Institution: University of Edinburgh		
Unit of Assessment: UoA 9 – Physics		
Title of case study: Accelerated Medical Imaging with Astronomical Data Compression Techniques: from MOPED to *Blackford Analysis Ltd*		
Period when the underpinning research was undertaken: 2000–2012		
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. Alan Heavens	Professor	1984–2012
Dr Ben Panter	PDRA (fmr); CEO, *Blackford Analysis Ltd* (current)	2006–2010
Prof. James Dunlop	Professor	1995–present
Dr William Hossack	Senior Lecturer	1990–present
Dr Raúl Jiménez	Research Fellow & Advanced Fellow	1997–2001 & 2002
Period when the claimed impact occurred: August 2013–December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Attribution: A new data-compression algorithm, MOPED, was developed in the School of Physics & Astronomy, University of Edinburgh (UoE). This led directly to the establishment of *Blackford Analysis Ltd*, a spin-out company successfully solving problems in medical imaging worldwide.

Impact: Improving and speeding up medical image analysis.

Beneficiaries: **Patients,** who have received fast and better-informed treatment using *Blackford Analysis* systems; **radiologists,** who have saved processing time; **hospital IT departments,** who benefit from simplified software maintenance and access to the latest AI algorithms; **the local economy** through job creation; and **partner companies** who have gained market access and faster growth.

Significance: Analysis of radiology images sped up by 10-50%, equivalent to treating >200,000 extra patients per year. The local economy has gained 42 jobs (headcount: 42; FTEs: 42). *Blackford Analysis* revenue in excess of GBP1,000,000 per year.

Reach: More than **2,000,000 patients per year** in over **750 imaging centres, clinics, and hospitals**, primarily in the USA. It has also reached **20 partner medical imaging companies**.

2. Underpinning research

The MOPED algorithm was invented by Prof. Alan Heavens [***R1***], then at the University of Edinburgh (UoE), and was subsequently developed and implemented (primarily) by Dr Benjamin Panter, then a PDRA at UoE and now Chief Executive of *Blackford Analysis Ltd*.

Many data analysis problems involve the need to handle large datasets in order to determine a small number of parameters. For large datasets, the volume of data may make this process slow, and 'brute-force' model-fitting to the full dataset is often impractical.

MOPED (**M**assively **O**ptimised **P**arameter **E**stimation and **D**ata compression) is a unique process which employs a carefully designed massive data compression step, which allows very rapid analysis without compromising accuracy. It was designed by Heavens for galaxy spectrum analysis [***R1***] and was subsequently developed and implemented at the Institute for Astronomy in work led by Panter, initially for the analysis of other large astronomical datasets [***R1–R4***].

In MOPED, multiple simulations of a large dataset are generated, each with small changes to the underlying parameters of the model [***R1***]. The variation among these simulations is used to construct a much smaller linear combination of the full dataset which retains almost all the information contained in the larger one.

For example, consider the two brain CT scans shown in the top panel of the figure below (from [***R5***]). A rotation, translation, and stretch requiring five parameters will bring them into alignment, but to test a single set of those parameters requires using all 1,000,000 pixels in the image, making a full parameter search impossible. In MOPED, images are simulated after making very small shifts, rotations, and stretches, and these simulations are used to construct five sets of weights per pixel. Applying each of these sets gives a new data set with only five data points instead of the million pixels; it is then hundreds of thousands of times faster to fit parameters to this compressed data set.

The method was initially devised to model spectral data from galaxy surveys [***R1***]. Spectra consist of 10^3 - 10^6 data points representing energy flux at different wavelengths, but are modelled using only a handful of parameters representing galaxy age, brightness, and a parametrised form of galaxy star-formation history. The large number of data points was reduced to one per model parameter. In the worst case, this increased measurement uncertainty by only 12% [***R1***].

Subsequent applications of MOPED to other astronomy analyses demonstrated that it could be applied to a range of problems of increasing complexity [***R3***, ***R4***], and at dataset sizes that would later make it applicable to medical imaging [***R2***].

In [***R5***] MOPED was applied to the alignment of translated and distorted 2D images and 3D volumes of medical data, as shown in Figure 1. Applications such as these form the basis of MOPED and *Blackford Analysis's* impact.

The MOPED method has been patented [***R6***] and has wide applicability. Its use has now been extended to areas as diverse as brain MRI scans and applications in the security business. In each case, the data analysis step can be accelerated by large factors without significant loss of accuracy.

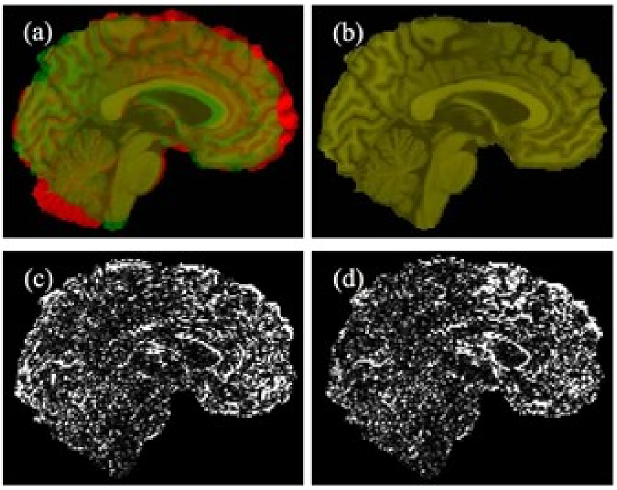

Figure 1: (from [***R5***]) MRI brain scan images after patient motion (a; first scan in green and second in red) aligned extremely well by MOPED (b). The resulting chi-squared mismatch values from the fast MOPED algorithm are shown (c), which are significantly lower (darker) and therefore better than those from the previous FLIRT algorithm (d), which was twice as slow for this analysis phase of the overall diagnosis.

3. References to the research

[***R1***] *Massive lossless data compression and multiple parameter estimation from galaxy spectra*. **Heavens A.F.**, **Jimenez R.**, Lahav O., 2000. Monthly Notices of the Royal Astronomical Society, 317, 965. Initial invention of MOPED and application to galaxy spectra. https://doi.org/10.1046/j.1365-8711.2000.03692.x *[150 citations, NASA ADS]*

[***R2***] *Star formation and metallicity history of the SDSS galaxy survey: unlocking the fossil record.* **Panter B.**, **Heavens A.F.**, **Jimenez R.**, 2003. Monthly Notices of the Royal Astronomical Society, 343, 1145. Tests of MOPED at large scale on a new problem, and analysis of information loss. https://doi.org/10.1046/j.1365-8711.2003.06722.x *[109 citations, NASA ADS]*

[***R3***] *The star-formation history of the Universe from the stellar populations of nearby galaxies.* **Heavens A.F.**, **Panter B.**, **Jimenez R.**, **Dunlop J.S.**, 2004. Nature, 428, 625. Application of MOPED to star-formation history. https://doi.org/10.1038/nature02474 *[388 citations, NASA ADS]*

[***R4***] *The star formation histories of galaxies in the Sloan Digital Sky Survey.* Panter B., **Jimenez R.**, **Heavens A.F.**, Charlot S., 2007. Monthly Notices of the Royal Astronomical Society, 378, 1550. Use of more complicated models in MOPED.
https://doi.org/10.1111/j.1365-2966.2007.11909.x *[248 citations, NASA ADS]*

[***R5***] *Ultra fast registration of multiple MR volumes using MOPED.* Bastin M.E., **Panter B.D.**, Tweedie R.J., **Hossack W.J.**, **Heavens A.F**., 2010. Joint Annual Meeting of the International Society of Magnetic Resonance in Medicine (ISMRM) & the European Society of Magnetic Resonance in Medicine & Biology (ESMRMB), Stockholm, Sweden, 2076. Application of MOPED to medical imaging.
https://cds.ismrm.org/protected/10MProceedings/PDFfiles/671_2076.PDF

[***R6***] **Heavens A.F.**, **Panter B.D.**, Tweedie R.J., **Hossack W.J.**, Bastin M.E. 2012. Object registration. European Patent 2218054, filed September 24 2008, granted January 4 2012.
https://patents.google.com/patent/EP2218054B1/

4. Details of the impact

Background: Company Formation

The initial move to explore the wider applicability of the MOPED algorithm [***R1–R4***] was initiated by Panter and Heavens. In 2006, they secured Scottish Enterprise funding for a proof-of-concept multi-disciplinary medical physics project in collaboration with the Brain Imaging Centre at the Western General Hospital in Edinburgh (with medical physicist Mark Bastin, and radiologist Jonathan Best). This initial work then led to a successful application for an STFC Follow on Fund Award in 2008, which supported further exploration of the possible applications of MOPED data compression in medical imaging.

Motivated by these developments, the spin-out company, *Blackford Analysis Ltd*, started trading in August 2010. The company has since built the *Blackford Platform*, collecting and connecting analysis tools to apply to medical images. The first generation of the Platform used MOPED as one of its primary algorithms [***R5, R6***]; the current second generation has focused on more general techniques and especially third-party tools. The case described below describes the impact that *Blackford Analysis* has had in the REF period, starting from their MOPED origins.

REF period Impact

Improving and Speeding Up Medical Image Analysis

Over 2,000,000 medical scans per year are analysed using the *Blackford Platform* at over 750 sites worldwide [***I1***] as of December 2020.

Assessing the changes between two medical scans taken at different times is a fundamental aspect of many medical diagnoses and can sometimes be very challenging for large or complicated images. The systems provided by *Blackford Analysis* make this analysis significantly faster and more certain, leading to more confident diagnosis, and enabling greater treatment confidence and better overall patient health outcomes.

One key application is lung nodules, small lesions detected in CT scans that must be followed up with regular scans to determine if they are malignant and potentially cancerous. The Platform locates scan images to compare in a database, and then a tool computes the transformation needed to align them extremely quickly. This comparison is then provided to the doctor who can then check them easily and determine with more certainty if they are dangerous. A more efficient and confident diagnosis [***I2***] means subsequent treatment options, such as surgery, can be both more timely and more appropriate.

The method and Platform have now been applied to a range of challenging registration problems, from cases where there is a rigid translation like a brain CT, to elastic compression and stretching shown in lung imaging, and even to complicated deformations and movement in the digestive tract.

Blackford won a Visionary Innovation Leadership award from analyst firm *Frost & Sullivan* in 2019 for "*best practices in medical imaging artificial intelligence (AI) marketplace solutions*" [***I3***].

Saving Radiologists' Time and Costs

The Platform is now installed in 750 facilities, primarily in the USA [***I1***]. This number doubled each year from 2016 to 2019 [***I4a***], representing wide and consistently growing reach.

Radiologists are typically sent scan images, through a database, from technicians, and may then search for previous scans of the same patient and compare them. They might attempt this without image alignment or using previous algorithms that perform a single rigid transformation and rotation to align the images. They then analyse the images by searching for changes between them [***I2***].

The Platform can reduce the overall time for this analysis by 10 - 50% depending on the type of scan [***I2***]. This substantially accelerates the computational part of the process, leading to faster diagnosis per patient and quicker treatment. Given the number of treatments the Platform is used for, this speed-up means that, worldwide, radiologists save an amount of time equivalent to treating >200,000 additional patients per year. The faster and more efficient processing in turn releases resources for further treatment.

Connecting More Algorithms to Medical Data

The newest *Blackford Platform*, launched in 2016, is also available to other companies and groups wanting to analyze medical imaging data within a hospital network [***I1***, ***I5a***]. In this way, other companies with new software can connect to a standard hospital database via the *Blackford Analysis* system, which provides a secure interface that searches for the scan data for the algorithm and provides results back to the database. This previously very technically complicated process enables new algorithms to be used on scan images without the need for extensive new data "plumbing".

This in turn has enabled a curated marketplace of analysis software to be offered to hospitals and imaging centres [***I5b***], decreasing the time to market for new tools and hugely simplifying the challenge of image data processing for hospitals. It also reduces the challenges in installing new software, reducing hospital IT spending. The cost in personnel time to install multiple new algorithms is reduced from being a "*multiple year project*" to "*a handful of hours*" by the Platform according to the Chief Technology Officer of *Canopy Partners* (a healthcare technology company specialising in radiology IT) [***I6***]. As noted in the Frost & Sullivan award [***I3***], the explosion in AI techniques for medical imaging has paradoxically made implementation "*a health IT nightmare*". The award describes *Blackford Analysis* as "*serv[ing] a previously unmet need for a marketplace"* and hence as a *"pioneer of the medical imaging AI marketplace model*". Blackford's Platform has also been cited as a case study in "Accelerating Artificial Intelligence in health and care", a 2018 report produced by the Academic Health Science Network, the Department of Health and Social Care, and NHS England. The Platform is identified as "*delivering value to the health and care sector*" [***I7***].

This advance has enabled new and highly innovative diagnosis methods to be applied in practice. One example is *axial3D*, which uses the Platform to enable 3D printing of traumatised tissue, coronary arteries, tumour locations, and other 3D scan images, so that surgeons can plan complex treatments. The CEO of Belfast-based *axial3d* states that the *Blackford Platform* "*removes the bottlenecks associated with data transfer and clinician input, streamlining access … making 3D printing immediately accessible.*" [***I5c***]

There are currently 27 tools (described as the "*best in class*" by the CEO of *Resonance Health* [***I4b***]) from 16 companies (including Blackford) offered through the Platform, addressing problems including: MRI brain scans, density scanning for breast cancer detection, radiation dose monitoring, liver iron measurements, head CT scans, 3D bone modelling, aneurysm tracking, abdominal navigation, chest and lung alignment, longitudinal tumour tracking, and lung nodule monitoring [***I5b***].

Boosting Local, National, and International Economic Growth

As of December 2020 Blackford employs 42 staff (headcount: 42; FTEs: 42) in the UK and the USA, including two former academics, and grew from 27 employees in the final year of the REF period. It has received a total of GBP6,1000,000 in investment since 2015 from Scottish investment syndicates (Archangel Informal Investments, Tweed Renaissance Capital, Scottish Investment Bank, and Old College Capital) [***I1***].

The company's Platform is now widely deployed, at 750 sites worldwide (with main market concentration in the USA), and generated more than GBP1,000,000 per year in revenue in financial year 2019-20 with GBP3,000,000 anticipated in 2020-21, given sales in the REF period [***I1***]. Sales of the Platform as a stand-alone server are made to hospitals both directly, and via partner organizations, including Dunfermline-based *Optos* (now part of *Nikon*) and *Intelerad* [***I8a, b***].

Via the curated marketplace, the *Blackford Platform* has sped up market access for 15 different companies [***I5b***], launching further economic growth for those companies. In total, working with *Blackford Analysis* has allowed 20 companies to access the medical imaging sector , enabling further technology transfer to industry [***I1***]. The Platform has been described as "*world-leading*" by the Head of Business Development at *HealthLytix* [***I4b***].

Finally, in December 2020 *Blackford Analysis* partnered with health multinational *Bayer* for the latter to use the Platform to deliver a virtual marketplace of new AI-powered radiology imaging and diagnostic tools [***I5d***].

5. Sources to corroborate the impact

[***I1***] Letter of support from *Blackford Analysis* (can be contacted for further corroboration).

[***I2***] "Improve Quality in Radiology with Blackford Smart Localizer" (pages 5 & 6). PDF copy provided, can also be downloaded here:
https://www.blackfordanalysis.com/2019/07/16/improving-quality-in-radiology-with-blackford/

[***I3***] Blackford case study written by *Frost & Sullivan* (quotes taken from page 4):
https://www.blackfordanalysis.com/2019/02/13/blackford-receives-visionary-innovation-leadership-award-frost-sullivan/

[***I4***] Video Material

a) Company conference presentation: https://www.youtube.com/watch?v=DrFAdVpO8R0

b) Interviews with Blackford partners: https://www.youtube.com/watch?v=12erxCglhSc

[***I5***] Blackford Website

a) Analysis Platform: https://www.blackfordanalysis.com/platform/

b) Curated Marketplace:https://www.blackfordanalysis.com/applications/

c) Partners: https://www.blackfordanalysis.com/partners/platform-partners/

d) Bayer Collaboration: https://www.blackfordanalysis.com/2020/12/01/bayer-and-blackford-collaborate-on-medical-imaging-ai-platform/

[***I6***] Blackford eBook "Adopting a Platform Strategy: Simplify the deployment and management of medical imaging applications and AI algorithms" (quote taken from page 9). PDF copy provided, can also be downloaded here:
https://info.blackfordanalysis.com/hubfs/Blackford%20eBook%20-%20Adopting%20a%20Platform%20Strategy.pdf

[***I7***] "Accelerating Artifical Intelligence in health and care" 2018 report (page 15 and 45):
https://wessexahsn.org.uk/img/news/AHSN%20Network%20AI%20Report-1536078823.pdf

[***I8***] Articles detailing collaborations with

a) Optos: https://www.blackfordanalysis.com/2015/11/03/blackford-analysis-engages-optos-ophthalmology-application/

b) Intelerad: https://www.intelerad.com/en/press-releases/intelerad-adds-blackford-integration-to-inteleviewer/