Enabling competitive high throughput LaserCom

Improves both ends of LaserCom links with MPLC technology

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Cailabs, a deep-tech company
Develop, manufacture & sell innovative optical components

**Unique technology** (MPLC) and **expertise** in beam shaping

- **43** employees
  - **18** PhDs

- **19** patent families

**8.6 M€ ++ raised**

References:
Placing Cailabs
Tailored beam shaping is photonics’ next disruption enabler

Beyond the usual properties …

- Power
- Wavelength
- Polarization
- Phase

… we control the shape of the light
Lasercom: why & when?
Why LaserCom?
New needs for data high-speed transmission

A growing number of aircrafts and spacecrafts…
- 23,600 airplanes\(^1\)
- 2,062 satellites\(^2\)
- + UAV

…with new booming data consuming needs…
- Earth observation
- Telecommunication coverage of remote areas
- In-Flight Entertainment

…but hindered by the current data transferring technology
- RF is too slow and too energy-intensive (<4Gbps)
- Data transmission is becoming a bottleneck

Spacecraft illustration
75% of active satellites need to transfer important and growing amounts of data

Active satellite applications
- Earth Observation: 37%
- Communications: 38%
- Technology Development: 7%
- Navigation/Global Positioning: 4%
- Space Science: 13%

1. Ascend 2. UCS
Why LaserCom?
LaserCom: a better SWaP and throughput

Optical communication over RF:

ADVANTAGES:
- Very High Throughput
- Better SWaP (Size, Weight and Power)
- Unlicensed spectrum
- High security

DRAWBACKS:
- Require **tight PAT** (Pointing, Acquisition and Tracking)
- Impaired by the atmosphere

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<table>
<thead>
<tr>
<th>Link</th>
<th>Optical</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO-LEO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna Diameter</td>
<td>10.2 cm (1.0)</td>
<td>2.2 m (21.6)</td>
</tr>
<tr>
<td>Mass</td>
<td>65.3 kg (1.0)</td>
<td>152.8 kg (2.3)</td>
</tr>
<tr>
<td>Power</td>
<td>93.8 W (1.0)</td>
<td>213.9 W (2.3)</td>
</tr>
<tr>
<td>GEO-GEO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna Diameter</td>
<td>13.5 cm (1.0)</td>
<td>2.1 m (15.6)</td>
</tr>
<tr>
<td>Mass</td>
<td>86.4 kg (1.0)</td>
<td>145.8 kg (1.7)</td>
</tr>
<tr>
<td>Power</td>
<td>124.2 W (1.0)</td>
<td>204.2 W (1.6)</td>
</tr>
<tr>
<td>LEO-LEO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna Diameter</td>
<td>3.6 cm (1.0)</td>
<td>0.8 m (22.2)</td>
</tr>
<tr>
<td>Mass</td>
<td>23.0 kg (1.0)</td>
<td>55.6 kg (2.4)</td>
</tr>
<tr>
<td>Power</td>
<td>33.1 W (1.0)</td>
<td>77.8 W (2.3)</td>
</tr>
</tbody>
</table>

Comparison of SWaP for GEO and LEO links using optical or RF communication systems – underlined figures are ratios

When LaserCom?
Intersatellite and ground-to-satellite links should be mature around 2022

Satellites architectures will be the first one to emerge:

- **2020**: Ground station with **adaptive optics**
- **2022**: Mega-constellations with ISL
- **2025**: Terabit/s-throughput optical **feeder link**

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1. Hydron roadmap
Multi-Plane Light Conversion
Multi-Plane Light Conversion
Take-home message about MPLC

Multi-Plane Light Conversion (MPLC)

- Derived from quantum optics at Laboratoire Kastler Brossel
- Complex beam shaping through succession of spatial phase profiles
- Passive optical beam shaping with no intrinsic loss nor moving elements
Multi-Plane Light Conversion
Compact implementation
Multi-Plane Light Conversion
Spatial multiplexer

S. Bade & al., PDP OFC 2019
Addresses optical drawbacks
Improve Space-to-Space & Space-to-Ground optical links

1. Space - Space
   Compensate pointing error

2. Space - Ground
   Mitigate atmospheric turbulence

3. Ground - Space
   Combine powerful sources for feeder links

4. Ground - Space
   Precompensate atmospheric turbulence
Space-to-space: mitigate pointing errors

Remove pointing errors with no moving parts
Space-to-space: mitigate pointing errors
Pointing errors degrade inter-satellite communication

Pointing errors

Degrade dramatically the performance of the entire network

Space-to-space: mitigate pointing errors
Mode decomposition of a misalignment

Tilt:

\[ E_0 \mid_{x+\delta x} = \varepsilon_0 \left[ HG_0 \mid_{x} + \frac{i\delta x}{w_0} \times HG_1 \mid_{x} + o \left( \frac{\delta x}{w_0} \right) \right] \]
Space-to-space: mitigate pointing errors
Mode decomposition of a misalignment

\[ E_0 \bigg|_{x+\delta x} = \varepsilon_0 \left[ H G_0 \bigg|_x + \frac{i \delta x}{w_0} \times H G_1 \bigg|_x + o \left( \frac{\delta x}{w_0} \right) \right] \]
Space-to-space: mitigate pointing errors
Mode decomposition of a misalignment

Tilt:

\[
E_0 \big|_{x+\delta x} = \epsilon_0 \left[ HG_0 \big|_x \frac{i\delta x}{w_0} + HG_1 \big|_x + o \left( \frac{\delta x}{w_0} \right) \right]
\]
Space-to-ground: Mitigating turbulence at reception

Adaptive optics in a chip
Space-to-ground: Mitigating turbulence at reception
Atmospheric turbulence deteriorates LaserCom links

Effects of turbulences:
- Beam spreading – Defocusing
- Beam wander - Tilt
- Scintillation

Impact on LaserCom:
- Less persistent link (milliseconds fades)
- Lower throughput (higher BER)
Space-to-ground: Mitigating turbulence at reception
Existing solutions are complex and expensive

ADAPTATIVE OPTICS

But:
- Are expensive
- Need feedback loop
- Display moving elements

Space-to-ground: Mitigating turbulence at reception
A similar function with a different approach

ADAPTATIVE OPTICS

Cartesian basis

\[ \sum A(x, y)e^{i\psi(x,y)} \]

SPATIAL DEMUX

Mode basis

\[ \sum \alpha_{n,m}HG_{n,m}e^{i\psi_{n,m}} \]

Deformable mirrors

MPLC
Space-to-ground: Mitigating turbulence at reception
Decomposing the incident beam

- Collect more incident light
- Modal diversity
- WDM compatible
- Passive component

Tip/Tilt compensation mirror

By Cailabs

MMF

SMFs

DEMUX

Receiver + digital signal processing
Space-to-ground: Mitigating turbulence at reception
A photonic integrated chip to recombine the outputs

- On chip optical recombining
- One single SMF output
- Plug and play optical receiver to mitigate atmospheric turbulence
Space-to-ground: Mitigating turbulence at reception
Experimental results: x5 increased reception

✓ 10 Gb/s over 400 km
Simulation of LEO-to-ground link

✓ Up to x5 (+7 dB) coupling efficiency
in 5% worst cases of strong turbulence

✓ Passive optical component
No use moving parts

References:
Space-to-ground: Mitigating turbulence at reception
Experimental results: x5 increased reception

LEO-to-ground communication

✓ Three mode digital combining
10 Gb/s QPSK

✓ Relax the transmitted power by:
12 dB at 20°, 9 dB at 30° and 4 dB at 90°
For 1% FEC error

✓ Passive optical component
No use moving parts

References:

Ratio that BER exceeds FEC threshold against the transmitted power, at the condition of elevation angles of (a) 20°, (ab) 30° and (c) 90°
Ground-to-space: Increase power at the emission

Coherent combination across wide spectrum
Ground-to-space: Increase power at the emission
Combining to increase source power - coherent

Very High Throughput Satellites
Telecom constellations

Need to handle high power (>100W) and high throughput
Need to be WDM compatible

Powerful feeder links needed

TILBA beam shaping enables more tolerant coherent combination thanks to constructive interferences
3. TILBA-T-Combine
Combine coherently high-power sources for feeder links (Tbits)

✓ High efficiency
✓ High power handling
✓ Combination of up to 45 coherent sources
✓ WDM compatible
Ground-to-space: Pre-compensate the turbulence

What if we could pre-compensate the atmospheric turbulence?
Ground-to-space: Pre-compensate the turbulence
Shape the emitted beam to precompensate atmospheric turbulence

1. Analyse the turbulence
2. Decompose it analytically on the MPLC bases
3. Send the corrected beam
Take home message
Improves the Space-to-Space & Space-to-Ground links

Improves LaserCom at the reception:
- pointing errors
- Turbulence mitigation

Improves LaserCom at the emission:
- Coherent combining
- Precompensation

TILBA roadmap

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>Ground station Field test</td>
</tr>
<tr>
<td>2020</td>
<td>Silicon Photonic Chip</td>
</tr>
<tr>
<td>202?</td>
<td>Satellite Tip-Tilt compensation</td>
</tr>
<tr>
<td>&gt;2024</td>
<td>Aircraft LaserCom Network</td>
</tr>
</tbody>
</table>
Thank you for your attention
Environment validation
Temperature, pressure, humidity, vibration

- Specific validation of novel optical components critical in aircraft context
  - Validate specific environmental conditions
  - Avoid the « concept » trap

- Temperature
  - Operation from -40 to 85 °C
  - Operation +- 2°C / minute

- Pressure
  - Operation from 0.1 Bar to 1 Bar

- Humidity
  - Operation at 50°C, 95% RH

- Vibration
  - Vibration, operation at 4.12g RMS
  - Shock, operation at 6g for 11ms

- Cabling
  - No impact of bending radius 2 cm