ACES MWL data analysis center at SYRTE

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The ACES-PHARAO mission aims at operating a cold-atom caesium clock on board the International Space Station, and performs two-way time transfer with ground terminals, in order to allow highly accurate and stable comparisons of its internal timescale with those found in various metrology institutes. Scientific goals in fundamental physics include tests of the gravitational redshift with unprecedented accuracy, and search for a violation of the Lorentz local invariance. Hopefully this is our last status update in Moriond with ACES still on ground... As launch is coming closer we are getting ready to process the data expected to come from ACES Microwave Link (MWL) once on board the International Space Station. Several hurdles have been cleared in our software in the past months, as we managed to implement algorithms that reach target accuracy for ground/space desynchronisation measurement. I will present the current status of data analysis preparation, as well as the activities that will take place at SYRTE in order to set up its data processing center.

1 Introduction

This presentation follows previous status updates, notably last Rencontres de Moriond [1]. General presentation of the ACES mission may be found in Laurent *et al.*, 2012[2]. The software is now almost finished, as it is able to process what we assume to be realistic MWL simulated data over full measurement sessions ($\simeq$10 days). We were therefore able to use this software for experiments (e.g. influence of ISS orbitography uncertainty on final results).

2 A brief reminder of the MWL measurement principle

The ACES Micro Wave Link (MWL) will be the main device used for time and frequency transfer between space and ground stations. It requires a specific terminal, 5 of them will be attached permanently to several high performance clocks around the world, while additional mobile units will perform measurements for shorter period of times either in colocation for calibration purposes, or at different institutes to increase coverage.

It applies the principle of two way time transfer, in which both clocks send a timing signal to the other one. Each incoming signal is then compared to the locally produced signal, which provides a " pseudo-range" observable. The difference between the ground and space observable nullifies (at first order) the signals propagation delay and gives access to the desynchronisation between the clocks [3]. Figure 1 shows the basic configuration for signal exchange. We use one uplink (Ku-band, 13.475 GHz) and two downlinks with very different frequencies in order to determine the Total Electron Content (TEC), Ku-band 14.703 GHz and S-band 2.24 GHz. The "lambda" configuration shown on figure minimizes the effect of our limited knowledge of ISSposition and also limits the impact of tropospheric delays estimate errors.

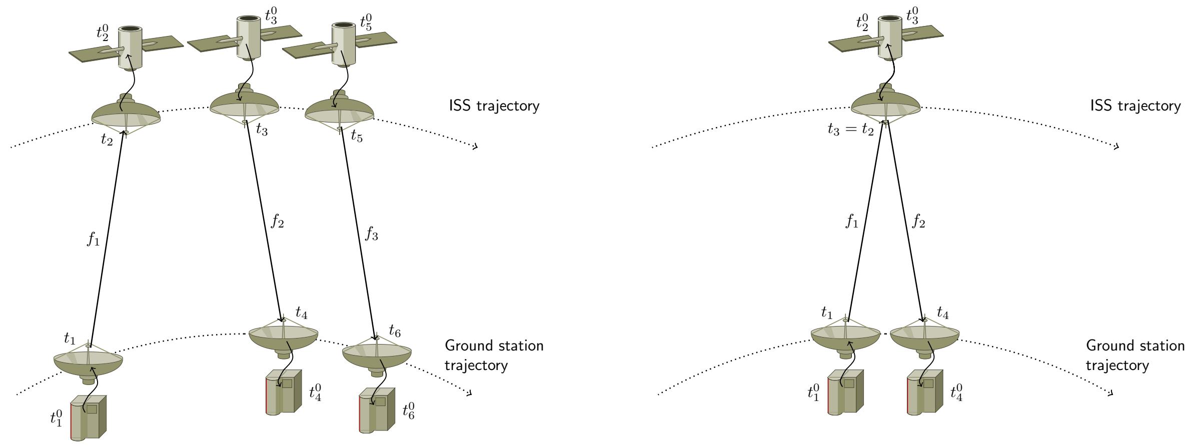

Figure 1 – Left : nominal configuration for signals exchange, the uplink signal and both downlink signals are not synchronised and both stations move during time of flight. Right : The "lambda" configuration, obtained by interpolation, where we match arrival at and departure from the space station in order to minimize the impact of its positional uncertainty.

3 Software development at Syrte

Basic ideas for the data processing where first explored in Duchayne, 2008 [4]. Actual coding of the present software started in 2011, the package now consists in roughly 6300lines of python / numpy code. For each pass of the ISSin visibility of the ground station, it takes raw (but demodulated) data + auxiliary files as input, and computes ground/space desynchronisation, Total Electron Content, and pseudo range every 80ms during the pass.

In parallel, a simulation software has been developed as independently as possible : different programming language (Matlab) and separate developers, only sharing basic understanding of the measurement principle.

3.1 Typical results

Figure 2 shows typical results coming out of the processing of one pass, from simulated data. The top row shows the actual value of the desynchronisation throughout the pass : we asked for a simulation with a $\simeq 1$ ms offset, plus a drift which is due to the difference in geopotential (i.e. Pharao is not de-tuned to compensate this). Tis means that, from the beginning to the end of the pass, the desynchronisation varie by a few tens of microseconds.

There are two measurements done simultaneously : the signal consists on an encoded modulation of the carrier, and the modem returns a "code" and a "carrier" observable. "code" is non ambiguous but as a 20 ps uncertainty on each point. "carrier" is more stable (1 ps at each point) but needs ambiguity removal and is affected by an unknown offset. The bottom graphs illustrate these characteristics.

It should be noted that the only noise source included here is the quantization noise generated by the measurement principle (which is based on counters running at $\simeq 100$ MHz, which translate into the observed spread). Therefore this represents the floor noise this technique may achieve : we expect real data to be much noisier.

One of our recent major achievements is the implementation of carrier disambiguation and offset conservation from pass to pass : as noted above, the most stable measurement (i.e.

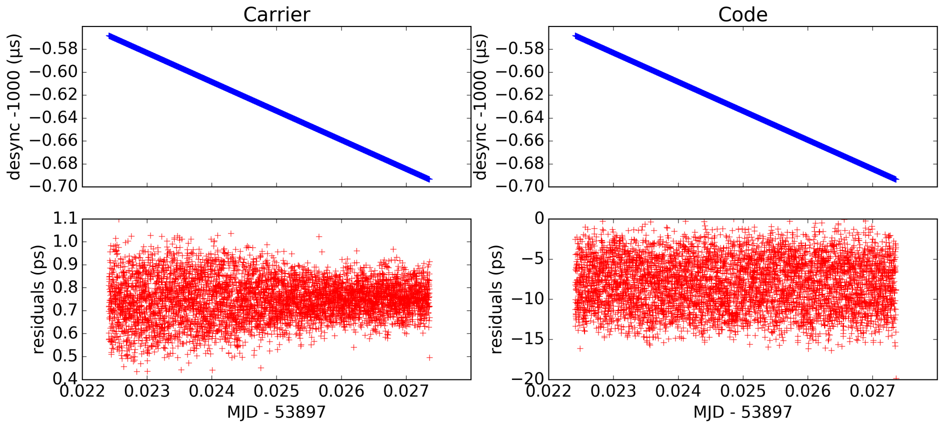

Figure 2 – A typical pass result. Top : input desynchronisation (drift = GR). Bottom : residuals (theoretical - calculated desynchronisation).

"phase") is affected by an unknown offset, but according to the specifications there is a way to link one pass to the next and therefore keep this unknown offset constant from one dataset to the next (provided no hardware reset has occurred in the mean time). This behaviour is illustrated on figure 3 : "code" measurement mean value can exhibit $\simeq 20$ ps jitter, while "carrier" measurement stays close to the same value (here, 0.8 ps away from the theoretical value).

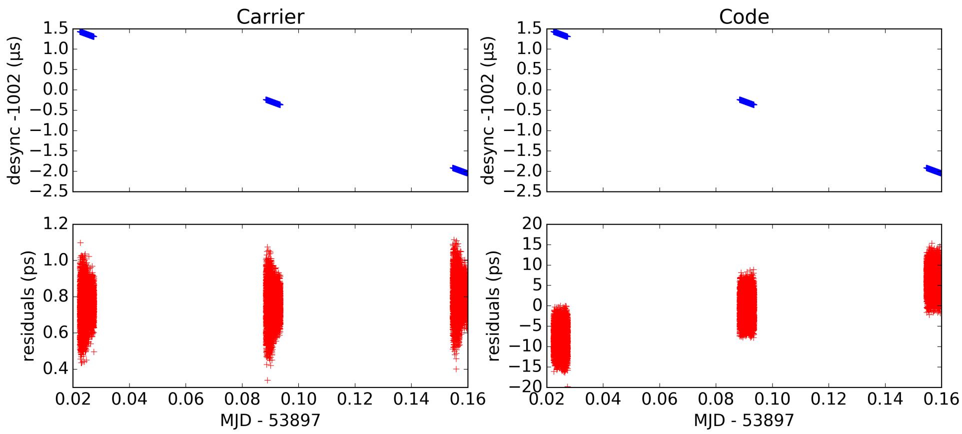

Figure 3 – Same as fig. 2, but spanning 3 consecutive passes (roughly separated by 1 ISS orbital period).

4 Experiments

Both processing and simulation software are very useful tools even before the mission start, as an efficient way to experiment on expected data : the very high flexibility of the simulation software allows to generate datasets that will test edge cases or peculiar scenarios, even non physical ones for test purposes (e.g. stop the ISS to allow "constant range" scenarios, switch atmosphere on and off, etc...). We regularly provide datasets to industrial Ground Segment developers to test their work chain. We also test our own ability to detect deviations to GR or possible technical mishaps.

For example, we have tested the impact of ISS orbitography uncertainty : we know that the ISS will always be slightly off the position we read from the orbitography files. First, with help from DLR (O. Montenbruck) we compared two orbitography datasets obtained for the ISS at the same time, one from the regular tracking device (SIGI), the other from a more precise GNSS receptor installed temporarily on the ISS in 2006. The SIGI error dominates, so the difference between the two gives an estimate of the error vector.

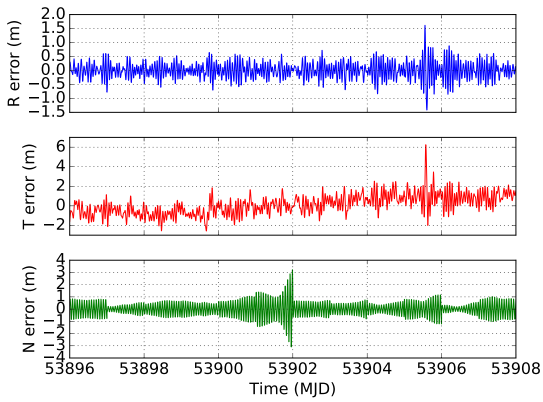

Figure 4 – Projection of ISS orbitography uncertainties.

Projection of this error vector on meaningful axes, for 12 days of data, is shown on fig 4. As expected, we observe a smaller dispersion on R (radial), i.e. a few meters, while T (transverse, along path) axis bears larger errors. N (normal) exhibits peculiar patterns due to the model used for fitting. Note that we have selected a "quiet" period, without major disturbances (such as altitude boosts, vessel docking, etc. . .). Once we have those projections we can re-apply them to our orbitography file, and change their amplitude (selectively on each axis) to test for degraded conditions.

This allowed us to verify theoretical calculations showing that using the "lambda" configuration effectively reduces the impact of ISS orbitography uncertainty : we show that, as far as the desynchronisation determination is concerned, our algorithm can cope with an error between 10 and 100 times worse than expected. Note however that it is another matter to check the impact of this uncertainty on our knowledge of the gravity potential during the orbit, which in turn shifts the clocks frequency during orbit. Tools are being developed to modelize and integrate this shift in various theoretical frames.

5 Conclusion

Work has progressed well and is in line for the planned launch date, one year from now. We already have demonstrated our ability to process large amounts of data within the required specifications, all remaining unknowns pending to comprehensive end-to-end hardware tests that are expected to happen this summer.

References

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