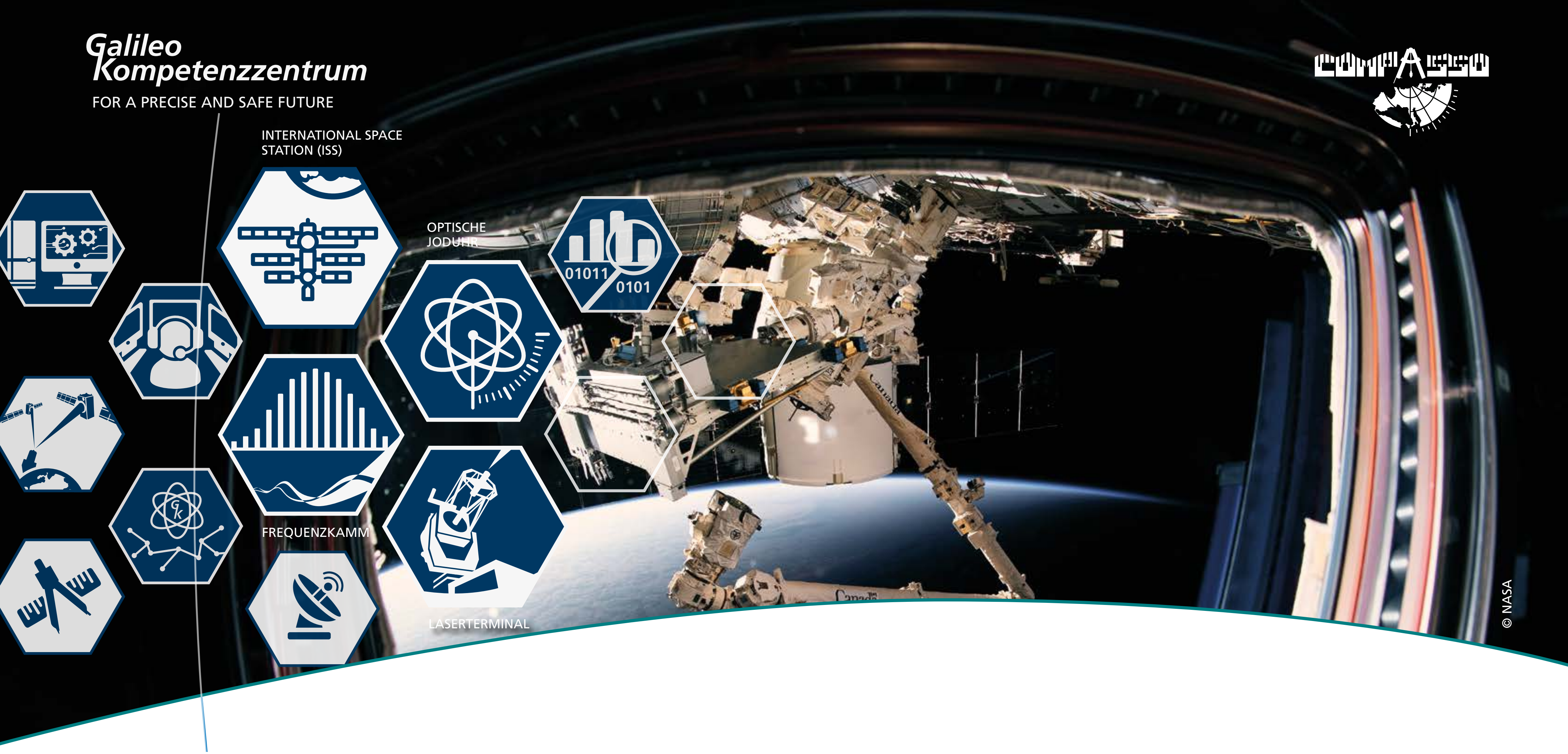


INNOVATIVE, HIGH-PRECISION QUANTUM OPTICAL TECHNOLOGIES FOR THE CONTINUING DEVELOPMENT OF EUROPE'S GALILEO NAVIGATION SATELLITE SYSTEM

COMPASSO

DLR

First In-Orbit Qualification of Quantum Optical Technologies

Galileo Kompetenzzentrum

DLR

About COMPASSO

Our motivation:
Technological and social progress

What does COMPASSO stand for?
Development and validation of a new generation of high-precision optical clocks and laser terminals

What does COMPASSO lead to?
Improvement of the overall Galileo system

Benefits for society/vision of the future
More precise and reliable services in the area of mobility (e.g. position determination in aviation, rail traffic, shipping, for highly automated vehicles), agriculture and forestry, surveying, time synchronization, climate protection, etc.

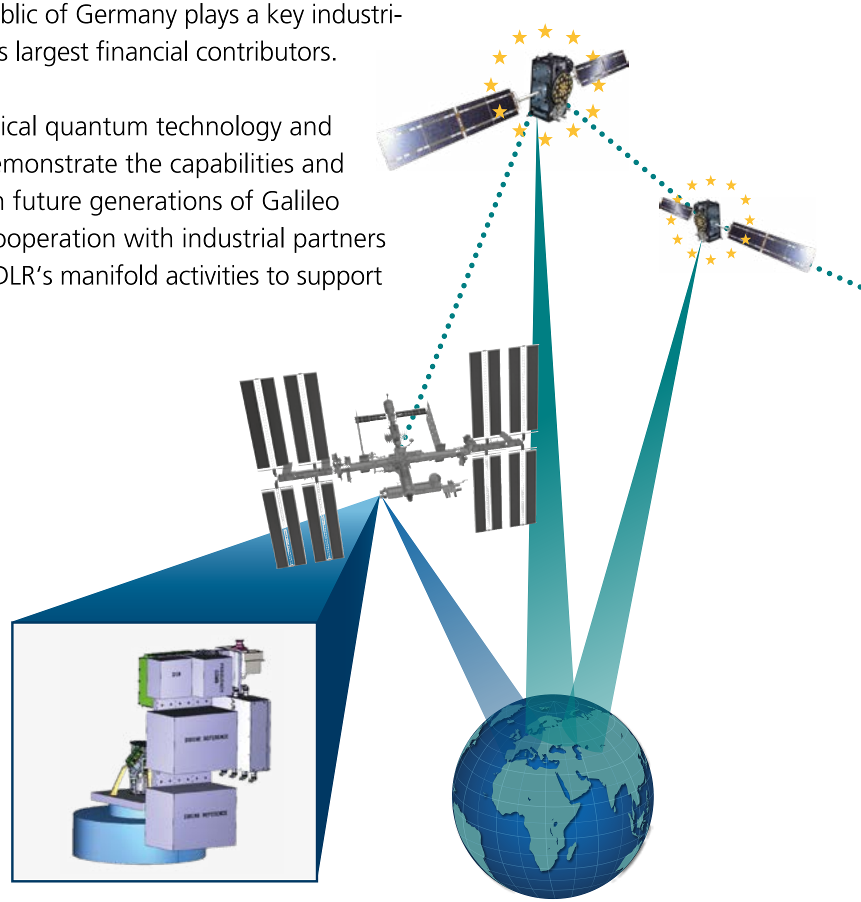
COMPASSO - Experiment: Payload
The payload consists of the instruments: iodine clock, frequency comb, laser communication terminal
It is mounted on the Bartolomeo platform attached to the European Columbus module of the International Space Station (ISS).

FOR A PRECISE AND SAFE FUTURE

Welcome to COMPASSO

Germany is one of the international forerunners of research into quantum technologies. The federal government has taken important steps to secure a leading role in such technologies in the medium term. Another field of high economic and social relevance is satellite navigation. Of particular interest is the further development of the European navigation satellite system, Galileo. The Federal Republic of Germany plays a key industrial role in the Galileo programme and is also one of its largest financial contributors.

The COMPASSO project unites the two fields of optical quantum technology and Galileo. The primary objective of the project is to demonstrate the capabilities and reliability of quantum optical technologies for use in future generations of Galileo satellites. COMPASSO is being developed in close cooperation with industrial partners and, as such, is another important building block in DLR's manifold activities to support technology transfer.



COMPASSO:
Qualification of compact and highly stable laser-optical clocks and laser terminals for outstanding future Galileo technologies

The World of Navigation

Position determination by calculation of the distances between the receiver on the Earth and at least three identified satellites (**trilateration**).

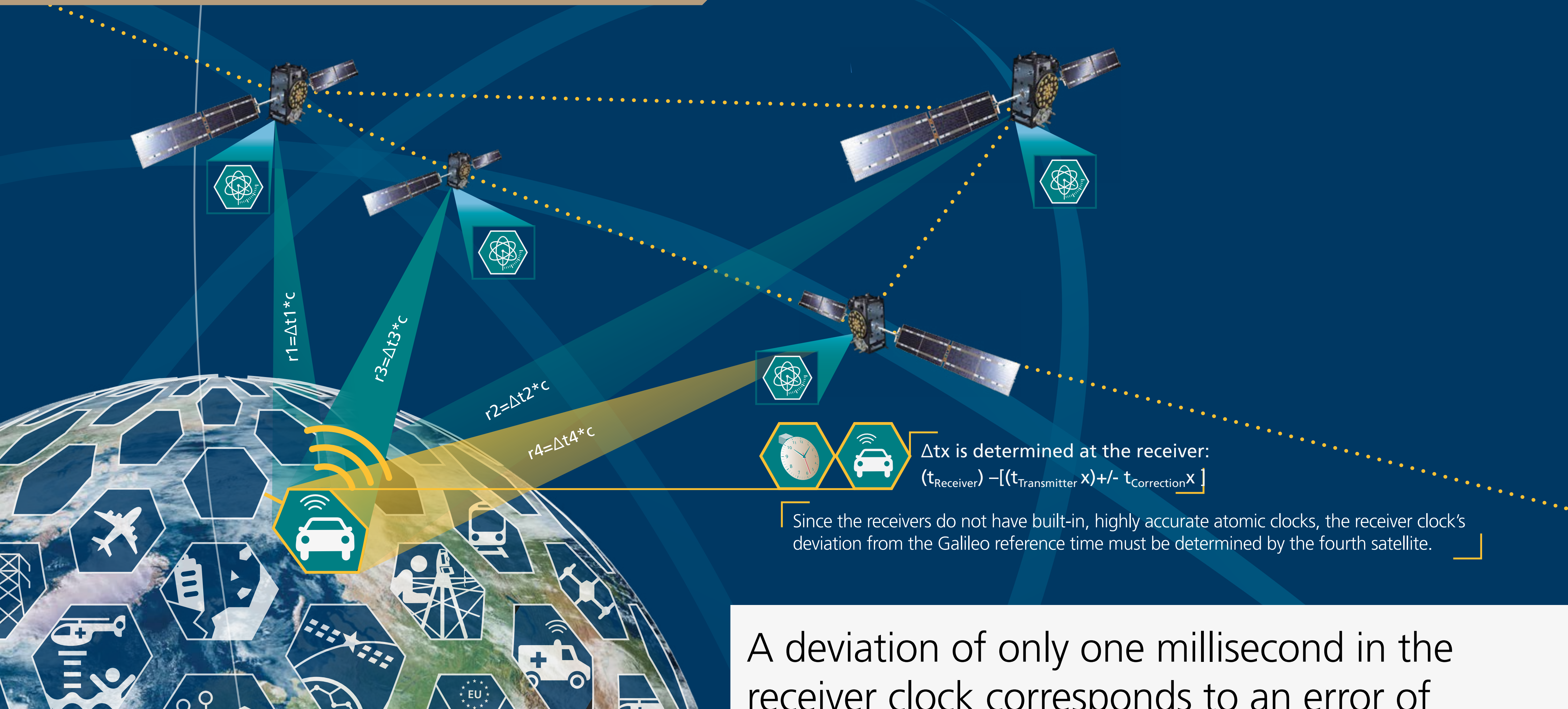
The point is thereby calculated at which the three vectors (r1, r2, r3) cross (comparable to x,y,z axes).
A fourth satellite is required to calculate the **time delay** (r4) of the receiver clock.

- At least 4 Galileo satellites are required. The more satellite signals received, the more accurate and stable the position determination on Earth will be.

This (simplified) representation does not portray additional sources of error, such as the effect of the atmosphere on signal propagation.

Telemetry data with the on-board clock time $t_{Transmitter}$, satellite orbit and time corrections $t_{Correction}$ are sent continuously. $t_{Correction}$ is calculated from the difference between the satellite clock time and the Galileo reference time on the ground.

Range measurement over run time $rx = \Delta tx * c$
Δtx = time required for the signal to travel from satellite x to the receiver
c = speed of light (~300,000 km/s)



Δtx is determined at the receiver:
$(t_{Receiver}) -[(t_{Transmitter}\, x)+/- t_{Correction}\, x]$

Since the receivers do not have built-in, highly accurate atomic clocks, the receiver clock's deviation from the Galileo reference time must be determined by the fourth satellite.

A deviation of only one millisecond in the receiver clock corresponds to an error of about 300 km on the Earth.

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Subjects covered in this Brochure

Innovation for Europe

Current Galileo system:

Galileo's time system accuracy: less than 8 nanoseconds deviation from UTC world time.

Positioning accuracy: better than 2 m

COMPASSO as an important project for future technologies on Earth

Rail traffic

Certain collision avoidance by highly accurate position determination (track spacing often only 3.5 m)

Shipping

Transport routes are optimized, and therefore environmental pollution and costs reduced. More accurate and reliable location determination for sea rescue.

Surveying and construction

Whether railways, roads, industrial plants or building construction, modern surveying technology today is reliant on the use of GNSS signals and enables not only (small-scale) surveying in urban or rural areas, but also on a large scale, e.g. in the field of global Earth measurement (geodesy).

Agriculture and forestry

Greater precision in farming reduces the use of fuel, pesticides and fertilizers - for an environmentally compatible and sustainable agriculture.

Aviation

Signals received everywhere (also over oceans)

▶ Disappearance without trace of an aircraft is thereby virtually impossible. Safe aircraft separation and high-precision landing can always be guaranteed in poor visibility.

▶ Precision landings in poor visibility

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INVOLVEMENT IN SOCIETY

COMPASSO – Future Potential

There is an extensive range of applications that benefit from **Global Navigation Satellite Systems (GNSS)** due to the high precision and global availability. These can be improved and expanded with COMPASSO because the use of optical quantum technology promises higher accuracy, reliability and performance, compared to the existing technology. Future services can thus become even more sustainable, secure and more efficient for us all.

Since the social relevance in the field of satellite navigation is growing rapidly, a large number of further innovative opportunities will open up in this market area in upcoming years. Industrial partner participation in COMPASSO secures a competitive advantage by developing know-how and technological capabilities by virtue of experiencing use of their technologies in space.

COMPASSO thus contributes to the promotion of the commercial use of innovative technologies in space and to the diffusion of quantum technology research in Germany. Within the framework of European cooperation, this project also enables DLR and Germany to make valuable contributions to the further development of Galileo while playing a significant role in its future.

Location based services
The „classic“ among navigation services is the determination of your own location, leading to a variety of associated services such as route calculations, destination options (restaurants, shops, etc.), geocaching, fitness programmes or emergency services.

Time services and synchronization
Although generally less well-known, exact time synchronization and time stamps are of considerable benefit to financial transactions, the mobile communications sector, as well as to power supply (e.g. power grids or wind farms)

Mobility
In the transport sector, all variants - from individual travel by rail, ship and air to autonomous driving - are no longer conceivable without GNS systems. These offer the ideal technology to guarantee maximum precision and safety in any weather, season, surroundings or light source.

Climate research
Highly accurate GNS data support and permit a variety of analyses in the field of climate research. Space based Earth Observation missions are prominent users in addition to terrestrial applications. These may use GNS data, for example, in high-precision gravitational measurements, or to measure and monitor seasonal changes in river flows.

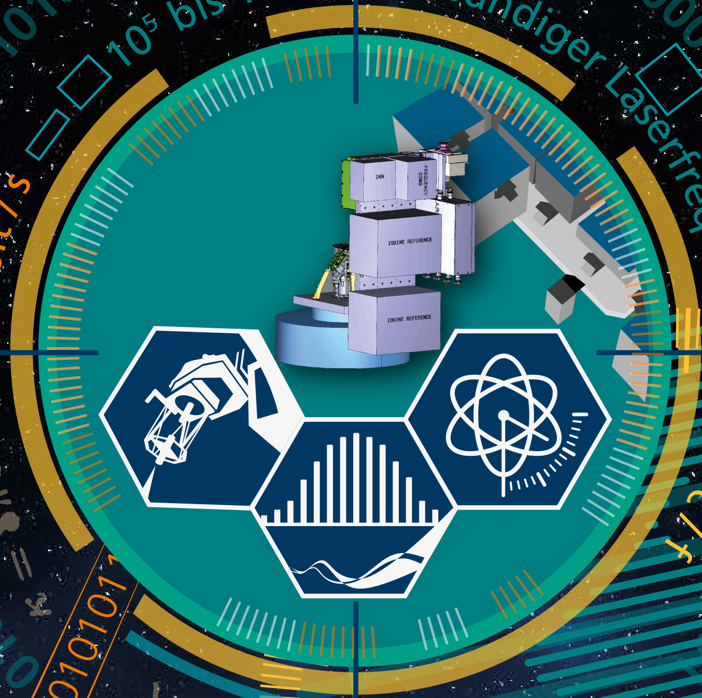
**Technological progress:
The clock in transition**

Mechanical clock working to the approximate frequency of 1 Hz
- Inaccuracy: around 1s per day

Quartz clock working in the order of MHz (10^6 Hz)
- Inaccuracy: around 1s a year

Atomic clock in GHz (10^9 Hz)
- Inaccuracy: 1s in a million years

Optical clocks in PHz (10^{15} Hz)
- Inaccuracy: 1s in a billion years



Laser
Laser communications systems transmit data at a rate of up to 10 Gbit/s (for comparison, mobile 4G communications are at 1 Gbit/s).

Enabling highly precise range measurement between satellite and ground, or between two satellites to the accuracy of millimetres.

Frequency comb
A frequency comb can be thought of as a laser ruler for light, consisting of about 10^5 to 10^6 extremely narrow bandwidth laser frequencies.

Uses:
- Measurement of high frequency optical frequencies (e.g. optical clocks)
- Interface between optical and radio frequencies.

Clocks:
In general, a clock consists of a pendulum (oscillator), which swings as evenly as possible, and a counter, which measures the number of swings. The faster the swing of the pendulum, the finer the time measurement.

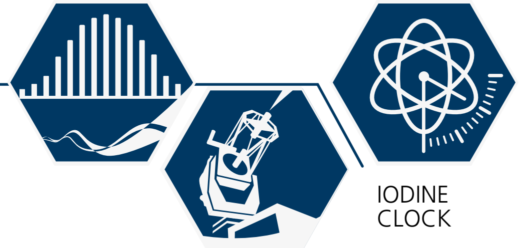
Optical clocks:
As an optical Oszillator (reference for the frequency) one uses an atom that transmits a precisely defined wave in an optical frequency, i.e. in visible light.

With COMPASSO, this is molecular iodine with a wavelength of approx. 500 nm (= green light).

One second lasts as long as 9192631770 oscillations of an atom of nuclide caesium 133

A second (s) is the SI unit of time

FREQUENCY COMB

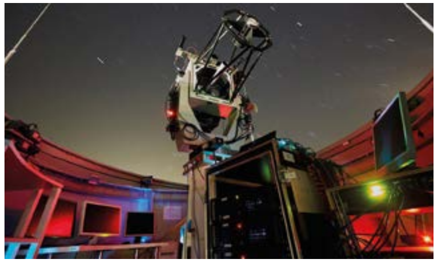


IODINE CLOCK

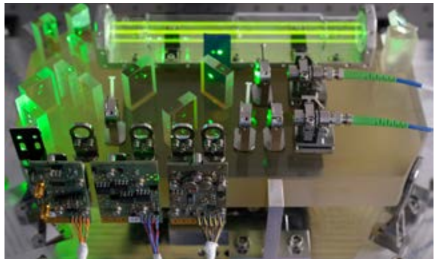
LASER TERMINAL

PAYLOAD ON THE ISS - THREE CORE TECHNOLOGIES:

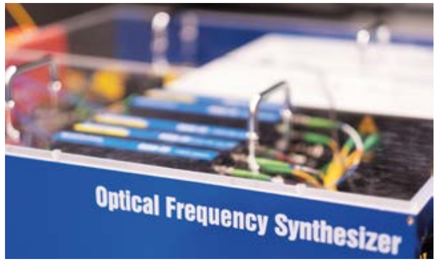
Iodine Clock, Frequency Comb and Laser Terminal



Optical ground station Oberpfaffenhofen



Optical iodine clock (Institute of Quantum Technologies)



Frequency comb from the company Menlo

1. BIDIRECTIONAL LASER TERMINAL

The enhanced laser terminal developed by Tesat in cooperation with DLR and used in the COMPASSO mission is an excellent alternative to exchange information between satellites and the ground station. Compared to communicating via radio waves, it offers significant technological advantages (e.g. weight, bandwidth, accuracy) and also enables high-precision range determination and novel possibilities for secure data exchange (e.g. using quantum cryptography).

2. OPTICAL IODINE CLOCK

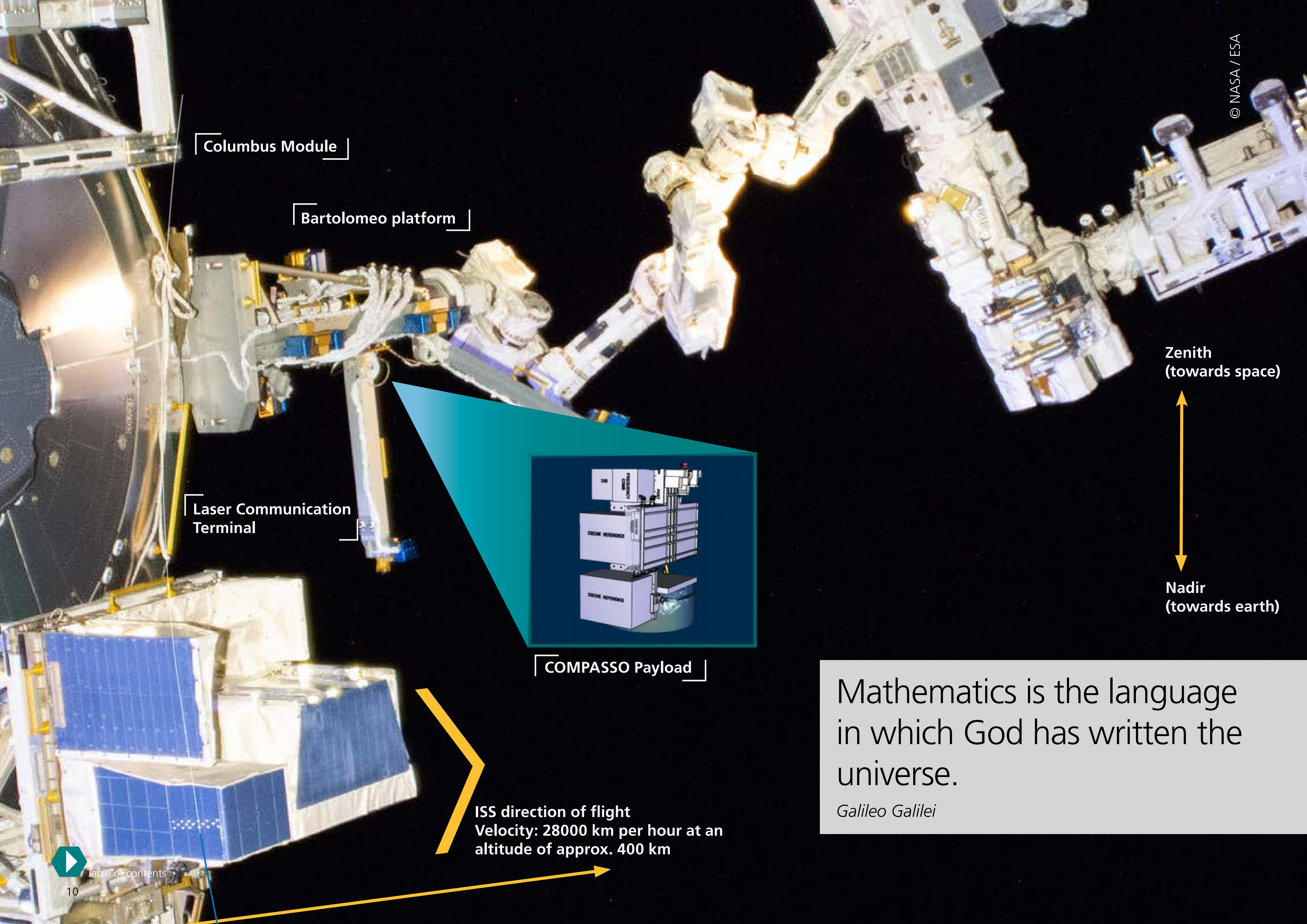
The optical iodine clock developed at DLR and tested both in the laboratory and on sounding rockets is a high-precision optical frequency reference and time base. It represents an innovative, technological alternative to the existing atomic clocks used in satellite navigation, and evidence of its suitability for future Galileo satellites (and for other scientific and commercial space missions) will be provided within the scope of COMPASSO.

3. FREQUENCY COMB

The frequency comb developed by Menlo is a physical interface between optical frequencies and the range of radio frequencies used for satellite navigation. The frequency comb, which has also already been tested on sounding rockets, will be adapted and certified for use in space as part of COMPASSO.

In the COMPASSO experiment, a system will be formed by connecting the iodine clock with the frequency comb to generate a highly stable (low-noise) frequency and thus a highly accurate time base. The combination of iodine clock and frequency comb is necessary because optical clocks oscillate extremely fast. However, there are no electronic systems that can directly count these oscillations. With a frequency comb, optical clock oscillations are converted into lower frequencies, which can then be combined and counted with conventional microwave systems.

The task of the laser terminal is to transmit the signal generated by the frequency comb and time information to the ground, and at the same time carry out highly accurate ranging measurements. A successful qualification of these technologies in space is the basic prerequisite for later use in future generations of Galileo satellites.



Mathematics is the language in which God has written the universe.

Galileo Galilei

CHRONOLOGICAL REVIEW

Mission Scenario

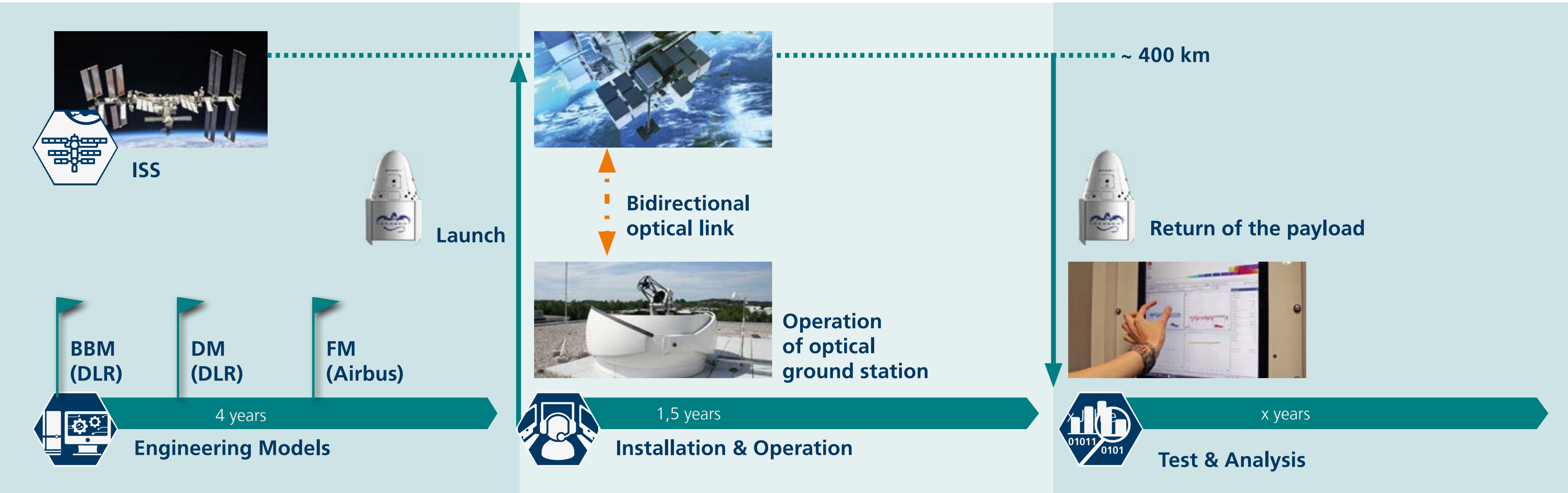
COMPASSO can be divided into three phases:

1. Payload Development Phase:
Within this phase, which is scheduled for a period of four years, the COMPASSO payload will be developed and tested.
Different models of the individual components (iodine clock, frequency comb, laser communication terminal, ...) will be qualified, depending on their development status in progressing towards the final payload.

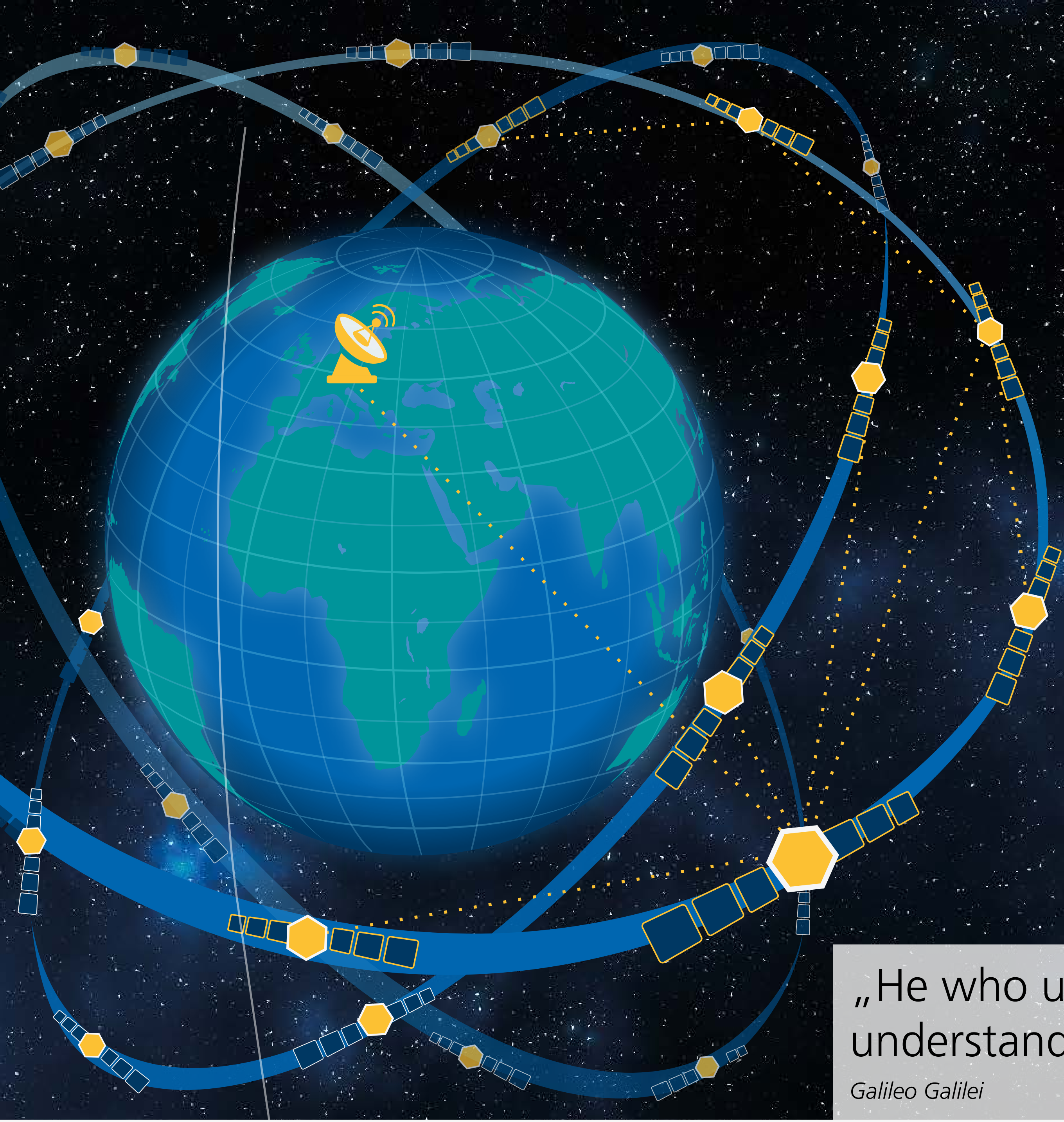
Three model versions are planned for the overall system, as shown in the diagram:
- Breadboard Model (BBM): a not fully representative model created from existing laboratory equipment which will allow first functional tests.
- Development Model (DM): a developmental model that is as close as possible to the final design of the payload and will enable comprehensive tests of the hardware and software.
- Proto-Flight Model (PFM): final payload, ready for use on the ISS.

2. In-orbit Operations / Experimental Phase on the ISS:
This phase includes the actual space mission and covers a period of 1.5 years.

3. Return and Validation
This phase concludes the mission. The payload will be disassembled into its components on the ISS, these will be returned to Earth and handed over to DLR for final analyses and tests.



Payload assembly on the ISS:
A launch of the COMPASSO payload is currently envisaged in the 202 timeframe.



30 Galileo satellites at around 23,000 km
For more independence for Europe

The civil Galileo system has been in operation since December 2016, all planned services should be available by 2021/22.
It guarantees Europe access to its own global navigation satellite system, even if other systems are switched off or lose accuracy.

„He who understands geometry is able to understand everything in this world.“

Galileo Galilei

GALILEO EVOLUTION - FOR THE NEXT GENERATIONS OF GALILEO SATELLITES

COMPASSO: Qualification of Optical Technologies

Galileo Evolution

Use of high-precision and robust frequency references and clocks on the satellites

Optical Inter-Satellite Links (ISL): Robust, secure and high-rate communications links between the Galileo satellites

Optical Inter-Satellite Ranging (ISR): High-precision measurement of satellite positions in orbit

Higher accuracy and reliability
▸ wider range of uses

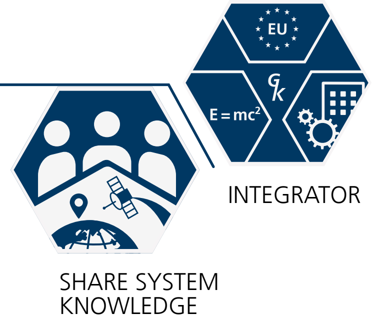
The Galileo programme must not only ensure the maintenance of its positioning and time services, but at the same time constantly evolve to meet the demands of a dynamically developing society and economy. Technological evolutionary scenarios for the next generations of Galileo satellites are therefore regularly discussed within the programme. Of great importance in this context are improved, high-precision clocks and laser terminals on the satellites, as well as inter-satellite links. The latter enable data transmission, range measurement and a (more) precise time and frequency transmission between the Galileo satellites.

These technologies must satisfy strict requirements in order to be admitted into the Galileo system. This means that they must not only have a significantly improved functionality in comparison with existing components but must also particularly satisfy space specific and operational aspects. Regarding future generations of Galileo satellite clocks, this means that they must not only be highly accurate and stable but must function over a long period of time under space conditions, have a low physical volume, low power consumption and be amenable to simple operation.

This is why COMPASSO is so important.
The optical clocks and terminals used here offer, in addition to other applications, the exact answers to the planned development scenarios. A successful space qualification of the optical technologies implemented in COMPASSO will be a milestone for their use in future generations of Galileo satellites. There, these optical clocks and the new generation of laser terminals can make a significant contribution to improving satellite orbit determination and Galileo system time generation. Compared to today's system, this will enable future users to determine their location 10 times more accurately and faster down to centimeter level. At the same time, new opportunities for Galileo applications will arise, e.g. for the synchronization of industrial and information technology processes.

All truths are easy to understand once they are discovered; the point is to discover them.

Galileo Galilei



STRONG TOGETHER

Cooperation and Synergies

DLR Galileo Competence Centre:
Responsible for overall project management and core tasks: requirements management, product assurance, quality management and subsystems' validation.

DLR Institute of Communications and Navigation:
Coordinates development of the Laser Communication and Ranging Terminal (LCRT), develops the components for high-precision range measurement and will provide the required optical ground station.

DLR Space Operations and Astronaut Training:
Responsible for ground operations software and mission operations.

DLR Institute of Quantum Technologies:
Designer, developer and supplier of the iodine based frequency references, supported by the DLR Institute of Space Systems, the DLR Institute of Optical Sensor Systems and other external suppliers.

DLR Institute for Software Technology:
Development of the satellite operating software for telecommand and telemetry.

Industrial partners:

Airbus:
Operator of the Bartolomeo platform and project support in the fields of systems engineering and safety.

Tesat-Spacecom:
Supplies the basic model of its Laser Communication Terminal (SmartLCT) and upgrades it in cooperation with the Institute of Communications and Navigation to an LCRT.

Menlo Systems:
The optical frequency comb is a development of Menlo Systems.

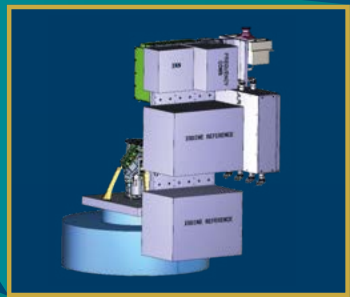
Partner

- **Institute of Communications and Navigation**
- **Space Operations and Astronaut Training**
- **Institute of Quantum Technologies**
- **Institute for Software Technology**
- **Institute of Space Systems**
- **Institut of optical Sensor Systems**

- Airbus
- Tesat
- Menlo
- ...

Vision/Future:
COMPASSO technologies for the next generation of Galileo satellites
FOR A PRECISE AND SAFE FUTURE

2021-2027: Development and demonstration of in-orbit operation of key quantum optical technologies for the future GNSS



Curiosity is the key to problem solving.

Galileo Galilei

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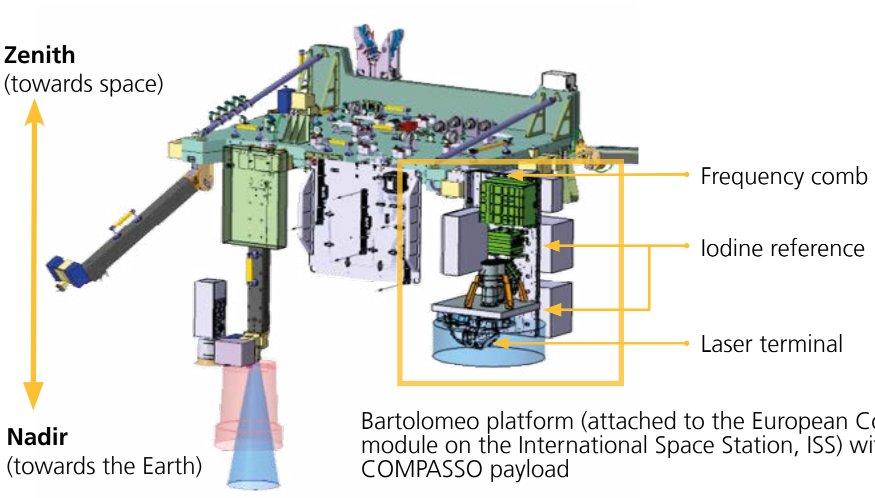
OPTICAL CLOCKS AND LASER TECHNOLOGIES ON THE BARTOLOMEO PLATFORM OF THE ISS

Technological Objective



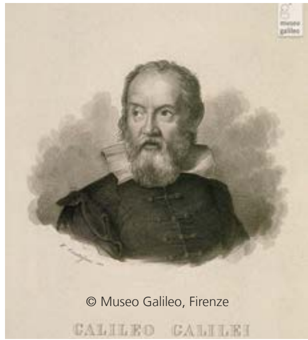
Bartolomeo platform (attached to the European Columbus module on the International Space Station, ISS) with the COMPASSO payload

- Demonstration of space operations with key quantum optical technologies for future Global Navigation Satellite Systems (GNSS), in particular the European Galileo System, as well as for earth observation and scientific missions
- Demonstration of the feasibility of operating optical iodine frequency references in space
- Demonstration of the viability of optical frequency comb operations in space
- Demonstration of the feasibility of operating a bidirectional Laser Communication and Ranging Terminal (LCRT) in space
- Demonstration of optical data transmission via a bidirectional optical link between the ISS and an optical ground station

THE NAME

COMPASSO

The name is derived from the first commercial, scientific instrument developed by Galileo Galilei: a geometrical and military compass. Designed in 1597, the device resembled a proportional divider made of two rulers which could be moved in a semicircle. This invention had many uses, also as a precursor of the slide rule.



Galileo Galilei

COMPASSO instrument

A new approach in systems engineering to handle complex missions.

COMPASSO_E_07/2021

DLR at a Glance

DLR is the Federal Republic of Germany's research centre for aeronautics and space. We conduct research and development activities in the fields of aeronautics, space, energy, transport, security and digitalisation. The German Space Agency at DLR plans and implements the national space programme on behalf of the federal government. Two DLR project management agencies oversee funding programmes and support knowledge transfer.

Climate, mobility and technology are changing globally. DLR uses the expertise of its 55 research institutes and facilities to develop solutions to these challenges. Our 10000 employees share a mission – to explore Earth and space and develop technologies for a sustainable future. In doing so, DLR contributes to strengthening Germany's position as a prime location for research and industry.

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DLR.de/GK/COMPASSO

The Galileo Competence Centre at a Glance

The Galileo Competence Center is supporting Europe in providing citizens with the best possible navigation technologies. We are working on this together with DLR's scientific institutes and facilities, and other partners from research and industry.
A central desire is the realization of common ideas and projects for the exploration and development of new technologies and concepts for industrial exploitation or marketing. Our consolidated knowledge of the complete system enables us to act as intermediaries and advisors to the diverse stakeholders.

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