Future-Proofing an Aircraft Self-Protection IR Signature Database

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ABSTRACT

Aircraft self-protection against heat seeking missile threats is an extremely important topic worldwide, recently even more so with the instability in the Middle East region due to, for example, the large number of man-portable air defense systems (MANPADS) that were stolen from army arsenals. A fundamental step in successfully achieving self-protection is the ability to capture and identify aircraft infrared signatures. This work discusses some of our efforts and results in creating an asset database for infrared signatures. The database was designed in a way that will feed an image processing engine to allow for automated feature and signature extraction. A common failing in the handling of target signature raw data is the fact that raw data files can become unreadable because of changes in technology, software applications or weak media archiving technology (e.g. corrupt DVD media). A second shortcoming is often the fact that large volumes of raw or processed data are stored in an unstructured manner, resulting in poor recall later. A third requirement is the portability of data between various processing software packages, legacy, current and future. This paper demonstrates how the challenge of future-proofing measured data is met with reference to the archiving and analysis of data from a recent measurement campaign. Recommendations for future work are given, based on the experience gained.

Keywords: Aircraft tracking, data fusion, database usability, IR signature, multi sensors, target detection.

1. INTRODUCTION

Infrared (IR) radiation signature measurement of targets has become an important aspect of research, along with rapid development of IR imaging and detection technologies [1]. The IR signature emitted from an aircraft can be used by the enemy to detect, track and destroy an aircraft by sophisticated infrared (IR) homing “heat seeking” missiles such as surface-to-air missiles (SAM) and Air-to-Air missiles (AAM). IR signature measurement of targets is one of the most important ways of signature acquisition and target identification. To mitigate the threat posed by IR seeker missiles; and for successful aircraft self-protection, it is crucial to study the IR signature emitted by the aircraft in the infrared spectral bands. The IR signature of the aircraft is mainly due to the thermal emission resulting from aerodynamic heating, internal heat sources and the reflected ambient radiation from the sun, the sky and the ground threats to military aircraft and helicopters. The temporal and spatial distribution of radiant intensity, emissivity and temperature from each main contributor should be studied and documented properly for future use [1].

In our previous work [2], the focus was on acquiring and growing capabilities in the field of measurement, test and evaluation of infrared systems and establishing an IR measurement laboratory in the Photonic System Research Department at the National Center for Electronics, Communications and Photonics (ECP) of the King Abdulaziz City for Science and Technology (KACST). This paper focuses on the efforts to future proof the IR signature database and the measurements procedures followed to have reliable IR data and associated dataset (meteorological data) as well as summarizing the work flow used to protect the data against usability extinction.

In order to future proof the IR data and associated dataset, different options must be explored to archive the dataset in various data formats such that the data can be used in future. Formal processes have been developed at the Council for Scientific and Industrial Research (CSIR) in South Africa to future proof IR signature data and associated dataset such that they will be used in the future.

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Once measured data are available, means must be found to future-proof the data, i.e. ensure that the various data are available for future use. This ambitious endeavor requires formalized processes and considerable discipline. In this paper the threat to long term data recall and use is considered and the methodology to reduce the risk to lose access to this precious data in the longer term is proposed. The methodology proposed was tested over the course of several field trials at the CSIR and is constantly being improved.

2. MEASUREMENT METHOD

The most effective tools for measuring IR signatures are Fourier transform infrared (FTIR) spectroradiometer and thermal imaging radiometers [2]. The FTIR spectroradiometer provides information on the infrared spectrum being measured, but not necessarily an image. Thermal imaging radiometer provides spatial information - images captured in well-defined broad spectral ranges, but not spectral information [2]. The Photonic System Research Department of ECP at KACST have acquired the spectral radiometer from ABB Analytical (Bomem) that is consist of two detectors (channel A and B), the near-IR extended Indium-Antimonide (InSb) detector covering the (2.2–5.5 µm) and the Mercury Cadmium Telluride (MCT) detector that covers a wide spectral range (2.2–15 µm). The department has also acquired thermal imaging radiometers from Xenics Infrared Solution covering the long wave (LW) infrared (7.7–11.5 µm), the medium wave (MW) infrared (2.5–4.8 µm) and the short wave (SW) infrared (0.85–2.5 µm) spectral bands. Figure 1 shows the spectral bands for the measurement equipment used during IR signature measurements by the Photonic System Research Department of ECP at KACST. In early 2012, a campaign to characterize IR signature of various aircraft, such as fighter jets and helicopters, was performed and the above mentioned instrument were deployed. The thermal infrared radiometers were deployed on a stable platform; and a tripod with two axis rotation was used to ensure smooth movement and tracking of the aircraft. The spectral radiometer was deployed on a tripod that does not rotate since it is a heavy instrument and it was not suitable for in-flight aircraft tracking. Both of the instruments, FTIR spectroradiometer and thermal imaging radiometer, were used to characterize the IR signature of the aircraft at static conditions. The thermal imaging radiometers were also used for dynamic (flight) characterization of the aircraft.

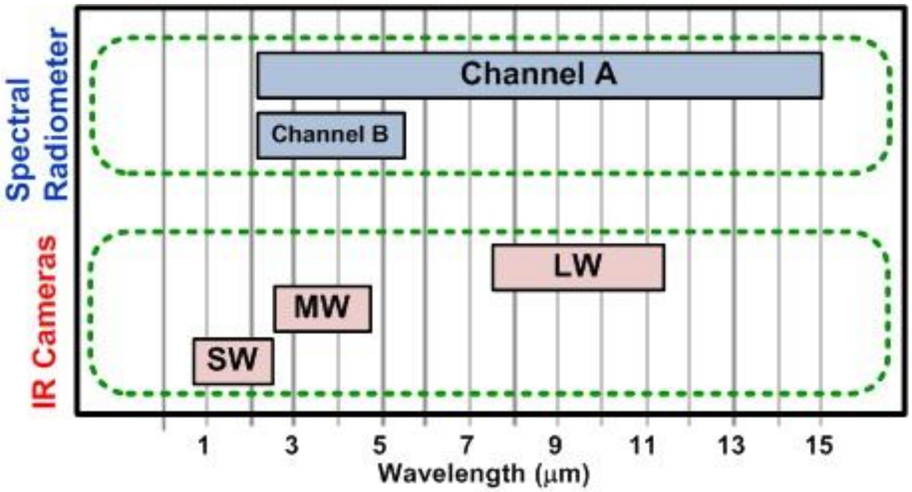


Figure 1. The spectral range covered by the five detectors that were used in this measurement.

By analyzing the measured IR signature data, we have extracted effective features that can help with discriminating the aircraft against other objects. Pre-processing of sample data is necessary to allow for storage of generic data, avoiding unnecessary expenses when repeating the measurements. However, to simplify data analysis, the data should be stored in a simple form such as treating the images as arrays. The numerical arrays that represent the measurements of the spectral radiometer (wavelength & spectrum) and histogram (IR signature & frequency) of the IR images are suitable for classification. Further data simplification or reduction can be done by noise reduction analysis, resulting in more reliable and compact data, requiring less storage. This requires noise estimation in different cases (day, night, humidity, temperature) as reference data. Normalized data is also important to avoid the uncertainty in measurement set up and weather conditions. This can also result in a reduction in effects caused by issues such as the distance between the target and the sensor. Data normalization should be effective in condensing the size of the stored data that is used in such an automated object recognition system. Once the data is recorded and pre-processed, it is necessary to secure the data and save it in a form for future re-use, as is explained in a later section of this paper.

3. DATA ANALYSIS

3.1 Classification based on instruments type

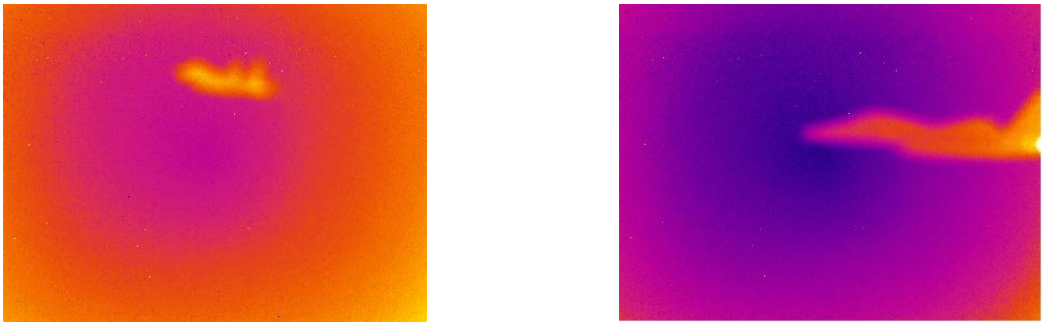
Using multiple sensors to detect target signatures gives us a variety of options to capture data with diverse results. Table 1 gives some examples of the results that can be obtained from two different types of sensors. This is important to allow for the creation of a flexible reference database that covers various target situations, such as standby, take-off, and in-flight at different velocities. One of our field measurements focused on measuring IR signatures for 3 different aircraft and one helicopter. In this experiment, we have obtained specific changes in the histograms values with aircraft movement and position. These changes those are similar for all aircraft, and will be explained further in the following section.

Table 1. A summary of the data and features that can be extracted from the different instruments with a selection of results.

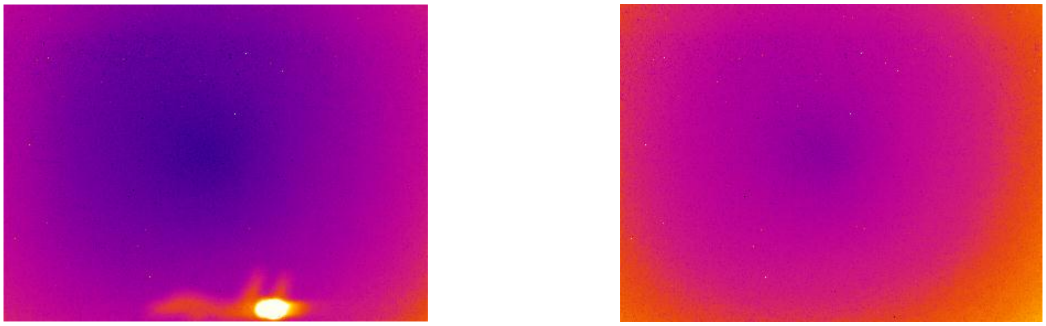
	Type of data	Feature	Result
IR cameras	Histogram	The maximum during four cases: head-on view, side view, tail view, and leaving immediately	1- Aircraft detection based on similarity in signatures for all fighters 2- Estimated velocity of aircraft
Spectral radiometer	Spectrum (volts/cm-1) vs. wavelength (μm)	Temperature as a function of wavelength	Discrimination model of aircraft based on available stored data

3.1.1 Sample result from cameras

Figure 2 shows the MWIR images captured at four different cases. These cases are: a) head-on view, b) side view, c) tail view and d) leaving immediately. Head-on view represents the aircraft fuselage from front side, while side view shows the plume as well as the fuselage. Tail view represents the plume and the very hot engine. Leaving immediately represents the status after aircraft signature disappears.



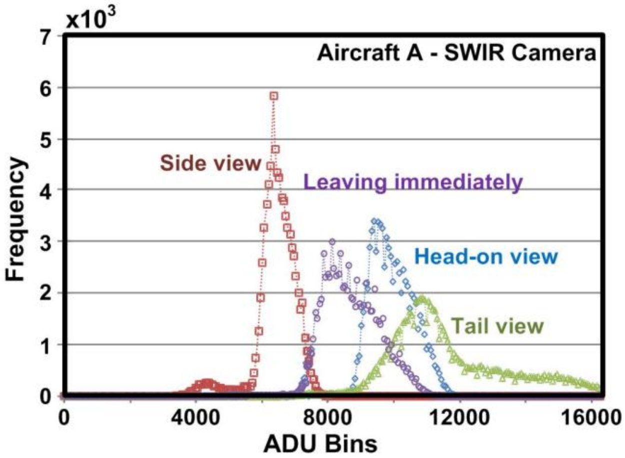
a. head-on view b. side view



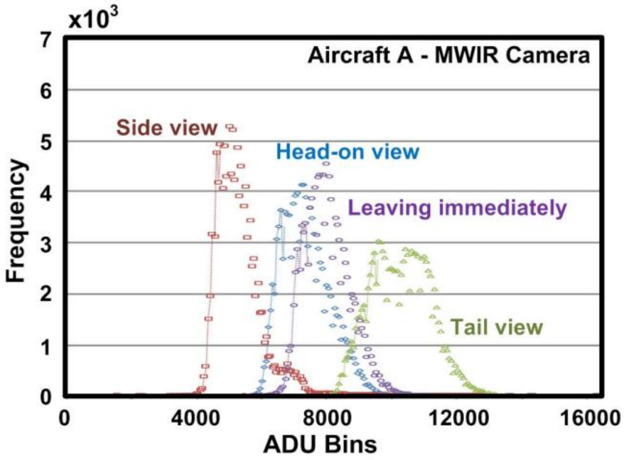
c. Tail view d. Leaving immediately

Figure 2. Sample MWIR images used to obtain histograms.

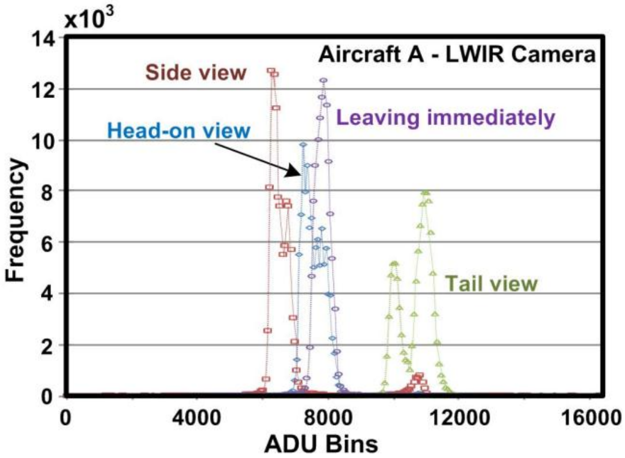
The four cases shown in Figure 2 can be represented as histograms instead of images to conclude the information that is captured by the cameras. The following figures show the combined histograms for all previous cases. These histograms are captured simultaneously by the three IR cameras for aircraft A at 350 mile/h.



(a)



(b)



(c)

Figure 3. Histograms produced based on the data collected from: (a) the short wave infrared (SWIR) camera for aircraft A, (b) the medium wave infrared (MWIR) camera, and (c) the long wave infrared (LWIR) camera.

In the histograms shown in Figure 3, changes in the x-axis represent changes in the infrared signature of the source. Changes in the y-axis represent the number of pixels at the different respective ADU levels. Head-on is expected to have lower frequency (smaller image) and lower ADU levels (less intensity) than side and tail view, since it represents only the smaller front view of the cooler aircraft fuselage. In side view, the plume as well as the fuselage (with a small portion of hot tailpipe) can be seen. Tail view represents the plume and the very hot engine, so this case is expected to have the highest ADU (intensity) of all. The histogram of the leaving immediately case approaches the histogram of background, without any IR due to the aircraft. These results show how the data can be simplified (reduced from images) so that the IR signatures can be interpreted by less experienced people, or by image processing engines. This allows for aircraft automated detection based on pattern matching, which is one of the simplest classification tools.

3.1.2 Sample results from spectral radiometer

Figures 4 (a) and (b) show the spectrum of the aircraft at static condition (before take-off) measured using the FTIR spectroradiometer. Figure 4 (a) and (b) shows the spectrum measured using the 2.2 - 15 µm spectral band (channel A) and 2.2 – 5.5 µm spectral band (channel B), respectively. These measurements represent aircraft at standby before take-off. These results allow us to differentiate between the IR signatures of the three aircraft for the fuselage and plume with information covering the entire IR spectrum of interest. The measurements are shown in radiometric units that give more options for data analysis.

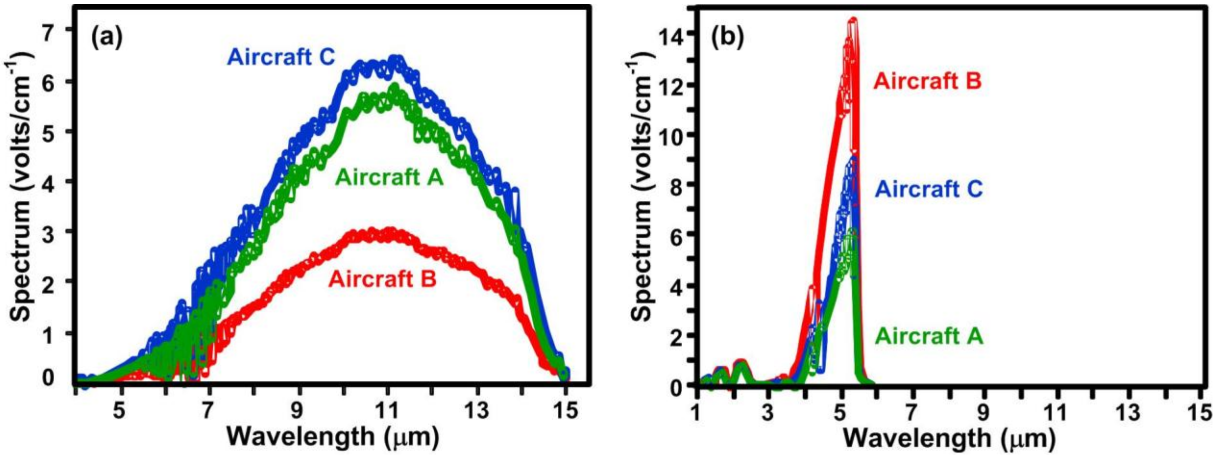


Figure 4. The spectra calculated for three different aircraft from: (a) the output of channel A (the MCT detector), and (b) the output of channel B (the InSb detector).

3.2 Speed estimation

Data reduction can be implemented in various analysis processes are used, such as speed estimation. This can help reduce the cost of data storage and future-proofing. Rather than saving a large amount of reference data, the relationships used next show an example of how the required reference data can be reduced by using appropriate proportionality ratios.

Based on various histogram data, velocity of an aircraft (V) can be estimated by relying on an inverse proportionality to time (number of frames) as well as the maximum values in the head-on view and side view measurements. This relationship is known as the velocity factor (V_f), which is:

$$V_f \propto V \times F \tag{1}$$

where F is the number of frames between the sequential peaks. This relationship is affected by the distance between the target and the sensors, as shown by:

$$V_r \propto V_f/(F \times d_{TS}), \tag{2}$$

where V_r is the relative velocity of the target against the sensors, given by:

$$V_r = V/d_{TS}, \tag{3}$$

and d_{TS} is a calibration ratio that is given by:

$$d_{TS} = \frac{d_{TS}\, Test}{d_{TS}\, Reference}, \tag{4}$$

where d_{TS} *Test* and d_{TS} *Reference* are the distances between the target and sensor (Figure 5) for the test case and the reference case (the archived reference images), respectively. A $d_{TS} > 1$ is given for a longer distance between the target and the sensors for test case compared to the reference case.

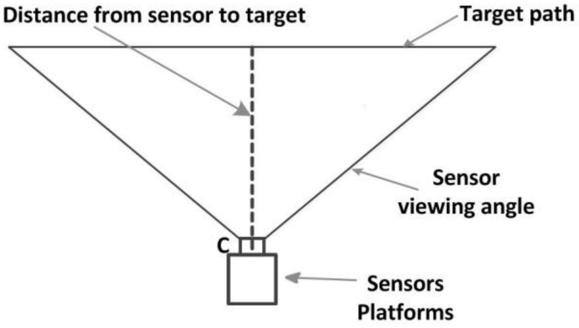


Figure 5. Measurement setup showing the distance between the target and sensors (d_{TS}).

Table 2 shows an example of how the aircraft speed can be estimated by changing the number of frames and the sampling period for Aircraft C. For the examples shown in Table 2, $d_{TS} = 1$ because the distances are similar for both the experiment and reference data, this means that $V_r = V$. The first two rows in the table show reference sample data, whereas, the third row shows the estimated relative value based on the process explained above.

Table 2. The relationship between the speed of the object and the number of frames between sequential peaks.

Relative Velocity (V_r) in mile/h	# frames (F)	Period (seconds)	d_{TS}*	Velocity factor (V_f)
350	1325	8	1	463,750
450	1000	6	1	450,000
~ 850	537	3	1	457,000

4. THREAT TO LONG TERM VALUE OF MEASURED DATA

Digital preservation or curation [5] is a complex field aimed at extending the lifetime of digital data, by the collection, maintenance, and archiving of digital assets. Data may only be considered usable if: (1) it can be accessed, (2) it can be unlocked, and (3) it can be informative or meaningful. Threats to the long term value of the measured data are any event or situation where one of the above three requirements are threatened.

4.1 Data archiving

The requirement of data access is self-evident; if the files are locked away or lost they are of no value. Data can be lost as a result of damaged media, such as the limited lifetime of compact laser discs. The topic of data archiving is well covered in the information technology business. It is essential to keep several copies of the data, in several different physical locations, and on different recording media. Media with the best long term recall should be used for data storage. Such storage is an actively managed process, rather than a passive approach of 'locking it up forever'.

4.2 Effects of changes in technology

Unlocking the data from a file requires that the file can be opened in an application that understands the file format. Shifting baselines in technological progress poses a significant threat to file formats. Recent history has shown that closed proprietary file formats can change with future software releases. Furthermore, companies can close down or terminate product support for some formats. To mitigate against this risk, one may decide to keep a backup of the original application (which should be done anyway) for future use. However, even this is insufficient, since computer hardware may change, resulting in old software not running on new hardware. Some laboratories maintain a museum of old hardware and software to ensure long term data lifetime. In this sense, technology poses a significant risk to future-proofing measured data.

4.3 Structured data storage

Most infrared/optical measurements are performed in the context of a target environment, an external natural environment, using instruments with calibration adjustments. The target conditions may have a significant effect on the measured value, e.g. an aircraft engine setting or flight history. Likewise, the external natural environment can have a significant effect on the outcome of a measurement, e.g. the effect of the atmospheric conditions on the measured intensity of a source. Finally, most instruments require a set-up file for the measurement and/or data processing, to convert from measured voltage signals to the desired radiometric quantity. Since the environment and calibration status of an instrument affects the outcome of a measurement, it is important that all such information be captured and recorded, together with the instrument output file. Typical information that must be stored, on the same disk, in the same directory structure, include meteorological information, target condition/settings, flight trajectory relative to the measurement point, measurement log (notes, pictures, sound and video recordings) and similar. The best way to ensure such data capture and storage is to develop a formal test procedure dictating in detail how tests are to be conducted and recorded.

4.4 Portability of data: formats

A key element of digital preservation is the migration of data from older to newer formats. However, careless migration may result in data loss or migration in meaning; that is, if the information in old formats is interpreted differently to information in new formats. For example, a section heading may migrate merely as a numbered line, losing its meaning as section heading. As a general rule, it is best to avoid the need for migration.

Binary formats are most difficult to migrate, especially if the format is not known. Without a code to read and interpret the file contents, the data in binary files are of no value. Text files (ASCII, Unicode, XML, etc.) can be opened and read with a number of tools, significantly reducing the risk of losing data. Yet, it is better to not rely on migration of old files, but rather to follow a strategy to extract the information to a new format completely under your own control.

5. WORKFLOW TO PROTECT DATA

Given the threats to the long term use of measured data, the work flow [3] shown in Figure 5 is used to protect the data against usability extinction. The core principle, is to "up-convert" the data from the raw measured state to more universally readable and useful formats. This conversion chain starts with the raw data gathered during the test, and ends with the coding and application of the analyzed data in a simulation model. The key steps in this process can be briefly summarized as follows.

Any significant test should be executed using a formally defined test procedure and test instruction/plan. During a measurement campaign; it is critically important to capture a complete description of the test execution, the environmental conditions and all other relevant test parameters. It is important to use continual reference measurements, where standardized, calibrated sources are measured to serve as "ground truth" observations. These reference measurements are used to confirm instrument status during the test and to validate the atmospheric transmittance calculated using radiative transfer code and meteorological data gathered during the test.

The measurement process yields a potentially large volume of raw data in a (mostly) proprietary file format, which normally requires vendor specific software for unlocking and access. Furthermore, the vendor software often does not provide the full feature set of required analysis needs. Conversion from the vendor format to a universal (and documented) format is therefore necessary.

Data analysis needs depend greatly on the test target and test outcome requirements. The theme considered in this paper is radiometric data analysis, which yields estimates of temporal and spatial variations in intensity or radiance. Key to the analysis is the various types of calibration data required to convert the raw data to radiometric unit results. The data analysis must account for environmental effects (e.g. reflected environmental irradiance and atmospheric transmittance/path radiance) and hence; adds value to the originally measured data. Such added value changes should be properly documented and the code and data stored with the results.

The resultant data from the analysis process normally describes the test data in the form of "this is what we saw". While this can be considered as a model of the test results, the model is not really re-usable much beyond the "this is what we saw" status. It is now required to interpret the results in order to develop a more fundamental model of the observation. This fundamental model should ideally be expressed in terms of physical parameters such as temperature, spectral emissivity, area and spatial properties. This new model has an application domain beyond just the measured values. Clearly, such a model should be validated over the intended operating range [3]. The fundamental model can be implemented in programmatic form and can then be used to predict signature values. Again, the computer implemented model should be validated prior to widespread use.

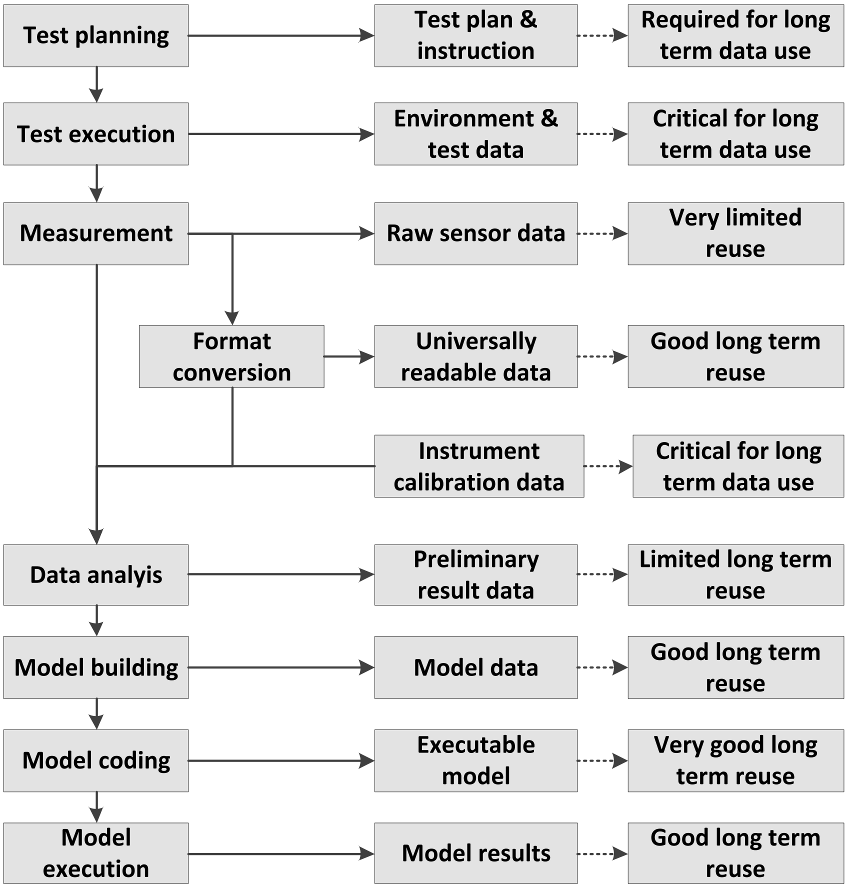


Figure 6. Workflow for data protection [3].

6. PRACTICAL APPLICATION OF THE WORKFLOW

An important requirement during infrared (IR) measurement trials is a deep scientific understanding of the measurement equipment, measurement processes or protocols, the unit under test (UUT), and the effects of the environment on the measurement outcome, especially since the measurements are performed in the field. In addition, consistently disciplined measurement practices are required, e.g. via suitably documented measurement procedures (protocols), traceability to the international system of units (SI), data management and accurate log recording methodology. To improve the value of the measurement protocols, researchers are continuously using, evaluation and revision procedures under field trial conditions [4]. In this section, successful examples of the measurements trials performed using the workflow described in section 5 are given. In this example, we consider the measurement and modeling of an aircraft.

6.1 Aircraft measurements

In order to obtain valid and therefore useful measurements, a detailed measurement plan needs to be constructed, so that during the actual field/laboratory measurement, all relevant data will be captured. During a field measurement, each test point should capture all the information relevant to a radiometric measurement. It captures information on the camera settings such as the lens used, filters and integration time used, atmospheric conditions, and specifics about the test point itself such as the time, the test point number and the recorded file names. The filename convention used stipulates that the camera, the lens used, the integration time selected, the filters used the test point number, the object measured and object settings is included in the filename. After each test point measurement, verification of the data should be done in a speedy and accurate manner to ensure that the data captured are of good enough quality to enable effective data reduction and can provide detailed spatial information to use when building a model. This will ensure that a test point can be repeated, should it be necessary. At the end of each sortie, infrared data captured and associated data (meteorological, range, etc.) data should be achieved to a secure external hard drive. After the measurement trial, the personnel who were present during the trial should sort the captured data and evaluate the files that can be used during data reduction. The criteria should be in place to assist in choosing the files that will be analyzed depending on the task at hand. For the aircraft characterization and model development, the distinctive spatial features of the fuselage (engine cowling, canopy, tail pipe, wings, vertical and horizontal stabilizer) and the plume should be visible. The files recorded should also be below saturation level and any observed saturation must be recorded (on a test card) and during data reduction, file that have reached saturation level should not be analyzed in order to ensure that only valid data is considered. During measurements the following parameters should also be measured, the range from the measurement instruments to the aircraft, the altitude that the aircraft is flying at, the speed the aircraft is flying at, and the outside temperature. The outside air temperature and the speed of the aircraft have a major effect on the fuselage temperature, whereas, the range between the aircraft and the measurement instruments is used when determining the transmittance.

The aircraft and flare signature measurements are performed in order to build models that capture all essential information of the object geometrical and radiometric properties. The model is required in a variety of simulation tasks, including signature prediction, aircraft vulnerability analysis, countermeasure development and flight test preparation. To develop aircraft models, distinctive spatial features of the fuselage (engine cowling, canopy, tail pipe, wings, vertical and horizontal stabilizer) as well as the plume should be visible.

6.2 Aircraft model

This section provides an example of one form of data analysis and model building. The aircraft model constitutes a geometric (spatial) wireframe with associated material, optical and infrared properties for each polygon. The wireframe model of the aircraft is constructed using polygons, where each polygon description consists of a list of the vertices in a three dimensional space. The radiometric fuselage information required to populate the wireframe model is obtained from the analysis of the raw data gathered during field trials. The data is analyzed using automated data reduction software that uses the version-controlled calibration and other sensor and environmental data.

The spatio-wireframe model is then used to calculate the infrared signature. The aircraft fuselage temperature is calculated using the well-known equation for aerodynamic heating stagnation temperature. The temperature on different parts of the fuselage is calculated as a delta or difference temperature, relative to the standard aerodynamic heating. This simple model provides a temperature variation over the surface of the aircraft, while at the same time, follows the general temperature increase with faster speeds. Polygons with the same and shared radiometric properties (i.e. temperature delta) are collected together as a group of polygons, known as an `object'. Different temperature behavior (called temperature equations) can be allocated to each object (e.g. variation with engine setting), by implementing the desired behavior in executable code and data.

Table 3 shows a subset example values of the temperature deltas and temperature equations for polygons belonging to the different objects. The temperature equations are implemented in C++ code and data read from files. The Material Type column in the table defines the material and infrared properties used in the simulation. For example, types 01 and 04 are metal surfaces and 03 is a polycarbonate canopy surface. The material types differs in terms of emissivity/reflectance/transmittance in different bands and bulk and surface thermal properties . The Temperature column in the table shows the temperature deltas obtained after analyzing the measured data of the aircraft. The data in the form of a model like this can be used over and over again; in different scenarios based on the task at hand. A model of this nature is successfully future proofed!

Table 3. Example of model object properties for an aircraft.

IR signature contributor	Object	Temperature equation	Material type	Temperature (K)
Fuselage, General	1	1	01	+2 (delta)
Engine Cowling	2	2	01	+15 (delta)
Canopy	3	3	03	-3 (delta)
Tailpipe	4	4	04	700 (absolute)

7. CONCLUSIONS AND FUTURE DIRECTIONS

Due to the importance of aircraft self-protection, a significant amount of research has focused on the study of measuring and analyzing aircraft infrared signatures. Usually such research activities result in the generation of massive amounts of critical data, where the importance of simplification and future-proofing of this data starts to increase significantly. In this paper, a simplified approach was shown that is suitable for data analysis and that does not require an experienced user. Simplifying the data in this way has allowed us to be able to perform target detection, identification and speed estimation, by relying on a much smaller information bank and training sample set.

This paper also describes a workflow that allowed us to meet the challenge of future-proofing measured data. The workflow provided a number of procedures to future-proof measured results, ranging from future access to the raw data, to the availability of the results from the measurement in future signature studies and applications. The work flow described has been developed and tested at the CSIR over several field trials, spanning several years and it is updated regularly with the growth of new experience and lessons learnt from previous measurement campaigns, data reduction and model development and validation.

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