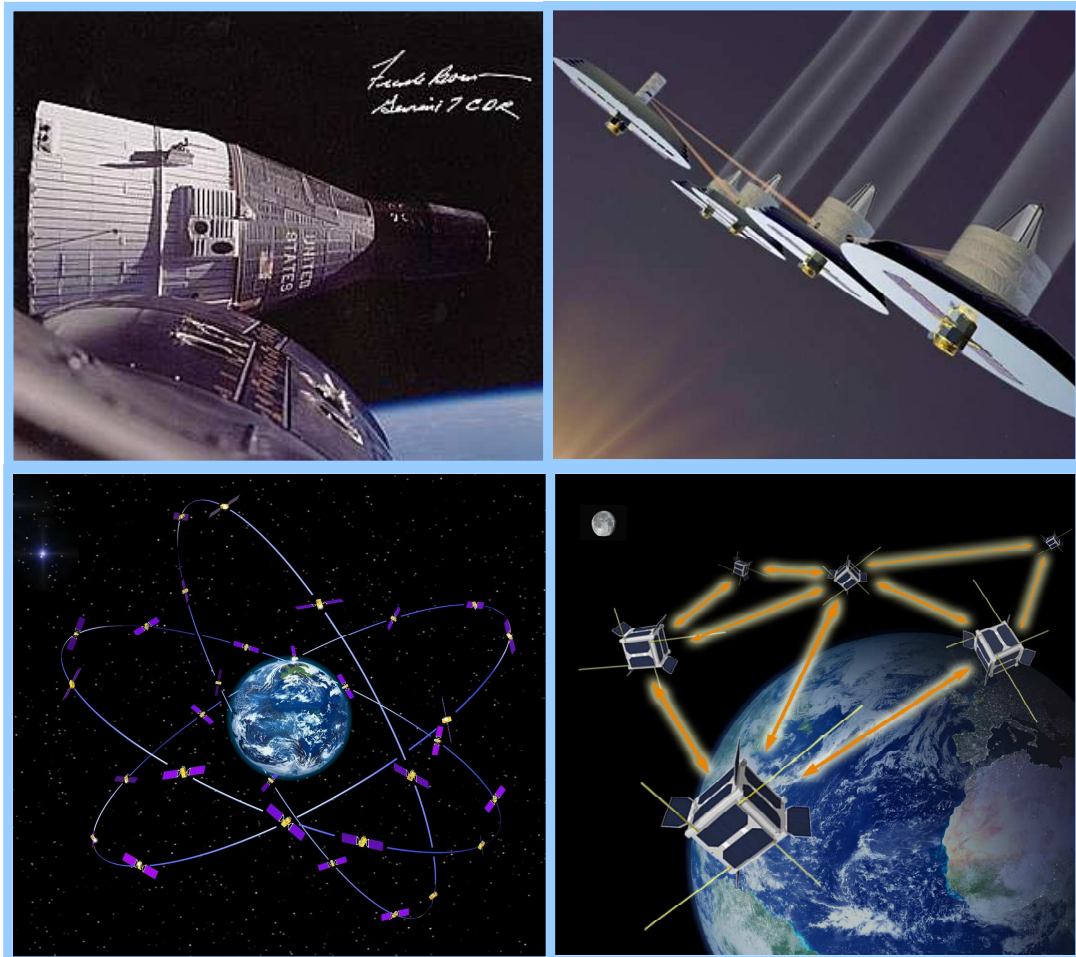


Together in Space

Potentials and Challenges of Distributed Space Systems

Inaugural speech

Prof. Dr. Eberhard Gill



September 17, 2008

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Front page:

Distributed Systems in Space: Rendezvous and Docking (upper left), Formation (upper right), Constellation (lower left), Swarm (lower right).

The thought of every age is reflected in its technique.

Norbert Wiener, 1948 (in: Cybernetics or Control and Communication in the Animal and Machine)

Distributed Space Systems

Introduction

This lecture is about how we do spaceflight. Most commonly, spaceflight is associated with launching a single satellite into space to fulfil the objectives of its mission. This can be to provide communication, navigation or remote sensing capability in the Earth's environment. It also can seek to explore other celestial bodies, like the Moon, other planets and stars or even the history of our universe.

However, a space mission may also need several craft in order to accomplish its mission. Astronauts and cosmonauts visiting the International Space Station must be lifted to and returned from our human outpost in space by specific vehicles able to escape the Earth's gravity and to withstand the extreme conditions of re-entry.

Nowadays, increasing cost pressure, the advent of new technology and more and more demanding mission objectives enforce and allow smart and new ways to do spaceflight. Distributed space systems are a particularly promising new way in this respect and their potentials and challenges are the topic of this speech.

Working together in the kingdom of animals

Before we turn our attention to space, we take an intuitive approach to concepts for distributed systems in the kingdom of animals. Many of the concepts we encounter there are familiar to us in our daily experience.

Let us start with two animals encountering each other. A critical situation for animals with close approaches down to physical contact is shown in Fig. 1a, where a pair of European storks is mating at their nest. We might associate the geometric conditions of such a close encounter with the approach and contact in *rendezvous and docking* scenarios in spaceflight.

If two or more animals of the same species are moving in a well coordinated way, we call this distribution a formation. In animal formations, individuals are typically separated neither strictly local nor global. Formations involve a moderate number of animals sufficiently separated and moving in a coordinated way. We all know species of large birds *flying in formation*, for example the V-shape formation as shown in Fig. 1b. Weimerskirch et al. (Nature, Vol 413, Oct. 18 2001) have studied pelicans. They found that pelicans flying in formation are able to glide for a greater portion of their total flight time with total energy savings of up to 14%.

While rendezvous and formation refer to distributed systems of animals on local or moderately separated scales, globally distributed and interacting animals are not that common but they exist. Actually, fin and blue whales form a global communication and navigation network which covers basically the entire planet. In 1971, Payne and Webb found that their calls can propagate across entire deep ocean basins before

falling to the level of the background noise. The frequency of these acoustic signals is typically around 20 Hz and they are used most probably for communication and navigation purposes. Occasionally, whales leave their winter waters in the middle of their song, and, after six months of travel when returning to the same geographical position, they pick up their song at precisely the spot they have left it off, beat for beat, measure for measure, sound for sound. Today, traffic noise from ships essentially limits whale communication to a few hundred kilometres. A global communication and navigation network in space, established by typically 20-30 globally distributed spacecraft, is called a *constellation*.

A common form of distributed animals of one species is a swarm. A swarm consists of a few ten to a few thousand individual members. Swarms are composed of individuals with limited functional capability, such as insects, fish or birds. Although some suggestions exist on the objective of building swarms, such as minimizing risk of being caught or sleeping, such as in Fig. 1d, the main reasons for swarm building are not known yet.



Fig 1a (top left) *Rendezvous* of a European stork with a mating partner. **1b** (top right) *Formation* flight of birds. **1c** (lower left) Whales forming a *constellation* for global communication and navigation. **1d** (lower right) Sleeping *swarm* of fish.

Concepts of Distributed Space Systems

Now, we move our attention to distributed space systems. Here, it is helpful to characterize the different concepts based on the distance between the satellites and the requirement for the control of their distances. We can distinguish local systems with separations between the spacecraft of a few meters from regional separations of typically a few 10 meters to several hundred of kilometres to global systems with separations of more than a thousand kilometres.

Rendezvous and docking typically involves two objects in space moving in the vicinity of each other. It is obvious that rendezvous and docking, for example ESA's Automated Transfer Vehicle (ATV) docking the International Space Station (ISS),

poses very high demands on the control accuracy. At a given separation of - let us assume - 10 m the control accuracy should be at least a factor of 10 smaller which would be 1 m in this case. The control is based on sensors which again have to provide an accuracy of better than a factor of 10, i.e. 10 cm.

Formation flying of satellites is typically associated with a small number of spacecraft flying in a concerted way at regional intersatellite separations. Here, the mission objectives drive the requirements on the control accuracy. A science mission using interferometry may have high control demands while a formation of two spacecraft each with different instruments for remote sensing can have very relaxed requirements. The Swedish Prisma formation flying mission is an example of a technology demonstration mission that applies various novel sensor and actuator technologies in a wide range of control accuracies.

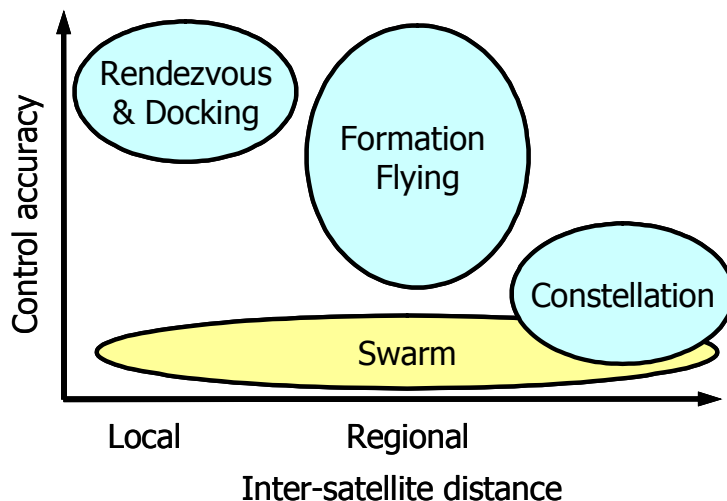


Fig 2 Distributed systems in space can be categorized with respect to their inter-satellite separation and their requirements on control accuracy.

To achieve global coverage on Earth, a constellation of satellites is required. The US Global Positioning System (GPS) and the corresponding Russian system GLONASS allow for worldwide satellite-based navigation and will be complemented by the European system Galileo which is expected to be operational in 2013. The space segment of Galileo will consist of a total of 30 spacecraft orbiting at 23,000 km altitude and is spread evenly over three orbital planes at an inclination of 56 degrees. Control accuracies for constellation keeping are often so low that the control can be easily planned and performed at the ground control centre.

While rendezvous and docking, formation flying and constellations are well established implementations of distributed space systems, swarms of satellites consisting of several ten to several thousand of spacecraft have not yet been deployed. As for animal swarms, the strength of these satellite swarms lies in the large number of individual spacecraft. However, due to the huge number of spacecraft involved, cost limitations will enforce small individual spacecraft which in turn limits their control accuracy. Swarms of small satellites can characterize e.g. the local, regional or global Earth environment by performing in-situ measurements of atmospheric or radiation conditions.

History of Distributed Space Systems

Distributed space systems are not new. In fact, the first formation flying experiment was conducted in 1965 with the two US capsules Gemini 6A & 7. Using manual piloting, Walter Schirra manoeuvred Gemini 6A to as close as 0.3 m from Gemini 7 and stayed there in close proximity for about 5 hours.

Only two years later, the Soviet Union demonstrated the first automated docking in space with Kosmos 186 & 188. The automation of the docking sequence was not primarily done for reasons of technology demonstration but instead due to the fact that the USSR had no own ground station outside its own territory. Because of the long rendezvous times involved, the sequence had to be done in an automated way. This docking proved it possible to launch smaller parts and assemble them in space, avoiding the need for exceedingly large rockets and allowing for large structures in space like the International Space Station.



Fig 3a (left) Close proximity operations of Gemini 6a and Gemini 7 in 1965 (source: NovaSpace).
3b (right) Soviet Union stamp of the docking of Cosmos 186 and 188 in 1967 (source: Wikipedia).

Rendezvous activities of increasing complexity have been conducted in 1969, 1975, and 1984 at the moon, involving two nations, or even two spacecraft and the astronaut Dale Gardner. These historic milestones of distributed space systems had very specific characteristics as compared to contemporary activities. Short mission durations of typically a few hours were supported by extensive ground control. In the Gemini 6A & 7 mission 125 aircraft and 16 ships were involved. Missions were realized with blank checks, meaning that cost was not a primary constraint. Again, taking the Gemini 6A & 7 mission as example, the US Department of Defense contributed more than 10,000 of personnel. Only one of the involved spacecraft was actively controlled while the other stayed passive.

Contemporary missions of distributed space systems can be considered to start with the autonomous formation flying of the Japanese ETS-7 and achieve a recent culmination in the fully autonomous docking of the European Automated Transfer Vehicle to the International Space Station in April 2008. In contrast to historic missions, future missions of distributed space systems will be characterized by long mission durations for operational usage, autonomous control and keeping of the system, tight cost constraints and cooperative manoeuvring of the spacecraft.

Tab 1 Key dates of Rendezvous and Docking (RvD) and Formation Flying (FF).

Type	Involved	Date
First FF experiment	Gemini 6A & 7	1965/12/15
First automated docking	Kosmos 186 & 188	1967/10/30
RvD at other celestial bodies	Columbia & Eagle	1969/12/07
RvD with vehicles from two nations	Apollo & Sojuz	1975/07/17
RvD of three "objects"	D. Gardner, Weststar VI, Discovery	1984/11/14
Collision due to FF	Progress & MIR	1997/06/25
Autonomous FF	ETS-7	1998/07/07
Fully autonomous docking	ATV & ISS	2008/04/03

Potentials

Distributed space systems offer specific potentials for science and technology, which are closely interconnected. In the field of remote sensing, scientists demand an ever increasing coverage of their subject in time and space to improve their models.

Single spacecraft in low earth orbits allow a revisit of locations with typical revisit times of hours to days which is not sufficient. Having two spacecraft separated along the orbit allows revisit times ranging from hours and minutes down to milliseconds. A 75 m along-track separation of two spacecraft flying with a velocity of about 7500 m/s in low earth orbit allows a time resolution of 10 ms.

A spatial distribution of spacecraft looking at the same ground region allows for direct interferometric observations and scientists may regard the multiple spacecraft as a single and huge virtual instrument in space. In contrast, large separations between spacecraft performing e.g. in-situ measurements of the magnetosphere allow global coverage and form a distributed network in space.

Scientific potentials of distributed space systems are closely interconnected with technological potentials. As these distributed space systems are not rigidly connected, their relative spatial geometry can be adapted in a flexible way to serve the mission needs. If common interfaces are adopted, an existing system can be augmented with further elements allowing for a scalable and expandable system. The inherent distribution of different payload and subsystems on several spacecraft implies that redundancy is naturally introduced in the concept and the robustness of the mission can be improved. A failure on a critical subsystem on one spacecraft will not lead to a total loss of the mission. Finally, autonomy allows for a mission realization with enhanced functional performance, e.g. since control accuracies can be met which are not achievable with ground-in-the-loop. Onboard resources such as propellant, which is available on multiple spacecraft, can be shared in mission operations to maintain the relative geometry of the space segment.

Sample Missions

Distributed systems in space can enhance science return, advance exploration, increase security, and demonstrate new technology in space in short timeframes. It

also can contribute to viable space businesses. Four examples of scientific and commercial applications may illustrate this.

The GRACE mission comprises two spacecraft launched in 2002 which fly one after the other at a separation of 250 km. Any irregularities in the Earth's gravity field, which are traversed by the formation, cause small changes in the separation of the two spacecraft. These perturbations can be sensed through an intersatellite link with an accuracy of 1 μm . With about three months of GRACE data, a gravity field has been generated which is a factor of 10 to 100 better than what had been produced over the past 30 years from available satellite and ground-based measurements.

LISA is a planned space interferometer with three satellites forming an equilateral triangle with an arm length of 5 million kilometres. LISA will sense the distortions of space-time caused, for example, by collapsing stars. These distortions are so tiny that they will lead to distance variations between the spacecraft of 10 pm (10^{-11} m). This corresponds to a relative accuracy of 10^{-20} and makes LISA one of the most ambitious space missions ever.

Another area of distributed systems is commercial space applications. Telecommunications satellites are designed for lifetimes of 10–15 years before they are transferred to a graveyard orbit as they run out of propellant. This is a waste of huge capital investment, because all or most of the satellites' revenue-generating communication payload is still functional. The ConeXpress Orbital Life Extension Vehicle is a novel spacecraft that can significantly prolong the operating lives of these valuable satellites. It also can recover satellites launched into incorrect orbits, or manoeuvre them into a disposal orbit.

There are currently about 300 operational communication satellites in geostationary orbit. This makes the allocation of orbital positions a very valuable resource. SES Astra SA, for example, owns and operates the Astra series of geostationary satellites which transmit approximately 1100 analogue and digital television and radio channels to 91 million households across Europe. SES Astra operates seven geostationary satellites at the same orbital slot at 19.2°E based on the principle of co-location. These satellites generate revenues of about 150 MEuro p.a. The smart principle of co-location of space assets has therefore a commercial impact of more than 100 MEuro of revenues p.a.

In the following, we will take a closer look into three examples of distributed systems in space.

TerraSAR-X and TanDEM-X

A fascinating satellite formation for Earth observation is the German TerraSAR-X and TanDEM-X mission. TerraSAR-X is a big satellite of more than 5 m length and a mass of 1200 kg which has been launched in 2007. With its Synthetic Aperture Radar (SAR) payload, it provides digital radar images of the Earth's surface with a resolution of up to 1 m which can be used for resource management, mapping of land use or monitoring the evolution of the cryosphere.

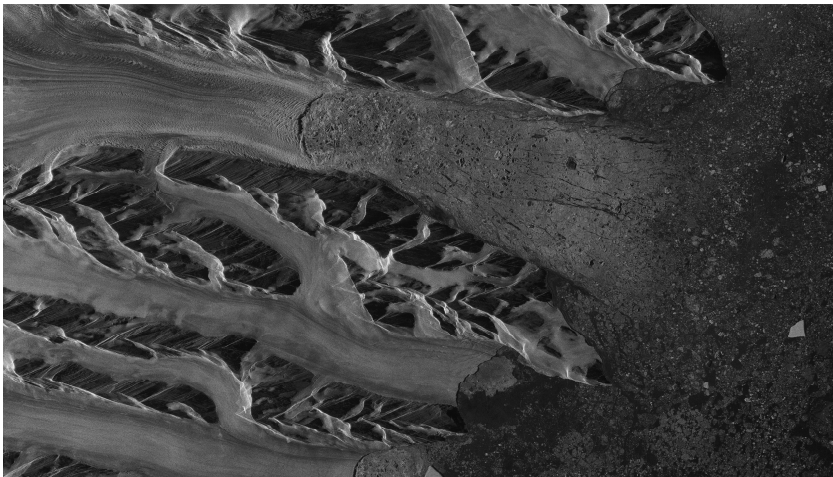


Fig 4 Radar image of the Larson ice shelf from TerraSAR-X (Source: DLR).

An example of a TerraSAR-X image is the Larsen ice shelf in the Antarctica. Part B of the shelf, which had been stable for more than 12,000 years, collapsed in 2002 and a part as large as the province South-Holland broke off, an event which became the source of the movie "The day after tomorrow". In the future, TerraSAR-X will help scientists to determine and predict the evolution of glaciers and ice shelves with a much better accuracy, timeliness and robustness than before.

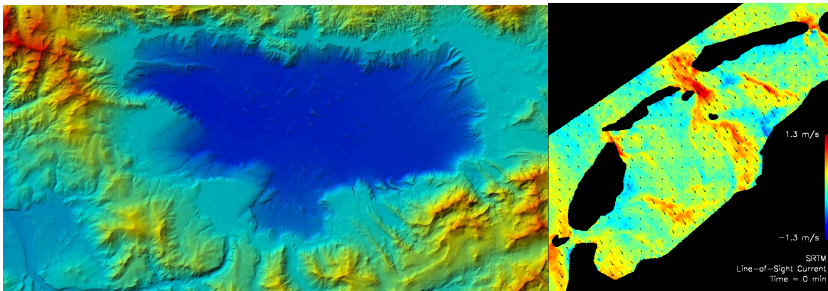


Fig 5 Expected data products from the TerraSAR-X/TanDEM-X mission. **5a (left)** Digital elevation model of Lake Tahoe (Source: Satellite Imaging Corporation) **5b (right)** Line-of-sight current field of the Dutch Waddenzees as derived from SRTM data (Source: DLR).

The mission is implemented as the first German Public Private Partnership between the German Aerospace Center (DLR) and EADS Astrium. It will be augmented with an almost identical satellite in 2009, TanDEM-X. TanDEM-X opens a new era in space borne radar remote sensing, as both satellites will act as a large single-pass radar interferometer with the opportunity for flexible baseline selection. Baselines can be cross-track at separations of a few hundred meters where the spacecraft are flying in two slightly tilted orbital planes. This enables the generation of a consistent set of digital elevation models which will cover the entire Earth's land surface, that is 150 million square kilometres, within a period of only 2.5 years and an accuracy of around 2 meters, which is up to now only achievable from airborne instruments. In addition to this, along-track interferometry allows to monitor ocean currents, such as jet streams in the Dutch Waddenzees or even to measure the velocity of traffic from space.

DARWIN

Darwin is a mission of the European Space Agency to detect Earth-like planets orbiting distant stars. The challenge is that at optical wavelengths, a star outshines an Earth-like planet by a factor of one billion to one. Therefore, Darwin will observe in the mid-infrared where the star-planet contrast drops to a million to one, making the detection a little easier. To achieve this, three to four telescope spacecraft have to point towards the same star at the same time and retransmit the light they detect to a central beam-combiner spacecraft. Here, the light from the individual telescopes is combined in a technique called 'nulling interferometry'. Through this technique, the light from the bright star is being cancelled out, leaving only the light from the possible planet around the star.



Fig 6 Artist impression of a possible configuration for ESA's Darwin formation flying mission at the Lagrange point L2.

This concept is so demanding that the formation has to be operated in a very benign and stable thermal and dynamical environment. Therefore, Darwin will be placed at the so-called Lagrange point 2 which is located 1.5 million kilometres behind the Earth as viewed from the Sun. Lagrangian points were discovered by the mathematician Joseph Louis Lagrange in 1772. At the Lagrangian points, the gravitational forces from the Sun and the Earth-Moon system cancel each other out. Darwin will be established at L2 not before 2025. The separations between the telescopes and the beam combiner are up to one kilometre and need to be controlled with an accuracy of 0.3 mm which is a technological challenge in itself. Even more demanding, the optical path differences between the different light paths need to be controlled with an accuracy of 1 nanometre. One nanometre is a distance which 10 hydrogen atoms need to line up!

FAST

Formation flying is not limited to large missions. The Formation for Atmospheric Science and Technology Demonstration (FAST) is a mission which has been proposed in 2007 as a cooperation project between the University of Tsinghua in Beijing, China and the Delft University of Technology. The design, development and operation of two micro-satellites of a few tens of kilograms will be used to achieve three main objectives. In terms of education, skills will be developed through the exchange of staff and students between the universities, cutting edge technology is taught using the FAST mission and the international view of students is broadened. In the field of technology, the formation geometry will be autonomously controlled using advanced sensors and actuators which will be the first autonomous formation flying demonstration for micro-satellites. One of the novelties of the FAST mission concept is that scientific objectives are addressed with micro-satellites. Certainly, this mission will not compete with big missions in terms of science but will stick to niche science. Nevertheless, miniaturized systems are more and more able to provide valuable contributions to scientific problems. In the case of FAST, the payload will allow to characterize aerosols in the Earth's atmosphere and to monitor the altitude of terrain in the cryosphere.

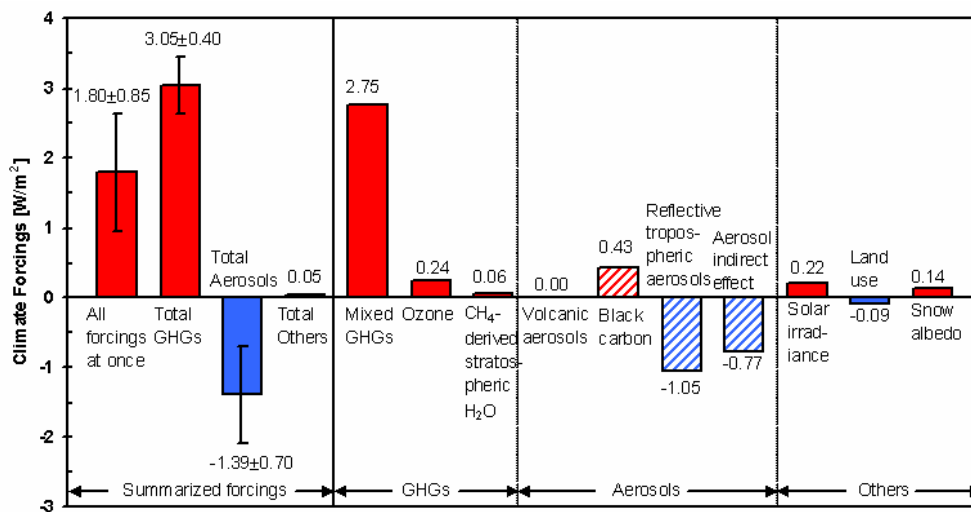


Fig 7 Effective climate forcings applied to drive the 1880 to 2003 simulated climate change. Left, the summarized forcings can be seen which are detailed (middle and right) for green house gases (GHGs), aerosol contributions and other originators. Slashed bars indicate contributions which can be characterized by FAST.

Let us take a closer look at the effect of aerosols in the Earth's atmosphere. The total climate forcing is governed by the positive effect of green house gases and the negative effect of aerosols. As often, it is even more instructive to look at the uncertainties of these values than at the values themselves. It is obvious that the uncertainty in the total forcing is dominated by the uncertainty in the effect of aerosols. A leading American group of scientists has recently written "Current uncertainties in the total solar irradiance and aerosol forcings are so large that they preclude meaningful climate model evaluation". The FAST mission will characterize black carbon aerosols, reflective tropospheric aerosols, and the aerosol indirect effect and thus contribute to improved climate models. It will also better characterize the temporal and spatial distribution of aerosols and their properties.

Challenges

When we implement ambitious space missions using distributed systems in an efficient way we are facing tremendous challenges. These are challenges for research and technology but eventually also challenges of finance, law and intellectual property or even culture, if we work in a transnational environment or within a multinational team.

Here we focus on the research and technology challenges. Each of these challenges can be regarded as an opportunity and a scientist will emphasize other aspects than an engineer. Typical questions of scientists range from very fundamental problems, such as "How can we improve the current knowledge of the system Earth using distributed space systems?" to more specific questions such as "How can we distribute sensors best to achieve optimized resolution and coverage?" or "How do we exploit the flexibility of distributed systems for optimum science return?".

An engineer, especially if he has a systems view on problems, will recognize for example that an abundance of control theories has been developed in the recent past. However, he also notices that most actual implementations of control theories in space are based on a few classical control schemes and that most of the advanced control theories have not considered their performance in the presence of sensor and actuator noise. So, his question will be "How can we best control distributed systems in the presence of sensor and actuator noise?". He will also recognize the potential of these systems to extend present capabilities to new solutions with questions such as "How can we share resources on distributed systems to optimize mission return?" or transfer technologies in a completely new context "Can we extend the concept of wireless communication and distributed systems to within a spacecraft?". Each of these questions provides a wealth of research potentials within the next decade.

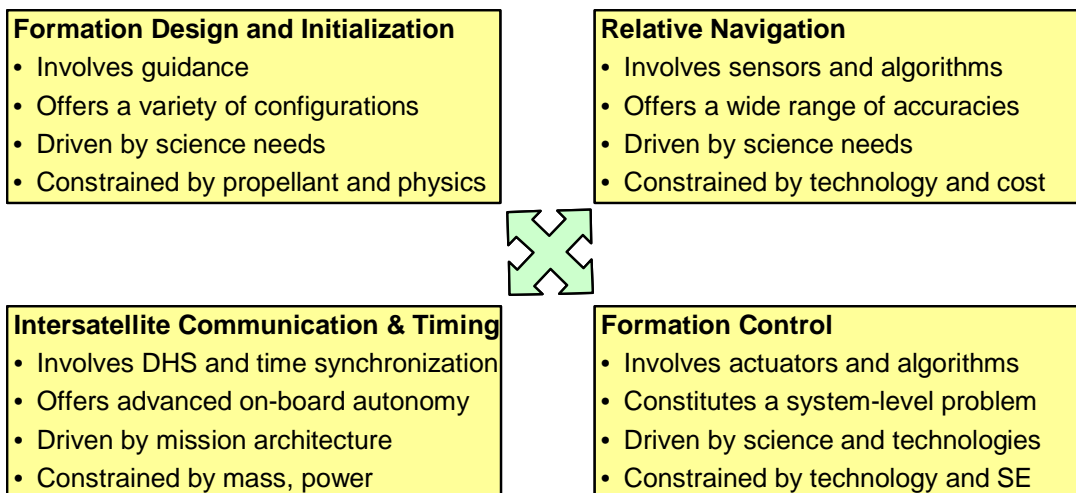


Fig 8 Technological challenges of distributed systems in space.

Technological challenges are shown in Fig. 8. Four key areas have been identified:

1. Formation design and initialization
2. Relative navigation
3. Intersatellite communication and timing
4. Formation control.

Each of these areas is characterized by its involved technologies, the potential it offers, as well as its drivers and constraints. We will have, for example, a closer look to the formation control problem. A formation of several spacecraft will, once put into a desired relative geometric configuration, inevitably be destroyed due to natural perturbation forces. So, actuators on the spacecraft have to be used which are activated by specific control algorithms. Since this control is fundamentally coupled to other sub-systems and depends on the mission requirements, it constitutes a system-level problem. The requirements from scientists on the control accuracy and the technologies applied for control are major drivers of formation control. The performance of this control is constrained by the available technology, such as minimum impulse bits of a thruster or the handling of complexity within systems engineering.

If we consider a more complex setting of distributed systems with, for example, multiple spacecraft with multiple payload types from multiple organizations, we can, on a more abstract level, link distributed space systems to the research field of system of systems. Here, resources and capabilities are pooled together for increased functionality and performance than what could be gained from the sum of the constituent individual systems.

Trends and Context

Science and technology of distributed space systems would not sufficiently address the topic without addressing current trends and embedding the topic in a context.

Miniaturization

One of the most important trends in contemporary spaceflight is miniaturization. There are two main drivers for miniaturization: cost pressure and technology push. If we look at the cost of space hardware, we find a typical value of 100,000 Euro per kilogram. One kilogram of gold costs about 20,000 Euro. Thus, space hardware is a factor of about 5 more expensive than gold. The cost pressure is even more pronounced if we look at the energy required to lift hardware to space. The kinetic and potential energy of 1 kilogram in a low Earth orbit is about 34 million Joules. If I look at the check for my regular electricity household, I pay about 10 Euro-cent per kWh. If we consider that launching 1 kilogram into orbit costs typically 20,000 Euro, it can be concluded that transferring energy to space is 20,000 times more costly than spending it on ground. So, we have to carefully trade and optimize mass versus functionality.

The technology push in fields such as electronics and materials opens up new ways to miniaturize components. In particular the advancement in MEMS technology,

which stands for Micro-Electro Mechanical Systems, allows the development of capable highly miniaturized sensors and actuators in space.

Two examples of recent developments in the framework of the Dutch research program MicroNed shall illustrate these potentials. The Autonomous Wireless Sun Sensor of TNO has a mass of only 80 gr and precisely measures the direction to the Sun. Furthermore, due to its integrated solar cell and since it transmits the measured data wireless within the spacecraft, this sensor does not require any cables, which saves mass and allows a very easy integration. The sensor flies successfully on Delfi-C³, the first Dutch university satellite which was developed at the chair of Space Systems Engineering of the faculty of Aerospace Engineering together with the faculty of Electrical Engineering, Mathematics and Computer Science. Delfi-C³ has been launched on the 28th April 2008 and is performing very well.

An example of a MEMS actuator is the T³μPS, a thruster resulting from a cooperation of TNO, TU Delft and the University of Twente. With a mass of only 200 gr, it will allow an active control of the orbits of miniaturized spacecraft and push the limits of what can be achieved with miniaturized spacecraft much further. T³μPS will be flown in 2010 on Delfi-Next, a successor of Delfi-C³. Both satellites are part of a development line of CubeSats at the Delft University of Technology.

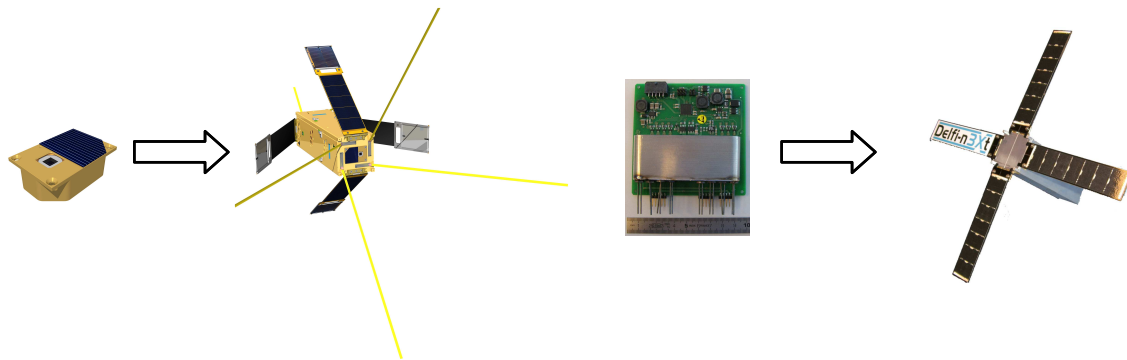


Fig 9a (left) Miniaturized Autonomous Wireless Sun Sensor (TNO) onboard the Delfi-C³ satellite launched in 2008. **9b** (right) Miniaturized micropropulsion actuator (TNO, TU Delft, UTwente) to be flown on the Delfi-NEXT satellite in 2010 (© Sensor and actuator: TNO).

Miniaturized systems in space do, however, not only reduce cost. Even more important: they allow rapid demonstration of new technology in space. Typical high-end scientific space missions have development times of up to 20 years which implies the use of conventional, well-proven, and often out-dated, technology. In contrast, miniaturized satellites can demonstrate with calculated risk new technology in space with development times of 2.5 years, as in the case of Delfi-C³. The potentials of miniaturized systems in space are more and more recognized by space companies, the military and space agencies, such as ESA. However, missions using micro-, nano- or pico-satellites will primarily not compete but complement missions relying on large spacecraft.

A Vision for Distributed Space Systems

Miniaturized single spacecraft missions have a rather limited and specific functional performance. On the other hand, distributed space systems using large spacecraft are in most cases neither affordable nor necessary. A unique situation arises, when we extend and combine these two concepts.

My vision for the decades to come is therefore to have:

Highly miniaturized, massively distributed autonomous space systems for unrivaled science and exploration

Not with two, five or tens of spacecraft, but with hundreds or even thousands. Not with spacecraft of one to 10 kilograms, but with spacecraft of a few grams. We call these spacecraft femto-satellites and none of these spacecraft has ever been flown in space. Examples are the design study of a satellite on a Printed Circuit Board of the Surrey University or the so-called nano-naut, a device of 5 millimetre diameter of the University of Berkeley in California. The path towards higher and higher miniaturization can start at pico- and nano-satellites, like Delfi-C³, and extend to satellites in a package, satellites on a chip to concepts even like smart dust.

Each of the spacecraft would certainly have a limited functionality, for example measuring a single quantity, such as radiation flux, but a swarm of many of them can build up a powerful network with exceptional characteristics, such as the global coverage of the Earth's radiation environment.

This vision holds a lot of opportunities and challenges. As it is so different from how we do spaceflight today, we have to leave the beaten paths and think of completely new application scenarios. The degree of miniaturization and the large number of spacecraft calls for processes of mass production. The vision might develop its full strength only if we can also abandon the conventional way in which we launch spacecraft. Which methods would be feasible and efficient? Last, but not least, when we design spacecraft we like to think of the subsystems a spacecraft is composed of: thermal subsystems, attitude and orbit control subsystems, structure and power subsystems or communication subsystems. How would the processes and concepts of building these miniaturized spacecraft be affected? Most likely, the conventional separation into spacecraft sub-systems will break down for this class of spacecraft and open up new ways for integrated design concepts with a strong impact on systems engineering.

Together on Earth

Working for space needs cooperation on Earth. The complexity of the undertaking needs engineering specialists and systems engineers alike. Cooperation on Earth means primarily people closely interacting. But it can also mean cooperation between academia and industry, agencies and research institutions, states or even international organizations.

Working together on Earth is inevitable to reach for the skies. It allows learning without limits: from persons, from approaches, from disciplines, from culture. It realizes synergies and allows for cross-fertilization. However, it holds threats such as

complexity and the management of interfaces. One of the greatest threats in cooperation is terminology. It appears as a trivial statement, but it is not. Whoever has participated in the development of a science mission knows how difficult it is to cross language barriers between scientists and engineers in order to understand each others needs.

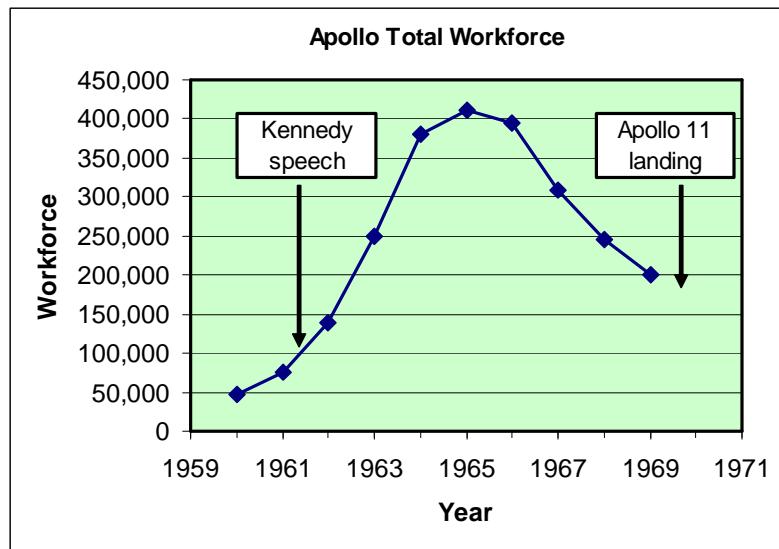


Fig 10 Apollo total workforce in the era of Apollo

It is instructive to look at the evolution of workforce in space. The emerging Apollo era saw a steady increase of the total workforce from 50,000 to more than 400,000 people in 1965. In 2008, the total NASA workforce comprises about 60,000 people, a level which NASA had more than 45 years ago. No manned spaceflight to the moon is foreseeable in the future with such limited resources.

Conclusions

Distributed space systems employ two or more spacecraft which act in a coordinated way to achieve common mission goals. The architecture of such distributed systems can be based on rendezvous and docking scenarios with two spacecraft in close vicinity, formation flying with two or more spacecraft with separations of a few 10 meters to a few 100 kilometres, constellations with several spacecraft distributed on a global scale or swarms with a multitude of spacecraft each with limited functionality.

We have seen that such distributed space systems can cover large areas in space and time which can not be realized with single spacecraft systems. From a scientific point of view, they allow the implementation of virtual instruments in space with small revisit times and high temporal resolution as well as interferometric observations of a specific region or parallel observations of multiple regions. Their application field in science ranges from classical geophysical and remote sensing tasks to fundamental physics and space science. In engineering, they enable the build-up of large flexible and robust networks and webs with classical application areas such as rendezvous and docking for servicing and maintenance and control of

distributed communication systems. Distributed space systems are in general, however, not competing with but complementing single spacecraft missions.

The cost pressure and technology advance enforces and enables an ever increasing miniaturization of spacecraft components, sensors and actuators and complete sub-systems and systems. This opens up the opportunity to combine miniaturization trends with distributed systems to realize ambitious missions through the mass-production of highly miniaturized individual craft with limited functionality. The applications are manifold and allow enhanced science return, advanced exploration, increased security, rapid technology demonstration and, last but not least, a viable space business.

Ladies and gentlemen,

We are witnessing the dawn of a new age of spaceflight. We face tremendous potentials and challenges which are not even fully visible. To realize these potentials we need a concerted effort. We need the students with their sparkling enthusiasm and their new ideas, we need the PhD students with their deep analytical skills, we need the staff members with their experience and capability of guidance, we need the professors with their visions and persistence, we need the faculties with their facilities and skills to treat the multi-disciplinary problems that we face, we need the deans, the rector, the members of the College van Bestuur and others for their support and small change, and, we need the cooperation with industry, knowledge institutes, agencies and politics.

Last, but not least, I need the support of my family; of my wife Margit, my daughter Katharina and my son Johannes. Thank you for what you have made possible.

In working for a future in space we have to work together on Earth now. Let us make that happen. I feel honoured to help shaping this future.

Ik heb gezegd.

Eberhard Gill