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A Survey on Small Satellite Technologies and Space Missions for Geodetic Applications

Vaios Lappas and Vassilis Kostopoulos

Abstract

Advances in microelectronics, materials, combined with affordable and frequent launch opportunities has led to a revolution which consists of small satellite missions used for technology validation, Earth observation, space exploration. Small satellites are now being developed in large volumes for mega-constellations for Earth observation, Internet of Things (IoT) and low latency communications (internet) thus democratizing space and making new space applications a reality. Advances in small satellite platforms, miniaturization of instruments and the availability of low-cost launches for small satellites, can enable new, geodetic missions which can benefit from the use of constellations of small satellites. An overview of some of the most important small satellite based geodetic missions is presented, along with a brief overview of new mission concepts which can significantly enhance our knowledge in the geodetic field.

Keywords: small satellites, GPS, geodetic, space missions

1. Introduction

Today, space geodetic techniques are the primary tools to study size, figure and deformation of the Earth, and its motion as a finite body in the inertial reference system. Space geodetic techniques have become the fundamental tools for geodesy, geodetic astronomy, and geodynamics. The development of space geodesy has increase significantly with the progress in space technology, miniaturization of satellites and the advent of Global Navigation Satellite Systems (GNSS) and GNSS technology such as receivers. GNSS is making a much greater impact in the last decade with the advent of small satellites, launch availability and the miniaturization of electronics. It should be viewed as the replacement of classical navigation and positioning (based on the observation of astrometric positions of natural celestial objects) by measurements of microwave signals emitted by artificial satellites [1–4].

With respect to space technology, the two main areas of geodetic research and space missions are:

- Gravity space missions: For geodesy and geodynamics, the CHAMP (Challenging Minisatellite Payload for Geophysical Research and Application) and CHAMP-FO missions, the GRACE (Gravity Recovery and Climate Experiment) mission, and the GOCE (Gravity field and Ocean Current

Explorer) mission are particularly fascinating. Our knowledge of the Earth's gravity field (thanks to the use of space-borne GPS receivers, accelerometers, and gradiometers) has significantly grown thanks to these missions. Gravity missions are of central importance for altimetry, because the precise geoids are required to refer the sea surface topography to the geoid [1].

- GNSS. GNSS stands for Global Navigation Satellite System. The current generation of GNSS may be viewed as the successor of the Doppler systems. The systems are based on coherent microwave signals (in the L-band) emitted by the satellites in (at least) two carrier frequencies. Simultaneity of measurement of the signals emitted by several satellites and recorded by a receiver allow for instantaneous positioning. The GPS (Global Positioning System) is probably the best known GNSS and is considered the best-known space geodetic technique today. The system has an impact on science and society as a whole, reaching far beyond space geodesy. GPS revolutionized surveying, timing, pedestrian, car, marine and aircraft navigation. Many millions of receivers are in use today. Space-borne applications of the GPS have a deep impact on geodesy and atmospheric sciences [1]. The development new GNSS systems from Europe (Galileo), China (Beidou) and others will bring new developments and substantially improve our knowledge of Earth's and planetary geodesy.

In summary, satellite geodetic missions offer the following capabilities:

1. Provide precise relative and geocentric locations of separated points on Earth by ground to satellite measurements
2. Provide knowledge of the time invariant and time variant gravitational forces and surface forces acting on satellite from precise analysis of orbital perturbations and by satellite borne gravity scanning devices
3. Provide precise geocentric location of a spacecraft
4. Provide measurements of time invariant and time variant aspects of vertical geometry of the oceans and land on a rapid and continuing basis by satellite-borne altimeters

The advent of microelectronics, miniaturization in combination with the proven use of commercial off the shelf (COTS) electronics, has led to the wide use of small satellites, i.e., spacecraft which have a mass of 500–1000 kg. Small satellites have proved to be an affordable means of demonstrating new technologies, but also allowing constellations of satellites to approach conventional space missions in a different manner by increasing the revisit time over multiple locations of interest, increase the number of scientific measurements but also enable the use of differential measurements using ranging techniques in combination with space-borne GPS receivers. The next section presents an introduction to small satellites followed by an overview of the most important geodetic small satellite missions in orbit or completed to date.

2. Small satellites

The size and cost of spacecraft vary depending on the application; some can hold in your hand while others like Hubble are as big as a school bus. Small spacecraft (smallsats) focus on spacecraft with a mass less than 180 kg and about the size

of a large kitchen fridge. Even with small spacecraft, there is a large variety of size and mass that can be differentiated. The accepted small satellite classification (per kg) in the space community is as follows:

- Minisatellite: 150–500 kg
- Microsatellite: 10–150 kg
- Nanosatellite: 1–10 kg
- Picosatellite: 0.01–1 kg
- Femtosatellite: 0.001–0.01 kg

Small satellites, miniaturized satellites, or smallsats, are satellites of low mass and size, usually under 500 kg (1100 lb). While all such satellites can be referred to as “small”, different classifications are used to categorize them based on mass. Satellites can be built small to reduce the large economic cost of launch vehicles and the costs associated with construction. Miniature satellites, especially in large numbers, may be more useful than fewer, larger ones for some purposes—for example, gathering of scientific data and radio relay. Small satellites have become a significant part of the space industry. The advent of small satellite technology in multiple areas such as micro-propulsion, cubesats, microelectronics, long distance communications and increased low cost rideshare launch availability has also led to new mission concepts and missions such as broadband internet, communications and Earth observation, which consist of mega constellations of small satellites. Given the available production capabilities of the Contractor and the trend of small satellites, seeking a demonstrator application in this market would be reasonable and would create market potential in the near future. The advent of microelectronics, electric micro propulsion and other small satellite subsystems has enabled a multitude of interplanetary and high power cubesat/nanosatellite mission to be

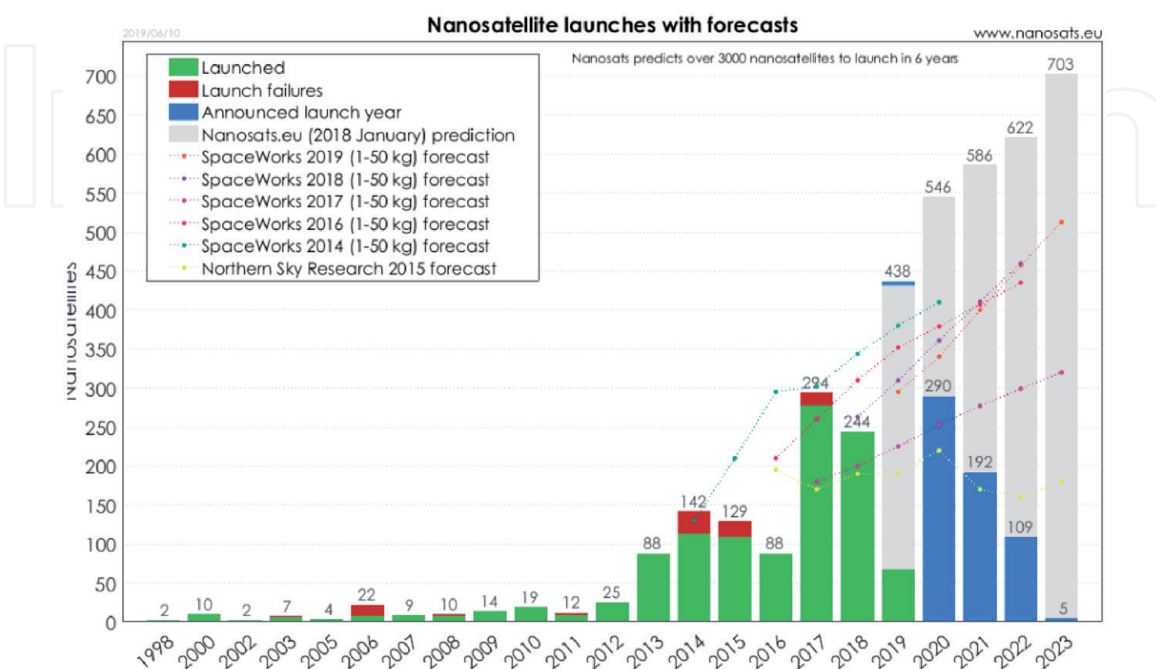


Figure 1.
 Nano/microsatellite (<50 kg) forecast.

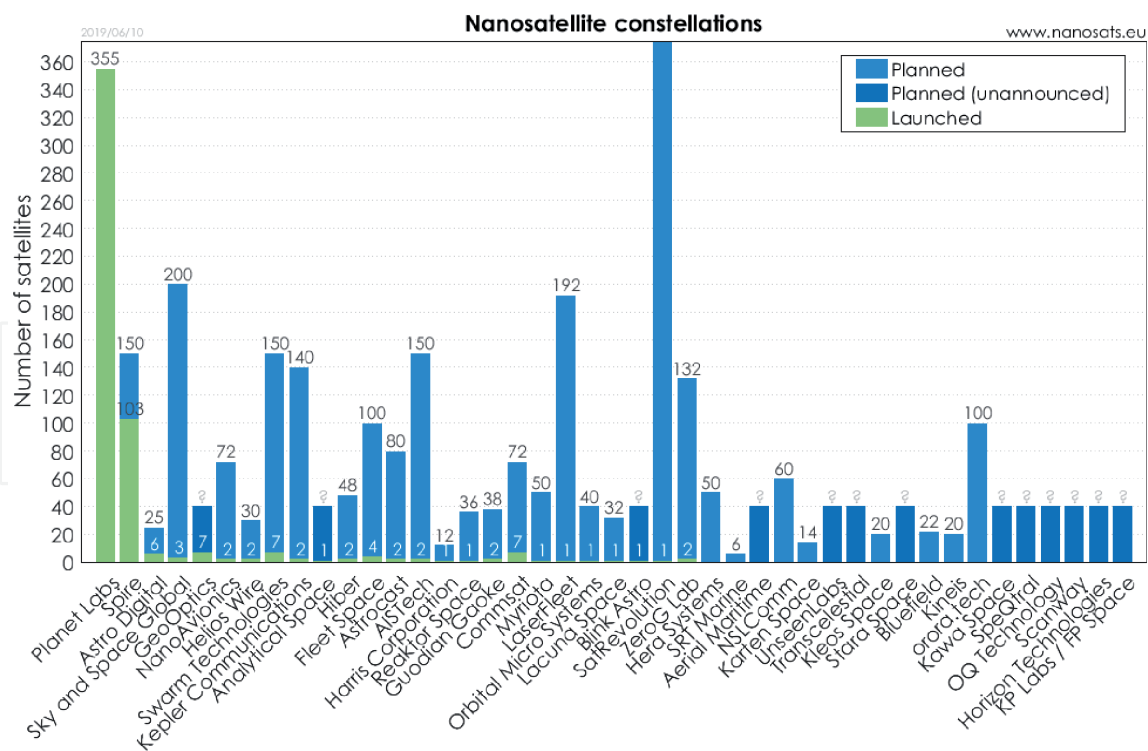


Figure 2. Microsatellite (<50 kg) constellations launched and planned.

Con/n	Num.	Maker	Weight	Year	Avail	Orbit (km)	Status
Iridium Next	66 + 9 spares	Thales Alenia+ Orbital ATK	860 kg	2009	2018	780	Complete
Boeing	1396-2956	Boeing Satellite	N/A	2016	N/A	1200	Unknown
LeoSat	78-108	Thales Alenia	1250 kg	2015	2022	1400	first launches in 2021
OneWeb	882-1980	OneWeb Airbus JV	145 kg	2015	2020	1200	6 pilot satellites in February 2019
SpaceX Starlink	4425-11,943	SpaceX	227 kg	2015	2020	550 km	120 launched in 2020
O3b (SES)	20 O3b 7 O3bm	Thales Alenia (O3b) Boeing (O3bm)	700 kg	2008: O3b 2017: O3bm	2014: O3b 2021: O3bm	8000	O3b complete
Telesat LEO	117-512	TBC	300 kg	2016	2021	1000-1248	Prototypes 2018
CASIC Hongyun	156	CASIC	<500 kg	2017	2022	160-2000	Prototypes 2018
CASIC Hongyan	320	CASIC	< 500 kg	2017	2023	1100	Prototypes 1 2018

Table 1. Mega-constellations planned/operations (assembled from multiple sources).

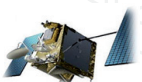
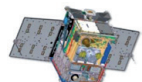
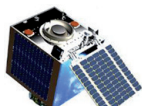

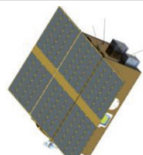
Parameter	Airbus	OHB	SSTL	16 U	SITAEL
					
Platform mass (kg)	150	120	100	20	55
Payload mass (kg)	60	80	50	8	20
Dimensions (m)	1 × 1 × 1.3	0.8 × 0.845 × 0.8	0.7 × 0.45 × 0.77	0.3 × 0.04 × 0.4	0.32 × 0.32 × 0.4
Propulsion	Xenon HET	Multiple	Resistojet	Multiple	Multiple
Lifetime (years)	>5	>5	5	5	3

Table 2.
 Small satellite comparison (assembled from multiple sources).

developed. JPL's MaRCO 3 U cubesat mission are operating already in Mars orbit as communication relays and the NASA funded LunarCube is a 100 W 3 U cubesat mission which will use a Busek iodine RF thruster for Lunar Exploration.

2.1 Small satellite market and trends

In addition to cubesats, larger small satellite missions are now being designed for high power missions due to the sophistication of their payloads and need to use micro electric propulsion which drive power demands. The smallsat (<500 kg mass satellites) market is going through significant expansion in terms of capabilities and demand. In the last couple of years, numerous companies have produced solutions, largely based around a constellation approach, to better deliver services and reach out to new users. These solutions are supported by new ventures, entrepreneurs investing in space in this so-called new or adaptive space environment. The logic of lower-cost constellations is to provide global connectivity from one system (satcom) or high-frequency change detection (in Earth observation [EO]) or connecting devices and vehicles (Information) for the Internet of Things (IoT), Machine to Machine (M2M), and traffic monitoring (AIS or ADS-B). It is aided by the advancement of satellite system miniaturization permitted by new technologies and/or advances in related sectors, particularly in computational technology with smallsats now providing operational services that were previously only achievable through heavier satellites. Over 300 nano/microsatellites were launched in 2017, shattering analyst' expectations and surpassing even SpaceWorks "full market potential" prediction from last year. 2017 represented a 205% increase in nano/microsatellites launched compared to 2016. SpaceWorks' estimates up to 2600 nano/microsatellites will require launch over the next 5 years. This creates space for new opportunities that could benefit from the technology developments in the activity and match the size and scope of the involved partners.

As it can be seen in **Figures 1, 2** and **Table 1**, mega-constellations with microsatellites up to a mass of 200–300 kg are the most popular trend in the space industry and indicate that the 200–300 kg mass and volume factor of 0.125–1 m³ are the near optimum to: (i) squeeze as many small satellites in medium size launch vehicles such as Falcon 9, Ariane 6 (ii) still launch 2–3 small satellites in dedicated small launchers VEGA, LauncherOne, Electron etc. (iii) are small enough to mass produce in lean, highly automated, automotive style production lines as OneWeb and SpaceX are currently undertaking.¹

Table 2 presents a summary and comparison of a representative selection of small satellites of different size, country of manufacture and capabilities.

3. Small satellite geodetic missions

Small satellites have significant benefits which have made them very popular in the last decade for scientific and commercial space missions:

- The advent of microelectronics, automated manufacturing, sensors, batteries, motors and the significant reduction in their cost of manufacture has enabled the miniaturization of larger conventional satellites and instruments bringing the launch cost (cost per kg) significantly down

¹ <https://www.nanosats.eu/#figures>

- Use of COTS components for Low Earth Orbit (LEO) small satellite missions has also lowered space mission costs, helped towards miniaturization and also has created large availability of components and sensors which can be used for space instruments, subsystems and platforms
- Miniaturized satellites such as cubesats or nano/microsatellites can be launched as secondary payloads which are very affordable
- New private and civilian launchers have increased the number and competitiveness of launches, bringing launch costs down and increasing launch availability significantly compared to 10 years ago
- Access to private funding, entrepreneurship has increased small satellite subsystem, sensor and platform quantities and thus reducing mission costs
- Miniature small satellites with low launch costs can enable constellations which can thus allow for a tremendous increase in the number, frequency and location of sensor measurements simultaneously across the globe

All the above advantages of small satellites have contributed to new space missions which were simply impossible, or too expensive to achieve in the past. Specifically for geodesy, there have been a number of scientifically rich satellite missions which used radar and laser altimetry as well as geodetical components to study Earth's gravity field such as CHAMP (CHALLENGING Mini satellite Payload), GRACE (Gravity Recovery and Climate Experiment), and GOCE (Gravity field and steady-state Ocean Circulation Explorer). These satellite missions, although in the boundaries of small satellite missions (with respect to mass and cost) used small satellite technologies to achieve complex mission objectives and provide unique science data about Earth's gravity field.

Table 3 shows a summary of small satellite geodesy mission types. In summary, the benefits of small satellites geodetic missions are that they can be a cost effective means to measure/estimate Earth's geopotential using ranging and GPS data, while constellations can help get polar region data (missing), increase temporal frequency (from months to weeks) and increase the amount, frequency and location of science measurements at a reasonable mission cost. The following section describes the most significant geodetic small satellite missions launched to date.

3.1 Reflector type satellite missions

GFZ 1 (Geo Forschungs Zentrum Potsdam 1) is the first satellite mission designed and funded by the GeoForschungsZentrum Potsdam, Germany. The mission objectives of GFZ-1 were to determine variations in the rotational characteristics of the Earth and to measurement changes in the Earth's gravity field. For the high-resolution determination of the parameters of the gravity field the satellite had to be launched into the lowest possible orbit. At its altitude of 400 km, GFZ-1 was the lowest geodynamic satellite to be ranged to by lasers (in 1995). As the vehicle's orbit was decaying, the satellite's orbital motion was used to calculate atmospheric densities [5, 6] (**Figure 3**).

GFZ-1 was a passive geodetic satellite which only used one instrument, the retroreflector array (RRA). The GFZ-1 RRA consisted of 60 corner cubes and has a center of mass correction of 58 ± 2 mm. These retroreflectors were quartz prisms placed in special holders recessed into the satellite's body. External metallic surfaces were covered with white paint for thermal control purposes and to facilitate visual

Mission	Approach	Example	Notes
Geodesy: measurement of the Earth's gravitation field	1 satellite with accelerometer + GPS GPS: m accuracy Accelerometer: 10^{-10} m/s ² (drag 0^{-6} m/s ²)	CHAMP (2000)	Low cost mission with medium resolution data
Geodesy with retroreflector array	1 satellite with retroreflector array	GFZ-1, Larets	Low resolution data
Geodesy by Differential measurement	2 satellites with accelerometers, GPS, ranging Ranging: nm to μ m	GRACE (2002) GRACE-FO (2010)	Performance limited due to acceleration noise
Multipoint geodesy (constellation), Reflectometry	Satellites with accelerometers, GPS, ranging Ranging: nm to μ m	TDS-1, GYCNSS, C-2	Application to multiple fields
Drag-free based geodesy	2 drag-free satellites with ranging, GPS Accuracy: 10^{-10} to 10^{-15} m/s ² Drag force canceled	Cubesats	Need high precision attitude/orbit determination/control

Table 3.
Small satellite geodetic mission types with mission examples.

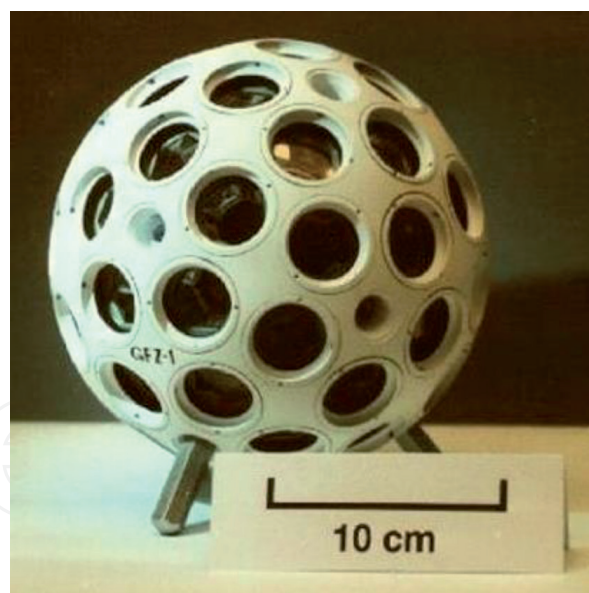


Figure 3.
Model of the geo research satellite GFZ-1 (GFZ) [6].

observation in space. The satellite was built by Kayser Threde GmbH and launched through the space station MIR by RKK Energiya and had a mass of 21 kg. GFZ-1 was transported to Mir Station aboard the Russian Progress-M 27 spacecraft and from there put into a low Earth orbit in April 1995 at an orbit of 382 km \times 395 km with an inclination 51.6°. On June 23rd, 1999, GFZ-1 completed its mission with the satellite burning up in the Earth's upper atmosphere. The GFZ-1 orbited nearly 24,000 times around the Earth and for 4 years and 64 days in space, 5402 passes of GFZ-1 were observed by 33 cooperating ground stations using satellite laser ranging, around the globe [5, 6].

The LARES mission concept represents an improvement of the LAGEOS-3 project proposed in 1984 by Ciufolini. The LAGEOS (Laser Geodynamics Satellite) series was designed to be a passive long-lived satellite with a stable, well-defined orbit. As such, it acts as a reference point in inertial space. An international ground-based network of laser ranging stations used the orbiting LAGEOS satellites as passive reflectors to obtain ranges to the satellite by precision laser echo-bounce techniques. Since the position of the satellites is determined by some laser ranging stations with uncertainties of <1 cm, there was a potential for measuring the 2 m per year drift of the nodes of LAGEOS satellites in orbit. The LAGEOS-1 (Laser GEodynamics Satellite-1, launch May 4, 1976) and LAGEOS-2 (launch Oct. 23, 1992) missions in MEO (Medium Earth Orbit) of NASA and ASI represented the origin of international cooperative research in geodynamics [7, 8] (**Figure 4**).

LARES was a completely passive satellite made of a dense tungsten alloy (THA-18 N) sphere of 376 mm in diameter and a mass of ~400 kg (density of ~18 kg/cm³) covered with retroreflectors that allowed the satellite's motion to be followed via SLR (Satellite Laser Ranging) from Earth. Once in orbit, LARES became the satellite with the highest mean density in the Solar System. The surface of the sphere was covered by 92 CCRs (Corner Cube Reflectors) evenly distributed so that the signal strength is practically independent on satellite attitude. The LARES spacecraft was launched on February 13, 2012 on the maiden flight of the Vega launch vehicle of ESA (the Vega flight was designated as VV01); the launch site was Kourou in French Guiana [7, 8].

Larets was a small geodesy and calibration satellite launched for IPIE (Institute of Space Device Engineering—Moscow). It was a 21 cm sphere with 60 laser retro-reflectors, very similar to the German GFZ 1 satellite. Larets was designed to address scientific and applied problems in the interests of geodesy and geodynamics. The LARETS mission launched in 1003 with a 21 kg mass and in a 675 km orbit, was a next generation satellite based on a low-target-error laser satellite design optimization, which started with the WESTPAC mission, another reflector type satellite mission launched in 1998 in a 835 km, 98.67°. Larets was launched with a cluster of small satellites in September 2003 on a Kosmos-3M rocket [9] (**Figure 5**).

3.2 Geodesy with GPS measurements of the Earth's gravitation field

Challenging Minisatellite Payload (CHAMP) was a German satellite launched July 15, 2000 from Plesetsk, Russia and was used for atmospheric and ionospheric research, as well as other geoscientific applications, such as GPS radio

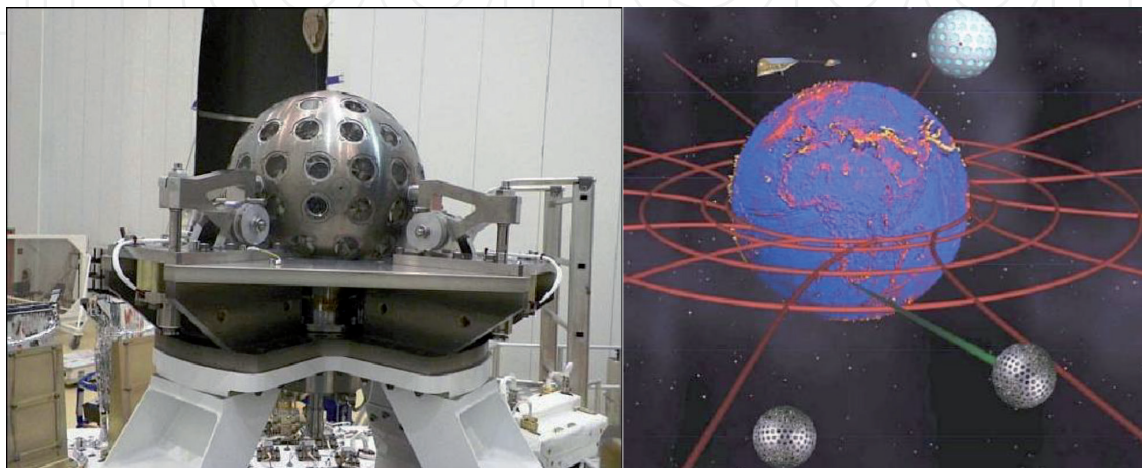


Figure 4.
(Left) Image of LARES satellite (Right) Schematic view of LAGEOS-1, LAGEOS-2 and LARES in orbit for the measurement of frame dragging [8].



Figure 5.
Larets satellite model [9].

occultation. CHAMP was managed by GeoForschungsZentrum (GFZ) Potsdam (GFZ). The spacecraft was the first application of Astrium's "Flexbus" platform (now Airbus Defense and Space); GRACE was the second. A heavily modified version flew as the GOCE mission. CHAMP completed its mission and re-entered the Earth's atmosphere on 19 September 2010 after 10 years (design life: 5 years) [10]. The three primary science objectives of the CHAMP mission were to provide:

- highly precise global long-wavelength features of the static Earth gravity field and the temporal variation of this field.
- high accuracy global estimates of the main and crustal magnetic field of the Earth and the space/time variability of these field components
- large number of GPS signal refraction data, with a good global distribution, caused by the atmosphere and ionosphere, which can be converted into temperature, water vapor and electron content.

With its multifunctional and complementary payload CHAMP aimed at contributing to the following Earth system components:

- Geosphere: investigation of the structure and dynamics of the solid Earth from the core along the mantle to the crust, and investigation of interactions with the ocean and atmosphere
- Hydrosphere: more accurate monitoring of ocean circulation, global sea level changes and short-term changes in the global water balance as well as interactions with weather and climate
- Atmosphere: global sounding of the vertical layers of the neutral and ionized gas shell of the Earth and relationship with weather on Earth and space weather (**Figure 6**).

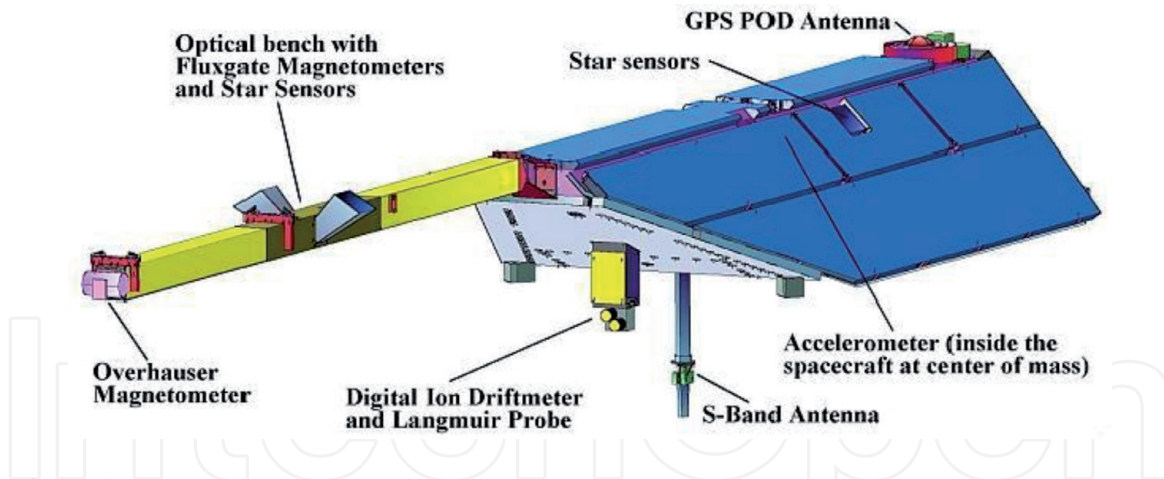


Figure 6.
Front view of the CHAMP spacecraft (image credit: GFZ).

The CHAMP satellite had a robust structure design with fixed solar panels. The primary structure was mainly based on aluminum sandwich panels with an additional kapton foam layer on the outer panels. The shape of the satellite was a compromise with respect to its aerodynamic behaviour, accommodation of instruments and subsystems and fitting into the fairing of the launcher [10].

- Total mass: 522 kg
- Height: 750 mm
- Length (with 4044 mm Boom): 8333 mm
- Width: 1621 mm
- Area to mass ratio: 0.00138 m²/kg

3.3 Multipoint geodesy and Reflectometry

GRACE was an international cooperative US-German dual-minisatellite SST (Satellite-to-Satellite Tracking) geodetic mission with the overall objective to obtain long-term data with unprecedented accuracy for global (high-resolution) models of the mean and the time-variable components of the Earth's gravity field (a new model of the Earth's gravity field every 30 days for 5 years). GRACE was also part of NASA's ESSP (Earth System Science Pathfinder) program [11, 12]. The science objectives were:

- To enable a better understanding of ocean surface currents and ocean heat transport
- To measure changes in the sea-floor pressure
- To study ocean mass changes
- To measure the mass balance of ice sheets and glaciers
- To monitor changes in the storage of water and snow on the continents

The mission concept made use of measurements of the inter-satellite range changes and its derivatives between two co-planar satellites (in low-altitude and polar orbits), using a microwave tracking system. The orbits of the two separately flying satellites are perturbed differently in the Earth's gravity field, leading to inter-satellite range variations. In addition, each satellite carried a GPS receiver of geodetic quality and high-accuracy accelerometers to enable accurate orbit determination, spatial registration of gravity data and the estimation of gravity field models. The fluctuations in the strength of the Earth's gravity field reflect in turn changes in the distribution of mass in the ocean, atmosphere, and solid Earth, and in the storage of water, snow, and ice on land. Since ocean bottom pressure represents a column integral of the mass of the atmosphere plus ocean, this measurement technique permits the deduction of ocean bottom pressure changes from space [11, 12].

Both satellite structures were of identical design. The shape of each satellite is trapezoidal in cross section, based on the FLEXBUS design of Astrium (now Airbus Defense and Space) (length = 3122 mm, height = 720 mm, bottom width = 1942 mm, top width = 693 mm). The FLEXBUS structure consists of CFRP (Carbon Fiber Reinforced Plastic). This material, with a very low coefficient of thermal expansion, provides the dimensional stability necessary for precise range change measurements between the two spacecraft. The actuators include a cold gas system (with 12 attitude control thrusters and two orbit control thrusters, each rated at 40 mN) and three magnetorquers [11, 12] (**Figure 7**).

Each satellite has a mass of 432 kg (science payload = 40 kg, fuel = 34 kg) and the satellite power is 150-210 W (science payload = 75 W). The top and side panels of each satellite are covered with strings of silicon solar cells; NiH batteries with 16 Ah provide power storage. The satellite design life was 5 years. About 80% of the spacecraft's on-board electronics parts were COTS (Commercial Off-the-Shelf) products. Mission operations exceeded the initial 5 years, operating for 15 years until the decommissioning of GRACE-2 on 27 October 2017 [11, 12] (**Figure 8**).

Based on the significant success of GRACE, the GRACE-FO mission, is also a collaboration between NASA and GFZ and was launched on 22 May 2018 aboard a SpaceX Falcon 9 rocket from Vandenberg AFB, California, sharing the launch with five Iridium NEXT satellites [13]. During in-orbit checks, an anomaly was discovered in the primary system component of the microwave instrument (MWI), and the system was temporarily powered down on 19 July 2018. After a full investigation by an anomaly response team at JPL, the backup system in the MWI was powered up on 19 October 2018 and GRACE-FO resumed its in-orbit checks. GRACE-FO entered the science phase of its mission on 28 January 2019 [13]. The orbit and design of GRACE-FO is very similar to its predecessor. GRACE-FO has a design life of 5 years. Astrium (now Airbus DS) uses a 3rd generation Flexbus for the GRACE-FO mission. Each of the GRACE-FO satellites measures approximately

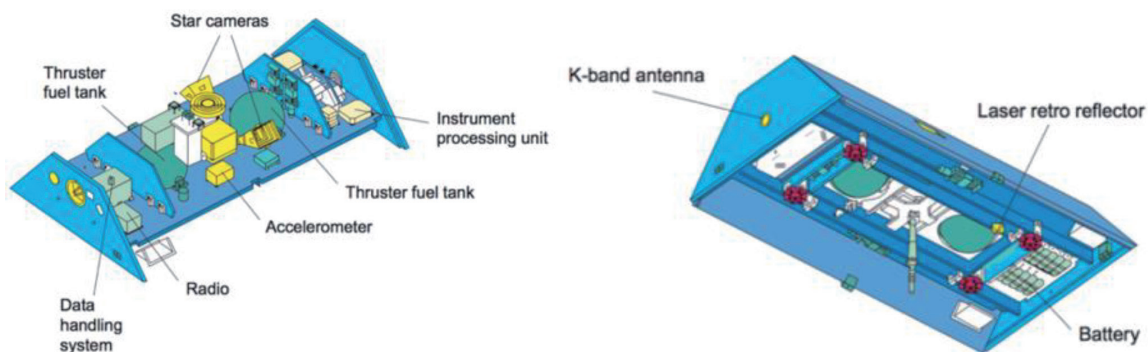


Figure 7.
GRACE satellite design [11, 12].

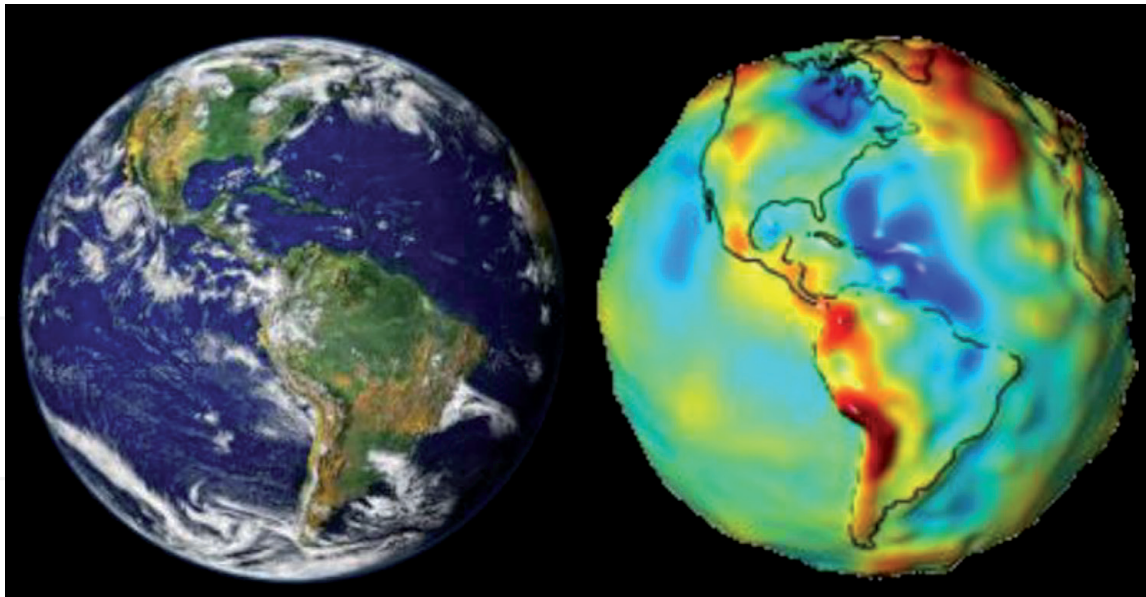


Figure 8.
GRACE gravity field maps [11, 12].

3 m × 2 m × 0.8 m and has a mass of around 580 kg. GRACE-FO employs the same two-way microwave-ranging link as GRACE, which will allow for similar inter-satellite ranging precision (**Figure 9**).

In addition, GRACE-FO employs laser-ranging interferometry (LRI) as a technological experiment in preparation for future satellites. The LRI allows for more accurate inter-satellite ranging due to the shorter wavelength of light, and additionally allows the angle between the two spacecraft to be measured as well as their separation, via differential wavefront sensing. Using the LRI, scientists have improved the precision of the separation distance measurements by a factor of more than 20 relative to the GRACE mission. The LRI lasers must be detected by a spacecraft about 137 miles (220 km) away. This laser approach will generate much more accurate measurements than the previous GRACE satellite mission. The GRACE-FO satellites obtain electricity from gallium arsenide solar cell array panels covering the outside of each satellite. GRACE-FO will continue to monitor Earth's gravity and climate. The mission will track gravitational changes in global sea levels, glaciers, and ice sheets, as well as large lake and river water levels, and soil moisture. In addition, each of the satellites will use GPS antennas to create at least 200 profiles per day of atmospheric temperature distribution and water vapor content, a first for the GRACE mission [13].

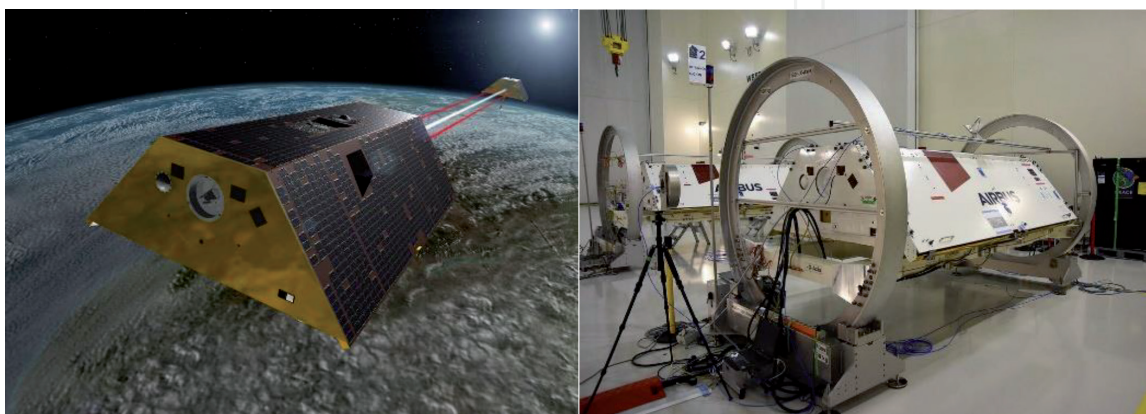


Figure 9.
(Left) Artist concept of GRACE-FO Mission; (Right) the gravity recovery and climate experiment follow-on (GRACE-FO) twin satellites [13].

3.3.1 GNSS reflectometry

GNSS-Reflectometry is a new technique that shows promise for many Earth observation applications including remote sensing of oceans, land, and ice. High grade GNSS payload has been developed in the last few years, that are low in size and power, and suitable for use on small satellites. One such GNSS payload is the SGR-ReSI GNSS Reflectometry Instrument flown on the TechDemoSat-1 microsatellite mission, launched in July 2014. The instrument has been operational since its commissioning in September 2014 and has been collecting delay Doppler maps routinely over many different surfaces. Preliminary work has been undertaken to develop and validate wind speed inversion algorithms against Advanced Scatterometer (ASCAT) wind measurements with promising results [14]. One of the first ever GPS Reflectometry experiments was flown again by Surrey Satellite Technology Limited on the UK-DMC microsatellite mission, launched in 2003, which proved the feasibility of using GNSS reflections for measuring the sea state and other geophysical observables through a partnership between SSTL and National Oceanography Centre (NOC) [14]. Preliminary work using UK-DMC GPS data focused on inverting the measurements into Level 2 products, specifically wind speed and mean-squared slope over the ocean, with promising results. Reflections recovered over the land surface showed a strong geophysical imprint, suggesting potential for hydrological and vegetation related retrieval. Subsequently, a new instrument was developed called the Space GNSS Receiver Remote Sensing Instrument (SGR-ReSI) to gather more space-borne reflectometry data and demonstrate the potential for a sea-state service. In parallel, a US mission called CYGNSS was selected by NASA that plans to measure hurricanes with reflected GNSS signals collected using an updated revision of the SGR-ReSI, (also referred to as delay Doppler mapping Instrument) as payload on each of the eight satellites [14, 15] (**Figures 10 and 11**).

3.3.2 Cyclone Global Navigation Satellite System (CYGNSS)

The Cyclone Global Navigation Satellite System (CYGNSS) is a space-based system developed by the University of Michigan and Southwest Research Institute with the aim of improving hurricane forecasting by better understanding the interactions between the sea and the air near the core of a storm. CYGNSS estimates the wind speed from its radar measurements [15–17]. Winds are measured continuously over the ocean in all weather conditions, although the mission objectives are focused on measurements made in and near the inner core of tropical cyclones Each CYGNSS satellite (eight in total) carries a Delay Doppler Mapping Instrument (DDMI), consisting of:

- a Delay Mapping Receiver (DMR)
- two nadir-pointing antennas
- one zenith-pointing antenna

The instrument receives GPS signals scattered by the ocean surface for the purposes of bi-static scatterometry. The CYGNSS mission was launched on December 15, 2016, at 13:37:21 UTC from a single Pegasus XL air-launched rocket at 35° inclination and 520-km altitude orbit. The eight CYGNSS microsatellites include a Delay Doppler Mapping Instrument consisting of a multi-channel GPS receiver, low gain zenith antennas and high gain nadir antenna.



Figure 10.
 (Left) TechDemoSat-1 (TDS-1) prior to launch (Centre) SGR-ReSI SGR-ReSI, part of sea-state payload on TDS-1 (Right) TDS-1 nadir GNSS antenna [14].

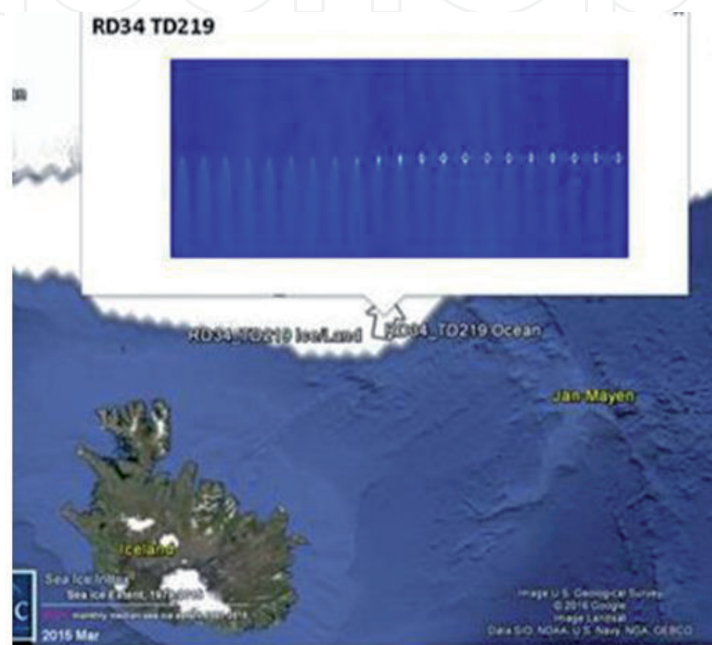


Figure 11.
 Sequence of delay Doppler measurements (DDMs) over a sea/ice boundary near Iceland, march 2015. The white arrow indicates the boundary as detected by canny edge detection routine [14].

Attitude is three-axis stabilized with 2.1° (3σ) knowledge and 2.8° (3σ) control using horizon sensors, a magnetometer, pitch momentum wheel, and torque rods. Satellite mass and power are estimated to be ~ 25 kg and ~ 38 Watts. The satellites were built by SwRI and the payload by SSTL USA, based on SSTL's TDS-1 GPS payload [14, 16] (**Figure 12**).

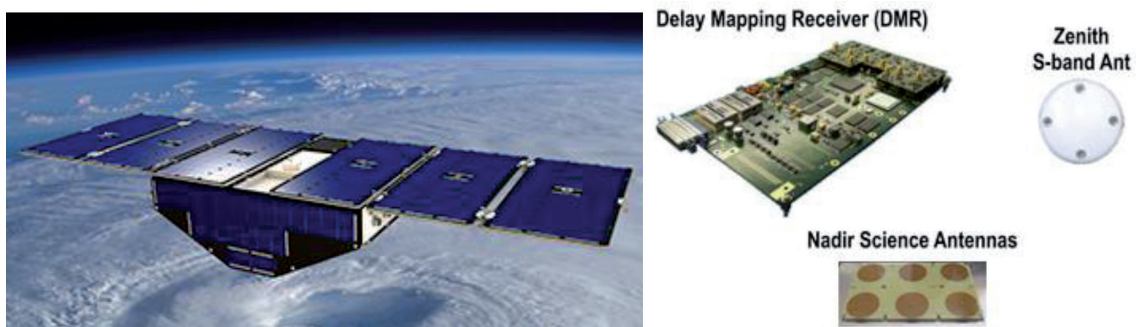


Figure 12.
 (Left) CYGNSS microsatellite platform built by SwRI (Right) delay Doppler mapping instrument (DDMI).

3.3.3 Formosa Satellite-7/Constellation Observing System for Meteorology Ionosphere and Climate (FORMOSAT-7/COSMIC-2)

The Formosa Satellite-7/Constellation Observing System for Meteorology Ionosphere and Climate (FORMOSAT-7/COSMIC-2, hereafter C2), is a recently launched equatorial constellation of six satellites carrying advanced radio occultation receivers, which exhibit high signal-to-noise ratio, precision, and accuracy, and the ability to provide high vertical resolution profiles of bending angles and refractivity, which contain information on temperature and water vapor in the challenging tropical atmosphere. The mission is an international collaboration between Taiwan (NSPO) and the United States (NOAA) that will use a constellation of 12 remote sensing microsattellites (planned) to collect atmospheric data for weather prediction and for ionosphere, climate and gravity research. Budget constraints have meant that the constellation will most likely remain to the current number of 6 currently in orbit [17]. The first six satellites, built by SSTL (UK) were launched on June 25 via the SpaceX Falcon 9 launcher to an initial circular parking orbit of 720 km. Eventually, they were positioned in a low inclination orbit at a nominal altitude of ~520–550 km with an inclination of 24° (using their propulsion system). Through constellation deployment, they are placed into 6 orbital planes with 60° separation. The satellites, built by SSTL in the UK have a mass of 300 kg and are based on SSTL's 150 kg microsatellite platform, with dimensions 100 × 125 × 125 cm³, uses S band (2 Mbps download), 2 GB data storage, utilize nine downlink stations and have a hydrazine mono-propellant propulsion system to lower their initial 725 km orbit to a 550 km final operational orbit.

After an initial calibration/validation phase, over 100,000 soundings of bending angles and refractivity that passed quality control in October 2019 and are being compared with independent data, including radiosondes, model forecasts, and analyses. The comparisons show that C2 data meet expectations of high accuracy, precision, and capability to detect super refraction. When fully operational, the C2 satellites are expected to produce ~5000 soundings per day, providing freely available observations that will enable improved forecasts of weather, including tropical cyclones, and weather, space weather, and climate research (**Figure 13**).

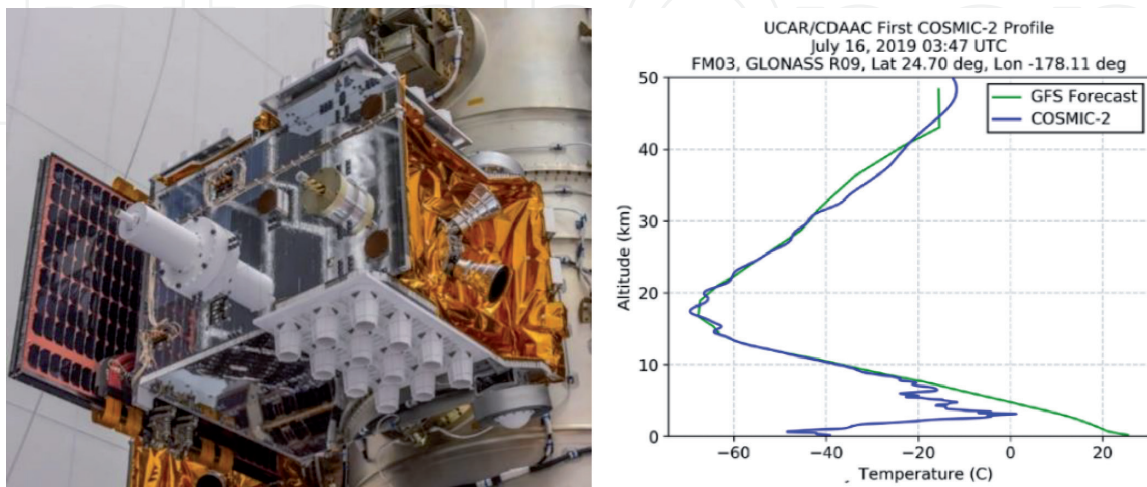


Figure 13.

(Left) COSMIC-2 on Falcon 9 Heavy (Right) 110 neutral atmospheric occultations within 3 h of receiving the first level 0 data [16].

3.4 Drag free space missions

Drag-free space systems [11–19] provide autonomous precision orbit determination, more accurately map the static and time varying components of Earth's mass distribution, aid in our understanding of the fundamental force of gravity, and ultimately open up a new window to our universe through the detection and observation of gravitational waves. At the heart of this technology is a gravitational reference sensor, which (a) contains and shields a free-floating test mass from all non-gravitational forces, and (b) precisely measures the position of the test mass inside the sensor. A feedback control system commands thrusters to fly the “tender” spacecraft with respect to the test mass [16]. Thus, both test mass and spacecraft follow a pure geodesic in spacetime. By tracking the position of a low Earth orbiting drag-free satellite we can directly determine the detailed shape of geodesics and through analysis, the higher order harmonics of the Earth's geopotential. In addition to geodesic information, the commanded thrust, test mass position and GPS tracking data can be combined to produce three dimensional maps of atmospheric winds and density. With multiple drag-free spacecraft, one can perform a more accurate differential measurement between two geodesics, for example with laser interferometry, in order to improve measurements made by NASA's twin GRACE satellites [12, 18].

The range of applications for drag-free technology is broad. A summary is provided in **Table 3** combined with other geodesic mission types [20]. The listed applications are separated into four distinct categories: navigation, Earth science, fundamental physics, and astrophysics. Two key performance metrics for each application are also shown. The first metric, called drag-free performance, is the residual acceleration of the test mass. For an ideal drag-free satellite, the residual acceleration is zero, but in practice small, residual forces act on the test mass, perturbing its trajectory with respect to a pure geodesic. The primary goal of drag-free satellite design is to minimize these residual forces. The second metric, called metrology, is either the measurement of the absolute position of a drag-free test mass (e.g. via GPS) or the differential measurement of the distance between two drag-free test masses. Space missions which implemented this concepts were the drag-free satellites: NASA's Gravity Probe B (GP-B), which tested two predictions of general relativity with ultra-precise drag-free gyroscopes in low Earth orbit [21–23], and ESA's geodesy mission, the Gravity field and steady-state Ocean Circulation Explorer (GOCE) [23].

As mentioned, the miniaturization of small satellites and instrumentation and the overall low cost of small satellite missions, makes them ideal vehicles to expand drag free mission principles. Section 4 details multiple cubesat based drag free mission concepts which are in the design phase and which will fly into space in the next few years. In the following section a brief overview of the GRACE and GOCE missions is presented.

4. Geodetic smallsat mission concepts

The availability of reusable launch vehicles such as the SpaceX Falcon 9 and 9 Heavy and the further miniaturization of small satellites and instruments to the cubesat form factor (1–3 U) and mass (<5 kg) has led to the proposal of multiple constellation based geodetic missions which are currently being investigated. The section below provides a brief overview of some of these mission concepts [19–27].

CNES has performed the preliminary design studies of a mission for a future nano-satellite constellation of GNSS-RO receivers for a targeted number of occultations:

- 10.000 per day main identified technical specifications to meet the end user requirements and comply with the low-cost constraint
- small size and small mass (<50 kg) with a minimalist instrumentation to remain a low-cost system
- main planned option for the constellation: 8 LEO satellites, altitude of 600 km
- receiver bi-frequencies (E1 and L5) and bi-GNSS constellation (GPS + Galileo)
- 2 polar ground stations
- array antenna with at least 8 dB gain and 50° coverage

MicroGEM (Microsatellites for GNSS Earth Monitoring) was a phase A study which proposed the use of satellites with a mass of 100 kg for monitoring of the Earth. The study explored how miniaturization of microsatellites and instrumental can enable low cost geodetic missions. Using GPS/Galileo receivers and the GFZ-satellite missions CHAMP (CHALLENGING Minisatellite Payload) and GRACE (Gravity Recovery and Climate Experiment) philosophy a small constellation is proposed. MicroGEM studied how to link the CHAMP and GRACE missions with cubesat/microsatellite technology and proposed for the first time to use the signals from the future Galileo-satellites for the GNSS-supported atmospheric and ionospheric remote sensing on a global scale. The study analyzed the significant improvements in this method. It also proposed to use GNSS-signals for the remote sensing of ocean and ice surface will be employed for the first time. The particular technological challenge of MicroGEM lies in the fact that this small satellite mission could serve as a predecessor for future multi-satellite systems with scientific GNSS-receivers as satellite payload. With such constellations the number of measurements can be considerably increased, and an improved global coverage can be achieved [24].

The proposed PRETTY (Passive Reflectometry and Dosimetry) mission included a demonstrator payload for passive reflectometry and scatterometry focusing on very low incidence angles whereby the direct and reflected signal will be received via the same antenna. The correlation of both signals will be done by a specific FPGA based hardware implementation. The demonstration of a passive reflectometer without the use of local code replica implicitly showed that also signals of unknown data modulation can be exploited for such a purpose. The PRETTY mission was proposed by an Austrian consortium with RUAG GmbH as prime contractor, relying on the results from a previous CubeSat mission (OPS-SAT) conducted by TU Graz under ESA contract [25].

GEOCON was another cubesat type study which is investigating the development of a new measurement concept using one or more space-based reference points (satellites) to significantly reduce the errors in the site ties between co-located geodetic ground stations. The proposed concept uses a novel idea of upconverting the Global Navigation Satellite System (GNSS) signal received at the satellite and transponding it to a Very Long Baseline Interferometry (VLBI) antenna ground station. This approach does not require the satellite to be in view of more than one VLBI station at a time, allowing the use of Low Earth Orbits. This is advantageous since it opens up the possibility of using inexpensive CubeSats or other small satellites, making it feasible to implement a cost-effective constellation of such satellites (GEOCON) to provide better global coverage and further improve the accuracy of the site ties for the Global Geodetic Observing System—GGOS, stations' network.

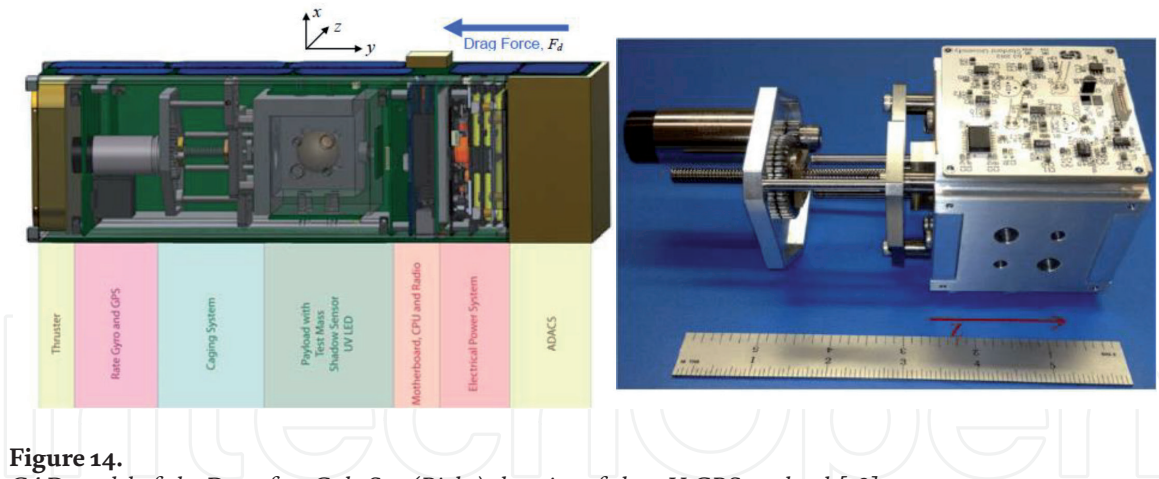


Figure 14. CAD model of the Drag-free CubeSat (Right) drawing of the 1 U GRS payload [28].

A Drag-Free CubeSat mission has been proposed recently, to demonstrate the feasibility of a Gravitational Reference Sensor (GRS) with an optical readout for a 3 units (3 U) spacecraft [27, 28]. A purely drag-free object is defined by the absence of all external forces other than gravity, which are shielded by the spacecraft. In a real case, the spherical test mass (TM) will still be affected by disturbances. Several of them are passively reduced by the design of the TM housing. This system is a thick-walled aluminum box that holds the shadow sensors and shields the TM. The housing has an effect on the mechanical, thermal and magnetic environment around the TM. All of them have been analyzed. The mechanical vibrations have to fit the launch environment and the modes have to be outside of the measurement range (0.0001–1 Hz). The housing, together with the TM, the sensors and the UV LEDs for charging control, constitutes the GRS, which would then fit into a 1 U. The other 2Us are occupied by the caging mechanism that constraints the TM during launch, the thrusters, the Attitude Determination and Control System (ADACS) and the electronics. The Drag-Free CubeSat will be the result of the combined efforts of Stanford, University of Florida, KACST and NASA and will be the first drag-free mission with an optical readout and the first GRS designed within the limits of a 3 U small satellite [27].

The 1 U GRS consists of a 25 mm diameter spherical test mass housed inside a 50 mm cubic cavity. The sphere's position is sensed with a LED-based differential optical shadow sensor, its electric charge is controlled by photoemission using UV LEDs, and the spacecraft position is maintained with respect to the sphere using a cold gas micro-propulsion system. The Drag-free CubeSat is a 3-unit (3 U) CubeSat, measuring 34 cm × 10 cm × 10 cm and weighing 4 kg at launch. The drag-free control system uses the satellite position measurement provided by the shadow sensor and a small cold gas thruster in the aft of the satellite to compensate for atmospheric drag and keep the spacecraft centred with respect to the test mass. A commercially available Attitude Determination and Control System (ADACS) will maintain the satellite's attitude pointed in the direction of the drag force, as well as control the satellite's roll angle [28]. The target performance of the Drag-free CubeSat is roughly 10 times better than the GRACE accelerometers and comparable to the drag-free performance of GOCE. The performance is limited primarily by the minimum impulse bit and thrust noise of available CubeSat scale thrusters (Figure 14).

5. Conclusion

Geodetic missions have benefited from small satellite technology, with space missions such as GOCE, CHAMP, CRACE, GRACE-FO. Advances in GPS technology, sensors (accelerometers), microelectronics and the wide use of cubesat (<5 kg)

nanosatellite technology allows for drastic mass and volume reduction of satellite platforms and instruments and thus allowing microsatellite/cubesat type constellations to offer unique measurement capabilities for geodetic applications. New mission concepts using reflectometry, occultation, ionospheric research and drag free payloads are presented focused on cubesat level technology and size factors, which in combination with lowering launch costs and an increase in launch opportunities bring a new setting to conduct unprecedented geodetic missions with higher temporal resolution and higher measurement accuracy compared to what is available at present.

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