Conquering the solar system with CubeSat Technology – first results of CubeSat hardware beyond low Earth orbit

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ABSTRACT

This paper sets out to show the in-flight results of The Netherlands-China Low-Frequency Explorer (NCLE) – one of the first times CubeSat hardware has left low Earth Orbit.

The Netherlands-China Low-Frequency Explorer (NCLE), is a low-frequency payload which is part of the Chinese Chang'e 4 mission. The NCLE instrument consists of three 5-meter long monopole antennas mounted on the Queqiao satellite and will be measuring in the 80 kHz - 80 MHz radio frequency range. The instrument is designed to address a multitude of high-profile science cases, but predominantly NCLE will open up the low-frequency regime for radio astronomy and will prepare for the ground-breaking observations of the 21-cm line emission from the Dark Ages and the Cosmic Dawn, considered to be the holy grail of cosmology.

The design of the instrument began in May 2016, with a launch scheduled May 2018. This left only 2 years to develop, build and test the instrument. Given the short development time the design is based on COTS and space qualified components as much as possible, and a design and model philosophy common to nano-satellites was adopted. Even so, special care had to be taken as one of the main challenges of this mission is EMC. This is an area which is only marginally considered during a typical CubeSat project and required a different approach.

Following the delivery in March 2018, less than 2 years after the project started, the instruments was successful launched in the 21st of May 2018 and saw its first return of telemetry January 2019. In this paper, the design of the instrument will be covered, as well as the first in flight results which were obtained. These results indicate NCLE is performing admirably after having spent over a year in interplanetary space.

The NCLE instrument represents one of the first times the CubeSat methodology and hardware left Low Earth Orbit. This, together with the strict EMC requirements have resulted in CubeSat hardware which can be used in future interplanetary missions. The promising results give strong confidence in the technology and enables new mission opportunities which could not be served by CubeSats in the past. This will fuel the next phase of the CubeSat revolution where they will venture out into interplanetary space in support of bigger missions.

INTRODUCTION

The Netherlands-China Low-Frequency Explorer – NCLE, is a low-frequency radio experiment for the Chang'e 4 mission that will go in a halo orbit around the Earth-Moon L2 point in 2018. NCLE is considered a pathfinder mission for a future low-frequency space-based or moon-based radio interferometer which has the detection and tomography of the 21-cm Hydrogen line emission from the Dark Ages period as the principle science objective. Low-frequency radio astronomy, i.e. below ~30 MHz, can only be done well from space due to the cut-off in the Earth's ionosphere, the man-made RFI and the AKR and QTN noise that make sensitive measurement from ground-based facilities impossible. At the Earth-Moon L2 point NCLE will be outside the Earth's ionosphere and relatively far away from terrestrial interference, which, however, will still be detectable. As the Earth will always be in sight we can measure and quantify this emission for the first time since 50 years and with unprecedented quality. This will allow us not only to study the radio- and plasma physics of the Earth-moon system, but also to explore mitigation and calibration techniques for exploring radio emission from the early universe and compare it with measurements made in true lunar far-side locations made by the future Chinese Lunar Lander mission.

Hence, the objective of the NCLE mission is two-fold. In addition to the characterisation of the lunar radio environment, NCLE will allow for unique radio science and astronomy. This includes a wide range of topics, such as constraining the 21-cm line Dark Ages and Cosmic Dawn signal, measuring the Auroral radio emission from the large planets in our Solar system, determining the radio background spectrum at the Earth-Moon L2 point, studying the Solar activity and space weather at low frequencies, creation of a new low-frequency map of the radio sky, studying the Earth's ionosphere and its interaction, and the detection of bright pulsars and other radio transient phenomena at very low frequencies. In addition, the access to a previously unexplored frequency regime will undoubtedly lead to new discoveries – NCLE will be the first step towards opening up the virtually unexplored low-frequency domain for astronomy.

The NCLE instrument on the Chang'e 4 relay satellite will break the ground for the radio experiments on the future Chinese Lunar lander mission and for which an intense collaboration between the Chinese and Dutch teams is foreseen, in particular on joint science collaboration on the above mentioned science objectives, instrument calibration, noise and radio background spectrum characterisation and VLBI. The opportunity of an experiment on the relay satellite with sufficient provision of power and mass, is ideal for flying one of the most advanced and flexible low-frequency radio receiver ever flown. The experiment will also open the possibility to demonstrate the first ever very long baseline interferometry on moon-space baselines.

The NCLE payload is a hosted payload on the Chang'E 4 orbiter. This satellite's main mission is to serve as a relay satellite between Earth and a lander which is to be placed on the far side of the Moon. The lander is expected to arrive approximately half a year after CE4 is placed in an orbit around the Earth Moon L2 point.

SCIENTIFIC OBJECTIVES

The main goal of NCLE is to determine the low frequency radio environment at the Earth Moon L2 point. It serves as a stepping stone missions towards low frequency observations, aimed at registering the hydrogen line at different frequencies and thus creating a 'moving picture' of the evolution of the early universe.

Human-generated radio emissions are known to 'leak' into space over a wide frequency range. At the lowest frequencies, these emissions will be partially shielded by Earth's ionosphere – but the extent to which they propagate into free space is poorly constrained. As NCLE will operate directly around the Earth-Moon L2 point, the instrument will have the unique opportunity to perform a thorough comparison between the radio spectrum when in view of Earth and the spectrum in the lunar 'radio shadow'. These measurements are instrumental to establish the science that can be done with a future Moon-based interferometry array. Furthermore, knowledge of Earth RFI aids in validation and interpretation of our other science results. Comparing the NCLE measurements to Earth-bound RFI measurements also allows us to gather data on ionospheric opacity.

The mission has identified two different objectives;

Technical objectives

These objectives are identified because the technology needed to measure these phenomena had not yet been implemented. To reach these objectives the NCLE instrument needed to be developed and its results will be used to refine future instruments which will study these phenomena in more detail.

Science objectives

The science objectives are all related to phenomena which can be observed with the NCLE instrument. While some of these phenomena have been studied before, doing this from Lunar orbit will provide valuable clues about the environment at this specific location. As it's considered for future missions, this data will be invaluable for future developments.

The various sources, techniques and phenomena associated with the mission objectives are schematically shown in Figure 3-1. The following sections gives a brief description of the different phenomena the NCLE instrument will observe.

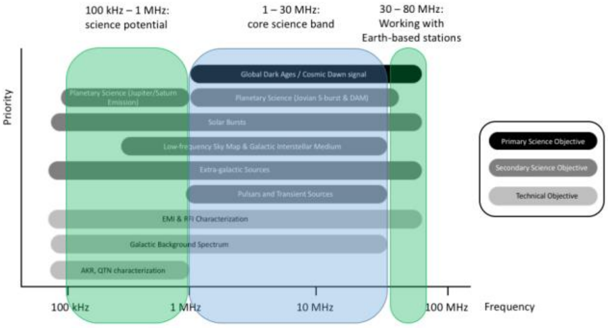

Figure 1: Science phenomena to be measured

Dark Ages and Cosmic Dawn

The signature emission from neutral hydrogen at 21 cm shows a spectrum over different redshifts that indicates its cosmic abundance as a function of time. Around the epoch of reionization in the younger universe, which was when neutral hydrogen was reionized by radiation from early stars, this signature should show a measurable dependence on redshift as a result in the range from 1 – 80 MHz. The detection or the constraining of this signature will have a strong impact on cosmology and science of the early universe, as it provides information on an epoch in the history of our universe from which we cannot receive much information through other means.

Solar Bursts

The Sun, our closest star, affects fundamentally the Earth's ecosystem and daily life thereby affecting the quality of life on Earth and the performance of technological systems (e.g. power grid). Superimposed on the powerful thermal emissions of the quiet Sun are the intense radio bursts associated with solar flares and coronal mass ejections (CME), clouds of ionized plasma are ejected into interplanetary space. Despite their great importance to Space Weather services, the physical mechanisms governing such events are poorly understood, with the consequence that neither accurate models nor reliable prediction tools exist.

The Sun often exhibits magnetic activity outside of its photosphere, in the form of rapid reordering of its smaller-scale magnetic field that may be accompanied by mass ejections. These field reconfigurations generate strong radio emission through synchrotron radiation from charged particles in these magnetized regions. The strength of this emission makes this a source that can be investigated by NCLE relatively easily, establishing statistics and correlations over a long observing period.

Two main types of radio bursts are observed from the Sun particularly in its active state: Type II bursts drive energizing shocks through the solar corona and interplanetary medium (~1000-2000 km/s), and Type III bursts result from mildly relativistic (~0.1 - 0.3 c) electron beams propagating through the corona and interplanetary space that excite plasma waves at the local plasma frequency but do not create a CME. Type II bursts and their ensuing CMEs can be followed by NCLE much further out than the few solar radii possible from the ground because of the ionosphere, see Figure 3 2.

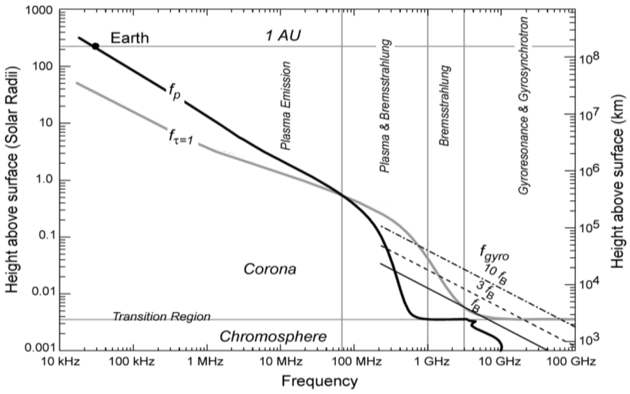

Figure 2: The frequency ranges of various emission mechanisms in the radio band. The black line shows the local plasma frequency, plotted as a function of distance from the Solar photosphere. From the Earth's surface, observations are limited to the frequency band above ~3 MHz

Lightning (Earth)

Rapid discharge of built-up electrical charge between different clouds in Earth's troposphere or between clouds and the ground generates bursts of wide-band radio emission. As such, lightning represents one component of Earth-based RFI with a unique signature that is critical for us to understand.

Auroral Kilometric Radiation / AKR (Earth)

Charged particles in the Solar wind are deflected by Earth's magnetic field. Under certain circumstances, these particles can become temporarily trapped and emit cyclotron radiation at very low frequencies. As this phenomenon arises from the interaction of the Solar wind with the Earth's magnetic field, measuring AKR allows us to learn about both of these systems.

Galactic Background

Interaction of cosmic rays (energetic charged particles) with the Galactic magnetic field generates a wide-spectrum Synchrotron background, which is especially prominent in the Galactic plane. Measurement of this spectral component in the form of a multi-frequency sky map helps us to understand the geometry of the Galactic magnetic field and the cosmic ray population in our Galaxy.

Quasi-Thermal Noise (QTN)

Interaction of the instrument antennas with local plasma causes small voltage variations in them, which manifest as an extra noise component in the measurements. The measurement of QTN outside of the strong influence of Earth’s magnetic field enables us to sample local solar wind properties (possibly allowing us to correlate these with solar outburst data), as well as to understand its influence on our other measurements.

Solar System Planetary Emissions

Analogous to AKR from Earth, the extended magnetospheres of Jupiter and Saturn can trap charged particles from the Solar wind, which proceed to generate low-frequency cyclotron radiation. As with Earth, measuring this AKR helps us to understand the magnetic fields of the most massive planets in the Solar system, as well as the Solar wind itself.

Bright Radio Transients From Outside The Solar System

There are many possible processes that might generate low-frequency radio emission with a rapidly varying temporal signature. One example is pulsar emission, which tends to have a strong low-frequency component. Fast Radio Bursts, from hitherto unknown origin, are another example. An issue with short pulses at low frequencies is that they get dispersed quite strongly by interstellar propagation. An ability to measure these transients from space at low frequencies offers the opportunity to correlate these detections with Earth-based measurements at higher frequencies. NCLE’s remoteness from Earth and regular occultation by the Moon, combined with its multidirectional sensitivity, should offer us ample opportunities to look for these events.

ENGINEERING CHALLENGES

Leaving low Earth Orbit

To support the science cases, there is no choice but to leave the well know low earth orbits and go further out. The NCLE instrument managed to find an agreement with the Chinese CE-4R satellite; a satellite travelling to the Moon Earth L2 point to act as a relay satellite for a rover which will land on the far side of the Moon.

Because NLCE is part of a larger satellite some of the obvious challenges have already been met. The host spacecraft will provide mechanical, power, communication and thermal interfaces. However, at the start of the project the host was already designed and built meaning the NCLE instrument needed to conform to the design as little changes could be made.

This proved to be just as challenging as designing without a spacecraft present. The information to and from the Chinese included large uncertainties as the final orbit, orientation of the instrument or configuration of the spacecraft were largely unknown when the NCLE design started. This directly translates to uncertainties in the design.

Schedule

At the start of the project only a few things were clear; the system must be below 10 kg, below 50 Watts, will orbit the Earth Moon L2 point and the launch will be in May 2018.

As the project started in earnest May 2016, this left only 2 years to develop build and test the instrument. The whole system architecture tried to follow the CubeSat approach as much as possible; special space rated components could not be procured on time, build and test, test and build and keeping the system as modular as possible to allow for early testing of the different subsystems. This allowed for all parts to be ready in March 2018, less than 2 years after the project started.

Electromagnetic Interference

The other big challenge for the instrument is to reduce its electromagnetic emissions as much as possible. This was needed to become sky-noise limited and detect the weak signals over the noise the instrument itself is making.

CubeSats generally are not designed to be as clean as possible from an EMC point of view. Rather, little care is given to this part of the design in typical CubeSat missions. To make matters worse, the interfaces coming from CE-4R also was not designed to be as clean as possible.

To combat these issues almost the entire power system had to be redesigned from the ground up. Care was taken to implement a star grounding scheme such that all power paths are well defined and controlled. Isolation between the incoming power, analog power and digital domain needed to be carefully created as well.

Using previous CubeSat designs as a blueprint, the power system was designed to be as modular as possible to facility all these requirements. In the end, no less than 4 boards have been designed, tested and integrated together, a far cry from the usual one a typical CubeSat needs!

Figure 3: The Electronic Box

Lastly, the mechanical design had to contain special measures to make sure internal signals wouldn't radiate to one another. This resulted in one dedicated box for the LNA system and compartments inside of the EBOX for the final analog stages.

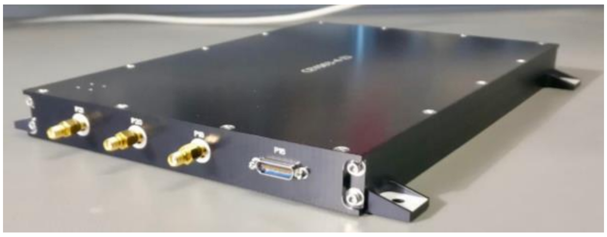

Figure 4: The LNA Box

NCLE SYSTEM DESIGN

The NCLE system functionally can be broken down into 4 main elements:

- Analog receiver system (analog electronics)
- Digital received system (FPGA based digital receiver, mass memory storage)
- On-board Data Handling and interface electronics (On-Board Data Handling, data interfaces, power regulation)
- Deployable antenna system (antenna mechanism and motor drive electronics)

An overview of the system architecture is shown in Figure 5. The analog parts are indicated in yellow, the digital system in blue, the antenna in red and the interface electronics in green.

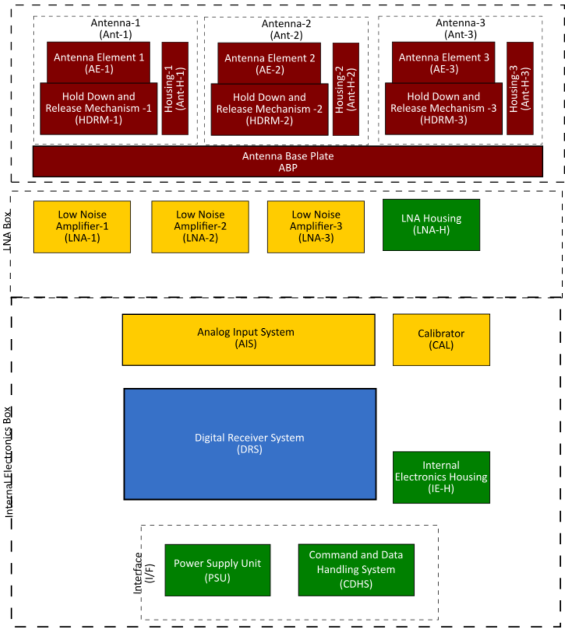

Figure 5: The NCLE system architecture. Analog parts are yellow, digital system in blue, antenna in red and the interface electronics in green

Analog receiver system

The analog receiver system consists of three antenna elements that pick up the external RF signals and are connected through RF connections to the Low-Noise Amplifier and Analog Input Stage electronics. Each antenna is connected to its own channel of analog electronics, where the RF signals are conditioned (amplified, filtered, etc.) before being sampled by the digital receiver system.

In addition to these three channels, a calibrator is included that produces a calibration pulse train that is fed into the three LNA input channels providing a signal reference.

Figure 6: Analog receiver system elements.

Digital receiver system

The digital receiver system consists of Analog to Digital Converters where the analog signals are sampled, a clock module for time synchronisation, an FPGA based programmable logic where signal processing is performed and mass memory to buffer the data. This includes for example FFTs, running data reduction algorithms and storing the data. It is based on CubeSat hardware; an SCS space image processor board has been repurposed to perform all these tasks.

On-board data handling and interface electronics

The on-board data handling and interface electronics consists of a number of elements.

The power supply unit provides regulation of the incoming power, galvanic isolation and signal filtering, and distribution of the different power lines for the analog and digital electronics. The board is a heavily version of an ISIS EPS system, with many additions to facilitate the special needs of this mission.

An ISIS On-Board Computer is included to provide data handling and to manage the data interfaces with the Chang'e 4R spacecraft. The control bus interface is a dual redundant CAN bus, while the payload data transfer is performed over a dual redundant LVDS bus.

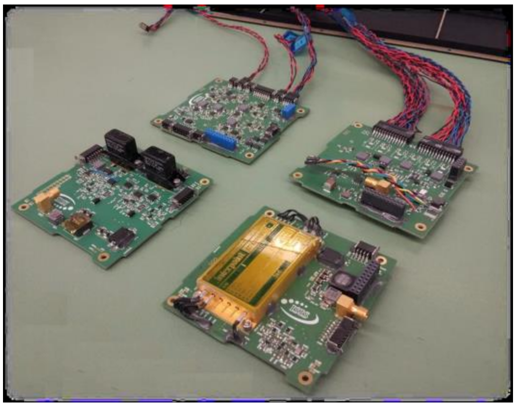

Figure 7: NCLE power supply unit

Deployable antenna system

To provide sufficient gain at low frequencies and the possibility to provide directionality information, three orthogonal 5-m long antennas were required. As the antenna system also had to meet strict stiffness, mass and volume constraints, a new design had to be made.

The antenna element was designed to be stiff enough to maintain its shape under all possible forces induced by the spacecraft, such as propulsion firings or attitude maneuvers, while meeting the mass and volume constraints. A C-shaped carbon fiber element was developed that could be rolled up on a drum before deployment.

The antenna deployment mechanism consists of a motor and gearhead with associated drive electronics, worm gear, slipring and a drum with the rolled-up antenna element. Deployment and end-stop switches provide information about the status of deployment.

Figure 8: Integrated deployable antenna systems

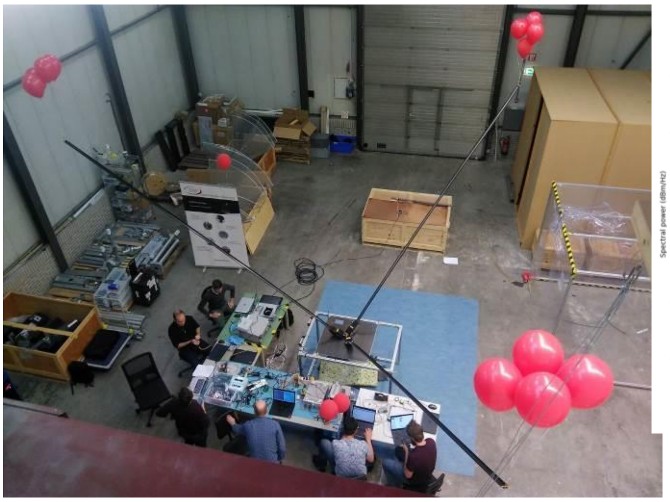

Figure 9: Fully deployed antennas

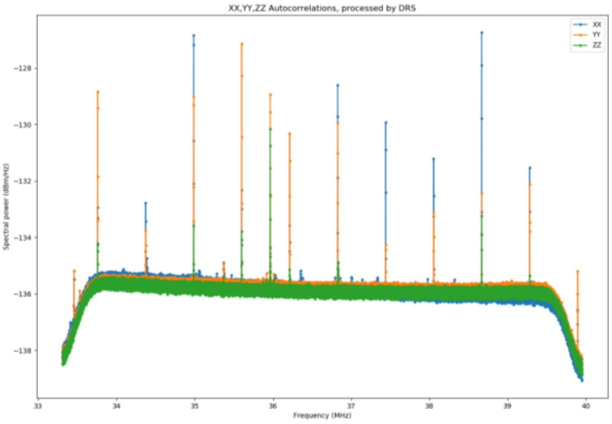

Figure 11: Spectra as obtained during while integrated onto the CE-4R spacecraft

SYSTEM PERFORMANCE

Prior to delivery several tests have been conducted with the NCLE instrument. Most of these where not conducted with the antennas deployed. If they were deployed, the environment was not EMC proof. The final tests was conducted while integrated on the CE-4R spacecraft, showing the environment most representative of flight conditions so far.

The results of these tests look promising: in a noisy lab environment the instrument picks up a significant amount of noise, see Figure 10. Integrated on the spacecraft, with antenna's stowed the picture looks much better, with a noise floor which is much reduced, see Figure 11. The noise floor is found to be around -130 dBm, with the spikes being interference generated by the platform or environment.

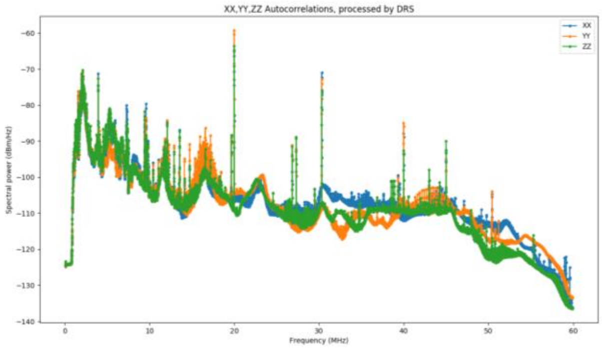

Figure 10: The spectrum as seen by the NCLE system in a noisy lab environment

FIRST ON ORBIT RESULTS

The first switch on of the NCLE instrument happened January 22nd, 2019 where a first initial sanity check was performed to verify the instrument had survived the launch, transit to lunar orbit, and 9 months in lunar orbit.

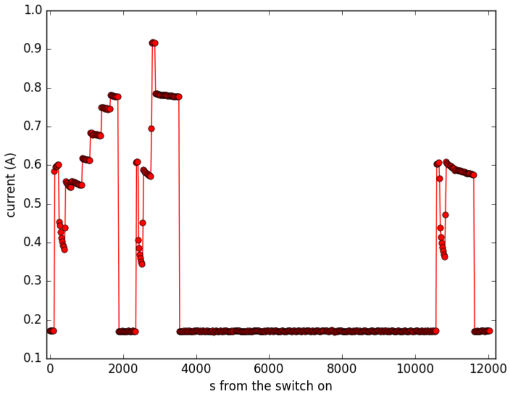

Figure 12: Current used by the NCLE instrument.

Figure 12 shows the power drawn by the NCLE instrument, which is seen to increase as progressively more subsystems are switched on. From this figure we can clearly see that at t=120 seconds the switch-on was commenced, by powering up the DRS OCXO clock. After that the other subsystems were switched on one by one. The current drawn by the system is exactly at the level what it should be, signaling the start of commissioning.

Currently, the instrument is undergoing a month worth of observations with antenna's in stowed configuration to characterize the noise over an entire lunar orbit. After this, the antennas will be deployed up to 0.5 meter, after which they will be extended slowly up to the total 5 meters.

FUTURE ROADMAP

NCLE is not supposed to be the last step in the quest to observe the early universe. Rather, it is considered to be a steppingstone mission towards more advanced missions and instruments. It all starts with the initial NCLE mission as described in this paper.

This will be followed by not only developing the instrument, but a complete platform as well. These satellites will also be deployed in Lunar orbit to take full advantage of the lessons learnt during the development of this instrument.

The last step is to have multiple of these satellites not only in lunar orbit, but even further out. The combination of these instruments at locations which are far apart will provide an excellent baseline to perform interferometer making all measurements even more precise.

Currently, the 2nd phase has just started with a phase A study. In this study suitable orbits have been identified and a preliminary system design was derived.

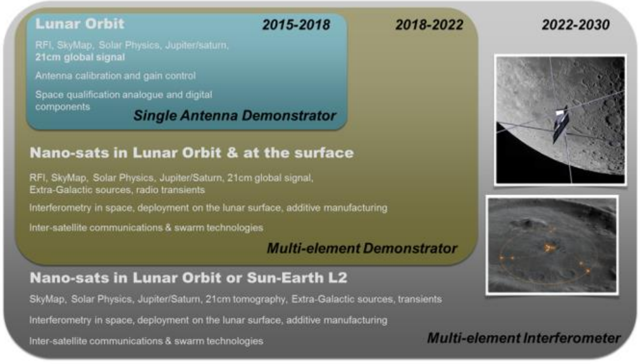

Figure 13 The roadmap for NCLE type instruments