Institution: Lancaster University		
Unit of Assessment: 9, Physics		
Title of case study: Artificial aurora research leads to improved wildfire detection		
Period when the underpinning research was undertaken: 01/01/2000 to 31/12/2020		
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:**
Professor Mike J Kosch	Professor of Space Science	01/08/2000 to present
Period when the claimed impact occurred: 01/08/2013 to 31/12/2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Rapid detection, accurate geo-locating and prompt reporting of wildfire smoke plumes through automated camera systems on strategically placed towers has substantially reduced commercial forest wildfire losses and their associated global CO_2 emissions. Kosch's pioneering research into artificial auroras has led to the development of advanced image processing techniques which have been exploited by the South African company EnviroVision Solutions (EVS) to continuously improve automated wildfire smoke detection. Commercialised as ForestWatch®, these systems are deployed worldwide, mainly in South Africa (154 cameras) and North America (137 cameras), but also elsewhere (47 cameras). By way of example, a study using MODIS satellite burn-scar data demonstrates that for regions in South Africa where ForestWatch® is deployed there are significant declines in burn-scar area compared to traditional manual lookouts, amounting to 120,000 ± 20,000 additional hectares of forest saved over the REF period, 35% of which EVS attributes to the underpinning research by Kosch. This decrease in burn-scar area equates to a total commercial saving of approximately GBP1.0 billion and CO_2 reduction of approximately 27 million tonnes, which is valued at approximately GBP1.2 billion, in South Africa alone. In North America, we indirectly estimate the corresponding savings to be approximately GBP1.6 billion in timber and approximately GBP1.9 billion in CO_2. The total impact of the underpinning research is thus estimated to be approximately GBP900.0 million in timber savings, and 23 million tonnes (GBP1.0 billion) in reduced CO_2 emissions.

2. Underpinning research

Artificial auroras are the optical signature of electron acceleration by plasma turbulence in the Earth's ionosphere, which is artificially induced by high-power, radio-wave pumping. Kosch is a world-leader in this research area, which was mainly focused on the UK-funded EISCAT facility in Norway. Existing methods and algorithms (pre-2000) for detecting and locating (artificial) auroras, but also other distant, ill-defined, moving objects such as clouds and smoke plumes, were further developed, refined and improved, as described below, in research led by Kosch from 2000 to present. Taking advantage of advances in imaging technology, *e.g.* black and white to colour, low resolution to high resolution, visible to infrared *etc.*, automated smoke plume detection under any lighting and weather conditions is now commercially available. A brief description of a representative selection of the outputs that characterise the body of underpinning research and the relevance to ForestWatch® is given below.

Smoke plume detection ([3.1], [3.2] and [3.3]).
This is at the core of ForestWatch® and generates the fire alerts. Image segmentation techniques in the algorithm are derived from those in Seviour *et al.* [3.1], where they were used to automatically identify clouds and natural auroras within monochrome all-sky images of the night sky. A 90% success rate was achieved over 125,000 images without motion analysis or spectral information. In the daytime, improved smoke plume detection is now mainly done by motion analysis of turbulent smoke columns, *i.e.* tracking small-scale, puffing features. This is implemented by difference imaging of a sequence of images taken a few tens of seconds apart, a technique derived from the temporal evolution analysis of artificial auroras [3.2]. In Kosch *et al.* [3.2], the optical temporal evolution was tracked by colour-coded difference imaging to highlight regions of increasing/decreasing optical intensity. This showed that the time for artificial auroras to reach a steady state after the pump was switched on was long compared to the expected optical emission lifetime. At night, improved detection is further enhanced by the characteristic orange glow of fire reflected from the smoke plumes using methods derived from the spectral analysis techniques of artificial aurora research [3.3].

False alarm suppression [3.3].
Given the huge cost of fighting large-scale fires (*e.g*. aircraft), false alarm suppression is a key feature of ForestWatch®. The single largest source of false alarms is the motion of cloud shadows on the ground. These are identified by spectral analysis, *i.e.* recognising that Rayleigh scattering makes cloud shadows appear bluer than smoke plumes enables their differentiation. The spectral analysis methods exploited are similar to those of Gustavsson *et al*. [3.3], who used calibrated multi-wavelength observations of artificial auroras in order to estimate the energy spectrum of the accelerated electrons, showing it was highly non-Maxwellian.

Range awareness [3.4].
Range awareness is a critical feature of ForestWatch® that compensates for geometric scaling effects due to the distance from the camera to the imaged ground for any pixel within the field of view, resolving the ambiguity of small fires nearby which appear similar to large distant fires. Its roots are in the mapping of non-optical data onto sky images of the artificial aurora for any altitude (range), *e.g.* radar beam patterns [3.4]. The research improved range awareness from previous crude near-mid-far categories to 10m resolution. Range awareness also allows accurate location of the source of a smoke plume from a single camera where standard triangulation is unavailable, such as on the fringes of a camera network.

Image registration ([3.4] and [3.5]).
Image registration is fundamental to range awareness within ForestWatch®, and also compensates for camera tower sway in the windy conditions that are typical during wildfire storms.

In the daytime, digital map terrain lines within ForestWatch® are fitted to intermediate and distant horizons within real-scene images. This ensures that image pixels map to the correct digital map location. The technique is derived from horizon fitting in all-sky images of artificial auroras [3.4]. Important here [3.4] was the horizontal spatial displacement of the artificial optical emissions relative to the pump beam, which is a function of the beam angular direction relative to the magnetic field orientation. This was determined by mapping the pump beam onto the image for the altitude (range) of the wave-plasma interaction. Spatial calibration of the image was done by locating the horizon in the all-sky images.

At night, this is done in ForestWatch® by fitting to known stationary light sources, such as a distant town or telecom tower, which is adapted from star position fitting in images of artificial auroras [3.5]. Gustavsson *et al*. [3.5] made the first volumetric estimates of the artificial aurora optical emissions using bi-static camera observations. Spatial calibration of the images for triangulation purposes relied on locating the stars within the field of view.

Tower location [3.6].
Heyns *et al.* [3.6] used a multi-resolution approach to a non-dominated sorting genetic algorithm, *i.e*. a bespoke approach to a multi-objective evolutionary algorithm, to optimise tower locations for a network of cameras within a real landscape topography. This maximises the observational coverage, which is usually set at 8, 16 or 24km, taking into account terrain features, land ownership, road access, power availability, forest canopy height and security. Coverage is improved by approximately 8.5% over manual site selection whilst also lowering the average tower height from 42m to 12m. Optimising camera tower locations for maximum coverage is important for reducing cost (average tower cost is USD20,000), and improving ForestWatch® detection and geo-location of smoke plumes in hilly terrain.

3. References to the research

[3.1] R. Seviour, **M. Kosch**, and F. Honary, "Identification of clouds and aurorae in optical data Images", New J. Phys. 5, 6.1-6.7 (2003).

[3.2] **M. J. Kosch**, T. Pedersen, E. Mishin, M. Starks, E. Gerken-Kendall, D. Sentman, S. Oyama and B. Watkins, "Temporal evolution of pump beam self-focusing at the High-Frequency Active Auroral Research Program", J. Geophys. Res. 112, A08304 (2007).
[32 citations, Scopus]

[3.3] B. Gustavsson, T. Sergienko, **M. J. Kosch**, M. T. Rietveld, B. U. E. Brändström, T. B. Leyser, B. Isham, P. Gallop, T. Aso, M. Ejiri, T. Grydeland, Å. Steen, C. LaHoz, K. Kaila, J.

Jussila, and H. Holma, "The electron energy distribution during HF pumping, a picture painted with all colors", Ann. Geophys. 23(5), 1747-1754 (2005) [45 citations, Scopus]

[3.4] **M.J.Kosch**, T.Pedersen, M.T.Rietveld, B.Gustavsson, S.M.Grach and T.Hagfors, "Artificial optical emissions in the high-latitude thermosphere induced by powerful radio waves: An observational review", Adv. Space Res. 40(3), 365-376 (2007). [27 citations, Scopus]

[3.5] B. Gustavsson, **M. Kosch**, A. Wong, T. Pedersen, C. Heinselman, C. Mutiso, B. Bristow, J. Hughes, and W. Wang, "First estimates of altitude distribution of HF-pump enhanced emissions at 6300 and 5577 Å: A comparison between observations and theory", Ann. Geophys. 26, 3999-4012 (2008).

[3.6] Andries Heyns, Warren du Plessis, **Michael Kosch** and Gavin Hough "Optimisation of tower site locations for camera-based wildfire detection networks", Int. J. Wildland Fire 28(9), 651-655 (2019).

Quality indicator: M. Kosch and F. Honary, PPARC, Solar system energy flows and fundamental plasma processes (PP/C000218/1), 1st April 2005 to 31st March 2008. GBP524,111

4. Details of the impact

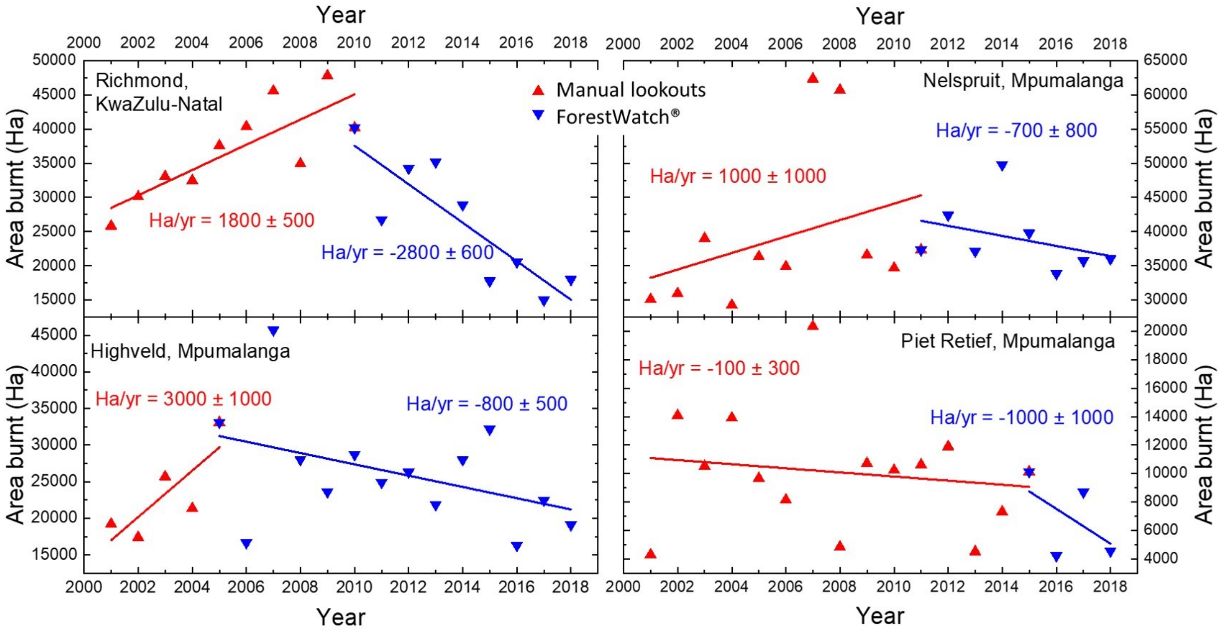
Remotely detecting smoke plumes has many significant similarities to detecting clouds or auroras in images. They are distant, indistinct, poorly-defined moving objects with irregular shapes; no two examples are identical although they share many common characteristics. This similarity between auroras and smoke plumes, and its potential for commercial exploitation, was recognised by the CEO of EVS, a fellow South African and long-standing associate of Kosch, who founded the company in 2002, based on (pre-2000) aurora research. However, the smoke plume detection algorithm within the ForestWatch® software undergoes continuous development, taking advantage of advances in imaging technology, *e.g.* black and white to colour, low resolution to high resolution, visible to infrared *etc.*, and drawing significantly on the methods and techniques derived directly from the underpinning research by Kosch at Lancaster University since 2000 [5.1]. Kosch is the EVS non-executive Director for Research (since 2011), and has been an EVS board member since 2015. Consequently, the underpinning research by Kosch described in Section 2 has resulted in improved smoke detection capability of ForestWatch®, leading to the growth of EVS and economic and environmental impact, as described below. According to the CEO of EVS, *"Prof. Kosch's research is inextricably linked to the present success of EVS and the on-going development of the ForestWatch® algorithm."* [5.1] Indeed, he estimates that 30% of the innovation within ForestWatch® existed pre-2000, and that the research by Kosch accounts for half of the post-2000 innovation [5.1]. Hence, 35% of the impact described below is directly linked to Lancaster research.

EVS currently employs 96 people and has an annual revenue of approximately ZAR30.0 million (approximately GBP1.6 million), which grew 20% and 18%, respectively, over the REF period [5.1]. (Here and below we use an exchange rate of 18.9:1 averaged over the REF period.) EVS also has a permanent office in Roseburg, Oregon, USA, with 6 staff who are responsible for the Canadian and USA markets. In Indonesia, EVS uses G4S as a contractor, and EVS is currently in negotiations with various contractors in China and elsewhere. To date, EVS has installed approximately 340 camera systems around the world, mainly in South Africa (154) and North America (137), including 20 and 79 new cameras in South Africa and North America, respectively, over the REF period. Trial installations are underway in various countries, including Australia, Chile, China, Indonesia, Greece and Spain [5.1].

4.1. 154 ForestWatch® systems deployed in South Africa have led to a large decline in fire damage

In order to quantify the scale of the impact of ForestWatch®, the results of a new, as yet unpublished, study are described. MODIS satellite burn scar data from 2001 (satellite launch) to 2018 are shown below for four distinct regional ForestWatch® fire detection centres in South Africa, the earliest of which was installed in 2005. During the fire season (May to October), when approximately 90% of wildfires occur, ForestWatch® detects up to 6,500 fires a month. In each case, monthly MODIS data is integrated over the fire season and limited to the combined ForestWatch® cameras' field of view. Burn scar hectares (Ha) are shown pre-ForestWatch®

(manual lookouts, red up-triangles) and post-ForestWatch® (blue down-triangles) with linear fits and their gradients shown. The data shows pre-REF years so that the switch from manual lookout to ForestWatch® is clear. Transition years are taken to fall in both categories. However, the burn scar areas, and consequent impact, are calculated for the REF period only.



ForestWatch® in Richmond, KwaZulu-Natal province, started in 2010 and involves 36 cameras covering 426,413 Ha. There is an evident reversal in burn scar trend after it was installed, with an average downward slope of 2800 ± 600 Ha/year, compared to the pre-ForestWatch® increase of 1800 ± 500 Ha/year. In Highveld, Mpumalanga province, 22 cameras have been fitted, covering 337,961 Ha, since 2005. Again, there is a noticeable reversal in burn scar after ForestWatch® was installed, with an average decline of 800 ± 500 Ha/year, as opposed to the previous increase of 3000 ± 1000 Ha/year. What is particularly striking in the data for these regions is that the upward trend in the burn scar is actually reversed after the installation of ForestWatch®, meaning that its efficacy increases with time, consistent with the continuous improvement in the system mentioned above, to which the underpinning research has contributed. For the other two regions the data is less dramatic, but there is nevertheless evidence of a decrease in trend post-ForestWatch® compared to pre-ForestWatch®. The system in Nelspruit, Mpumalanga province, comprises 27 cameras covering 335,955 Ha and was started in 2011. It shows an overall change in gradient of -2,000 ± 1,000 Ha/year. ForestWatch® in Piet Retief, Mpumalanga province, was started in 2015 and has 15 cameras covering 225,586 Ha. This is the only area of the four where there was a small downward tendency before the installation of ForestWatch®, but data are consistent with an improvement in the reduction of burn-scar afterwards, with an average value of -1000 ± 1000 Ha/year. The relatively large uncertainty in all cases reflects the erratic nature of wildfires. We note that the three regions in Mpumalanga were subject to a massive regional wildfire in 2007, and that Nelspruit was badly hit again in 2008. Whilst these fires were detected, extreme weather conditions (hot and windy) meant that they could not be contained. We also note that Richmond appears to have less variability and responds better to ForestWatch®, but this is a different province with a different contractor.

Clearly, the impact of ForestWatch® is not uniform across the different regions shown above. Thus, in order to evaluate the total impact we have combined all the data, taking the uncertainties into account. This analysis covers 81% of all ForestWatch® deployments in South Africa, with only pre-MODIS and very recent deployments excluded, for which there can be no pre- and post-ForestWatch® comparison. In addition, MODIS burn scar analysis does not distinguish between different types of land use. On average, plantation trees account for approximately 40% of land usage within forested areas of South Africa, the rest being roads, settlements and steep terrain unsuitable for trees [5.1]. For the areas specifically covered by ForestWatch®, adjusted for the start date of the Piet Retief sites (which was during the REF impact period), we have used the difference between the linear trends pre- and post-ForestWatch® to calculate the impact over the REF period only. The total number of additional hectares of land saved from fire for the REF period is thus 310,000 ± 60,000 Ha, of which 120,000 ± 20,000 Ha is forest. The commercial value of forest is approximately ZAR200,000 to ZAR450,000 per Ha, dependent on tree type and maturity [5.1]. Hence, the value of timber saved by ForestWatch® amounts to between ZAR (25 ± 5) billion and ZAR (56 ± 11) billion, which is GBP1.3 billion to GBP3.0 billion. Burnt timber may retain up to 60% of its original value [5.1], hence the total savings realised in South Africa are estimated to be GBP800.0 million to GBP1.8 billion, with between GBP280.0 million and GBP630.0 million attributable to the underpinning research [5.1].

In addition, each hectare of forest stores on average 209 tonnes of CO_2 [5.3]. Taking into account the reduction in lost timber calculated above, this translates into an estimated saving of 27 million tonnes of CO_2, 10 million tonnes of which is attributable to the underpinning research [5.1]. At an average discounted CO_2 cost of GBP45.70 per tonne over the REF period [5.4], this has a further financial impact of approximately GBP1.2 billion (GBP420.0 million from underpinning research [5.1]) for the ForestWatch® deployment in South Africa.

4.2. 137 ForestWatch® systems deployed in North America increase wildfire detection
The economic burden due to wildfire, made up of direct and indirect losses and costs for prevention, preparedness, mitigation and suppression, is estimated to be USD70.0 billion to USD350.0 billion per annum in the USA alone [5.5]. EVS USA has deployed 137 ForestWatch® systems in North America, mainly in Canada, covering 1,072,265 Ha in Alberta and Saskatchewan, but also in the USA covering 683,030 Ha in California and Oregon. A report by the Oregon Department of Forestry shows that ForestWatch® fire detections from 2017 to 2019 exceeded all combined human fire detections over the 11 previous years [5.2]. Extrapolating the results from the MODIS satellite study in South Africa to North America, based on hectares covered, the approximate overall estimated saving realised is GBP1.0 billion to GBP2.3 billion in timber, plus an estimated saving of 38 million tonnes of CO_2 with a further financial impact of approximately GBP1.9 billion. Given the 35% attribution [5.1], GBP350.0 million to GBP800.0 million in timber savings and 13 million tonnes (GBP670.0 million) in CO_2 savings are a result of the underpinning research. Although ForestWatch® only covers a tiny part of North America, authorities are investing in the system, which is currently expanding (79 new cameras since 2014).

5. Sources to corroborate the impact

[5.1] Supporting testimonial from the CEO of EnviroVision Solutions dated 18th January 2021. Corroborates impact of research of ForestWatch and the impact this system has had on fire detection.

[5.2] 2019 SWO Detection Statistics, 2020 (Oregon Dept. of Forestry report, USA).

Background references

[5.3] Understanding the carbon and greenhouse gas balance of forests in Britain, J. Morison *et al*., Forestry Commission: Edinburgh, 2012, ISBN 978-0-85538-855-3. (CO_2 data is not available for South African forests, hence we use UK published data).

[5.4] Forests and carbon: valuation, discounting and risk management, G. Valantin, Forestry Commission: Edinburgh, 2011, ISBN 978-0-85538-815-7.

[5.5] The costs and losses of wildfires, D. Thomas et al., National Institute of Standards and Technology, Publication 1215, 2017,