ELT Data Processing –
about Noise, Calibration Capability and Synergies

Anja Schlicht, Christoph Bamann, Stefan Marz, Ulrich Schreiber
Technical University Munich

Ivan Prochazka
Technical University Prague
ELT Data Processing – about Noise, Calibration Capability and Synergies

1. European Laser Timing: Measurement principle and data analysis
2. Complications I: due to ISS
3. Complications II: Complexity of the measurement on ground
4. Comparison: ELT versus MWL
5. Synergies: ELT and microwave techniques
Measurement principle

Optical link, pulsed

ACES/ELT

t\text{start}_1 \quad \text{calibration} \quad t\text{stop}_1 \quad t\text{stop}_2

Ground station
Measurement principle

Principle of ELT (optical link, pulsed)

- One way:
  \[ \text{tof}_{1W} = R_{CoM} + \tau_{troposphere} + \tau_{Sagnac} + \tau_{Shapiro} + \tau_{attitudeDetector} \]

- Round trip:
  \[ \text{tof}_{2W} = 2 \times (R_{CoM} + \tau_{troposphere} + \tau_{Shapiro} + \tau_{attitudeReflector}) + \tau_{Reflector} \]

  with \( R_{CoM} \): Distance between spacecraft CoM and station reference point

- Time transfer:
  \[ \tau = \frac{t_{return} + t_{start}}{2} - t_{detector} \]
  \[ \tau_{corr} = \frac{\text{tof}_{2W}}{2} + t_{start} - t_{detector} + \tau_{corr} \]
Round-trip measurements
One-way measurements

Unfiltered data

Filtered data for $N \geq N_t = 1$

Histogram of filtered residuals according to $2.2\sigma$ (00)

Filtered residuals according to $2.2\sigma$ (00)
Time transfer

Station to ACES time offsets (00)

- Station to ACES time offsets
- reconstructed
- mean value: -5.3 ps
- standard deviation: 36.4 ps

picoseconds

seconds of day

-100 -50 0 50 100
Multireflector problem

<table>
<thead>
<tr>
<th>Name</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEM LRR Hemi A</td>
<td>10.878</td>
<td>-5.448</td>
<td>7.021</td>
</tr>
<tr>
<td>JEM LRR Hemi B</td>
<td>10.876</td>
<td>-6.092</td>
<td>7.017</td>
</tr>
<tr>
<td>IDA 1 Hemi B (a)</td>
<td>15.789</td>
<td>0.891</td>
<td>6.239</td>
</tr>
<tr>
<td>C2V2 S3 Forward Antenna Boom Hemi (c)</td>
<td>1.524</td>
<td>22.887</td>
<td>-1.417</td>
</tr>
<tr>
<td>C2V2 P3 Nadir Antenna Boom Hemi (c)</td>
<td>-2.621</td>
<td>-22.887</td>
<td>-0.978</td>
</tr>
</tbody>
</table>
Multireflector problem

For reflectors $i = 0 \ldots N$ with distances $d_i \leq d_{i+1}$ with respect to the observer the probability of detecting a signal is:

$$p_{i,\text{eff}} = p_i \prod_{j=0}^{i-1} (1 - p_j)$$

The single-reflector probabilities $p_i$ may account for differences in the effective cross section among the reflectors.

With a constant background noise rate, the noise statistics follows an exponential distribution in single photon mode:

$$p_{\text{signal},i} = p_{\text{eff},i} e^{-n_{\text{noise}} \Delta t_i}$$
Detector identification

Simulation: Two-way range residuals - time series (00)

Timebias calculation
Complexity of ELT for ground stations
ACES clock prediction

Clock correction difference for satellite between real and predicted data
New noise reduction algorithm

\[ P_{s > thr} = \sum_{m=N_t}^{\infty} p_{\text{binomial}, n+s}(m) \]

\[ P_{n+s}(T_x) = 1 - \exp \left[ -(n_n T_x + N_s) \right] \]

\[ p_{\text{binomial}, n+s}(m) = \frac{y!}{m!(y - m)!} P_{n+s}(T_x)^m (1 - P_{n+s}(T_x))^{y-m} \]

\[ P_{n>thr} = \sum_{m=N_t}^{\infty} p_{\text{binomial}, n}(m) \]

\[ P_n(T_x) = 1 - \exp \left[ -n_n T_x \right] \]

\[ p_{\text{binomial}, n}(m) = \frac{y!}{m!(y - m)!} P_n(T_x)^m (1 - P_n(T_x))^{y-m} \]
New noise reduction algorithm

Unfiltered data for $1 \times 10^7$ noise rate/s

Filtered data for $T_x = 1.6$ and $T_y = 0.5$

Filtered data for $T_x = 1$ and $T_y = 1$

Filtered data for $T_x = 2.8$ and $T_y = 0.5$
Simulation capability

Geometric components
- ISS attitude simulation (3 axes, constant offsets and oscillations)
- Detector and multi reflector positions
- Intra-reflector delay (function of incidence angle)
- Visibility constraints (minimum elevation, clouds)
- Tidal motion and atmospheric loading

Stochastic components
- Background noise
- Laser Jitter
- Pulse width
- Clock noise and offsets
- (Fluctuations in the troposphere)
Clock simulation

Frequency stability of PHARAO and SHM
Comparison with MWL

ELT:

- Optical -> calibration -> 50 ps accuracy
- no wet tropospheric delay
- Time tagging of events -> jitter per detection
- pulse length 10 ps / 1 kHz -> 4 ps @ 300s
  7ps @ 1 d

MWL:

- Microwave -> no calibration -> 100 ps accuracy
- wet tropospheric delay
- Phase locked loop -> jitter per contact
- 100 Mchip/s / 14 GHz -> 230 fs @ 300s
  8 ps @ 1 d
Calibration

Calibration Device

Detector SPAD

Cable

NPET epoch timing

Common epoch “1pps”;
identical cable
common clock frequency
Calibration of MWL

⇒ Calibration of MWL for time transfer and ranging
⇒ Troposphere
⇒ Short arc orbit adjustment
⇒ Systematic effects
⇒ Try a common parameter estimation and compare to time transfer in Lambda configuration
Calibration of GNSS links

⇒ Calibration of GNSS receiver
⇒ T2L2 only in common-view
⇒ ELT now also in non-common-view
Conclusions

ELT Data Center delivers the following products:

Space to ground clock comparison

Ground to ground clock comparison in common-view

Ground to ground clock comparison in non-common-view

MWL calibration