CNES contribution
to discussions for interoperability
and standardization of optical space telemetry links

Some system aspects (mainly air interface)
for the LEO--earth direct links

27 september; J-Luc. ISSLER
International coordination between space agencies is ensured through several organisations.

- Consultative Committee for Space Data Systems (CCSDS)
- Interagency Operations Advisory Group (OOG)
- Optical Link Study Group (OLSG)
- Interagency Operations Advisory Group (OOG)
- Consultative Committee for Space Data Systems (CCSDS)
- Regional organisations

Interoperability Plenary
Interagency agreements on space interoperability

Consultative Committee for Space Data Systems
Open international standards for mission interoperability

Optical Link Study Group
Looking at requirements for optical coms in space
- CNES opinion regarding the laser beam pointing laws is to drive them from a need such as "no or minimum constraints on the host LEO satellite", in order that a ground station could communicate with different types of satellites.

- That would mean that the ground station would be provided with a beacon, to also allow a quick and reliable acquisition process.
Some important system needs (2)

The following generic system features are prefered

Beacon based acquisition system as it provides the best system performances in the following areas:

- Best robustness during the critical acquisition phase, best availability performances, best acquisition duration

- Robustness to host interfaces thanks to acquisition and tracking sensor arrays

- Maximum autonomy versus ground operations thanks to on-board processing.

Nota Bene: Compact, stiff and lightweight aerial to minimize perturbations (due to wind, sismology, …) is also a need
- **Telescope:** this optical antenna is an afocal on-axis afocal telescope. The diameter of the primary mirror, dimensioned by the link budget, is dependent of the application.

- **Fine Steering Mechanism:** this 2-axis mechanism is composed of the azimuth and elevation articulations, a U bracket and optical relays to transfer the output pupil of the telescope to the Fine Pointing Mechanism located inside the focal plane. The pointing angle is typically hemispherical on LEO terminal to allow for direct transmission (fresh information needs) over a wide Earth coverage.

- **Focal plane:** Core of the terminal, the focal plane provides highly stable environment to key units located either on transmit or receive optical paths. On the receive path, the optical beam is directed towards the communications sensor input fibre and the Acquisition and Tracking sensor. On the transmit path, the focal plane combines beacon (only on master terminal) and communication signals from power booster amplifiers towards the telescope. The focal plane includes beam splitters and filtering optics, a Fine Pointing Mechanism, and optical collimators. These units are mounted on a stable bench. Redundancy of the communication channels is ensured thanks to optical multiplexing.

- **Satellite interface assembly:** it provides the aerial interface structure with host spacecraft and, therefore, depends of the selected accommodation. It aims at rejecting the singular point outside the area of interest. An interface structure supports the Fine Steering Mechanism, the focal plane and its proximity electronics and the power booster amplifiers.
General terminal architecture (2)
Electronic equipment subassembly

Includes three to four electronic functions depending the type of terminal (master or slave):

- **Terminal Control Electronics**: manages the interfaces with the platform and the terminal equipments, deliver the electrical power to the terminal equipments, and performs the terminal control (high level modes, thermal control, open loop pointing, partner detection, closed loop high frequency tracking and pointing).

- **Laser & Communication Electronics**: interface with the receive channels using optical fibres, demodulates the incoming communication signal from the partner and transmits it to the spacecraft payload. It also receives the Uplink communication signal and delivers the modulated optical signal to the power booster amplifier using an optical fibre. It interfaces with the Terminal Control Electronics for the data management.

- **The Power booster amplifier**: receives the modulated signal from the Laser & Communication Electronics, amplify the signal to few watts thanks to dopped fibre amplifiers and then, transmitts the amplified optical signal to the aerial (focal plane).

- **The beacon electronics**: provides commands, monitoring and power supply of the beacon diodes.
The OIT optical link main characteristic is its mono-directional feature as the mission consists in downloading data from a Low Earth Orbiter satellite to ground.

This mono-directional feature allows for dramatic simplification of the overall system. Indeed, the use of beacon on-ground (master terminal) to initialize the link can be extended to tracking.

Furthermore, the distance to ground being far lower than the one with geostationary satellite, the antenna gain can be decreased so as to allow for high relaxation of beam divergence and consequently pointing requirements. This relaxation (~12.5 μrad) permits to configure the flight terminal with only one mechanism stage for tracking. So, in summary:

<table>
<thead>
<tr>
<th>Terminal</th>
<th>PAT</th>
<th>Laser &amp; Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATS</td>
<td>FPM</td>
</tr>
<tr>
<td>LEO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground</td>
<td>1.55 μm sensor</td>
<td>X</td>
</tr>
</tbody>
</table>

ATS : Acquisition & Tracking Sensor; FPM : Fine Pointing Mechanism
Conclusions of the Space Optical Communication Workshop in Berlin the 17th of may 2011

This table was elaborated by all the participants*** to the 17 may 2011 workshop. Discussion occured for the criteria and the colors, and the quasi concensus obtained is presented here.

<table>
<thead>
<tr>
<th><strong>EYE SAFETY</strong></th>
<th>850 nm</th>
<th>1066 nm</th>
<th>1550 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna size</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data rate (including WDM consideration)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Availability of COTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Atmospheric attenuation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Turbulence</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Background light</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Optics quality requirement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Year dependent</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This table was elaborated by all the participants*** to the 17 may 2011 workshop. Discussion occured for the criteria and the colors, and the quasi concensus obtained is presented here.

* Technology Readiness Level (TRL) estimations agreed in the Optical Space Communication workshop are for Rb>1 Gbits/s in 2011: For 850 nm: 5; for 1066 nm: 9; for 1550 nm: 6


*** DLR, JAXA, ESA, NASA, CNES, MIT-Lincoln Lab, DIN, HHI-Fraunhofer, RUAG-Space, TU Gratz, Tesat, Carl Zeiss Optronics, …
LEO terminal:
- 1,55 µm Transmission chain
- 1,55 µm Acquisition and Tracking Sensor (ATS)

Ground terminal:
- 1,55 µm ATS
- 1,55 µm Beacon
- 1,55 µm Reception chain

- option: 1,06 µm ATS and reception chain in addition to 1,55 µm, if 1,06 µm take part of a futur LEO ground TM worldwide standard, and in that case, if the owner user wants to be also interoperable with an eventual mission at 1,06 µm
The main specificity of the optical link in the HDR TM application is the data rate dissymmetry between the upwards link (from ground to LEO) that requires only of few kbps for TC transmission purpose and the downward link (from LEO to ground) where tens Gbps are necessary. Consequently only one mono directional telecom channel is required to perform the downward link, while the beacon signal can be used to perform both the link acquisition and tracking and the upward communication thanks to beacon modulation.

Such architecture presents the advantage of implementing the power demanding beacon in the ground terminal, where power consumption is not an issue. Indeed the LEO terminal has to cope with mass, volume and power consumption constraints to ease its implementation on the spacecraft, while similar consideration are less severe for the ground terminal that only needs to be transportable.

Based on these considerations, the following pupil size could be considered from 60 to 100 mm for the LEO and from 250 up to 450 mm for the ground terminal.
Communication chain architecture (2)
The signal acquisition budget is provided here after for the downward link considering different LEO pupil size ranging from 60mm to 100 mm with 10mm steps and a ground terminal pupil of 250 mm.

- First the LEO emitted power $P_{com}$ is assessed according to:

$$P_{com} = P_{opt} \cdot G_e \cdot G_T \cdot T_{tel}$$

with:

- $P_{opt}$ = Optical power of the telecom channel – 2W is considered as such optical power is available
- $G_e$ is the emission antenna gain
- $G_T$ is the LEO telescope emission loss due to obscuration
- $T_{tel}$ is the LEO telescope transmission loss - a 10% loss hypothesis is considered

$G_e$ is given by

$$G_e = \frac{\pi^2 \cdot D^2}{\lambda^2}$$

with:

- $D$ = Leo emission pupil diameter
- $\lambda$ = telecom link wavelength – 1.55 µm link considered
The principle of ACM is to vary the coding level as a function of the link conditions. Based on past experience, the DVB-S2 coding level can be changed during transmission without prior notice to the receiver (or with prior notice).

### DVB-S2 coding levels & corresponding efficiency

<table>
<thead>
<tr>
<th>Coding rate</th>
<th>Real rate</th>
<th>Coding only</th>
<th>Coding + 2% framing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>1/5</td>
<td>19.0%</td>
<td>18.6%</td>
</tr>
<tr>
<td>1/3</td>
<td>1/3</td>
<td>32.3%</td>
<td>31.7%</td>
</tr>
<tr>
<td>2/5</td>
<td>2/5</td>
<td>39.0%</td>
<td>38.2%</td>
</tr>
<tr>
<td>1/2</td>
<td>4/9</td>
<td>43.4%</td>
<td>42.5%</td>
</tr>
<tr>
<td>3/5</td>
<td>3/5</td>
<td>59.0%</td>
<td>57.8%</td>
</tr>
<tr>
<td>2/3</td>
<td>2/3</td>
<td>65.6%</td>
<td>64.3%</td>
</tr>
<tr>
<td>3/4</td>
<td>11/15</td>
<td>72.3%</td>
<td>70.9%</td>
</tr>
<tr>
<td>4/5</td>
<td>7/9</td>
<td>76.7%</td>
<td>75.2%</td>
</tr>
<tr>
<td>5/6</td>
<td>37/45</td>
<td>81.2%</td>
<td>79.6%</td>
</tr>
<tr>
<td>8/9</td>
<td>8/9</td>
<td>87.9%</td>
<td>86.1%</td>
</tr>
</tbody>
</table>

The simplest VCM strategy consists in deterministic change of the coding level vs. the link elevation. For instance, this figure shows a typical case where three DVB-S2 coding levels are used, 1/2 for elevation between 20 & 30 deg, 2/3 between 30 & 40 deg and 4/5 above 40 deg. The average useful data rate over a zenital pass and 20 Gbps channel data rate is 13.2 Gbps, i.e. 55% improvement vs. the constant data rate sized to worst case elevation (8.5 Gbps). The interest of VCM is therefore quite significant with only minor impact on the communication chain, and ACM-like techniques could also bring more in term of quantity of downloaded data.

**Data rate & volume with adaptive coding**

20 Gbps channel rate
ACM like techniques can contribute to HDRTM strategy, in complement to:

- Space diversity for ground station sites, preferably discorelated from a meteorological point of view

- On board storage capability

- Use of DTN like techniques to cope with meteorological disruptions

- ...
The proposed acquisition strategy is a fast beacon based acquisition. The beacon is implemented in the ground terminal for two obvious reasons: (1) the implementation constraint is less severe on ground compared to the LEO terminal; (2) the power consumption is not a real issue on ground, consequently more optical can be available if needed. The acquisition sequence is:

- Both terminal (ground and LEO) are pointing towards the opposite terminal theoretical location based on orbitography data

- The ground terminal is emitting its beacon signal and starts scanning its uncertainty cone

- The LEO terminal is scrutinizing its acquisition sensor field of view

- The LEO terminal detects the beacon signal

- The LEO terminal is tracking the beacon signal and is emitting its HDRTM signal towards the ground terminal measured location

- The ground terminal detects the LEO signal, stops scanning its uncertainty cone and tracks the LEO terminal signal
Fast beacon acquisition strategy principles

The OGS uncertainty cone is dominated by the LEO position uncertainty (linked to orbitography data propagation), and thus the worst case corresponds to nadir (but acquisition occurs at minimum elevation). +/-4.5 mrad uncertainty cone is considered for beacon sizing, covering with margins typical acquisition for LEO passing away from OGS zenith. The LEO uncertainty cone is smaller by a factor of two (+/-2.5 mrad) because the LEO position is accurately known from on-board GNSS receiver.
Beacon link budget (1)

The beacon wavelength can be preferably 1.55 μm for consistency with downlink.

The beacon link budget is provided for several LEO pupil size ranging from 600mm to 100 mm by 10mm steps. It is at first order independent from the wavelength since the beam divergence is far larger than the diffraction. The beacon acquisition threshold has been set to 20 pW. The beacon optical power is adjusted to provide a 2 dB margin above this threshold which is a safe objective with respect to the beacon acquisition.

The first step is to compute the ground terminal beacon emitted optical power $P_{\text{ground}}$, given by:

$$P_{\text{ground}} = P_{\text{opt}} \times G_{e} \times G_{T} \times T_{\text{TEL}}$$

with:

- $P_{\text{opt}}$ = beacon optical power
- $G_{e}$ is the emission gain
- $G_{T}$ is the ground telescope emission loss due to obscuration
- $T_{\text{TEL}}$ is the LEO telescope transmission loss - a 10% loss hypothesis is considered
Optical link parameters

Based on the preliminary sizing presented previously, the link handles:

- the link initialisation principle is a fast beacon acquisition type, the beacon being implemented in the ground terminal where power consumption is not an issue.

- the upwards link requiring only a very low data rate, the communication is performed by the beacon signal modulation, therefore no telecom channel is necessary in the ground terminal.

- the chosen wavelengths are 1.55 μm for the downlink communication channel or 1.55 μm (TBC) for the beacon.

- terminal pointing is performed only by the fine steering mechanism, no fine pointing mechanism is implemented in the PAT function.

- The only fine pointing mechanism is implemented in the ground terminal to perform the fibre injection of the received telecom signal.
Satellite terminal architecture
The optical detection sensitivities is about -44.6 dBm for RZ-DPSK at 20 Gbps data rate and 10-3 BER. The link conditions are highly variable during the LEO-OGS visibility period since both link distance and atmospheric loss depend strongly on the LEO elevation angle as seen from the OGS. The figure here illustrates preliminarily the atmospheric loss evolution vs. elevation. For 20 deg elevation (minimum assumed value), 12 dB additional loss compared to typical link conditions at 40 deg elevation need to be handled by the coding system or by over-sizing of the link.
Basics definitions

Information bits \( E_b/N_0 \) → **Channel coding**: Code rate \( R \) → Coded bits \( E_c/N_0 \) → **Modulation**: \( \log_2(M) \) bits/symb → Modulated symbols \( E_s/N_0 \)

\[
\frac{E_c}{N_0} = R \times \frac{E_b}{N_0}
\]

\[
\frac{E_s}{N_0} = \log_2(M) \times \frac{E_c}{N_0} = \log_2(M) \times R \times \frac{E_b}{N_0}
\]

where \( E_s \) is the average energy per coded bit, \( E_b \) the average energy per information bit, \( E_s \) is the average energy per symbol, \( M \) is the number of symbols and \( R \) is the code rate.

For the QPSK modulation scheme (formula also valid for the BPSK modulation scheme):

\[
TEB_{\text{QPSK}} = Q \left( \sqrt{2 \frac{E_c}{N_0}} \right)
\]

For the DPSK modulation:

\[
TEB_{\text{DPSK}} = \frac{1}{2} \exp \left( -\frac{E_c}{N_0} \right)
\]

For the OOK modulation (with optical preamplification):

\[
TEB_{\text{OOK}} = \frac{1}{2} \exp \left( -\frac{E_c}{2N_0} \right)
\]
BER for QPSK (BPSK), DPSK and OOK as a function of the average Ec/No ratio (especially for OOK) at the receiver input.

Nota Bene: The DPSK modulation scheme exhibits a better sensitivity than OOK.
Comparison of RS(255,239) and LDPC DVB-S2 performances for DPSK

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Code</th>
<th>Code Rate</th>
<th>$Es/No$ @ BER&lt;10e-12</th>
<th>$Ec/No$ @ BER&lt;10e-12</th>
<th>$Eb/No$ @ BER&lt;10e-12</th>
<th>Coding gain (dB)</th>
<th>Gain on Ec/No vs. RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPSK</td>
<td>RS (255,239)</td>
<td>0.94</td>
<td>9.00</td>
<td>9.00</td>
<td>9.28</td>
<td>5.02</td>
<td>9.45</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 1/4</td>
<td>0.25</td>
<td>-0.45</td>
<td>-0.45</td>
<td>5.57</td>
<td>14.75</td>
<td>9.45</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 1/3</td>
<td>0.33</td>
<td>0.01</td>
<td>0.01</td>
<td>4.82</td>
<td>14.29</td>
<td>8.99</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 2/5</td>
<td>0.40</td>
<td>0.67</td>
<td>0.67</td>
<td>4.65</td>
<td>13.63</td>
<td>8.33</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 1/2</td>
<td>0.50</td>
<td>1.48</td>
<td>1.48</td>
<td>4.49</td>
<td>12.82</td>
<td>7.52</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 3/5</td>
<td>0.80</td>
<td>2.45</td>
<td>2.45</td>
<td>4.67</td>
<td>11.85</td>
<td>6.55</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 2/3</td>
<td>0.67</td>
<td>2.88</td>
<td>2.88</td>
<td>4.64</td>
<td>11.42</td>
<td>6.12</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 3/4</td>
<td>0.75</td>
<td>3.54</td>
<td>3.54</td>
<td>4.79</td>
<td>10.76</td>
<td>5.40</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 4/5</td>
<td>0.80</td>
<td>4.05</td>
<td>4.05</td>
<td>5.02</td>
<td>10.25</td>
<td>4.95</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 5/6</td>
<td>0.83</td>
<td>4.43</td>
<td>4.43</td>
<td>5.22</td>
<td>9.87</td>
<td>4.57</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 8/9</td>
<td>0.89</td>
<td>5.19</td>
<td>5.19</td>
<td>5.70</td>
<td>9.11</td>
<td>3.81</td>
</tr>
<tr>
<td>DPSK</td>
<td>LDPC 9/10</td>
<td>0.90</td>
<td>5.35</td>
<td>5.35</td>
<td>5.81</td>
<td>8.95</td>
<td>3.66</td>
</tr>
</tbody>
</table>
DPSK offers excellent detection sensitivity performance
- better than OOK (by at least 3 dB)
- almost as good as BPSK

DPSK can be detected / demodulated either by direct detection w/ interferometer demodulator or by heterodyne/homodyne detection

DPSK enables relatively simple implementations
- requirements on laser linewidth are relaxed (typ. < 0.3 % of bit rate): semiconductor DFB lasers applicable at medium to high bit rates
- no optical local oscillator is needed, if direct detection is used
- optical interferometer demodulator can be achieved w/ micro-optics or integrated optics

Components are commercially available for high bit rates applications

Readily compatible w/ the implementation of multiple channels through WDM
Annexe

Eye safety issues  (additional to « Eye Safety Issues with Optical Communications” . “Free Space Optical Communications Between “LEO and ground” or “GEO and ground” “. SF32-39I. SFCG-32. 12-20 June, 2012. Darmstadt, Germany)
Eye safety issues (1)

In terms of atmospheric attenuation, infra-red band offers 3 windows within wavelengths 850nm, 1310nm and 1550nm.
Laser emissions laser in visible and near-infra red (400 – 1400 nm) can cause damages to retina. This band is knowns as the « critical retinian region »*

Laser émissions in ultra-violet (290 – 400 nm) and in far-infra red (1400 – 10600 nm) can cause dommages respectively to lens and to cornea.

Versus wavelength, light absorption is made in different parts of the eye. Eye act as a pass band filter for visible light, which go through cornea, focused in the lens and reach retina to form the image. Other wavelengths interact differently with eye tissues. Places of the eye where laser energy absorption is made depend on the wavelength.
Visible and near-infra red light is focused in the lens on the retina. Because in this band (400 – 1400 nm) the focusing creates a high power density on retina, lasers in this bands are the more susceptible of eye damages.

Higher wavelengths are absorbed at the level of cornea. Infra-red, and far- ultraviolet also, are absorbed at the level of the cornea and can provoke a « photokératite », a painfull eye irritation which causes pain.

Lesion types observed for continuous transmissions are from burn-type and photochimical types. Photochimical reactions provoke a not clear vision or a sensitivity loss to light. Near ultra-violet is absorbed by the lens and has an effect on the proteins, creating a cataract making vision not clear.
### Ocular absorption versus wavelength (3)

Damages that laser could create to human eye are summarized hereafter:

<table>
<thead>
<tr>
<th>Laser wavelength</th>
<th>Lesions of eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet C: 100-280 nm</td>
<td>« Photokératite » of cornea</td>
</tr>
<tr>
<td>Ultraviolet B: 280-315 nm</td>
<td>« Photokératite » of cornea</td>
</tr>
<tr>
<td>Ultraviolet A: 315-400 nm</td>
<td>Photochemical cataracts</td>
</tr>
<tr>
<td>Visible 400-760 nm</td>
<td>Photochemical and thermal retinal damage</td>
</tr>
<tr>
<td>Infrared A: 760-1400 nm</td>
<td>Cataracts and retinal burns</td>
</tr>
<tr>
<td>Infrared B: 1400-3000 nm</td>
<td>Cornea burned-type lesions, cataracts, damages of aqueous humor</td>
</tr>
<tr>
<td>Infrared C: 3000-10600 nm</td>
<td>Cornea burned-type lesions</td>
</tr>
</tbody>
</table>

At equivalent power, laser beams in visible and near-infrared (400-1400 nm) stay the most dangerous since all energy is focused on the retina.