Human Spaceflight
SPACE FOR LIFE

ACES: ATOMIC CLOCK ENSEMBLE IN SPACE

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For ELT DS______________________________ __________

Signature Date

1. INTRODUCTION

1.1. SCOPE

This document describes the data format and file names, which are exchanged between the SLR tracking stations and the ELT Data Center during ELT operation. It explains the measurement principle and the resulting actions that must be taken at the ground stations to allow for a successful tracking of the ISS with optimal time synchronization between the clock system on the ACES module and the clocks on ground. This document **does not** describe the actions taken by the ground stations to fulfill the laser safety regulations.

1.2. PURPOSE

This document informs the management of the SLR ground stations about the actions that must be taken to successfully range to the ELT detector on-board of the ACES module mounted on the ISS.

1.3. DOCUMENTS

RD-01: CAD-CI-CE2311-4469-CNS
RD-02: Consolidated Laser Ranging Data Format (CRD) Version 2.01
RD-03: Consolidated Laser Ranging Prediction Format Version 2.00

2. ELT ON ACES

The European Laser Timing (ELT) Experiment will allow synchronization of ground clocks with the Atomic Clock Ensemble in Space (ACES). The synchronization works with short laser pulses with a wavelength of 532 +/-0.1 nm, as usually used in Satellite Laser Ranging (SLR). The measurement principle is a combination of the typical two-way ranging, in which laser pulses are send to satellites equipped with retroreflectors and the echo detected again on ground. This is a time of flight measurement, where the range is extracted. On board the ACES module, a single photon avalanche photodetector (SPAD) registers the arrival times of part of the laser pulse. The clock desynchronization is the difference between the time of reflection in the ground time scale and the time of detection in the ACES time scale. The detector on-board is gated regularly 10 to 100 times a second according to the ACES time scale and is active until a noise or a laser photon triggers the avalanche process. Since the background noise of the ELT detector is very high at daytime, the gate window may not remain open for longer than 100 ns. This fact makes a highly accurate determination of the laser pulse transmit epoch (laser trigger epoch) necessary. For the determination of the laser fire time also the ACES onboard clock drift and the ACES orbit have to be taken into account to successfully perform a time transfer (see Section 4).

3. THE ELT DATA CENTER

The ELT Data Center is responsible for the data processing, the coordination between ESA and the ground stations as well as the organization of the exchange of data. For this purpose, the ELT Data Center has a close cooperation with the Eurolas Data Center (EDC) of the International Laser Ranging Service (ILRS). The data products delivered by the SLR stations will be collected by EDC. Therefore, the stations connect to EDC as usual. The ISS predictions in cpf format will be available on the EDC server as well. Stations that would like to participate in ELT will receive a separate account to the EDC prediction server. EDC further distributes the data to ESA and the ELT Data Center. You can contact the ELT DC via the following e-mail: elt@sgd.lrg.tum.de

4. DATA EXCHANGE BETWEEN STATIONS AND ELT DATA CENTER AND FORMATS

ACES RANGING DATA

SLR typically produces two data products on a regular basis. One is the so called fullrate data product, a collection of all returns measured to one satellite within one pass. This file records the laser firing epoch together with the time of flight until the laser pulse is registered again on the station. The second data format is a collection of normal points. The measurements are already bundled here, which makes orbit determination more convenient. The EDC collects these two data formats together with a third one. For time transfer not only the laser fire epochs, where also returns are registered on ground are of interest, but all other fire epochs, too. It is possible that returns will be detected in space while no photons were registered on ground. The ILRS has developed the data format called ff2 for that purpose.

Stations that would like to participate in ACES must therefore provide the two ranging data files: full-rate (fr2) and all laser-fire times (ff2).

The naming of the files should be handled according to the conventions used in the ILRS:
The ILRS document **RD-02** describes the data format used for data exchange.

ACES PREDICTION DATA

The SLR stations need to know the position of the object in order to track it in advance. The orbit information is provided in the consolidated laser ranging prediction format (cpf). The description of the data format can be found in the ILRS document **RD-03**. The file is named in the following way:

aces_cpf_ yymmdd_nnnvv.src

- aces: mission id
- _: delimiter
- cpf: data type/format
- _: delimiter
- yy: year of observation epoch start time
- mm: month of observation epoch start time
- dd: day of observation epoch start time
- _: delimiter
- nnn: ephemeris version number.
- vv: version number within the day.
- .: delimiter
- src: prediction provider code, 3 characters long

The accuracy of the predictions directly influences the possibility of the SLR stations hitting the gate window of the on-board detector. For this reason, ESA provides a prediction of the ISS every 90 minutes. It is the responsibility of the stations to use the newest predictions available.

For transponder missions such as ELT, an additional header entry is foreseen in the prediction format. Header H4 delivers the offset and drift of the on-board clock. As the gate opens in the ACES time scale and the stations usually operate in UTC(k), the two time scales have to be converted to each other. Due to the Theory of Relativity, a moving clock not located on the geoid will drift away from UTC(k). With the two parameters offset and drift, a conversion between the two time scales can be performed with the necessary accuracy. The ELT Data Center determines offset and drift by calculating the relativistic effects along the predicted orbit of the ISS. The convention is to use the parameters in the form of equation 1.

$$t_{UTC(k)} = t_{ACES} + (t_{ACES} - t_0) \cdot 10^{-15} \cdot drift + offset, \quad (1)$$

with t_{UTC} time in UTC, t_{ACES} ACES time, t_0 time for which offset and drift are determined.

Header 4:

Header type 4 Transponder information
1-2 A2 Record Type (= "H4")
F12.5 Pulse Repetition Frequency (PRF) in Hz
F10.4 Transponder transmit delay in microseconds
F11.2 Transponder UTC offset in microseconds
F11.2 Transponder Oscillator Drift in parts in 1015
F20.12 Transponder Clock Reference Time (seconds, scaled or unscaled)

Important for each participating station is to know an estimate of UTC(k) to UTC.

5. SAFETY FIRST

Docking manoeuvers regularly take place on the ISS when another crew or equipment is brought on board. As laser light may disturb the docking, tracking is not allowed while these manoeuvers happen. A go/nogo flag is used to handle this issue. It is the responsibility of the station to retrieve the flag from EDC right before tracking a pass of the ISS. The validity of the flag is 5 minutes, so if requested just before the start of a pass the flag will be valid for the whole pass and a new retrieve is not necessary. The file name of the go/nogo flag is

aces.gng.

Data format example for ICESAT:

ICESAT 0300201 8201 0 nogo 20110221T114350

The go/nogo file is distributed by the EDC in the same way as the prediction data.

6. HANDLING OF TIME AT THE STATION

The stations have to control different parameters on ground in order to be able to hit the gate window on the detector in space. First of all the time offset of ACES to UTC (see section 4) and the time offset of the station itself to UTC. With GNSS time synchronization an accuracy of about 10 ns is possible. The stations should aim at such an accuracy. While the gate on-board will open 100 times a second maximum, kilohertz two-way ranging is welcome, as this makes the adjustment of the orbit more relaxed. A maximum repetition rate is a matter of laser safety (treated separately). For the 100 Hz one-way measurements, the fire epoch has to be calculated according to the orbit prediction, the UTC offsets, the laser delay times within the atmosphere calibration factors, and delays of the laser to the fire event, if necessary. In addition, a calibration of the one-way delay of the laser pulse at the station should be foreseen. A discussion with Ivan Prochazka or Jan Kodet on that topic may be helpful (ivan.prochazka@fjfi.cvut.cz, jan.kodet@tum.de).

The most critical part for hitting the range gate at the ELT detector on ACES is the accuracy of the predictions. Even predictions prepared every 90 minutes may be too bad to allow ranging at daytime. Therefore, an analysis of the two-way ranges for a time bias of the ISS is advisable when firing the laser. We recommend using real-time sharing of time biases so that the information of prediction uncertainty can be disseminated within the community.
To access all available status messages, connect to AIULI3.UNIBE.CH port 7810 with, e.g., TELNET command:

```
telnet aiuli3.unibe.ch 7810
```

Example:

```
---------------------------------------------------------------------------------
--
Graz 2008-01-24 15:24:10 Lageos2 CUR 11k HTS5241 0.000
Zimmerwald 2008-01-24 15:24:00 DWN
Yarragadee 2008-01-24 15:24:07 Calibrate CUR 391
Potsdam-3 2008-01-24 15:24:01 OUT
Wettzell 2008-01-24 15:24:05 BeaconC CUR 0 HTS5231 0.000
San_Fernando 2008-01-24 15:24:12 Calibrate LST 871
MLRO-Matera 2008-01-24 15:23:45 BeaconC CUR 213 SGF5241 0.000
Herstmonceux 2008-01-24 15:24:15 Lageos2 CUR 642 SGF5241 0.000
```

In a first tracking experiment, we had along track errors of 13m, which would correspond to a timing error of 50ns. This is equivalent to half the gate window on the ISS at daytime.

In order to make optimal use out of time synchronization, a common clock experiment with GNSS time transfer should be aimed at. For such experiments, distributing time on calibrated cables is mandatory.

If a high precision clock is available on the station or a connection via optical fiber to an optical clock or another frequency normal is foreseen, a file has to be send to EDC, which compares the frequency between the local oscillator connected to the event timer and the precise clock together with a configuration file.
The file format is described below:

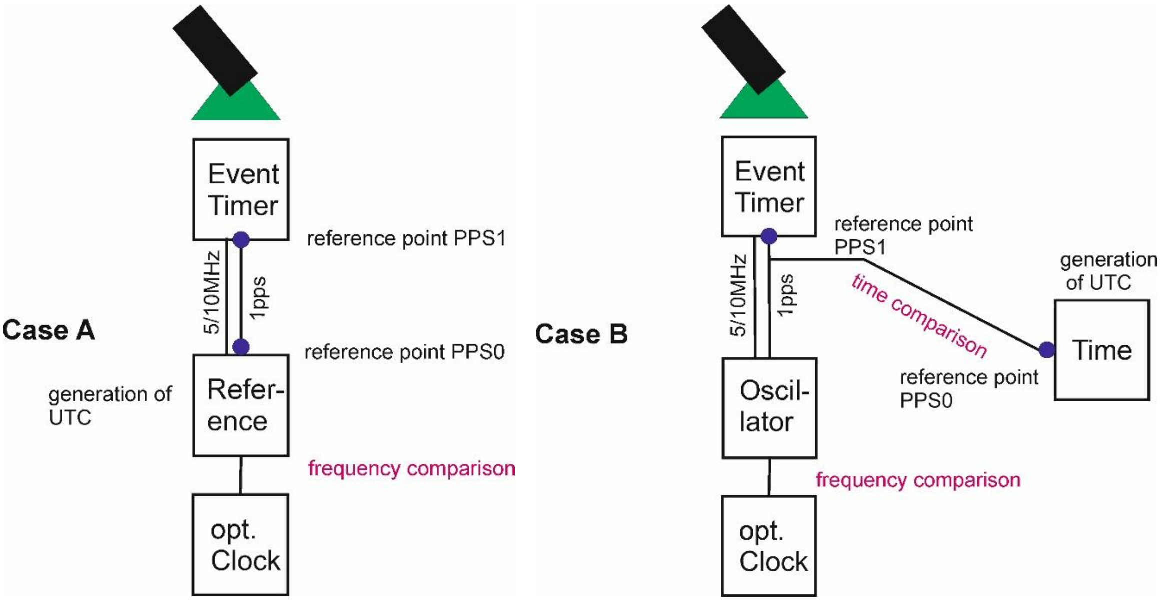
6.1. CLOCK STATUS FILES

The exchange of clock status files is in accordance with ACES-TN-SYRTE-SB-001-1 issue 1 revision 2 explaining the situation for the microwave link (MWL). Small changes take care of special circumstances related to ELT. The clock status files include a configuration file and one or more frequency comparison files between the available highly accurate clocks and the UTC reference. These clocks can be Cesium and Rubidium fountain clocks or optical clocks.

Two cases of connecting a clock to the SLR stations have to be distinguished:

Case A: the eventtimer is directly connected to reference UTC and an additional optical clock is placed into the timing system

Case B: the eventtimer is connected to an oscillator not representing local UTC and an additional optical clock is placed into the timing system



6.1.1. CLOCK CONFIGURATION FILE

The clock configuration file keeps data, which will not change often and should be exchanged only when a change in the configuration occurs.

6.1.1.1. CLOCK CONFIGURATION FILE CONTENT

Parameter	Description
applicability_start	Date at which those parameters come into effect
station_id	CDP Pad Identifier
code_type	String specifying wether the following code is belongs to the official BIPM nomenclature (“BIPM”) or to a customary ACES nomenclature (“ACES”).
instrument_code	4 character instrument identifier
clock_inventory	Holds one or more occurrences of "clock" item
clock	Holds clock identifications data
clock_name	String used to identify a particular clock (left to the laboratory’s choice, only constraint is that this identifier is unique within the laboratory
clock_code_type	Denotes the type of clock. string chosen among the following list : Cs_Fountain / Rb_Fountain / Opt_Neutral / Opt_Ion / MW_Ion / Opt_Res / MW_Res / Other. In this last case, a "comment" field should be open to specify the type of clock.
clock_code	6 digit code unique for each clock at the station.
timeref	Holds the characteristics of the time reference
timeref_is_utck	boolean. True = "Case A", False = "Case B" (in case A the oscillator at the eventtimer is identical to the UTCk reference in case B the reference oscillator is independent from the UTC reference)
timescale_type	May be "BIPM_UTCk", "BIPM_TAk", or "ACES".
timescale_code	If timescale_type is "BIPM_UTCk" or "BIPM_TAk", this string should match the BIPM identifier of the timescale.
oscillator	Type of device, may be H-Maser / Cs / BVA / MW_res / Opt_Res
PPS0_delay_ns	Value of the delay between the UTC reference point and the Eventtimer reference point, in ns
PPS0_uA_ns	uncertainty on the previous value, in ns.
PPS1_delay_ns	If timeref_is_utck = False (i.e. case B): value of the delay between the UTCk reference point and the lab’s reference point
PPS1_uB_ns	If timeref_is_utck = False (i.e. case B): uncertainty on the previous value, in ns.

Parameter	Description
PPS2_delay_ns	The one-way calibration delay, bringing UTCk to the telescope reference point.
PPS2_u1way_ns	Uncertainty of the above parameter
station_pos_ITRF	holds the value and uncertainty of x, y and z coordinates for the station position in meters, ref frame : ITRF2008
timescale_pos_ITRF	holds the value and uncertainty of x, y and z coordinates for the timescale device in meters, ref frame : ITRF2008
time_transfer_capacity	holds an arbitrary number of time_transfer_device
time_transfer_device	Holds the characteristics of available time transfer devices
ttdev_type	Type of time transfer device, may be GNSS / TWSFT / ELT / Fiber / Other
ttdev_name	Identifier (should allow to find the corresponding files).
contact	Holds contact information
name	Contact full name
email	Contact's email address
phone	Contact's phone number (in international format)
comments	Free form string

- Volume: File size is ~10kB per station (15 participating SLR stations assumed at ACES end of mission)
- Format: see below
- Filenaming: see below

6.1.1.2. CLOCK CONFIGURATION FILE NAMING

Product	Clock configuration file
CI-No.	
Format	XML
Sampling Rate	N/A
Data Coverage	N/A
Update Rate	With change
File Naming	File naming: ssss_clock_config_yyyymmdd.xml • ssss is the CDP Pad Identifier (station id)

	• yyyymmdd is the start date of file ○ yyyy year ○ mm month ○ dd date

Examples:

`1893_clock_config_yyyymmdd.xml`


```
<? xml version = "1.0" encoding = "UTF−8" stand alone = “Yes” ?>

< elt: lab_config >

    < applicability_start  > 2013−06−19 </ applicability_start >
    <!−−<applicability_end> 2021−01−01 </ applicability_end >−−>

    < lab_id >
        < code_type > ACES </ code_type >
        < lab_code > 8834 </ lab_code >
    </ lab_id >

    < clock_inventory >
        < clock >
            < clock_name > SOC2 </clock_name >
            < clock_code_type > Sr-clock </ clock_code_type >
            < clock_code > 883401 </ clock_code >
        </ clock >

        < clock >
            < clock_name > FO2Rb </ clock_name >
            < clock_code_type > Rb_Fountain </ clock_code_type >
            < clock_code > 0803 </ clock_code >
        </ clock >
    </ clock_inventory >

    < timeref >
        < timeref_is_utck > false </ timeref_is_utck >
        < timescale_type > BIPM_UTCk </ timescale_type >
        < timescale_code > 08 </ timescale_code >
        < oscillator > Hmaser </ oscillator >
        < PPS0_delay_ns > 60.0 </ PPS0_delay_ns >
        < PPS0_uA_ns > 0.010 </ PPS0_uA_ns >
        < PPS1_delay_ns > 1200.0 </ PPS1_delay_ns >
        < PPS1_uB_ns > 0.020 </ PPS1_uB_ns >
        < PPS2_delay_ns > 120.0 </ PPS2_delay_ns >
        < PPS2_u1way_ns > 0.020 </ PPS2_u1way_ns >
        < station_pos_ITRF >
            < x_m > 0.0 </ x_m >
            < x_unc_m > 0.0 </ x_unc_m >
```

```
                    < y_m > 0.0 </ y_m >
                    < y_unc_m > 0.0 </ y_unc_m >
                    < z_m > 0.0 </ z_m >
                    < z_unc_m > 0.0 </ z_unc_m >
            </ station_pos_ITRF >
            < timescale_pos_ITRF >
                    < x_m > 0.0 </ x_m >
                    < x_unc_m > 0.0 </ x_unc_m >
                    < y_m > 0.0 </ y_m >
                    < y_unc_m > 0.0 </ y_unc_m >
                    < z_m > 0.0 </ z_m >
                    < z_unc_m > 0.0 </ z_unc_m >
            </ timescale_pos_ITRF >
    </ timeref >

    < time_transfer_capacity >
            < time_transfer_device >
                    < ttdev_type > GNSS </ ttdev_type >
                    < ttdev_name > OPMT </ ttdev_name >
            </ time_transfer_device >
    </ time_transfer_capacity>

    < contact >
            < name > Jan Kodet </ name >
            < email > jan.kodet@tum.de </ email >
            < phone > +49 9941 603118 </ phone >
    </ contact >

    < comments />

</ elt: lab_config >
```


6.1.2. CLOCK FREQUENCY COMPARISON

The clock frequency comparison file keeps data, which are necessary for the time transfer product and should be exchanged once a day.

6.1.2.1. CLOCK FREQUENCY COMPARISON FILE CONTENT

The file containing the frequency comparisons between the clocks consists of a header defining the clock which frequency is compared to the UTC(k) reference clock. The header lines begin with a "# " and the value is assigned by an " = ".

Header:

Parameter	Description
station_id	4 digits station id (like 8834)

Parameter	Description
clock_code-ITRF	A four digit number identifying the clock
clock_name	Name of the clock.
u_A(ref)	Uncertainty of the frequency of the reference utc clock
u_B(ref)	Uncertainty of the frequency of the reference oscillator on the eventtimer in case B, where the reference oscillator is not representing UTCk
u_link	Uncertainty of the link = noise contribution of the link
x_pos_ITRF,y_pos_ITRF,z_pos ITRF and x_unc_ITRF, y_unc_ITRF, z_unc_ITRF	ITRF positions of the clock with its uncertainties
redshift	Redshift
uncertainty	Uncertainty of the redshift
nu_ref	Frequency of the clock
u_nu_ref	Uncertainty of the frequency of the clock

Body:

Each line contains the following parameters separated by a blank:

1. The UTC date as a MJD (float, 6 digits precision)
2. The UTC date as a gregorian date (YYYY/MM/DD)
3. The UTC time of day (HH:MM:SS)
4. The frequency differences between the clock and the time reference
5. The confidence level of this data point (int):
    - Level 0 : discarded data.
    - Level 1 : experimental data.
    - Level 2 : operationnal data.
    - Level 3 : validated data.

- Volume: File size is ~1MB per station per day (15 participating SLR stations assumed at ACES end of mission)
- Format: see below
- Filenaming: see below

6.1.2.1.1. CLOCK FREQUENCY COMPARISON FILE NAMING

Product	Clock frequency comparison file
CI-No.	

Format	ASCII
Sampling Rate	N/A
Data Coverage	N/A
Update Rate	On a daily bases, if clock is available

File Naming	File naming: ssss_clockid_frequcomp_yyyymmdd.txt
	• ssss is the CDP Pad Identifier (station id)
	• clockid as listed in the configuration file with 6 digits
	• yyyymmdd is the start date of file
	  ○ yyyy year
	  ○ mm month
	  ○ dd date

Example of file names:

```
1893_189301_frequcomp_yyyymmdd.txt
8834_883401_frequcomp_yyyymmdd.txt
```

Example of file content:

```
# station id = 8834
# clock_code = 883401
# clock_name = SOC2
# u_B(ref) = 3.3E-16
# u_A(ref) at 1s = 4E-14
# u_link = 0.000
# x_pos_ITRF = 0.000
# x_unc_ITRF = 0.000
# y_pos_ITRF = 0.000
# y_unc_ITRF = 0.000
# z_pos_ITRF = 0.000
# z_unc_ITRF = 0.000
# redshift = - 65.4E-16
# uncertainty = 1E-16
# nu_ref : 6 834 682 610.904 312 Hz
# u_nu_ref : 1.3E-15
56433.76152 2013/05/21 18:16:35 9.543E-16 2
56433.76163 2013/05/21 18:16:45 9.60912E-16 2
56433.76175 2013/05/21 18:16:55 -3.15198E-15 2
56433.76186 2013/05/21 18:17:05 -1.76456E-15 2
```

7. LINK BUDGET CONSIDERATIONS

The accuracy of the ELT experiment depends on the station to maintain the single photon mode on the ISS. To make one-way and two-way tracking in the optical possible, the on-board detector is diminishing the laser intensity by a factor of $1x10^7$. Even with this high attenuation, the one-way ranging may not be in single photon mode. The attenuation is tuned such that a single photon ranging in the two-way measurements will result in a single photon ranging at the ISS. Thus, ensuring a signal photon mode on ground will result in a single photon mode in space, when performing the attenuation of the laser beam rather at the outgoing than on the incoming branch. The tuning of the system parameters can also be performed to measurements to Swarm, GRACE-FO, TerraSar or TandemX, as they all have the same reflector array and are in comparable orbit heights.

8. ISSUE WITH MULTI-RETROREFLECTORS ON ISS

For docking manoeuvers, the ISS has installed retroreflectors on many positions. Some of these reflectors will also reflect photons coming from ground. Ranging to the ISS will result in more than one trace on the range gate window. Albeit, the trace of the ACES reflector should be dominant in the O-C window, any automated algorithm to extract the echoes from the ELT reflector returns may not be extracting the right returns. The ELT Data Center provides a piece of software based on Matlab or Octave for extracting the returns of the ELT reflector. If this cannot be implemented in your ranging software, please ensure that you are sending unfiltered fullrate data to the Data Center, where all returns are captured. We can also provide an algorithm for extracting the returns so you can implement this feature your own. Please contact the ELT Data Center for more information (anja.schlicht@tum.de).

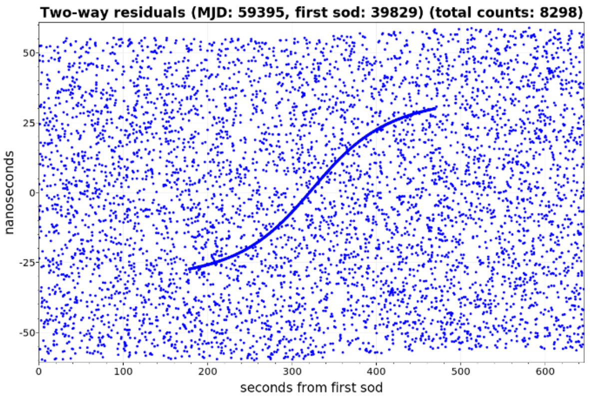
9. QUICK-LOOK RESPONSE FROM ELT DATA CENTER

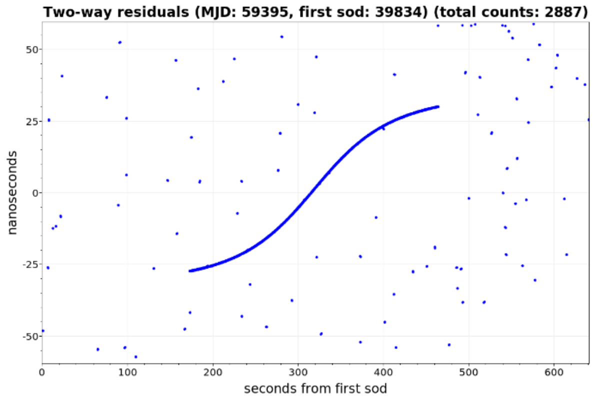
The tracking station do not get an immediate response from ACES if they managed to hit the gate window of the onboard single photon detector. To give the station operators the possibility to correct for desynchronization sources, the Data Center will analyze the data as soon as one-way data is downloaded from the ISS and the two-way measurements are available from the stations. So please send the crd data files as soon as possible to EDC. This analysis is preliminary and only serves as a quick-look on the data. The operator can see if you managed to hit the gate at all, if the return rate is much too high, if the full pass is tracked and if the analysis we did is correct. The communication between the Data Center and the stations observer is via email. The stations should inform the Data Center about the relevant mail address. The address of the Data Center is elt@sgd.lrg.tum.de .

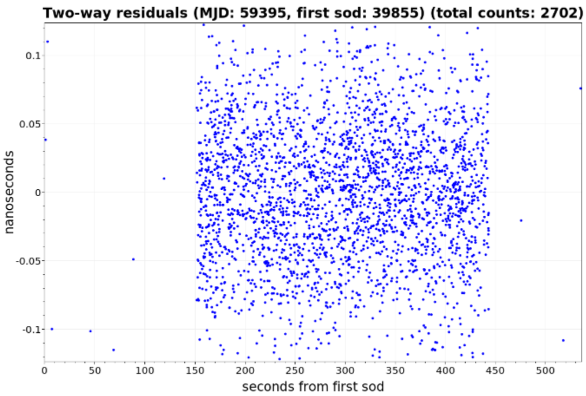
The processing report will look like this:

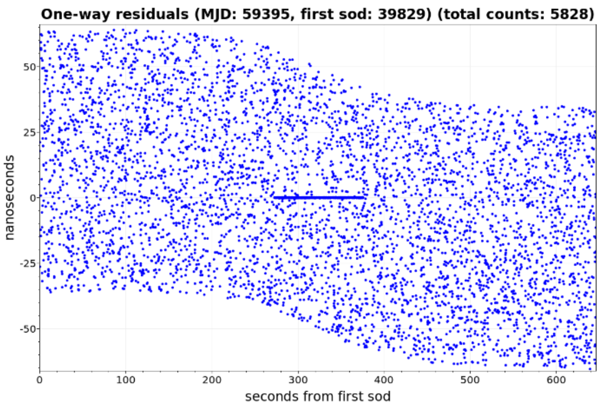
```
Dear ELT participant,

thank you for sending your measurements rapidly.
In a quick-look analysis we estimated
the mean time offset to ACES as: 14.6ps
the standard deviation as: 36.0ps

Kind regards,
the ELT-DC team
```

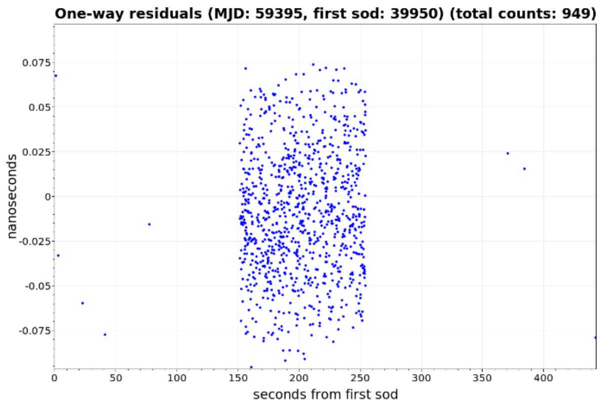
The appended zip-file contains all the plots of the analysis:

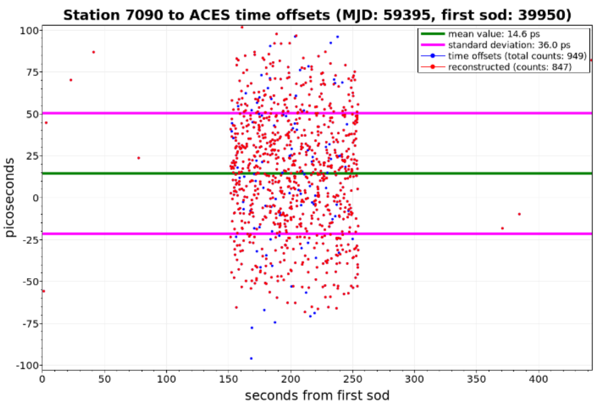












The first row shows the analysis of the two-way data from the residual plot (left side) to the first filtering (right side). In the next row on the left, the residuals of extracted two-way returns with respect to an adjusted short-arc orbit are shown. The third row of figures shows the steps of the data analysis of the one-way data from the residual plot (left side) to the detected returns (right side). The figure in the last row shows the analysis of the time transfer. The real triplets are plotted in blue. In this case the start epoch is available together with the one-way and the corresponding two-way return. In red color, the so called reconstructed triplets are shown. In this case only the start epoch and the corresponding one-way return are available. The missing two-way returns are estimated by the short-arc estimation of the orbit.