High repetition rate SLR at GRSM

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Why increasing the repetition rate?

Our motivation: 2 colors measurement at the mm level

\[ 2D = R_{Green} + a (R_{Green} - R_{IR}) \]

=>

It requires an high improvement of the time-of-flight measurement on the both wavelength.
Why increasing the repetition rate?

Limitations:
- Multi corner cubes target
- Timing jitter of SPAD
  $\Rightarrow \sigma_{\text{single-shot}} = 15\, \text{ps}$
- Atmospherical dispersion & spectral width of pulses
  $\Rightarrow$ limit the use of pulse width between 5 ps - 20 ps

Limitations:
- Atmospherical backscattering & turbulence

One solution in single-photon mode:
Try to increase the repetition rate of the measurements to push the TVAR on the left
What is it necessary to implemented?

High repetition rate picosecond laser => 100 MHz HighQ laser

High repetition rate event timer

We have a sub-picosecond STX 301 event timer (purchased now by SigmaWorks) acquired during the T2L2 mission.

- Time Stability @ 1000s: < 20 fs
- Linearity: 0.3 ps rms.
- Thermal Sensit. < 200 fs/°C
- Repeatability error
  - Synchronous: 600 fs rms
  - Random: 700 fs rms
- Rate
  - Dead time: 130 ns
  - Continuous rate 35 kHz
What is it necessary to implemented?

**High repetition rate SPAD**

Collaboration in 2014 with

And with the help of the

Development of two high repetition rate SPAD detections

<table>
<thead>
<tr>
<th>Si-SPAD</th>
<th>InGaAs-SPAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area diameter</td>
<td>100 µm</td>
</tr>
<tr>
<td>Max repetition rate</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Timing jitter</td>
<td>33 ps FWHM</td>
</tr>
<tr>
<td>DCR @ 7 V</td>
<td>74 Hz</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>53% @ 532 nm</td>
</tr>
<tr>
<td>Active area diameter</td>
<td>50 µm</td>
</tr>
<tr>
<td>Max repetition rate</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Timing jitter</td>
<td>76 ps FWHM</td>
</tr>
<tr>
<td>DCR @ 7 V</td>
<td>200 kHz</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>47% @ 1064 nm</td>
</tr>
</tbody>
</table>
Green SPAD @ 1MHz
Green SPAD @ 1MHz

Skew = 1.8 ; Kurtosis = 5.5

Clearly not a Normal distribution !
Green SPAD @ 1MHz

Histogram Green @ 1 MHz

- Dark red: raw data
- Red: after filtering +/- 2.5 sigma

Y-axis: count
X-axis: residuals (fs)
Green SPAD @ 1MHz

Histogram Green @ 1 MHz after +/- 2.5 sigma filtering

Boxplot (median, 25th-75th interquartile)

Probability plot & comparison to Normal distribution
Green SPAD @ 1MHz

TVAR Green @ 1 MHz filtering +/- 2.5 sigma

150 fs @ 0.6 s
IR SPAD @ 100 kHz
IR SPAD @ 100 kHz

Histogram IR @ 100 kHz

Boxplot (median, 25th-75th interquartile)

Probability plot & comparison to Normal distribution

Skewness = 0.9 ; Kurtosis = 4.2
IR SPAD @ 100 kHz

- **Histogram IR @ 100 kHz after filtering +/- 2.5 sigma**

- **Boxplot (median, 25th-75th interquartile)**

- **Probability plot & comparison to Normal distribution after +/- 2.5 sigma filtering**
IR SPAD @ 100 kHz

TVAR IR @ 100 kHz filtering +/- 2.5 sigma

213 fs @ 2s
High repetition rate on a ground-ground link
Laser ranging on a fixed target at a distance of 2.5 km @ 100 kHz at 1064 nm
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm

Modulo $10^7$ fs $\Rightarrow$ 10 ns

Residuals from the non complete extinction of the pulse picker in front of the 100 MHz repetition rate laser
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm

Limitation of the event timer:
130 ns deadtime but limitation due to internal time for the transfer of data and the limited size of the fifo
=> continuous rate 35 kHz max
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm

Maybe pb with the laser lock-in on the external clock
Laser ranging on a fixed corner cube at a distance of 2.5 km @ 100 kHz at 1064 nm

Average wind > 15 m/s (54 km/h)
Conclusion & Perspectives

• We characterized two high repetition rate SPAD working:
  – at 1 MHz in Green
  – at 100 kHz in IR

• We measured a white noise behaviour for our two detection channels in Lab with:
  – 150 fs @ 0.6 s for the green SPAD
  – 213 fs @ 2s for the IR SPAD

• We will have to confirm that high repetition rate laser ranging allow to see the impact of the atmospheric turbulence on the range measurements

• Lot of works in perspective on all the SLR sub-system !!

• A new laser dedicated for SLR should arrive soon !
Thanks for your attention
Motivation

Currently:

$$2D = R_{Green}$$

with

$$R_{Green} = \frac{(t_{return} - t_{start}) \cdot c_0}{n(\lambda, T, P_v, P_a, CO_2)}$$

Unknown parameter

=> uncertainty at the cm level
Motivation

Our objective: 2 colors measurement at the mm level

\[ 2D = R_{Green} + a (R_{Green} - R_{IR}) \]

Correction term => Dispersion effect (due to dry atmosphere)
Improve accuracy in SLR

\[ D = \frac{(t_{\text{arrival}} - t_{\text{depart}})}{2}.c \]

avec

\[ c = \frac{c_0}{n(\lambda, T, P_v, P_a, CO_2)} \]

Idea of 2 colors

(K. B. Earnshaw and E. Norman Hernandez, 1972; Abshire, 1980)

Send simultaneously pulses at 2 different wavelengths.

Not used routinely by most of the ILRS stations:

- Technological limits
- Global performances of the same order of index models

Fig. 3. Differential atmospheric delay time for a one-way traversal vs zenith angle for the three possible pulse pairs.

J. B. Abshire, October 1980 / Vol. 19, No. 20 / APPLIED OPTICS
Improve accuracy in SLR

\[ R_1 = \int_{p_1} n(f_1, \vec{r}_1) ds_1 \]
\[ R_2 = \int_{p_2} n(f_2, \vec{r}_2) ds_2 \]

- \( R_1 \) & \( R_2 \) contains the same quantities of total atmospheric and water vapor density, the same curvature effects. The unknown integral \( \int_{p_1} \rho_t(r_1) ds_1 \) can be rigorously eliminated

2 colors measurement

\[ 2S = R_1 + \nu(R_1 - R_2) + (vP_{21} - \kappa_1) + H_{21}\text{SIWV} \]

\( P_{21} \) represents the propagation corrections from the ray path \( p_2 \) to \( p_1 \)
\( \kappa_1 \) is the arc-to-chord correction for the ray path \( p_1 \) which accounts for the curvature effect
\( \nu \) the power of dispersion
\( H_{21} \) the water vapor factor
\( \text{SIWV} \) the slant integrated water vapor
**Improve accuracy in SLR**

Dispersion effect (term due to dry atmosphere)
Curvature of optical paths
Water vapor density effect

<table>
<thead>
<tr>
<th>$E$ (°)</th>
<th>$ν(R_1 - R_2)$</th>
<th>$νP_{21} - κ_1$</th>
<th>$H_{21} \cdot SIWV$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$-36,782.5 \pm 162.2$</td>
<td>$-390.1 \pm 11.3$</td>
<td>$30.8 \pm 10.4$</td>
</tr>
<tr>
<td>5</td>
<td>$-25,574.7 \pm 99.8$</td>
<td>$-143.2 \pm 3.6$</td>
<td>$19.8 \pm 6.8$</td>
</tr>
<tr>
<td>10</td>
<td>$-14,069.6 \pm 49.9$</td>
<td>$-25.2 \pm 0.6$</td>
<td>$10.4 \pm 3.5$</td>
</tr>
<tr>
<td>15</td>
<td>$-9,639.8 \pm 33.4$</td>
<td>$-8.2 \pm 0.2$</td>
<td>$7.0 \pm 2.4$</td>
</tr>
<tr>
<td>20</td>
<td>$-7,351.9 \pm 25.3$</td>
<td>$-3.4 \pm 0.1$</td>
<td>$5.3 \pm 1.8$</td>
</tr>
<tr>
<td>30</td>
<td>$-5,057.9 \pm 17.3$</td>
<td>$-1.0 \pm 0.0$</td>
<td>$3.6 \pm 1.2$</td>
</tr>
<tr>
<td>40</td>
<td>$-3,942.3 \pm 13.4$</td>
<td></td>
<td>$2.8 \pm 1.0$</td>
</tr>
<tr>
<td>60</td>
<td>$-2,930.1 \pm 10.0$</td>
<td>$\leq -0.3$</td>
<td>$2.1 \pm 0.7$</td>
</tr>
<tr>
<td>90</td>
<td>$-2,538.7 \pm 8.6$</td>
<td></td>
<td>$1.8 \pm 0.6$</td>
</tr>
</tbody>
</table>
How to achieve millimetric accuracy in SLR with 2-colors measurements?

Millimeter accuracy possible with a significant precision improvement

Precision to reach at each wavelength

From D. D. Wijaya et al., Springer Verlag, 2011