Time and Frequency Links for STE-QUEST

Peter Wolf
LNE-SYRTE
Observatoire de Paris, CNRS, LNE, UPMC
1. Best “present” links and STE-QUEST requirements
2. The ACES MWL extension for STE-QUEST
3. “Continuous” optical links
4. The STE-QUEST optical link
5. Next steps
6. Conclusion
Best “present” links and STE-Q requirements

- Existing techniques: GNSS, TWSTFT, T2L2, ground fibre
- Near future: ACES-MWL, ACES-ELT

T2L2 is a two-way pulsed optical link (532 nm)
- Typically 10 to 2000 pulses per second
- Best performances MDev $\approx 5 \times 10^{-11}$ @ 1 s
ACES-MWL: two-way link with three frequencies (KU and S band)
Specs: MDev \( \approx 9 \times 10^{-12} \) @ 1s

\[ f_1 = 13.5 \text{ GHz} \text{ modulated by PRN code at 100 Mchip/s} \]
\[ f_2 = 14.7 \text{ GHz} \text{ modulated by PRN code at 100 Mchip/s} \]
\[ f_3 = 2.25 \text{ GHz} \text{ modulated by PRN code at 1 Mchip/s} \]
Best “present” links and STE-Q requirements

STE-QUEST Space to Ground comparison

Modified Allan Deviation vs. Integration Time (s)
Best “present” links and STE-Q requirements

![Graph showing Modified Allan Deviation vs. Integration Time for Ground Clocks, MWL G2G, Optical Link G2G, T2L2, and ACES.]
The ACES-MWL extension for STE-QUEST
(see also poster by T. Feldman)

• Studied in ESA-ITT-AO6404 – Phase 1 finished (TimeTech, DLR, SYRTE, ONERA, PTB, NPL)
• Phase 2 (breadboarding) calls expected soon

Difficulties:
• Larger distance (S/N) and its variation
• Doppler dynamics
• Ionosphere
• Turbulence
• Phase cont. during dead times

Solutions:
• Build on ACES-MWL experience
• Increase frequencies (Ka-band, X-band)
• Increase chip rates
• Model higher order ionospheric terms
• Mitigate turbulence (troposphere) by two-way configuration
• Increasing frequency of pulsed optical links is not an option (limited by pulse width and repetition rate)
• Continuous links in optical fibres (phase coherent or modulated) have shown very good performance, well compatible with STE-QUEST specs.
• First experiments in free space (SYRTE-OCA, NIST) show promising results, turbulence limited.
• Space-space and space-ground coherent links for optical communications (> Gbit/s) have been demonstrated (TRL=9)
• The application of such techniques to time/frequency transfer for space missions (STE-QUEST and beyond) is being studied under ESA contracts.
Continuous link example: Mini-DOLL

Principle of DOLL (Deep space Optical Laser Link):
• two way, phase coherent optical link for timing and ranging
• heterodyne measurement of $\Delta y$ between local and incoming signal
• Doppler ranging: $2\Delta v/c = (y_u + y_d) + \text{corr.}$
• Frequency transfer: $2\Delta f/f = (y_u - y_d) + \text{corr.}$
• In practice more complex (Doppler compensation, stray light, turbulence, ….)
Ground tests (2009) in ranging mode to study atmospheric limitations (see also Poster by N. Chiodo)

- Single terminal with passive corner cube
- Full atmospheric contribution
- Telescope diameter: 1.5 m
- Beam diameter: 380 mm

Turbulence limit

NIST 2012

[Giorgetta, Nat. Phot. 2013]

Turbulence noise very similar to stellar interferometry measurements

\[ D_x(\tau) = \langle (x(t) - x(t + \tau))^2 \rangle \]

Two-way compensation of turbulence

- Assume geostationary satellite \( T \approx 250 \text{ ms} \)
- Calculate \( (y(t)-y(t+T))/2 \) from our ground ↔ ground link and look at its statistics:

\[
\text{Averaging time, } \tau \text{ / s}
\]

<table>
<thead>
<tr>
<th>Fract. freq. Allan deviation, ( \sigma_y(\tau) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncompensated (measured)</td>
</tr>
<tr>
<td>Compensated (estimation)</td>
</tr>
<tr>
<td>STE-QUEST</td>
</tr>
<tr>
<td>SYRTE-OCA</td>
</tr>
</tbody>
</table>

\[
10^{-12} \quad 10^{-13} \quad 10^{-14} \quad 10^{-15} \quad 10^{-16} \quad 10^{-17} \quad 10^{-18} \quad 10^{-19}
\]

\[
0.001 \quad 0.01 \quad 0.1 \quad 1 \quad 10 \quad 100 \quad 1000
\]

- OK at turbulence limit and if two-way compensation works (temporal + spatial)
- Require sites with low turbulence (astronomical observation sites)
- Investigate adaptive optics schemes to mitigate cycle slips
STE-QUEST optical link (preliminary design choices)

- Nd-YAG lasers at 1064.5 nm (TESAT-LCT heritage)
- S/C telescope $D = 125$ mm, S/C $P_e = 1$ W (TESAT-LCT heritage)
- modulation frequency 1 GHz, detection BW = 3 GHz (can be reduced)
- optional carrier phase measurement
- dual ground telescope:
  - emission: $D = 0.09$ m, $P_e = 25$ W
  - reception: $D = 0.4$ m
  (→ SLR heritage, eg. Yargadee: 0.16 m / 1 m
  Graz: 0.1 m / 0.5 m )
STE-QUEST optical link (some design drivers)

- Existing technology in space and on ground (TESAT, eLISA, SLR)
- Phase noise and turbulence limitations
- Pointing errors
- Link budgets

- Uplink phase noise at apogee with 8 μrad pointing error as fct. of emission diameter
- Turbulence effect on downlink heterodyne efficiency \([S/N = m (S/N_{opt})]\) from Monte Carlo simulations with PILOT software (ONERA)

\[S_x(f)/(s^2/Hz)\]

\[100 \text{ MHz} \]

\[1 \text{ GHz} \]

\[D/m\]

\[D = 47 \text{ cm}\]
Next Steps

Laboratory breadboarding of MWL and of optical « back-end »
  - Demonstrate ACES-MWL upgrade in laboratory end-to-end test
  - Demonstrate modulation/demodulation of optical carrier in realistic Doppler/Power environment

• Turbulence simulations to estimate limits of two-way compensation (essential for MWL and optical)
  - time series of up and down link heterodyne phase fluctuations
  - time series of up – down as fct. of temporal and angular separation
  - explore various scenarios (wind speed and profile, turbulence strength and profile, outer scale, etc.

• Extension of ground-ground experiment to ground-space in particularly adverse conditions. First tests carried out in 2012/13.
  - “replace” reflector at 2.5 km by satellite corner cube
  - require stabilized laser to reach turbulence limit
  - very low return power (< 1 pW); STE-QUEST ≈ 10 nW to 100 µW
  - high Doppler (±12 GHz, 120 MHz/s); STE-QUEST about half that
  - “double blind” pointing; STE-QUEST to lock to incoming signal (eg. TESAT-LCT)
Encountered difficulties:

- Low return power ⇒ full 1.5 m telescope required ⇒ high order adaptive optics
- Pointing of reception (point ahead) ⇒ tip/tilt correction AO
- ILRS satellites not luminous enough for on-site AO system
- Unsuccessfully tried “double blind” pointing
- All of these problems are already solved for “high power” system (Opt. Telecom)
• First design studies have shown that upgrade of ACES MWL (Ka band, faster modulation) is feasible (ESA study just finished).
• Breadboarding of STE-QUEST MWL to be started in upcoming ESA call.
• Optical link design based on existing telecom “front end” and modulation of optical carrier (ESA study just finished).
• Breadboarding of “back end” to be started in upcoming ESA call.

• Ground-ground optical free space links show performance well within STE-QUEST specs.
• Extension to ground-space with passive space segment (corner cube) difficult because of extremely low return power (>10^4 times less than STE-QUEST).
• Turbulence mitigation in two-way configuration remains an open question (extensive numerical simulation required).