Institution: Queen's University Belfast		
Unit of Assessment: 9		
Title of case study: Development of large-format, high-cadence scientific CMOS devices with Andor Technology		
Period when the underpinning research was undertaken: 2009-2016		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Prof. Mihalis Mathioudakis	Professor School of Mathematics and Physics	1997 - present
Prof. Francis Keenan	Astrophysics Research Centre (ARC)	1982 - present
Period when the claimed impact occurred: 2015-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Scientific innovation is linked to technological breakthroughs. Recognising that standard commercially available equipment was unable to deliver the scientific objectives of current and future research programmes, the Astrophysics Research Centre (ARC) at QUB teamed-up with Oxford Instruments' Andor Technology to develop the Balor imaging sensor and synchronisation platform. The impact is two-fold. First, this partnership has allowed Andor to expand into the large-format detector market and increased their revenue by more than GBP3,000,000 since September 2019 alone. Second, striking Balor-enabled solar images have generated significant press and industry coverage, engaging new audiences in Solar science and helping to accelerate Andor's leading position in the global scientific camera market.

2. Underpinning research

Prof. Mathioudakis and Prof. Keenan work in the Astrophysics Research Centre (ARC) in Queen's University Belfast (QUB). They performed the underpinning research that both revealed the need for new large-format, high-cadence scientific CMOS (complementary metal-oxide-semiconductor) devices and guided their development. Prof. Mathioudakis was the academic lead on the collaboration with Andor.

Studies of the Sun and its outer atmosphere have always been the source of notable physical insights. From the discovery of helium, first made in the solar atmosphere, to the identification of nuclear fusion as a power source for stars and the unexpected physics of neutrinos, our nearest star is a unique source for our understanding of the Universe in its many forms. The Sun is the most important astronomical object for humankind, with solar activity driving space weather and having profound effects on climate and communications. Its atmosphere and interior provide a working example where structures and dynamics can be studied over an enormous range of spatial (100km – 100,000km) and temporal (seconds to months) scales. The Sun provides a vantage reference point where the complex interplay between the plasma and the magnetic field is visible and can be studied continuously at unprecedented detail.

Research in ARC has proved the existence of Alfvén waves in the lower solar atmosphere **[R1]** and discovered the smallest magnetic flux cancellations in the photosphere **[R2]**. Alfvén waves and magnetic flux cancellations are key to understanding the structure and dynamics of the Sun's outer atmosphere. First, spectropolarimetric data was inverted to obtain the magnetic energy dissipated and it was compared to the radiative losses **[R3]**. Next spectral imaging was used, alongside radiative hydrodynamic models to disentangle the physical processes in rapidly evolving events and solar flares **[R4, R5].** This established strong evidence for ubiquitous compressive waves in the Sun's chromosphere **[R6]**. This research, however, has also emphasised the need to push the limits of solar instrumentation, and highlighted the requirement for a new generation of large format, high-speed camera equipment.

As a result of their research pushing the boundaries of what is currently possible with existing instrumentation, QUB researchers have played a central role in defining the science specifications for the next generation of solar telescopes, such as the US-led Daniel K Inouye Solar Telescope (DKIST) and the European Solar Telescope (EST). These are unique facilities that will revolutionise the field. Key advances that will be offered by these instruments are ultra-high spatial (25km) and temporal (millisecond, ms) resolution, photospheric and chromospheric imaging spectroscopy, vector magnetometry, plus infrared coronal magnetometry. Prof. Mathioudakis is a member of the DKIST instrumentation team, a board member of the European Association of Solar Telescopes, and a member of the EST Science Advisory Group. The requirement for large format, high cadence detectors became apparent.

Profs. Mathioudakis and Keenan have partnered with Andor Technology to realise this vision and develop the detectors for these telescopes. This project was funded by an STFC grant for GBP1,900,000 to QUB in January 2015 (PI: Mathioudakis) and H2020 grants of GBP50,000 in June 2015 and October 2016 (PI: Mathioudakis). This research resulted in QUB leading the development and supply of all the optical cameras that equip the US DKIST telescope. The resulting product, named Balor, has been taken to market by Andor. Balor is the largest-format, high-cadence scientific Complementary Metal Oxide Semiconductor camera commercially available. This development will allow Oxford Instruments/Andor to maintain a leading position in the high-tech market. It opens new technological markets and also provides growth and diversity in existing markets.

3. References to the research

[R1] Jess, D. B., **Mathioudakis, M**., Erdélyi, R., Crockett, P. J., **Keenan, F**. P. & Christian, D. J. (2009). "Alfvén Waves in the Lower Solar Atmosphere." Science 323, p. 1582-1585. https://doi.org/10.1126/science.1168680

[R2] Reid, A., **Mathioudakis, M.,** Scullion, E., Doyle, J. G., Shelyag, S. & Gallagher, P. (2015). "Ellerman Bombs with Jets: Cause and Effect." The Astrophysical Journal 805, 64. http://dx.doi.org/10.1088/0004-637X/805/1/64

[R3] Reid, A., **Mathioudakis, M**., Doyle, J. G., Scullion, E., Nelson, C. J., Henriques, V. & Ray, T. (2016). "Magnetic Flux Cancellation in Ellerman Bombs." The Astrophysical Journal 823, 10. http://dx.doi.org/10.3847/0004-637X/823/2/110

[R4] Kuridze, D., Henriques, V., **Mathioudakis, M**., Erdélyi, R., Zaqarashvili, T. V., Shelyag, S., Keys, P. H. & **Keenan, F. P.** (2015). "The Dynamics of Rapid Redshifted and Blueshifted Excursions in the Solar Hα Line." Astrophysical Journal 802, p. 1-8 26. https://doi.org/10.1088/0004-637X/802/1/26

[R5] Kuridze, D., **Mathioudakis, M**., Simoes, P. J. A., Rouppe van der Voort, L., Carlsson, M., Jafarzadeh, S., Allred, J. C., Kowalski, A. F., Kennedy, M., Fletcher, L., Graham, D. & **Keenan, F. P.** (2015). "Hα Line Profile Asymmetries and the Chromospheric Flare Velocity Field." The Astrophysical Journal 813, 9 p., 125. https://doi.org/10.1088/0004-637X/813/2/125

[R6] Morton, R. J., Verth, G., Jess, D. B., Kuridze, D., Ruderman, M. S., **Mathioudakis, M**. & Erdélyi, R. (2012). **"**Observations of ubiquitous compressive waves in the Sun's chromosphere." Nature Communications 3, 1315. https://doi.org/10.1038/ncomms2324

4. Details of the impact

Andor Technology (now within Oxford Instruments) is a spin-out company from QUB. Over the past 12 years, researchers from ARC in QUB have worked closely with Andor on the development of several scientific cameras and instruments for astronomical applications. This partnership involved the specification, testing and evaluation of both hardware and software to achieve microsecond-accuracy synchronisation across several camera platforms. This improved Andor's understanding on a number of technical issues allowing novel solutions to be applied to camera products such as the Neo, Zyla and Marana of the sCMOS range and four models of the iXon EMCCDs. This success helped Andor gain a leading position in the scientific camera market on a global scale, particularly in the growing area of astronomy.

However, as outlined above, the demands of research have outstripped the capabilities of these detectors. This created the need for innovative technological breakthroughs to enable the next generation of scientific investigations of the Sun. In order for Andor to maintain and grow its current global lead, it must match the pace of development. This is only possible by working closely with frontline researchers that are leading the charge into new scientific territory.

"*Balor was initiated through the solar physics research programmes undertaken at Queen's University Belfast, and developed in collaboration with staff in the Queen's Astrophysics Research Centre, University College London, Armagh Observatory, Northumbria University, University of Glasgow, University of Sheffield, University of St Andrews, University of Warwick and the US National Solar Observatory, from funding provided by the Science and Technology Facilities Council, part of UK Research and Innovation*" **[S1].**

By partnering with QUB for this project, Andor gained access to numerous research groups in the UK, allowing them to develop a good understanding of the market-place (as a company it would only make sense to pursue a project with a sustainable user base). As outlined by Dr. Colin Coates, Head of Product Management for Physical Sciences and OEM at Andor, this research-led approach has generated an international success story:

"*Balor was formally launched in Sept 2019 and to date we have sold almost 30 units across a range of countries, including USA, UK, China, Korea, Germany, Switzerland and Sweden, amounting to > £3m revenue.*" **[S2].**

This new breed of large-format, high-cadence cameras **[S3]** has also been deployed on the DKIST. DKIST is a USD400,000,000 facility, constructed by the National Solar Observatory in Hawaii, USA. It operates in the optical and near-infrared wavelength ranges and will be the pre-eminent ground-based solar telescope for the foreseeable future. DKIST has 4 main instruments that will operate in the visible part of the electromagnetic spectrum, and QUB led a consortium of 8 UK universities and Andor to deliver the detector equipment for all 4 instruments in the visible. QUB's lead role in this was highlighted in the STFC Innovations Club newsletter in 2015 **[S4]**. For DKIST to meet its scientific objectives the cameras had to cover a large field-of-view at the diffraction-limited resolution of the telescope and at very high temporal resolution. The specific scientific objectives require large-format (16,000,000 pixels), highly sensitive cameras obtaining approximately 60 high-fidelity images of the Sun every second. The leading role of QUB in the development of Balor and its relevance to DKIST is outlined by the Head of Product Management for Physical Sciences and OEM at Andor **[S3]**:

"The joint UK funding initiative spearheaded by QUB, through which the UK designed and supplied Balor detectors to the new DKIST solar telescope in the USA, provided the necessary commercial and financial stimulus to support a challenging and innovative technology development that opens up new scientific possibilities across astronomy and beyond. Furthermore, QUB Astrophysics offered invaluable technical and usage expertise that proved critical at various stages of development and as well as taking a leading role in both alpha and beta testing."

As Richard Morgan reports for the BBC *"Experts have said it will enable a new era of solar science."* **[S5].** The telescope came online in mid-2019 and, through the QUB-driven Balor system produced stunning images of the Sun in late 2019 (Fig 1) **[S6].**

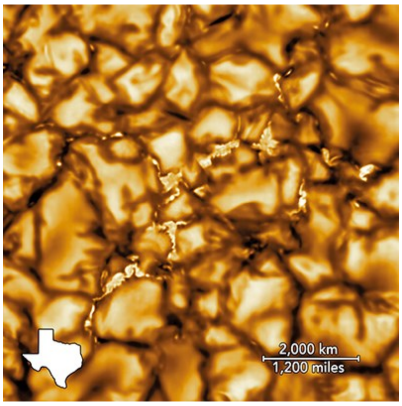

Fig 1. [S6] *"The highest resolution Solar images have been captured by Andor Balor sCMOS cameras at the largest solar telescope in the world"* (Note Texas to scale) "*The images were taken with the newly released 16-megapixel Andor Balor sCMOS camera, which was developed as part of the telescope project which involves a research consortium with key driving from **Queen's University Belfast**"* **[S7].** Image credit NSO/AURA/NSF.

The impact generated by this was immediate. The ability to relate the size of features on the Solar surface to the size of states in the US captured the public's imagination, with popular science articles appearing in newspapers with a huge circulation such as the **New York Times**:

"*These images show the Sun's surface in greater detail than ever before. The Daniel K. Inouye Solar Telescope released the highest resolution observations of the sun's surface ever taken. These cell-like structures — each about the size of Texas — are the signature of violent motions that transport heat from the inside of the Sun to its surface"* [**S8**].

From a broader impact perspective, it is important to note that a movie of the data in Fig. 1 is available in **[S5]** and **[S8]**. The ability to make videos of solar dynamics not only allows researchers to study the Sun in real time but provides a crucial new modality for educating and inspiring the general public about the work that is performed in our universities. This is made possible by the ability of each camera to generate approximately 2.5 Gbytes of data per second. This capability has revolutionised the use of large-area sCMOS cameras for the acquisition of scientific data. This was driven directly by the need to obtain high resolution spectropolarimetric data in real time (a requirement revealed in **R1** to **R6** above) and its development and testing were performed by QUB researchers.

In addition, it is crucial to acknowledge the impact of this ability to reach into mainstream media for Andor Technology's strategy to accelerate their growth in international markets.

The solar astronomy market alone is substantial, given the continued investment in existing solar facilities in Europe, US, India and China. A significant part of this market is migrating towards the next generation of sCMOS detectors which offer faster speeds and lower noise. Non-solar applications include: near-Earth object detection, speckle interferometry, lucky imaging and other projects related to high-time resolution astrophysics. It is important to recognise that the unit volume of the large area sCMOS market size will not be as high as that of the current breed of mid-range sCMOS cameras developed for microscopy and optical electron microscope instrumentation applications. However, the large-area astronomy detectors are typically priced significantly higher than mid-range detectors (in excess of GBP100,000 per unit), so a lower-volume market yields an appropriate business case. In the longer term, it will be worthwhile adapting the camera platform for high-speed X-ray detection applications, including protein crystallography and computed 3D X-ray tomography. Andor introduced the Balor camera to the market in September 2019 and has sold units to 7 different countries, generating a revenue of over GBP3,000,000 for the company. Their target is for the Balor platform "*to contribute over £7 million per annum to Andor's revenue and the UK economy within the next 3 years*" [**S2**].

5. Sources to corroborate the impact

[S1] Balor 17F-12 Specifications Document produced by Andor Technology, page 9
https://andor.oxinst.com/assets/uploads/products/andor/documents/andor-balor-17F-12-specifications.pdf

[S2] Letter of support from the Products Manager at Andor Technology plc

[S3] Product information from Andor website: https://andor.oxinst.com/products/scmos-camera-series/balor-scmos#product-information-tabs

[S4] Page 17 “UK to be key partner in the world’s most advanced solar telescope”, Science and Technology Facilities Council Innovation Club Issue 53 February 2015 https://stfc.ukri.org/files/innovations-club-newsletters/inn-newsletter-issue-53/

[S5] “Sun images: Andor Technology and Queen's University involved” https://www.bbc.co.uk/news/uk-northern-ireland-51308335

[S6] “The sharpest images of the sun – Balor sCMOS camera from Andor” https://qd-europe.com/ch/en/news/product-application-news-spectrum/the-sharpest-images-of-the-sun-balor-scmos-camera-from-andor/

[S7] “Andor Balor sCMOS cameras enables scientists study sun’s atmosphere with incredible details” https://www.expo21xx.com/news/andor-balor-scmos-cameras/

[S8] “These Images Show the Sun’s Surface in Greater Detail Than Ever Before” https://www.nytimes.com/2020/01/29/science/daniel-inouye-solar-telescope-pictures.html