An Innovative Step-by-Step Construction of Navigation Network around/on the Moon and Other Celestial Bodies

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Abstract

As recent lunar exploration activities spread, there have been studied a number of navigation schemes, which look at the construction of Lunar-based Navigation Spacecraft System (LNSS) like Global Navigation Satellites System (GNSS). However, while the number of users is few, building the LNSS is not an efficient way with a huge investment. The paper presents a different way to realize the positioning service for the users such as mobile vehicles on the lunar surface. It is a step-by-step development of the positioning service. The application also enables a similar way for the small bodies' exploration, by which the ascent module is navigated to the mother spacecraft on orbit. The key here is the Asynchronous One-Way Range (AOWR) scheme devised by the authors.

I. INTRODUCTION

Classical and conventional navigation represented by orbit determination has utilized radio transponders for decades. However, the transponders cannot provide instantaneous range in real time, but can measure round-trip time instead. And the transponders are useless in clock synchronization that requires instantaneous range information with respect to the other party, to which clock information is referenced.

The authors in 2021 published an innovative range measurement and simultaneous clock synchronization scheme, Asynchronous One-Way Range (AOWR) measurement scheme. It does not require any transponder. But instead, it uses a transceiver whose clock does not need to be synchronized at all, in asynchronous manner. It acts like relaying an absolute clock to the other via spacecraft-to-spacecraft way in semi-real time, in a one-way communication time. With the use of a certain stable oscillator such as Chip-Scale Atomic Clock (CSAC), the AOWR eventually enables the clock at the other side to be synchronized in real-time.

When it comes to the moon and small bodies without atmosphere, at the initial phase of exploration, geographical position information becomes available with relatively high accuracy. Even 3D Digital Elevation Map (DEM) becomes available through the gravity potential field construction and global altitude measurement. For instance, about the surface of the moon, the position information within the accuracy of less than 30m is available anywhere globally. Especially about some areas, the resolution reaches within several meters. As a result, talking about bases and mobile vehicles on the lunar surface, the position accuracy is well secured via terrain-based navigation autonomously. There is no impending/immediate demand for the navigation network like GNSS services to the bases and the mobile vehicles on the lunar surface. A lot of studies so far have drawn scenarios building Lunar Navigation Satellite System (LNSS) around the moon. However, it is not true. There is no weather issues and stars are visible in daytime on the moon. Consequently, building LNSS may be postponed until a lot of users appear on the lunar surface in future.

On the other hand, high demand is anticipated for navigating / positioning spacecraft flying in cis-lunar space. Current navigation scheme based on the radio transponder measures the round-trip time to the spacecraft from the ground. And it accompanies orbit determination process with the sophisticated combination of flight dynamics and ephemeris, and the task completes considerably long time after the round-trip time is measured. This process is not useful to make the clock onboard synchronized.

However, the AOWR scheme realizes real time clock synchronization, in other words, an absolute clock to be relayed. At the initial step, positioning of a certain accuracy becomes available, with the clock synchronized via the AOWR and GNSS signals through the side lobes of the GNSS satellites. It lowers the number of GNSS satellites required for the positioning down to three, since the clock difference is eliminated via the AOWR method. At the second step, the bases on the lunar surface whose clocks are synchronized via the AOWR scheme will constitute the ground-based network to navigate and position the spacecraft flying around the moon. Those spacecrafts will in turn present the navigation information serviced to the vehicles on the lunar surface finally.

As shown, the paper will present an innovative step-by-step construction strategy of navigation network

servicing positioning to the spacecraft deployed around the moon, interplanetary small celestial bodies and Mars etc. The paper will assess the navigation/positioning accuracy with the theoretical and mathematical description of the AOWR scheme.
There have been many studies concerning the extension of GNSS services beyond geostationary orbits. The use of side lobes of the GNSS(GPS) satellites' radiation pattern has been studied for possible positioning in cis-lunar space and beyond [1,2]. The GNSS(GPS) link was also analysed on a Halo orbit at the Earth–Moon L2 point [3]. Ref. [4] studied the characterization of transmission antenna patterns for those applications. The geometric dilution of precision (GDOP) figure becomes explosively high [5,6] and degrades navigation performance in cislunar space. [7] Futuristic lunar-based GPS-like systems and intersatellite ranging were studied in Refs. [8] and [9]. The oscillators and retransmission of multi–GNSS signals have been reported in [10] and [11].
Kawaguchi et. al. first published an asynchronous one-way ranging (AOWR) method using the GNSS transmitters and receivers in 2021 and 2022. [12], [13] Ref. [14] and Ref. [15] study the use of near-Earth bands of 7 to 8 GHz and a possible bandwidth broadened up to 10 MHz was discussed. The authors recently investigated and published. [16, 17] The paper briefly introduces and describes the mathematical background first.

II. TRANSPONDERS AND CLOCK SYNCHRONIZATION

Recent space exploration activity spreads to small entities such as universities and start-ups.
One of the obstacles those small missions face is in navigation. Most typical deep space navigation assumes the reliance on space agency and asks supporting range measurement at the agencies' facilities. It in turn requests small probes to carry classical/strictly specific radio transponders aboard.
The authors, Kawaguchi et. al., first in 2021 published an Asynchronous One-Way Ranging (AOWR) method applying GNSS transmitters/receivers' technology. The method, at the same time, enables the clocks onboard the probes to be synchronized.
There is some misunderstanding about the range measurement. Most believe a range information is extracted/obtained by a transponder.
However, uplink range is different from down link range owing to relative motion/range-rate between a ground station and a spacecraft. The orbit is determined through sophisticated process with flight dynamics and ephemeris. The range information is retrieved considerably later after the round-trip time is measured.
A key is in acquiring an instantaneous range almost in real time, which enables a clock synchronized with an affordably available clock onboard. The AOWR scheme here provides a solution to it by introducing an information exchange process and enables clocks at both sides synchronized in (semi-)real time. It can act like relaying an absolute clock to the other.

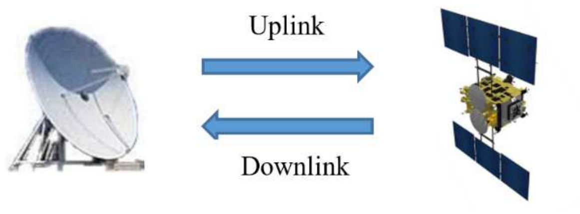

Fig. 1. Bi-lateral but Asynchronous One-Way Communication

III. RANGE MEASUREMENT

Consider a clock in which a long hand is at 12 o'clock and a shorthand is at 8 o'clock. (Fig. 4) A second hand starts at 12 o'clock to catch up with the shorthand, in which the second hand revolves at (6-0.1) deg/s on the rotation coordinate that revolves with the motion of the long hand. The relative revolution speed between the shorthand and the long hand is 0.1–0.1/12 deg/s. The time Δt when the second hand reaches the shorthand is calculated as follows:

$$240.0 + \int_0^{\Delta t} (-0.1 + 0.1/12)\ d\tau = (6 - 0.1)\Delta t \quad (1)$$

Δt is calculated as 40.06 s. The revolution speed of (6-0.1) corresponds to the speed of light in the radiometric range measurement.
(6 - 0.1) × 40.06 gives the instantaneous angle between the long and short hands when the second hand reaches the shorthand. Note that the speed of the long hand of 6 deg/s on the clock dial is modified to (6-0.1) deg/s here. The speed of radio propagates at the speed of light regardless of any inertial frame. However, in the clock example, the speed must be rearranged for explanation. It is a distinct point from the case of the radio signal.

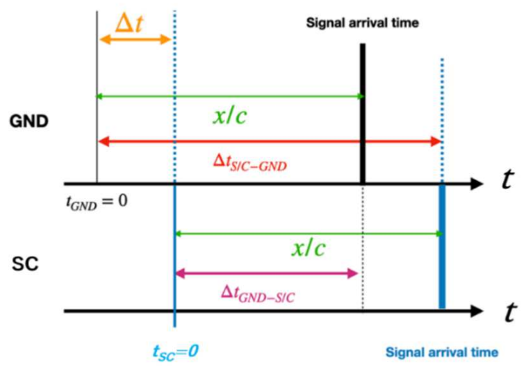

Fig. 2. Conceptual Drawing of the Signal Flow in Asynchronous One-Way Ranging Scheme

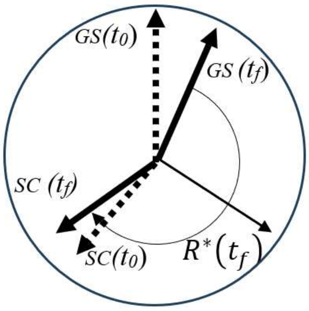

Fig. 3. Range Rate and an Instantaneous Range

A. Instantaneous Range

Since the speed of radio c is frozen in an inertial/stationary coordinate and range-rate makes the target evade/approach. The remaining distance designated as dR to the other side behaves as

$$dR = -\left(c - \dot{R}(t)\right) dt \quad (2)$$

The travel time for the signal to reach the other side is obtained by integrating the equation above.

$$R^*(t_0) + \int_{t_0}^{t_f} \dot{R}(\tau)\ d\tau = c\left(t_f - t_0\right) \quad (3)$$

It should be noted that the remaining distance is reduced/lengthened always affected $\dot{R}(t)$.

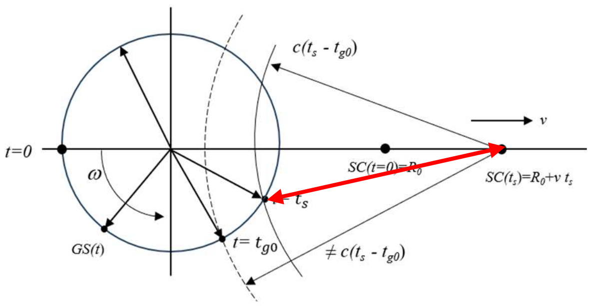

Fig. 4. Instantaneous Range

Here, $R^*(t_0)$ expresses the instantaneous range at t_0, at departure. And the left-hand side eventually and literally expresses the instantaneous range $R^*(t_f)$ at time t_f. Simply,

$$R^*(t_f) = c\left(t_f - t_0\right) \quad (4)$$

The distance the signal has traveled represents the instantaneous range when the signal reaches the other side, provided t_f and $t_0$are known.

It also provides the basis for GNSS, in which the GNSS receiver finds an instantaneous distance from each GNSS satellite.

Here is given another example.

$$R^*(t_s) = c\left(t_s - t_{g0}\right) \quad (5)$$

Fig. 4 shows the geometry example in which the spacecraft is frozen at time t_s, when the signal reaches to the spacecraft. What $c\left(t_s - t_{g0}\right)$ may be conceived as the distance between the spacecraft at t_s and the ground station at t_{go}. But that is not true. The property $c\left(t_s - t_{g0}\right)$ must be solved and determined through the light time equation.

In this example, the ground station approaches to the spacecraft at t_s, and the distance is apparently contracted. Time t_0 (t_{g0}) is rebuilt on the AOWR device as a replica clock by counting the pulses from the other party by itself, regardless of doppler effect.

Simply, the property $c\left(t_s - t_{g0}\right)$ expresses the instantaneous range when the radio signal arrives to the other side.

Here are given more precise expressions.

$$R_s^*(t_s) = R_s^*(t_{g0}) + \int_{t_{g0}}^{t_s} \dot{R}_s(\tau)\ d\tau = c\left(t_{s,true} - t_{g0,true}\right)$$

$$R_g^*\left(t_g\right) = R_g^*(t_{s0}) + \int_{t_{s0}}^{t_g} \dot{R}_g(\tau)\ d\tau = c\left(t_{g,true} - t_{s0,true}\right) \quad (6)$$

The left-hand sides above denote the instantaneous ranges. And here is found an important relation of

$$R_s^*(t_s) - R_g^*\left(t_g\right) = \dot{R}^* \Delta t_{RX,true} \quad (7)$$

This property supports the essence of the AOWR scheme, in which the clock difference appears multiplied by the range-rate NOT by the speed of light. It significantly alleviates the synchronicity requirement and provides the basis for AOWR, which runs asynchronously.

B. Asynchronous One-Way Range (AOWR) Scheme

With internal time delays Δt_{gs} and Δt_{sc} at ground station and a spacecraft below, especially in simplified case the range is obtained as below.

$$R_s^* = R_g^* = \frac{1}{2}\left(R_s + R_g\right) + \frac{c}{2}\left(\Delta t_{gs} + \Delta t_{SC}\right) \quad (8)$$

Also, Δt_{RX}, receivers' clock difference is expressed as below.

$$\Delta t_{RX} = \frac{1}{2c}\left(R_s - R_g\right) + \frac{1}{2}\left(\Delta t_{gs} - \Delta t_{SC}\right) \quad (9)$$

Making Δt_{RX} zero during AOWR process implies the clock onboard the spacecraft becomes synchronized with that at the ground station. At the first exchange of information, t_s does not match with t_g, and the clocks can be asynchronous. And R_s^* and R_g^* become identical gradually in subsequent process.

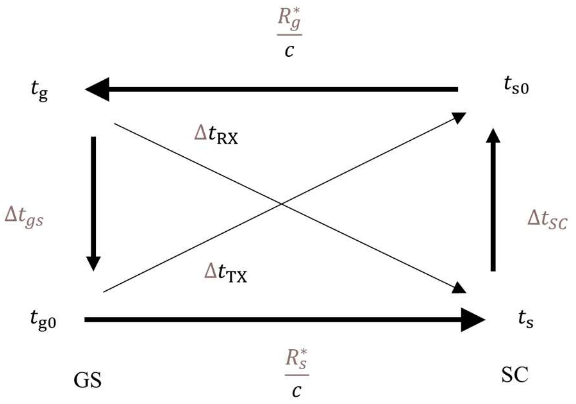

Fig. 5. Transceiver Configuration

C. *Field Radio Demonstration*

The ground station used is an antenna dish operated at Tohoku University. The dish is 2.4 m in diameter. The experiment suppresses transmission power below a legally specified threshold. The distance at the experiment is taken about 500 m.

Fig. 6 Field Experiment Setting-

Based on the theoretical properties developed, *Rs** (*Rg**) were calculated. The result is shown in Fig. 7, which presents the range fluctuation almost within +/- 3m. It well corresponds to the fluctuation observed in the pseudo-range measured. (Current pseudo range measurement/correlation was performed in one code length, 1 msec.)

The other important property, Dt_{RX}, the clock difference between the receivers at ground station and spacecraft is plot in Fig. 8.

Also, the residual remains positively offset since the spacecraft's clock drifts faster than that at the ground station at the rate of 10^{-9}. The measurement interval taken is every 6 second and around 10 nano-second or more drift is observed. This is circumvented when more accurate clock such as CSAC is adopted.

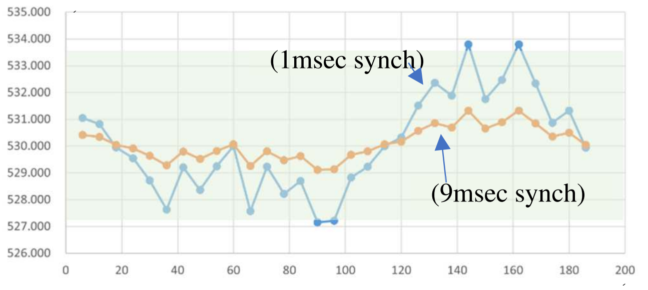

Fig. 7 *Rs**(=*Rg**) Quick Solutions (m)

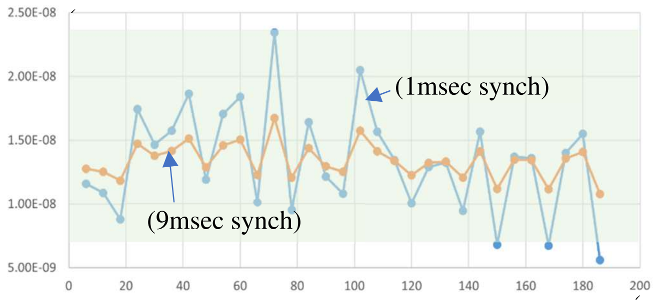

Fig. 8 Δt_{RX} Fluctuation (sec)

There was found some discrepancy between the measurement and the actual distance, which may have derived from the cables' length between the dish antenna and the operation area. The follow-on tests were carried out to measure the distance directly using a laser range finder. The station delay is now estimated about 80 meters with a certain uncertainty of 5 meters or so, which corresponds to about ten nano seconds. In view of dielectric constant for the cables used, the delay seems well accounted for the discrepancy, which corresponds to 40m to 50m cables' length. Note current pseudo range measurement/correlation was performed in one code length, which is 1 msec.

IV. FUTURE AOWR APPLICATIONS – CIS-LUNAR SPACE NAVIGATION

A. *Background and Solution to Navigation*

Despite the consortium's involvement in the Artemis program, flight management, particularly the navigation of vehicles such as landers, relies on classical orbit determination using radio transponders. There is confusion regarding the allocation of frequencies for communication and tracking toward the moon, which is impacted by all antennas in every country. Furthermore, real-time navigation or positioning is hardly achievable through conventional orbit determination, as it takes several days to complete the estimation.

Recent studies have sought to use GNSS in cis-lunar space. However, the poor geometry resulting from the short span length of GNSS significantly degrades the

accuracy of positioning. The difficulty in estimating the time is primarily due to the geometry. Especially when it comes to landers approaching the intended landing point in polar regions, accurate real-time positioning is essential. This is still important even when combined with terrain-based navigation which relies on various imaging parameters.
Our focus is on facilitating the flight management and traffic control of spacecraft, including landers in the vicinity of the moon, as well as spacecraft traveling from Earth toward the moon in cis-lunar space, using the asynchronous one-way range (AOWR) scheme. It is a technology for simultaneous semi-real-time range measurement and clock synchronization, such as relaying an absolute clock to another.

B. Characteristics of asynchronous one-way range (AOWR) scheme

Navigation and orbit determination of spacecraft usually involve range and range rate measurements. However, the range or distance is not directly measurable. A spacecraft carries a radio transponder that provides a round-trip time. The exact time of the signal's return is uncertain and can only be determined by consulting rigorous flight dynamics and ephemeris data. The orbit is estimated and determined a few days or weeks after the round-trip time is obtained. The range information becomes available afterward.
Clock synchronization requires instantaneous range/distance information in near real-time, so a portable clock maintains accuracy despite delays. So, the transponder never works for clock synchronization. Currently, there is no available method for clock synchronization except GNSS which serves timing in the vicinity of the Earth.
On the other hand, the AOWR scheme can provide instantaneous range/distance information with minimal delay in semi-real time and will be the only scheme synchronizing the clock at the other side in deep space. It acts by relaying an absolute clock to the other via a pair of spacecraft/entities.
AOWR will be applied to deep space VLBI, deep space formation flight, and deep space navigation, which includes positioning in cis-lunar space and the step-by-step development of a navigation system around the moon and celestial bodies in the solar system.

C. Applications in International Lunar Exploration

<u>Deployment Scenario</u>
One important step is to install a primary synchronizer or a calibrator on board the lunar gateway station. The clock does not need to be highly stable, as it can be synchronized using the same mechanism with the GNSS clock.
The calibrator synchronizes the clocks on multiple scattered landers and facilities on the lunar surface in the polar region. Those clocks do not need to be highly stable. They can even be crystal-based oscillators.
Once the landers and facilities have landed, their positions are accurately determined and identified through multiple observations, including terrain images, stars, and accelerometers. The landers and facilities offer navigation and positioning services to any spacecraft flying over the polar region. The spacecraft receives the service passively, without the capability to transmit only with the receivers.
For spacecraft traveling from Earth to the Moon in cis-lunar space, the calibrator onboard the lunar gateway provides clock synchronization and timing independent of GNSS. The reception of GNSS signals through the side lobes, in combination with the timing service provided via the AOWR by the calibrator, greatly improves real-time navigation and positioning accuracy by eliminating clock uncertainty.

(Strategy)
As described, the key in our focus is to have a calibrator on board the lunar gateway, as well as AOWR transceivers on board the landers/facilities and on board the spacecraft to be serviced.
The technology is based on the existing GNSS and does not pose any challenge.
Unlike the construction of vehicles and structures in the Artemis international lunar exploration program, the investment required is relatively modest and well affordable even for non-spacefaring nations.
Despite a small investment, the contribution to the exploration program is significant and positions those nations as the core elements in the exploration program.

<u>STEP-1</u>
With scattered bases / landers on the surface, the navigation/positioning is serviced to spacecraft flying over the region. The positions of bases/landers are known precisely even as of today via terrain-based navigation.
However, it requires the clocks at the bases/landers to be synchronized to a unique clock. The method is sought. The answer is the AOWR scheme presented.
Spacecraft flying in cis-Lunar space / polar region is provided with the positioning service from the scattered nav-aides. (Only with receivers)

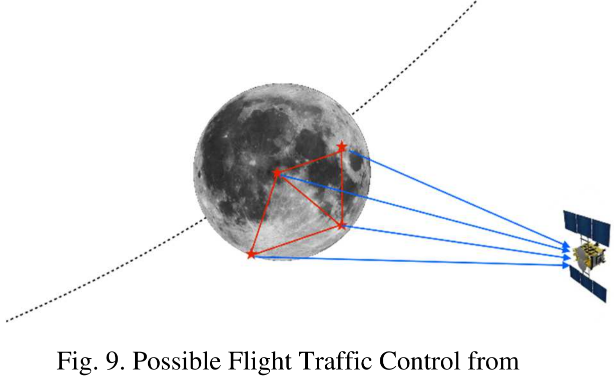

Fig. 9. Possible Flight Traffic Control from Navaids on the Surface (STEP-1)

STEP-2

The AOWR scheme between a synchronizer spacecraft and the bases / landers synchronizes the clocks onboard them. The bases / landers have only to carry low-stability clocks. The bases / landers can provide the navigation / positioning service to the spacecraft flying over the region in a step-by-step construction way. The lunar gateway / an orbiter synchronizes the surface clocks at the same time.

As in STEP-1, the spacecraft flying in cis-lunar space / polar region is provided with the positioning service from the scattered nav-aides. (Only with receivers)

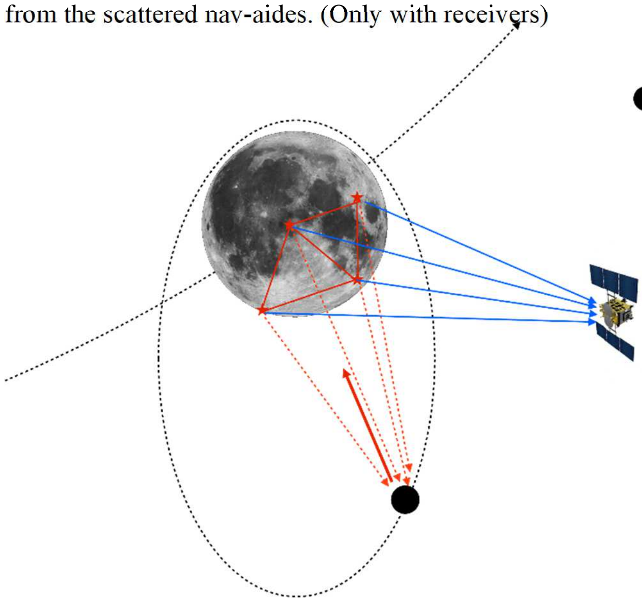

Fig. 10. Possible Flight Traffic Control from NRHO & Navaids on the Surface (STEP-2)

STEP-3

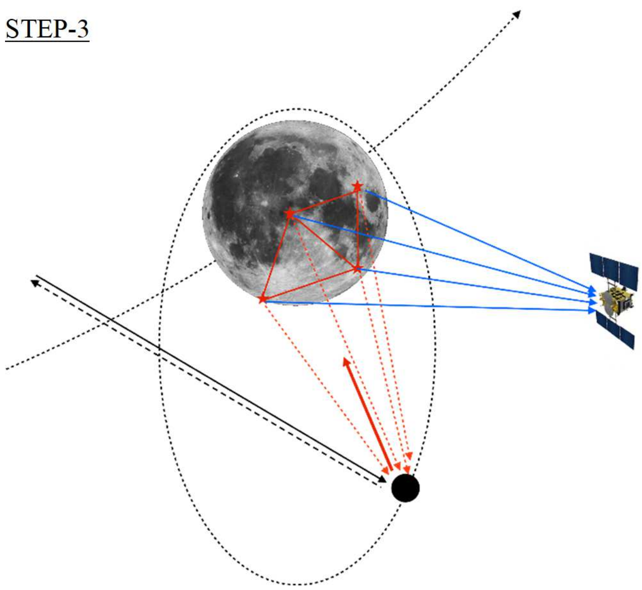

Fig. 11. Possible Flight Traffic Control from NRHO & Navaids on the Surface combined with GNSS (STEP-3)

The synchronizing spacecraft also does not have to carry an ultra-stable clock. It can be synchronized with the ground station, whose clock is also tuned to the GNSS clock. In this step, the scattered mobile navaids result in being synchronized with GNSS via an AOWR s/c. (Relayed clock synchronization)

STEP-4

The service can be provided also for the spacecraft operated / flying in cis-lunar space. The combination of AOWR with side-lobe GNSS signals enables enhanced positioning service for them, since the AOWR can independently relay GNSS clock to those spacecrafts.

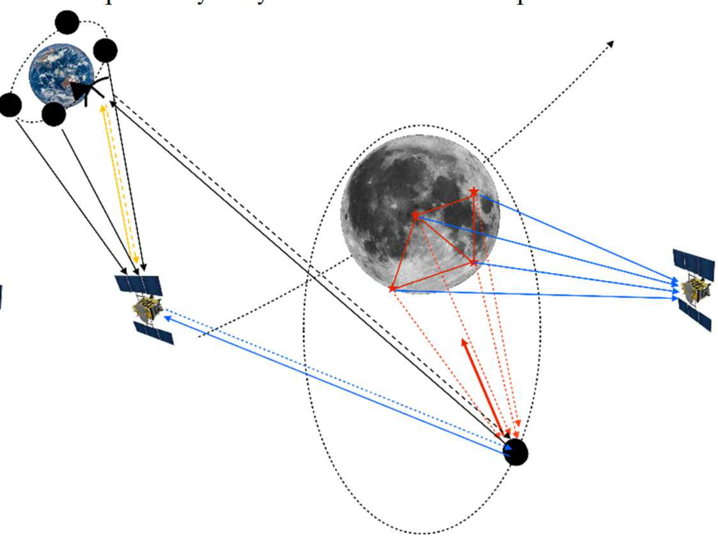

Fig. 12. Possible Flight Traffic Control from NRHO & Navaids on the Surface combined with GNSS (STEP-4)

STEP-5

The number of the spacecraft serviced with positioning is increased gradually. So, those spacecraft in turn provides positioning service to the mobile vehicles on the surface.

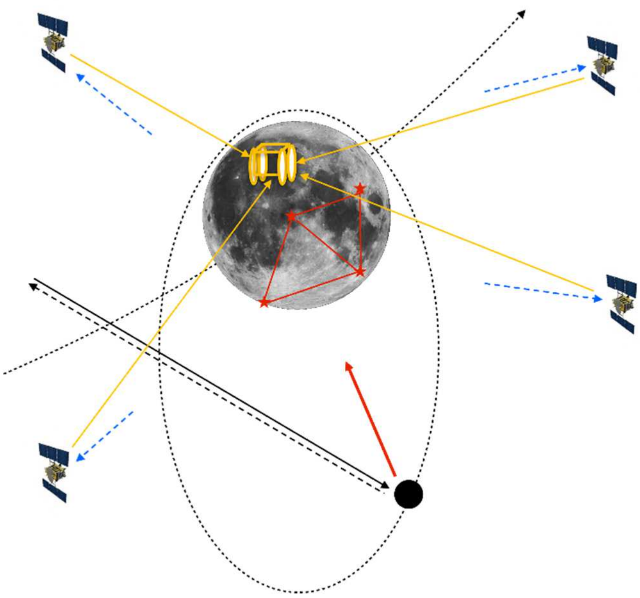

Fig. 13. A step-by-step construction of navigation network around the moon (STEP-5)

Like this way, the global coverage navigation system is built in a step-by-step manner with suppressed initial investment. Nav-constellation is maintained from the scattered navaids. (Only with receivers)

Navigation / Positioning around Small Bodies
The scenario is applied for the advanced exploration to small bodies. Those celestial bodies that do not have atmosphere, the positioning is obtained via terrain-based navigation.

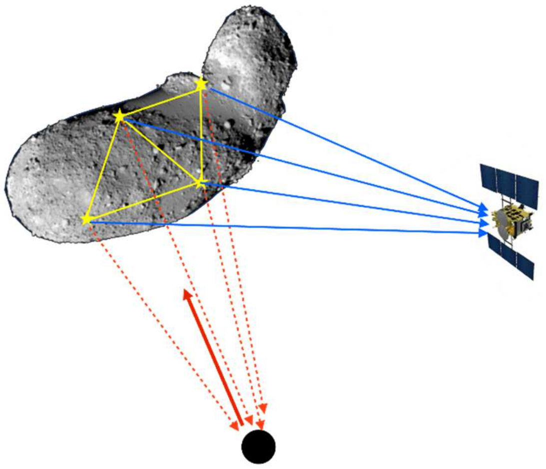

Fig. 14. Navigating Landing/Ascent Vehicle around a Small Body

There are no weather issues for those celestial bodies like on the moon. Even starts are visible in day side. The key is in synchronizing the clocks scattered on the surface. To that end, the AOWR scheme plays an important role. The mother spacecraft transmits the calibration signal to which the scattered clocks are synchronized, so those scattered probes constitute the navigation network. It works to navigate the spacecraft approaching for landing. Also in the advanced exploration, it navigates both the ascent module and the mother spacecraft for transferring samples on orbit.

V. CONCLUSION

The paper reported the recent development status of the AOWR scheme including the field radio tests outcome. The AOWR device schedules to have an on-orbit demonstration flight at the beginning of 2025.
The paper also presented the applications of the AOWR scheme not inly for the lunar exploration but for the advanced deep space missions for the small bodies. For instance, it is a sample & return mission. Those advanced exploration needs to perform the precise landing and uses the ascent module that transfers the samples to the mother spacecraft for recovery. The strategy here provides the useful solution for the mission's operation.

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