COLORS: a COnmunication Link with an Optical Relay Satellite

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ABSTRACT

We present a new concept to link two ground–based optical stations through a satellite. In our approach the optical relay in orbit is a completely passive one, with no requirements in terms of active control attitude and with a more simple opto–mechanical design. The relay acts as a reference source for the ground stations, equipped with an adaptive optics system to enlarge the photon return and the bandwidth of the transmitted signal. The technological requirements are mainly on the ground side, then technological up–grades are easily obtainable and less cost–demanding.

1. INTRODUCTION

The transmission rate of a link increases with the frequency of the carrying wave. This is one of the reasons why broad band connections can be easily obtained using fiber optics instead of traditional phone cables. Free space optical communications can be distinguished in three main areas: ground–ground connections, space–space connection and ground–space links. The first are limited to ranges of no more than few kilometers, while for space–space optical links several experiments have been performed in order to evaluate the possibility to transfer huge amounts of data between couples or constellations of satellites\textsuperscript{1,2}. The main limitation of these systems, however, relies on the complexity of the opto-mechanical design, since they must be equipped with control systems able to keep the pointing accuracy to few arcseconds for a period of time long enough to allow the transmission of the data. The last possibility is related to optical links between ground stations and satellites. One of the main issues discussed in the study of this kind of links is related to the effects of the atmospheric turbulence on the quality of the beam carrying the signal. Adaptive optics correction\textsuperscript{3,4} is an increasingly used method to overcome the limitation of the atmospheric turbulence on the image quality in both military activities\textsuperscript{5} and astronomical observations\textsuperscript{6}, but specific studies on the subject of communication links are very recent and few experiments have been done up to now or are planned in the near future. Except some special activities as involve Earth–prospecting, scientific and military satellites or manned spacecraft, the main interesting field is related to data communication between two points on the Earth surface. In this paper we discuss a new concept to realize a ground–space–ground connections, that would overcome many technological limitations and could open new opportunities in the field of data communications. The Italian company AIEM has been funded by the Italian Space Agency ASI to make a preliminary study on the feasibility of the project; the work is made in collaboration with the Astronomical Observatory of Padova, where the adaptive optics module of the Italian National Telescope Galileo (TNG) has been developed\textsuperscript{7}.

2. THE CONCEPT

One of the main limitations of any kind of orbital transponder, regardless of the wavelength used, is the connection between its lifetime and the complexity of its structure. Generally speaking, the largest is the number of elements, kind of materials or more in abstract terms the number of function it should exploit (receiving, elaborating the signal, transmitting it, \ldots), the largest is the probability of malfunctioning and the shortest will be its lifetime. Then, the reduction of the technology on board of the satellite could drive to a longer lifetime; furthermore, if the technology is mainly concentrated in the ground stations, upgrades are easier from a practical point of view and
Figure 1. Ray-tracing plot of the back-reflector: two surfaces are simple flat mirrors, while the third one is a mirror covered by a prism. Only one frequency is shown. The arrows shows the axis that cannot be controlled passively without the prism.

less expensive. Presently large amounts of investment are made in the R&D area of optics data communications; it is expected that once optical links becomes widely used and competitive with micro-waves communications, the development of new lasers and sensors will further increase and, in this framework, having the largest part of the opto-mechanical complexity on the ground segment of a communication link could turn out to be a good choice.

Our system has been conceived to fulfill these requirements: the optical relay in space is a completely passive one and the greatest part of the technological difficulties are moved to the ground stations.

In order to obtain such a passive orbiting system to connect two points on the Earth surface with an optical signal several solutions can be conceived. The most simple one makes use of a single flat mirror with high reflectivity and a couple of ground stations equipped with adaptive optics systems to correct for the atmospheric turbulence. The main limitation of these systems is the high accuracy required in the positioning of the mirror, so that active control systems are needed in order to stabilize its orbit and orientation, since passive ones, like magnetic stabilization or gravity gradient allow only a poor control of the satellite orbital parameters. A development of this basic idea is related on the adoption of a skewed back-reflector as optical relay. This simple device is made of three flat mirrors arranged on the faces of a sort of corner cube, where the angles between each plane are significantly larger than 90°; with this configuration and an appropriate choice of the angle between the faces, any angle between the incoming beam and the outgoing one can be obtained, and from a geometrical point of view any couple of stations can be connected by the relay.

This modified version of the optical transponder can be controlled in a passive fashion with respect to rotations around all the axis but its proper one, that is the axis forming with the faces of the reflector equal angles and passing through the vertex of the prism (see Fig.1).

Now, let us suppose to introduce some chromatism into the system. In particular, we apply on one surface of the relay a prism: in this way the angle between the incoming beam and the outgoing one will depend on the wavelength of the radiation. We can suppose that, for a certain orientation of the relay, with some error with respect to the nominal one, the transmitted signal will be received only at a certain wavelength, that correspond to the proper angle for that orientation of the back-reflector. Provided the usable bandwidth of the transmitted laser beam is large enough, by changing the wavelength of the laser it is possible to establish the connection between the stations. Both of them will use a tunable laser to select the proper wavelength and continuously
Figure 2. Linking procedure with the back-reflector. First station A sends a signal towards the satellite at a certain frequency. Because of the poor attitude control of the satellite the reflected beam miss B (left). Now A starts to sweep the band of its laser and change the frequency. The direction of the outgoing beam from S changes because of the presence of the prism on one surface (center). When the signal is received by B, the spectrograph of the station measures the wavelength and B sends back a signal at the same frequency (right). By reciprocity, the signal is received by A that stops sweeping the laser band.

track the signal in closed loop. In this way the precision required to the control of the orientation and position of the satellite is further reduced, allowing for a purely passive control.

3. LINKING PROCEDURE

The procedure used to establish the connection can be divided into few steps; notice that some of them are accomplished by both the stations simultaneously and that keeping the connection during the transfer of the data requires that also the receiving station send a signal to the emitting one. In the following we will call the stations A and B while the optical relay will be S (see Fig.2). The stations are equipped with a tunable laser in a certain wavelength band, a spectrograph and an adaptive optics system. The connection is accomplished as follows:

1. Station A starts to send the signal at a certain wavelength; because of the poor attitude determination of S (supposed to be controlled only in a passive way), its orientation will be different from the nominal one required to link the stations at the wavelength used by A. Then, the signal will miss B.

2. Station A starts to sweep the band of the laser. Provided the conditions on the band, the achromatism induced by the prism and the control attitude system match, the signal reflected by S will sweep an area large enough to include the location of B.

3. As soon as B receives a signal, it measures through the spectrograph its wavelength, which is used to fire the laser at the proper frequency towards the direction of S.

4. By reciprocity, A will receive the signal from B, measures the wavelength and stops sweeping the band of its laser.

At this point we can consider the connection $A - S - B$ as accomplished. Now the satellite is visible from the stations and can be used as reference source. It is worth noting that the atmospheric aberrations enlarge the beam section either in the upward path and in the downward one, leading to huge photons losses. The power of the laser should be selected in such a way that, taking into account for these effects, the reference source is bright enough to allow a correction of the aberrations up to the desired Strehl Ratio (SR); furthermore, this requirement must be extended to the whole band swept by the tunable laser during the connection. If the beam is large enough, it is possible to obtain six outgoing beams: for a fixed direction of the incoming beam, the first reflection can take place over one of the three surfaces of the back-reflector and for each of them there are two possible combinations for the successive two reflections (we do not consider the case with only two reflections, because this is not the operative condition that would be usually met by the system). The six beams intercept
Six areas over the Earth surface, in a circle. As the satellite rotate around its axis, the areas move on the circle, while a tilt of the axis results in a shift of the center of the circle. Beams at different wavelength are slightly shifted with respect to each other and lies on the same circle. During the first step of the connection procedure, it is possible that a fraction of the light emitted by A could be back-reflected, leading to a spurious locking in frequency. This case can be avoided by introducing a different modulation on the signal emitted by each station. This trick also applies to the light emitted by Rayleigh back-scattering processes in the atmosphere. As soon as the adaptive optics loops are closed on both stations, the beam size will drop consistently and in the most favourable case only the spots on the station B and A will survive.

The position of the satellite should be known with a certain precision, in order to prevent the lost of a larger part of the signal, which would lead to the already mentioned problem of the brightness of the reference source, i.e. the satellite. Small non-skewed back-reflectors could be added in order to obtain a more effective determination of the position of the satellite, lowering the requirements on the control of the orbit. The back-reflector can be used to connect more than one couple of stations, but it is unlikely that the same frequency would be used simultaneously, leading to cross-coupling between the different links.

4. CONCEPT ANALYSIS: FIRST RESULTS

The aim of the project is to obtain the largest transfer of the technology from the orbital segment to the ground one as possible, keeping costs on the same ground of presently available connections through satellite at microwave and radio bands and increasing the transfer rate thanks to the high frequency of the link. A critical issue is the sensitivity of the connection on the orientation and position of the satellite, in order to evaluate if purely passive attitude control systems have the required precision. Starting from an ideal case of perfect alignment, the calculation of the radiation flux received by the satellite should take into account for the power of the laser, the effects of atmospheric turbulence and the telescope aperture. The beam enlargement can be evaluated as follow. Let us suppose to have a station with a primary mirror of diameter $D$ and a laser with power $W$; we indicate with $r_0$ the mean Fried parameter that describes the site where the stations are located (actually, in general the atmospheric turbulence over the two sites will be characterized by different properties and we consider this approximation only in the frame of an order of magnitude estimate). Then the flux received by the back-reflector will scale as the ratio of the beam areas when it leaves the projector and when it reaches the satellite. Let us suppose that both ground stations and satellite aperture is $D$ and that, by means of adaptive optics, diffraction limited performances are obtained (see Fig.3). In this configuration the size of the spot at

![Diagram](http://proceedings.spiedigitallibrary.org/other/jpg/225.jpg)
the level of the satellite, generated by the beam fired from the transmitting station will be of the order of $r\lambda/D$
where $4r$ is the range of the satellite. The fraction of energy retro-reflected by the satellite will be:

$$I_{\text{reflected}} \approx I_{\text{fired}} \left( \frac{D}{r\lambda/D} \right)^2 = \frac{D^4}{r^2\lambda^2}$$

(1)

The same considerations do apply for the satellite to ground link and the final relationship for the efficiency of the correction is given by:

$$I_{\text{received}} \approx I_{\text{fired}} \frac{D^8}{r^4\lambda^8}$$

(2)

This interesting relationship is valid whenever $r\lambda/D > D$ a condition equivalent to the following one:

$$D = \sqrt[4]{r\lambda}$$

(3)

For a geostationary satellite $r = 3.6 \times 10^7$ m and the ideal $D \approx 4.2$ m at $\lambda = 500$ nm and 3.3 m for $\lambda = 300$ nm giving a rough idea of the maximum size of telescopes and mirrors for this type of approach. Note that there is a very strong dependence upon $D$ so one should be forced to have diameter close to the ideal $D$ unless technical or economical considerations does not impose something different.

4.1. Marketing considerations

We have started to analyse how the markets of telecommunications are structured, in order to evaluate the requirements that our optical link should satisfy to be competitive with presently available links in radio and microwave bands and with the next generation of satellites. Furtherly, our aim is to evaluate the niches that could be covered by the activity of an optical link, taking into account for the characteristics of our proposal, that allows for the transfer of a huge amount of data on an intercontinental scale.

Available data on the characteristics of the most important European satellites used for telecommunications show that the trend of the last few years is an increase of the mass of the relay, but the ratio of the total emitted power to the weight show a positive trend, leading to the conclusion of an increase of the advantages of satellite communications, making the assumption that the cost of 1Kg of orbited payload has been kept fixed. Published data also show that the lifetime of the satellites has been slightly improved (from 12 years of the first satellite of Astra to 15 of the most recent), but if we consider the increased complexity of the systems, that can be parametrized by the number of available channels, and plots the ratio of this number to the lifetime, which can be considered as a measure of the reliability of the satellite, we can see an increasing trend.

The main activities related to the transmissions of huge amounts of data through satellite include Internet connections, digital TV, Intranet services. Available studies on the field of digital television show that in the last year the number of users has continuously increased in Italy and that the future perspectives for both Italy and European Union are of a continuous growth of this segment. Worldwide, digital TV is already transmitted by the largest part through satellite.

In this framework, we believe that the perspectives of COLORS, or generally speaking of optical links, are very encouraging. Transmissions in optical band allow for a larger bit-transfer rate, while moving the technology on the ground segment should result in a lowering of the weight of the in orbit segment and a consequent lowering of the costs. From the markets perspective, one of the limitations of this kind of link is related to the difficulty in making multicasting transmissions: while it is conceivable that more than a couple of stations could be connected by the same relay, each of them using its proper signal, it is impossible to obtain an efficient transmission of the same signal from one station to more than one destination. Nonetheless, even in the case of presently available satellites a typical link consists of an emitting station and a receiving one, with the very final destinations reached by means of cables or ground-based radio links from the receiver of the optical communication, which acts as a further relay.
Figure 4. Structure of the simple model used to evaluate the effects of thermal loads and the correspondence with vibrational constraints. No particular care has been used in the selection of the materials for both the frame and the mirrors.

<table>
<thead>
<tr>
<th></th>
<th>Frame</th>
<th>Mirror</th>
</tr>
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<tbody>
<tr>
<td>Density (Kg m$^{-3}$)</td>
<td>2700</td>
<td>3000</td>
</tr>
<tr>
<td>Modulus of elasticity (N m$^{-2}$)</td>
<td>$7 \cdot 10^{10}$</td>
<td>$9.8 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.35</td>
<td>0.23</td>
</tr>
<tr>
<td>Thermal expansion coeff. (K$^{-1}$)</td>
<td>$2.3 \cdot 10^{-5}$</td>
<td>$1.0 \cdot 10^{-5}$</td>
</tr>
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</table>

Table 1. Physical properties of the materials used in the finite element calculation of the frequency spectrum and thermal loads response.

4.2. Thermo-mechanical analysis

We started to analyse a simple model of the optical relay, in order to evaluate environmental effects on its structure (Fig.4). Our model includes an aluminum frame made of a regular pattern of empty segments with circular section, outer radius of 100mm and inner radius of 90mm; the segments are arranged on a non-skewed back-reflector configuration with squared faces and sides 1m long. This configuration could be helpful in case we need to deploy the skewed back-reflector once it has reached its parking orbit. Each face of the back-reflector is covered by a mirror modeled as a square plane with a side of 800mm and a thickness of 50mm, centered with respect to the frame. We summerize the properties of the materials used in the model in Tab.1.

The analysis is performed on both theoretical and numerical grounds, where theory is used to have an order of magnitude estimate of the result and to obtain constraints for the numerical simulation. We considered two main topics: the spectrum of proper frequencies of the model and the effects of thermal loads on the structure. The knowledge of the first is necessary in order to evaluate the matching of the constraints on the vibrations response. Depending on the type of launcher and the phase of the flight, the payload is supposed to be subject to vibrations with a given spectrum. If the first frequency in the spectrum of the payload is of the same order of magnitude of the first frequency of the launcher vibration spectrum, in any given phase of the deployment, some resonance phenomena could lead to serious damages of the structure and even to the failure of the payload during the launch phase. Tab.zzz reports values of the first frequency for the main modes of vibration of the mostly use launchers and for several phases of the flight; the calculation of the frequency spectrum of the model has been accomplished by means of a finite elements analysis, considering a condition of constraints on four vertices of the structure (during the launch one face is supposed to be anchored to they payload bay). Our results, summarized in Fig.5 show that this general constraint is matched by the model.

We calculated the effects of the thermal loads on the structure of the relay, once it is on its parking orbit. We first evaluated the contribution of thermal conduction inside the mirrors to the process of heat transfer
between the system and the environment. We supposed to have a mirror with one face completely exposed to the solar radiation while the other is shaded. The first surface is supposed to behave as a grey body; by applying the standard laws of heat conduction we calculated the temperature of the second surface for the case of a negligible thickness (uniform distribution of temperature inside the mirror) and the case with a thickness of 100mm (presence of a gradient). We made standard assumptions on the spectrum of the Solar radiation, the value of the Solar constant and the amount of radiation reflected by the Earth (albedo) and emitted by the Earth itself; we assumed a emission coefficient $\varepsilon = 0.05$ and a conductivity $\ell = 0.76\text{Wm}^{-1}\text{K}^{-1}$. We found for the first case a steady state temperature of $\sim 60.2^\circ\text{C}$, while in the second case $\sim 62.4^\circ\text{C}$ for the illuminated face and $\sim 57.9^\circ\text{C}$ for the shaded one.

Finally, we calculated the duration of the transient, making the same assumptions as outlined above. We obtained that the time needed by the mirror to reach a steady state is about 90 hours. This result should be compared with the time it takes to the satellite to cross the shadow of the Earth; it is simple to show that in the geostationary orbit this happen only near the equinox, while at the solstice the relay will be always exposed to the Solar radiation. At the equinox, we found that it takes about one hour to completely cross the shadow. On this grounds, the finite elements calculation has been accomplished assuming a uniform distribution of temperature inside the structure and with the conservative hypothesis of a thermal-shock. The distribution of thermal loads on both the frame and the mirrors results in a deformation of the structure; we calculated the angle between one side of the loom without thermal loads and the same with thermal loads, which turn out to be of the order of 1/10 of degree. Such an unacceptable figure suggest that care is to be given to thermal control of the satellite. This can be done preferably in a passive manner (thermal shielding) or in an active one. Of course the latter option is to be traded-off with active control of the mirror position.

Table 2. Fundamental frequencies of some of the mostly used launchers. ($^1$) 31Hz for dual payload and 18Hz for single payload.

<table>
<thead>
<tr>
<th>Launch system</th>
<th>Fundamental frequency (Hz)</th>
<th>Axial</th>
<th>Lateral</th>
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<tbody>
<tr>
<td>Atlas II, II A, IIAS</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Ariane 4</td>
<td>(1)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Proton</td>
<td>30</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>13</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Tiatn II</td>
<td>24</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Oscillation modes studied by the finite elements simulation and one face contrained on its vertexes. On the left, two faces oscillates in phase, while on the right the oscillation of the faces is in opposition of phase. The first frequency of the spectrum of this modes is shown.
5. CONCLUSIONS

The interest in a system described here strongly depends upon the directions of need for data communications between very far places in the world in the near future. The completely passivity of the system in space is likely an attractive feature and a detailed exploitation of this and related techniques that have been only pointed out in this paper deserves a study and maybe some in-space demonstration, to assess its competitiveness with respect to more complex (but likely more flexible) systems that are going to be experimented by several Space Agencies in these days of rapidly increasing demand on data rate communications.

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