WHITE PAPER

Wireless Laser Communications

Successfully combining weather forecasts and free-space optical communications

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Background

Airbus and Reuniwatt presented the state-of-the-art of free space communications and some of the latest advancements in wireless laser communications research in their joint webinar “Wireless Laser Communication: Don't let clouds get in the way of success!” on the 24th of June 2021. The webinar discussed the opportunities for the widespread use, standardisation, and optimisation of Free Space Optical Communications (FSO) systems, with a focus on using precision weather forecasting to ensure the best possible transmission of the signal through the atmosphere at any given time. In this white paper, Reuniwatt presents an overview, with contributions from Kevin Shortt, research project leader at Airbus.

Glossary

COD	Cloud Optical Depth
EDRS	European Data Relay Satellite System
FSO	Free Space Optical Communications
GEO satellites	Geosynchronous Equatorial Orbit Satellites
HAP	High Altitude Platforms
LEO satellites	Low Earth Orbit Satellites
OGS	Optical Ground Station
RF	Radiofrequency

Executive summary

Radiofrequency (RF) communications have been used for many years, but a number of limitations have led to consider optical communications as the next technology to communicate with satellites. Indeed, they offer a vast unlicensed spectrum compared to RF's congested band, provide up to 100 times the data rates of current RF systems, are extremely difficult to detect and, therefore, to jam.

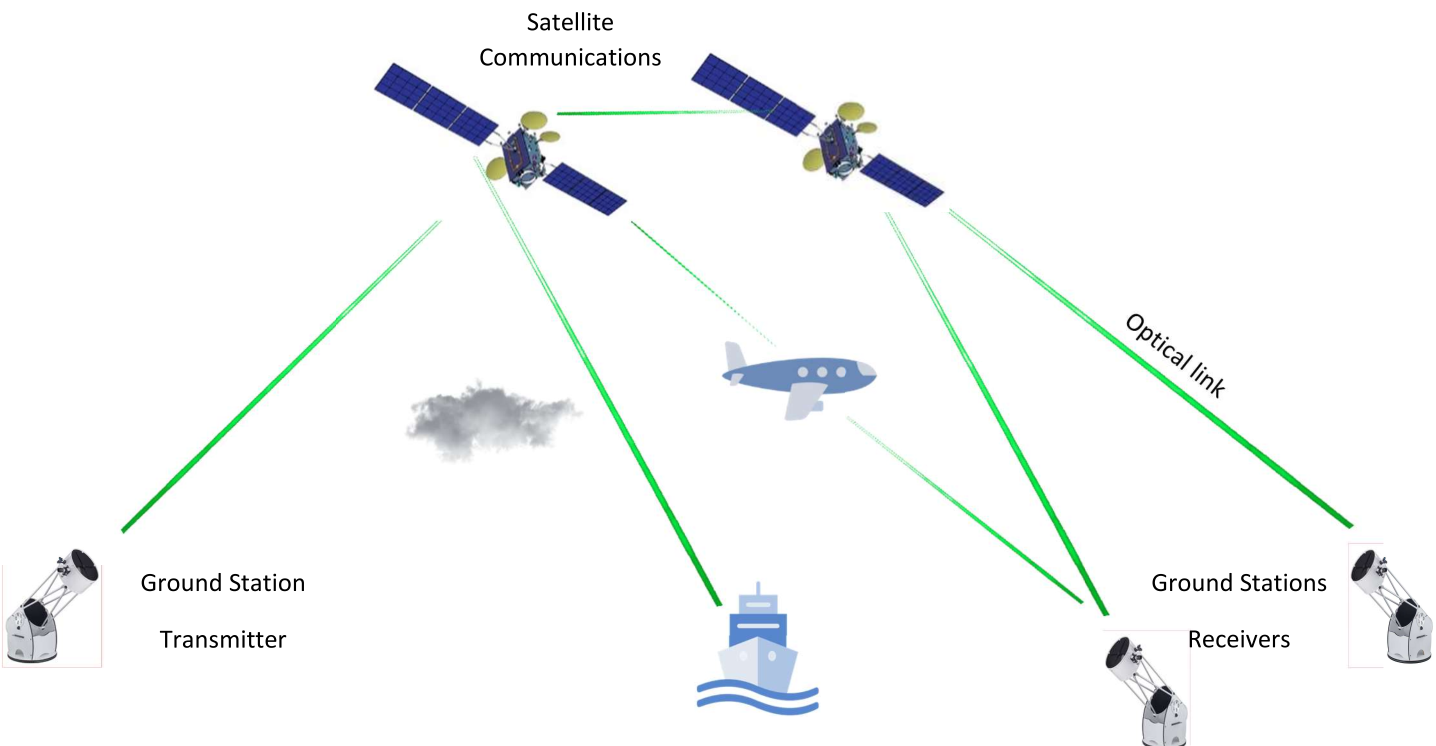

Figure 1: Free-Space Optical Communication can provide high speed connectivity between different platforms (satellites, ground, air and maritime)

Free Space Optical Communication technology, more colloquially known as wireless laser communication, provides a high-speed means of exchanging data and other services as transmission is performed wirelessly with the use of lasers. Such links can be used for communication between different devices (satellites, ground stations, boats, airplanes…), as shown in Figure 1.

Regarding its applications, wireless laser communication has primarily been used operationally between satellites. For instance, in EDRS (European Data Relay Satellite System), LEO (Low Earth Orbit) and GEO (Geosynchronous Equatorial Orbit) satellites communicate with an optical link while communication with the ground stations is done with RF.

However, wireless laser communication between ground stations and satellites and/or aircraft poses an additional challenge compared to links between satellites themselves because the transmission of the laser beam through the atmosphere causes instability of the communication link, in much the same way as rain affects radio signals. However, in the case of laser communication, it is turbulence and aerosols in the atmosphere that interfere with the transmission of the signal, while thick clouds can even make communications impossible.

This white paper presents the state-of-the-art of wireless laser communication and examines the opportunities for the future development, and eventual deployment, of heterogeneous communication networks that incorporate the use of wireless laser communication systems. Such networks have the potential to provide data transfer rates to a wide variety of platforms flying above the Earth's surface, in particular aircraft, that are several orders of magnitude faster than today's air-to-ground communication systems. However, in order to ensure the seamless operations of these optically enhanced networks, the negative effects of weather must be minimized by means of precision cloud forecasting. The ability to exploit cloud forecasts will allow for timely, as well as automated, decisions to be made in order to optimize the packet routing within a network of ground stations at any given time, a critical element of the overall network operations when routing data at 10s or 100s of gigabits per second (Gbps) to moving platforms.

State-of-the-Art: FSO in Aerospace Communications

Demonstrations of various applications and hardware for wireless laser communication have taken place over the last 20 years. They have ranged from links to aircraft to links all the way to the Moon. While successful in their own right, they have often not progressed much beyond the demonstration phase for a number of reasons, primary of which has been the maturity of the technology. As is often the case with new technologies, a sufficiently established business case is required in order to see significant enough advancements in the technology for it to find viable commercial applications.

One of the earliest demonstrations for laser communications in space was the European Space Agency's SILEX programme, which concluded in 2001. The purpose of the mission was to establish an optical link between the SPOT-4 Earth observation satellite in low Earth orbit and the Artemis satellite operating in geostationary orbit, some 31,000 km above the Earth's surface. The mission showed that images could be relayed from SPOT-4 to Spot Image located in Toulouse, France, via the Artemis satellite and the then incredible speed of 50 Mbps. The success of the demonstration paved the way for what eventually has become the European Data Relay System (EDRS), which continues to deliver data transfer services at the more impressive rate, albeit still modest by telecommunication standards, of 1.8 Gbps.

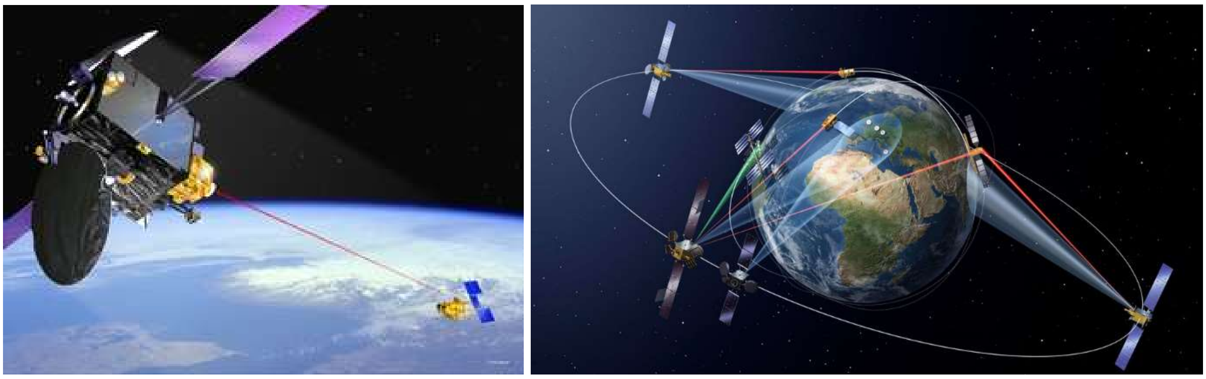

Figure 2– ESA's SILEX programme was the world's first demonstration of inter-satellite laser links (left) and laid the foundation for today's European Data Relay Satellite system (right). (Image credits: ESA)

In the ensuing years, other space agencies have pursued their own developments in wireless laser communications, most notable of which has been NASA with their ambitious pursuit of establishing high speed links to such far off destinations as the Moon and Mars. NASA likely has one of the most comprehensive roadmaps when it comes to wireless laser communications for space exploration and they have already tested successful links from ground stations to the Moon with their LADEE mission. This feat was made no less challenging by the fact that after traversing millions of kilometers in space, the signal had to contend with Earth's atmosphere and possible cloud coverage at the ground station sites, which is why one ground station was located in a desert in the U.S. while the other was located at ESA's astronomical observatory on the island of Tenerife. While the choice of sites offered relatively pristine atmospheric conditions to ensure the success of the demonstration, these sites are located far from terrestial fiber networks and so would be unsuitable for broader commercial exploitation without an alternative way of dealing with atmospheric outages.

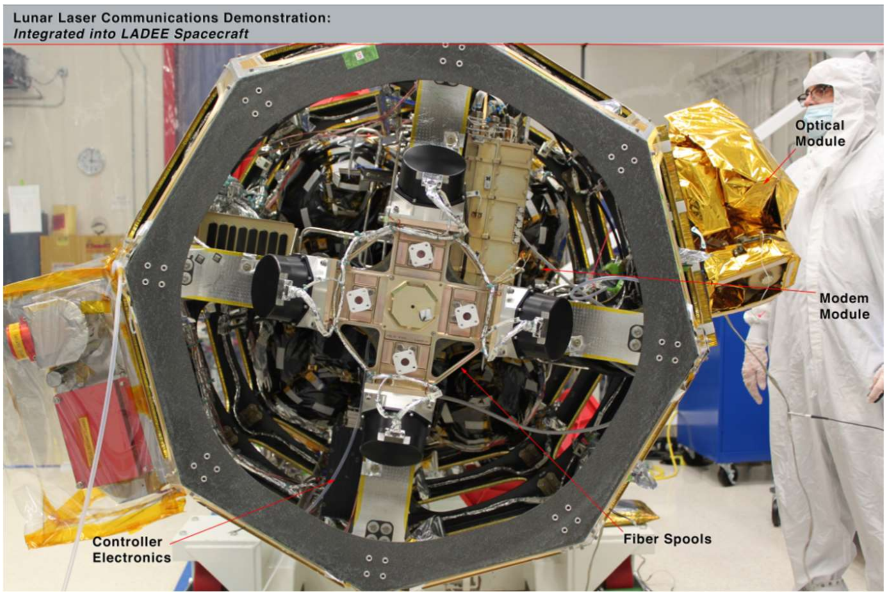

Figure 3 - Laser communication hardware integrated into the LADEE spacecraft. (Image credits: NASA)

It has really been only in the last 6 or 7 years where wireless laser communications has received a higher profile in the mainstream market. The two main catalysts to this trend were Google X's Loon programme and Facebook's Aquila programme, both of which were predicated on the idea of providing internet access to those geographic areas that are either underserved or unserved – an expression that has become a rallying cry for expanding the business of telecommunication operators all around the world. While both programmes have since shut down in pursuit of more lofty concepts, they both envisaged an architecture based upon providing internet access from thousands of so-called high altitude platforms (HAP) or pseudo-satellites flying at altitudes of 20 km that would be interconnected using wireless laser communications. This vantage point offered a number of advantages over traditional satellite or terrestrial infrastructure in that a single platform had a wider coverage area than that of a cell phone tower but were capable of landing, being repaired or upgraded, and being launched again unlike a satellite. In the end, the balloon and aircraft technology upon which Google's and Facebook's concepts were based was not deemed mature enough for commercial deployment.

Figure 4 – One of Google Loon's early test flights with the laser communications payload located on the platform below the balloon. (Image credits: Google)

At the same time, however, low Earth orbit satellite constellations were seeing a re-emergence from the likes of SpaceX and OneWeb who had similar ambitions of extending the reach of today's internet. Since satellite launch costs have seen a significant decrease over the past decade, helped in no small part by the efforts of SpaceX, space has become more accessible and the idea of operating a large constellation of satellites – on the order of thousands of satellites – has become more attainable. Again, wireless laser communications stands center-stage as the technology that would connect the satellites to each other as they orbit the Earth and deliver internet access to users around the world. Other companies, such as Telesat, Amazon, and Kepler Communications, have since joined these earlier efforts by proposing their own constellations. The jury's still out on whether any of these latest orbital efforts will be a commercial success in the long run but, for the moment, they're giving commercial momentum to the advancement of wireless laser communication technology.

Figure 5 - A batch of Starlink satellites readied for launch in January 2021 that were confirmed to be equipped with inter-satellite optical links. (Image credits: Pranay Pathole at Twitter)

One aspect that each of these network architectures share is the fact that, in order for them to provide a true extension of fiber networks, laser links will need to traverse the Earth's atmosphere. Such links will either be the so-called feeder links between the ground and whatever platform they are connecting to above the Earth's surface, be it HAP or satellite. Furthermore, links between HAPs will be impacted by the atmosphere despite the platforms flying above a bulk of it. Laser links through the atmosphere not only pose a quality of service challenge but also an operational challenge as the laser links will need to navigate around such obstacles as clouds. A network of cloud and turbulence monitoring will play an essential role in providing a robust network service from above the Earth's surface.

Conclusion

The number of demonstrations of wireless laser communications in the aerospace and space sectors over the past number of years have contributed significantly to the overall advancement of the technology. However, the challenge still remains as to how this technology can be exploited within a larger commercial context in order to support viable communication services business models.

Adopting FSO in everyday communication

Today, people worldwide are becoming more and more reliant on the Internet, which is putting pressure on service providers to feed that demand. Internet service providers are racing to lay fiber optical cables where they can in order to increase the capacity of their networks. However, the regulatory and logistical challenges to obtaining permits and burying the cables create a bottleneck to the growth of networks. In this context, wireless laser communications has carved out a reasonably meaningful niche for itself in the form of so-called static links that provide high bandwidth network capacity over distances spanning a few kilometres between two buildings. While this application of the technology has addressed the "last mile" problem, it does not address the more rapidly growing mobile market or markets that exist beyond the reach of current fiber networks (e.g. rural regions). It is in these areas of application where the technology demonstrations described in the previous section become more pertinent.

Given that wireless laser communication technology can provide throughputs on the order of hundreds of gigabits per second, which are more in keeping with the throughputs of terrestrial fiber networks, telecommunication operators are looking to the aerospace industry with greater interest. No longer will they have to limit their business cases to the paltry data rates that are now available via satellite. Wireless laser communication technology now opens up the opportunity for these operators to view constellations of satellites as a natural extension of their fiber networks. Furthermore, data can not only be delivered around the world by a few short hops over satellite but can also reach people on the move as if they were connected to their home internet service. Such availability of bandwidth to mobile platforms opens up tremendous possibilities for delivering new services to places that were impossible to reach previously.

Consider for a moment the idea of sitting on a plane over the ocean and having a conversation with family members elsewhere in the world with the latest in high definition video calling. Or even having that important board meeting in augmented or virtual reality. Just as fiber connectivity on the ground has changed how people interact from home or work, wireless laser communications will change the way people stay connected when they are away from these fixed locations. It is this future that the likes of all those pursuing constellations of satellites, networks of high flying solar powered aircraft, or other exotic network architectures are committed to realizing.

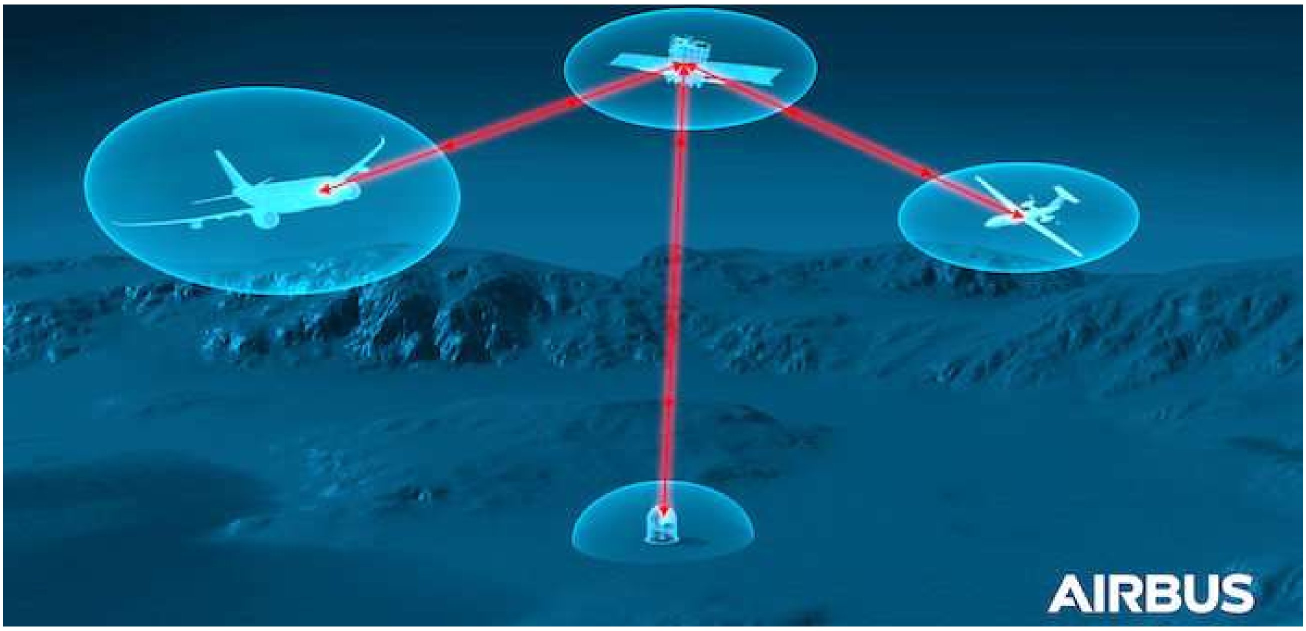

Figure 6 – Airbus, together with partners in the Netherlands, is developing technology to connect aircraft to satellites with lasers. (Image credits: Airbus)

Conclusion

Despite the individual successes, there still is a lack of critical mass of proven technology to really break into the mainstream market. The maturation of the technology can be seen in the efforts of the companies that are currently taking the early steps of deploying this hardware in systems that are attempting to deliver viable services to end customers. As the deployment of this next generation infrastructure continues, it will surely accelerate the advancement and subsequent adoption of the technology of the wider telecommunications industry.

"The idea is simple: Establishing a ground station network that allows switching the link from one station to another when necessary."

Olivier Liandrat, Sky Imaging Expert at Reuniwatt

The impact of weather on wireless laser communications

Weather is a key factor for establishing a successful FSO transmission link through the atmosphere. A loss in signal intensity or attenuation, can be caused by several weather conditions, such as heavy rain or fog, and weather is the main cause of attenuation overall. The system design and direction of the laser beam are other factors impacting the signal.

About 70% of the Earth's surface is covered by clouds, which are a main part of the Earth's atmosphere. Free space optical communication is affected by clouds, which are basically water deposited above Earth's surface. The most-used wavelength (1550nm) favours a good transmittance through the atmosphere and is now being standardly used for FSO. However, the occurrence of clouds directly impacts the laser communication signal passing through the atmosphere. Cloud Optical depth (COD) is the key parameter to assess the effect of clouds on free space optical communications from satellites to the ground or from/to aircraft, with I_0 being the original intensity and I the final intensity after the beam passes the cloud

$$COD = -\ln\left(\frac{I}{I_0}\right)$$

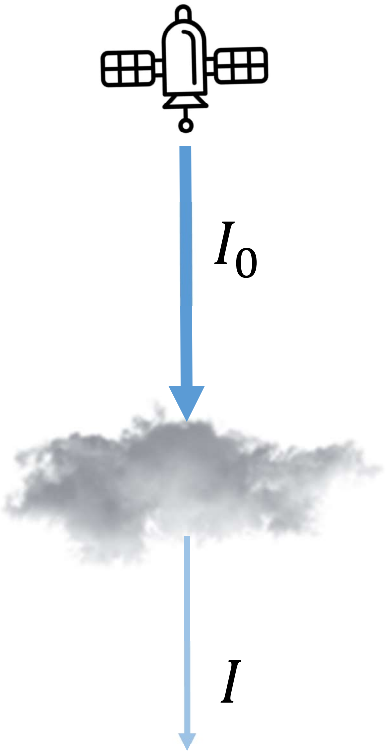

Figure 7: Free-Space Optical Communication signals will be impacted by the clouds' optical properties

COD is proportional to the cloud's liquid water density (kg/m^2) and allows to estimate the scattering and absorption properties based on the cloud thickness and particle sizes. The typical radiative properties of the common types of clouds can be evaluated by different means: Global annual mean data sets are available from different providers, but offer only statistical evaluations by region and cloud type. Satellite imagery can also be used to obtain cloud data in real time and is especially useful to forecast low elevation clouds which might not be on the sky imager's horizon because they are still too far away.[1] However, the most accurate short-term forecasts of cloud motion and cloud properties for one location can be obtained from the ground using a sky imager in the infrared spectrum.

Sky Imagers for Cloud Forecasting

Infrared sky imagers are the means of choice to tackle the upcoming minutes' forecasting challenges for FSO systems as they must provide cloud data 24/7 to ensure their operational status. These devices can

[1] Nugent, P.W., Shaw, J.A. and Piazzolla, S. (2009): *Infrared cloud imaging in support of Earth-space optical communication*. Optics Express, 17(10), pp. 7862-7872.

provide highly precise solar irradiance and cloud property forecasts for the next 30 minutes. It takes a couple of minutes to half an hour to handover operations from one ground station to another in case of a cloud event, therefore, it is crucial to anticipate the changes in the cloud cover before it impacts the actual signal, and make sure the stations are always selected accordingly.

In general, cloud cover and solar irradiance forecasts are distinguished by their forecasting horizons:

- Day-ahead (**DayCast**™) – based on Numerical Weather Prediction (NWP) models, up to several days ahead
- Intra-day (**HourCast**™) – based on satellite images, from 15 minutes up to 6 hours ahead
- Intra-hour (**InstaCast**™) – using an all-sky camera, from 1 minute up to 30 minutes ahead.

The thermal-infrared camera **Sky InSight**™ (8-13µm) is providing a 360° field of view thanks to a hemispherical mirror. With its embedded computer for data acquisition and processing, it allows either for offline processing or communication via the Internet. The product is robust and durable, resistant to all-weather conditions. Using an infrared-range camera instead of a visible-range camera allows to avoid the sun glare effect or diffusion which happens in the image area where the sun is located. It also allows for a clear distinction between clouds and the clear sky. Reuniwatt's intra-hour forecasting technology **InstaCast**™ gives highly precise forecasts for the upcoming 30 minutes. For FSO purposes, it can be used to ensure night and day operationality of the available optical links.

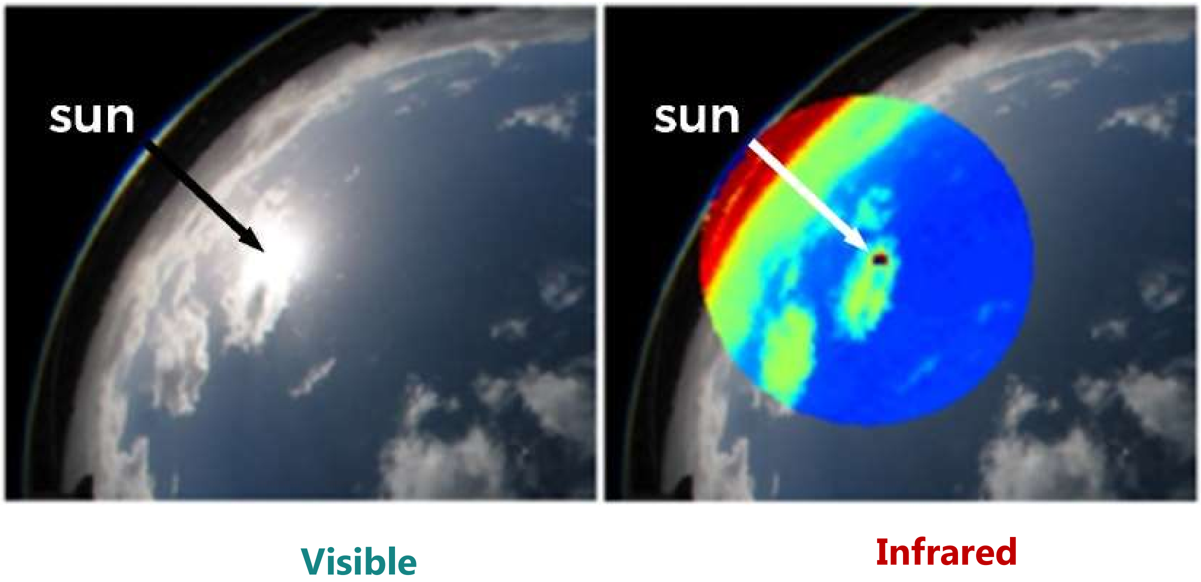

Figure 8: A visible range sky imager (left) is affected by the sun glare effect from the surrounding clouds. Infrared technology (right) allows to overcome this issue, and provides images with the same clarity during the night as it does during daytime.

Reuniwatt's software **InstaCast**™ processes the obtained images to precisely and reliably forecast cloud motion and properties and provides real-time information sent to the concerned Optical Ground Station. Uses of sky imagers besides FSO includes atmospheric sciences, solar energy and monitoring of the sky for air traffic controls.

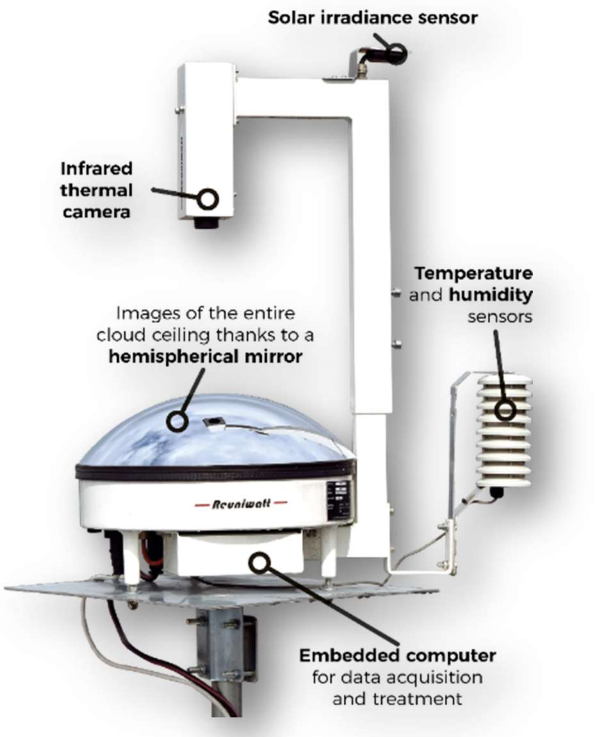

Figure 9: Sky InSight™ sky imager by Reuniwatt

Once installed, the sky imager's optical field-of-view must be calibrated according to its position relative to the sun. After this initial calibration, raw images are processed every 30 seconds, deriving the optical properties of the clouds as well as retrieving the cloud movements by optical flow algorithms. The cloud motion vector can be assessed from consecutive images using Farneback's optical flow algorithm and allows to derive the unique wind direction. Forecasting errors can occur, including due to the complex non-linear movement of the clouds in the field-of-view of the sky imager. Besides the deterministic approach, machine learning and statistical models are methods being used to make the forecast a valuable decision-making tool for a ground station handover, even in the case of multi-layered clouds, rain or other phenomena.

Satellite Images for a smooth Handover

For satellite-to-ground line-of-sight forecasting, it can be beneficial to combine the forecasts from a sky imager with forecasts derived from satellite imagery, because the field of view of the locally installed sky imager is limited (depending on the presence of clouds at low altitude and the surrounding landscape). Meteorological satellites are delivering quality data worldwide and provide high-resolution images ca. every 10 to 15 minutes (depending on the satellite). Processing these raw images allows us to compute the cloud motion vector using an optical flow algorithm and extrapolate the cloud motion for the upcoming minutes and up to 6 hours ahead. These forecasts derived from satellite imagery have a much better resolution for this time horizon than Numerical Weather Prediction models, which are best suited to longer time horizons. Therefore, they are a welcome bonus to the highly precise short-term forecasts from sky imaging technology and will enable the FSO control centres to activate a handover from one FSO ground station to another, when necessary, while optimizing the number of handovers and allowing for a stable transmission.

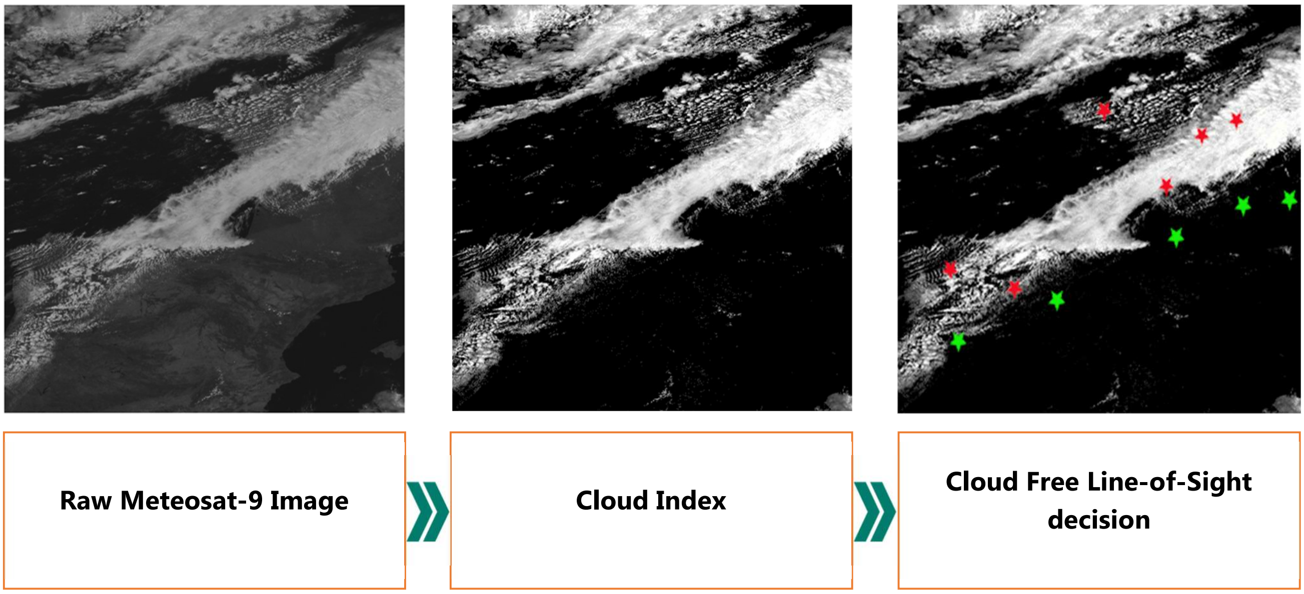

Figure 10: Satellite image processing for Free Line-of-Sight Decision (Red stars indicate a potential blockage of the signal by clouds, and green stars indicate a free line-of-sight)

Conclusion

There are several challenges to face in implementing FSO systems, but their expected massive expansion, as recently promoted by a few companies, will enable high-speed services at many places.

FSO experts are aware that cloud forecasting technology is essential to establishing stable and high-quality transmission systems. With these forecasts, optical ground station networks can determine the most efficient and stable connection between the ground and aircrafts and/or satellites. Because the optical wave can be degraded or even blocked by turbulence, aerosols and clouds, all-sky cameras and satellite images are the necessary means to forecast which ground station(s) can provide the best connection to a satellite.

FAQ

Will FSO be the base of space-to-Earth communication in the future?

Historically, that was one of the areas which pushed the development of FSO technology forward. Wireless Lasercom offers two advantages: It needs little energy supply while providing high data rates, which makes it very attractive for space missions, e.g. it allows for the use of much smaller telescopes to be able to transmit a certain amount of data back from Mars to us, and has expanded the data transmission boundaries for space missions beyond the earlier standards.

Which key advances in optical components will support inter-satellite FSO?

We see improvements in technology happening in mirror designs, fiber amplifiers and positioning technologies. Latter are mature from a capability perspective, but still relatively expensive. From the optical antenna and back-end electronics perspective, it is important for improving communication payload to rely on optical communication as long as possible: For this purpose photonic integrated circuits were developed, which allow for higher efficiency in the areas of multiplexing, demultiplexing, managing channels etc. Bringing these technologies into orbit and installing them on satellites is essential to counteract potential bottlenecks inside the spacecraft and update the state-of-the-art of onboard payload communication. In short: The communication onboard the satellite must support the communication to/from it.

What are current FSO related activities of Reuniwatt and Airbus?

Airbus is a world leader in optical communications. Regarding satcom, we have a lot of operational experience. One notable project is the Space Data Highway, a public-private partnership between ESA and Airbus. One focus of airbus lies in closing the hardware compatibility gap between LEO and GEO satellites and the terrestrial networks. Reuniwatt has been working together with the Saint-Exupery Technological Research Institute IRT. Together with them, we have been working on the BroadBand Satellite Access project ALBS (2014-2020). Currently, we are on board the 4-year research project ANAtOLIA funded by ESA, aiming to overcome cloud cover, aerosols and turbulence in FSO.

How do you evaluate forecast accuracy?

What is important to remember is that performance can be described along three axes:

- The weather sensitivity for the location: For the French overseas islands, it is mainly the tropical climate, to which must be added the extremely important concept of microclimates. For example, on the 2500 km² of Reunion Island, there are no less than 200 microclimates! We must also add the notion of seasonality. In tropical climates, the summer is generally very hot. With the sea nearby, this will create a favourable ground for evaporation and therefore for cloud formation. In winter, evaporation being weaker, we will mainly see clouds moving. Thus, the meteorological phenomena to be taken into account vary according to the location and will directly influence performance.

- The quality of input data: Reuniwatt aggregates a lot of data from different sources, such as measurements from pyranometers in real time. This input data is then used to calibrate our forecasts, which means that there is a real O&M (Operations & Maintenance) challenge to work on over time so that this quality monitoring system remains effective.

- The metrics: How do we evaluate the precision of a forecast? The most commonly used scientific metric is the nMAE ("normalized Mean Absolute Error"). Climatological analyses to identify the meteorological phenomena at the sky imager location or "backtests" (forecasts made under real conditions but on past data sets) can help estimate forecast performance. It should also be noted that forecast performance will improve with time.

The forecast accuracy will decrease with the forecasting horizon, so a combination with satellite-based forecasts and NWP is necessary for longer forecasting horizons.

What do you think would be the optimal constellation for commercial FSO systems?

The market is driven by the LEO constellation segment. They are marketed as having lower latency, better connectivity and cheaper access. It will allow for deployments of FSO systems. However, GEO satellites have much larger coverage and LEO constellations might be supplemented by them. Also, the type of service will play a role in whether the constellation involves LEO satellites, GEO satellites or both.

I would like to contact you.

If you have questions concerning our research and activities in wireless lasercom, you can contact our experts Kevin Shortt (Airbus) and Olivier Liandrat (Reuniwatt) directly – we are happy to answer your questions! For any other questions, be sure you will be forwarded to the right counterpart when contacting us here:

Airbus: https://www.airbus.com/

Reuniwatt: https://reuniwatt.com/en/

Thank you to Olivier Liandrat and Kevin Shortt for their contributions to this white paper.

About Reuniwatt

Reuniwatt is a major player of the solar radiation and cloud cover assessment and forecasting industry. Based on solid Research and Development works, the company offers reliable products and services intended for professionals of various fields, making the best out of two key facets of meteorology: atmospheric physics and data sciences. The company has won many grants, including two H2020 programmes, which makes Reuniwatt a European Champion with regards to innovation. Reuniwatt has also been selected among the national fast-growing companies to join the prestigious French Tech 120 programme in January 2020, and remains in the selection in 2021.

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