ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

V-UV spectrographic imager (FUV) for Icon mission: from optical design to vacuum calibration

Jérôme Loicq

Pascal Blain

Christian Kintziger

Richard Desselle

et al.

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056236 · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296047

V-UV SPECTROGRAPHIC IMAGER (FUV) FOR ICON MISSION: FROM OPTICAL DESIGN TO VACUUM CALIBRATION.

Jerome Loicq*[1], Pascal Blain[1], Christian Kintziger[1], Richard Desselle[1], Yvan Stockman[1], Kodi Rider[2], Cathy Chou[2], Harald U. Frey[2], Stephen B. Mende[2]
[1] Centre Spatial de Liege, University of Liege, avenue du pré aily, 4031 Angleur, Belgium;
[2] Space Sciences Laboratory, University of California, 7 Gauss Way, Berkeley, CA 94720, USA

I. INTRODUCTION:

The ICON mission is led by the University of California-Berkeley (Space Sciences Laboratory). In the frame of this mission the Space Center of Liege was involved in the optical design optimization and related analysis, and VUV on ground calibration.

The ICON mission (NASA) will explore the boundary between Earth and space to understand the physical connection between our world and our space environment. Recent NASA missions have shown how dramatically variable the region of space near Earth is, where ionized plasma and neutral gas collide and react. This region, the ionosphere, has long been known to respond to space weather drivers from the sun, but in this century we have come to realize that the energy and momentum of our own low altitude atmosphere regularly affect the ionosphere with equal or greater magnitude. ICON will weigh the impacts of these two drivers as they exert change on our space environment.

During the day, photoelectrons colliding with atmospheric neutrals, N2 and O, produce emissions and by observing the limb brightness of the N2 Lyman-Birge-Hopfield (LBH) band and of the OI 135.6 nm line, the density ratio of the neutral N2 and O atmospheric constituents can be retrieved. At night the recombination of O+ ions with ionospheric electrons also creates OI 135.6 nm emissions and the nighttime electron density can be estimated from the limb brightness of 135.6 nm. ICON FUV will measure the altitude distribution of the OI 135.6 nm and N2 LBH dayglow emissions at 157 nm and the altitude and spatial distribution of the OI 135.6 nm nightglow emissions. These quantities can then be used to determine dayside O and N2 densities and altitude profiles, and the nightside O+ densities in the F-region. The ICON-FUV instrument is based upon the IMAGE Spectrographic Imager (SI) [1] [2] [3]. Like this predecessor, ICON-FUV is a two-channel imager that uses a grating spectrometer for spectral discrimination [4] [5] [6]. The two channels are required to provide the daytime profiles of two wavelengths characterizing the N2 and O species (centered at 157 nm and 135.6 nm respectively). This grating type of spectrographic imager minimizes contamination by out-of-band light leaks that are a typical problem for non-grating type FUV cameras. The instrument is composed by two parts, a Czerny-Turner spectrograph selecting the science wavelengths. This spectrograph is then combined with two imagers respectively working in the two wavebands of interest. The challenge of this space instrument was to be designed for a very wide FOV (24° vertical by 18° horizontal).

The instrument has been optimized in two main steps including payload platform constrains. First the Czerny-Turner spectrograph has been designed to reduce as much as possible the astigmatism generated by the grating and spherical mirror and to give the same spectral properties over the entire field of view, secondly the two imagers based on aspheric and off-axis mirrors have been designed.

The calibration facility developed at CSL is based on the combination of two light sources (Deuterium and a white laser) connected to a vacuum Mc Pherson monochromator (Model 225) coupled itself to a collimator. The light going out of the exit slit of the monochromator illuminates a pin-hole and an MgF2 diffuser to create an extended source for the collimator. The collimator is based on an off-axis parabola which produces approximately a 10 cm diameter collimated beam.

The line of sight control during thermal cycle qualification campaign and optical calibration is enabled through an auto-collimation process with the help of a mirror cube and a CMOS camera in the visible domain. This one is using the reflection by a reference cube placed on the instrument turret structure (scanning mirror). The light reflected by the reference cube returns back into the collimator and is focused into the camera.

Specific strategies have also been developed to align the instrument under vacuum to meet spectral properties and imagery requirement (PSF). Three of the instrument mirrors were actuated to align the instrument under vacuum. Alignment achievements will be presented. Instrument concept design, tolerances and alignment cases simulations were presented on the paper [7].

II. FUV INSTRUMENT CONCEPT:

A. Description

ICON FUV is a Czerny-Turner (CZT) spectrographic imager. The ICON-FUV instrument is based on two specific parts. Wavelengths are first selected by a CZT spectrograph, beyond two exit slits light is focused by two independent imagers, one per science wavelength respectively centered at 135.6 nm and 157 nm.

The CZT spectrograph acts as a wavelength filter. All fields contained into the whole FOV go through the entrance slit and are refocused on the exit slits. Fields are then focused on the detector plane by two aspheric and off-axis mirrors (CM1 and CM2) to create image spots in both channels (SW: 135.5 nm and LW: 157 nm).

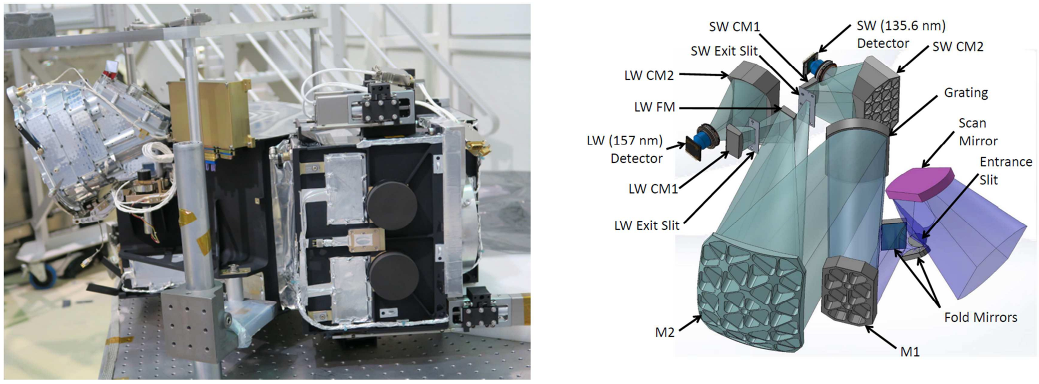

Figure 1: Optical design of the FUV instrument: Light enters into the instrument by a scan mirror and the entrance slit directly placed after the scan mirror. Two fold mirrors bend the beam into the FUV principal plane. The CZT spectrograph is formed by two spherical mirrors (M1 and M2) and a 3600 ln/mm grating. Images are created on detector planes by aspheric off-axis mirrors CM1 and CM2 on both channels.

The entrance slit object viewed over the whole FOV is collimated by the M1 mirror to the grating where light is diffracted and next focused by M2 on the exit slits. The image position of the entrance slit depends of the wavelength and in this specific case 135 nm and 157 nm are selected by the use of two separated exit slits. The two wavelength channels are then completed by separate back imager optics and detectors. The optical scheme is presented in Figure **1**.

An intermediate image of the sky is appearing close to the grating which is re-imaged on the detectors by M2 and the back imager optics.

The CZT spectrograph has two asymmetric arms, with a magnification factor of about 1.52. The linear dispersion achieved is 0.6 nm/mm.

The instrument is surmounted by a motorized scan mirror called the "turret". The aim of this item is essentially to adjust the FUV boresight over a range of ±30 degrees. The central optical axis of the scan mirror is oriented at an angle of 20 degrees with respect to the local horizontal. The turret is also equipped with an entrance baffle to exclude parasitic light coming from out of the instrument FOV.

B. Optical Requirements

The optical design of the FUV instrument has to meet the following requirements:

1. The FUV instrument shall have 2-dimensional ultraviolet imaging capability at 135.6nm, the 'short wavelength channel' and the LBH band, nominally 157 nm, known as the 'long wavelength' channel.
2. The FUV instrument absolute intensity sensitivity shall be greater than 13 counts per kRayleigh per second per resolution cell in the short channel.
3. The FUV instrument absolute intensity sensitivity shall be greater than 8 counts per kRayleigh per second per resolution cell in the long channel.
4. The FUV shall have a horizontal field of view greater than 18 degrees and a vertical diagonal field of view equal to or greater than 24 degrees.
5. The FUV boresight shall be directed vertically 20 +/- 0.5 degrees below the local horizontal in the nominal launch position.

6. For day time observation the FUV shall have a resolution cell in the short and long wavelength channel corresponding to 4 km (0.094 degrees) in the vertical direction and 16 km (0.374 degrees) in the horizontal direction on the limb at a range corresponding to a limb tangent altitude of 140 km.
7. Ensquared Energy of 2x2 sample cells (192 µm) is > 90% on the detector plane
8. SW Transmission > 9.5% (BOL) / 8% (EOL) and LW Transmission > 8.5% (BOL) / 7% (EOL)
9. The FUV total background count rate at the detector on-orbit due to combination of dark emissions, dark currents and inadequate out of band rejection shall be no more than B counts per second per resolution cell where B is 0.060 for nighttime 135.6 nm, 0.277 for daytime 135.6 nm, and 0.139 for daytime LBH.
10. Suppress 130.4nm to <2% of 135.6nm; 121.6nm to <0.5% of 135.6nm; 149.3nm to <0.5% of 157 nm; 164.1 nm to <0.5% of 157 nm (Remark: BOL= Beginning of life; EOL = end of life)

Optimisation process of the optical design is described in details into the reference [7]. Even if the spectral selection of the instrument is performed identically for both channels with the CZT, the objectives followed by both channel are different. The Figure **2** describes a spectrum including some atomic lines the FUV will look at. SW channel is mainly dedicated to Oxygen line centered at 135.6 nm whereas LW is dedicated to some N2 LBH lines around 157 nm.

Lines to be rejected are:

- 121.6 nm Hydrogen Lyman alpha
- 130.4 nm atomic oxygen line
- 149.3 and 164.1 nm atomic Nitrogen and oxygen lines, respectively

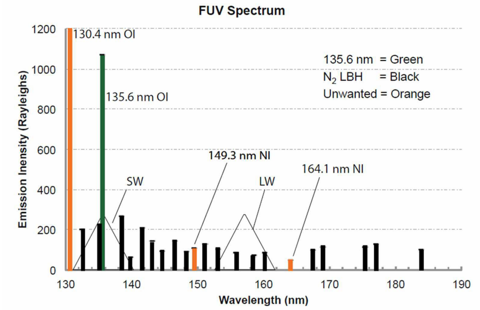

Figure 2: Far UV imager specified spectrum intercepting SW and LW channel, respectively OI and N2 LBH lines.

SW channel has to be as narrow as possible to reject the unwanted oxygen line at 130.4 nm, on the other hand the LW channel has to get most of the N2 lines energy covered by the LW exit slit. This is the reason why LW channel can accommodate a larger slit than the SW.

III. OPTICAL CALIBRATION

Optical calibration gathers many concepts described below [5]. Before flight the instrument has to be calibrated to characterize how it behaves and to know how close it works from the optical design. Calibration has to be done close to its operational conditions as much as possible. This is why during optical calibration, environmental aspects (thermal, vacuum,...) have to be taken into account. The optical calibration tasks for any instrument can be summarized in three major groups: the determination of the imaging capabilities, the imaging quality, and the quantitative sensitivity or photometric calibration.

The following items are characterized:

A. Field of View

The field of view (FoV) of the FUV is determined by the total view angle through the slit aperture, and any potentially beam size limiting elements inside of the instrument like mirror or grating masks, window holding fixtures, and even unwanted restrictions from misaligned baffles. The size and shape of the FoV will be determined with the laboratory setup described later in the paper. The instrument is rotated around the entrance pupil with respect to the incoming parallel light beam coming from the collimator.

B. Line of sight

The pointing of the center line of sight of the instrument is determined with respect to alignment cubes on the instrument body. In the case of ICON-FUV, the instrument was placed on a tip/tilt and rotation stage (Figure 3). This Mechanical Ground Support Equipment (MGSE) provided the ability to rotate the instrument around the entrance pupil and to cover more than the entire FOV [24° vertical, 18° horizontal]. The manipulator is composed of three linear actuators (tripod) on which a rotation table is placed through a “3 point isostatic mount”. The absolute accuracy and repeatability of the manipulator is 3 arcsec. The control of the line of sight during thermal cycles is enabled with a mirror cube placed on the instrument body and a CMOS camera in the visible domain (see Figure 3). This alignment is based on an auto-collimation process and uses the reflection by a reference cube placed on the instrument structure (scanning mirror). The light reflected by the reference cube returns back into the collimator and is focused into the camera. The comparison of the reflected beam imaged onto the camera as a function of the different angles gives the ability to realign the instrument. Misalignments are mainly due to the thermo-mechanical constrains of the structure interfacing the instrument with the manipulator. This auto-collimation process then gives the knowledge of the pointing properties of the instrument by the MGSE. That gives the ability to discriminate the thermo-mechanical effects coming from the structure and those internal to the instrument itself. Later, the alignment with respect to the spacecraft structure will be determined by theodolites looking at the instrument alignment cube and alignment cubes on the spacecraft structure.

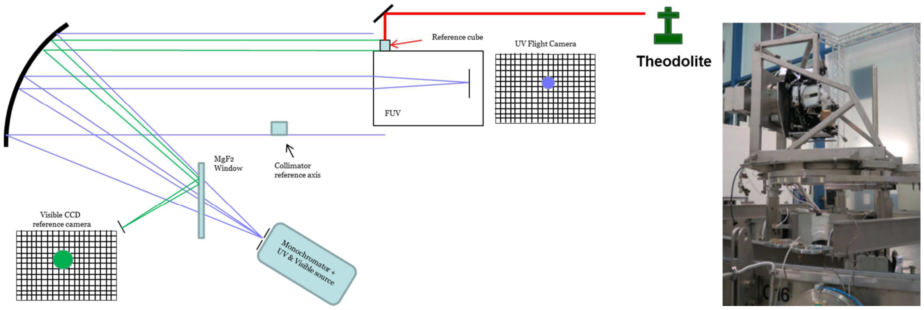

Figure 3: (Left) Line of sight auto-collimation process; (Right) The tip/tilt and rotation stage at CSL Liege which was used for the motion of the ICON-FUV instrument during testing and calibration.

C. Imaging properties

The FUV imaging properties are characterized by the aim of PSF (point spread function) measurements on the detectors’ focal planes. Spot sizes and shapes are characterized over the entire instrument FOV. Over all fields 90% of encircled energy has to be included in 2x2 sciences pixels as described in the Instrument requirement section. Imaging properties are characterized by recording images of spots for all the fields to be analyzed.

D. Imaging distortions

By design, FUV suffers from some degree of optical distortions. This is mainly due to the optical properties, shapes and positions of the optical elements. Moreover, manufacturing uncertainties and misalignments can create additional aberrations and distortions. Very often, imaging distortions are determined together with imaging properties and field of view measurements using a narrow beam of light. The instrument is rotated horizontally/vertically (tip/tilt) by fixed angular steps, the relative position of the resulting spot is determined, and compared to expected positions in pixel space.

E. Spectral properties

Careful characterization of the spectral band pass is important for instruments such as spectro-imagers. This instrument will not look at just one single wavelength but will see several spectral lines simultaneously. Spectral band pass characterization is realized thanks to a wavelength scanning monochromator GSE. Throughput at each wavelength is recorded onto the detectors. Photon counts with wavelength are analyzed. To be complete, spectral characterization is also done over all fields. Indeed optical components misalignments can create fields’ vigneting as consequences of slight wavelength shift and throughput decrease on spectral curves with fields.

F. Stray light background

Stray light (SL) background has different sources:

1. Out of bandpass light entering the instrument through the entrance aperture.
2. In-band light from outside of the FoV which scatters through the entrance baffle.
3. Zero order grating reflection within the instrument
4. Higher diffraction orders that could reach the detector

5. Light scattered within the instrument by walls, edges,…
6. Light entering the instrument through unwanted paths (venting holes for instance)

IV. GROUND SUPPORT EQUIPMENT (GSE)

A. Overall setup description

The FUV calibration setup is based on three independent vacuum chambers that can be pumped down separately. When valves are opened, vacuum is continuous from source to detectors of the FUV instrument. To avoid any throughput losses, no window is placed between vacuum chambers.

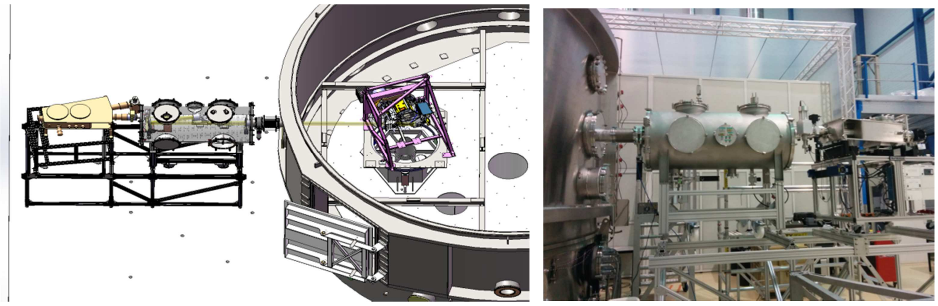

Figure 4: (Left) Scheme of the whole setup. It is based on three independent vacuum chambers. From left to right: the illumination part composed by two sources (fiber connected visible source and Deuterium lamp) and a McPherson monochromator to select wavelength, the collimator part and the main vacuum chamber where the FUV instrument is mounted on the manipulator. (Right) The experimental setup installed inside CSL's class 100 clean room facilities. From right to left: the illumination part, the collimator part and the vacuum chamber in which the instrument is mounted on a manipulator.

B. Illumination part

The illumination device is based on a vacuum monochromator (M225 from McPherson Inc.) coupled with two light sources [8].The monochromator has F # of 10.4 and a 1 meter focal length. The wavelength accuracy is around 0.1 nm. The slits width control and grating orientation are fully automatic and computer-controllable. The light sources are a calibrated deuterium lamp (with a wavelength range from 115 to 180 nm) and a visible fiber coupled source. Visible light is used for FUV visible alignment process, cube shooting referencing and verification purposes. Deuterium lamps were used mostly for UV alignment process and instrument calibration under vacuum. The monochromator is fitted out by two selectable gratings with diffraction efficiencies optimized in function of selected wavelength region (visible or VUV). The UV source is a calibrated deuterium lamp and the visible source is a white light Energetiq source (Energetiq Technology, Inc.) [9].

C. The collimator

The second part of the setup is a vacuum collimator assembly based on a 1 m focal length Off-Axis Parabola (OAP) to produce a 10 cm diameter collimated beam. Figure 5 represents the optical scheme of the collimator assembly.

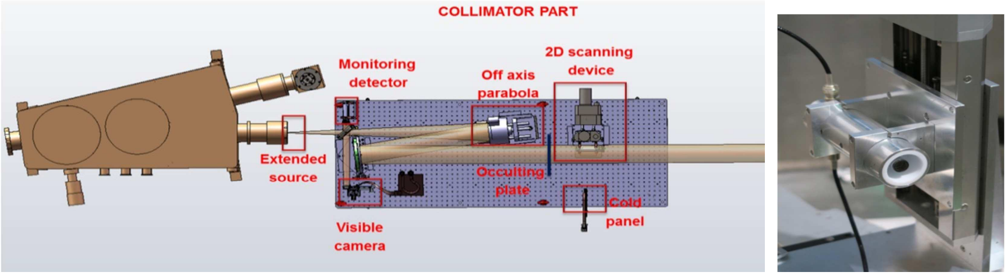

Figure 5: (left) Beam and collimator part of the OGSE. (right) Detector based on a PMT [10].

The monochromator illuminates an extended source to create a slightly divergent beam. The divergence objective is to illuminate more than one instrument pixel to perform centroidation for geometric calibration and registration. The extended source is created by the use of a filter wheel with different sized pinholes coupled with MgF2 diffusers.

An empty filter wheel slot allows maximizing the output flux if needed. As the filter wheel depth is not negligible, we have to adapt the Off-Axis Parabola position to keep a collimated beam. The two OAP positions place its focus either on filter wheel diffusers or on the monochromator exit slit. The OAP is mounted and aligned on a translation stage. Its position may even be controlled during operation under vacuum if necessary. An Aluminum mirror protected with MgF2 is placed after the OAP in the light path to fold the beam onto the FUV instrument. Monitoring of the source fluctuations is done and recorded with the help of a 45° MgF2 beamsplitter combined with a Photomultiplier Tube [10]. This detector is a solar blind R1081 Photomultiplier Tube (PMT) from Hamamatsu with a wavelength range of 115 to 200 nm. A visible bare CMOS camera is used on the back side of the beam splitter window for relative instrument pointing (cube shooting process) relative to the OGSE beam. A reference cube placed on the instrument reflects back collimator light to the CMOS camera. This device is designed to measure misalignment behaviors and pointing errors during thermal calibration cases. The whole system measures misalignment with a few arcsecond accuracy.

The OGSE beam illuminates the FUV entrance slit through the turret mirror (scan mirror). As the entrance slit acts as the optical pupil, the instrument has to be rotated around this component to illuminate every field of view. Practically, the instrument has to rotate around the image of the FUV entrance slit through the turret mirror.

D. *GSE instrument manipulator*

The scientific FUV fields of view are located in the following range: [-9°, +9°] horizontal and [-12°, +12°] vertical. As the test beam is collimated, the instrument is placed on a tip/tilt and rotation manipulator (Figure 6). The manipulator is based on three linear actuators (tripod) on which a rotation table is mounted through a « point-groove-plan » kinematic mount. The manipulator angular range is [-11°, +11°] for the tilt (linear actuators) and [-60°, +60°] for the tip (rotation stage). The angular positioning accuracy of the cradle is 3 arcsec. Thus each field of the instrument can be addressed.

E. *Thermal tent*

Optical Calibration requires to record data for different operational temperatures. The use of a thermal tent is then mandatory to set different temperature cases and gradients as well. The thermal tent designed and used for the ICON-FUV calibration is based on five active copper planes with Nitrogen pipes. Each of the thermal panels is independently controllable with thermal sensors (PT100 & PT1000). Temperature is set by a regulated N2 gas flow from -150°C to +80°C. Liquid Nitrogen can also be flown into the installation. The sixth side of the box is passive and is based on a MLI (Multi-Layer Insulator) blanket. In the front side panel, a hole has been created to allow collimator light to reach the instrument.

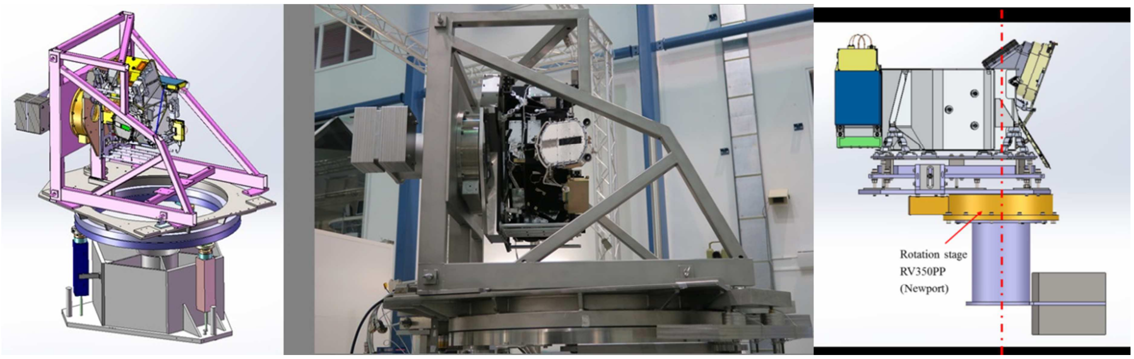

Figure 6: (left and middle) FUV-Instrument mounted on the GSE manipulator. (right) device to allow turret motion compensation.

Alignment details of the instrument and calibration are described in the following papers [18] [19].

V. CONCLUSION

In this paper, we described the FUV instrument designed for the ICON mission (NASA). Calibration OGSE and MGSE are also described. They were designed and built for the alignment and calibration campaign of the FUV instrument of the ICON mission. The vacuum OGSE includes an illumination part (monochromator) coupled with a collimator that provides a collimated beam to illuminate the FUV entrance slit. The instrument has been placed on a specific MGSE that allows the rotation of the instrument around the entrance pupil (entrance slit) to provide illumination of the different fields of view of the instrument. The calibration plan has been described. Finally, alignment strategies have been presented.

VI. ACKNOWLEDGEMENTS

This work was supported by The Belgian Federal Science Policy Office (BELPSO) under grant number C4000113654. ICON is supported by NASA's Explorers Program through contracts NNG12FA45C and NNG12FA42I.

VII. REFERENCES

[1] S. Mende, H. Heetderks, H. Frey, M. Lampton, S. Geller, S. Habraken, E. Renotte, C. Jamar, P. Rochus, J. Spann, S. A. Fuselier, J. Gerard, R. Gladstone, S. Murphree et L. Cogger, «Far ultraviolet imaging from the IMAGE spacecraft: 3. Spectral imaging of Lyman-α and OI 135.6 nm,» *Space Sci. Rev.*, vol. 91, p. 287, 2000.

[2] S. Mende, H. Heetderks, F. Harald, M. Lampton, S. Geller, S. Habraken, E. Renotte, C. Jamar, P. Rochus, J. Spann, S. A. Fuselier, J. Gerard, R. Gladstone, S. Murphree et L. Cogger, «Far ultraviolet imaging from the IMAGE spacecraft: 1 System design,» *Space Sci. Rev.*, vol. 91, p. 243, 2000.

[3] S. Mende, H. Heetderks, F. Harald, M. Lampton, S. Geller, S. Habraken, E. Renotte, C. Jamar, P. Rochus, J. Spann, S. A. Fuselier, J. Gerard, R. Gladstone, S. Murphree et L. Cogger, «Far ultraviolet imaging from the IMAGE spacecraft: 2 Wideband FUV imaging,» vol. 91, p. 271, 2000.

[4] S. Habraken, C. Jamar, P. Rochus, M. Stephen et M. Lampton, «Optical Design of the FUV spectrographic Imager for the Image Mission,» *proc SPIE* , vol. 3114, p. 544, 1997.

[5] S. Habraken, Y. Houbrechts, E. Renotte, M.-L. Hellin, A. Orban, P. Rochus, S. Mende, H. Frey, S. Geller et J. Stock, «Optical calibration of the FUV spectrographic imager for the IMAGE mission,» *proc. SPIE,* vol. 3765, pp. 508-517, 1999.

[6] E. Renotte, S. Habraken, P. Rochus, M.-L. Hellin, A. Orban et I. Tychon, «Design and verification of the

Far Ultraviolet Spectrographic Imager (FUV-SI) for the IMAGE mission,» *ProcSPIE,* vol. 3445, pp. 427-438, 1998.

[7] J. Loicq, C. Kintziger, A. Mazzoli , T. Miller, C. Chou, H. Frey, T. Immel et S. Mende, «Optical design and optical properties of a VUV spectrographic imager for ICON mission,» chez *Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 990507,* Edimburgh, 2016.

[8] M. Pherson, «http://mcphersoninc.com/spectrometers/vuvuvvis/model225.html,» [En ligne]. [Accès le 2016].

[9] E. T. inc., «http://www.energetiq.com/DataSheets/EQ99XFC-Data-Sheet.pdf,» [En ligne]. [Accès le 2016].

[10] Hamamatsu, «https://www.hamamatsu.com/us/en/R1081.html,» [En ligne]. [Accès le 2016].

[11] A. inc, «http://www.breault.com/software/about-asap,» [En ligne]. Available: http://www.breault.com/software/about-asap.

[12] «Code V,» Synopsis, [En ligne]. Available: https://optics.synopsys.com/codev/.

[13] D. Austin, T. Witting et I. Walmsley, «Broadband astigmatism-free Czerny–Turner imaging spectrometer using spherical mirrors,» *APPLIED OPTICS* , vol. 48, n° %119, p. 3846, 2009.

[14] L. Murphy, et J. Dalton, «Astigmatism Compensation in the Czerny-Turner Spectrometer,» *APPLIED OPTICS,* vol. 5, n° %17, p. 1121, 66.

[15] X. Qingsheng, W. Shurong et L. Fengqin , «Aberration-corrected Czerny–Turner imaging spectrometer with a wide spectral region,» *APPLIED OPTICS,* vol. 48, n° %11, p. 11, 2009.

[16] J. Loicq, C. Kintziger, A. Mazzoli , T. Miller, C. Chou, T. Immel, H. Frey et S. Mende, «Optical design and optical properties of a VUV spectrographic imager for ICON mission,» *ProcSPIE,* Vols. %1 sur %29905-6, June 2016.

[17] P. Blain, R. Desselle, I. Domken, C. Kintziger, E. Renotte, Y. Stockman, C. Chou, H. U. Frey, K. Rider , S. Mende et J. Loicq, «VUV optical ground system equipment and its application to the ICON-FUV flight grating characterization and selection,» chez *Proc. SPIE 9912, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II, 99124O,* Edimburgh, 2016.

[18] J. Loicq, P. Blain, C. Kintziger, R. Desselle, Y. Stockman, I. Domken, E. Renotte, L. Clermont, K. Rider, C. Chou, C. Poppett, H. Frey et S. Mende, «Alignment and calibration of the ICON-FUV instrument: development of a vacuum UV facility,» chez *Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 99052W,* Endimburgh, 2016.

[19] J. Loicq, P. Blain, R. Desselle, I. Domken, C. Kintziger, E. Renotte, Y. Stockman, C. Chou, H. Frey, K. Rider et S. Mende, «VUV optical ground system equipment and its application to the ICON-FUV flight grating characterization and selection,» *ProcSPIE,* vol. 9912, 2016.