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SCOPE: A Coronagraph for Operational Space Weather Prediction – Phase A/B1 Design and Breadboarding

Kevin F. Middleton*[a], Heiko Anwand[b], Volker Bothmer[b], Jackie A. Davies[a], Andrew Earle[a], Klaus Ergenzinger[c], Chris J. Eyles[a], Robert Hardie[a], Marie-Laure Hellin[d], Johannes Hinrichs[b], Philipp Huke[b], Piers Jiggens[e], Volker Kirschner[e], Emmanuel Mazy[d], Thomas McCarron[a], Bogdan Nicula[f], Lars Stopfkuchen[c], S. James Tappin[a], Ian A. J. Tosh[a], Nick R. Waltham[a], Matthew J. West[f]
[a]RAL Space, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK; [b]Institut für Astrophysik, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany; [c]Airbus DS Space Systems, EO & Science Programmes (TSPED41), 88039 Friedrichshafen, Germany; [d]CSL – Centre Spatial de Liège, Univ. of Liege, Belgium; [e]European Space Research and Technology Centre (ESTEC), Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, NL; [f]Royal Observatory of Belgium, Ringlaan - 3 – Avenue Circulaire, B – 1180 Brussels, Belgium

ABSTRACT

Accurate prediction of the arrival of solar wind phenomena, in particular coronal mass ejections (CMEs), is becoming more important given our ever-increasing reliance on technology. SCOPE is a coronagraph specifically optimised for operational space weather prediction, designed to provide early evidence of Earth-bound CMEs. In this paper, we present results from phase A/B1 of the instrument's development, which included conceptual design and a program of breadboard testing.

We describe the conceptual design of the instrument. In particular, we explain the design and analysis of the straylight rejection baffles and occulter needed to block the image of the solar disc, in order to render the much fainter corona visible. We discuss the development of in-house analysis code to predict the straylight diffraction effects that limit the instrument's performance, and present results, which we compare against commercially available analysis tools and the results from breadboard testing. In particular, we discuss some of the challenges of predicting straylight effects in this type of instrument and the methods we have developed for overcoming them.

We present the test results from an optical breadboard, designed to verify the end-to-end straylight rejection of the instrument. The design and development of both the breadboard and the test facility is presented. We discuss some of the challenges of measuring very low levels of straylight and how these drive the breadboard and test facility design. We discuss the test and analysis procedures developed to ensure a representative, complete characterisation of the instrument's straylight response.

Keywords: coronagraph, space weather, straylight

*kevin.middleton@stfc.ac.uk; phone +44 (0)1235 445815; http://www.ralspace.stfc.ac.uk/ralspace/

1. INSTRUMENT CONCEPTUAL DESIGN

SCOPE is an imaging camera in visible light. To image the solar corona over the full 360° azimuth, the camera points at the solar disc centre and has an occulter to block the direct light of the solar disc. SCOPE uses a more compact design than traditional coronagraphs. Instead of the conventional arrangement of multiple lens, baffle and occulter stages with a field stop at an intermediate solar disc image and a Lyot stop at an image of the entrance pupil, SCOPE has a single external occulter at the entrance of the instrument, which blocks light from the solar disc, followed by an objective lens which images the corona directly onto a detector contained in the focal plane assembly. SCOPE shares a common design with the COR instrument being developed for the Lagrange space weather mission and the terms SCOPE and COR (the name of the corresponding coronagraph on Lagrange) are used interchangeably in this paper.

Figure 1 shows the SCOPE instrument block diagram, while Figure 2 shows the corresponding physical layout. Figure 3 shows the electrical block diagram.

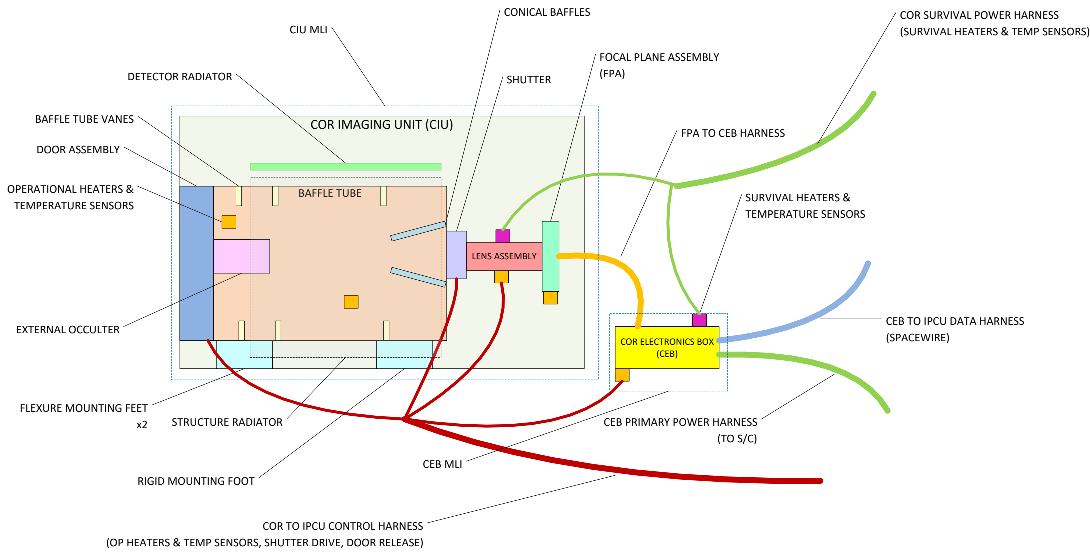

Figure 1: SCOPE block diagram

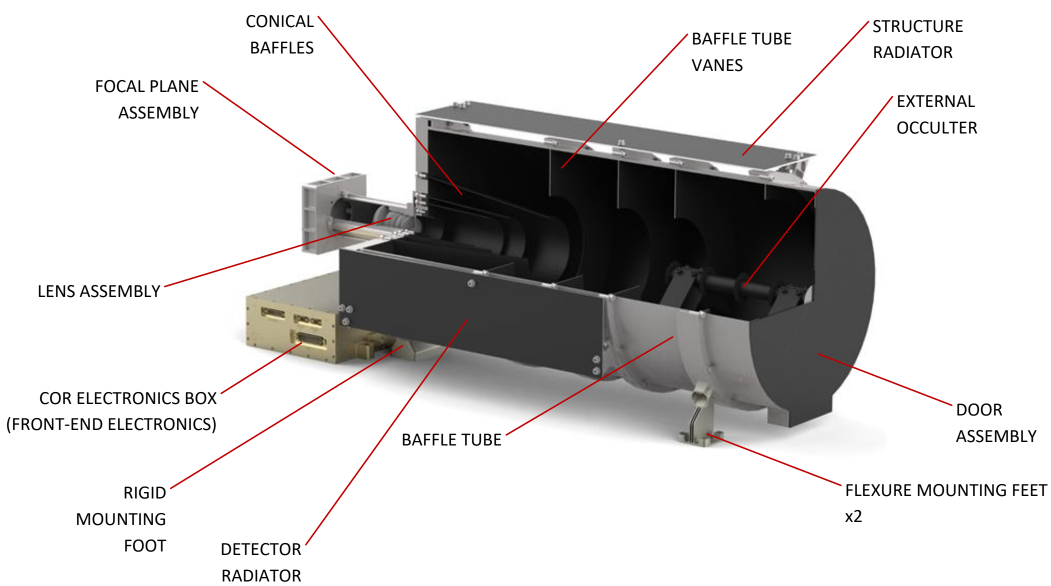

Figure 2: SCOPE instrument layout

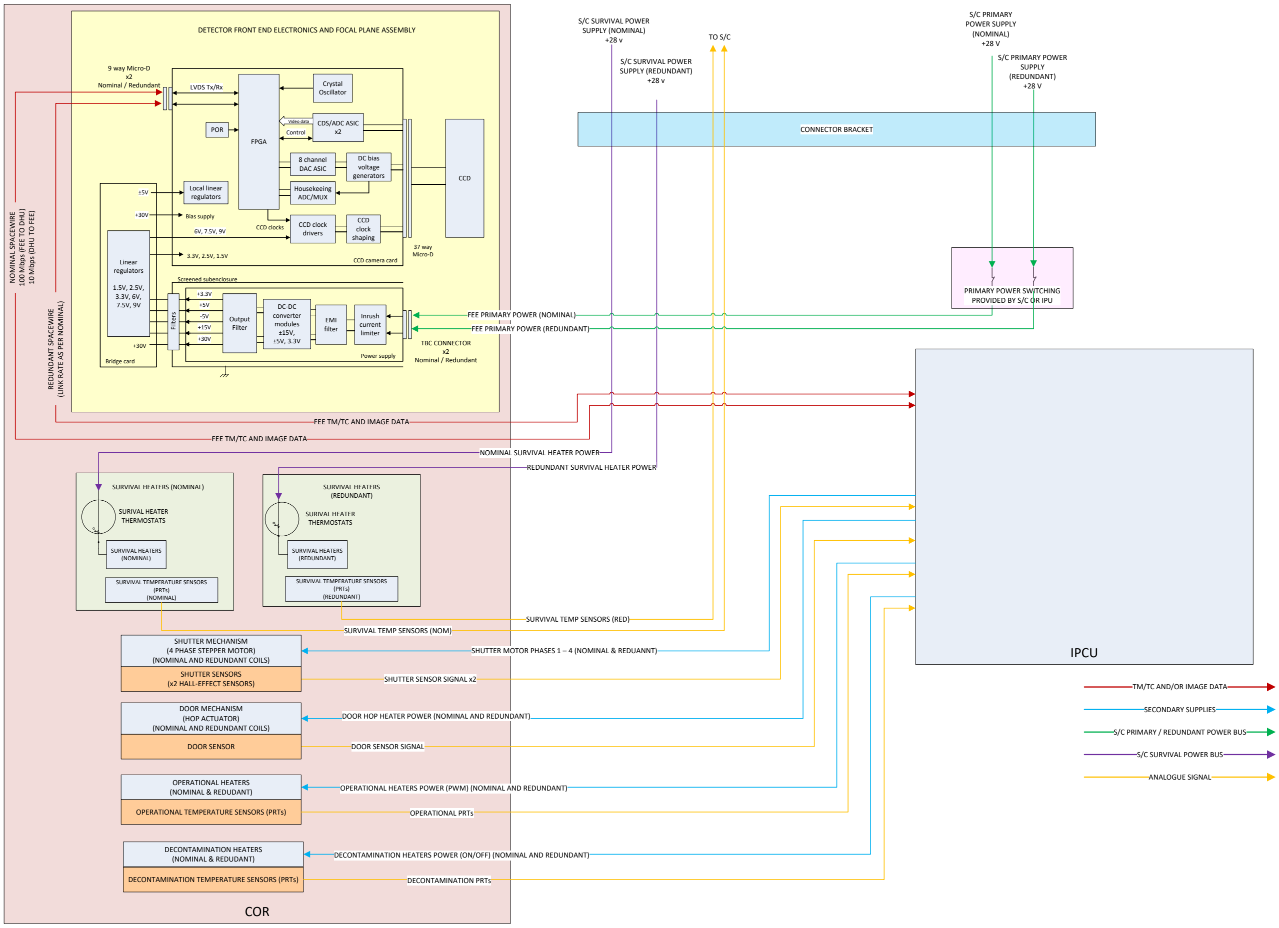

Figure 3: SCOPE electrical block diagram

The instrument is divided into two main functional blocks: the COR imaging unit (CIU) and the COR electronics box (CEB). The primary function of the CIU is to image the solar corona onto the detector at the focal plane assembly while blocking direct solar radiation. The primary function of the CEB is to drive the CCD (located in the focal plane assembly), retrieve images, digitise them and send them on to the instrument processing and control unit (IPCU) for processing.

The external occulter (EO) is a stack of five tapered discs. The first disc is designed to block the image of the sun out to the inner FOV limit. Each subsequent disc is designed to block diffracted light from its predecessor. The EO is mounted in a baffle tube whose function is to block stray light from beyond the outer FOV limit. Care must be taken to do this without introducing additional stray light, scattered into the optical system from the baffles themselves. This leads to a design with a number of flat annular vanes along the length of the baffle tube and a series of conical baffles close to the objective lens.

The objective lens is a custom, five lens assembly with a 25 mm entrance pupil diameter, held in a lens tube attached to the baffle tube. Radiation stabilised glasses are used throughout. The aperture stop is located in front of the first lens to help in stray light control and the lens clear apertures are sized for a maximum radial FOV of about 60 Ro to minimise stray light scattering from the lens edges. COR is designed to detect broad-band visible radiation in the band 500 – 900 nm. The waveband is defined by a combination of filters (housed in the lens assembly), the detector response and the inherent absorption of the glass lenses.

A spring-loaded, one-shot door (retained by a HOP-actuated pin puller) is used to protect the instrument from contamination during AIV and launch. On orbit, protection against off-pointing at the sun is provided by a shutter, located in front of the objective lens. The shutter can also be used to protect the most sensitive parts (objective lens and detector) against contamination during critical s/c operations such as thruster firing. The shutter is not used to control the exposure time; instead the CCD is read out with the shutter open. The shutter mechanism comprises a rotating disc with opposite quadrants removed, giving four positions (two open and two closed), driven by a 90° 4 phase stepper motor. Both the shutter and the door are driven and controlled by the IPCU.

The baseline detector is a 2k x 2k CCD with a 15 µm pixel. The selected sensor option can be procured as a standard product (for example, the e2v CCD230) or as a custom sensor, allowing options such as a frame store or additional read-out ports. The sensor is housed in a small focal plane assembly, connected to the CEB, which houses the front-end electronics (FEE), by a short (< 100 mm) length harness.

The FEE contains all of the functionality needed to supply and drive the CCD and to read out and digitise the resulting images. All onboard image processing (such as compression, pixel binning and cosmic ray scrubbing) is carried out by the IPCU. The FEE is supplied directly from the spacecraft primary power supply and contains its own local power conversion module to generate the required secondary supplies. Data are transmitted to the IPCU over nominal and redundant 100 Mbps SpaceWire links. The same SpaceWire link is also used for sending configuration files and instructions from the IPCU to the FEE. The FEE has significant flight heritage from the STEREO/HI, SDO AIA/HMI and GOES-R SUVI camera electronics boxes developed at RAL.

The thermal design allows the detector to be operated at -60°C to protect against degradation of charge transfer efficiency due to radiation damage, while the rest of the instrument sits at between about 5°C and 20°C. Two dedicated radiators are required – one to cool the detector and another to cool the rest of the instrument – although shared radiators with other instruments may be feasible for the Lagrange mission, depending on the other instrument requirements and the spacecraft interface requirements. Short lengths of aluminium plate are used to conduct heat away to the radiators (although these could be substituted for heat straps in the case of common, s/c-provided radiators mounted remotely). Control heaters (controlled by the IPCU with feedback from temperature sensors mounted on the instrument) are used to stabilise the instrument's temperature. The COR instrument is thermally isolated from the spacecraft. Radiative isolation is provided by covering the instrument in MLI; conductive isolation is provided by the use of insulating materials at mounting interfaces, such as Tufnol gaskets.

The mechanical interface between the CIU and the spacecraft utilises two flexure mounting feet at the front of the instrument and a single rigid mounting foot at the rear, designed to provide stable pointing while allowing some compliance to cater for differential thermal expansion of the instrument and spacecraft. The CEB is mounted separately to the s/c structure by a simple bolted interface, connected electrically to the focal plane assembly containing the detector by the harness previously mentioned.

SCOPE has an overall volume of 880 x 340 x 340 mm and an estimated mass (including margin) of about 13 kg.

There are a number of direct electrical interfaces between COR and the s/c: the CEB primary power harness provides nominal and redundant primary power from the s/c to the CEB; the COR survival power harness provides nominal and redundant survival power from the s/c to the survival heaters (switched by thermostats) on the CEB and CIU, and carries the signals from the COR survival temperature sensors to the s/c.

There are also some electrical interfaces between the IPCU and COR. A number of harnesses are required to connect COR to the IPCU: a CEB to IPCU data harness, used to make the SpaceWire link between COR and the IPCU; a COR to IPCU control harness, used to supply the operational heaters, carry signals from the operational temperature sensors, drive the shutter (and read associated shutter sensors) and release the door (and read the associated door sensor).

2. PERFORMANCE SIMULATION

A model of diffraction at the occulter discs has been developed based on a modified version of the PROPER optical propagation library for IDL[1]. This was used to optimise the number and spacing of occulter discs. The figures below show the simulation outputs, including a prediction of the diffracted straylight signal in flight (Figure 4), a simulation of the expected signal at the focal plane and the effect of detector defocus (Figure 5), and a simulation of the expected signal during the straylight test described in the next section (Figure 6).

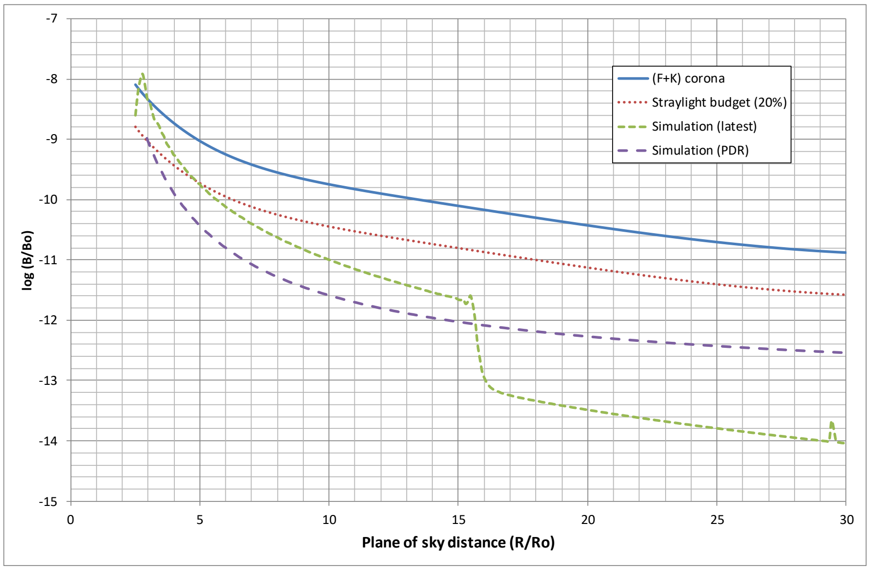

Figure 4: Diffraction simulation of SCOPE straylight signal. The straylight budget (20% of the F+K corona) is also shown

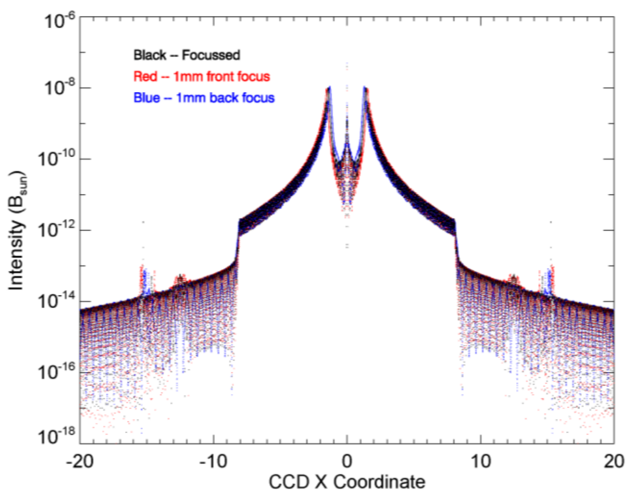

Figure 5: Diffraction simulation of the straylight signal at the focal plane

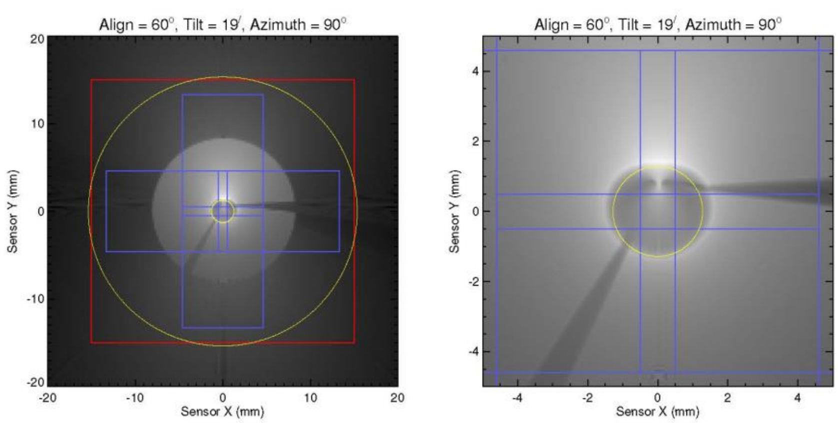

Figure 6: Simulated signal at the focal plane during straylight test

3. STRAYLIGHT TESTING OF THE OPTICAL BREADBOARD

An optical breadboard (Figure 7) has been constructed with the objective of verifying the end-to-end straylight performance of SCOPE. This will be tested in the FOCAL3 chamber at CSL (Figure 7, Figure 8). Results will be reported during the conference presentation.

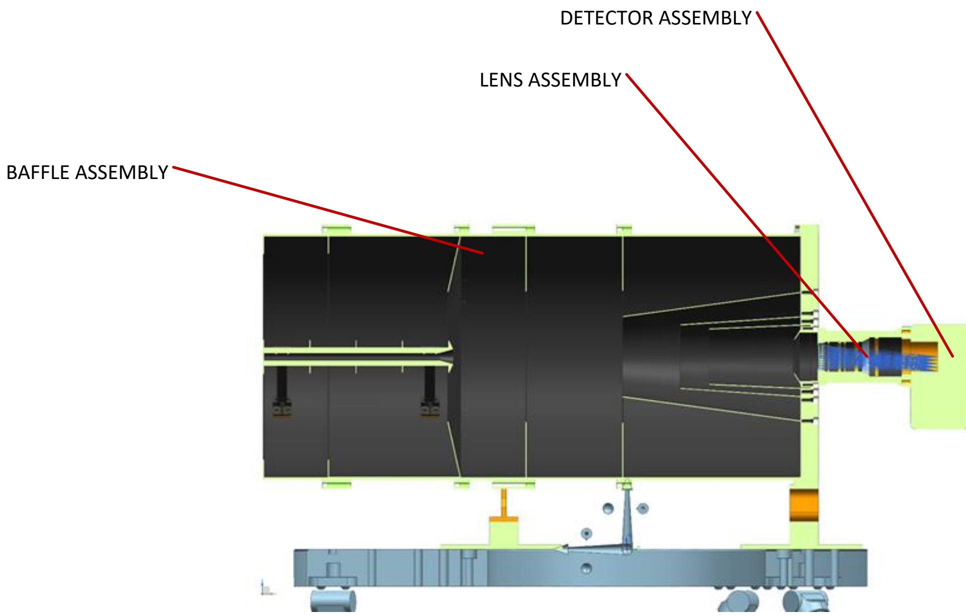

Figure 7: The SCOPE optical breadboard

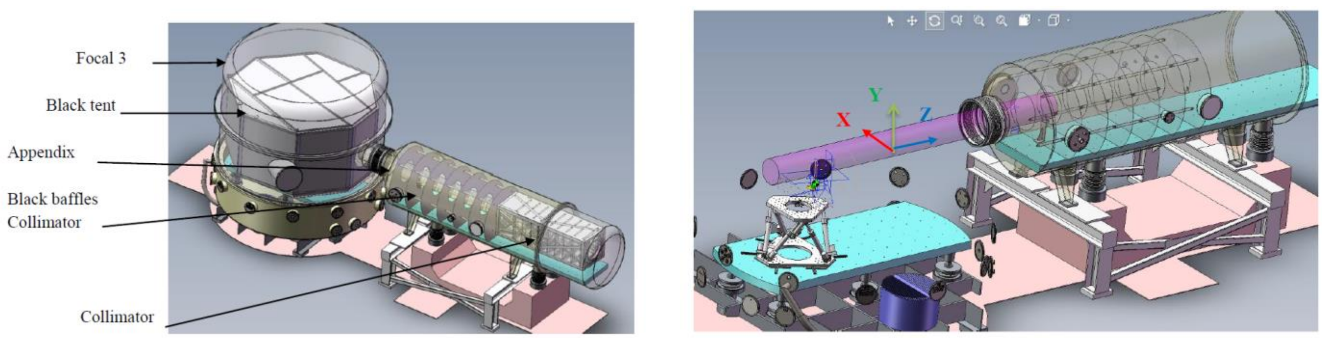

Figure 8: The FOCAL3 test chamber (left) and the hexapod mounting for the breadboard (right, chamber hidden)

4. ACKNOWLEDGEMENTS

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[1] Krist, J. E., “PROPER: an optical propagation library for IDL,” Proc. SPIE 6675, (2007).