ACES – ELT laser link performance and ps accuracy optical time transfer

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Outline

- Optical time transfer capabilities on photon counting level
- ELT detector package EM tests
- ELT timing properties
- Single photon Two Way Time Transfer
- Possible future applications
- Conclusions
WHY Single photon in metrology ?
Not just „.. higher sensitivity ..“

- quantum nature of light = > two states detected 0 / 1
- NO analog signal processing = > NO systematic errors
- Extremely weak signals = > High dynamical range
- Measurement by-products
  optical signal intensity
  signal shape
  measurement precision ~ N^{-1/2}
  = > sub-ps precision, ps accuracy and ps stability
- Space qualified devices existing – see next ...
  T2L2 space segment, OCA Grasse, GNSS network,..
Photon Counting Approach Limitations

- Background photon flux, Sun, Earth albedo, etc…
- Large data volumes
- Complex data processing
- All items solvable (operational missions > 6 yrs)
European Laser Timing ELT-ACES
Detector EM assembly and tests

Detector EM assembly in CTU labs 2011

Detector package EM
500 grams
0.6 Watt

Flying unit FM nearly complete 2013
Detection delay LONG TERM STABILITY

Sub-ps timing

< +/- 1 ps
In 3 days
Entire chain

Laser Start ELT detector
ELT Detection delay LONG TERM STABILITY

ELT EM Time stability
Entire chain Laser+Start+NPET+ELT EM

100 Hz, 8%, 3 days span +/- 1 kHz

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ESA specs

1 ps

< 200 fs/day
Detection delay temperature dependence

- Solid CO² -80° C
- Hot air +70° C

**Graph:**
- Detection delay [ps]
- Internal temperature HK [Celsius]
- Mean slope 0.48 ps/K
- 0.38 ps/K
- 0.75 ps/K
Ground + Space segments delay calibration – demo

- Range 50 …. 250 mm in 6 steps
- Angles +/- 5 to +/-60 degrees
- One day averages

Ground + Space segments delay calibration, indoor test

ELT <=> SLR delay calibration

[Graph showing calibration data with a mean value of 1484.4 ps and accuracy estimate of +/- 3 ps]

Ground "SLR"
SPACE EM
NPET #1 timing NPET #2 timing
Common 10MHz, 1pps

=> ~ 3 ps Accuracy estimate
Detector ELT Background Illumination tests

CONCLUSIONS
- acceptable for the daylight operation, range gate 300 ns (90m) before
- operational (photon counting) under direct Sun exposure (!!!)

Dark count rate
0.4 Mc/s

Pointing to
Sun 45 deg.
white paper, +/- 60°
trees
< 6 Mc/s
< 3 Mc/s
< 1 Mc/s
CONCLUSION # 1 – ELT detector package

- EM device tested, radiation resistant, space qualified, safe for ISS
- FM is being completed

- Detector parameters
  - Jitter < 20 ps rms
  - Delay drift + 480 fs / K
  - Delay stability Tdev ~ 200 fs / day

- System delay calibration schemes designed and tested for both ground and space segments overall ~ 10 ps accuracy expected

- Operational under Solar background flux
  - Earth vegetation < 1 MHz
  - Ideal white surface < 3 MHz
  - Direct Sun exp. < 6 MHz (operational!)
Two Way Time Transfer - Operating Principle

- Resulting time scale difference $DS$
- Propagation delay $DC$

- Electrical coax. cable
- Optical free space

- Prerequisite for ps accuracy
- Symmetry

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- Photon counting approach
  $\Rightarrow$ ultimate accuracy
SINGLE PHOTON OPTICAL TWO-WAY TIME TRANSFER EXPERIMENT
SINGLE PHOTON OPTICAL TWO-WAY TIME TRANSFER

RESULTS

- Histogram of epochs EAx
- Timing resolution < 50 ps rms
- Useful data rate 20-50 readings / s
- Common reference T / F for both scales
- Long term stability test of DS
- +/- 2 ps over two days, +/- 1K

+/- 2 ps in 50 hours
SINGLE PHOTON OPTICAL TWO-WAY TIME TRANSFER
TIME SCALES DIFFERENCE

- Common reference T/F for both scales, +/- 1K
- Recorded at a useful data rate of 20..50 readings/s
- Improvements > 30x are expected for rates up to 1k read./s

< 500 fs @ hours
- the accuracy of time scales difference $DS$ is higher than accuracy of optical path delay $DC$.

- The evaluated $DC$ was equal to optical path length within $1 \text{ mm} / 3 \text{ ps} \ (p-p)$.

- $\Rightarrow$ **TWTT ACCURACY better than 3 ps**
Photon counting two-way time transfer

POSSIBLE APPLICATION # 1

Time scales comparison in (deep) space
Analogy to asynchronous laser transponder

- Small, compact and reliable lasers for space
- Space qualified photon counting receivers
- Optical apertures 20… 100 mm only (in space)
- Laser altimeter hw may be used
- Ground – space **distances up to Jupiter / 9 AU**
- Propagation delays ionosphere + TEC independent (!)
CAPABILITIES OF PHOTON COUNTING
Demonstrated on Satellite Laser Ranging of GNSS satellite, Graz, Austria

Ground to space propagation time, 2kHz rate, ~ 30 000 km

300 fs @ 100 s
Achievements demonstrated 2013:

SLR up to 35,000 km =>
TDEV \( \sim 3 \times 1 \times 10^{-13} \) @ 100 s

Indoor tests of 1 photon TWTT
Stability \( < 5 \times 1 \times 10^{-13} \) @ day

Ground to space time scales comparison
Frequency \( \sim 6 \times 1 \times 10^{-18} \) @ day

There is a space for further improvement \( \sim 2 \ldots 3 \) times
CONCLUSION # 2
Optical Time Transfer based on photon counting

- Photon counting approach provides sub-ps precision, stability and ps accuracy

- **Optical time transfer** (indoor tests)
  - 300 fs precision
  - 500 fs / day stability
  - < 3 ps accuracy

- **Ground to space optical time transfer** (demo via GNSS satellites)
  - 300 fs precision
  - 500 fs / day stability
  - < 10 ps accuracy

- All the components & procedures are available 2013