Establishing an Infrared Measurement and Modelling Capability

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***Abstract*—The protection of own aircraft assets against infrared missile threats requires a deep understanding of the vulnerability of these assets with regard to specific threats and specific environments of operation. A key capability in the protection of own assets is the ability to perform infrared measurements, analyse the data and construct signature models of aircraft, countermeasures and the background. The creation of such a capability is a complex task. A framework for capability development was used to identify all required elements and to ensure an optimal and complete programme. Topics covered include Personnel, Organisation, Support, Training, Equipment, Doctrine, Facilities, Information and Technology (POSTEDFIT). This paper reports on the process that was followed and its initial outcome after a two year project was concluded.**

***Index Terms*—infrared, measurement, modelling, capability, POSTEDFIT**

I. Introduction

A. The Requirement

The Electronics, Communication and Photonics Programme (ECP) of the King Abdulaziz City for Science and Technology (KACST) in the Kingdom of Saudi Arabia (KSA) decided to acquire and grow capabilities in the field of measurement, test and evaluation of infrared systems. This initiative was intended to give ECP the capability to do infrared radiometric measurements of objects at different temperatures, with different emission characteristics and in different environments. These measurements could take place in the laboratory or during field trials. ECP approached CSIR to develop a plan that lead to a collaborative programme to establish such a capability at KACST. Through a number of workshops the plan was formulated and the first phase put into practise.

The question confronting the team was '*How does one transfer competence (an integrated collective of capabilities) that was built up over many years by a team of domain experts, to a new team with no knowledge or experience in this specific field of applied physics and engineering?*' The road-map designed and implemented to establish the required capabilities in terms of knowledge, skills, processes, methods, equipment and facilities is described in this paper.

The operational need included an infrared signature measurement capability for 'target' objects, background objects and reference sources. Typical targets include fixed wing fighter and transport aircraft as well as unmanned aerial vehicles, helicopters, ground vehicles, naval vessels, countermeasure flares and missiles. Background objects include the sky, terrain, natural objects and man-made objects. Reference sources include laboratory thermal sources. Infrared signatures comprise self-emitted radiation from an object's surface and the reflectance of sun and sky light from the object's surface. An object can be heated by internal heat sources, the sun, aerodynamic heating, etc. Some objects have hot gas plumes or heated particles in flames.

The requirement can be summarised as the capability to perform measurements and modelling in the spectral range of the 1–14 μm spectral bands with imaging and spectral instruments.

For the sake of generality, members of the CSIR team will be referred to as the 'domain experts', while the KACST team members will be referred to as 'the team'.

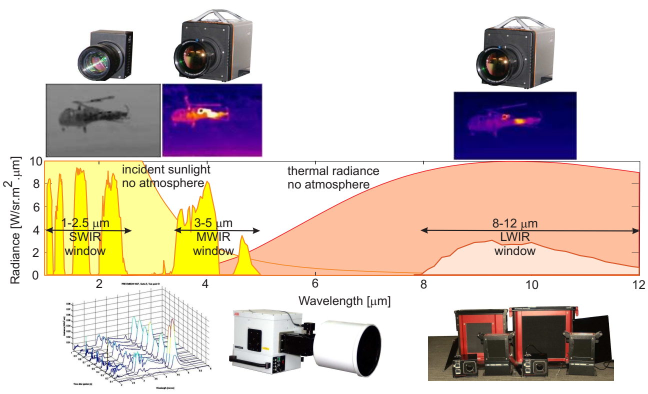

Fig. 1. Instrument requirement for KACST capability

B. Definition of Capability

The word 'capability' has many different meanings in different contexts and levels of abstraction. Capability is "the quality

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of being able to do something" [1], which includes elements of training, equipment, personnel, infrastructure, procedures, organisation, information and logistics [3]. In this paper, capability establishment is considered in the POSTEDFIT framework [2], [4], comprising nine elements: Personnel, Organisation, Support, Training, Equipment, Doctrine, Facilities, Information and Technology. Not all elements are equally important in this context, but the framework does serve as a useful reference for the sake of completeness. In this programme it transpired that the Personnel, Training, Equipment and Doctrine elements received the most attention (refer to Fig. 2).

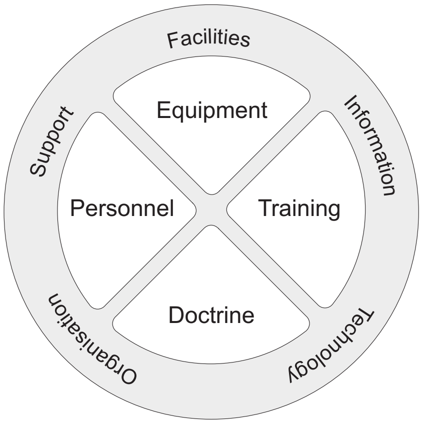

Fig. 2. POSTEDFIT framework elements

II. Programme Design

The high level goal of the programme was to establish a competence with capabilities in infrared measurement, modelling and radiometry, with specific reference to objects of military relevance. This high level goal was broken down as outlined in the following paragraphs.

Personnel: The capability requires a balanced team of tertiary trained personnel in the fields of physics, electronics and computer science. It was determined that effective teamwork is essential to achieve success. The nature of the work requires overlap of personnel skill sets and areas of responsibilities, in order to effectively complete tasks.

Organisation: The capability is structured into three areas of operation: spectral measurements, image/spatial measurements and modelling. This organisational breakup serves to provide focus areas, not to create isolated 'ivory towers'.

Support: Organisational and management support is provided by the ECP programme in KACST. Specialised instrument hardware and software maintenance support is provided by the instrument suppliers. Internal laboratory (technical) maintenance is effected by establishing a working culture of documenting procedures, check lists and reference test results for future use.

Training: Although there are world-class universities in the KSA the situation in the Kingdom, as in most other countries, is that these specific branches of physics and engineering related to this capability are not offered as formal courses at university. The training of the team was therefore identified as a primary importance to the success of the programme.

As the language of tuition was defined to be English, a three-month course for adult non-English speakers was identified.

The first phase technical training focussed on the transfer of knowledge and experiential learning. Theoretical training is supplemented with a considerable body of self-study material, tutorial assignments and laboratory demonstrations.

A series of six significant experiments was used to demonstrate, in a practical manner, some future test scenarios and to reinforce theoretical principles. The experiments demonstrate the use of the instruments and also provide a rich data set for data analysis and modelling.

Advanced training served to train personnel on the use and application of the newly acquired equipment. The training covered hands-on use of the equipment in the execution of a series of experiments.

In the final phase, the fully operational capability will be used to perform an out-of-laboratory field trial in a real-world scenario. This trial shall be designed and executed by the trainees under purposefully remote supervision.

Throughout the capability development, a balance was maintained between solid theory and experiential laboratory work. Flexible, pragmatic adaptation of the course material and presentation was identified as a crucial approach to ensure the success of this programme.

Equipment: Infrared signature measurement requires two types of instruments: spectral radiometers and imaging radiometers. The spectral radiometer provides information on the infrared spectrum being measured (but not necessarily an image). The imaging radiometer provides spatial information — images captured in well-defined broad spectral ranges, (but not spectral information). Instruments providing spectral spatial information are available (ABB MR-i [5] and Telops HyperCam [6]) but were beyond the current project objectives.

Remote sensing through the atmosphere requires the recording of atmospheric conditions. A simple portable weather station provides local meteorological data encountered during a test — adequate for short horizontal measurement paths.

Doctrine: A doctrine is the body of principles or beliefs used to govern a human undertaking — be that religious, military or otherwise. In the infrared measurement environment, doctrine prescribes procedures, guidelines, work flow and lists. This body of directive documents were designed to ensure maximum effectiveness and minimum risk in the execution of activities. These documents also serve to capture past experience and lessons learnt.

Facilities: The measurement capability requires static and mobile laboratory, computing and related infrastructure. Static laboratories have to be equipped with services appropriate to support the equipment, including electrical supply, liquid nitrogen, dark room and clean room facilities and access control measures. Field operations require a mobile laboratory in the form of containerised laboratories or custom built vehicles equipped with the necessary resources.

The capability also requires support facilities such as information and communication technologies: voice and data communication, data storage, retrieval and processing, report generation and presentation facilities.

Information: A key element in any measurement undertaking is the capturing, manipulation, documenting, presentation and archiving of raw data and processed information. These information activities directly influence all the other POSTEDFIT elements, e.g. personnel, equipment, training, doctrine, facilities and so forth.

Technology: Infrared measurement and modelling is in essence, a technology-driven activity; exploiting various technologies such as detectors, optics, electronics and computers. The objective was to obtain and exploit the available technology most effectively. In this case, the strategy was to buy the best equipment, rather than to design from scratch.

III. Programme Details

A. Overview

The programme ran over a 24-month period, covering training and equipment acquisition as outlined below.

B. Personnel

KACST contracted eight engineers, scientists and computer scientists, all new to the field of electro-optical / photonic measurement.

C. Initial Training

The first formal course was an in-residence, conversational English course. The team had opportunity to meet English language students from all over the world. Friendships were forged and no doubt, their use of the common denominator, the English language, benefitted their English language skills significantly.

The initial technical courses comprised (a) one-week introduction to optics, (b) one-week introduction to optical sensors, (c) two-weeks intensive radiometry course, (d) three-weeks intensive measurements and data analysis course, (e) one-week introduction to Fourier Transform Infrared (FTIR) spectroscopy, optical surveillance and infrared electronic warfare. The courses had extensive homework assignments to reinforce the material covered in the classroom. In all the courses the team members were evaluated with assignments, tests and by observing their participation in the classroom situation.

The **Introduction to Optics** covered geometrical optics, the wave nature of light, including reference to spectroscopy, examples of optical instruments and an introduction to Photometry. The principles and topics covered during these lectures were explained in laboratory demonstration sessions. *'Physics'* by Giancoli [7] was used in this course.

The **Introduction to Optical Sensors** course was based on *'Electro-Optical System Technology'* by Willers [8], covering the topics of noise, the operation of photoconductive detectors, photovoltaic detectors and thermal detectors, low noise electronics and sensor optics. Several case studies were investigated.

The **Radiometry** course, based on *'The Technique of Radiometry: Analysis & Modelling'* by Willers [9], covered radiometry nomenclature, solid angle and form factor, radiance and flux transfer, Planck radiators, emissivity, atmospheric effects on optical systems, multi-spectral radiometry, effective transmittance, the range equation, object appearance in an image as a function of range (effects of transmittance and path radiance) and the contrast of resolved and unresolved targets in an image. A thorough theoretical base was laid covering all the important concepts and principles. Considerable time was invested in homework assignments and worked tutorials.

The **Measurements and Data Analysis** course, employed more advanced concepts in [9] covering complex optical signatures, data reduction and modelling techniques, thermal camouflage and the modelling and performance analysis of a solar cell, a remote sensing flame sensor, a laser range finder and a thermal imager. The effect of the atmosphere in different atmospheric windows was also investigated. Students had to develop complex models in Matlab to model these and other photonics systems in homework assignments.

Lectures on **Fourier Transform Infrared (FTIR) Spectroscopy, Optical Surveillance and Infrared Electronic Warfare** provided a detailed introduction to the principles of FTIR and overview introductions to optical surveillance and infrared electronic warfare.

D. Experiential Learning

Practical work was found to be pivotal in this programme; theory provides background and insight, but the students need to 'see' the theory in practice. Only when experienced[1], does the theory become relevant.

A series of six experiments was executed, each designed to illustrate key radiometric concepts or to serve as examples of data reduction. These experiments were executed prior to the delivery of the KACST instruments and hence were done on the CSIR's similar equipment. The experiments all employed 1–3 μm, 3–5 μm and 7–11 μm imaging cameras, a 2.5–5 μm spectral radiometer and contact and non-contact temperature probes.

These experiments formed an essential part of the training in serving as real world examples, not just dry theory. As an additional bonus, the experiments yielded a huge amount of useful raw data that serve as a handy source of diverse measured data, suitable for training purposes.

The first experiment introduced temperature measurement and illustrated the effect of emissivity on the radiometric measurement of temperature. The temperature and emissivity of three targets with high, medium and low emissivity were determined by using contact temperature measurement, imaging camera measurement and spectral radiometer measurement.

The second experiment introduced flame-type target objects, together with spectral emissivity and the calculation of nebulous flame areas. The targets investigated included a bunsen burner, a candle, a petro-chemical fire starter bar and a safety match. The spatial structures of the different flame types were studied. For each target a simple model based on temperature, emissivity and area was determined.

The third experiment determined the spectral transmittance of a number of samples, including the atmosphere, window glass, infrared filters and plastic sheets.

[1]Experiential learning is the process of making meaning from direct experience (http://en.wikipedia.org/wiki/Experiential_learning).

The fourth experiment investigated the applicability of the three imaging cameras' spectral ranges for temperature measurement of objects in the open sunlight. A secondary objective was to determine the true temperature and emissivity of the test targets' surfaces. The test surfaces were four similar aluminium plates (with different emissivity): the first thickly painted, the second polished and then thinly painted, the third oxidised and the fourth, a finished in a mirror surface. The surfaces were oriented in different orientations relative to the earth, the sky and the sun. The effect of reflected sunlight from low emissivity surfaces was evident in the various orientations with respect to the earth and the sun.

The fifth experiment set out to determine cloud signatures as a function of angle between the sun and the cloud, for both the bulk of the cloud and the silver lining. The execution of the experiment was difficult since the clouds were quite uncooperative — a flexible and opportunistic measurement strategy was required. This experiment clearly illustrated the complexity of remote sensing measurements in rapidly changing environments.

The final experiment was to measure the temperature by contact and non-contact methods, of 56 different samples, over a 24 hour period, at 15 minute intervals, while the samples were heated by the sun. Samples included objects typically found in the outside environment: wood, PVC plastics, painted, rusted and polished steel, aluminium and galvanised steel roofing, rocks, various types of grass, sand and loamy soil, brick walls, cement paving, tree/shrub foliage, asphalt and a rubber car tyre. The information so obtained was used to develop an understanding of the thermal signature and behaviour of different materials. A secondary objective was to obtain diurnal temperature information for thermal property characterisation. This experiment was troubled by some cloud in the afternoon and the experiment was aborted in the evening when it started to rain — typical field trial experiences!

E. Advanced Training

While the initial eight-week training had a subject focus, the advanced training, on-site at KACST, had an instrument and outcomes focus. The intention with the advanced training was to investigate real-world experiments, executed with the newly acquired instruments, by the newly trained team.

The team performed instrument set-up, acceptance testing and measurement tasks under the guidance of the domain expert. The instructor did not direct the work, he set the objectives, determined the pace of work and monitored the progress. The teamwork in the team crystalised — each member took up a role in which he was comfortable. The atmosphere was one of learning, not one of teaching — in a way, the team was training itself.

The advanced training required the execution of a number of laboratory experiments and a mock 'field trial' in the open just outside the building. The team came to appreciate the role of procedures and packing lists.

By the end of the advanced training, the team members had overcome their apprehension of working with the instruments and have demonstrated proficiency in using their instruments.

The final step in the advanced training is a true field trial; planned and executed by the team. This trial must still take place. The team must interact with a real client to determine his need, design the trial, execute the trial and complete the data analysis and documentation. The domain experts will keep a watchful eye, but will only act in case of emergency.

F. Equipment

Several discussions and workshops were held on the measurement equipment requirements. Prospective suppliers were visited and the instrument requirement was discussed. A prepared questionnaire formed the basis of the structured meetings with suppliers. After the instrument specifications and quotations were received the final supplier selection was made and the instruments ordered.

The spectral radiometer was acquired from ABB Analytical (Bomem) [5]. The instrument specifications are summarised in Table I. The mono-pixel instrument was selected on the basis of performance and price and as an introductory instrument. If the need arises, KACST can always later buy an imaging instrument — the mono-pixel instrument was deemed sufficient for the current need.

The imaging instruments were acquired from Xenics [10]. A summary of the instruments' specifications is shown in Table II. The instruments employ detectors from AIM [11].

The measurement laboratory is amply equipped with black body sources, to serve as calibration sources in the static laboratory, but also to serve as reference sources during field trials. Two Thermoteknix Thermaref 700B (ambient to 700°C) sources provide for small aperture, high temperature work. Two HGH DCN1000H7 (−10 to 150°C) sources will be used for non-uniformity correction measurements. Field trial measurements at intermediate range will be supported with one HGH ECN100N20 (50 to 300°C) large area (500×500 mm) and one HGH ECN100H12 (50 to 550°C) large area (300×350 mm) source.

TABLE I
ABB MR304SC FAST SCANNING MID IR SPECTRORADIOMETER

Scan speed at 16^{-1} resolution	82 scans/sec
Cold source	Liquid nitrogen
NearIR extended InSb detector	1–5.5 μm
Increase linearity Photovoltaic HgCdTe detector	2.2–13.33 μm
1.3 m narrow field of view telescope	4.9 mrad
0.23 m medium field of view telescope	28 mrad

TABLE II
XENICS INFRARED IMAGING CAMERAS

XEVA SWIR HgCdTe	
Spectral range	0.85–2.5 μm
Image size	384×288
ONCA MWIR HgCdTe	
Spectral range	2.5–4.8 μm
Image size	640×512
ONCA LWIR HgCdTe	
Spectral range	7.7–11.5 μm
Image size	640×512

Fig. 3. ABB MR304SC fast scanning mid-infrared spectroradiometer

Fig. 4. Xenics infrared imaging cameras

Fig. 5. Thermal sources

Fig. 6. Weather station

General support equipment include a number of sturdy QuickSet tripods to mount the instruments in the laboratory and in the field and a 7.5 kVA generator to power the large area black body sources. A portable weather station (Weather Hawk) was purchased to support atmospheric characterisation during remote measurements.

The purchase of long focal length reflective collimators has been postponed until specific requirements for such equipment becomes clear.

G. Doctrine

Formally written procedures, test plans, guidelines, check-lists and packing lists are key to success when executing a complex measurement trial. Throughout the training programme the importance of formal documentation was stressed and demonstrated by example.

The team was given examples of the domain experts' documents covering: (a) 'Golden Rules' (best practice) for radiometry data analysis, (b) a data management policy (data handling, configuration control and archiving), (c) instrument summary reports (summarising key instrument characteristics), (d) calibration reports (careful analysis and checking of calibration data), (e) measurement work flow guidelines with extensive check lists, (f) reference measurement procedures (the use of a reference source during field trials), (g) instrument pre-trial acceptance test procedures (verify operation prior to and after a trial), (h) test plan/instruction (the details for a specific test, including test sample description and test point definition, measurement work flow, logistics, safety and more), (i) examples of test history reports including test history, meteorological data, etc. and (j) test report (results of the test and conclusion from modelling effort).

Clearly, examples of other teams' doctrinal documents are not sufficient for this team. The team was encouraged to develop and maintain their own unique doctrine documents.

H. Facilities

The static laboratory requirements for this infrared capability is merely a relatively clean laboratory environment with laboratory tables, electricity (15 A and 32 A 230 V wall plugs), good lighting, good airflow and a container of liquid nitrogen. A useful addition will be an optical bench for some experiments, but this is not essential. At least one dimension of the room exceeds 15 metres to allow for long focus sensor requirements.

The team had a custom-built field trial vehicle constructed. This vehicle is equipped with two large doors, telescopic masts, external video cameras, desks, chairs and shelves, and an air conditioning unit. The vehicle is fully self-contained with an electrical generator for field work.

I. Information

The long-term availability and usability of measured data require special consideration. A capability without long term information recall is structurally weak, since there is little accumulated learning. A strong focus on information management is essential to meet current and future information needs.

The data management policy distinguishes between transient measurement data and persistent instrument data. Instrument data (e.g. calibration files) remain more or less constant over the long term, while measurement data only have relevance to a particular measurement. Each data type has to be managed differently.

Persistent instrument information and data reduction code are managed in a software revision control system in order to maintain configuration control of such information. The subversion [12] server is regularly backed up to an off-site server.

The large volumes of measurement data require special handling. This data are stored in a network-attached storage (NAS) server. From this server the data are accessible to all to work on and to contribute added value (e.g. data reduction products). This server is also regularly backed up to an off-site server.

Information handling such as data capture, management, processing and documenting is described in detail in the capability's doctrine documents.

IV. Lessons Learnt

It is too early to see the full benefit of the POSTEDFIT approach to establishing the capability. In the short term, however, a number of observations have been made.

The language barrier had an effect on the speed of execution. Language training is essential, and more would have been better. Out-of-country training proved useful since it forced the team to use more English language. It is quite evident that the team members' command of the English language improved tremendously over the past two years.

A balance between classroom and experiential training must be maintained, but hands-on training was more effective in capturing the team's imagination. There is however the danger of being able to operate the instrument, but with less understanding of the underlying principles.

Doctrine is critical to sustained success in measurement. The requirement for doctrine was evident throughout the programme, especially during the experiential learning. The enforcement of 'best practice' doctrine will minimise the adoption of poorly-informed bad habits.

The theoretical training was done first, simply because of the instruments' long lead delivery. It is evident now, that a follow-up session is required to reinforce the theoretical concepts, after the team's experience with the instruments.

Conventional, mark-based individual assessment was less effective and in some cases impossible in this project. An outcomes-based approach with the clear objective and well defined rubric or memorandum would be easier to administer. Furthermore, assessment of the individual is largely irrelevant, since all operations are executed in team context.

Instrument acquisition proceeded smoothly except for one product where a critical technology change, shortly before delivery, caused unnecessary performance degradation and specification compromises. The lesson here is to stick with known technology on critical deliveries.

V. Conclusion

At the time of writing, the programme is two months from completion. Almost all of the tasks have been completed. It is, however, true that any capability establishment programme is never finished — there is always more to be accomplished; weapons to be honed and mountain peaks to be conquered.

The set of six experiments performed as part of the training exercise, must now be repeated; this time with the new instruments and without guidance. The successful completion of such a trial will finally demonstrate the quality of the new capability.

A long term co-operation programme is currently discussed, with the aim to jointly do further research, interlaboratory tests on standardised or shared targets, execute joint field trials, do data analysis and publish papers. Such a programme will serve to identify shortcomings, new requirements and future directions.

POSTEDFIT provided a useful framework for the establishment of the capability and assessment of the capability, as established.

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References

[1] *Oxford Wordpower*, Oxford University Press, 2006.
[2] O. A. Schür, Presentation on Department of Defence Acquisition Process, Revised Acquisition Priorities and Strategic Industry Requirements, South African Aerospace, Maritime and Defence Industries Association, Centurion, South Africa, 2007. Last accessed on the World Wide Web at http://www.amd.org.za/docs/Acquisition_Process_-_30_Aug_07.pdf.
[3] C. Kerr, R. Phaal, & D. Probert, A Framework for Strategic Military Capabilities in Defense Transformation, 11th ICCRTS Track 9: Network Centric Metrics, 2006. Last accessed on the World Wide Web at http://www.dodccrp.org/events/11th_ICCRTS/iccrts_main.html.
[4] R. Oosthuizen, & J. H. S. Roodt, Credible Defence Capability: Command and Control at the Core, Land Wafware Conference 2008, Brisbane, October 2008.
[5] ABB Analytical and Advanced Solutions, Quebec, http://www.abb.com/analytical.
[6] Telops, http://www.telops.com.
[7] D. C. Giancoli, *Physics Principles with Applications*, Sixth Edition, 6th edition, Prentice Hall, ISBN-10: 0130606200, 2004.
[8] C. J. Willers, *Electro-Optical System Technology*, unpublished.
[9] C. J. Willers, , *The Technique of Radiometry: Analysis & Modelling*, in preparation for future publication, 2010.
[10] Xenics, http://www.xenics.com/.
[11] AIM INFRAROT-MODULE GmbH http://www.aim-ir.com/en/main/home-news.html
[12] Apache subversion http://projects.apache.org/projects/subversion.html
[13] A. A. Al-Ghamdi, N. M. Al-Hosiny, *Basmah Project semi-technical Report*, No. ECP-PRD- B001, King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia, February 2010.
[14] A. A. Al-Ghamdi, N. M. Al-Hosiny, *Basmah Project: Final Report*, No. ECP-PRD- B002F, King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia, March 2011. (first draft)