FOCUS ON...

Free Space Optical communications & Adaptive Optics with C-RED 3

C-RED 3 is a 640 x 512 SWIR camera running at 600 FPS full frame. It holds the legacy of all the developments of astronomical infrared fast wavefront sensors on top of specific features for industrial applications: smart, low cost and low SWaP. It is particularly well suited to be the detector used in an Adaptive Optics loop for wavefront sensing in a complete Free Space Optical communication system.

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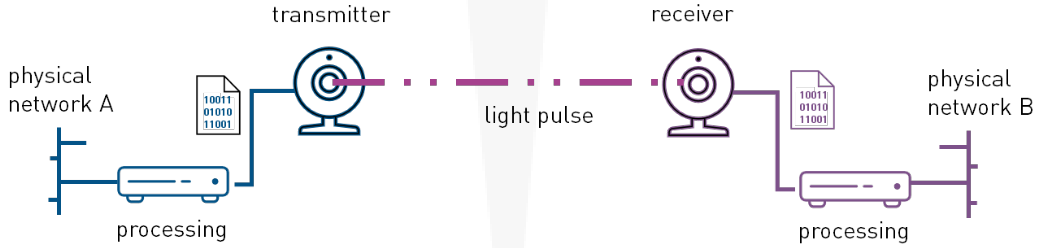
1. Free Space Optical communications

Information can travel from point A to point B through a solid cable, a common example would be corded phones. However, physical connections (cable, wire, fiber) may sometimes be impractical or too expensive. In these cases, being able to transmit data through "free space" (air, outer space, vacuum, *etc.*) is crucial. Using light to transmit data through Free-Space Optical (FSO) communications overcomes the major drawback of cable-based communications.

Free Space Optical communication systems

An FSO system in its simplest form is illustrated below. The data to be transmitted is converted to a binary format (1 and 0), then into light pulses (ON/OFF). A transmitter (laser source and focusing lens) sends the light pulses, aiming the direction of a receiver. The receiver collects the light pulses, which are then processed and converted. Note that the system can be used in the reverse direction. The system is interfaced at both ends with a physical network (cable, fiber). In more complex implementations, the laser beam can be modulated.



Free Space Optical communication basic principle

Applications

FSO can be used for ground to ground communication: outdoor wireless 2G/3G and 4G networks, to cover the edge of physical networks ("the last mile access"), CCTV surveillance networks, *etc*. More importantly, it can be used for ground to space (satellite) communications. FSO enables simultaneously establishing a large number of independent links with high throughput; two major advantages compared to the radio bandwidth which is limited by its low directionality and radio frequency throughput (< 40 GHz). For example, Earth-observation satellites only overpass ground stations for a couple of minutes per day, it is critical that the large amount of data they collected can be transmitted in a short amount of time. Even more so for military satellites which very often may only communicate with ground stations within a limited geographical zone. Finally, FSO is the best option for extra-terrestrial communication which may come in use in the next decades... In short, FSO is a fast-growing segment for telecommunications, both in civil and military fields.

Take-home message

Free Space Optics can be used for high throughput and long-distance communications. Demanding applications, such as space telecommunications, can be addressed.

2. SWIR boosts Free Space Optics

FSO communications are limited by a series of factors. Fortunately, some can be overcome by using Short Wave InfraRed (SWIR) (900 – 1700 nm) rather than visible (400 – 700 nm) or Near InfraRed (700 – 900 nm) wavelengths.

Optimized transmission

Disturbances inherent to air/free space may influence the optical transmission:

1) weather conditions such as fog, rain, snow...
2) various other effects like water/dust absorption, scintillation, scattering
3) physical obstruction: trees, birds or buildings

These factors attenuate the transmitted signal, leading to a higher number of errors when detecting the signal. Laser power increase is not the solution as the laser power density is limited to class 1M in order to keep an eye-safe environment.

The use of SWIR band lasers is extremely pertinent because of their ability to go through obstacles such as fog or some types of plastics. The recent rise of eye-safe lasers in the SWIR band has allowed a major improvement. A camera based on an InGaAs detector array must be used at the receiver end, as visible cameras are not sensitive to SWIR wavelengths.

Use cases

The following figures illustrate the advantage of using SWIR cameras in earth-to-earth and earth-to-space configurations. Visibility is increased compared to visible range imaging, demonstrating how SWIR signal propagates efficiently.

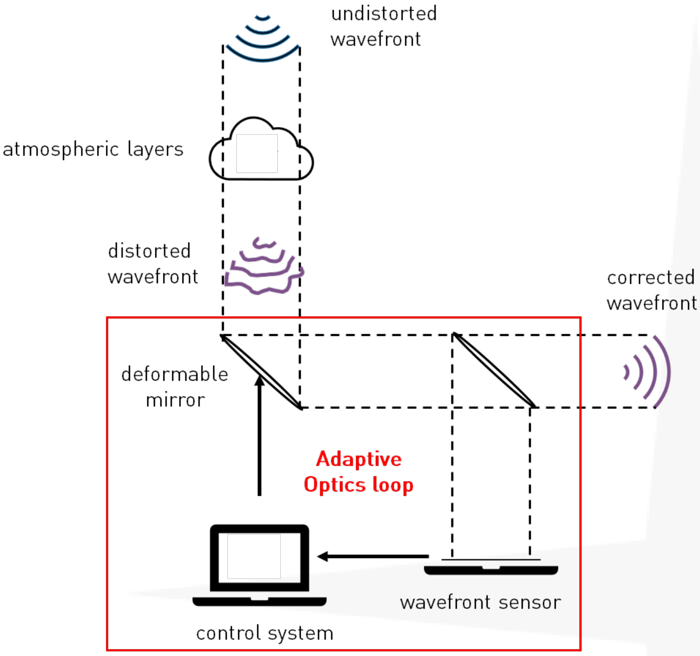
Visible versus *SWIR imaging of a landscape in foggy conditions. Note how the view is much clearer and we can see some 10 km further in SWIR. Raw images acquired with a Nikon D5200 camera (left) and a C-RED 3 camera (right).*

Detection of astronomical objects in a foggy maritime weather conditions using a C-RED 2 camera.

In conclusion, Free Space Optics benefits from using SWIR wavelengths (typically 1550 or 1330 nm), rather than shorter infrared ones (typically 785-850 nm).

3. Adaptive Optics in the SWIR range

Light propagating through the atmosphere is known to be disturbed by atmospheric turbulence. The most difficult-to-deal-with problem is beam scintillation: as the atmosphere in the beam path fluctuates, the optical power, tilt, *etc*. of the light beam vary, causing random phase aberrations and often-large variation in detected intensity.



Several mitigation strategies have been developed, but the best way to suppress scintillation is to use Adaptive Optics (AO). The idea of correcting the atmospheric turbulence in real time for astronomy was firstly introduced by Babbock as early as 1953[1]. With the progress of wavefront sensors, deformable mirrors and real time computers, AO systems have become very popular and relatively straightforward to make. The figure illustrates the working principle of the close loop approach.

The key parameter of an adaptive optics system is the wavefront sensor and its ability to give an instantaneous picture of the incoming wavefront. A wavefront sensor typically consists of a Shack-Hartmann combined to a photon sensor. First Light Imaging worked a lot on the improvements of visible cameras for wavefront sensing with the OCAM[2], which is to date the fastest and lowest noise (visible photon counting) camera, tailored for this application[2].

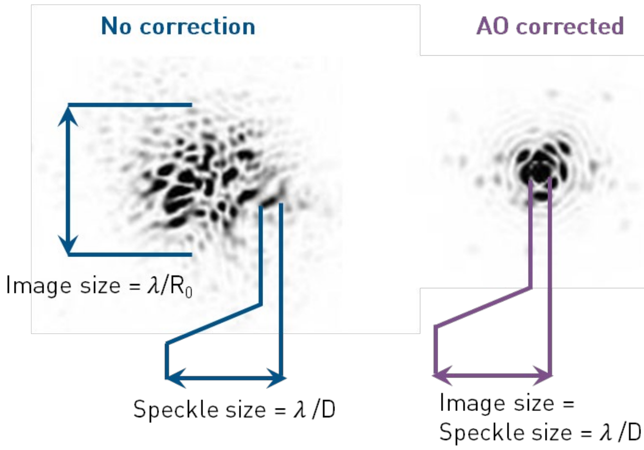
Simplified schematic of the Adaptive Optics closed-loop approach*. The wavefront from a distant object is distorted by the atmosphere. The deformable mirror compensates the distortions. The control system computes the commands for the deformable mirrors. The wavefront sensor measures the deviation from an undistorted wave.*

As we have seen previously, there was a real interest to go to SWIR wavelengths. To optimize communication speed, small diodes are used. To reduce power losses and enable the injection of the transmitted optical beam into a single mode fiber[3], AO is mandatory (see the figure on the right).

The major constraint on the camera used as an AO wavefront sensor is that it must provide a real-time snapshot of the wavefront to enable real-time compensation. Hence the camera should have a high framerate, low latency, and high sensitivity.

For example, very high framerate correction is required to perform FSO with Low Earth Orbite (LEO) satellites, where the apparent wind is high due to the satellite speed.

C-RED 3 has been designed specifically for this purpose[4], and completely addresses the challenges of high speed wavefront sensing.



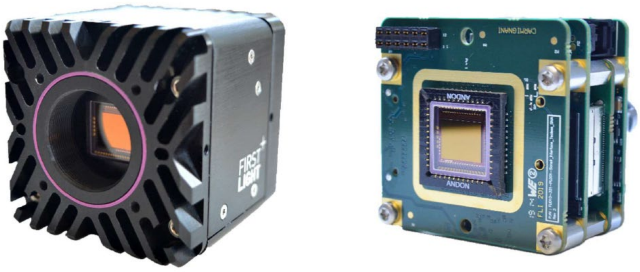
Example of the improvement provided by an AO correction to the detection of a laser spot. *λ is the wavelength, D is the optic's diameter, R_0 is the diameter of the atmosphere turbulence nodule.*

Take-home message

Compared the visible range, SWIR allows a deeper penetration through atmospheric perturbations. Using small diodes enables fast FSO communications but requires fast and sensitive cameras to perform wavefront sensing. C-RED 3 has been designed for this purpose.

4. C-RED 3 camera

Designed by astronomers for astronomers and benefiting from the expertise gained when designing the OCAM² and C-RED One cameras, First Light Imaging's C-RED 3 is the best choice for your SWIR FSO applications.



C-RED 3 camera, in housed (left) and OEM formats (right).

In the C-RED 3 camera, all the cooling system has been removed and the electronics squeezed to give a very compact high-speed SWIR camera. Below is a few insight into its advantages.

- **Easy integration.** The camera can be easily integrated in a system thanks to the holes on the bottom, the side, or the front, and has a C-Mount/CS-Mount/T-Mount optical interface for the objective. The OEM version is even more easy to fit any custom system. C-RED 3 is supported by our multi-camera software First Light Vision. Additionally, thanks to a versatile SDK, the camera can be interfaced with MatLab, LabView, Python, *etc*.

- **High sensitivity.** C-RED 3 compensates the dark current, necessarily high for a non-regulated camera, by a very high frame rate. When used in windowing (ROI) mode at higher frame rates (up to 32 066 fps), the dark current is completely negligible.

- **On-the-fly adaptive bias/dark correction.** To compensate the effects of temperature and exposure time variations on the dark frame, C-RED 3 offers an adaptive correction. Dark frames are automatically computed by the camera firmware. Calibrated in factory, this process eliminates the need to perform multiple experimental bias/dark acquisitions, hence simplifying your experiments.

- **Electronic shutter**. C-RED 3 embeds an electronic shutter with integration pulses shorter than 5 µs in full frame mode.

- **Windowing and Region of Interest (ROI)**. Windowing mode allows to achieve faster image rate while maintaining a very low noise, which is very interesting for FSO applications where a limited number of modes will be corrected, so a smaller amount of pixels needed.

- **High framerate.** C-RED 3 can work at 600 FPS in full frame mode. The frame rate increases up to several kHz in ROI mode (for example 9.5 kHz for a 64-by-64 pixels ROI).

- **Low camera latency.** The delay between the end of integration and the first valid data on camera link in normal readout mode full frame is 22.2 µs (default) and can be tuned down to 7.4 µs.

- **Numerous synchronization mechanisms.** Internal and external triggers allow optimal interface of the camera to the rest of the FSO and AO system (laser, computer, *etc*.).

C-RED 3 is a plug-and-play SWIR camera.
Our C-RED range of cameras offers hardware optimization to adjust to your specific use case.

5. Conclusion

The availability of low noise fast infrared cameras to build wavefront sensors changes somewhat the paradigm of Free Space Optical communications. With improved penetration of SWIR lasers – compared to visible range lasers – in bad weather conditions, and reduced effects of atmospheric turbulence, there is a real benefit of performing FSO in the SWIR range. Adaptive optics can further optimize the signal detection.

C-RED 3 is a high-performance camera designed for short wave infrared applications. It enables very high-speed high-quality sensing (up to 600 fps in full frame) and gives its best performance at short exposure times. The camera was developed for Free Space Optical communications applications, particularly for adaptive optics.

The use of the camera is, of course, not restricted to Free Space Optics. C-RED 3 is very flexible and can be used for multiple applications, ranging from surveillance to agriculture monitoring. Moreover, the low size, weight, and power consumption (SWaP) opens the possibility to use this technology on airborne material (planes, UAVs).

For applications requiring lower framerates and longer exposure times, the C-RED 2 camera is the cooled equivalent of C-RED 3. The cooling allows to reach a lower dark current (< 600 e-/pix/s).

Going further…

And as we want our customers to always stay one step ahead in their own market, First Light Imaging supports them on the spatial version of C-RED 3… Stay tuned, more information soon!

6. Bibliography

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