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Solar Limb Darkening Color Imaging of the Sun with the Extreme Brightness Capability CAOS Camera

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Abstract

Experimentally demonstrated for the first time is Coded Access Optical Sensor (CAOS) camera-based imaging of the Sun. Only by using both the shortest 0.029 ms integration time of the scientific CMOS sensor and a very large factor of 10,000 optical attenuation at the entrance of the CMOS camera, one is able to produce the desired unsaturated image of the Sun. In sharp contrast, a small factor of 3.2 optical attenuation is required over a much smaller single photo-detector zone of the CAOS camera to capture the unsaturated Sun image, including color images obtained using red, green, and blue filters. Image data processing shows that both the CMOS camera and CAOS camera show similar Sun limb darkening measurements consistent with prior-art works. The CAOS camera empowers optically and operationally efficient full spectrum (e.g., 350 nm to 2700 nm) imaging of bright heavenly bodies in space, with the potential for creating impact for solar energy farms, space navigation, space exploration and astronomical science.

Introduction

Imaging of super bright human-made targets (e.g., lasers and laser illuminated objects) as well as nature provided super bright objects (e.g., celestial bodies, i.e., stars, planets, and moon) is an important endeavor in the world of industrial (e.g., sun tracking for solar panels) and space operations (e.g., determining altitudes for satellites), as well as basic sciences (e.g., study of planets) [1-7]. Depending on the spectrum of interest, mission platform and application, silicon CMOS and silicon CCD [8] 2-D image sensor-based cameras as well as near IR 2-D FPA (Focal Plane Array)-based imaging instruments, including bolometric [9-10] imagers are deployed with customized optical attenuators with large (e.g., > 100) light reduction factors for imaging super bright objects. These attenuators, in some cases, such as via thermal lensing can spoil the original optical image spatial and spectral properties leading to a modified observed image of the bright target. Hence it would be prudent to avoid the use of an optical attenuator between the far-field target light object plane and the 2-D image sensing plane. Recently proposed is such a desirable camera design called the CAOS camera [11]. Hence this paper for the first time describes the use of the CAOS camera for experimentally imaging the bright Sun, including imaging the far-field solar disc with color filters to produce spectral solar limb darkening data.

CAOS Camera Basic Design and Operations

The CAOS smart camera (see Fig.1) is designed on the principle of a multiple access RF/optical wireless network (see Fig.2) [12-14]. The key components used in the camera are: TI Digital Micromirror Device (DMD), point Photo-Detector Module (PD-M), point Photo-Multiplier Tube Module (PMT-M), lenses (L), shutter (S), aperture (A1), CMOS sensor, Mirror-Motion Module (MM-M), and Variable Optical Attenuators (VOAs). The DMD acts as the required space-time-frequency optical coding device used to generate the wireless style CAOS signals required for linear high dynamic range imaging via high speed Digital Signal Processing (DSP). The important point to note is that there is no optical attenuator deployed between the front imaging lens module L1 and the DMD plane where the imaged object irradiance is time-frequency encoded and sent to the point PDs for optical-to-electrical data conversion. Thus the object irradiance map incident on the DMD plane suffers no optical attenuation or alteration before encoding capture. Any minimal optical attenuation takes place using the smaller aperture VOAs positioned just before the point PD modules and thus does not affect the incident image trueness of the sampled object 2-D irradiance. Here one assumes that the VOA spectral and polarization properties are known and have minimal impact on the desired spectral band time-frequency encoded light signals. In addition, the imaging lens L1 optical design (e.g., MTF: Modulation Transfer Function) is optimized for the application (e.g., for imaging of far-field celestial bodies) so that it does not alter the spatial and spectral information of the far-field observed objects. Another point to note is that in the CAOS camera, color and polarization filters can also be placed near the point PD planes, again minimizing the possible negative effects on the original image if such larger aperture optics were placed in front of lens L1.

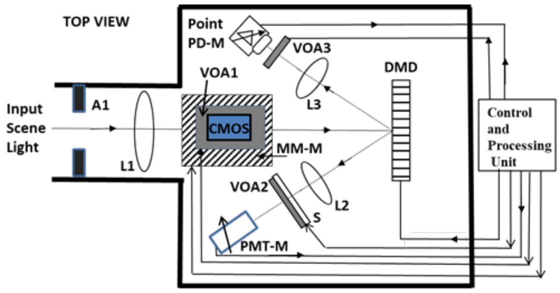


Figure 1. *Shown is the top view of the CAOS smart camera.*

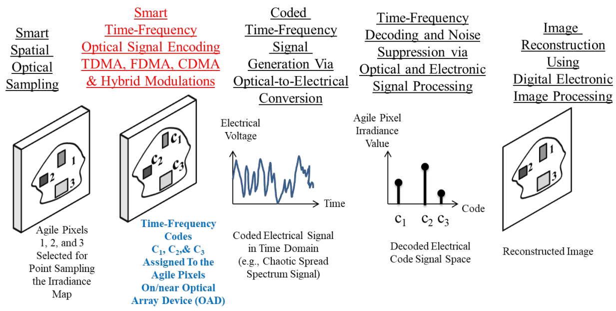


Figure 2. *Shown is the RF/optical Wireless Multi-Access Network principles-based operational design of the CAOS camera.*

The CAOS camera imaging operation works as follows. Simultaneous capture of imaged irradiances on the DMD plane is implemented by creating multiple CAOS pixels that are time-frequency modulated by the high speed binary tilt micromirror operations of the programmed 2-D DMD with near million micromirrors. Fig.2 shows 3 CAOS pixels in the image plane that are time-frequency coded (via a 2-D optical time-frequency coding device such as a DMD) for simultaneous detection by a fast large enough area point optical detector that converts the optical time-frequency signals containing image pixels irradiance information to one electrical RF time-frequency signal that undergoes advanced DSP (e.g., RF style time-frequency correlation and spectrum analysis processing) for pixels irradiance recovery. CAOS has various coding modes of operations similar to an RF wireless multiaccess phone network [15]. For example, the Code Division Multiple Access (CDMA) CAOS mode is implemented in this paper for Sun imaging where one has an extreme brightness target, but with low to moderate intra-Sun zone dynamic range. In the CDMA-mode, all chosen CAOS pixels in the image map are simultaneously time-frequency coded with Walsh code orthogonal binary sequences and also simultaneously detected by the two point detectors such as shown in the Fig.1 camera design. Thus, the CAOS sampled object pixel irradiances are sent to the two point PD modules that generate AC signals that undergo time-frequency correlation-based decoding via high speed DSP for observed scene image recovery. With proper choice of CAOS pixel size and the Time Division Multiple Access (TDMA) mode, the instantaneous quantum well capacity of the CAOS camera can be greatly enhanced, eliminating the need for a VOA before a point PD.

Note that the CAOS smart camera includes a CMOS/CCD/FPA/Bolometer Array 2-D sensor engagement mode via a DSLR reflex mirror design that can provide initial scene intelligence to the CAOS smart camera operations. In other words, a traditional 2-D image sensor can provide preliminary scene information that can be used to optimize POI (Pixels of Interest) CAOS modes selection to provide CAOS centric high end features such as extreme camera linear dynamic range (e.g., 177 dB) [14] and controlled Signal-to-Noise Ratio (SNR) irradiance extraction for robust, i.e., reliable pixel irradiance measurements. An important point to note in the CAOS camera operations is the ability to filter output signal noise, i.e., time-frequency noise suppression via DSP. A simple example illustrating noise reduction is the use of the CAOS Frequency Modulation (FM) CAOS-mode where a pixel is time-frequency modulated with a specific frequency carrier, e.g., 10 KHz. As this encoding 10 KHz coherent RF carrier is known, DSP gain and filtering can be optimized (e.g., for SNR > 5) and realized using spectral processing DSP methods such as FFT (Fast Fourier Transform) engaging the high speed digitization (via fast Analog-to-Digital Converters) of the point PD raw RF signal output of the CAOS camera. Indeed, CAOS camera experiments have demonstrated this noise suppression ability in recent experiments to produce extreme 177 dB linear dynamic range CAOS pixel irradiance recovery [14]. It is important to point out that traditional pixelated image sensors such as CMOS/CCD sensors generate DC signals responding to starring mode photo-charge collection in their tiny quantum wells. The 2-D image sensor pixel level noise value is experimentally projected using the photo-response of a NIST calibrated large area photo-cell of the same material as the image sensor, and is based on RMS read-out noise calculations using the much smaller tiny pixel area of the deployed image sensor. Typical state-of-the-art image sensors report RMS read noise per pixel of a few electrons (e), including some sensors under a single electron such as 0.44e [16]. As a sensor's dynamic range can be computed using this tiny (e.g., sub-electron) read RMS noise value versus the sensor's pixel near full quantum well capacity given by a large electron count (e.g., >100Ke), a very large (e.g., > 140 dB) dynamic range number can be computed for the image sensor. It is important to point out that such computations can be misleading and do not experimentally demonstrate the true much limited instantaneous (i.e., single exposure) dynamic range of the sensor when subjected to a real calibrated high linear dynamic range target [17]. While classic image sensors are "DC" signal cameras, CAOS is an "AC" signal camera with AC-type noise that can be greatly suppressed due to the coherence properties of the encoded optical signal carrying the image irradiance information. This powerful attribute of CAOS, much like the RF wireless phone network, lends itself to a naturally Extreme Dynamic Range (XDR) imaging capability. The CAOS smart camera combines both the classic image sensor mode and the new CAOS-mode, hence a DC+AC camera is realized with many complimentary features that enhance imaging capabilities given the merger of two distinct and unique methods for making a novel powerful image sensor.

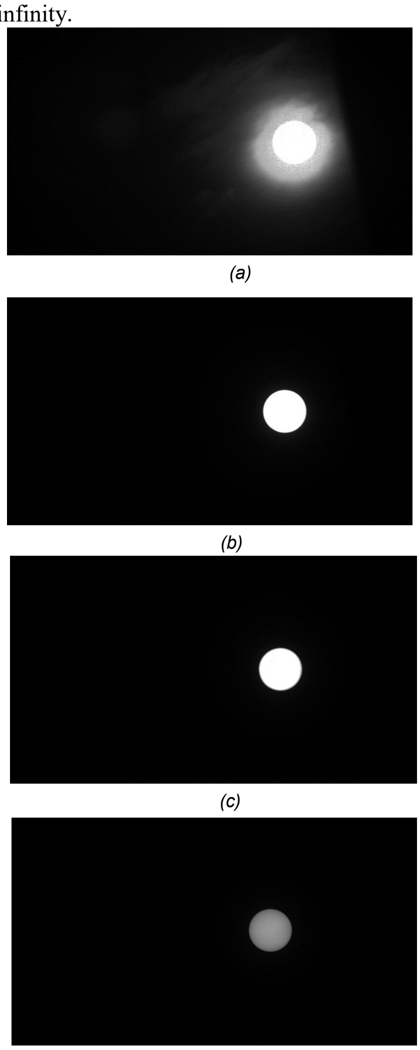
Figure 3. *Shown is the Apple 12 Mpixel iPhone 8 Plus camera view of the saturated SUN through the windows of the N. A. Riza Photonics Laboratory, University College Cork, Cork, Ireland.*

Figure 4. *Shown is the Thorlabs s-CMOS sensor-based camera.*

CMOS Camera Sun Imaging Experiment

To implement bright Sun imaging within a controlled camera environment, a bright sunny day in the month of November 2019 is chosen using a view through the laboratory windows (see Fig.3). This photo is taken with an iPhone 8 Plus camera and shows at best a saturated Sun image within the overall scene. Given the current CAOS smart camera is not fully automated for tracking a moving Sun across the laboratory window, two separate camera assemblies, namely an independently steered s-CMOS camera (see Fig.4) and a manually steered and adjusted CAOS camera are deployed for imaging the Sun. As the first step in the Sun imaging experiment so that one has a reference image, deployed is the CS2100M-USB Quantalux Thorlabs 87 dB dynamic range scientific s-CMOS sensor-based camera with a C-mount

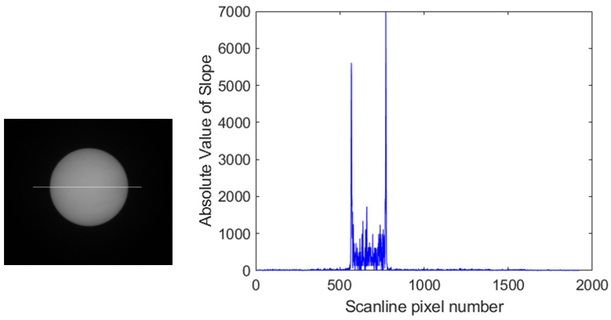
Stemmer lens. Various value ND (Neutral Density) filters are placed before the CMOS camera front lens and many integration time settings of the CMOS sensor are tried before achieving a non-saturated CMOS sensor provided image of the Sun. Specifically, an ND filter with OD (Optical Density) of 4 giving a 10,000 factor optical attenuation and the CMOS sensor integration time set to its shortest 0.029 ms gives the first unsaturated image of the Sun. Note that the camera lens settings are adjusted to produce the sharpest focus solar disc for the far-field Sun target that appears on the CMOS sensor plane as an object at infinity.



(a) (b) (c) (d)

Figure 5. Sequence of CMOS camera images taken with reducing CMOS sensor integration times and an ND filter providing a 10,000 factor optical attenuation. Integration times in ms are set to (a) 2.014, (b) 0.088, (c) 0.059, and (d) 0.029.

Fig. 5 shows a set of four solar images obtained with the CMOS camera using different CMOS sensor integration times. Only the Fig.5 (d) image has unsaturated pixels and hence is used to compute the observed solar limb darkening, i.e., the gradual drop in optical irradiance from the center of the solar disc to the edge/boundary of the solar disc. Specifically, as shown in Fig.6 (a), a horizontal scan line is drawn through the center of the solar disc. The high spatial resolution pixel irradiance values along this scan line are used to compute adjacent pair-pixel absolute slope values as shown in Fig.6 (b). Next thresholding operations on the slope values is used to estimate the position of the Sun boundary. This operation is done for multiple scan lines across center of solar disc (e.g., use an additional vertical scan line) to get an averaged data set. Fig.6 (b) plot also allows the computation of the observed Sun average measured diameter by noting the average pixel distance between the highest slope peaks that indicate a presence of the Sun boundary. For the present CMOS camera provided data, the average diameter is measured to be 205 CMOS pixels which is physically equal to 205 x 5.04 microns = 1033.20 microns on the CMOS sensor plane. Fig.7 shows the Sun limb darkening plot produced using the unsaturated image from the CMOS camera. The plot scaled irradiance variations are consistent with prior-art Sun limb darkening results [18-22].



(a) (b)

Figure 6. (a) Shown is the Fig.5(d) unsaturated Sun image with a CMOS sensor 5.04 micron pixel width horizontal scan line across the solar disc image. (b) Plot of absolute value of slope (i.e., adjacent pixel pair irradiance variation per spatial pixel line space) versus all the pixel positions on the scan line.

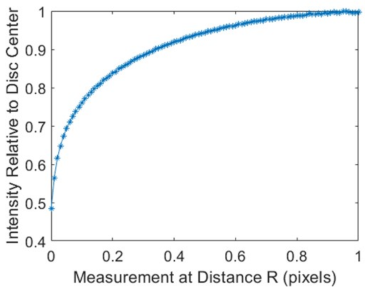


Figure 7. *Shown is the computed solar limb darkening plot using the unsaturated Sun CMOS camera image data.*

CAOS Camera Sun Imaging Experiment

As shown in Fig.8, a version of the Fig.1 CAOS smart camera design without the CMOS sensor is assembled in the laboratory using key components that include the Vialux V-7001 DMD board with a 13.68 μm micro-mirror size, a point PD-M Thorlabs switchable gain silicon detector model PDA100A2, a National Instruments model USB 6366 DAQ 16-bit analog-to-digital converter, a Dell laptop model i7 Latitude 5480 for DSP and an ND filter with OD=0.5 to provide a factor of 3.2 optical attenuation to the light just before it enters the point PD-M so the photo-current does not reach the 10 V limit of the DAQ. The PMT port is not deployed given the brightness of the targeted Sun. The front lens assembly L1 is adjusted in focus so the Sun appears in sharp focus on the DMD plane.

Fig.9 shows the first ever CAOS camera acquired image of the Sun. The camera is operated in its CDMA-mode using 4096 bits Walsh sequences at 50 KHz bit rate giving a 68 x 60 CAOS pixels grid. Each CAOS pixel is 3x3 micromirrors. The DAQ operates at 2 MSps. Using the centered scan line adjacent pixel slope method mentioned earlier, the CAOS camera image data gives a 29 CAOS pixels Sun diameter which translates to 1190.16 microns physical space on the DMD plane. This CAOS measurement of Sun diameter is close to the CMOS camera provided measurement within experimental tolerances as different camera positions and imaging lenses are used to acquire the two far-field images. Fig.10 shows the solar limb darkening plot computed from the acquired image data, showing the expected optical intensity variations over the solar disc center to boundary with R=1 corresponding to the CAOS pixel normalized Sun disc center position. Fig.11 shows CAOS camera obtained Sun images using red, green and blue color filters. The color filters are 1 inch diameter dichroic filters from Thorlabs models FD1R, FD1G and FD1B. Fig.12 shows the spectral responses of these experimentally deployed R, G, B color filters.

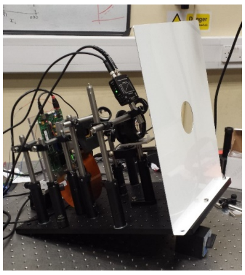


Figure 8. *Shown is the side view of the assembled CAOS camera.*

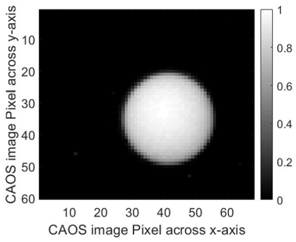


Figure 9. *CAOS camera provided white light unsaturated image of the Sun.*

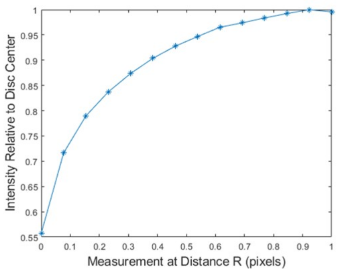


Figure 10. *CAOS camera provided white light solar limb darkening plot.*

Fig.13 shows the computed limb darkening plots for the three colors showing the expected optical frequency dependent solar limb darkening consistent with prior art where higher frequency blue light has slightly more limb darkening than lower frequency red light.

Conclusion

For the first time, the CAOS camera has been used to directly image the bright Sun, i.e., without placement of an optical attenuator in front of the input imaging lens. The CAOS camera provided white light and three color (R, G, B) data are used to compute the observed solar limb darkening behaviour. The CAOS camera data is compared to a scientific CMOS camera provided Sun image where a factor of 10,000 optical attenuation was used in front of the input lens. CAOS camera data within experimental limits matches CMOS camera limb darkening data as well as prior art data for multi-color limb darkening. With the use of telescope optics, the CAOS camera has the potential to generate high spatial resolution and robust image data for bright celestial objects. The CAOS camera offers an alternative to classic CCD/CMOS/FPA/Bolometer sensor-based cameras for future imaging of unattenuated bright heavenly bodies, perhaps offering features desirable by both space mission operators (ESA, NASA) as well as users in the astronomy/astrophysics and solar energy industry communities.

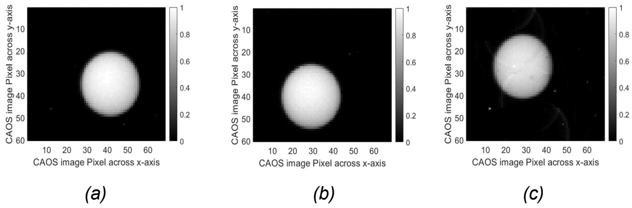


Figure 11. *CAOS camera provided Sun color images using (a) red, (b) green, and (c) blue color filters.*

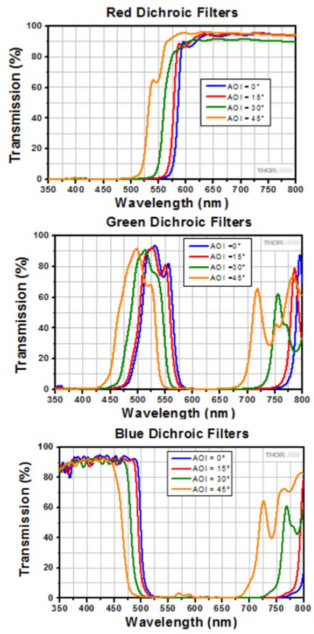


Figure 12. *Shown are the spectral responses of the deployed Thorlabs R, G, B color filters.*

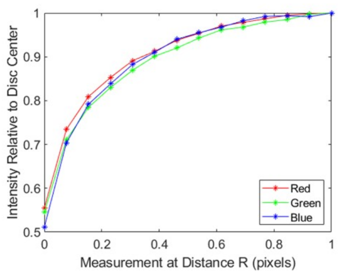


Figure 13. *CAOS camera provided solar limb darkening plots for red, green, and blue optical frequencies.*

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