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OLFAR, A RADIO TELESCOPE BASED ON NANO-SATELLITES IN MOON ORBIT

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ABSTRACT

It seems very likely that missions with nano-satellites in professional scientific or commercial applications will not be single-satellite missions. Well structured formations or less structured swarms of nano-satellites will be able to perform tasks that cannot be done in the "traditional" way. The Dutch space-born radio telescope project OLFAR, the Orbiting Low Frequency Array, is a good example of a typical "swarm-task". The OLFAR radio telescope will be composed of an antenna array based on nano-satellites orbiting the moon to shield the receiving nodes from terrestrial interference. The array will receive frequencies in a band from around 30 kHz to 30 MHz. This frequency band is scientifically very interesting, since it will be able to detect signals originating from the yet unseen "Dark Ages" ranging from the Big Bang until around 400 million year after. Another science driver is the LF activity from (exo) planets.

In this paper the design parameters for the satellites and the swarm will be given and status of the OLFAR project will be reported. Details will be given about the antenna system, the LF-receiver and the signals that are expected.

INTRODUCTION

Ever since Karl Jansky detected radio signals from space, there's been an active and thriving astronomical community mapping and investigating as much of the electromagnetic spectrum as possible. Unfortunately (at least for astronomers), the atmosphere is not transparent for the full spectrum, requiring space missions to fill in the gaps.

ESA and NASA have been focussing on building spacecraft for observations in the very high frequency bands (e.g. Herschell, Planck), yet the only spacecraft ever launched to observe the low-frequency part of the spectrum were the Radio Astronomy Explorer's 1 and 2. Initially, RAE 1 was placed in earth orbit, but the interference proved too high. RAE 2 [(1)] was therefore placed in lunar orbit. The results were extremely promising, but it lacked depth, due to the fact the satellite only had a single antenna. No real hardware has been developed since, even though countless paper studies[((1) (2) (3) (4) (5) (6) (7) (8))] highlighted the interesting aspects of access to a low frequency observatory in space.

Lately however, due to the lowering cost of access to space, and the increased applicability of Commercial Off The Shelf (COTS) hardware, opportunities for solving these issues are slowly becoming a reality. OLFAR, the Orbiting Low Frequency Array, intends to use these opportunities to build a large, low frequency array in space. In order to limit the cost of each node, the spacecraft will be built as swarm elements, which incidentally will allow an increase in science output, whilst significantly lowering the operational cost of the mission.

In this paper we will address the OLFAR space segment. First a brief overview of the science is given, after which the design parameters of the satellites will be defined. One important result is that no clear definition of a spacecraft swarm exists; hence that issue will be addressed.

THE SCIENCE CASE FOR OLFAR

As one of the last under-explored regions of the electromagnetic spectrum, the ultra-long wavelength range (1000 - 10m) remains a region with great potential for scientific enquiries. Amongst them are studies of the dark ages, tomographic studies of the interstellar medium, and observations of emissions by planets and even nearby exo-planets [(3).]

Earth's ionosphere however severely distorts any radio emissions below 50 MHz, and it completely blocks emissions below 30 MHz, indicating the only feasible way for studying these emissions is through a space mission [(4)]. The rather serendipitous discovery of the so-called Auroral Kilometric Radiation (AKR) by the earth-orbiting Radio Astronomy Explorer 1 (RAE-1) [(9)] showed high sensitivity studies were impossible to be performed from earth-orbit. RAE-2 was therefore launched into lunar orbit, to allow shielding by the moon. As an added bonus for the Moon orbiting array, the moon acts as a high energy particle detector [(3)], increasing the predicted science output of a science orbiter.

An extensive overview of astronomical science is given in the paper by Jester [(3)].

In order to achieve sufficient resolution in any observations made near, or even on the moon, a vast array of antennas would be required. Jester and Falcke [(3)] even predict numbers in the order of 10^4-10^8.

Although those numbers are high, a lot of useful science could be performed with a thousand units, and those numbers aren't that improbable, given a sufficient time span for development and deployment. This is a luxury most scientific missions cannot afford however, an easier to achieve target number of 50 is therefore considered [(10)] for the OLFAR mission, which still produces excellent science.

PAYLOAD

OLFAR will consist of a swarm of 50 nano-satellites orbiting Earth's moon. They will form an autonomous sensor-network, capturing data at the earth-eclipse phase of their orbits. This is to occur in a coordinated manner, as the elements are instructed to try to remain in a swarm with a baseline of about 100 km.

The target values for the receiver component of the elements as given in Bentum et al. [(10)] is repeated in Table 1. The orbital position wasn't fixed at the time, and it still isn't. A lot of useful science would be lost by not moving to a lunar orbit, yet the best science can be obtained in an Earth-Moon L2 halo or Lissajous orbit. Data relay to earth is impaired by the moon however, requiring separate relay satellites in lunar orbit.

Table 1: The OLFAR preliminary specifications as given in Bentum [(10)]

Frequency range	1-30 MHz
Antennas	Dipole or tripole
Number of elements	50
Maximum baseline	Between 60 and 100 km
Spectral resolution	1 kHz
Processing bandwidth	100 kHz
Spatial resolution at 1 MHz	0.35 degrees
Snapshot integration time	1 s
Sensitivity	Confusion limited
Instantaneous bandwidth	TBD
Deployment location	Moon orbit, Earth-Moon L2 or Sun-Earth L4/5

Studies performed on the DARIS mission [(11)] show that in order to perform useful science, only 7 active nodes are required, and that a dipole of two monopole antennas of 2.5 m are sufficient. Moreover, the dipoles require a cross-sectional area of only 1 mm^2, allowing for a lightweight solution. Increasing the integration time would be beneficial, yet is dependent on the stability of the relative positioning of the elements in their orbits.

For a swarm satellite, drifting out of the useful range of a single wavelength is a real threat. However, as many satellites are sampling simultaneously, the correlator can simply exclude data from satellites which exhibited too much drift.

A SWARM SATELLITE

Lately, a lot of missions involving a satellite swarm are envisaged. No clear definition of a spacecraft swarm has been defined to date however, causing a lot of confusion. The authors therefore attempt to clearly define a spacecraft swarm, in order to avoid confusion and any associated problems in designing one.

In order to do so, a swarm should be lined out against the background of other distributed systems in space, and it should be placed in its own niche.

A Swarm as a Distributed Space System

A satellite swarm consists of a large number of physically identical elemental satellites in which interactions amongst the satellites lead to the emergence of behaviour on the swarm level which cannot be traced back to the behaviour of an individual satellite. A satellite autonomously stays within the area of the swarm, keeping sufficient distance to the other satellites. No hierarchical or otherwise global command structure is present to control their individual behaviour.

The main challenge in designing and controlling such a system lies in the fact there's no possibility for external (e.g. through a ground station) control on the position or the behaviour of each individual satellite. Commands are given to the swarm as a whole, and results are produced by the swarm as a whole. The actions of each individual element cannot be predicted and are never relayed to the ground station. The rules for the behaviour of each element therefore have to be designed in such a way to ensure robustness for both a successful operation of the element, as well as the swarm as a whole.

A satellite swarm can be seen as different elemental satellites cooperating; yet it can also be seen as a single large satellite with distributed sensors, each with their own bus, allowing for the basic functions. It is this bus which allows for the emergent behaviour, of which the source lies mostly in the software component of the on board computer, and the communication protocols used.

Distributed Space System Classification

Various satellite constellations, in effect forming distributed systems in space, have been devised. The satellite swarm is no different, and should be treated as such. However, in order to be able to qualify a distributed system as a spacecraft swarm, a clear definition is in order. First, it is of importance to list the various forms of distributed space systems.

- *Formation flying spacecraft*

Formation flying spacecraft, consist of two or more satellites flying in a closely and tightly controlled formation, usually determined by ground station operators. They fly in formation to increase either the spatial or temporal coverage of a certain area of interest, as is done by SSC's PRISMA mission, or to form an interferometer in case of NASA's Terrestrial Planet Finder or ESA's Darwin. Flying in such a tightly controlled formation is a very intensive process, and propellant is consumed at rapid rates. For swarm elements, the benefits do not outweigh the excessive propellant consumption, as the issues with coverage are simply solved by numbers.

- *Satellite constellations*

Satellite constellations are commonly used as a general umbrella for all satellite missions using multiple satellites, and in fact a spacecraft swarm would indeed be characterisable as a satellite constellation.

The term however can also be interpreted as missions covering the globe, at equal angles across the celestial sphere. They are in fact formation flying spacecraft, distributed across trains of spacecraft in an array of orbits spread over multiple orbital planes, covering as much of the globe as possible. Due to the geometry and the long distances, their relative positioning accuracy is of very low importance, and no range measurements are generally taken between the satellites.

Examples are the various GNSS satellites circling the globe, as well as the Iridium constellation (12).

- *Fractioned spacecraft*

Fractioned spacecraft are a term coined by Brown and Eremenko (13), and consist of separate spacecraft busses, each designed with a single subsystem function in mind. This would allow a much shorter development time, as each subsystem required by the mission could be developed at its own pace, and in fact, could even be launched at its own pace, completing the mission bit by bit. This comes at a mass penalty however, in the sense that each subsystem will require its own power supply, short-range communication system and perhaps even an attitude or orbit control system. When one subsystem breaks down however, it can easily be replaced by another, at a much lower launch cost, due to the relatively lower mass.

ESA's XEUS (14) space observatory would be one of the first missions to benefit from using this configuration.

- *Satellite swarms*

Satellite swarms are rather different systems when compared to traditional satellite constellations. They most closely resemble fractioned spacecraft, in the sense that all subsystems are distributed across the swarm, yet each element is an identical copy of the other, and hence is capable of functioning by itself.

The behaviour of each element can differ depending on the specific task that is available in the swarm.

The demand for redundancy has shifted from a subsystem level to a satellite level, as the entire satellite is a redundant copy of the other swarm elements.

Swarm satellites are best considered as simple satellites with a limited number of payloads, communicating with other (identical) satellites, flying in similar orbits. They form loosely coherent groups or clusters, based on simple, opportunistic rules.

This implies they do not fly in a closely controlled and monitored formation - the swarm in fact controls the relative position of its elements independently through primitive inter-satellite interactions, rather than through strict control of each element by ground station operators.

Examples of swarm missions are NASA's ANTS mission concepts (15), or indeed the Dutch OLFAR mission (16).

- *Comparison*

Table 2 lists a comparison between the various existing forms of distributed space systems. Several advantages of a satellite swarm immediately become apparent, yet the downsides are visible as well. It must be stressed swarms aren't always applicable – certain missions require accurate positioning for example, which swarms cannot offer.

Table 2: A comparison of the various distributed satellite systems

	Formation flying S/C	Constellation	Fractioned S/C	S/C Swarm
Navigational accuracy	Very high	Moderate	Moderate	High
Orbital control precision per element	Very high	Moderate	High	Low
Position control of the virtual instrument	Very High	Moderate	High	High
Redundancy	Very low	Low	Moderate	Very high
Impact of the loss of an element	Loss of mission	Reduced functionality	Loss of specific function	Reduced coverage/ resolutio n
Element complexity	High	High	Moderate	Very low
System design complexity	High	Low	Moderate	High
Time-to-market	Very long	Long	Short	Short
Launch window flexibility	Low	Moderate	High	Very high
Maintainability	Low	Low	Moderate	High
Possibilities for extension /expansion	Low	Low	Low	Very high
Autonomy	Moderate	None	Low	Very high

Definition

When reflecting upon the different distributed space systems, a definition for a spacecraft swarm can be formed.

It reads: ***"A spacecraft swarm is a globally controlled cloud of primitive satellites".***

More specifically:

"*A group of simple satellites, behaving in such way the collective achieves a pre-set goal, which a single element in itself would not have been able to"*

They are in effect a distributed system. The swarm can have a mother-ship, with a hive-like function, yet this ship is not part of the swarm, as a swarm element should never be unique. In a way, the ground-station generally performs this function, as the workers return the results of their foraging to it. Redundancy and robustness are achieved primarily through the sheer volume of elements.

Moreover, the swarm elements apply their numbers to underscore one of their primary strengths: They are not designed for precision (formation) flight, but their knowledge of their position and state is as exact as possible. All location-related discrepancies are compensated for post-sampling through computation, which is a lot more efficient in terms of propellant consumption, while additionally allowing for more detailed analysis of the data on-ground. Given their knowledge of their location, a full (virtual) reconstruction of their environment could become possible.

Applicability of a Swarm

Swarms have their own niche in mission designs. This eliminates certain types of missions, and others will require a shift in design philosophy to allow for the use of a swarm.

Large, complex payloads, such as high resolution telescopes are unlikely to end up on a swarm element, and optical interferometers with a synthetic baseline, such as NASA's Terrestrial Planet Finder are unsuitable for swarm missions, due to the required physical positioning accuracy. A swarm could be used to handle their data transfer and (pre-) processing however.

When considering earth observing missions, swarms fail at delivering precisely timed observations – those are predominantly the domain of traditional constellations.

In general, it is best to use swarms for non-time critical missions – data will come in (in volume), yet at indeterminable points in time, due to the nature of the protocols used. Some data will even be sent multiple times in a row, whilst others might never arrive at all. This requires a shift in mission design philosophy for certain missions, shifting from absolute, single measurements to post-processed data, scanned multiple times, with some data overlap, whilst other data might only be scanned once. A swarm can detect rapid transients, yet the reporting rate is rather indeterminable, and it can last a good while before the transient is reported to a ground station, if no provisions have been made to account for such events.

THE OLFAR SPACE SEGMENT

The OLFAR space segment will consist of a cloud of 50 autonomous nano-satellites. They will be self-propelled, and the cloud will autonomously control itself. Ground-station operators will mostly, except for debug purposes, only control the satellites' science phases, by configuring the observation beam, and the timing.

Since all elements have a full propulsion system on board, and launches towards the moon are scarce, a solution had to be found to allow the satellites to travel towards the moon on their own power, and it has presented itself in the form of TNO's colloid thrusters [12], which will allow insertion of the elements into any random earth orbit. At that point, each element is to plot its own trajectory towards the moon, and the GS operators should merely verify the computation for a go/no-go decision.

This way, the swarm can be completed at an arbitrary rate, when launches are available. This implies however, not all elements are completely identical, as newer models might include updated hardware. Therefore, the protocols used are to be quite flexible, and most of the software should be in-space upgradable, which would allow increasing the number of active elements in the long term, in case this would be desirable.

Orbital Phases

Each element will follow a dynamic program, based on the location in the orbit. The science phase is the determining phase, and it is the design driver. Figure 1 shows the phases of an element, in the ideal case. Note the position of the moon with respect to the Earth- and sun-vector will change over time.

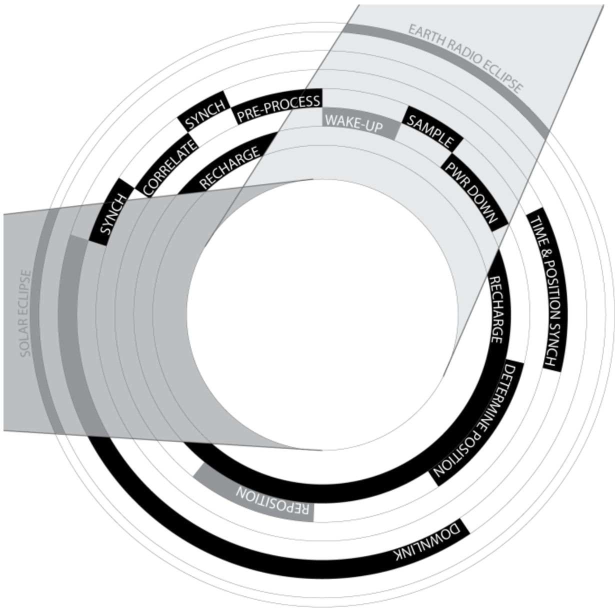

Figure 1: The program phases of a single element in a counter-clockwise lunar orbit

Certain elements however will drift out of range of the main swarm, and eventually will form a second science cluster, unless propellant is consumed to allow them to reposition themselves in the orbit.

The program phases, in a 2 dimensional form, are shown in Figure 2. They show when and where communication between the elements is required, and stress the necessity of a high speed inter-satellite link.

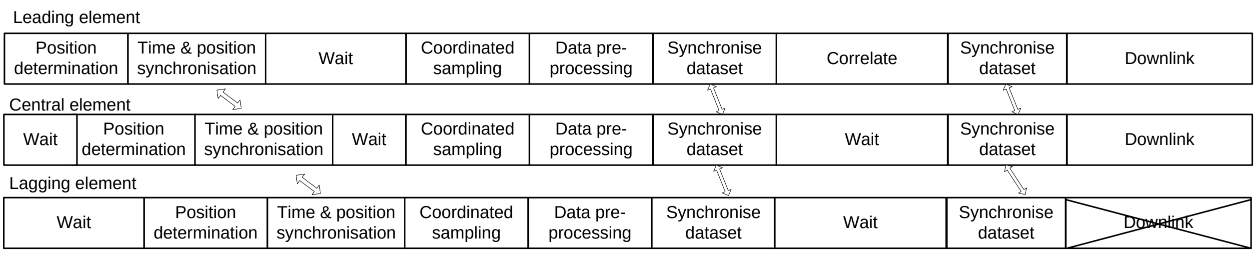

Figure 2: The program phases for three elements

Radio Links

The data collection rate for an 8-element cluster is given in Saks [(11)] as 2 Mbps per receiving antenna. This is for the case of a 1 MHz signal bandwidth, at a 1 bit sampling resolution. This implies the interlink of the satellites would have to transfer at a rate of 2 Mbps, each time the dataset is synchronised. The correlator of a 50-satellite array however would receive a data stream of 100 Mbps.

Correlation generates, according to Saks [(11)], a data stream of $2 \times 50 \times 50 \times \frac{1\,MHz}{1\,kHz} \times \frac{1\,bit}{1\,s} = 4.77\,Mbps$ per second of observation. Note that for OLFAR the effective bandwidth was defined as 100 kHz, rather than 1 MHz, resulting in a data stream of 200 Kbps and a correlator output of 477 Kbps respectively. The exact bandwidth hasn't been defined yet however, nor the sampling resolution.

Moreover, the science phase time span depends on the altitude of the orbit of the swarm, as well as the number of satellites in a useful science orbit. The worst case scenario would be a low lunar orbit, with a full useful science output cluster of 50 satellites. At an altitude of 1000 km, the eclipse duration has a maximum of about 2500 seconds, which would generate a data volume of 1165 megabits for the correlator to process and store.

Due to the inherent flexibility of the system, the likely case will be a dynamic sample time, determined by the element's separation distance and orbital altitude at that point in time. Therefore, the interlink speed is more of a design driver, rather than an output, as it will determine the maximal processing ability of the array, as well as the instantaneous one.

Currently, both the inter satellite link and the long-range transmitter are expected to operate at frequencies above S-band, in order to manage the required data rates. An investigation is running as to whether the solar panel-substrate can be used to double as a phased patch antenna array.

Attitude and Orbit Control

The attitude control of an OLFAR swarm element is relatively relaxed, as the pointing vector of the antennas is not important to the science output. Its orbit determination however is crucial to the accuracy of the science results.

An alternative navigation system is being developed, using radio-pulsars [(13)], which would be able to provide both accurate navigation and accurate timing information to the array. However, as a back-up solution, a miniature star-tracker will be designed, as well as an accurate sun-sensor to determine the orbit of the satellite.

On Board Computer

The OBC (On Board Computer) is the brain of the satellite. It controls the interlinks, as well as the data storage, and will therefore have to be able to process the raw data throughput rates put forth by the array. Moreover, it is in charge of applying the rules which determine the behaviour of the satellite in interactions with the other swarm members. It is this behaviour which allows for the emergent behaviour of the swarm.

These rules are not expected to place a heavy burden on the processor. Finding the proper rules however will require a tremendous research effort and it is therefore one of the most challenging subsystems to design.

PROJECT STATUS

The OLFAR project is already partly funded and research and development has started both at Dutch academia and research institutes, supported by Dutch industry. A test of one of the subsystems for OLFAR, an LF radio-chip, has been designed and is planned to be tested on board the Delfi-n3Xt satellite, which is being built by the Delft University of Technology at the time of writing.

It is a 2x2 mm chip, using AMS 350 nm CMOS technology. It has a frequency span of 30 kHz to 30 MHz, and an output bandwidth of 50 kHz.

Its noise floor is equal to the system noise, at -152 dB, with a noise bandwidth of 50 kHz.

Other critical components of the space segment have been identified, and missions and projects are being outlined focussing on their development.

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