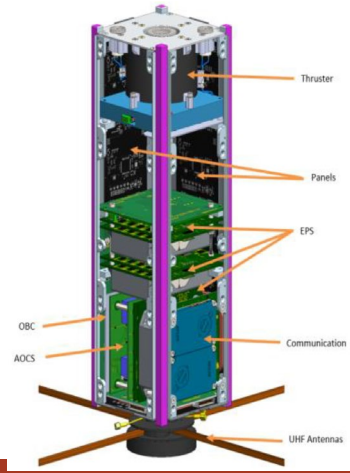
LoLaSat: Minimal Signal Latencies in Satellite Communication at VLEO



operations of a VLEO demonstrator satellite in an orbit between 200 km and 300 km altitude with a tele-communication payload in Ka-band

Applications

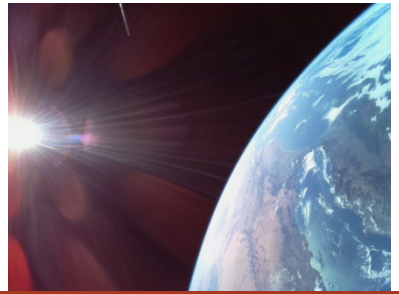
- real-time aspects are essential in 5G / 6G
- key application fields:
  - collision-free, autonomous driving of networked vehicles,
  - control of transport drones in air,
  - support in emergency operations,
  - high frequency trading of stock options



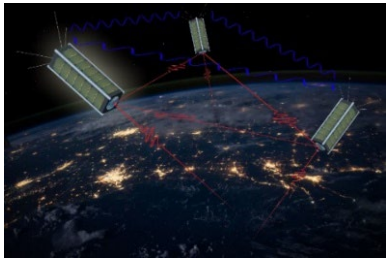
Our current research missions in formations

technology development for nano-satellite formations

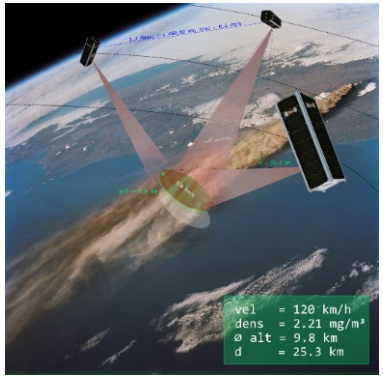
NetSat (launched 28.9.2020)
networked control, intersatellite links, and relative navigation for small satellite formations



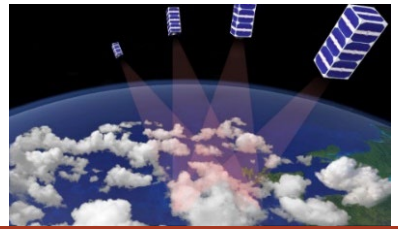
applications



QUBE (2022)
Quantum key distribution for secure communication



TIM / TOM (2022)
3D-Earth observation by photogrammetric methods



CloudCT (2023)
computertomo-graphy of clouds for improved climate predictions

Crucial Technologies: Capabilities for Production of Several Satellites per Day, Used at NetSat (launched 2020)

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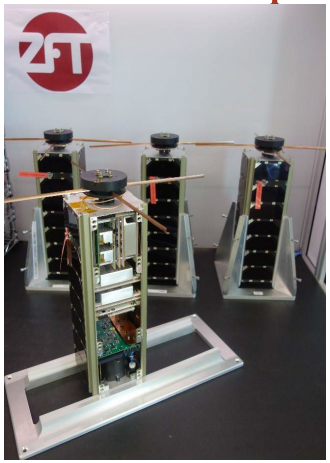
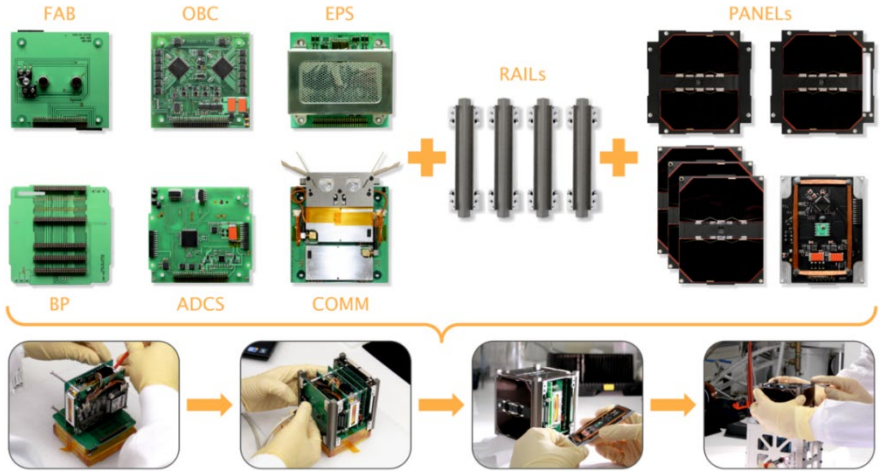
Winner 2017



the four NetSats



modular, flexible integration by UNISEC Europe standard electrical interfaces

recent NetSat image

inter-satellite link tests in Würzburg with high precision, high dynamics turntables

Further information:
klaus.schilling@s4-space.com

Use case:
Robotic Assembly of solar cells on satellite side panels (in orbit)

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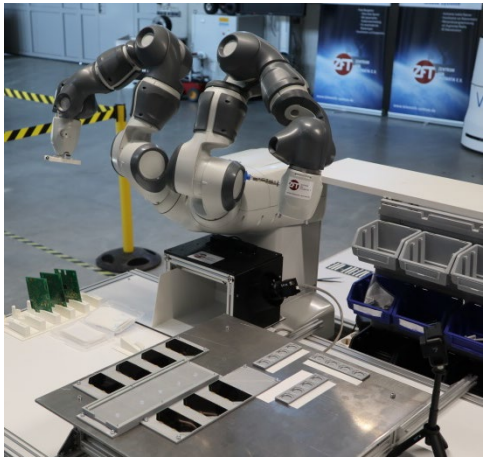
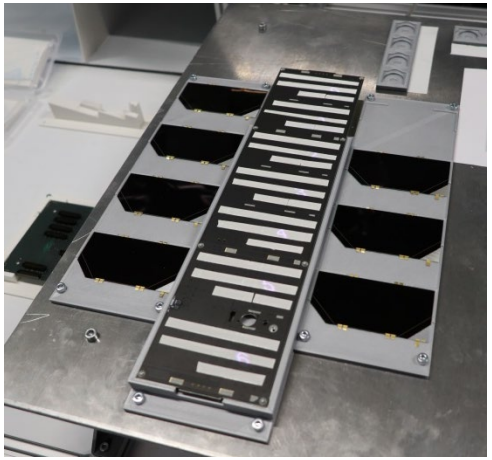
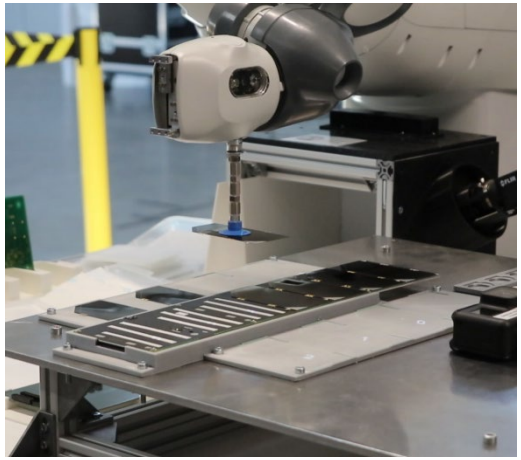
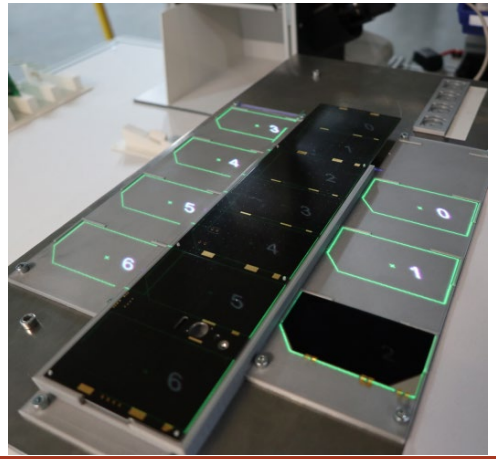
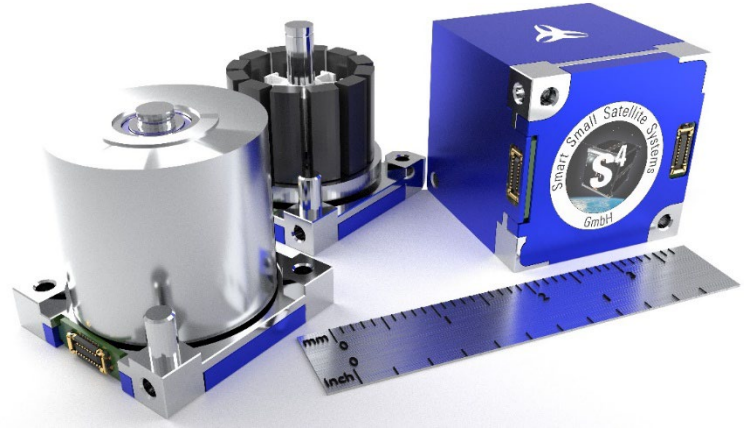
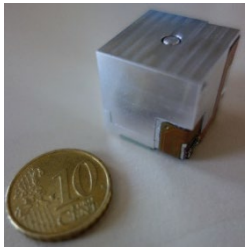
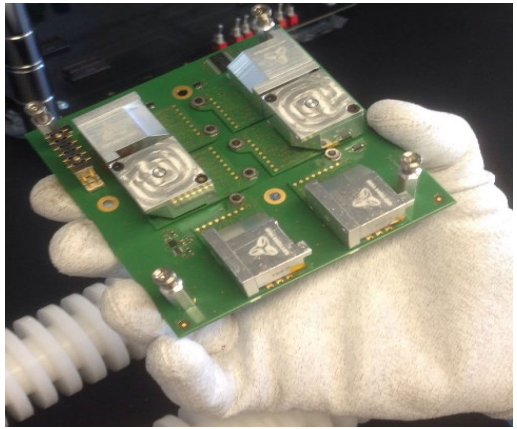





Technology Challenge:

Miniature, Precision 3-Axes Attitude Control System







Efficient Reaction Wheel

- Momentum storage 2.0 mNms
- Nominal rotational speed 19 000 rpm
- Nominal torque 0.1 mNm
- Mass < 20 g
- Dimension 20×20×20 mm
- Power (nominal) < 200 mW

Future 3-Axes attitude control system

Four such miniature reaction wheels are combined to form a 3-axes control system with nominal operation power need of just 0.5 W, providing even redundancy by the fourth wheel; for desaturation magnetorquers are used.

NetSat electric propulsion system used in combination with 3-axis attitude control

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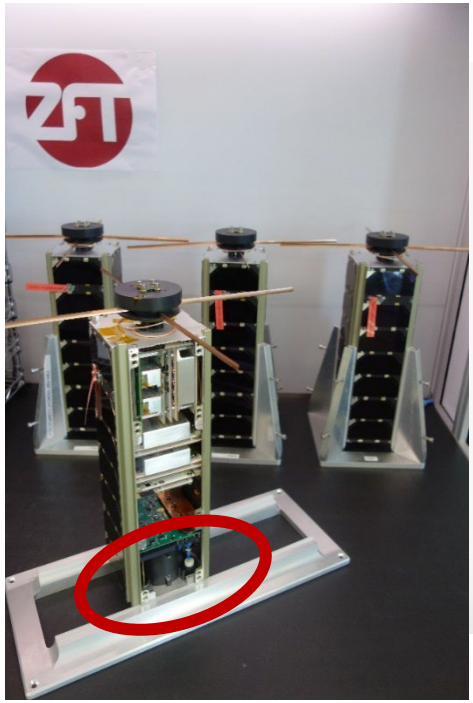

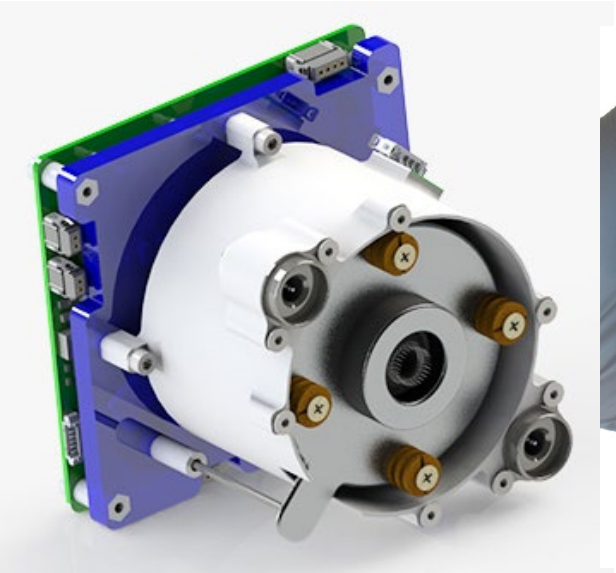

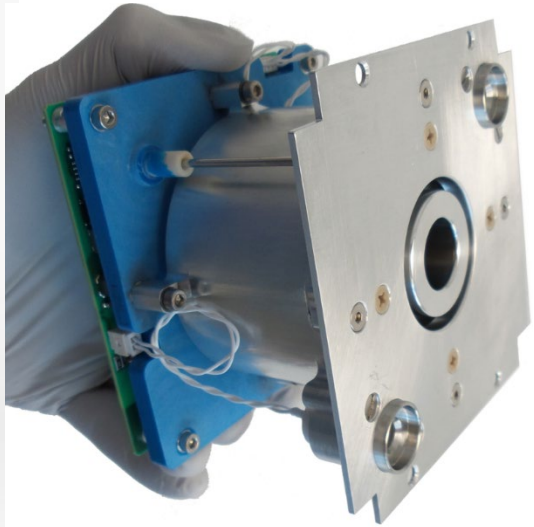

PARAMETER	VALUE
Dynamic thrust range	10 µN to 0.5 mN
Nominal thrust	350 µN
Specific impulse	2,000 to 5000 s
Propellant mass	250 g
Total impulse	more than 5,000 Ns

Power at nominal thrust	35 W incl. neutralizer
Outside dimensions	94 x 90 x 78 mm
Mass (dry / wet)	640 / 870 g
Total system power	8 – 40 W
Hot standby power	3.5 W
Command interface	RS422/RS485

Technology Breakthrough:
Orbit Control for Pico-Satellites

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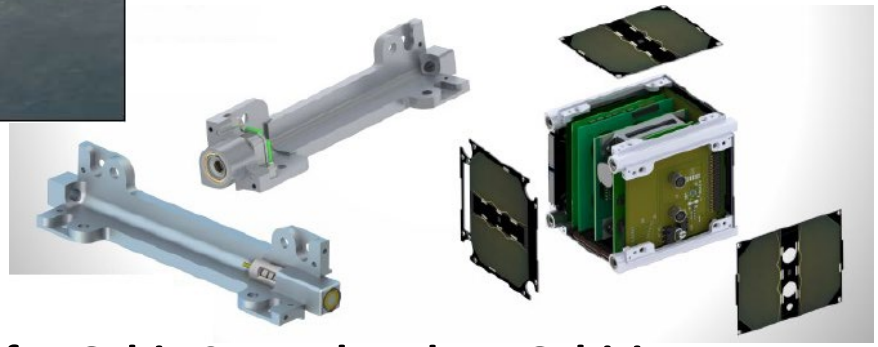
Determination of attitude by magnetometers, gyros and Sun sensors, while an electrical propulsion system is used for corrections

Electrical propulsion systems comparing FEEP- und Micro-Arc-Thrusters

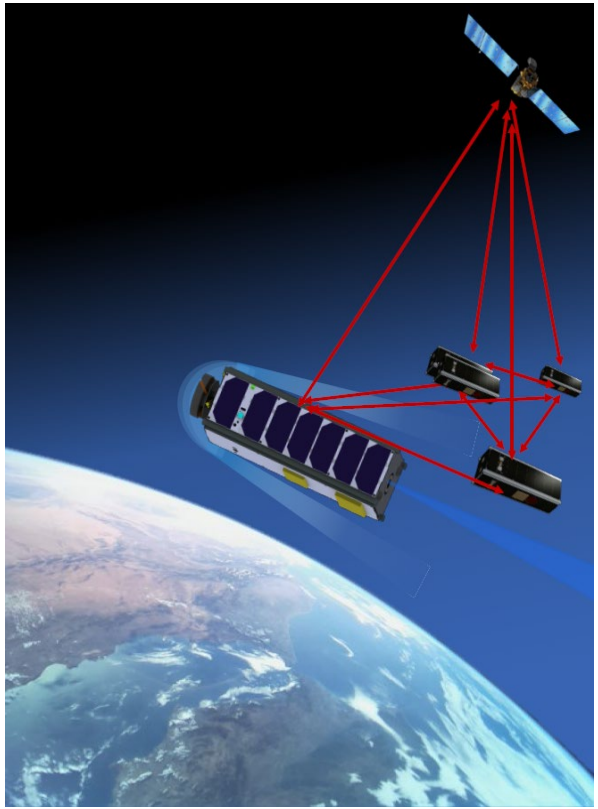


Electric Propulsion System for Orbit Control and De-Orbiting

is flown on UWE-4 (launched 27. December 2018); Worldwide first collision avoidance manoeuvre by pico-satellite July 2020

Crucial Formation Technologies:

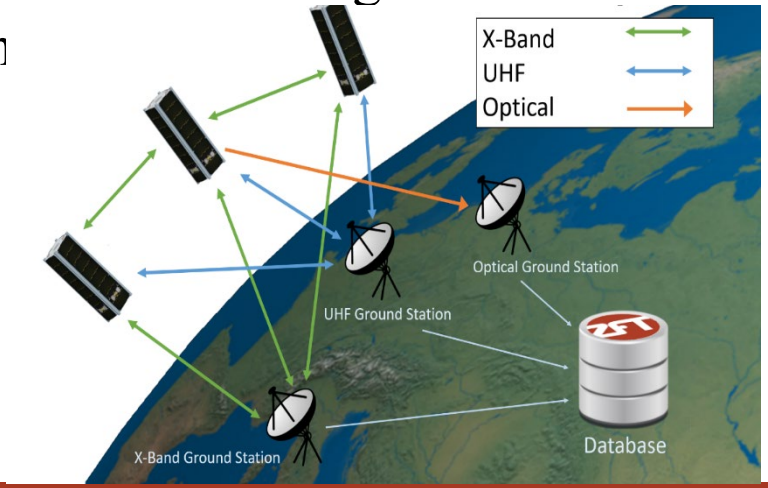
self-organization, collision avoidance, planning, inter-satellite links, networked control



Inter-Satellite Links

Complex coordination of antenna pointing ISL in multi-satellite systems; multi-objective optimization needed

Coordination of LEO / GEO / ground station commun



Multi Satellite Simulation Environment in Würzburg

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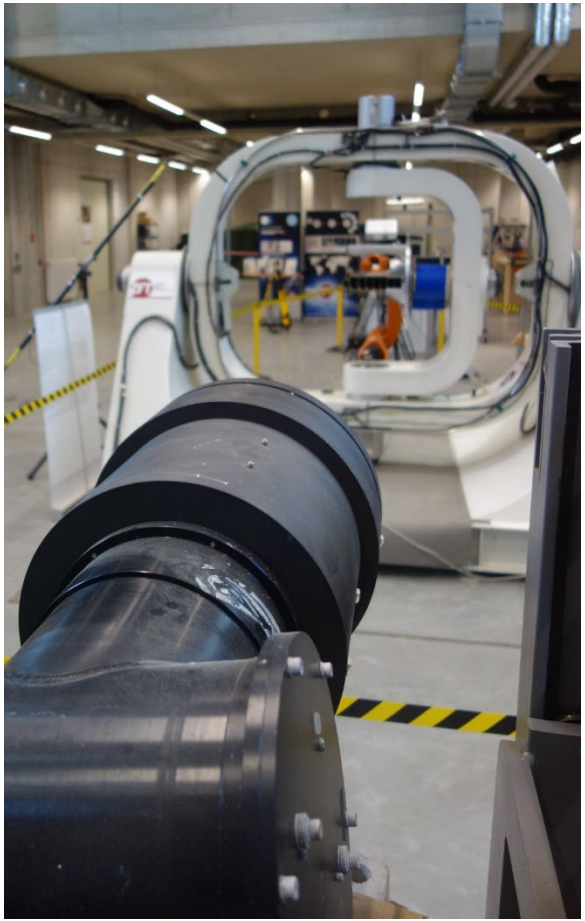
Turntables providing high precision and high dynamics capabilities

NetSat
Hardware in the Loops Tests:
Solar Illumination Simulations



Conclusions for Distributed Satellite Systems

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- The paradigm shift from large spacecraft with multiple payloads to decentralized, distributed, networked, small satellite systems is obvious
- High level of autonomous operation capabilities is implemented.
- Advantages for telecommunication systems and Earth observation are higher fault tolerance and robustness of the overall system, as well as better temporal resolution.
- Formations and constellations are scalable : according to application needs additional satellites can be added to increase resolution and coverage.
- Satellite systems, composed of few large and many small satellites will provide high data quality, as well as flexibility and robustness.
- Significant application potential in Earth observation and communication, in particular for IoT and highly dynamical processes.
- Challenging control topics for future research in self-organisation, networked and model-predictive control

Excellent opportunities for international cooperation !

Conclusions

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Technology achievements in the field of small satellites

- modular, flexible design with standardized interfaces via backplane
- suitable attitude determination and control capabilities
- robust miniaturized on-board data handling system
- orbit control capabilities by electric propulsion

Networked systems composed of small satellites offer efficient approaches for

- high spatial and temporal resolution
- affordable low-bandwidth communication
- cooperatively solving faster more complex tasks by parallelization
- higher fault tolerance and robustness of the overall system
- scalability (according to application needs further satellites can be added)

Application aspects

- efficiency in flow of materials and logistics can be increased at global scale
- closing the control loop via real-time communication links by LEO satellites enables interactive IoT solutions, e.g. in telemaintenance
- low cost, secure IoT approach by small satellite networks