The ACES Microwave Link: Instrument Design and Test Results

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***Abstract*— The Microwave Link (MWL) is a key piece of equipment of the ACES payload. Consisting of a flight segment and a ground terminal, the MWL is used to transmit the ACES clock signal to the ground. It performs space-to-ground clock comparison and ground-to-ground comparison of time & frequency reference systems.**

I. Introduction

Atomic Clocks Ensemble in Space (ACES) is an ESA fundamental physics mission based on the operation of atomic clocks with high stability and accuracy in the microgravity environment of the International Space Station (ISS). The time scale generated by the ACES clocks on-board the ISS is delivered to Earth through a high-performance microwave two-way time and frequency transfer link. The MWL is used to perform space-to-ground as well as ground-to-ground comparisons of atomic frequency standards. Suitable ground terminals (G/T) will be located at sites and laboratories equipped with high performance clocks.

MWL design uses a bi-directional dual frequency PN-coded spread spectrum signal with simultaneous operation in both directions. Two frequency bands are used for the cancellation of the ionospheric delay. The MWL shall exhibit very high delay stability at pico-second level, compatible with a clock stability of 10^{-16}.

In this paper, the principle, the design of the end-to-end MWL system, and the current development status are discussed. Results of a recent test campaign using the MWL Flight Segment (MWL FS) are presented and compared to the MWL requirements as derived from the ACES scientific objectives.

The three major MWL stability requirements are

1. TDEV @ 300s ≤ 230 fs
2. TDEV @ 1d ≤ 5.5 ps
3. TDEV @ 10d ≤ 15 ps

The work is performed in the frame of the ESA-financed ACES project.

II. Measurement Principle

The proposed MWL concept is an upgraded version of Vessot's two-way technique used for the GP-A experiment in 1976 [1]. Higher frequency bands are used together with high-rate modulation to perform both precise carrier- phase and long-term stable modulation-phase measurements.

A Λ-link configuration has been chosen to achieve symmetric up- and down-link paths, significantly reducing errors arising from the MWL configuration on-board the ISS, which is travelling at a high relative velocity and high acceleration relative to a ground observer [2].

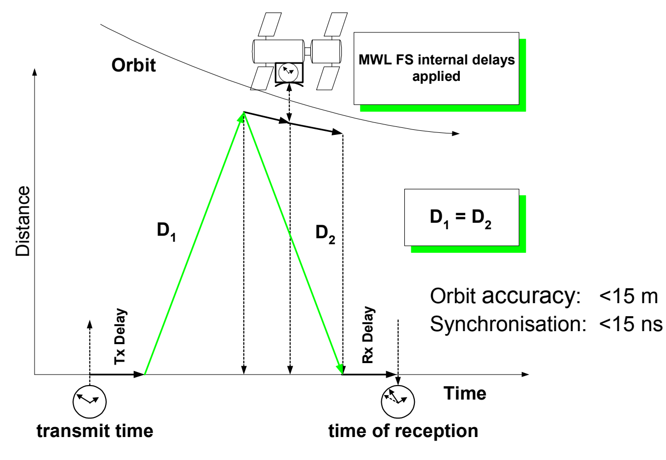

Figure 1. Λ-Link Measurement Configuration [2]

The Λ-link configuration relies on a bi-directional signal link between two clocks, operated simultaneously in both directions. Both sides transmit time-tagged signals synchronously to their local clocks. Assuming perfectly synchronized clocks, i.e. the ideal case, signal transmission should be co-incident on both sides. For ACES, the space-clock is affected by relativistic frequency shift, which causes a continuous time drift in comparison to ground-based clocks.

In real operation, the measurement system synchronises to within 15 ns prior to the actual measurement.

At both ends, the phase of the carrier and the modulation of the received microwave signal is determined according to the local time. The clock difference is then calculated as the difference between the two local observations divided by two. It is a differential measurement principle with the following major capabilities:

- The system is independent from the absolute link geometry and from the actual location of the clocks.
- The system is unaffected by changes to the geometry, i.e. by relative velocity or acceleration.

In the ideal case, instrumentation at both ends is identical; both with respect to hardware and software, including measurement algorithms. This directly entails that the MWL G/T exhibits a high similarity to the MWL-FS in all aspects of the system, including hardware elements and software algorithms. It can be shown that implementation deficiencies arising either from electronics or from the data generation process can be tolerated to a considerable extent, as long as it is ensured that they affect measurements at both ends in a similar way. This is due to the differential nature of the measurement method.

III. Design of the End-to-End MWL System

A suitable range of measurement parameters plus additional calibration means has to be devised that must be able to properly account and compensate for all identified errors. Each additional measurement is likely to add to the system complexity, thus requiring further resources. Therefore, care has been taken to identify the minimum required number of measurements to be acquired in the context of sufficient confidence and experience being available to make such a determination while continuing to assure the achievement of mission objectives. Reliance on external data and models shall be minimum, however. The signal link design is shown in Fig 2.

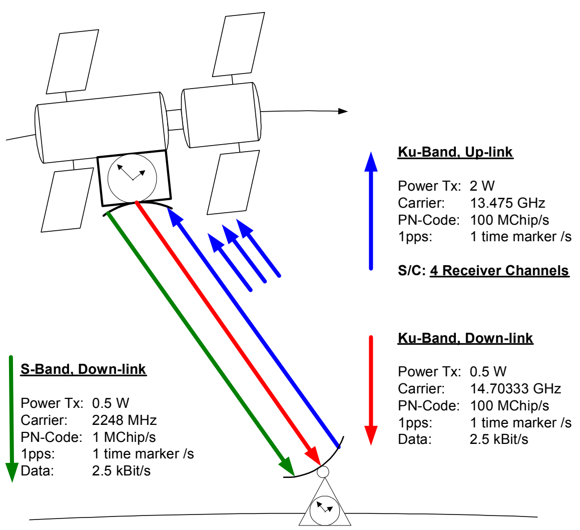

Figure 2. MWL Signal Link Design

The proposed system realises the clock monitoring measurement along the following rules:

- The system uses absolute carrier phase measurements in up- and down links to achieve ultimate precision.
- A very high code modulation rate of 100 MChip/s allows precise absolute signal delay measurements.
- Code-phase measurements resolve carrier-phase ambiguity to allow cycle identification in Ku-band
- The transmitted carriers and the receiver local oscillators are generated coherently to local time.
- Code and carrier measurements are performed as time-tagged phase measurements in a mostly digital implementation, which is similar for all four kinds of phase data.
- Time tagging is according to local time, i.e. all code- and carrier phase measurements are executed simultaneously and at precisely defined events defined by local time.
- Internal sampling rate is in excess of 100 ksamples for Ku-band carrier- and code-phase measurements.
- A 3rd frequency (S-band) is used in the down-link to compensate for the dispersive ionosphere
- Short-term ionospheric variations within one pass are compensated by
  (a) differential carrier phase measurements between Ku- and S-band at each GT individually,
  (b) by difference between group- and phase-velocity in the Ku-band links
- Absolute ionospheric delay is detected by differential code phase between Ku-band and S-band at the G/T
- Detection of the total ionospheric delay is performed within less than 20s of dual frequency measurements.
- Removal of Ku-band carrier ambiguity is performed within less than 20s of code-phase measurements.
- PN-code correlation properties suppress multipath effects on code- and carrier phase, as soon as the reflected signal path is 3 m longer than the direct path.

The MWL hardware and software architecture closely resembles the PRARE (Precise Range-Rate Equipment) instrument [3], which operated successfully on-board ERS-2 during 12 years in space.

Key parameters have been augmented to achieve the mission requirements. The major differences between PRARE and ACES MWL are in the PN-code rate, which has been increased by a factor of 10 and by use of higher carrier frequencies in the Ku-band. The substantially higher Chip-rate is mandatory to improve timing accuracy and stability while reducing multi-path effects. The increased carrier frequencies are mainly to fulfill the high frequency comparison requirements, to reduce ionospheric effects and also to comply with international frequency allocations.

The space segment consists of two transmitters (S- and Ku-band) and four Ku-band receiver channels, allowing simultaneous contact with up to 4 ground stations. The ground station has two receivers (S and Ku) and one Ku-band transmitter. Built-in calibration loops monitor instrumental delays in space and on ground simultaneously with instrument operation.

All signals are PN coded, ‘spreading’ the signal energy over a bandwidth roughly equal to the chip-rate. Correlation receivers are used to re-construct the phase of the signal at the receiving side, both for the PN-code and for the carrier. Measurements are performed by phase-comparison of the re-constructed signals according to the local clock.

A 1pps ‘time-marker’ is modulated on each PN sequence to uniquely identify its epoch and to remove ambiguity. Both downlinks carry MWL-specific H/K data to ground in real-time. These data are mainly required to establish initial time synchronisation at the beginning of a pass and to maintain the space-to-ground link.

IV. Current Development Status

Currently, the following items have been developed:

- MWL FS Electronics Unit, Engineering Model: Verification of code- and carrier phase stability has been performed recently. Some hardware examples are shown in Figs 3 and 4 below.

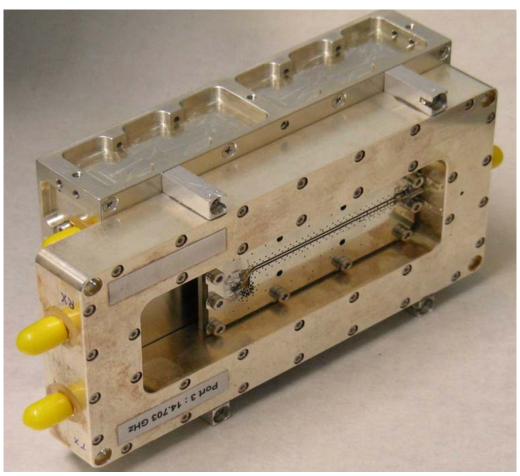

Figure 3. MWL FS Diplexer

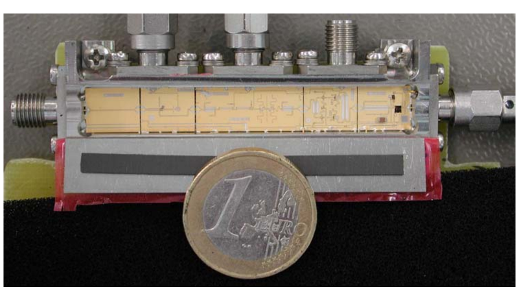

Figure 4. MWL FS Ku-Band Transmitter

- MWL Flight Segment Antenna

Fig 5 shows the Ku-band version, the S-band antenna is of a similar design, adapted to the larger wavelength.

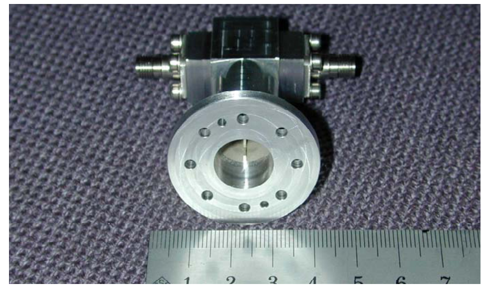

Figure 5. Ku-Band Antenna Design

Fig. 6 shows a cut of the antenna phase pattern, which has been measured carefully in a high performance anechoic chamber. These data are used to compensate in flight for phase center variations vs incident angle. For typical pointing and calibration errors, the antenna introduces less than 10% to the link stability error budget.

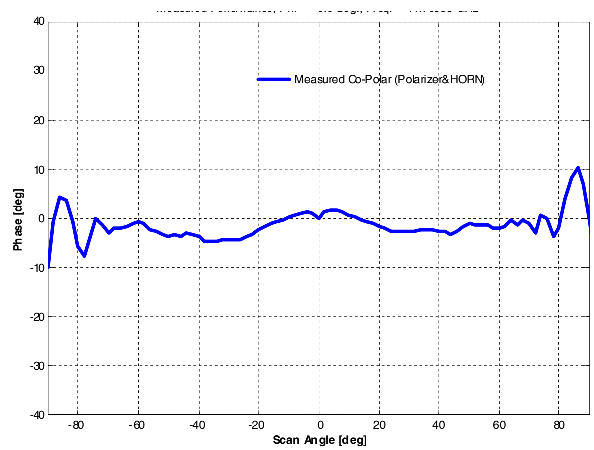

Figure 6. Ku-Band Phase Pattern

- MWL G/T Electronics Unit: the design is highly similar to the FS Electronics Unit. The first prototype will be built using modules directly derived from FS once it has been thoroughly tested.
- MWL G/T Antenna (Ku- and S-Band in one antenna): The combined S- and Ku-Band feed is shown in Fig 7. Mounted in a 60 cm dish, the gain and pattern were as expected.

Figure 7. Ground Terminal Antenna EM in Test Chamber

V. MWL FS Electronics Unit Results

Fig. 8 shows the carrier phase stability of the MWF FS Electronics Unit, shown as TDEV using an external loop-back transponder. No further calibration data have been applied as yet.

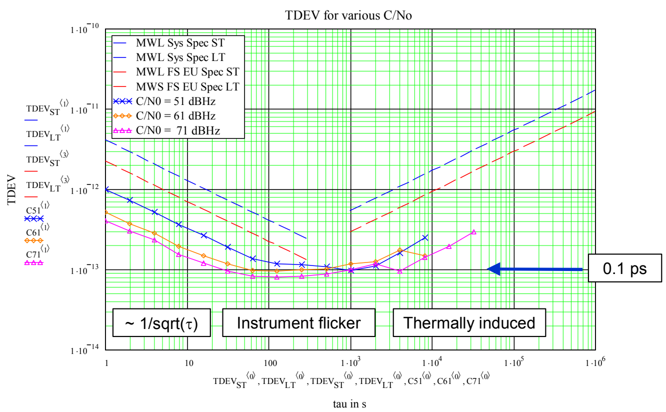

Figure 8. TDEV Carrier Results for various C/No

Fig. 8 also displays the requirements for:

- The MWL end-to-end specification including instrumentation and link-induced errors: lower dashed red
- The portion of error attributed to the FS Electronics Unit (without FS antenna): upper dashed blue.

Fig. 9 shows the code-phase stability results, as TDEV. The unit must achieve 5 ps link stability within a pass (< 300s) for carrier cycle identification. This is pre-requisite to using carrier-phase data for long-term measurement as well. The requirement is achieved already after 10-20s, even under unfavourable C/N_0 conditions.

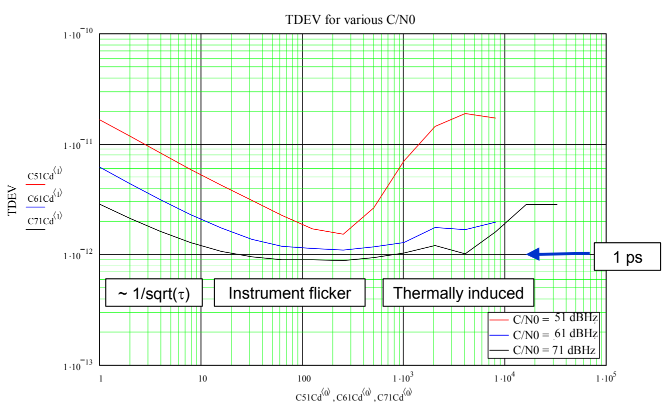

Figure 9. TDEV Code Results for various C/No

The carrier-to-noise density ratio (C/N_0) was changed in 3 steps from 51 dBHz to 71 dBHz, according to the link budget. At small integration times, i.e. below tens of seconds, the receiver's thermal noise dominates until after 50s the instrumental flicker noise floor is reached. Above several thousand seconds, thermal effects limit the obtainable long-term stability. There is no discernible difference in the long-term TDEV between code- and carrier-phase measurements. This will be tested in more detail in the near future.

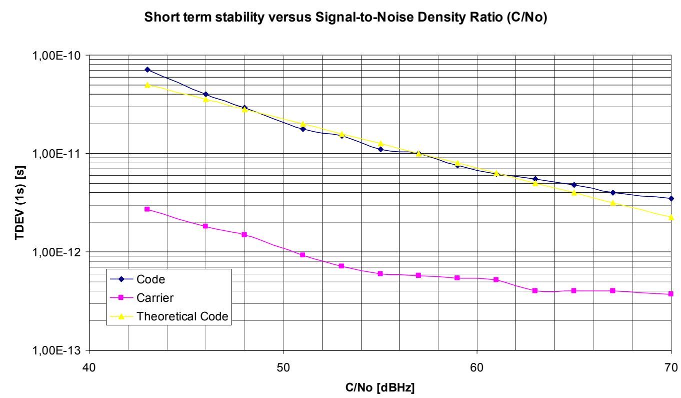

Figure 10. TDEV @ 1s vs. C/No

Fig. 10 shows the measured TDEV for code (top) and carrier (lower) data versus different values of C/N_0. The implementation loss for the 100 MChip/s code tracking loop is less than 1 dB.

VI. Conlusions

The performance measured with the MWL FS Electronics Unit and the FS and GT antennae shows full compliance to, and even exceeds, the specifications. This demonstrates that the MWL performance is well suited to support the demanding ACES mission requirements. It is compatible with common and non-common view clock comparisons at a level better than 10^{-16}.

Following these encouraging results, the MWL GT will now be designed and built, leading to ground based integrated MWL system testing by the end of 2008.

Acknowledgment

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