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Photonic swarm for low frequency radio astronomy in Space

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Abstract

Radio astronomy from 100 kHz to 30 MHz allows compelling science that requires a new space based interferometer at a considerable distance from the Earth. We propose a new satellite concept which has a series of dipole antennas connected to the satellite using tethers. Power over fibre is used to transfer power to the remote antenna units and digital radio over fibre is used to transport the astronomical signal back to the satellite. This approach allows launching an interferometer using only one satellite, and it allows scaling by using multiple satellites. In this paper, the overall preliminary system concept is presented.

1. Introduction

Radio astronomy is a science area that traditionally uses ground based observatories. In the radio window with wavelengths between approximately 10 metres and 5 cm, the atmosphere is mostly transparent. For the higher frequencies in the radio window, single dishes [e.g., 1, 2] and dish based interferometers [e.g., 3, 4] are used to collect signals from astronomical sources. For frequencies below 1.5 GHz, telescopes based on aperture arrays are becoming mainstream facilities today [5, 6, 7]. The next generation ground based facility is the Square Kilometre Array (SKA) which is currently in the design phase and aims for a dish based and aperture array based interferometer [8].

Although the atmosphere at these radio frequencies is transparent, the ionosphere distorts the astronomical signals due to the relatively high density of free electrons. This distortion is particularly strong at frequencies below 200 MHz. For LOFAR, these distortive effects can be calibrated out [9]. At frequencies below 30 MHz, observations with ground based instruments become increasingly difficult due to the reflective and distortive properties of the ionosphere (Figure 1). As a consequence, the electro-magnetic spectrum below 30 MHz is the only frequency band which has been hardly explored so far. A space-based observatory is the only practical solution to perform science at these low frequencies. For example, a sky map below 10 MHz at only very low spatial resolution has been produced on the basis of data from RAE-2 satellite [10].

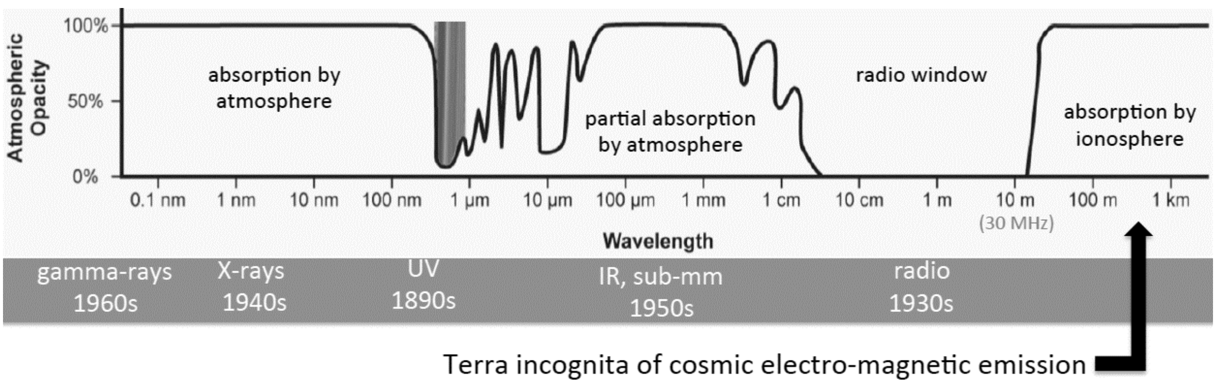

Figure 1: Atmospheric opacity as a function of wavelength.

DOI: 10.13009/EUCASS2017-273

Yet, this frequency band contains very interesting astronomical signals originating from solar and planetary bursts [11] to the dark ages and cosmic dawn [12]. Therefore, the astronomical community has explored various system concepts over the past two decades to enhance sensitivity and boosting spatial resolution by considering low-frequency interferometry in space. The Netherlands China Long Wavelength Explorer (NCLE) will be the next step in the space based radio astronomy [13]. It consists of 3 monopole antennas at the side of the Chinese Chang'e 4 relay satellite [14] which is planned to be launched in 2018 and will operate in the Earth-Moon L2 Lagrange point in view of the far side of the Moon, at frequencies below 80 MHz. The instrument will be used for preparatory observations with respect to the Dark Ages, measurement of RFI and detection of solar and Jovian radio bursts. In addition, the rover which is part of the Chang'e 4 mission will land on the lunar far-side and will have an antenna for detection of low frequency radio signals as well, so that in principle interferometry can be tested.

Eventually, full science in this frequency band can only be performed with an interferometer with a substantial collecting area [12]. Such an instrument should ideally not be deployed in an orbit close to the Earth for two reasons. First, man-made radio signals can leak through the ionosphere causing elevated noise levels. Secondly, the ionosphere reflects and absorbs astronomical low frequency radio radiation signals [15], making low altitude orbits unsuitable. Therefore, a future instrument will have to be deployed at a considerable distance from the Earth, e.g. in a Sun-Earth Lagrangian point, or at or beyond the far side of the Moon, either in an orbit around the Moon which then blocks interfering signals from Earth in a part of the orbit, or at the surface.

Several types of interferomeric system concepts have been proposed in the past, including a nanosat swarm at the L2 Lagrange point of the Earth and the Sun [16,17], a nanosat array in an orbit around the Moon [18] and a LOFAR-like instrument at the surface of the Moon [19]. In this paper, we propose a new system concept for low frequency radio astronomy in space based on photonic technology. This concept can be used both in a satellite configuration and at the surface of the Moon. Fibres and photonic technology are used both for distribution of energy as well as transport of the signals. The first big advantage is that close to the antennas, the required functions are reduced to a minimum. As a consequence, its second advantage is that the system consists of only limited amount of satellites or ground stations at the Moon, which is much cheaper in terms of launch, deployment and operation.

This paper is organized as follows. In Section 2 we will briefly review the science cases for such a mission. The system concepts and relevant technologies studied previously are summarized in Section 3. The new system concept is introduced in Section 4. The innovation in our system concept depends on photonic technology and Section 5 provides a brief description of the photonic technology required. In Section 6, a preliminary design of the photonic subsystem is provided. A discussion on the advantages and disadvantages of this concept is provided in the last section together with the conclusions.

2. Science

There is a broad range of science cases in the lowest part of the electromagnetic spectrum. A summary of the various science cases in relation to the frequency at which they can be observed is presented in Figure 2. A main science area is the red-shifted 21-cm Hydrogen line from the Dark Ages and Cosmic Dawn. This science area is cosmologically closely related with the Epoch of Reionization that is a transformative science case for the Square Kilometre Array. A large-scale interferometer in space would not only allow constraining the Dark Ages and Cosmic Dawn signal, but also to create maps of this very early phase of the universe. The frequencies at which this science is expected is between 1 and 80 MHz. An important science goal for a space based interferometer is also to create a sky map at these frequencies, for studying the evolution of strong extragalactic sources, such as galaxies with active galactic nuclei. Heliophysics and space weather are other areas that are not only scientifically but also societally and economically very relevant. Extreme space weather can have significant impact on vital infrastructures. Using scintillation effects and Faraday rotation on polarized galactic background allows mapping of the solar wind density, velocity and magnetic field. A space based interferometer significantly increases the radius around the sun at which these effects can be studied and used. It would furthermore allow the study of the auroral radio emission of the large planets in our solar system, Jupiter, Saturn, Neptune and Uranus. Especially the last two have low flux densities requiring substantial collecting area to do science. One of the science areas that receives a great deal of attention today is related to the transient sky. Detection and study of pulsars is the second important science case for the low frequency part of SKA. However, studies today are limited by the ionospheric cut off, and new pulsars are expected to be detectable in this new low-frequency range. The other intriguing area of transient radio science is the detection and localization of radio bursts. And last but not least, a full-scale low-frequency radio interferometer in space would exceed its predecessors with one to three orders of magnitude in terms of sensitivity, dynamic range, spectral coverage, and spatial resolution. History has shown that such a significant extension of parameter space invariably leads to unexpected and exciting discoveries.

DOI: 10.13009/EUCASS2017-273

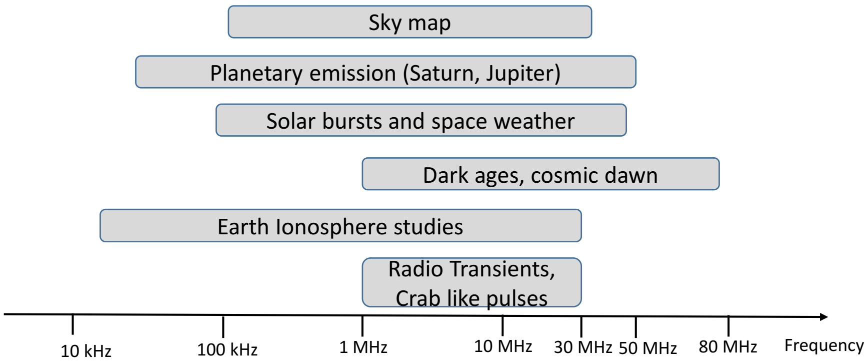

Figure 2: Science cases for space based low frequency radio astronomy.

3. Review of system concepts and technology

Different concepts for low frequency radio observatories have been presented in the past. In this section, an overview of some of the basic proposed concepts will be presented.

3.1 OLFAR, nanosatellites in lunar orbit with distributed processing

Several years ago, a concept study was conducted for the Orbiting Low-Frequency Antennas for Radio Astronomy (OLFAR) concept [18, 20, 21, 22]. The aim of OLFAR was to develop a space-based low frequency radio telescope concept for the ultra-low frequency regime of 1 – 30 MHz, which is difficult to observe from the Earth. The concept consists of a swarm of nanosatellites (≥ 10, and scalable), carrying 2 or 3 dipole antennas each at baselines up to 100 km and drifting in a three-dimensional dynamic constellation (see Figure 3). The preferred orbit of the swarm is around the Moon, in order to have periods in which the Moon is shielding the Earth and the interference coming from it. Processing, including correlation, is distributed over the satellites.

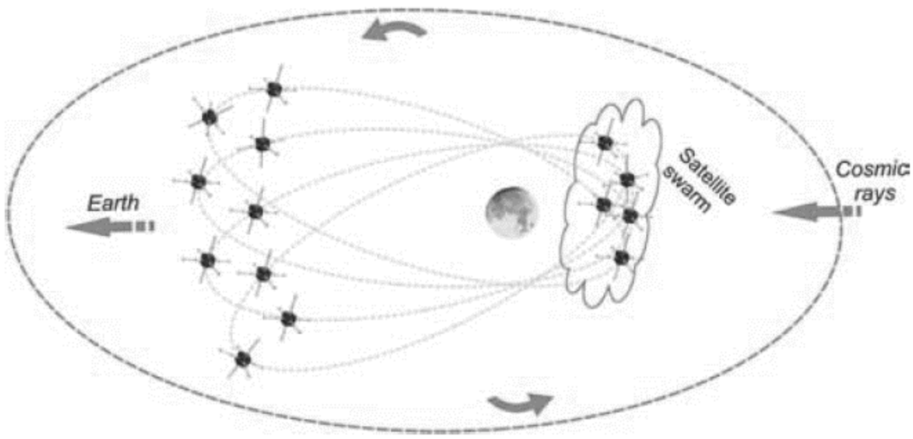

Figure 3: Nanosatellite swarm as proposed by [18].

DOI: 10.13009/EUCASS2017-273

3.2. DARIS, orbiting mini-satellites with central processor

In 2009 an ESA project, Distributed Aperture Array for Radio Astronomy in Space (DARIS), set out to investigate the space-based radio telescope concept for low frequencies (1 – 10 MHz) [16, 17, 23]. The focus of the DARIS project was to study the feasibility of a distributed aperture synthesis array in space, consisting of a three-dimensional satellite constellation of 8 small satellite nodes and a mother-ship. All nodes will have 3 dipole antennas each. The small nodes will send the measured data to the mother ship, which correlates and integrates the measured data. The processed data is sent to Earth for further processing and analysis. The inter-satellite communication was considered one of the main challenges because all satellites simultaneously need to send their raw data to the central mothership for correlation. Assuming high TRL mini-satellite concepts, and certain given mass and power constraints, a maximum instantaneous bandwidth of 1 MHz for each of the satellites was deemed feasible. The bidirectional link would consist of an RF-link, which needs to be strictly separated from the radio astronomical receiver. This study looked into the pros and cons of concepts for the different deployment locations, including lunar orbit, Earth orbit, Sun-Earth L2, and Earth leading and training orbits.

3.3. DSL, a precessing linear array in lunar orbit

Discovering the Sky at the Longest Wavelengths (DSL) has been proposed by a Chinese - European team. Its concept was a radio interferometer to be deployed in low-altitude lunar orbit, exploiting the radio quietness of the lunar far side. The proposed system consisted of a mother-spacecraft for data transport and control, plus eight small micro-satellites each equipped with three orthogonal dipoles. These satellites form a virtual distributed observatory with adjustable baselines, allowing different scientific observation strategies. The satellites are configured in a flexible quasi-linear array in nearly identical orbits, guaranteeing low relative drift rates. Short orbital periods and orbit precession ensure quick filling of the interferometric spatial frequency space, enabling high quality imaging [24].

3.4. FIRST and SURO-LC, a radio array in Sun-Earth L2

The ESA study FIRST [25, 26] looked into a slowly drifting constellation to be deployed at the Sun-Earth L2 point. An advantage of this deployment location is that longer integration times can be allowed due to the fact that the relative satellite drift is much lower than at a lunar orbit. This reduces the bandwidth required for the data down-link. A disadvantage is that, due to the slow relative drift, it will take longer to obtain the required interferometric spatial information. Technologies proposed in both FIRST and DARIS ESA studies were combined in the SURO-LC concept based on a constellation of cubesats in Sun-Earth-L2 [27].

3.5. DARE, LRX, FARSIDE, NCLE, Chang'e 4, single element receivers and lunar landers

In addition to the Chang'e 4 lander mission and NCLE mounted on its relay satellite as mentioned in the introduction, several other concepts have been proposed. For example, the DARE concept [28] which aims at observing the sky-averaged neutral hydrogen from the Dark Ages and Cosmic Dawn with a receiver located at the far side of the Moon (or in a low altitude lunar orbit). This includes a co-located multiple antenna-receiver system. A similar proposed system, but aimed at a wider range of science cases, is ESA's LRX lunar lander [29] and FARSIDE [30].

3.6. Technology developments

In recent years, the concept of formation flying satellite systems is getting more interest, thanks to the rapid development of nano- and pico-satellites (cubesats). By splitting up large satellites carrying many different instruments, e.g. for Earth-observation, one can build a series of small specialised satellites with one or a few instruments each that fly in formation. The development time of a small satellite is significantly shorter than that of a big satellite and with that the costs are much lower. It is also possible to replace a malfunctioning instrument, just by replacing one of the small satellites in the formation by a new one, or to upgrade instruments. As the technology is still in development, several advantages have not yet been fully exploited. A number of missions have been prepared or launched to investigate and progress technologies.

DOI: 10.13009/EUCASS2017-273

Formation flying in radio astronomy is an obvious concept. However, as in low frequency radio astronomy the wavelengths are rather long, and as usually the instantaneous spatial aperture is sparsely sampled, there is no need to a-priori constrain the relative positions to within a small fraction of a wavelength. This holds as long as all relative positions are accurately known, and as long as over time all required spatial frequencies (baselines) are sampled.

Nodes is a technology demonstration mission from NASA that was deployed from the International Space Station in May 2016 [31]. The mission consisted of two cubesats that demonstrated that commanding of a spacecraft could be done by crosslinking commands through a space network, without a direct link of both cubesats to the ground. Also, science data could be transferred through the space network. And the formation could automatically select which satellite was best suited to serve as the ground relay, each day. This will make the control of a formation of satellites significantly simpler.

ESA is developing the Proba-3 mission [32], which should demonstrate technologies and techniques for highly-precise formation flying. Launch is scheduled for 2018. It consists of two small satellites that will form a 150-m long solar coronagraph. The satellites will autonomously maintain the formation with a precision in the order of millimeters and arc seconds.

Already in the beginning of space exploration, inflatable structures have been tested in space. One of the first projects that used inflatable structures was NASA’s Project Echo [33]. In 1960 Echo 1 was launched, which was a 30.5-m diameter balloon made of metalized Mylar, which acted as a passive communication satellite. To keep the sphere in shape, Echo 1 was equipped with a slowly evaporating gas system. In 1964 Echo 2 was launched. Echo 2 was a 41.1-m diameter balloon with a rigidized skin. After inflating in space there was no gas needed to keep it in shape. Apart from its function as a passive communication satellite, Echo 2 was equipped with two beacons. Due to their large size and low mass the Echo balloons experienced a solar sail effect, affecting their orbits. It is interesting to note that the large Holmdel horn antenna that was constructed in 1959 to support Project Echo was later used by Penzias and Wilson for their Nobel Prize-winning discovery of the cosmic microwave background radiation. To reduce the solar sail effect, PasComSat or OV1-8, a passive communication satellite, was made in 1966, consisting of a soft aluminium wire grid embedded in a special plastic designed to dissolve in space under the sun’s strong UV radiation. After launch, the structure is inflated with helium, after which the plastic covering dissolves, leaving an open aluminium structure. As active communication satellites were replacing passive satellites more and more often, very little development took place in this field. Recent work at JPL [34] shows some interesting new work on inflatable structures for cubesats.

4. Proposal new system concept

The rationale for proposing a new system concept stems from the disadvantages of the system concepts mentioned in the previous section. The swarm systems described in the previous section require a continuous control of the location of each antenna in the swarm. This implies functions for tracking and control of its location. Each antenna also requires a wireless bidirectional communications link to the central processor both for the distribution of timing signals to the antenna and the transportation of astronomy signals back to the central processor. All these functions require energy, so that each antenna also needs solar panels and batteries. The antennas need to be deployed once the nanosat swarm arrives at its destination. All these functions add to the overall system complexity, weight and cost.

Photonic technology provides a different solution to overcome those disadvantages. The concepts that we describe in this paper allow deployment in a Lagrange point as well as at the surface of the Moon at the far side. In this section, we assume deployment in a Lagrange point. A potential new system configuration is shown in Figure 4 and consists of a single cube-shaped satellite with 6 strings of tethers rolled on cylinders on each side of the cube. For large collecting areas, multiple satellites can be combined into a single system. One of the satellites then acts as a central satellite and will be in contact with the Earth for science data off-loading and TM&TC.

Only after the satellite arrives at its final destination, the tethers will unroll using thrusters at the end of each tether. The tethers consist of two different fibre types. Dipole antennas will be located alongside the tethers at various instances from the satellite. Unrolling the tether therefore also serves as the deployment mechanism for the antennas. An alternative deployment scenario not detailed here, would include slowly rotating satellites, limiting the location of the tethers for each satellite to a single plane.
Only by controlling the tether end and keeping the tether straight, the location of all the antennas alongside the tether is known and there is no longer a need for tracking and control of each antenna position individually. Short baselines (< 1 km) can therefore be realized by the combination of antennas connected to the same satellite. Large

DOI: 10.13009/EUCASS2017-273

baselines (~ 1000 km) can be achieved by creating a system of several satellites. The relative position can be determined with technologies as developed for Proba-3, or with the joint ranging and synchronization approach as described in [20]. The structures are exchanging data with each other using laser communication. The formation will communicate with each other using technologies as developed for Nodes.

The constellation of multiple tethered satellites would allow the creation of a large radio interferometer. This could be done by combining all raw sampled data into one big correlation matrix. This data product could be created in a central satellite, or distributed over all participating tethered satellites.

The fibres in the tether are also used for transmission of optical energy to the antennas using Power over Fibre (PoF). The transport of the astronomical signals is also done using digital Radio over Fibre (d-RoF) technology as described in Sections 5 and 6. The functions of the electronic components required at each individual antenna, the so-called remote antenna unit (RAU), are then reduced to filtering, low noise amplifiers (LNA), analog to digital (AD) conversion, transmission of the digital signal to the central processor, and conversion of the energy from the PoF to electrical energy, mainly for the LNA and the AD conversion.

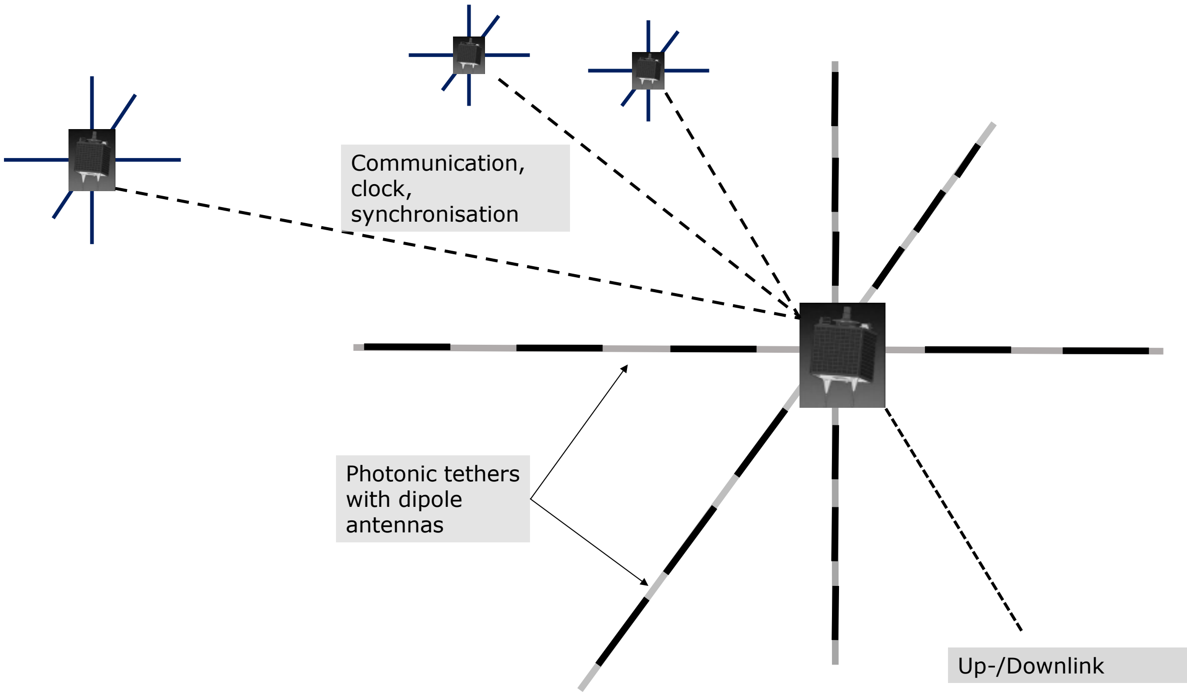

Figure 4: System concept showing the satellite and the antennas on the tethers

5. Review of relevant photonic technology

In the proposed space telescope system, optical communication technologies are applied for the transfer of signals from the antennas to the central satellite that houses the central processor of the telescope system. The tethers that are applied for connecting the antennas to the central satellite consist of a glass fibre. In this way, the tethers can be used for both the realization of a mechanical connection between each antenna and the central satellite, and for establishing a fibre-optic link along which the antenna signals are transferred.

Currently both analogue and digital Radio over Fibre (RoF and d-RoF resp.) techniques are being developed for the transfer of signals in distributed antenna systems like the photonic swarm. Most of these techniques are focused on 5G mobile networks.

The application of antenna units with analogue RoF links is attractive thanks to their low complexity and low power consumption. The architecture of RoF based systems assigns only limited functionality to the remote antenna unit (RAU), while at the central location most functionality, like A/D conversion, is present. In this way,

DOI: 10.13009/EUCASS2017-273

relatively low cost antenna systems can be realized, both from a capital expenditure and operational expenditure point of view, especially in the case of a large amount of remote antenna units (RAUs) that are distributed over a large area. An example of this latter situation is the SKA-LFAA telescope in which RoF based antenna connections are applied [8].

However, in case a large dynamic range is required in the antenna links, like in the photonic swarm telescope, the use of RoF technology is less attractive due to its limited spurious free dynamic range (SFDR). Instead, d-RoF is capable of providing the dynamic ranges that are needed in e.g. the space telescope, by applying ADCs with sufficient bits at the RAUs. An ADC at a RAU needs to be accompanied by an oscillator and, in case of a radio telescope, a clock reference that is synchronized with all other clocks in the telescope system. The use of digital electronics at the antenna necessitates the use of high quality EMI shielding in the RAU, to avoid that any of digital electronics EMI is picked-up by the RAU antenna. As a result, the use of d-RoF links increases the RAU complexity and the related challenges in their technology development track.

Currently, a wide range of d-RoF technologies and accompanying standards [35, 36] are available thanks to the huge efforts on the terrain of 5G mobile network technology development. Unfortunately, these d-RoF techniques have a relatively large power consumption and require relatively high bit rate links for the transfer of just narrow frequency bands. Since space systems need to use the available power in an efficient way with low power consumption, additional d-RoF R&D will be needed for a future space telescope, with a focus on low power, low weight d-RoF technologies, and efficient d-RoF signal formats and synchronization.

An efficient use of the fibre infrastructure of the space telescope is realized via the use of WDM techniques. In this way, the signal from an antenna is placed on an optical carrier with a specific wavelength (color). By multiplexing the various colors in a single tether based fibre the number of fibres in a tether is reduced strongly, as such reducing the weight and the related launch costs of the space telescope. Nowadays suitable (integrated) WDM lasers are available for both RoF and d-RoF applications.

In addition to the fibre-optic transfer of signals, also the power needed at the RAU can be transferred along the tether, using Power over Fibre (PoF). The use of PoF for powering the photonic swarm RAUs is attractive thanks to the galvanic isolation it provides between the RAUs and the central satellite, as such, leading to a less complex and more reliable design. The main disadvantage of PoF is mainly related to the limited efficiency of PoF links, which currently is about 20%. An assessment of PoF and alternative RAU powering approaches will show whether or not to use PoF in the future space telescope.

6. Preliminary design

Using both the approach of a digital transfer from the RAUs to the central signal processor satellite and a PoF based RAU power supply, the general design of the photonic swarm system is defined according to the scheme depicted in Figure 5. This general scheme is in-line with the architecture of existing radio telescopes like LOFAR [5].

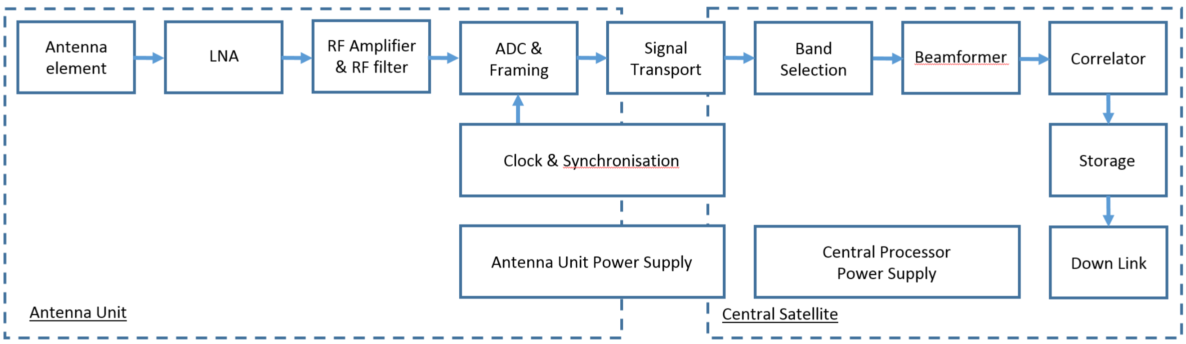

Figure 5 Scheme of general system design

The impact of the relative complex antenna unit architecture on e.g. weight, space envelope and performance can be reduced by integrating the various antenna unit based components on IC level into a single package. In the past years a mature infrastructure for the design [37] and fabrication [38] of photonic integrated circuits and the accompanying electronic / photonic integration and packing [39] has emerged. The presence of this infrastructure, opens the way to the application of integrated electronic/photonic components in future systems like the photonic

DOI: 10.13009/EUCASS2017-273

swarm telescope. The most attractive approach for the electronic / photonic integration in the photonic swarm front-end is to combine its RF amplification and filtering components, the ADC and the optical transmitter on IC level (see Figure 6).

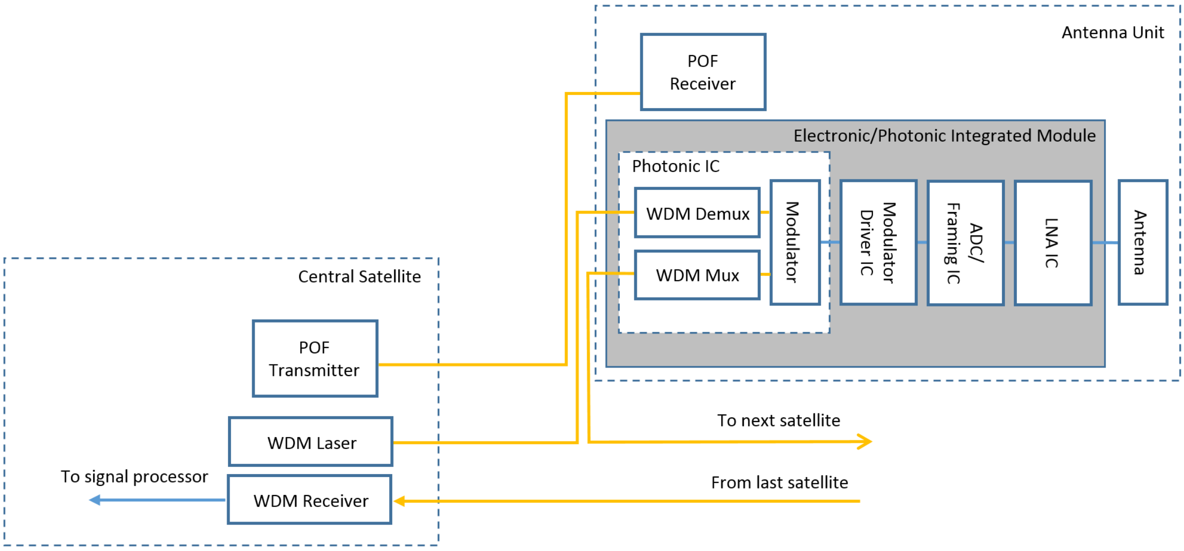

Figure 6 Schematic design of the photonic swarm front-end including the photonic system

The current approach for this integrated module uses a reflective modulator for placing the antenna signal onto an optical carrier that is generated by DFB lasers at the central satellite. By placing the laser at the central satellite, the power consumption at the antenna unit is strongly reduced, as such relaxing the requirements for the RAU power supply system. The earlier mentioned WDM concept is introduced into the system by using a multi-wavelength laser at the central location. By assigning a specific wavelength to each antenna unit, the signals from the antennas along the tether can be spatially separated at the central satellite using a WDM demux. The wavelength selection at the antenna unit is realized with the use of WDM mux/demux which are integrated with the modulator on the photonic IC. The synchronization of the antenna signals can be realized by placing an out-of-band pulse pattern on each optical carrier (wavelength) at the central satellite. By monitoring the time delay between transmission and reception of this pattern, all antenna signals can be aligned.

7. Discussion and Future work

The system concept photonic swarm that we propose in this paper has a number of advantages of the concepts described in earlier work. By using the photonic technology, the remote antenna units (RAU) distributed over the satellite tethers are much smaller in size and weight than compared with discrete antennas connected via free-space RF links. The position of the RAU in the “swarm” is automatically known once the system has been deployed and also clock distribution is much easier using the photonic links. There is no longer the need for deployment mechanism of the antennas, but instead a deployment mechanism of the tethers. This in itself poses new challenges of course and further research is needed to define these challenges and the design of solutions. The realisation of short baselines in a nanosat system poses challenges for formation flying. The photonic swarm allows the short baselines in a very elegant way. A disadvantage of the photonic swarm is that it will not provide the possibility to reconfigure the baselines between the antennas. Secondly, a photonic link may not be the optimal solution for very long baselines (> 1 km) from the perspective of weight. Therefore, for the design of a large-scale system consisting of thousands of antennas, a single central satellite may not be the ultimate solution. Instead a system of systems in which multiple satellites are combined, each connecting several tens to several hundreds of antennas is probably a better solution. The short baselines are then provided by the antennas connected to the same satellite, whereas the long baselines are provided by antennas on different satellites. New technological challenges require solutions such as for the charging of the fibres in the plasma if the system is deployed in space. If the system is deployed at the surface of the Moon, this is less of an issue. The last challenge to be mentioned here is the risk of this overall system in space for other satellites. Although the cross section of a fibre is small, having a system with very long fibres in space may not be desirable from the perspective of other satellite owners. Deployment on the surface of the Moon is therefore also interesting, or Earth leading/trailing orbits could be considered.

A series of developments is required to further raise the maturity levels of the technologies and the system concept. The associated roadmap contains the following steps:

DOI: 10.13009/EUCASS2017-273

- Technology development including increase of Technology Readiness Levels (TRL)
    - Development and characterization of a photonic demonstrator on RAU level
    - Development and characterization of a subsystem consisting of multiple RAUs connected to a central unit
    - Investigation of technology solutions for tethers supporting signal and power transport that are resilient to space environments and that meet maximum mass requirements
    - Investigation of technology solutions for (dis)charging of tethers in the plasma
    - Development of technology to deploy the tethers in space
- System development
    - Research in the energy management of the system and the associated system design
    - Configuration of the system for optimal spatial ("UVW") coverage and sensitivity (bandwidth), including full correlation and beam-formed modes, both for single tethered satellites and for a constellation of multiple tethered satellites
    - Research in the optimal deployment location
    - Dynamic analysis of long tethers in space and research into ways to spatially constrain them
- System test
    - Ground based test of the overall concept
    - Launch of a single prototype satellite with short tethers to test the interferometric system in space
- Large scale system
    - Design of a large-scale system
    - Launch and operations

All phases include the required analysis of requirements, and design reviews where applicable. We believe that a system test in space can be achieved around 2025 - 2030 and a full system launch will be viable around 2035 - 2040. The first phase can be completed by 2020.

The system concept that we have proposed here is in our view a very attractive alternative to other system concepts proposed previously since application of photonic technology allows a substantial reduction of the system complexity. It also allows a very elegant path towards an interferometer in space with the launch of only 1 satellite, and it allows efficient scaling to a large system by using multiple satellites.

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