

## ACES Data Processing Center at SYRTE

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Systèmes de Référence Temps-Espace



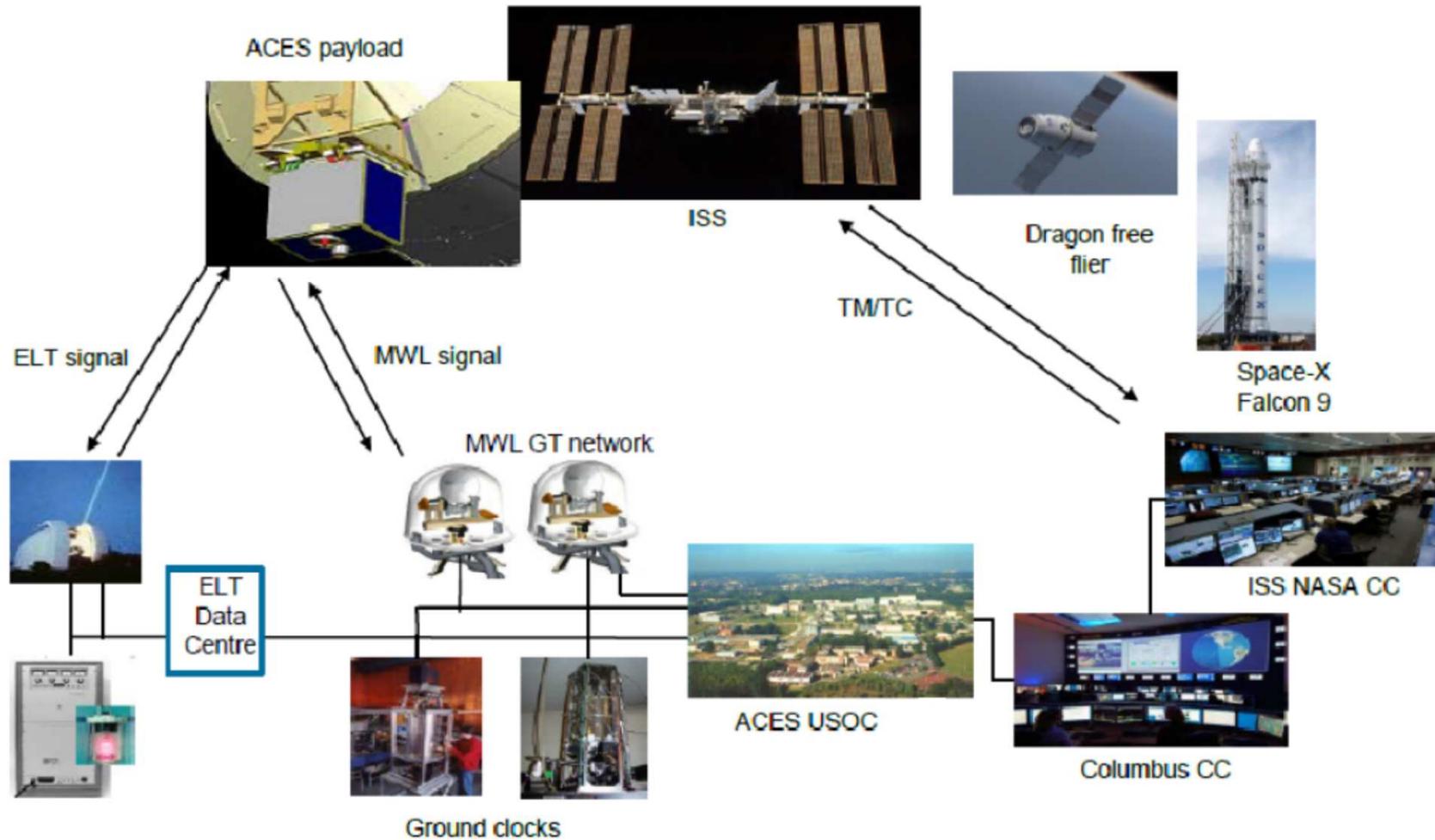
# Outline

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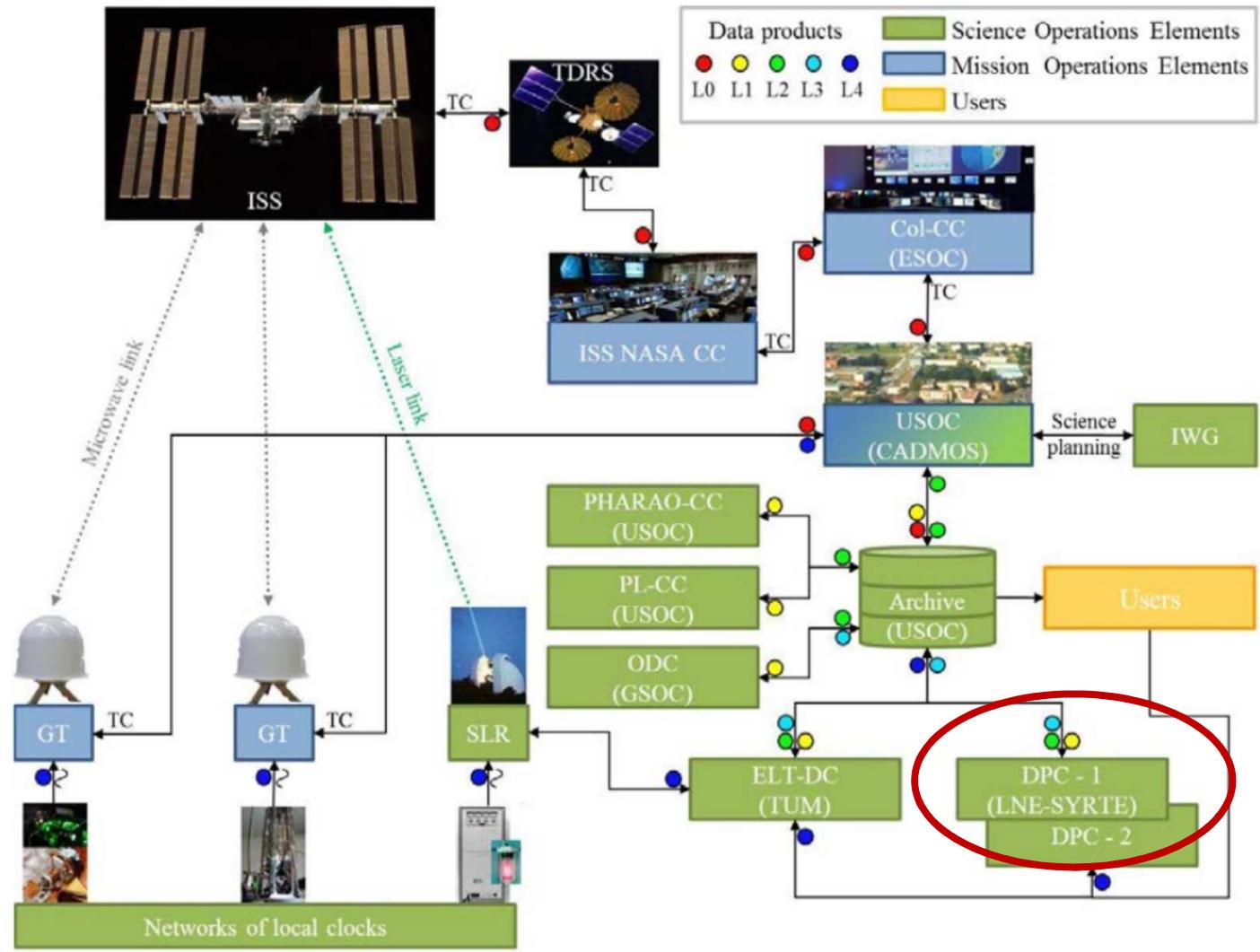
- Overview of ACES ground segment and SYRTE DPC
- MWL data processing at SYRTE
- Some results
- Using the software even before launch
- Example: Effect of ISS orbit determination errors
- Preparation for gravitational redshift test
- Next steps
- Summary and conclusion



# ACES ground segment and SYRTE DPC

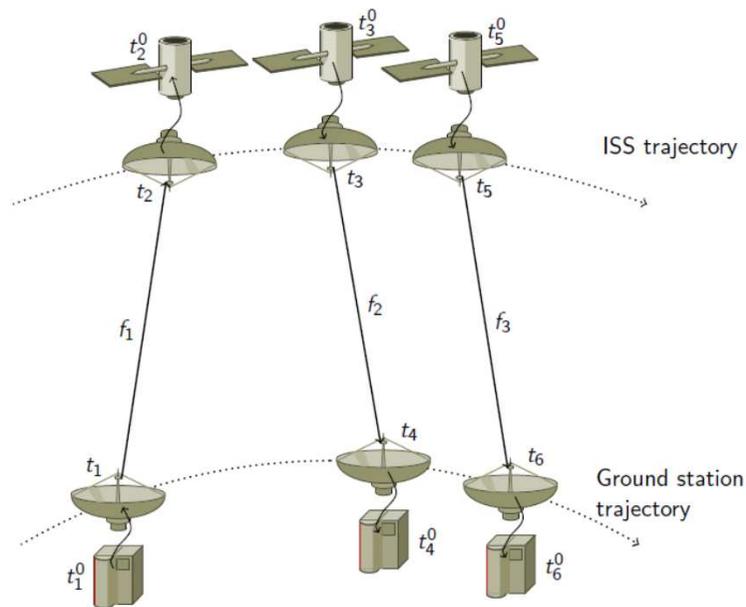


# ACES ground segment and SYRTE DPC

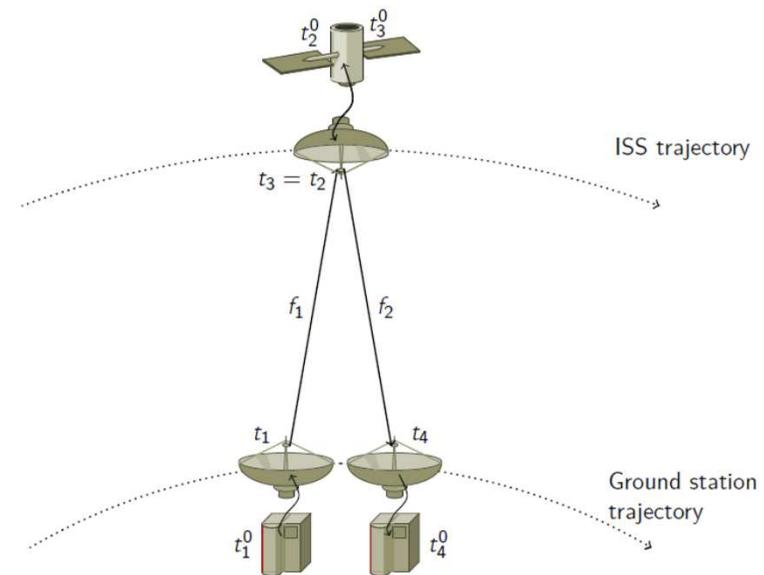


# The ACES Microwave Link (MWL)

- Ku band uplink (13.475 GHz) and downlink (14.703 GHz) with 100 Mchip/s code.
- S band downlink (2.25 GHz) for ionosphere determination.
- Two-way configuration cancels Range and troposphere to 1st order



General case:  
Asynchronous measurements (80 ms)  
on ground and in space



$\Lambda$  configuration (interpolated):  
Minimises impact from orbit errors

# MWL data processing at SYRTE

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## Processing software:

- Early developments  $\approx$  10 years ago. First lines of today's code written in 2011.
- More than 6000 lines of Python code.
- Takes raw MWL data, orbit, attitude, EOP, pressure, humidity, ... as input.
- Provides clock desynchronization, Range, TEC.

## Simulation software:

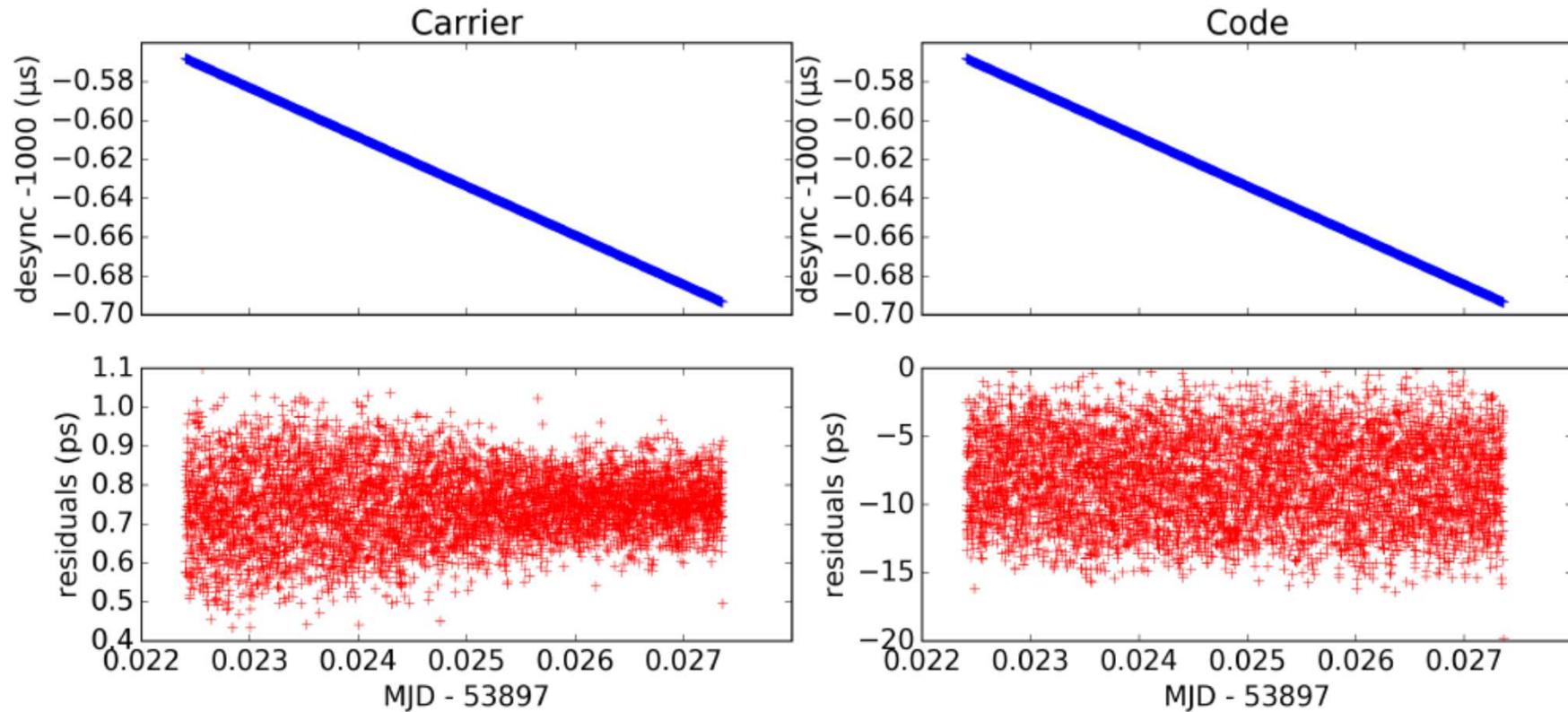
- Parallel development – different developer, different language
- More than 1500 lines of Matlab code
- Takes desynchronization, orbit, attitude, EOP, ionosphere profiles, pressure, humidity, ... as input.
- Provides simulated MWL raw data (best guess sometimes).

## What we can provide:

- Simulated data for testing and validation purposes
- Post processing of real data on IWG request
- Some limited 24/24 quick look processing in near real-time

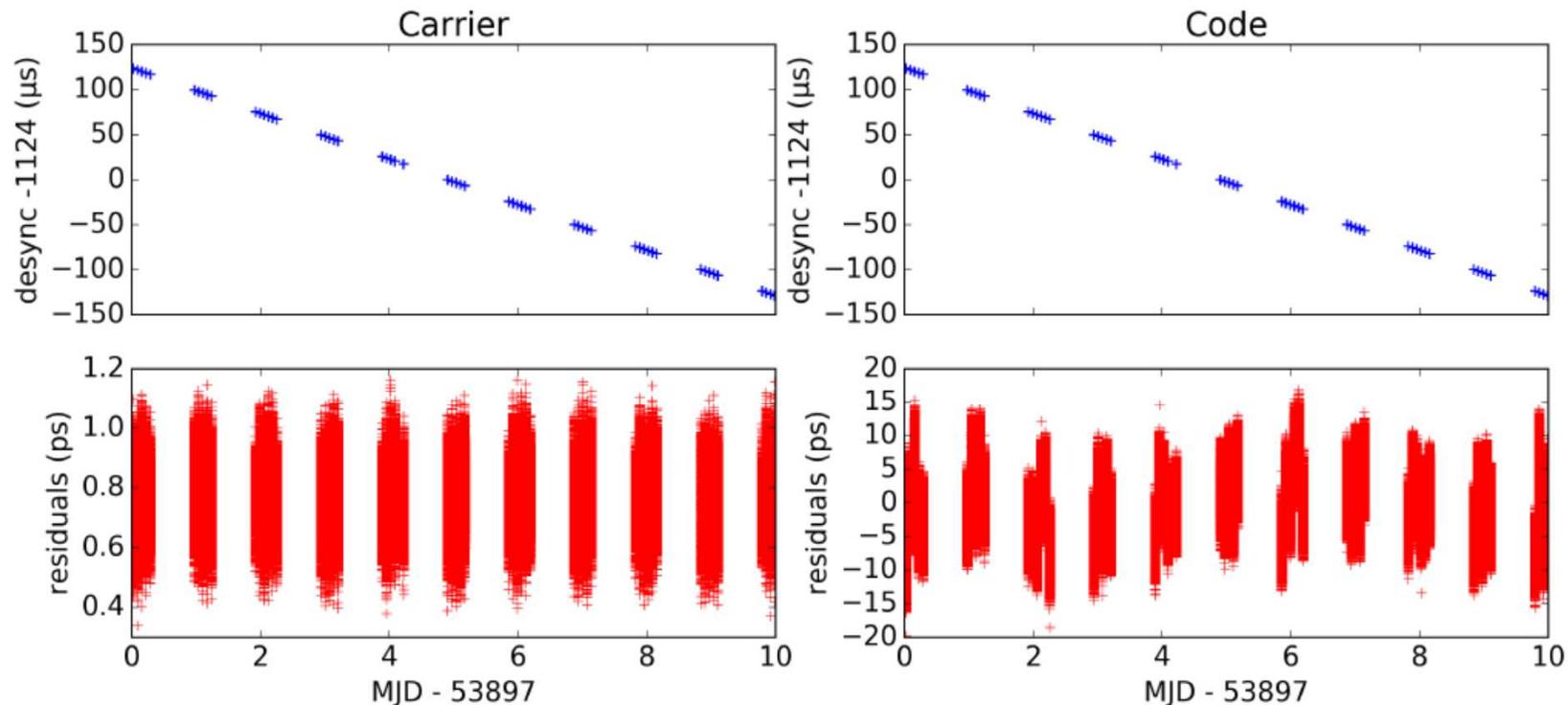


# Some results: Single pass



- Full simulation (GR, atmosphere, Kepler orbit, clock offset, etc...)
- Residuals of desynchronization i.e. processing result – simulation input
- Noise is the MWL counter quantization (= noise floor)

# Some results: Multiple pass



10 days ( $\simeq 50$  passes) during a “quiet” period (no ISS boosts).

- Uses real ISS orbit data for simulation and analysis
- Full carrier phase ambiguity resolution (up to a global offset)
- 20 ps pk. to pk. on code as expected (counter quantization)
- $< 1$  ps on carrier as expected

# Using the software even before launch

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## Produce test data for Ground Segment developers:

- General debugging
- Special cases scenarios
- Validation data (e.g. provide simulated data to ESA for validation of industrial software (ADS))

## Prepare for future data analysis:

- Check sensitivity to GR deviations
- Get ready to deal with expected perturbations
- ...

## Carry out tests:

- Effect of orbitography errors
- ...



# Example: Effect of ISS orbit determination errors

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- Duchayne et al. have evaluated rough limits on orbit determination to meet ACES specs:

$\delta R$ /m	$\delta T$ /m	$\delta N$ /m
8	16	1400

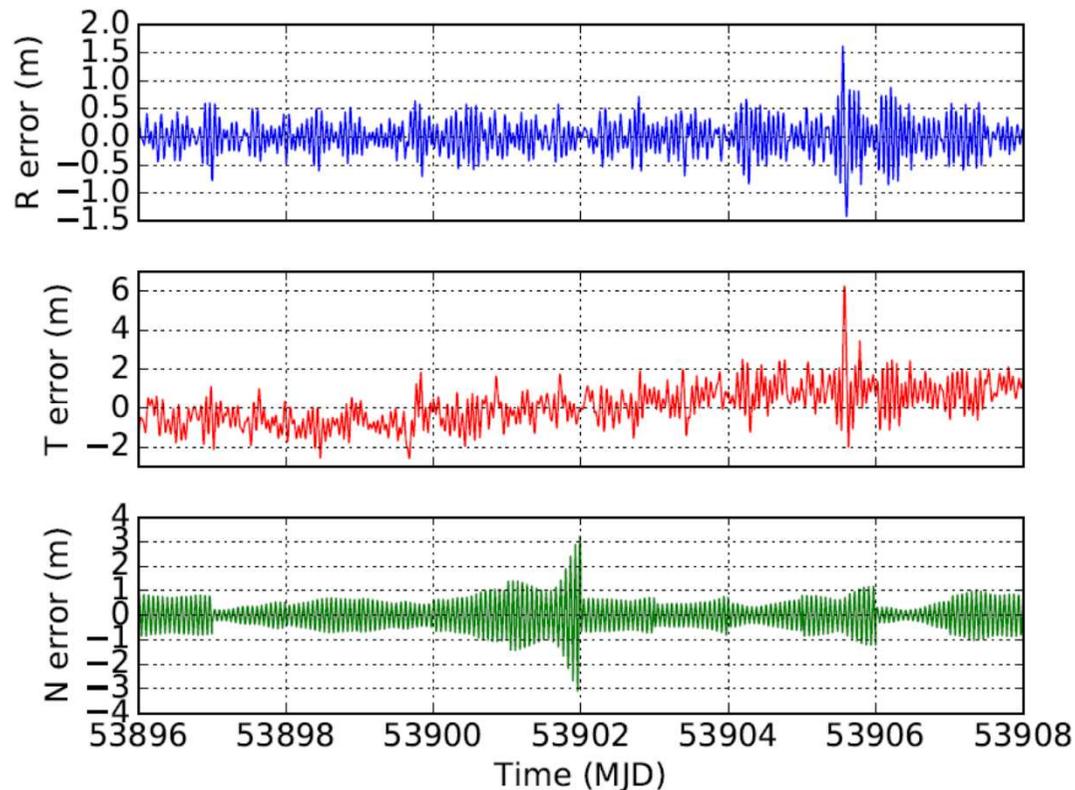
[Duchayne et al. A&A **504**, 603, (2009)]

- The limits on  $R$  and  $T$  are conditioned by the necessity to correctly calculate the frequency shift from gravitational redshift and second order Doppler.
- The limit on  $N$  comes from higher order Range error terms in two-way link.
- We check these results using real ISS orbit data and error estimation.



# Example: Effect of ISS orbit determination errors

Starting point : difference between SIGI orbitography (OD) and more precise GNSS orbitography (POD), data provided by O. Montenbruck (DLR).



OD - POD

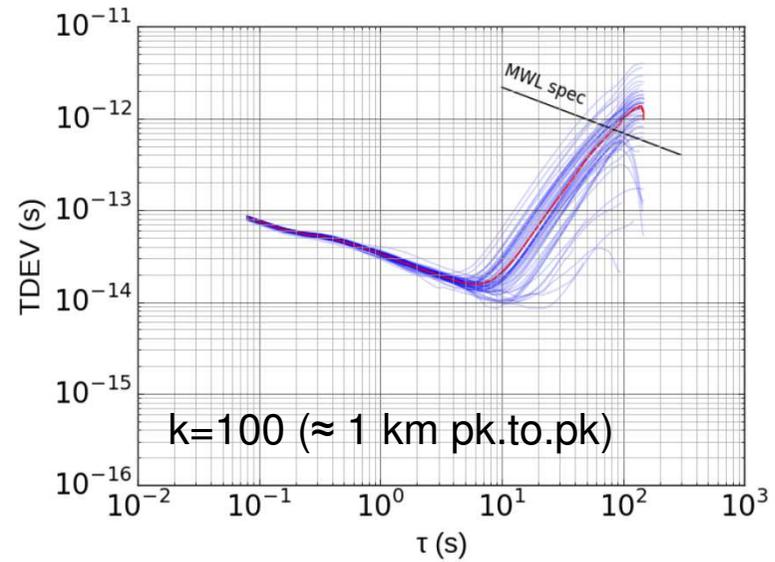
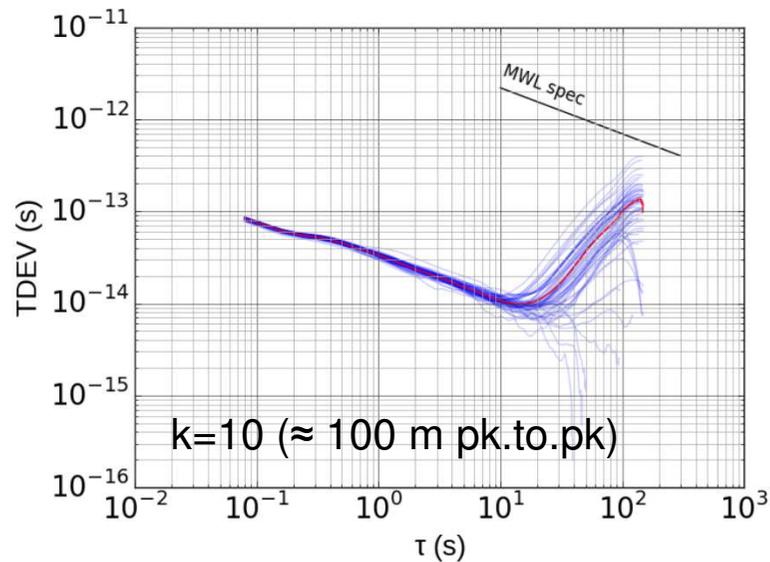
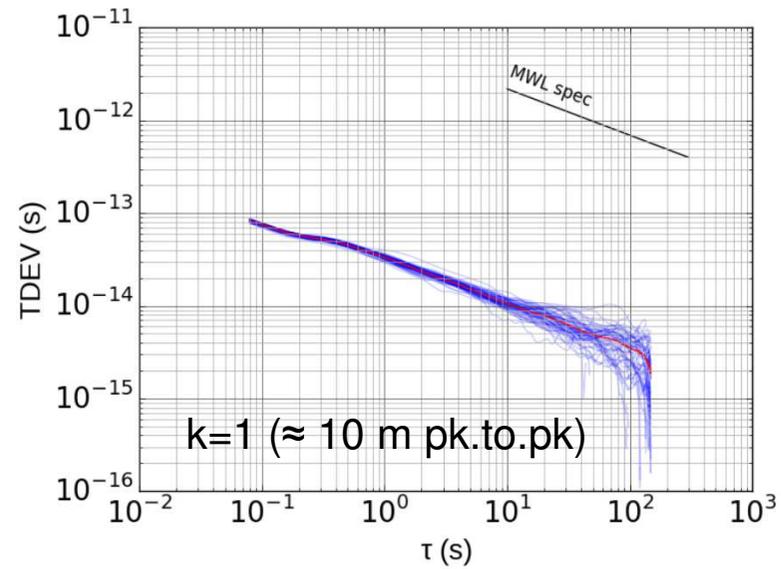
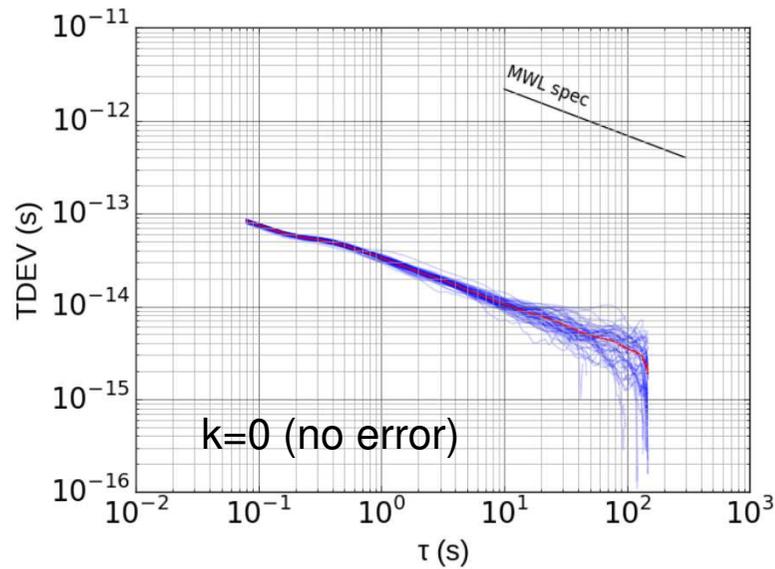
We choose a quiet period (no boost).

Simulation is generated using precise orbitography (POD data).

Then we generate « fake » orbitography as input for data processing (POD +  $k \times$  error)



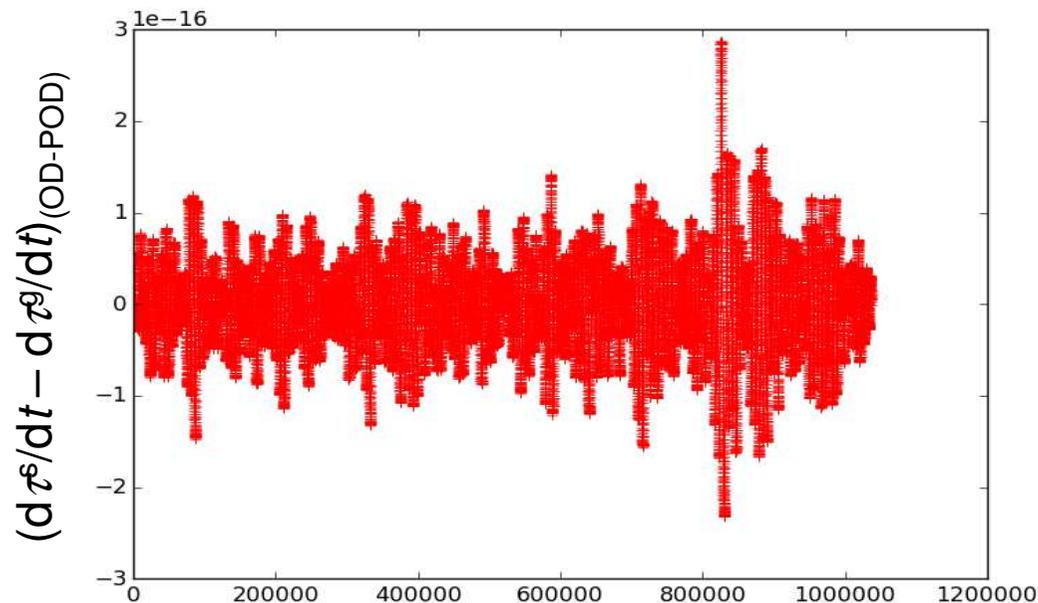
# Effect on two-way link



# Effect on redshift and D2 correction (preliminary)

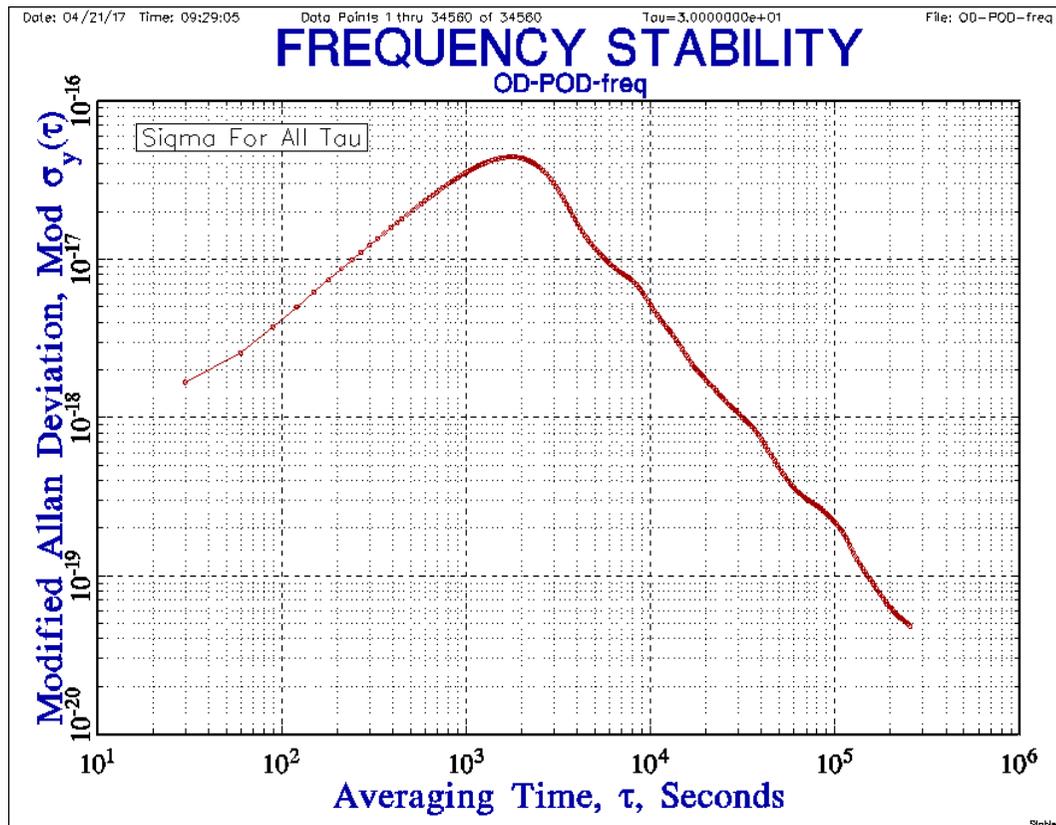
$$\frac{d\tau^{s/g}}{dt}(t) = 1 - \frac{U(\mathbf{x}^{s/g}, t)}{c^2} - \frac{\mathbf{v}^{s/g}(t)^2}{2c^2}$$

- Calculate  $(d\tau^s/dt - d\tau^g/dt)_{OD} - (d\tau^s/dt - d\tau^g/dt)_{POD}$
- Use EGM 2008 for  $U(\mathbf{x}, t)$
- Use full ITRF -> GCRF transformation
- Software has been extensively checked with respect to external source (thank you Anja). Several bugs corrected!



k=1 ( $\approx 10$  m pk.to.pk)

# Effect on redshift and D2 correction (preliminary)



$k=1$  ( $\approx 10$  m pk.to.pk)

- Frequency offset (average over 12 days)  $< 10^{-18}$  !
- Well within specs!
- Duchayne et al. 2009 were a little optimistic for effect on link, pessimistic for effect on redshift and D2 correction.

# Preparation for gravitational redshift test

Data analyzed: difference between experimental and theoretical values (closer to 0)

Model adjusted: gravitational redshift deviation + initial desynchronization

$$\Delta\tau(t) - \int_{t_0}^t \frac{\Delta U}{c^2} dt - \int_{t_0}^t \frac{\Delta v^2}{2c^2} dt = \alpha \int_{t_0}^t \frac{\Delta U}{c^2} dt + \Delta\tau(t_0)$$

- $(t,x)$  taken as the **GCRS spacetime coordinates** (Earth centered, non-rotating)
  - experimental data: every 80 ms, only when ISS in sight (<5 min duration passes)
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- Fit  $\alpha$  and an offset per station
  - Software implemented in Python and tested. Operational for several stations.
  - In current version we add white frequency clock noise only.
  - Allows ordinary least squares within Monte Carlo routine in time or frequency domain.

# Next steps

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- Tie up some remaining issues on main analysis software (Ku - S band antenna offset, dispersive troposphere correction, ...).
- Implement realistic noise in simulation software.
- Fully implement analysis for redshift test: colored noise, all realistic error sources, long term analysis (> 20 days) with several ground stations (up to 9), other analysis techniques (Bayesian, MCMC, ...).
- Pray for some real data from MWL hardware (e.g. from end to end MWL ground tests) for checks.
- Prepare interface with CADMOS for data exchange – ongoing.
- Prepare interface with scientific community (data server, web-site, etc...) – activity just started.



# Summary and Conclusion

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- We are capable of analyzing large amounts of data (> 10 days) with full carrier ambiguity resolution and all expected perturbations.
  - Some minor items still to be included.
  - We can provide test data to interested parties.
  - We are hoping for some real data from the MWL hardware !!!!
  - Interface with CADMOS and science users is being set up.
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- We have carried out tests on effect of orbit uncertainties confirming (so far) that orbit errors of  $\approx 10$  m (expected from DLR analysis) have negligible influence.
  - A full demonstration on main science objective (redshift test) is ongoing.