GEOSTATIONARY DATA RELAY SATELLITES FOR EARTH OBSERVATION: THE GERELEO CONCEPT

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Abstract

From a GEO satellite's perspective a LEO satellite is visible on more than half of its orbit. Albeit the free-space loss of an inter-satellite link is much higher than the one of a direct ground link, considerable data rates and download volumes per overflight can be achieved. In this paper we describe an integrated approach for a data relay satellite system developed in the context of the GeReLEO research project. The system has been developed and optimized especially for small LEO satellites with very limited transmit power.

1. INTRODUCTION

Low-earth-orbit (LEO) satellites require both data links for telemetry, tracking and command (TT&C) and for download of mission data. A single ground station can maintain a contact to a passing LEO satellite for relatively short time only (typically ~10 minutes), and together with high-resolution sensor systems on-board the satellites producing high amounts of data this leads to a serious bottleneck. In fact, depending on the actual orbit parameters (altitude and inclination) the long-term average visibility as seen from one ground station is only 1% to 6% of the overall orbit time.

State-of-the-art is a world-wide network of ground stations. More specifically, satellites on polar orbits typically require costly ground antennas in polar regions (e.g., German Antarctic Receiving Station O'Higgins) so that during each orbit period at least one contact can be established.

Geostationary-earth-orbit (GEO) satellites acting as data relays are another elegant possibility to overcome this problem, since the majority of LEO satellites will be visible to the GEO satellite for at least 50% of their orbital period. The advantages for TT&C are obvious, and data download benefits from more relaxed data rates resulting in decreased transmit power requirements on-board the LEO satellites. The goals of the project GeReLEO were to explore and to demonstrate new key technologies for the realization of GEO data relays for LEO satellites in the Ka band (26 GHz and more).

This paper describes the key innovations of the GeReLEO research project. Main objective was the support of several LEO satellites at the same time with one single data relay requiring both a suitable data transmission protocol and a multi-beam receive antenna on-board the GEO satellite for the mission data. Furthermore, channel adaptive transmission schemes (i.e. variable modulation and forward error correction) were developed so that utilization of available bandwidth and transmit power is as optimal as possible. Finally, we describe synchronization issues caused by the high relative speed and resulting Doppler shift.

2. SYSTEM CONCEPT

The GeReLEO data relay concept includes two types of links: a low-rate telemetry and telecommand link and a unidirectional high-rate link from the LEO satellite(s) via the GEO to the ground station (see BILD 1). For the low rate links a small conical horn antenna on the GEO satellite provides a global beam illuminating the LEO satellite orbits. In contrast to existing geostationary data relay concepts like the Tracking and Data Relay Satellite System (TDRSS) by NASA or the European Data Relay Satellite System (EDRS) by ESA, the GeReLEO concept aims at providing several data links in parallel. Each high-rate link shall reach data rates of up to 100 Mbit/s.

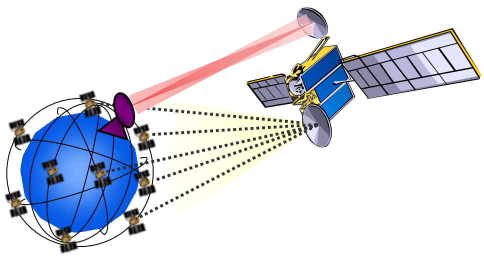


BILD 1. Concept of the high-rate data relay between a GEO satellite and several LEO satellites.

A reflector antenna located on the GEO satellite delivers the necessary gain by focusing the radiation from different directions to separate spots on a patch antenna array. This corresponds to a multi-beam approach where separate beams cover separate angular directions. The spatial signal separation enables switching off all low-noise amplifiers (LNAs) of not illuminated patch elements. In contrast to a phased array antenna where all LNAs have to be active this enables an efficient power and thermal design. With the help of a switch matrix the received signals are routed to the transparent transponders. It is based on RF micro-electro-mechanical systems (MEMS) switches which besides their low signal losses and low power consumption save mass and space.

The antenna on-board the GEO satellite provides a field of view of +/- 10° covering LEO satellite orbits up to 950 km completely. It facilitates an average access time of 65%. Since most of the LEO satellites fly on polar orbits, the spatial density of LEO satellites is maximal above the poles. In order to avoid two or more LEO satellites appearing within one spot-beam, the spot-beam size was selected to be smaller than 1°. This reduces the overlap probability to less than 5%.

The hardware setup as well as the communication architecture are described in detail in the following sections.

3. RX MULTIBEAM-ANTENNA

3.1. Overview

Tracking of several satellites in parallel with high gain can only be done electronically. There are two basic antenna architectures capable of fulfilling all requirements for a GEO antenna for high-rate data relays: the direct radiating array (DRA) and the array-fed reflector. Analysis of both architectures revealed that the array-fed reflector is more suitable for the aimed application [1].

3.2. Array-fed Reflector

The proposed antenna concept based on the array-fed reflector architecture is shown in BILD 2 for an offset configuration. Signals coming from different directions (different LEO satellites) focus on different parts (subsets of patches) of the active multifeed array that is positioned close to the focal point of the reflector. A reconfigurable switch matrix located behind the multifeed array switches the array elements involved in the data reception to satellite transponder front-ends. Signal from each array element can be amplified by low noise amplifiers (LNAs) integrated into the multifeed array structure. The LNAs are independently controlled and switched-on only in the case of data reception by the corresponding array element.

LEO satellites can be tracked by switching between different beams for best signal reception. The radiation characteristics of the antenna can further be improved by enabling electronic steering of each beam in a small region [2]. Such steering can be realized by receiving signals with more array elements (e.g., with a sub-array of 2x2 elements) and performing digital beamforming on the level of sub-arrays.

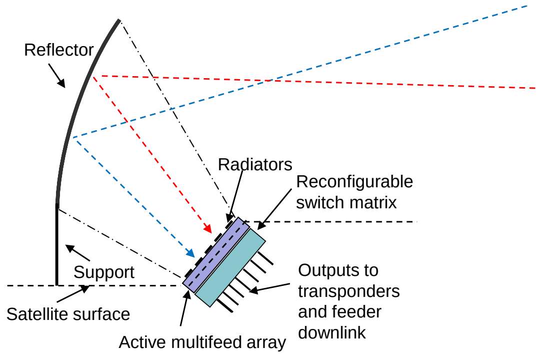


BILD 2. Array-fed reflector in offset configuration

3.3. RF-MEMS Switch Matrix

3.3.1. Switch Matrix

The switch matrix is located between the outputs of the multifeed array and the RF front ends. It connects the antenna elements, which are currently in use for data transfer, to the RF front ends for amplification, frequency down-conversion, and further signal processing.

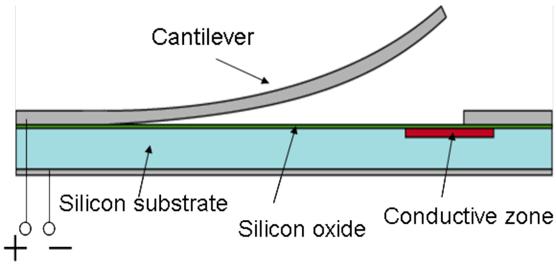
There are a number of constraints which make the design of the switch matrix a challenging task. First of all, the high number of inputs makes the system very complex. In addition, the switch matrix deals with RF-signals at around 26 GHz. Since the system is meant for a space-borne application, size, weight, and DC-power consumption are crucial parameters.

The core functionality needed to realize a switch matrix is a multi-throw switch for RF-signals, in the most basic case a single-pole double-throw (SPDT) switch. There are a number of technologies available for switching RF-signals: coaxial switches, FETs, PIN diodes, and RF MEMS among others. The technology of choice here is RF MEMS because it promises lowest signal loss, compactness, low weight, and low DC-power consumption at the same time.

For this project, a technology which is being developed by EADS Innovation Works was selected (see BILD 3) because of its high concept-inherent reliability and temperature stability, the demonstrated RF-performance parameters and the design flexibility offered [3].

The RF MEMS switch concept relies on a fixed-free curled cantilever which is implemented as series element in a microstrip line.

The main challenge for the packaging consisted in the minimization of thermal impact on the switch element during the bonding process in terms of maximum process temperature and duration. For functional testing of the device a glass cap was chosen (see BILD 4).



a) A cross-sectional view of the EADS RF MEMS switch concept.

b) SEM photograph

BILD 3. Schematic (a) and SEM photograph (b) of the EADS RF MEMS switch. The curled cantilever is 400 µm long.

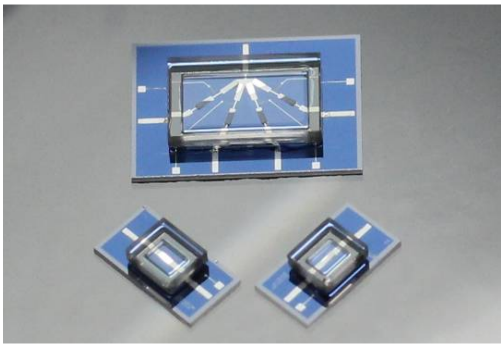


BILD 4. SPST and SP4T switch elements after final dicing process.

3.3.2. RF MEMS Switch Matrix

The switch matrix for the demonstration system must provide 16x8 switch functionality. Due to the overall system design, some of the possible combinations are redundant. Removing such combinations allows for significant reduction of switch matrix complexity. Consequently, the design is reduced to four simple switch modules with four inputs and two outputs each. BILD 5 depicts such a single module during assembly.

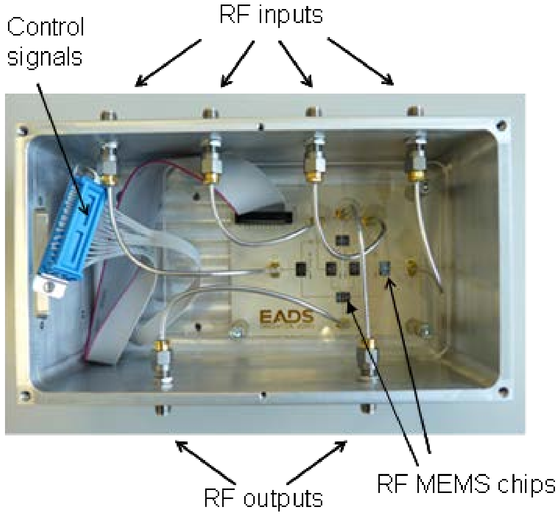


BILD 5. Photograph of a 4 x 2 switch matrix module, looking through the lid of the housing, with RF inputs and outputs, control signals, and printed circuit board with integrated RF MEMS chips.

3.4. RF-Frontend

Each LEO satellite sends its data using a different frequency in the 26 GHz ISL band. To reduce the interference between simultaneously transmitted data from several LEO satellites, a frequency division scheme is used.

The main functions of the RF frontends are to tune to the LEO-satellite transmit frequency, amplify the received signal, filter out-of-band signals, and down convert it to an intermediate 70 MHz centre frequency, where it is handed over to the digital beam forming unit. The 70 MHz frequency was selected to have a wide range of commercially available components (e.g., SAW-filters).

The maximum available bandwidth of 1 GHz is divided into 25 transmission channels, each providing 36 MHz of signal bandwidth with a channel spacing of 40 MHz.

The receiver is based on the double super-heterodyne concept (BILD 6), which is the preferred topology in terms of image rejection and channel separation.

The first intermediate frequency was selected to be in the 5.8 GHz ISM-band to minimize in-band mixing products and to take advantage of a great variety of components available for this frequency range.

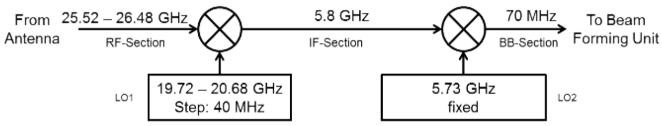


BILD 6. Block diagram of double super-heterodyne receiver.

For channel selection a tuneable local oscillator (LO) is used as the first mixer stage. Thus, each receive channel is down converted to the same intermediate frequency band centred at 5.8 GHz. For easier LO generation at half the LO frequency and less interference between LO and RF a subharmonic mixer is selected. Each signal path needs its individual first LO, since different receive channels will be selected via serial commands from the beam forming unit.

The second LO generates a fixed frequency and is realized as a phase locked oscillator (PLO).

Although the relatively small step size of 40 MHz at 26 GHz output could be easier realized using a fractional-N phase locked loop (PLL) synthesizer, both LOs are designed as Integer-N PLL synthesizers to avoid fractional spurs in the passband, often associated with fractional-N PLL synthesizer architectures. Both LO synthesizers are phase locked to a built-in 100 MHz ovenized crystal oscillator (OCXO) providing frequency stability and an ultra-low phase noise 100 MHz signal for the phase detectors.

4. DATA TRANSMISSION

4.1. Multiple Access

A multi-frequency time-division multiple access (MF-TDMA) scheme is used on the high-rate links and on the low-rate telemetry links, whereas a time-division multiplexing (TDM) scheme is used on the low-rate telecommand link. In contrast to typical TDM(A) implementations in the scope of the GeReLEO project both the TDMA and the TDM schemes are used without a regularly repeating frame structure, but it is foreseen to introduce this feature in the future in order to enable better synchronization. The length of the time slots is restricted by the visibility time of the LEO satellite, and determined by the radio resource allocation algorithm running at the GeReLEO network control centre (NCC) with a service level agreement (SLA) as input.

4.2. Adaptive Coding and Modulation

Adaptive coding and modulation (ACM) and variable coding and modulation (VCM) are supported by the GeReLEO system. The idea in both cases is to adapt the modulation scheme and code rate to the actual link condition, which is subject to the distance between LEO and GEO and atmospheric effects between the GEO and a ground station. In case of bad link conditions (high free space loss or clouds/rain), more robust modulation and coding schemes (ModCods) are used. ACM requires a feedback channel, whereas VCM does not. VCM is not as robust as ACM against random effects, but VCM can be very well applied in case the inter-satellite link is weaker than the feeder link, thus saving system costs. The GeReLEO concept envisages using both on the high- and on the low-rate links quadrature phase shift keying (QPSK) or 8PSK modulation together with low density parity check (LDPC) codes as forward error correction (FEC). Later, the modulation schemes can be extended to higher order modulations as well.

4.3. Modem Architecture

One of the most critical parts in the concept is the modem on the LEO satellite due to typical restrictions in size, weight and power. Furthermore, the modem has to withstand the space environmental conditions so that space grade electronic hardware and a suitable design is required.

To keep the modem as flexible as possible, the signal processing is performed on a reconfigurable field programmable gate array (FPGA), while the upper protocol control layers can be delegated into a processor. With typical satellite interfaces given and supporting a LDR Tx/Rx link and a HDR Tx link the architecture was designed as follows (see BILD 7 which is a further development within the GeReLEO-MODULOS project):

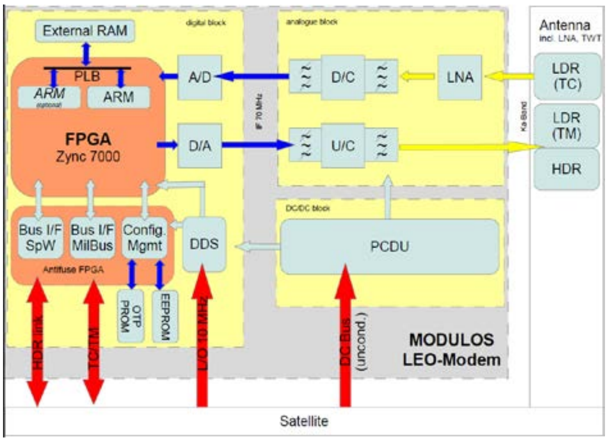


BILD 7. GeReLEO LEO modem.

- HF board: (I/F 70 MHz / Ka-band)
  - 1 Tx path with up-conversion, filtering and pre-amplification (for HDR and LDR)
  - 1 Rx path with down-conversion, filtering and amplification (LDR only)
- Digital board:
  - FPGA for signal processing and link control
  - ADC (Rx) and DAC (Tx) conversion (70 MHz intermediate frequency)
  - antifuse FPGA and memory for satellite data bus interface for TM/TC and HDR data stream
- Power control and distribution unit
  - interface to satellite power bus (DC)
  - DC/DC conversion and distribution

The main processing core is a XILINX Zync 7000 FPGA including two ARM processor cores. The performance-critical physical layer which is in charge of fast signal processing (forward error correction and (de)modulation) runs as task on the FPGA itself, whereas the upper protocol layers run in the ARM core, using a QNX real time operating system. This approach is an elegant compromise between power consumption, flexibility in reconfiguration, and signal processing performance.

The FPGA configuration is managed by an antifuse FPGA, which is also providing the digital interface to the satellite, using IP cores for MIL-Bus and SpaceWire data interfaces. A new configuration can be uploaded and programmed via the MIL-Bus TC interface.

The analogue signal is generated on an intermediate frequency of 70 MHz. The HF board does directly up- (Rx) or down-conversion (Tx) to/from the transmission frequency in the Ka-Band. A power control and distribution unit finally provides the internal power.

The total power consumption is assumed to be in the order of 50 W (Rx and Tx in parallel) and the hardware will have an estimated mass of 5 kg. The size of the initial design is 250 mm × 150 mm × 85 mm.

5. PERFOMANCE

The system performance was determined with system simulations. During the system simulations, a reference LEO satellite was propagated and for each satellite position a link budget analysis was performed, based on which the available data rates were calculated. A two weeks long orbit propagation was performed assuming a TerraSAR-X [4] like orbit (509 km altitude, 98° inclination angle) as example.

5.1. Low Data Rate Link

According to the simulation results, the optimum channel bandwidth of the low-rate telecommand link is 20 kHz. At this bandwidth the maximum of the average amount of transmittable data per pass is around 41 Mb, whereas the maximum of the mean data rate during line-of-sight (LOS) is around 11.9 kb/s. If the channel bandwidth was decreased, the symbol rate would not be sufficient to reach high data rate (although less robust ModCods can be used). If the channel bandwidth was increased, the system would start to run out of ModCods, thus, the data rate decreases. By using a bigger LEO satellite antenna, the mean data rate can be increased, and of course the average transmittable data amount can also be increased.

In case of the low-rate telemetry link the optimum channel bandwidth is 53 kHz. At this bandwidth the maximum of the average amount of transmittable data per pass is around 109.2 Mb, whereas the maximum of the mean data rate during LOS is around 30.9 kb/s. By using more LEO satellite transmit power, the mean data rate can be increased, and of course the average transmittable data amount can be also increased. The same effect can be achieved by enlarging the LEO satellite antenna, but in addition the interference caused to other satellite systems can be decreased.

5.2. High Data Rate Link

BILD 8 shows the average amount of transmittable data per pass and the mean data rate during LOS in case of the unidirectional high-rate link.

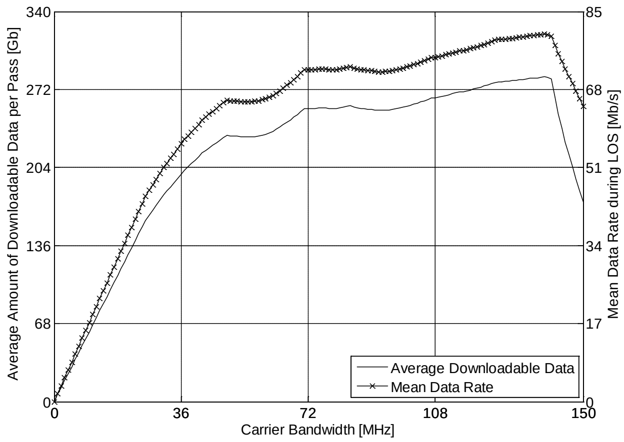


BILD 8. Performance results in case of the unidirectional high-rate link.

A maximum of around 283 Gb data on average can be downloaded from the LEO satellite per pass, in case of 139 MHz channel bandwidth. The maximum of the mean data rate during LOS appears also at around 139 MHz channel bandwidth, just like before. The maximum is around 80.1 Mb/s. By using greater LEO satellite transmit power, the mean data rate can be increased, and of course the average transmittable data amount can also be increased. The same effect can be achieved by increasing the LEO satellite antenna, but in addition the interference caused to other satellite systems can be decreased.

6. OUTLOOK

The in-orbit verification of the antenna array, the MEMS and FPGA performance and degradation over time are objectives of a successor project called GeReLEO-SMART. Since there is little knowledge about the long term performance of Teflon based multi-layer patch antennas, the experiment will verify the use of such materials in free space. Inside the multilayer antenna stack there are included a strip line band pass filter as preselector and a LNA die providing initial gain as close as possible to the antenna [5]. Five arrays of 2x2 circular patches at about 26 GHz were designed to provide redundancy and the possibility to perform statistical analysis. At one time just one array can be fed through towards the satellites transponder to measure signal characteristics. It is planned to generate the transmission received by the GEO satellite from both earth-based ground stations and LEO satellites capable to steer their beam towards the GEO orbit. A radiation sensor placed next to the antenna will record the accumulated radiation doses even when the payload is electrically switched off. This data is needed for further degradation analysis of the Teflon based patch antenna. To test even more the characteristics of MEM switches a dedicated test board consisting of RF source, MEM switch matrix and power meter will provide the possibility of analysing independently from the receiving multi-layer antenna and the LNAs included. The controlling of the MEM switches will be done by an FPGA verifying also the reliability of such devices in geostationary orbits.

Main objective of the second successor project GeReLEO-MODULOS is the development of a hardware engineering model for a LEO modem including up/downconverters for the Ka-band. The software/firmware for all protocol layers and connectivity to the satellite bus will be developed so that a possible later proto-flight model can be directly supported.

7. ACKNOWLEDGEMENTS

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