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Time-Transfer and Clock-Synchronization Technique for Microsatellites in the Lunar Region

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Abstract

The growing number of scientific and commercial missions to the Moon surface poses the need for a dedicated communication and navigation infrastructure. A precise Positioning, Navigation and Timing (PNT) service is a key technology to allow lunar assets to determine their position and velocity, to plan and execute maneuvers and to maintain time. Argotec is working on ANDROMEDA, an end-to-end Communication and Navigation service for users on the Moon surface and in Low Lunar Orbit, based on a constellation of 24 microsatellites operating in high-elliptical frozen orbits around the Moon. To support missions with Communication and Navigation capabilities, an accurate on-board frequency reference and a time-transfer technique are crucial technologies. This paper presents a trade-off analysis of different time-transfer techniques, including existing GNSS, Two-Way Pseudo-Noise ranging, Network Time Protocol, Two Way Satellite Time and Frequency Transfer and Optical links. Furthermore, an additional investigation on crucial constraints on microsatellites' design is performed with the goal of choosing the most suitable time-transfer technique and frequency reference for a microsatellite platform. A Two-Way coherent time transfer technique compatible with Consultive Committee for Space Data System (CCSDS) standards is studied and proposed. Special attention is given to synchronization accuracy, which is one of the most critical requirements for the navigation service. The choice of the technique has been supported by a trade-off analysis on the frequency reference to be adopted on board. Parameters such as Size, Weight and Power consumption (SWAP) have been taken into account in this phase, as well as costs and ground effort, paying particular attention to low-SWAP solutions. Finally, an error budget assessment is carried out considering free space propagation losses, relativistic effects, ephemeris errors, synchronization errors, and Earth's atmosphere contribution such as ionospheric and tropospheric delay.

Keywords: Time-Transfer, Clock-Synchronization, Microsatellites, Moon, Communication, Navigation

Acronyms/Abbreviations

ADEV	Allan DEViation
ADSL	Asymmetric Digital Subscriber Line
ANDROMEDA	Argotec Network Design for Real-time Operations in Moon Environment and Deep-space Applications
ASM	Attached Sync Marker
BPSK	Binary Phase Shift Keying
CCSDS	Consultive Committee for Space Data System
CE	Code Epoch
DFE	Direct-From-Earth
DOP	Dilution Of Precision
DTE	Direct-To-Earth
DSS	Deep Space Station
ESA	European Space Agency
GMSK	Gaussian Minimum-Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground Station
H-MASER	Hydrogen-Microwave Amplification by Stimulated Emission of Radiation
ISL	Inter-Satellite Link
ITU	International Telecommunication Union
LAN	Local Area Network
LEO	Low Earth Orbit
MDEV	Modified ADEV
NASA	National Aeronautics and Space Administration
NTP	Network Time Protocol
OCXO	Oven Controlled Crystal Oscillator
OD	Orbit Determination

OTWTFT	Optical Two-Way Time and Frequency Transfer
PN	Pseudo Noise
PNT	Positioning, Navigation and Timing
PSD	Power Spectral Density
RAFS	Rubidium Atomic Frequency Standard
RTLT	Round-Trip Light Time
SC	SpaceCraft
SNR	Signal to Noise Ratio
SWAP	Size, Weight And Power consumption
TAI	International Atomic Time
TDEV	Time DEViation
TEC	Total Electron Content
TMTC	Telemetries and Telecommands
TWSTFT	Two-Way Satellite Time and Frequency Transfer
USO	Ultra-Stable Oscillator
UTC	Universal Coordinated Time

1. Introduction

1.1. Background and Motivation

With over fifty scientific and commercial planned missions by the 2030, a new era of the Moon exploration has just begun, with the goal of establishing a fixed presence on it. Towards this direction, NASA's Artemis Program aims to land the first woman on the Moon by 2024, in a critical area such as the lunar south pole region, because of water sources, essential for a long-term human presence. This strong interest in lunar exploration has led to the study and the successive implementation of advanced communication and navigation systems with the purpose of establishing high reliable Earth and Moon connection. The effectiveness of such systems largely depends on the achievable accuracy of time synchronization between ground-based architectures and those on-board spacecrafts. However, unlike Earth planet, the Moon does not currently have an absolute lunar reference time. Consequently, every lunar mission relies on time transfer from Earth, which is based on Universal Coordinated Time (UTC) introducing significant challenges in terms of time and frequency synchronization accuracy for lunar space systems; this approach works when considering different independent missions, but represents a difficulty when multiple spacecraft work together. Furthermore, if a local lunar time reference was present, all missions could benefit from it, representing an important step for lunar economy and cooperation. Even a common local time source would need an occasional update from Earth, but this would significantly reduce the effort from ground and decrease possible conflicts and difficulty in conducting basic operational coordination necessary for lunar activity.

Time transfer is the expression adopted to describe the action of different coordinating actors that share a timing reference. In a one-way time transfer architecture an actor transfers its time to another one. In a two-way system, the two actors both transmit and receive time messages, performing two one-way time transfers. In this way, regardless the chosen type of time transfer technique, a clock synchronization is performed.

In this context, this work focuses on the study and design of a time transfer and clock synchronization technique within the ANDROMEDA (Argotec Network Design for Real-time Operations in Moon Environment and Deep-space Applications) framework, Argotec's lunar telecommunications infrastructure, aimed at supporting and encouraging the grow of scientific and commercial assets anywhere on the Moon surface.

The main objective of the current work is to propose the best solution among different Earth to Space time transfer techniques, after a preliminary survey on available space qualified frequency standards for microsatellites.

1.2. Argotec and ANDROMEDA

Parallel to the current new Moon race, which emphasizes the need for a dedicated communication and navigation infrastructure, Argotec has developed ANDROMEDA, an end-to-end telecommunication architecture designed to orbit around the Moon providing continuous real-time data access to lunar assets while relaying directly with Earth.

The ANDROMEDA project aims to provide an end-to-end Communication and Navigation service based on a constellation of microsatellites orbiting the Moon [1]. Microsatellites' choice allows to be highly flexible with respect to the progressive growth of lunar assets and their respective data needs over time, permitting limited costs compared to larger platforms.

ANDROMEDA architecture has been defined considering performance and design parameters such as data rate, data volume, system complexity. An accurate trade-off has identified 24 satellites orbiting the Moon along the four elliptical orbital planes, depicted in Fig. 1.

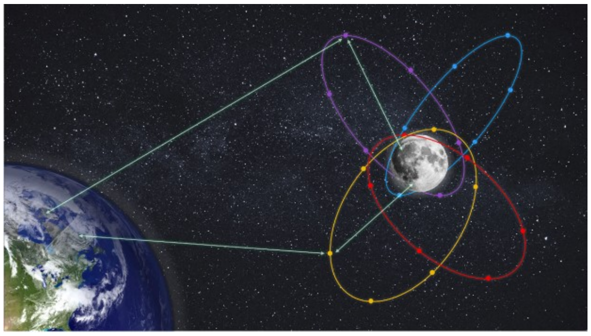

Fig. 1. ANDROMEDA Constellation

Specifically, the baseline configuration selected for ANDROMEDA is composed of 6 satellites per orbit, for a total of 24 for a complete constellation. Within each orbital plane, satellites are phased by equal mean anomaly (0°, 60°, 120°, 180°, 240°, 300°). This orbital configuration allows to increase global performance in terms of coverage and service continuity. Data relay occurs via each satellite individually, without Inter-Satellite Links (ISLs), and each satellite needs to establish direct links both with Lunar assets and Earth's Ground Stations (GSs).

The main activity performed by ANDROMEDA's architecture is the services provision, with the capability of functioning as a global network for lunar users, providing communication services to multiple assets on the surface at the same time. To achieve this, a prioritization of some regions such as high-latitude and polar regions will be guaranteed, with a 24/7 service provision enabled.

Two main types of data can be exchanged:

- User data (e.g., video, voice, images, and scientific data)
- User Telemetries and Telecommands (TMTC)

providing both Moon-to-Earth Communication and Moon-to-Moon Communication services, in real-time and store&forward manners.

The active links of the ANDROMEDA Communication service are shown in Fig. 2. In particular, S-band proximity link is used for low/medium data rate communication and hailing, K-band proximity link for high data rate communication and K-band trunk link always active (or scheduled) for real-time services.

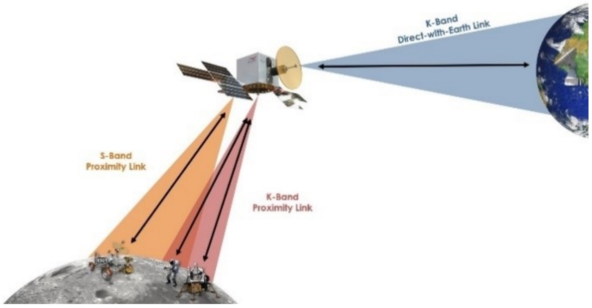

Fig. 2. Active Links of the ANDROMEDA Communication Service

Table 1 reports the ANDROMEDA frequency plan. S and K-band frequencies are proposed for the proximity links while the only K-band is proposed for the Direct-To-Earth (DTE) and Direct-from-Earth (DFE) trunk links. All frequency allocations are compliant with the Space Frequency Coordination Group (SFCG) Recommendation 32-2R4 [2].

Table 1. Frequency allocation and bands

Band	Link	Frequency
K-band (trunk link)	DFE	22.55-23.15 GHz
	DTE	25.5-27 GHz
S-band (proximity link)	Forward	2025-2110 MHz
	Return	2200-2290 MHz
K-band (proximity link)	Forward	23.15-23.55 GHz
	Return	27-27.5 GHz

1.3. ANDROMEDA navigation – Needs and Objective

The several missions planned to the Moon within the next decade pose the need of defining a lunar time reference with the goal of maintaining a reference time common to the whole constellation. The present work is placed in parallel to the in-progress research from different agencies such as ESA and NASA; as previous Moon missions have operated on their own timescale from Earth, there is a need of defining a common lunar reference time, internationally accepted and towards which all lunar systems and users may refer.

A time reference frame definition is necessary in a Communication and Navigation service and a time-transfer technique is mandatory for the definition of such a service, along with a clock synchronization. For this reason, a study of the state of the art has been done with the scope of proposing a possible solution to the problem, performing a trade-off to choose the optimal one with predefined system requirements.

Talking about Navigation services it is often referred to PNT as a unique system capable of accurately determine:

- the location of an object (or a user)
- the path required from the current position to a desired one, with the ability of applying corrections to course, speed and orientation
- the travel time between locations and the ability to maintain a precise time

Using information such as traffic data and weather conditions in combination to PNT services results in the renowned Global Navigation Satellite System (GNSS).

In the current work, the Timing branch of the ANDROMEDA PNT system is deeply investigated. Specifically, Timing services include the scope of providing both clock synchronization techniques, so to maintain a common reference time on-board constellation satellites, and time transfer techniques, Earth-Moon and Moon-Moon.

ANDROMEDA performs Orbit Determination (OD) and provides ranging measurements by adopting two-way ranging from Earth. In particular, ANDROMEDA's satellites acts as a bridge in a bent-pipe approach between Earth and Moon.

To properly study and design a possible Time-Transfer technique and a suitable atomic clock for ANDROMEDA's satellites, system requirements need to be defined and motivated. One of the architecture's main goals is to relay on two-way ranging techniques from Earth, being compliant with CCSDS 413.1-G-2 [3]. This implies that the choice of the time transfer technique has to be selected considering the previous requirement.

2. State of the Art

2.1. Existing Timescales

Satellite navigation techniques are very sensitive to time errors. Each system is based on its own time reference in which all elements are synchronized. As such system, also ANDROMEDA needs a time reference, to which synchronize the entire constellation. The most common existing timescale are basically:

- International Atomic Time (TAI)
- Universal Coordinated Time (UTC)

TAI is composed by a weighted average of time measurements taken from 450 atomic clocks of different laboratories worldwide, to achieve the highest possible level of accuracy. It is at the basis of UTC, a composite time scale comprised of time derived from atomic standards and information regarding Earth's rotation. UTC deviates from TAI being adjusted by leap seconds: specifically, UTC is 37 seconds behind TAI. UTC is the standard used for all general timekeeping applications and is also the global time reference regulated by the International Telecommunication Union (ITU). For these reasons, UTC has been chosen as ANDROMEDA reference time system to which synchronize the entire constellation.

2.2. Atomic Clocks for Microsatellites

Within microsatellites, time scales are based on atomic clocks, which are Ultra-Stable Oscillators (USOs), ideally represented by a device that generates a perfect sinusoidal signal at a nominal frequency [4]. Actually, clocks are affected by random fluctuations which results in clock instabilities and represent clock noise. An atomic clock is therefore a frequency device in which sinusoidal cycles are counted to identify seconds, hours, days, which is ready to be distributed. Clocks consist of two components: a device that produces a series of periodic events and a counter that counts the number of events and possibly interpolates between consecutive ones to improve the resolution of the measurement.

Clock performance is measured by observing the USO frequency stability during a specified interval τ. Depending on this duration, it is referred to [5]:

- short term stability, when $\tau \leq 100$ s
- long term stability, when $\tau > 100$ s

The characterization of such stability can be performed either in frequency or in time domain. Referring to frequency domain, Power Spectral Density (PSD) is considered; in time domain Allan Deviation (ADEV) is instead evaluated.

The best technology for PNT purposes depends on different factors. In particular, two categories of space qualified frequency standard on which the current work has been conducted are:

- Oven Controlled Crystal Oscillator (OCXO), a crystal oscillator in which a temperature-controlled oven is used to maintain constant the operating temperature of a quartz crystal. This prevents changes caused by variations in ambient temperature at the specified frequency;
- Rubidium Atomic Frequency Standard (RAFS), in which a hyperfine transition of electrons in rubidium atoms is used to control the output frequency.

Based on this classification, some frequency sources from different companies have been considered, giving a special attention to accuracy in terms of ADEV, which is one of the most critical requirements for the navigation service. Other metrics such as Size, Weight And Power consumption (SWAP), crucial when considering a microsatellite platform, have also been considered in the trade-off.

An internal company analysis proposes as frequency reference for the platform the Rakon's miniUSO RK410, belonging to the OCXO devices category and shown in Fig. 3, with a size of 99x88x51 mm, a weight of 550 g and 3 W of power consumption, with a short term stability of $5 \cdot 10^{-13}$ in a considered interval of 100 seconds.

Fig. 3. Rakon's miniUSO RK410

A measure of time error to which a time source is subject to is needed. In navigation purposes the question "How many seconds a considered clock keeps X nanoseconds?" spontaneously arises. To answer for this question, a simple parameter named Time Deviation (TDEV) is introduced, being a measure that describes the expected time error of a clock after some holdover time τ_{hold}. Even the best atomic clock in terms of accuracy accumulates error, which grows with time. TDEV can be calculated through the following equation [6]:

$$\Delta \mathrm{T}(\tau_{hold}) = \mathrm{T}_0 + \frac{\Delta f}{f}\tau_{hold} + \frac{1}{2}D_{\tau_{hold}}^2 + \frac{\tau_{hold}}{\sqrt{3}} M\sigma_y(\tau_{hold}) + \varepsilon(\tau_{hold})$$

where T_0 is the initial time error, $\Delta f / f$ is the initial frequency error, $D_{\tau_{hold}}$ is the frequency drift,

$M\sigma_y(\tau_{hold})$ is the Modified ADEV (MDEV) and $\varepsilon(\tau_{hold})$ takes care of the environmental errors over time. For an interval $\tau_{hold} \approx 1$ s, MDEV is equal to the ADEV.

If clock's initial time and frequency offsets are set to a known value with respect to a calibrated standard and environmental effects neglected, the third and fourth terms can be used to calculate the predicted time error after some holdover time τ_{hold}.

Considering the ADEV of the chosen miniUSO to be $5 \cdot 10^{-13}$ @100s, Table 2 summarizes different values of TDEV when considering interval of 100 s, 1 hour and 1 day.

Table 2. TDEV for different considered τ_{hold} values

τ_{hold} (s)	TDEV (ns)
100	0.028
3600	1.04
86400	25

2.3. Time Transfer Techniques

Once chosen the best atomic clock for the ANDROMEDA architecture, different time transfer techniques have been analyzed and are briefly described below.

Existing GNSS

The use of GNSS signal in space has been already demonstrated in Low Earth Orbit (LEO), thus the question "Why not using GNSS signals already delivered also for spacecraft navigation in higher altitudes?" spontaneously arises, such as for lunar missions, even if they were not purposed to do so. The main limitations in using GNSS signal in space on the Moon are:

- Long distances and occultation of the Earth, thus difficult signal reception and processing
- Weak side lobes signal, characterized by low-power levels
- Poor geometry of the GNSS constellation from a lunar user point of view, resulting in a very high value of the Dilution Of Precision (DOP)
- Limited access to navigation data due to very low Signal to Noise Ratio (SNR), which is below the navigation data demodulation threshold

Previous limitations may be overcome in communication and navigation lunar scenarios adapting high-sensitivity receivers coupled with high gain antennas that fuse GNSS measurements with advanced orbital dynamic models [7]. Additional augmentations are needed to compensate also for the bad geometry, increasing complexity and costs. Concerning the accuracy, catching the GNSS signal in space that "misses" the Earth arriving on the Moon through side lobes results in a much lower accuracy than that achievable using classic GNSS, in the order of microseconds, which may not be sufficient for applications such as navigation ones.

Two-Way Coherent PN Ranging

It is a novel technique based on coherent Pseudo-Noise (PN) ranging, using a two-way implementation, compatible with CCSDS 414.1-B-3 [8]. Two-way ranging is the most common technique performed by Deep Space Stations (DSSs) in which a GS transmits a signal to a Space Craft (SC) and the latter retransmits it back, having so an uplink channel and a downlink one, measuring the Round-Trip Light Time (RTLT). A coherent relation on the spacecraft is present, meaning that the downlink frequency is equal to the uplink one multiplied by a factor called transponding ratio. In this way, same chip rate and phase are used in both links. The retransmission of the signal back is done in a regenerative ranging manner, based on the correlation of the received signal with a locally generated on-board code replica. One of the main advantages of this technique is that time synchronization is based on nominal ground tracking operations, i.e. normal two-way PN ranging measurements from Earth. This technique can reach a nanosecond level accuracy. A slight variation can be done using carrier phase measurements rather than the code signal; in this way, more than an order of magnitude higher accuracy level can be reached, in the order of picoseconds. A drawback of this implementation is that it suffers of phase ambiguity cycles; failure in these cycle slips identification results into inaccurate results, compromising the time transfer service.

TWSTFT

The Two-way Satellite Time and Frequency Transfer (TWSTFT) technique relies on two asynchronous links and involves the use of two locally separated GSs exchanging signals in pairs to compare clocks [9]. Two-way time measurements are done at each GSs, then exchanged between them. This requires a great effort from the ground point of view and costs, while achieving a high level of accuracy in the order of picoseconds.

NTP

The Network Time Protocol (NTP) is a packet-switched network protocol used to synchronize a computer time server to a hardware reference clock, such as the Global Positioning System (GPS) one. It is a client-server method, in which protocol packets consists of timing information that travels between a client that synchronizes its system time to the server time. The architecture is organized hierarchically and an atomic clock, which can be for example on-board GPS, distributes the time reference to the highest level of the hierarchy, Layer 1 servers. The method proceeds down and each layer below obtains time reference from the layer above, until final users.

Hierarchical architecture permits clients to be accurately synchronized without the need of having access to the highest level server. NTP uses UTC time reference to synchronize computer clock, reaching an accuracy level of about 10 ms over the public Internet, 100 ms over Asymmetric Digital Subscriber Line (ADSL) and more than 1 ms in Local Area Network (LAN), considering ideal conditions. The accuracy to which NTP clients synchronize their clocks depends on root time source accuracy at highest levels and on physical distance between client and server at lower ones.

Optical Time Transfer

An optical version of the TWSTFT is the Optical TWSTFT (OTWTFT), which is based on ultra short laser pulses and involves two concatenated highly stable two-way lasers links, reaching a femtosecond level of accuracy. Range information and Code Epoch (CE) are provided by satellite laser ranging, instead on ground there is an actively stabilized fiber-based ground link which provides the accurate time reference between an H-MASER (Hydrogen-Microwave Amplification by Stimulated Emission of Radiation) on the ground and the ranging system [10]. Optical frequencies permit to reach improved accuracy due to reduced time delay uncertainties with respect to radio frequencies, being thus more suitable for high-precision time and frequency measurements. A further higher level of accuracy of this technique can be achieved via carrier-phase implementation.

2.3.1. Time-Transfer Techniques' Trade-off

After a description of currently available time-transfer techniques possibly adoptable for the ANDROMEDA architecture, a trade-off analysis between these has been performed by adopting suitable metrics and assigning a weight to each one. Chosen metrics are ground effort, system complexity, platform compatibility, cost and above all accuracy. A company analysis on these revealed that the most promising technique is the two-way coherent PN ranging time transfer technique which shows to be the medium cost and complexity system, fully compatible with space standards and ground support. Consequently, it has been selected as time transfer technique to be adopted by the ANDROMEDA platform, and below detailed in Section 3.

3. System Definition and Description

Fig. 4 shows the proposed time transfer technique based on two-way coherent PN ranging. Two timelines are shown, one associated to the GS (the bottom one) and the other to the SC (the top one).

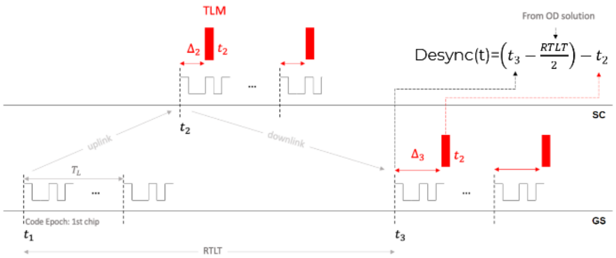

Fig. 4. Time-synchronization technique using Two-Way Coherent PN Ranging [11]

Specifically, there are three distinct epochs involved in the measurements:

- t_1 , epoch of the signal transmission from GS
- t_2, epoch in which the signal is received on-board the SC and coherently transponded back
- t_3, epoch of the signal reception on ground

A two-way ranging is performed. When a predefined code sequence is identified on the SC, that assumes a special meaning and defines the CE, the received PN code is acquired and tracked. This CE of the PN code repetition is used as trigger event on-board the SC in uplink and on ground in downlink. The code sequence repeats itself after one code period T_L, being the ratio between code length and chip rate:

$$T_L = \frac{1009470}{2 \cdot 10^6} \approx 505 \text{ ms}$$

In the current work, a weighted-voting balanced Tausworthe code has been adopted, recommended by CCSDS [8], of length equal to 1009470 chips. The steps of the algorithm are described below:

- A PN ranging signal is sent from the GS to the SC
- On-board time stamp operation is triggered by the received PN CE (acquired and tracked)
- At the same moment, on-board time stamp is recorded and transmitted in the downlink data stream
- On ground time stamp operation is triggered by the received PN CE (acquired and tracked) and recorded
- Received data containing downlink time information is decoded, read and recorded
- Time desynchronization is calculated with the aid of OD as:

$$desync(t) = \left(t_3 - \frac{RTLT}{2}\right) - t_2$$

in which the RTLT is the elapsed time it takes for a signal to travel from Earth to the SC and back to the starting point, provided by the OD solution. Calculation of desynchronization is carried out on-ground and resent on-board the SC with a new loop. A minimum of 2 two-way loops is thus necessary to perform clock synchronization.

When the CE is received on board, it triggers a time stamp operation and the on-board time t_2 is recorded and sent in the data channel for transmission to ground. Data encoding and transmission may add a delay Δ_2, as Figure 4 shows. This delay is considered to be $\Delta_2 << \mathrm{T}_L$ for correctly working method or, in other words, is always possible to unambiguously coupling any CE event with the telemetry data. This can be achieved because, even though there are large delays in telemetry channel, these are mostly deterministic and their residual uncertainty is expected to be much lower than T_L. A similar time stamp operation is triggered on ground by the received CE associated to epoch t_3 . When also the navigation message is received on ground with t_2 information and is decoded, an additional Δ_3 delay could be present, for which same considerations of Δ_2 apply. Delays Δ_2 and Δ_3 introduced by data encoding and decoding in the telemetry transmission may even exceed the code repetition period; the important thing is that Δ_2 and Δ_3 are both $<<\mathrm{T}_L$.

The final desynchronization accuracy depends both on OD performance, thus on accuracy in RTLT computation, and on the precision of time stamp operations, i.e. when measuring t_2 and t_3.

3.1. Signal Model

A transmission of both navigation data and ranging at the same time is necessary to entirely satisfy the purpose of this work, being the proposed technique based on ranging and having the need of a time transfer from ground. Standard CCSDS 413.1.G-2 [3] defines the "Simultaneous Transmission of GMSK Telemetry and PN Ranging". Figure 5 shows the transmitter scheme in which two branches corresponding to telemetry input and PN ranging sequence add together before a phase modulator, ready to be concurrently phase modulated and transmitted as a unique GMSK (Gaussian Minimum-Shift Keying)+PN Ranging channel.

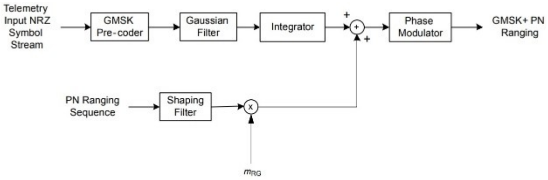

Fig. 5. GMSK + PN ranging modulation scheme [3]

Taking as reference the just mentioned modulation scheme, a custom implementation of transmission data and PN ranging is performed also for the ANDROMEDA architecture, by adopting a simplified implementation which considers the parallel sending of navigation data from one branch and the PN ranging code on another, being the focus of this work the time transfer service. This modified scheme allows to focus on the time transfer technique by adopting the ranging system already developed internally by Argotec. In particular, a simple Binary Phase Shift Keying (BPSK) is proposed for both the PN ranging system and the time transfer technique, instead of the recommended GMSK modulation.

A navigation message is needed to transfer the precise time from Earth to on-board ANDROMEDA platform, after having modulated the content. Essential information is the precise CE associated to PN ranging sent from ground, and possible clock corrections to take account for clocks desynchronization. Fig. 6 proposes a custom navigation message adopted for the ANDROMEDA time transfer technique.

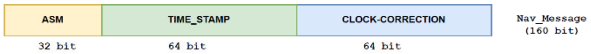

Fig. 6. ANDROMEDA Navigation Message

It is composed by three fields:

- Attached Sync Marker (ASM): used in many applications for synchronizing transfer frames. It precedes real data, i.e. time stamp in this case, and is a unique way to indicate the beginning of the navigation message. It needs to be known at both parts, sender and recipient of the message, and permits to read data from the beginning unambiguously, by synchronizing to the starting of the message any time the ASM is encountered. For this application the word "TIME" in binary has been chosen as ASM:

  01010100 01001001 01001101 01000101

  thus 32 bits are needed for this field.
- Time Stamp: defined in the format

  HH:mm:ss.SSSSSSSSS

  in which HH represents the hours, mm the minutes, ss the seconds and SSSSSSSSS permits to reach a nanoseconds precision. The maximum number corresponding to hours is 23, thus 5 bits are required (given from $2^5 = 32$); for minutes and seconds there is a maximum equal to 59, thus 6 bits each are required. For nanoseconds precision instead, the worst case is represented by "999999999" combination, thus 30 bits are needed (being $2^{30} = 1.073.741.824$). A total of 47 bits is needed. Not being a power of two, this number will be rounded to the next power of two which is 64.

The first 17 bits will be filled by zeros, as done in classical world of binary numbers.

- Clock Correction: defined in the same way as the Time Stamp field, thus composed by 47 signed bits. In the first loop it will be equal to zero because no desynchronization is calculated, thus by default set to: "00:00:00.000000000"

The total length of the custom navigation message is therefore 32+64+64=160 bits. An internal analysis has revealed that for the current navigation message a data rate of 1 kbps is adequate, obtaining a data period of 160 ms.

Needing to have at least 2 two-way links, any adequate correction can be done through the corresponding clock correction field in the navigation message. In this way, both clock desynchronization and channel effects described in Section 4 can be fully compensated by acting on the internal atomic clock.

4. Channel Effects

Considering the Earth-Moon link, as any other communication link, channel effects must be considered when designing all the involved parameters to correctly model the system under study and to possibly mitigate errors. Weather effects such as rain, snow and clouds are critical factors to be taken into account, at K band more than at lower frequencies, as they affect the signal propagation in the considered radio link. These effects will result into a worsening of the received signal presenting variations in amplitude and phase, polarization and angle of arrival. Certainly important in a link budget calculation, atmospheric losses are crucial parameters that need to be considered.

Concerning the time transfer technique, the following effects must be considered:

Synchronization errors, concerning satellite clock offset, tracked and compensated by the Ground Segment after desynchronization computation;

Incorrect values of satellite ephemeris, estimated from an accuracy point of view; due to a wrong information on satellite's position, they are calculated as the difference between the expected and the actual orbital position of a satellite, reducing its accuracy indeed. A internal evaluation on OD for a single ANDROMEDA satellite reports errors below 20 meters in 3σ, i.e. with the 99.73% of measurements around 20 meters from the mean value.

Relativistic effects, mainly summarized in [12]:

- Time dilation, caused by the relative movement of clocks;
- Time differences, caused by differences of the gravity field (time rate is slower on Earth's surface rather than in the satellite orbit);
- Relativistic effects on frequency, caused by the relative movement and difference in gravity field between the satellite and the receiver;
- Relativistic path range effects, through which influence of Earth gravity field is taken into account; Moon, Sun and other planets are subject to tidal forces with a very small correction;
- Relativistic Earth rotation effects, also called Sagnac effect, due to Earth's daily rotation;
- Relativistic effects due to orbit eccentricity, considered in precise OD;
- Acceleration of the satellite: relativistic correction of the satellites OD includes corrections of the equation of motion, time transformations and measurement model.

Other effects are present but not considered because too small to be relevant for this application. For the same reason, being these effects smaller with respect to other channel effects, they are neglected and not considered.

Atmospheric effects, due to associated signal delay in both ionosphere and troposphere.

For the ionospheric component, the Total Electron Content (TEC) is introduced, being the total number of electrons integrated between two points, which slows down the propagation of signals in this region of the atmosphere. Expected ionospheric delay at K-band is between 2.5 ps and 2.5 ns for a TEC ranging from 10^{16} to 10^{19} el/m^2. Being this delay frequency-dependent, a total compensation can be achieved when a dual-frequency receiver is available on ground. In this work, such a dual-frequency receiver is assumed to be available, obtaining thus a total ionospheric delay compensation.

Tropospheric delay can be associated to two components, a hydrostatic (dry gases) and a wet one (water vapour). A company analysis based on a tropospheric delay model for standard point positioning has been conducted, in which meteorological parameters are considered for a given receiver latitude and in a specific day of the year. The analysis has been conducted by considering Goldstone DSS-24 and obtaining a hydrostatic component equal to 7.7 ns and a wet one equal to 0.66 ns, for a total tropospheric delay of 8.36 ns. As can be observed, the hydrostatic component is the most impacting between the two.

As in any other telecommunication system, hardware non idealities and in general receiver noise effects are inevitably present and should be considered in a link budget assessment, even though they are out of the scope of this subsystem implementation. Noise sources such as transponder and mechanical antenna vibration are relatively smaller and have been neglected.

5. Conclusions

Until now, every mission has relied on independent ground to space time transfer. As the number of Moon exploration missions will increase, a local lunar time reference will be necessary. This would be an important step forward that would mark the support of the current need and subsequent development of a reliable telecommunication platform, capable of providing communication and navigation services to lunar assets. Towards this direction, Argotec proposes the ANDROMEDA architecture, on which the development of an Earth to Space time transfer and clock synchronization technique has been proposed. This was achieved through a study of the state of the art supported by trade-offs to individuate the best solution for the ANDROMEDA architecture. The preliminary study aimed to identify the possible time transfer techniques, from the most classic to the most innovative ones. These, together with research on the state of the art of space-qualified frequency standards, have made possible a trade-off analysis and subsequent choice of a moresuitable solution for the lunar platform ANDROMEDA but also easily applicable in other environments such as the Martian one.

The analysis revealed that the optimal choice of time transfer technique from Earth is incentered on a two-way coherent ranging system based on PN codes, compatible with the CCSDS and supported by a miniaturized USO.

By defining a custom navigation message, time stamp corresponding to particular time instants and clock corrections for both clock synchronization and impairments correction can be transferred.

The ground to space time synchronization can be performed any time a satellite is in visibility from the GS. Even though an Earth-to-Moon time synchronization has been presented here, the same applies also for Moon-to-Moon synchronization, i.e. between ANDROMEDA satellite and lunar assets.

The individuated atomic clock and technique confirmed that the chosen system is adaptable to the ANDROMEDA platform, being compatible with microsatellites design constraints and relying on nominal ground tracking operations. The time synchronization can be performed by a simple combination of orbit determination and two-way ranging, reaching an accuracy of few nanoseconds fulfilling the accuracy constraints imposed by a navigation service like time transfer in an architecture without ISLs where the navigation performance of each constellation node rely on direct contact with ground only.

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