Using Light-Emitting Diodes for Intersatellite Links

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Abstract— We examine the utility of Light-Emitting Diodes (LEDs) for short-range intersatellite links (ISLs), and compare and contrast LEDs with existing laser technologies used for long-distance ISLs. A hypothetical low-end LED ISL link is described, and applications are suggested.

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1. INTRODUCTION

Current thinking on intersatellite link communication is that either the links use radio (e.g. operationally in the existing *Iridium* constellation) or via laser (demonstrated in experimental LEO/GEO connections, e.g. the SILEX payload onboard the geostationary *Artemis* satellite.) We can classify intersatellite links (ISLs) for geostationary satellites according to the distance between the communicating satellites:

(a). Long-distance ISLs, connecting distant geostationary satellites. Examples of this are the long connections outlined in Arthur C. Clarke's 1945 paper in wireless communications, making a triangle around the Earth [1], or the high-speed laser intersatellite links that were originally proposed for the satellite component of the US TSAT (Transformational Satellite Architecture) program [2]. (Its proposed link rate of 40Gbps was the maximum rate then available on commercial terrestrial optical fibres.)

Since these links between geostationary satellites traverse tens of thousands of km through free space, use of expensive highly directed lasers is expected. Such long-distance ISLs are actually not that useful for network communications, as their propagation delays add significantly to the end-to-end path delay that the geostationary satellite uplink and downlink previously dominated. This long delay degrades the performance of many network transfer protocols such as TCP, and is far less than ideal for interactive real-time applications. Still, the military desire to be able to communicate to anywhere, without relaying through bottleneck ground stations, drives their demand for long-distance ISLs.

Laser links have also been proposed for connecting geostationary satellites with low-Earth-orbiting satellites, with aircraft or direct to the ground. Connecting to rapidly-moving LEO satellites poses engineering challenges for acquisition and tracking; connecting through the atmosphere adds additional signal loss and interference.

(b). Short-distance ISLs, between formation-flying satellites that are relatively near to each other (tens of km or less) and stationkeeping together. The satellites are close enough to be able to interact to create a 'virtual satellite' cluster that is made up out of all the communicating satellites, and is more than the sum of its parts. This clustering can also be applied to nearby stationkeeping geostationary satellites [3]. Formation flying is the foundation of the DARPA F6 effort [4].

Because the local links in b) are much shorter distance than the links discussed in a), use of lasers and the extremely accurate pointing they offer can be considered engineering overkill for this application. These shorter local links are commonly expected to be high-frequency wireless links.

Reuse of terrestrial wireless technologies, adapted for space and for increased distance, has been proposed [5]. However, these terrestrial technologies are constrained in frequency to the intersection of the sets of what works well in atmosphere, and what is permissible in allocated terrestrial regulatory bands. One disadvantage to using high-frequency radio is the possibility of electromagnetic interference from sidelobes affecting other payloads, complicating electromagnetic interference, testing and payload integration.

In the vacuum of space, where there is no need to contend with atmosphere and its attendant scattering, rain fade and turbulence affecting polarization and phase, free space loss remains the major consideration. This free space loss with distance is much less than with the long-distance links described earlier in (a). A wide beam spread to encompass a swath of volume where a neighbouring satellite is stationed is advantageous, because it simplifies tracking and pointing. Broadcast shared by multiple neighbouring satellites becomes possible with a wider beam spread. Such a spread can be provided by LED-based assemblies.

Free-space optical communication with LEDs has been demonstrated successfully terrestrially for communication across a distance of one hundred and sixty kilometers using low-power one-watt LEDs with Fresnel lenses to collimate

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[1] 978-1-4244-3888-4/10/$25.00 ©2010 IEEE
[2] IEEEAC paper#1418, Version 7 final, Updated 2009:11:30

the light [6]. That in-atmosphere test suggests that LEDs can easily meet distance requirements for short-range ISLs.

2. REVIEW OF EXISTING OPTICAL ISLS

Laser intersatellite link technologies are available from several suppliers, including TESAT-Spacecom and COMDEV. A number of laser links are now in use in orbit, and are briefly summarized here.

SILEX and Artemis

The ESA SILEX laser terminals onboard the geostationary *Artemis* and low-Earth-orbit SPOT 4 satellites use a 60mW GaAlAs laser diode with a 25cm telescope aperture. The assembly masses 160kg and uses 150W of power to provide a data rate of 50Mbps. Over a period of three years, from March 2003 to late 2006, these terminals have had a total active time of less than two weeks, due to occasional experimental use [7]. *Artemis* has also communicated by laser with the Japanese *OICETS*/*Kirari* satellite [8].

Even with optimistic use of half an hour of operation per day to transfer data from LEO satellites, SILEX is unlikely to reach the operational lifetime of its laser components before the experiment is declared a success and shut down, or the satellites carrying the SILEX terminals are decommissioned.

However, we can expect geostationary satellite use of intersatellite links for network communication to be continuous, so that two weeks' operational activity will be achieved in two weeks for the components in question, and the lifetime of the laser components will be reached as rapidly as possible.

CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (*CALIPSO*) satellite was launched in April 2006 with redundant laser assemblies onboard.

A leak in the primary gas laser was recognized before launch, but considered slow enough that the initial test campaign could be completed successfully. Operations then switched to using the backup laser in March 2009 [9].

The *CALIPSO* laser assemblies were made by Ball Aerospace. Although this is a LIDAR sensing rather than a communications application, with rather different requirements, Ball Aerospace had also previously considered redundancy as necessary for laser intersatellite links due to lifetime issues, and discussed placing backup laser assemblies onboard to address this [10].

NFIRE and TerreSAR-X

An intersatellite link between these two satellites has been operated since February 2008 [11]. Similar hardware is planned for the long-distance links between the satellites of the planned European Data Relay Satellite System (EDRSS).

Laser life is recognized as short, requiring backups and replacement in-orbit. (This will be familiar to anyone who has had a compact disc player stop working after a few years because its laser diode has reached end of life – although the LED indicating the power is on continues to glow well.) As such, laser diode or gas laser life is not a good match with the increasing lifespans of geostationary spacecraft. LEDs have longer lifetimes than laser diodes, provided that they are not overheated [12]. This long component lifespan is a better match with the lifespan of a geostationary satellite.

3. LEDS FOR COMMUNICATION

LEDs were a precursor to laser diodes for optical fibre communication. Fiber distributed data interface (FDDI) uses 1325nm-peak LEDs illuminating multi-mode fibre at 100Mbps [13].

Use of LEDs for free-space communication is well-known for infra-red remote controls and low-speed links on computing equipment, standardized by the Infrared Data Association (IrDA).

Existing IrDA components can provide link speeds of up to 4Mbps, while gigabit speeds are under development by the IrDA association. However, IrDA is targeted to very short range use. The IrDA IrPHY physical specification only requires an operational range of 1m and a beam width of a minimum of 30 degrees at approximately 875nm; existing available hardware exceeds this specification.

LEDs have been experimented with previously for high speed communications, e.g. the early experiments in [14] which demonstrated communication rates of 2Gbps and estimated a useful LED lifetime of over ten years. Refi [15] discusses uses of LEDs in fixed optical networks. Komine [16] discusses use of modulated white LEDs for illumination and indoor communications at rates of 1Gbps or better.

LEDs have been evaluated and flown in orbit for *intra*-satellite communication between internal assemblies onboard satellites [17], but have not been used for *inter*-satellite communication with LED intersatellite links.

4. HYPOTHETICAL LED ISL USE

Let's examine a hypothetical link between satellites established using LEDs and photodiodes [Fig. 1]. We assume a conservatively short 1km distance between station-keeping formation-flying satellites. Examining data sheets from LED suppliers such as Cree Inc., let's use an example 1W blue LED with an output peak around 465nm.

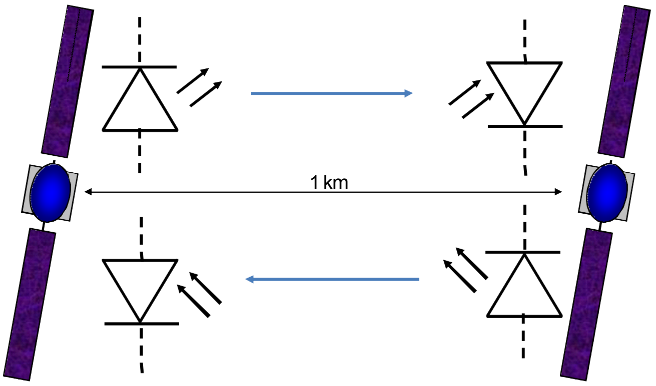


Figure 1: LED/photodiode links between satellites

This LED has an output of 20 lumens across a cone of 40 degrees, i.e. 6.37 candela. That equates to:
6.37 * 18.4mW = 117mW output across the 40 degree cone. (Infrared LEDs do have higher optical-to-electrical power efficiencies, but the higher frequency range of the blue LED offers higher modulation rates.) We presume that the LED's relatively wide beam of 40 degrees can be relied on to compensate for positioning variation in the satellites, without being aimed or focused.

For receivers, avalanche photodiodes have increased quantum efficiency over, and lower power consumption than, traditional photodiodes with photomultiplier tubes [18]. Some commercially-available avalanche photodiodes are able to work with high detection efficiencies at remarkably low incident photon rates, and links of over 100kbits/s have been established with very few photons striking such diodes [19].

Large avalanche photodiodes with surface areas of 100mm^2 or greater are now commercially available from Hamamatsu and are being considered for use in space instruments [20] [21]. We select a simple photodiode without more sophisticated optics to examine what is possible with minimal low-end hardware.

A sample avalanche photodiode to be used for the receiver has a typical Noise Equivalent Power (NEP) of roughly $7\text{x}10^{-15}\text{W/Hz}^{0.5}$. Assuming a bandwidth of 3MHz, that equates to a noise power of $2.9\text{x}10^{-12}\text{W}$. The photodiode has an active surface area of 100mm^2.

At 1km distance, the power of the LED's output will be spread over a 40 degree cone whose circular area is of diameter 2πr(40/360) = 2π1000/9 = 698m. This leads to an area of $\pi(349)^2$, or $382{,}649\text{m}^2$, or $3.8\text{x}10^{11}\text{mm}^2 0.117\text{W}$ / $3.8\text{x}10^{11}\text{mm}^2$ * 100 mm^2 = $3.1\text{x}10^{-11}\text{W}$ falling on the receiver – above the receiver noise floor. This gives a signal-to-noise ratio of 20.5dB, which leaves some margin for degradation in performance over time in both transmitter and receiver due to proton fluence in irradiation.

Avalanche photodiodes have fast rise times, in the hundreds of picoseconds range or faster [22]. With a conservative photodiode receiver rise time of 1ns, and an LED rise time of around 150ns, the LED rise time will be the limiting factor on communication speed. (AlGaAs heterojunction emitters have previously been recommended for their fast rise times and their decreased sensitivity to displacement damage when compared to homojunction LEDs [21].)

A simple on-off keying (OOK) mechanism, as used in IrDA protocols, can be implemented. Return-to-zero (OOK-RZ) was recommended for its simplicity and ease of use [17]. Assuming the rise and fall times are included in a conservative pulse width of 600ns, a raw bitrate of over 1.5Mbps can then be supported before coding overhead to decrease errors. Such a rate is more than sufficient for remote networked telecommand and control. More advanced modulation and coding schemes can increase the supported bitrate.

Addition of a Fresnel lens to focus the beam, at the loss of some spread, can increase the received power as in [6], allowing for more sophisticated modulation choices.

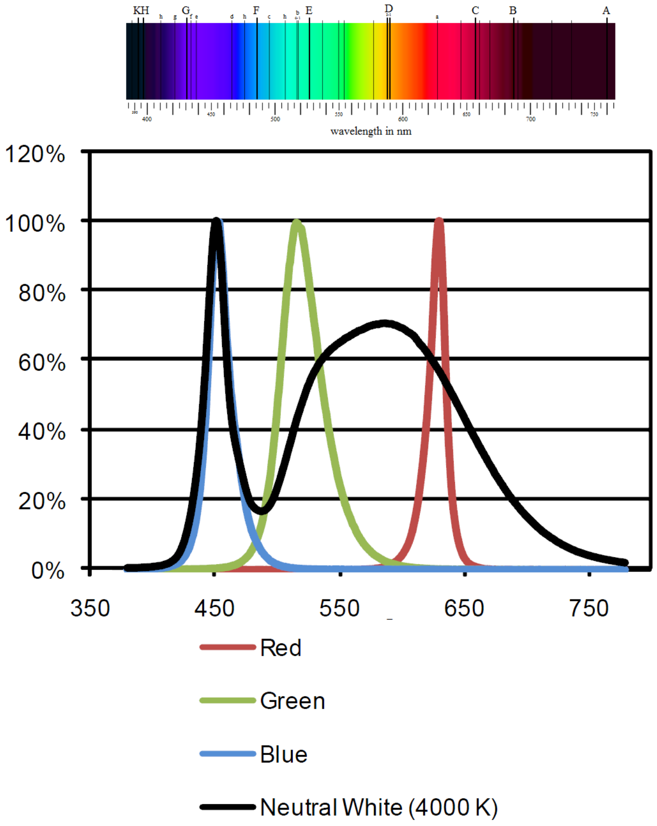
5. FRAUNHOFER ABSORPTION LINE OVERLAP

Our simple worked example has neglected other noise sources. Noise from the Sun affecting detection of laser signals, where it is significant when compared to the laser strength, is recognized as a problem for intersatellite links. Sunlight will also be reflected off satellite bodies and thermal shielding. However, at some frequencies – the Fraunhofer lines – the Sun's output spectrum has already been absorbed by elements present in the Sun, and the power and resulting noise from the Sun at those frequencies is reduced.

Using photodetectors behind optical filters selected to match Fraunhofer lines can enable clear signal detection even when the detector is directly facing the Sun. An LED's broader spectrum output can be certain to overlap Fraunhofer lines, as shown in Fig. 2; a laser's narrow output needs tuning to match the line frequency.

The narrowness of the line restricts available power at those frequencies and thus signaling rates. Very low-rate signaling, at low power, that is robust to peering into the Sun, becomes possible simply by using photodiodes and filters selected to monitor Fraunhofer absorption line frequencies. A yellow-green LED's peak emission overlaps the Fraunhofer Na (sodium) absorption lines of the Sun (peak around 594nm, vs 589.6 and 589nm for D1/D2). A blue LED's spectrum overlaps with the G lines for Fe/Ca (iron and calcium) at around 430.78nm.

A sensor behind a filter tuned to a specific absorption line frequency will not be concerned with Sun interference. (Note that passive filters will also limit the acceptable incident angle.)



sources of graphs used for this comparison:
Cree Inc. data sheets, Wikipedia entry on Fraunhofer lines.

Figure 2: Overlap of Fraunhofer absorption lines and relative peak intensities for coloured LEDs

Some rotation in the observed satellite or Doppler effects can be dealt with by the LED's peak just shifting a little back and forth in *f* while still covering the selected line without retuning. Effects of movement due to Doppler could be measured by characterizing the LED power at distance and comparing measured power at the D1 and D2 frequencies, although this would be likely to require sensitive receivers.

6. COMPARISON OF LEDs AND LASERS

We can summarize the relative advantages and disadvantages of LED- and laser-based intersatellite links as follows:

Advantages of LED-based intersatellite links

- Inexpensive.
- Robust to (potentially radiation-induced) overcurrent and reverse bias, unlike diode lasers.
- Wider operational temperature range and tolerance than laser diodes.
- Longer lifespan better matching geostationary satellite lifetimes – far longer than gas lasers, longer than diode lasers.
- Less fragile or complex than gas lasers.
- Significantly lighter mass of components than gas lasers. Better size, weight and power consumption.
- Wider beamspread eases pointing, simplifying pointing assembly complexity and mass.
- Wider frequency band can provide robustness to some Doppler effects.
- Do not require special eye-safety precautions or protective goggles during assembly, integration and test.

Disadvantages of LED-based intersatellite links

- Wider beamspread, lower overall power and non-monochromatic emission means lower power/surface area, limiting overall useful distance compared to more complex laser assemblies.
- Lack of self-interference from non-coherence is an unimportant factor outside atmospheric turbulence.
- Lower frequency decreases top modulation rate and overall communications rates.
- Slower rise and fall times than diode lasers, limiting maximum switching speed and thus overall link throughput.

Other applications

As well as being useful for formation-flying clusters of satellites, the spread beam of LEDs may be useful at short distances as spacecraft exchange information while coming in to dock with one other. Once docked, the LED and photodiode mounts can be perfectly positioned to continue communication without needing to connect cables.

7. CONCLUSIONS

LEDs are more robust than laser diodes or gas lasers. There is a slower top modulation rate than for a laser, but link rates of megabits per second can still be expected to be supported.

Use of relatively cheap LED technology for short, low-range, low-performance intersatellite links appears able to complement the power and directionality of more expensive optical laser intersatellite links intended for long distances and high performance, while creating robust links with long lifespans.

Light-emitting diodes appear to have potential as a technology enabling low-cost, light, relatively short-range, low-rate intersatellite links for formation-flying spacecraft and satellites. This warrants further, more detailed, investigation.

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