**Development & Testing of a
Microbolometer-Based Satellite Earth Sensor
Utilizing Commercial Off-the-Shelf Technology**

By

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ABSTRACT

In response to the recent growth of the microsatellite and nanosatellite marketplace, Spectral Applied Research initiated a program to fully commercialize its design of an innovative new Earth horizon sensor technology, known as the Satellite Attitude Sensor (SAS). As a result, the Commercial-Off-The-Shelf Satellite Attitude Sensor (COTS SAS) project was undertaken to explore the feasibility of using commercially available optical and electronic components in space-based applications, specifically in the area of satellite attitude control.

The scope of this thesis was to explore the viability of utilizing this Commercial-Off-The-Shelf (COTS) technology in the creation of a low-cost Earth horizon sensor based on the SAS operational principles. Specifically, this COTS technology was to consist of components (both optical and electrical) which were widely available on the commercial market, but not normally intended for use in the environment of space.

To fulfill this requirement, a functionally representative breadboard prototype satellite attitude sensor model was constructed, based on a commercially available uncooled poly-Silicon-Germanium microbolometer infrared detector array, and a generic 16-bit analog-to-digital signal conversion module.

The preliminary results obtained from the characterization of this prototype sensor model, under adverse electrical and high-energy gamma radiation conditions, demonstrated that the use of COTS technology, in this application, provides a sufficient margin of performance to satisfy the attitude control requirements of a small satellite during a typical two-year mission in low Earth orbit.

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NOMENCLATURE

ACS	Attitude Control System
AD	Analog Devices (Inc.)
ADC	Analog-to-Digital Converter
ADCS	Attitude Determination and Control System
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial-off-the-Shelf
CPLD	Complex Programmable Logic Device
DR	Dynamic Range
EIRP	Equivalent Isotropic Radiated Power
EMI	Electromagnetic Interference
FFT	Fast Fourier Transform
FOR	Field of Regard
FOV	Field of View
FPGA	Field Programmable Gate Array
GEO	Geostationary / Geosynchronous Orbit
HP	Hewlett Packard (Inc.)
IMEC	Inter-University Microelectronics Center
iSAS	Integrated (electronics) Satellite Attitude Sensor
IR	Infrared (light or image)
LED	Light Emitting Diode
LEO	Low Earth Orbit
LWIR	Long Wavelength Infrared
MBO	Microbolometer
NETD	Noise Equivalent Temperature Difference
NI	National Instruments (Inc.)
QWIP	Quantum Well Infrared Photodetector
RF	Radio Frequency
ROIC	Readout Integrated Circuit
SAR	Successive Approximation Readout
SAS	Satellite Attitude Sensor
SEM	Scanning Electron Microscope
SNR	Signal-to-Noise Ratio
SNRfs	Signal-to-Noise Ratio (Normalized to) Full-Scale
TEC	Thermoelectric ("Peltier") Cooler
TCR	Temperature Coefficient of Resistivity
TI	Texas Instruments (Inc.)
TLD	Thermoluminescent Dosimeter
WIS	Waves In Space (Inc.)

1.0 AN INTRODUCTION TO THE COTS SAS PROGRAM

1.1 The Goal

In the summer of 2002, the Spectral Applied Research Corporation¹, in response to the rapid growth observed in the small satellite industry and the lack of corresponding growth in space sensor technology, recognized the opportunity to innovate. As a result, the Commercial Off-the-Shelf Satellite Attitude Sensor (COTS SAS) program was initiated, with the goal of developing a feasible, optically-based, satellite Earth sensor for use on small satellites and payloads of opportunity, where a low cost, self-sufficient, alternative to current sensor technologies could be utilized.

At this early stage of development of COTS SAS, the scope of the project has been limited to the development of a prototype electrical and optical breadboard model, whose performance would be functionally equivalent to the envisioned final “space-qualified” version of the sensor technology.

The basic principles underlying the Satellite Attitude Sensor (SAS) technology, while quite novel, demand a high level of performance from customized hardware that is typically of only commercially average quality at the component level.

In doing so, the SAS system is capable of providing a consistent level of accuracy that is often an order of magnitude higher than that of currently existing sensor technologies with similar operational requirements in terms of mass, volume, and power.

The COTS SAS program takes the SAS technology one step further, by attempting to design a satellite Earth sensor which shares the operational principles of SAS, but integrates commercially available (non-space-qualified) technologies to deliver an improvement in sensor capability, while negating the requirement of passing on the development cost of “new technology” to the end-customer.

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2.0 BACKGROUND: WHY IS THERE A NEED FOR (COTS) SAS?

2.1 The Trend Towards Smaller Satellites

In today's world of fiscally governed realities, there are few in the space industry who better understand the impact of ever-rising launch and operations costs, than the small satellite industry[3].

Driven by the international failure of commercial (and military) launch service providers to develop the technology necessary to provide a relatively low-cost means of gaining regular (and reliable) access to space in or around Earth orbit, government, commercial, and academic interests have been forced to gravitate towards small satellite technology in an attempt to satisfy even the most basic of their space-related interests and service requirements.

In an effort to rationalize the cost and/or inherent risk associated with a space project in which the immediate technical or financial benefits will not be immediately evident, small satellite technology has become an increasingly popular (in some cases the only) option. Through the segmentation of larger space efforts into a series of smaller, simpler, and arguably more manageable, small satellite projects, the costs (and risks) associated with such endeavors can be better managed.

Essentially, by spreading the overall project cost over a longer period of time (the operational life of all the associate small satellites involved), it becomes possible to present the appearance of a more fiscally responsible ("acceptable") program. Similarly, in the event of the possible loss of a single satellite, the impact, both financially and scientifically, to the overall project goals is viewed as being less severe.

When all the various factors are weighed, the argument can be made that limited scope of each satellite mission makes achieving all of the overall program objectives more likely, allowing each successive satellite to benefit from the advances in both knowledge and technology gained through the operation of its predecessors. Such operations can also add a degree of redundancy to the achievement the overall mission goals, if the individual mission objectives of each satellite are structured to provide a small amount of overlap to allow for the often unpredictable nature of spacecraft operations.

Unfortunately, despite the credible intentions under which many of these small satellite projects are first undertaken, the potential benefits realized from these "reduced

projects” are often proportionally reduced as well, leading to the need to place higher quality payloads on satellites while maintaining a fixed cost structure.

Further, small satellite design leads to the creation of highly individualized (specialized) components, reducing their commonality for use in other satellite applications. Hence these small satellites become “one-off” designs whose overall true value to future applications is in fact diminished. For this reason, every effort has to be made to reduce costs in all aspects of the satellite design and development, since further gain from the financial investment the satellite represents is often quite limited.

It is also of some interest to note that, despite the reduction in mission costs that small satellite technology is thought of as providing, the relative perception of the mission costs also seems to scale proportionally, so that the investment in, or potential loss of, a “low-cost” satellite is still viewed as being an unacceptable financial risk.

On a more positive note, with the recent decline in overall demand for satellite / space services, small satellite programs have been emerging as the key to continued access to space. Serving as what has been termed [3] “engines of innovation”, the comparatively small budgets and short development schedules have encouraged continued innovation, and the ability to reduce the inherent risks of any new technology to manageable proportions in situations of failure.

Thus, as satellites grow smaller, the already stringent size and mass constraints placed on their design, grow exponentially in proportion. With the need to dedicate just about every available resource within the satellite bus to the primary payload² the resources available for the support and operation of the satellite are placed at an even higher premium [11]. One such area of support is that of satellite attitude control, consisting of the technology necessary to maintain a satellite's orientation in space.

2.2 Focus on Satellite Attitude Control:

As the capabilities of microsatellite and nanosatellite technology continue to be exploited, the demand for smaller, faster, and increasingly accurate attitude determination systems will remain in great demand [2]. In addition to superior performance, these next-generation systems, if they are to be commercially successful, must also offer increased

² The justification for the financial and technical expenditure to begin with

flexibility for use in a wide range of potential satellite applications, while still remaining comparable, in terms of cost and mass, with the existing systems currently on the market.

Until recently, these requirements have often been in conflict with one another due to technological limitations. This has often necessitated design compromises that add both cost and complexity to current satellite systems [23].

In keeping with the focus of this thesis and the COTS SAS program goals, it will be shown that recent advances in sensor technology, combined with the increasing availability of highly accurate digital electronic components, now permits many of the classic performance conflicts to be largely circumvented through the implementation of innovative new techniques for image acquisition and discrimination.

2.3 Overview of the Problem:

The basic problem facing most passive Attitude Control System (ACS) sensors currently being employed in satellite systems today is one of versatility (or adaptability) vs. accuracy.

Current sensor technology, be it analog or digital, is designed based on a trade-off between the ability of the sensor to function in a dynamically changing environment (or multiple modes of operation), and the inherent accuracy (precision) of the attitude information that the sensor is designed to provide. This, in turn, has often resulted in the requirement to employ multiple sensor technologies on a given satellite in order to provide adequate attitude control information during all phases of operation that might reasonably be encountered in the satellite's lifetime.

2.4 ACS Sensor Technology:

Although a diverse spectrum of technologies is normally employed in the determination of the attitude and dynamic rates of a satellite, for the purposes of this thesis, discussion will be limited to the area of passive optical sensors, which is to say sensor systems that provide attitude data based on visual observation of external reference points. It is within this general family of sensor technology that the proposed COTS SAS system can be classified or characterized.

Generally speaking, three sub-classifications of passive optical ACS sensor technology exist, as outlined below. Not surprisingly, each sub-class has its own basic

advantages and disadvantages, which in large part dictate its suitability for a given satellite or spacecraft application.

2.4.1 Earth (or Horizon) Sensors:

Function: To determine the orientation of a satellite using the Earth as the primary reference source.

Mode of Operation: Commonly utilizes infrared sensor technology to detect the thermal transition between the limb (“horizon”) of the Earth and “deep” space. Essentially, a thermal image of the Earth’s horizon arc (limb) is taken against the background of the “empty” space behind it, and the transition region is then identified. This yields the phase and chord angles with respect to the nadir vector which, when combined with knowledge of the satellite orbit and the sensor mounting orientation on the satellite bus, allows for attitude determination.

Applicability: Both three-axis stabilized and spin-stabilized satellites. Average accuracy range of 0.1° to 1.0° .

Advantages: Low cost, low weight, simple technology base, high reliability, usually require little if any external inputs for normal operation.

Disadvantages: Requires an unobstructed view of the Earth / space horizon in order to function, hence multiple sensors (beyond that needed for redundant operational purposes) are often required to ensure that this transition always remains in the field of view (FOV) of at least one sensor at all times. Can only provide information in two axis (usually pitch and roll).

2.4.2 Sun Sensors:

Function: To determine the orientation of a satellite with respect to the Sun.

Mode of Operation: Usually employ visible-light sensor technology to detect the optical signature of the Sun (based on relative image luminosity) against the background of “deep” space. The functional assumption made is that the Sun represents the brightest observable image source. Basic functional requirements are similar to those of Earth sensors with regards to the need for prior knowledge of at least some of the satellite orbital parameters (in addition to sensor mounting orientation) in order to adequately determine attitude in two dimensions (again, most commonly in the pitch and roll axis).

Applicability: Both three-axis stabilized and spin-stabilized satellites, particularly those intended for operation in a Sun-synchronous orbital environment, and generally effective anywhere within the inner solar system. Average accuracy range of 0.005° to 3.0°

Advantages: Low cost, low weight, simple technology, high reliability, can function continuously once initial orientation with respect to the Sun has been established. For most applications, the normally unmistakable prominence of the Sun makes it an ideal reference point provided it is within the FOV of an appropriate sensor.

Disadvantages: Requires an unobstructed view of the Sun, hence is rendered nonfunctional in eclipse conditions, thus the Sun must remain in FOV of the sensor, often requiring that multiple sensors be employed on a given satellite. Like the Earth sensor, it can only provide attitude information in two axis.

2.4.3 Star Sensors:

Function: To determine the orientation of a satellite with respect to “fixed” coordinate frame of the celestial sphere.

Mode of Operation: Usually employ infrared or visible light sensor technology to capture images of the background star field within the FOV of the sensor. Stars may be treated either as simple points of light of a specified luminosity, or as identifiable star patterns, which are compared to an on-board database (“star map”).

Applicability: Primarily used on three-axis stabilized satellites (“Star Trackers”) where more accurate knowledge of attitude is required. Can also be applied in spin-stabilized applications (“Star Scanners”). Average accuracy range of 0.0003° to 0.01° .

Advantages: Capable of very high accuracy (less than 0.0005°), Can provide direct attitude knowledge with respect to the inertial / celestial coordinate frame, Can be made to function in nearly any spacecraft orientation with a clear FOV of a star field [16]. Have the ability to provide attitude information in all three spacecraft axis, depending on sensor design and number of stars observable in the sensor FOV. Can function in nearly any orbital trajectory, and does not require orbit or trajectory parameters to make an attitude determination, although this information is often required to achieve full measurement sensitivity from the instrument.

Disadvantages: Comparatively large (with respect to other sensor technologies) and costly in terms of physical size, weight, power requirements. Requires external input and support

equipment to update the reference star database. In the event of a mission anomaly where satellite orientation strays beyond the limits of the star database, sensor accuracy is either degraded, or functionality of the sensor is lost.

2.5 Adaptability vs. Accuracy Trade-Off: The Justification for SAS / COTS SAS Development [4]

Currently, most passive optical sensors (regardless of sub-classification) fall into one of two categories[22]:

- **Coarse Pointing:** Typically possess a large FOV (90° to 120° on average) and have a repeatable pointing accuracy limit of 0.1° under design conditions. The large FOV makes these sensors ideal for spin-stabilized platforms or for situations where basic attitude determination in a rapidly translating coordinate frame is required. Sensors of this type are normally carried to aid in the establishment of the initial attitude of a satellite after launch, as well as to serve as a safeguard in the event of failure of more accurate Attitude Determination and Control System (ADCS) instruments.
- **Fine Pointing:** Possess a much more limited FOV (usually not more than 30° on average), but can provide attitude determination to accuracies of 0.01° or better, making them desirable for 3-axis stabilized platforms where pointing accuracy is usually paramount to mission performance.

As it can be noted, there exists a direct trade-off involved between the accuracy of the sensor and its resulting FOV. For this reason, it is almost standard practice to equip most satellites with multiple ACS sensors, with at least one type of sensor from both classes, in order to allow for acceptable attitude determination and control during all phases of the satellite's operational life.

Owing to the resulting higher toll on satellite resources (mass, power, volume), in addition to the potential complexity of attempting to seamlessly integrate multiple sensor technologies into a coherent attitude control solution, it would clearly be desirable to have an ACS sensor with the best properties of both classes (i.e. Utilize a large FOV without sacrificing measurement accuracy). Such a sensor could then be utilized during all phases a given satellite's mission, reducing the need for duplication or potential waste of sensor

capabilities (coarse pointing sensors are often not utilized once the initial attitude of the satellite is established within the FOV of the more accurate fine pointing sensors).

2.6 Multiple Field-of-View Sensor Systems

The design of a typical optical sensor suggests that in order to create an instrument that could combine a large FOV of a coarse attitude sensor with the resolution of a fine pointing sensor, the introduction of multiple fields-of-view (FOVs) will be required. If such an approach is used, the detector elements currently utilized in existing fine pointing optical ACS sensors can be employed with increased efficiency, taking advantage of their superior resolution to differentiate between multiple images simultaneously, which then eliminates the need for multiple discreet sensors.

The introduction of multiple FOVs does introduce an additional layer of complexity into the attitude determination process, as issues relating to image discrimination and the question of associating a detected image with the appropriate FOV it originated from, must now be addressed, before the process of extracting the attitude information can even begin.

A first-order “obvious” solution to the issue of image discrimination, when using multiple FOVs, would appear to be a sensor design in which each individual FOV is associated with its own imaging array / detector element. However, with a little more thought, it can be seen that such a solution differs little, in terms of complexity and hardware requirements, from employing several discreet sensor elements.

After some thought, it becomes evident that, if the benefits of multiple FOVs is to be fully utilized, the question of image discrimination must be solved for the situation of a single detector element receiving the image data from multiple FOVs. Only in this way can the reductions in overall sensor cost, mass, and complexity, resulting from the use of multiple FOV technology, be fully realized in an efficient design.

2.7 The Field-of-Regard

In order to better understand the operation of a sensor employing multiple fields of view, it is convenient to establish the concept of the Field of Regard (FOR) of the sensor. Quite simply, the FOR is the net sum or “total” of all of the individual FOVs of the sensor package, allowing for any overlap which may exist between adjacent FOVs.

$$\Sigma \text{FOV} - \Sigma \text{Total Overlap} = \text{FOR}.$$

For example, a sensor employing 3 FOVs, each of 28°, with a 3° overlap between neighboring FOV, with respect to a given satellite axis has an effective FOR of 78° [(3)x(28° per field of view) – (2)x(3° of total overlap between neighboring FOVs)]. This is illustrated below in Figure 2.7-1.

Figure 2.7-1: Hypothetical Field of Regard (FOR) Created By Three Optical Apertures, Each Having A 28-Degree Field Of View (FOV). In this case, an overlap of 3-degrees exists between adjacent FOVs.

In principle, by combining multiple FOVs, the sensor as a whole can function as if it were a sensor with a single FOV equal to its FOR, while still maintaining most if not all of the resolution obtained from any one of the individual FOVs. Further, this FOR is achieved without the need for mechanical scanning, allowing simple, fixed, optics to be utilized.

2.8 Multiple FOV Technology Applied to Earth Sensor Systems

For Earth sensors, the application of multiple FOVs can be a non-trivial exercise, as these sensors are inherently designed to be as simple as possible, in keeping with the low cost, low power, high reliability philosophy that make them an attractive option to begin with.

Earth sensors function primarily on the ability to detect and track the thermal transition denoted by the horizon arc between Earth and background space (Figure 2.8-1). To an Infrared (IR) imaging detector, this transition is simply denoted by a linear region transecting the imaging array, with the position of this line on the detector corresponding

to the relative orientation (hence satellite attitude) of the detector array with respect to the observed Earth-space horizon. The application of multiple FOV capabilities to Earth sensors is primarily focused on applications in LEO orbits, where high precision attitude information is required, and the issues associated with the high accuracy $\Leftrightarrow$ small FOV limitation of most sensors becomes particularly acute.

Figure 2.8-1: Representation Of The Earth/Space Horizon Arc

Given that, in most relatively circular LEO orbits, the Earth fills such a large FOV for the satellite, numerous discrete sensors are required to be arrayed around the periphery of the satellite bus in order to ensure that the Earth / space transition boundary is viewable by at least one sensor at all times during the orbit.

Thus, by employing multiple FOVs, it becomes possible for one Earth sensor to, in effect, perform the same function that might otherwise require two to three times as many single FOV sensors to achieve. This increased functionality clearly allows such a sensor design to provide an overall reduction in satellite cost, complexity, and weight.

2.9 The Original SAS Concept

At the time of writing, the only Earth sensor technology which has attempted to exploit the capabilities of multiple FOV (simultaneous) imaging was the proposed Satellite Attitude Sensor (SAS), Figure 2.9-1, which was in development³ by Spectral Applied Research (Spectral) in the late 1990's, but never saw application due to shifting priorities in the satellite marketplace.

As first proposed, the SAS satellite Earth / horizon sensor system was designed to utilize the combined output from a series of optical subassemblies, each a reflective optical

³ Development work which continues to this day, partially through the COTS SAS program

array which can superimpose four separate FOVs onto a single microbolometer detector element, using a process referred to as the “overlay principle”[21].

Figure 2.9-1: Spectral Satellite Attitude Sensor Optical Module[1] Figure 2.9-2: Sodern STD 16 [24]

In both cases, a Canadian \$2 coin is shown for scale at right

The stated goal of the SAS technology was to provide, without sacrificing accuracy or reliability, a series of significant improvements in the mass, volume, power, operational envelope (thermal / electrical), and scan pattern update rate, when compared to currently available Earth sensor technologies.

To satisfy these goals, Spectral pioneered a design effort to create a compact optical subassembly that, when used in two clusters of two or three, would have been capable of providing satellite attitude information in two axis (most often roll and pitch [17]) to a resolution of better than 0.05° .

Each optical subassembly (or “optical module”) was to have possessed an effective FOR of 45° (4 FOV of 12° each, with 1° of overlap [13]), and when employed in a four-to-six module cluster, would have permitted simultaneous imaging of nearly the entire Earth horizon arc, as depicted in Figure 2.9-3.

An entire SAS system, utilizing a 6-module cluster, would constitute an approximate mass of 0.5 Kg, consume on the order of 2.0 W of power (including the processing electronics), and occupy an equivalent volume of 1 L [5]. The large individual FOV and the larger still FOR, obviate the need for mechanical scanning assemblies. This, combined with a high microbolometer scan frequency (>1.0 kHz), was to have permitted rapid attitude update rates (≈ 100 Hz), if required, while only moderately sacrificing measurement precision. It should be noted that there exists a direct trade-off between the attitude update rate and the resulting measurement precision.

Figure 2.9-3: SAS Field Of Regard Configuration Using A Four FOV Module

Here 6 modules shown arrayed at equidistant angles so as to provide a 360° view of the Earth/Space transition boundary (adapted from G. Pitre [13])

In most applications, such a trade-off is considered acceptable based on the assumption that rapid and highly precise attitude measurements are typically mutually exclusive requirements. Rapid scan / update rates are required for correspondingly rapid changes in satellite attitude, where precision measurement of the satellite attitude (with respect to external references sources such as the Earth) is not usually required, as such rates are better measured by inertial means⁴.

Conversely, high precision attitude determination is often required in applications where it is desirable to maintain either a fixed (constant) satellite attitude, or sustain a constant (typically small magnitude) slew rate.

Referring back to Figure 2.9-3, it can be noted that the choice of using a clustered configuration for the optical modules was made in order to provided an imaging solution with the maximum possible imaging ability in a variety of satellite orientations, while minimizing the complexity and resource requirements of the system.

Further, by design, only two subassemblies out of every three would actually be required for full system performance, so in applications where more than two subassemblies are used, there would always be a minimum of one redundant assembly

⁴ Such as sensors integrated into the active attitude control element (e.g. a momentum wheel) which is creating the rapid change in satellite orientation

available for the further enhancement of the overall system performance, which would accommodate the use of the SAS sensor in applications where the performance / pointing requirements are typically more stringent than what can currently be accommodated for by existing Earth sensor technologies.

As originally designed, each of the optical modules would have utilized a generic, commercially available⁵, uncooled⁶ infrared microbolometer linear detector array, and were designed so as to allow this detector array to function with only passive thermal control requirements, aside from those temperature control elements present within the detector design itself. This thermal control requirement for the module was established to minimize the overall system complexity and power requirements.

Depending on the final SAS system configuration, there were also provisions made in the module design to allow for integration of all the necessary electronics for array scanning, and detector output signal amplification.

Consistent on-orbit performance levels over the operational design life of the module, were to have been maintained through the strategic use of electrical and radiation shielding elements, as well as the employment of thermally invariant (low coefficient of thermal expansion) optical components. This, combined with periodic on-orbit calibration and fault correction (via software) of the system as a whole, was believed to extend the operational life of the SAS system to the point where it became a viable attitude determination solution for both LEO and GEO satellite applications.

2.9.1 SAS Functional Principle:

As mentioned in previous sections, attitude determination and control using the SAS modules would be accomplished through the use of the overlay principle, where the images generated by the multiple FOVs would all be mapped onto the same imaging detector array. The governing problem related to attitude determination would then become one of image discrimination, as opposed to image acquisition.

⁵ Though specially tested and certified for use in the SAS application

⁶ “Uncooled” in this case meant that a small chip-integrated TEC cooler is used to maintain an essentially constant detector array operating temperature

Application of the overlay principle, as it was developed for the original SAS concept⁷, proceeded in the following manner (for complete details, please refer to references [5] and [13]).

As noted earlier, each SAS module employs a system of reflective optics to allow for the simultaneous imaging of four distinct fields of view. Four mirrored surfaces are placed at incremental angles such that each surface reflects an image from a different location onto a concave focal mirror, which then projects the combined image onto the microbolometer detector array.

The fields of view typically represent radial image segments of the Earth and are combined to form the larger angular FOR of the detector. There is a small portion of overlap allowed between fields of view in order to eliminate any gaps in the coverage within the FOR of the sensor. The overlap also allows for tracking of the Earth horizon as it transitions between the individual FOVs, thus ensuring that the Earth / space transition boundary remains within the FOR of the sensor at all times. This in turn permits continuous measurement of both the satellite attitude and dynamic rates if so required.

If six FORs, obtained from using SAS detectors, are employed to view the Earth horizon arc, the situation depicted earlier in Figure 2.9-3 is obtained. The horizon arc is defined by the shape of Earth as viewed from the LEO orbit of the satellite. As indicated in the figure, for optimal performance, the SAS modules are positioned on the body of a satellite in such a way that their FORs are spaced equidistant around the horizon arc.

If we now consider just one of the detectors depicted in Figure 2.9-3, for example at the top of the horizon arc, it can be noted that the relative transition in IR flux from space (low flux) to the Earth (high flux) occurs in the FOV that is second from the top of the FOR. The uppermost FOV observes only the background space IR flux and the bottom two FOVs see only IR flux emitted from the Earth itself. Thus, overlaying the images from the four FOVs onto the detector on the right-hand side of the diagram, produces the image finally superimposed upon the detector. The resulting image consists of a region of IR flux (corresponding to roughly twice the observed Earth IR flux) appearing on the top portion of the detector, and a separate IR flux (corresponding to three times the Earth IR flux) appearing on the bottom portion of the detector. The pixels on the detector array can

⁷ This work pre-dates the time period covered by this thesis

observe the transition of the level of IR flux resulting from the transition from Earth to space, but additional information is still required in order to properly determine within which of the four FOVs this transition actually occurs in.

This issue is subsequently resolved by comparing the initial readings from at least two independent SAS module views, combined with the values of several geometric parameters that are pre-determined from the initial positioning and alignment of the sensor on the satellite bus. When combined, these factors can be used to establish the basic orientation of the satellite, which then allows further correlations to be made in order to resolve the imaged thermal transition boundary into the proper FOV of each module. With this accomplished, it is then possible to determine the angle between the bore sight of each SAS module and the Earth horizon.

Knowing the geometric orientation of each module on the satellite bus, this bore sight angle can then be used to determine the orientation of the satellite nadir vector. In the case of Figure 2.9-3, images obtained from four of the six SAS optical modules would be required to produce an nadir value with sufficient angular resolution to satisfy the specified SAS performance requirements, although three modules could be used if they are selected such that they are equally spaced with respect to their FORs around the horizon arc of the Earth.

With the nadir vector established, the bore sights of the SAS modules can now be oriented towards the centre of the Earth, and the horizon arc can then be tracked continuously as it passes between the individual FOVs / FORs of adjacent modules, allowing continuous knowledge of satellite altitude to be maintained if so required.

A comparable sensor technology to the SAS, in terms of accuracy (0.06°), can be found in the Sodern STD 16 Earth sensor, Figure 2.9-2 (shown beside the SAS of Figure 2.9-1 for comparison purposes), which possess a FOV of 4° , but employs a rotating mirror assembly to in-effect move this FOV around to scan what might be considered a larger FOR, whose size is chosen to match the specific mission requirements of the satellite. The sensor assembly weighs a respectable 3.6 Kg, consumes nearly 7 W of power, and occupies a volume of 13.4 L. Thus, when compared to the SAS system, the potential advantages of the multiple FOV technology are clearly evident. In fairness to Sodern, it should be mentioned that the STD-16 is a spin-off technology from a sensor designed for

geostationary (GEO) satellites (which are traditionally much larger physically than their LEO counterparts), and hence has the larger physical form factor as a result. It also boasts an impressive, manufacturer guaranteed, 22 year operational life on all components, including the rotating mirror assembly.

2.10 The Benefits of COTS SAS

In the current space industry, and industry in general, it is extremely difficult to get new concepts, even those as innovative as SAS, introduced into the marketplace. This holds particularly true in the area of satellite manufacture, where reliability has always been a commodity that is sacrificed at a manufacturers' peril, and new technology is viewed with a great deal of suspicion until such a time as it can be proven reliable through actual use in a suitable space-related application. Flight-testing "unproven" technology is thus a high-risk, high-cost, proposition, and since repeated testing is required to establish reliability, technological progress is made incrementally, at a rate determined by how rapidly the cost of a product's initial development and testing can be passed along acceptably to potential consumers.

As if to further complicate matters, today's fiscally stringent business environment now demands that new technology not only be inherently reliable from the outset, but also profitable from the moment of a product's inception, making the development and testing of such new technology an even greater challenge.

For SAS, however innovative a concept it may be, to succeed in such an environment long enough to establish a market for itself, it must be introduced in a manner which not only accents its superior performance aspects, but one that is also immediately cost competitive by offering this higher level of performance at or below the same revenue outlay as any existing products on the market which serve a similar or identical function.

For this reason, the COTS SAS project was initiated, with the stated goal of not only making the SAS technology a reality, but doing so with existing, commercially available; components whose properties, as delivered from their respective manufacturers, would be sufficient to satisfy the demands of the SAS system. Through a series of electrical, radiation, and optical trials, it was the project's goal to demonstrate that the SAS concept could be made a reality using non-class S components that would withstand the

rigors of prolonged exposure to a space environment without significant degradation in performance.

The developmental cost savings realized through the adoption of the COTS approach can then be passed directly along to potential consumers, allowing COTS SAS to compete directly on a cost-per-unit basis, leading to what is thought to be a more rapid adoption of the product as it establishes its performance and reliability through early use.

The COTS SAS approach was believed to be feasible based on the current state of digital electronics technology, which has made all the necessary components required for COTS SAS available at prices that would allow the manufacture of the COT SAS system, and allow that system to be competitively marketed at a cost to the end user that could potentially be up to an order of magnitude less than competing products of similar specifications to the SAS system.

3.0 AN INTRODUCTION TO THERMAL DETECTOR ARRAY TECHNOLOGY: THE MICROBOLOMETER

The heart of the COTS SAS system, or any infrared imaging system for that matter, is the choice of photodetector technology used to measure, and then convert, the incident infrared radiation from an external source being imaged, into a quantifiable electrical signal.

As has been generally stated in previous sections of this thesis, the COTS SAS attitude sensor, like its predecessor, the original CresTech / Spectral Applied Research SAS sensor, is designed around a semiconductor detector element known as the microbolometer detector array.

Due to the design constraints imposed by the operational requirements of the COTS SAS system, it will become clear in subsequent sections of this thesis, that this detector array represents the key design element upon which the feasibility of the COTS SAS program is dependent.

In view of this fact, it is therefore beneficial to review some of the basics of infrared photodetector technology in more detail, to better understand the rationale behind the current design choices made for the COTS SAS program, and the operational principles behind the microbolometer detector array which was selected for the first design iteration of the system.

3.1 Classification of Infrared Photodetectors

Infrared detectors and detector arrays are commonly used in a diverse range of applications, and can be generally classified as functioning according to one of two general methods [26].

The first of these methods, on which a large majority of IR detector arrays are currently based, is that which defines the process of the **passive** detection of thermally emitted electromagnetic radiation as described by the well known Planck's Law. Using this principle, it is possible to image objects in darkness, or carry out contact-less temperature measurements. The key feature of note in these systems is that the object being viewed or imaged provides its own illumination via the process of blackbody radiation.

The alternative functional principle for a thermal detector, defines the so-called "active systems", which are based on the illumination of the target object to be viewed by

an infrared source, such as a thermal emitter or an infrared laser. The details of the operation of these active imaging systems is currently beyond the scope of this thesis or the COTS SAS program.

At this point the reader is reminded that the COTS SAS sensor, or just about any satellite Earth / horizon sensor, is best characterized as a thermal (temperature) detection (or imaging) system. These systems function by “viewing the world” in terms of heat, or, more properly, in terms of the emitted infrared energy that all objects radiate. Thus it is evident that such detectors (sensors) are “passive” IR detector arrays, the operational principles of which will now be briefly summarized.

3.2 Planck’s Law Governing Blackbody Radiation

The emission of thermal radiation by a body can be generally characterized by the expression:

$$R_E d\lambda = \frac{2\pi ch\nu}{\lambda^2 \left[\exp\left(\frac{h\nu}{kT}\right) - 1 \right]} d\lambda$$

Where:

R_E = Spectral Radiant Existence⁸

c = Vacuum speed of light

h = Planck constant

ν = Frequency

λ = Wavelength

k = Boltzmann constant

T = Absolute temperature

Planck's radiation law states that every object at a temperature above that of absolute zero emits electromagnetic radiation. From the equation, it is evident that the higher the temperature, the higher the emitted intensity of the resulting (thermal) radiation [26].

Additionally, it should be noted that the wavelength of maximum intensity decreases as temperature increases (defined by Wien's Displacement Law).

⁸ Defined as the emitted power within a half sphere field of view per unit area and unit wavelength

In the interest of being theoretically precise, it is noted that the Planck relationship is strictly valid only for cases of “ideal blackbodies” which, by definition, have a 100% thermal absorption and equally efficient thermal emitting properties (emissivity of 1).

Naturally, it is possible to extend the Planck relationship to real-world objects (such as the Earth itself in the case of COTS SAS) by introducing the concept of emissivity, a scaling factor less than unity, and which is defined as being equal to the ratio between the emitting intensity of the object in question, and that of a corresponding “true” blackbody having the same temperature as the object. Generally speaking, the emissivity of a body is wavelength dependent, hence real world bodies can have multiple values for their emissivity, depending on the IR wavelengths in which they are viewed.

In most applications, infrared imaging is performed in one of two different atmospheric transmission windows:

- 3 to 5 μm range MWIR - Medium Wavelength Infrared
- 8-14 μm range LWIR - Long Wavelength Infrared

Within these spectral windows, the atmospheric transmission is found to be a maximum or, equivalently, the absorption of IR energy is at a local minimum. This avoids unwanted degradation of the IR optical intensity due to the high IR absorption properties of carbon dioxide (4.2 μm), and atmospheric water vapor (6 μm).

3.3 Dark Current and the Noise Equivalent Temperature Difference

Before we can begin our discussion of microbolometer specifics, it is useful to define the two principle criteria by which the sensitivity of most, if not all, solid-state (semiconductor) photodetector technologies are evaluated. These criteria are the detector Dark Current, and the resulting Noise Equivalent Temperature Difference.

The Dark Current can be thought of as “background noise” inherent to a detector design due to thermally generated free charge carriers in the semiconductor materials, the number and density of which are proportional to the ambient temperature of the detector array. As a result, a semiconductor thermal photodetector element generates a signal response that is a combination of noise (related to its own temperature) and incident infrared radiation incident upon its surface from the external source it is being used to image. Therefore, it can be reasoned that, if the detector array temperature is too high, the

perceived signal due to the Dark Current noise will saturate the detector and drown-out any detected signals from the external infrared source.

In theory, since the Dark Current arises from the presence of “self-generated” (or thermally excited) free charge carriers in the detector material itself, the Dark Current can only be eliminated by reducing the detector temperature to “absolute zero” ($T = 0$ degrees Kelvin). For this reason it is an accepted fact that, in reality, the Dark Current response (noise) is always present in the detector output signal, and must be accounted for in the processing of the detector output signal. Hence, the selection of the appropriate detector technology, and the conditions under which it will be expected to operate, is governed, to a large extent, by the Dark Current properties of the detector material.

In an effort to better account for the effects of the ever-present Dark Current in the detector, a second detector performance criteria, the Noise Equivalent Temperature Difference (NETD), can be defined as representing the magnitude of smallest change in temperature (ΔT in degrees K) of the external IR source being imaged, which would correspond to the average fluctuation in the Dark Current levels present in the detector material when operated at a specified temperature.

The NETD effectively defines the detector sensitivity, stating that any perceived temperature variation smaller than the stated NETD value may not be sufficiently differentiated from fluctuations in the Dark Current in the detector material (within the thermal operating envelope of the detector) to be reliably (or repeatedly) measured. In electrical parlance, temperature variations smaller than the NETD, are “in the noise floor” of the detector output signal, and can not be differentiated (or reliably extracted) from random noise signal fluctuations generated by Dark Current responses.

NETD performance of different detector technologies has varied widely over time, but recent detector systems are typically expected to offer performance levels of 200 mK⁹ or less, and performance levels into the micro-Kelvin (μK) are now routinely achievable with some sensor technologies.

⁹ 200 mK = 0.2 degrees Kelvin

3.4 Thermal Detector Array (Microbolometer) Technology

Historically, high-resolution infrared imaging systems have relied on thermally regulated, often cryogenically cooled, detector technology in order to achieve (and maintain) the level of performance required of them. In recent times, technologies such as the Quantum Well Infrared Photodetector (QWIP) have allowed for the broad commercial application of IR imaging techniques to a wide variety of applications ranging from food processing to earth resources management.

However, despite their ability to achieve remarkable NETD performance levels of 30 to 40 mK or better, the use of technologies such as QWIP in space / satellite related applications has been limited by the often prohibitive¹⁰ mass and power requirements that are associated with the ability to maintain the necessary cryogenic operating temperatures (70 to 73 K) for the detector arrays. Thus, space-based imaging systems employing this type of technology are almost exclusively the primary payloads for satellites, but are not generally considered widely suitable for “utility applications” such as satellite attitude control.

Fortunately, for technologies such as COTS SAS, the past decade has seen an unprecedented growth in semiconductor device engineering and manufacture, which has stimulated a revolution in the development of solid-state imaging solutions that span nearly the entire electromagnetic spectrum in their possible applications.

One such technology to recently emerge in the specific area of IR imaging is the thermal detector array, sometimes referred to more specifically as Infrared Focal Plane Array (IFPA). These devices, which recently have been able to approach levels of performance comparable to QWIP technology, operate under conditions that are similar to those of CMOS Active Pixel Sensors (APS) or the CCD arrays found in digital cameras and other commonplace consumer-level digital imaging systems.

These detector technologies are classified as “uncooled” or “room-temperature” imaging arrays, as they usually require little, if any, thermal control to operate efficiently. This is of particular significance to IFPA detectors, which are specifically designed for imaging in the IR-segment of the electromagnetic spectrum.

¹⁰ Relative to the ultra-stringent resource management requirements associated with space technology in general

Furthermore, due to the ability to operate at “room-temperature” (15 to 50°C)¹¹, any cooling requirements that these imaging devices might have, are proportionally less demanding than those required for cryogenically cooled devices like QWIP, which makes them much more attractive for use in satellite or spacecraft applications.

An Aside: A Note About Operational Principles:

Before addressing the specifics of the thermal detector array device operation, it is first helpful to clarify the principle distinction between an IFPA and that of an APS, CCD, or QWIP detector.

Technologies such as APS, CCD, and QWIP detectors can all be generally characterized as purely “optical” devices, which convert photons with wavelengths within their designated performance range, into a direct electrical analog, which is then used to represent the detected signal or image. The principle process involved, particularly in the case of a QWIP, relies on the energy of an incident photon to generate a free charge carrier of comparable energy in the detector material, thus **creating** an electrical current or generating a potential difference in or across the detector element. It is this current generating ability that differentiates these types of detectors from the operating principles which govern thermal detector arrays.

In the operation of a thermal detector array, the key feature to note is that **no charge carriers** (hence electrical currents or potentials) **are created**. Instead, these devices function through an “indirect” process by which photons of a designated wavelength are absorbed by the detector material and **converted into heat**, generating a temperature change in the detector element, which in turn induces a change in the electrical resistance properties of the material. The magnitude of this temperature / resistance change, is, essentially, inversely proportional to the wavelength of the photon absorbed, and directly proportional to the photon (energy) density incident upon the detector surface.

Thus, if a known (constant) voltage is applied across the detector element (treated as a simple resistive load), the change in resistance can be measured in terms of the

¹¹ The definition of “room-temperature” is admittedly subjective but usually falls within this temperature range

resulting change in current through the load, which can then be quantified as the detected signal.

Hence, it is perhaps helpful to think of a thermal detector array as being comprised of a series of **thermistors**, the design of which allows for the potential difference across them (actually expressed in terms of a differential current through them) to be measured to a high-degree of accuracy. Thus, the principle operation of a thermal detector array is a two-step process:

1. Infrared absorption gives rise to a temperature increase of the detector element
2. This temperature increase changes the resistance properties of the detector element
3. This change in resistance is measured indirectly by monitoring the voltage across, or the current through, the detector element
4. This measured change is then correlated to express the temperature of the external source, or used directly to generate a thermal (i.e. infrared) image of the source itself

Thus, in summary, when dealing with microbolometers or other similar technologies, it is important to remember the distinction that **IFPA devices are**, from a purely electronic standpoint, **current regulators**, NOT current generators.

Unlike QWIPs, whose structure (the quantum wells) must be specifically “grown” through atomic / electron deposition means, thermal detector arrays are, most commonly, surface micro-machined or etched into a pre-grown semiconductor wafer. This allows for the creation of three-dimensional bridge structures or membranes which provide a critical means of thermal isolation for these devices [19]. Further, since this machining process is conducted during the post-processing phase of the semiconductor material itself, it is possible to grow the necessary CMOS readout circuitry needed for measuring the thermal changes in the detector elements themselves. Hence, the detector array can be seamlessly integrated with its associated processing electronics, which allows for a high-density of detector elements to be achieved on a given array.

3.5 Microbolometer Functional Specifics

Regarding the specifics of the device operation, a resistive microbolometer (thermal detector array element) consists of a thermometer with a predetermined heat capacity, mounted on an absorbing substrate, and weakly coupled to a heat sink at a constant (over short time / measurement periods) temperature via thermal conductance alone. Resistive microbolometers (including both composite and transition-edge¹² bolometers) use the temperature dependence of the resistive element (thermometer) to measure the infrared signal incident on the absorber. In steady-state operation, the thermometer will heat up until the dissipated power matches the power conducted through the thermal link to the heat sink. For a diagram of one representative pixel element design, please consult Figure 3.5-1 below.

Figure 3.5-1: SEM micrograph of a 25μm-pitch Amorphous Silicon Microbolometer (© J. Tissot, ULIS) [20]. Notice the vacuum cavity between the thermometer and reflector, necessary for proper thermal insulation

In most cases, each detector element (active pixel) is coupled by direct injection to a detector amplifier circuit, and operated in a pulsed bias mode to reduce substrate thermal sensitivity fluctuation. Most of the background current (due to the ambient temperature of the detector array at a given time) is suppressed through the use of a thermally compensating reference, known as the “blind pixel” element, which is usually shared sequentially between multiple, usually sequential, active pixels in the detector array.

The useful current from the active pixels is then integrated in a Capacitive Trans-Impedance Amplifier (CTIA) a current-voltage conversion is performed by this amplifier¹³. Several integration capacitors may be implemented in the feedback of the amplifier to

¹² Transition-edge microbolometers (TREMBOL) are superconductive devices (cryogenically cooled) and are beyond the scope of this thesis

¹³ Depending on the device / array design, there may be more than one CTIA utilized

provide significant signal gain and to deal with different operating conditions. The information is multiplexed, per row of active pixels, after the current-voltage conversion stage which then permits the transfer of the detected signals from the amplifier to the output of the detector circuit. Please refer to Figure 3.5-2 for a simple illustration of the thermal detector array concept.

Figure 3.5-2: Representative Circuit Arrangement For A Typical Thermal Detector Array[20]

3.6 COTS SAS Microbolometer Operational Theory

Although the general operational principles discussed in the previous section apply to nearly¹⁴ all thermal detector arrays / microbolometers, the specifics of how these principles are implemented by different detector manufacturers does vary to some degree. Thus it is worthy to explore in more detail how the specific microbolometer selected for COTS SAS (an IMEC / XenICs XLIN-λ8.0-200-B) is intended to operate, so that the reader has a better appreciation of some of the design logic behind the COTS SAS system and its specified (proposed) operational requirements.

The microbolometer selected for the COTS SAS program utilizes a linear arrangement of 200 active pixel elements whose thermal response (i.e. resistance variation due to incident IR radiation) is determined via the following process:

The active microbolometer pixel elements are placed in a Wheatstone Bridge voltage divider configuration to measure the pixel resistance variation (with IR radiation intensity) in terms of a potential difference across the voltage divider. The divider is coupled to a buffered CTIA sample and hold circuit for sequencing and amplification of

¹⁴ It should be noted that the transition-edge microbolometer devices do function according to slightly different rules, due to their involvement of effects resulting from superconductivity

the detected signal. An equivalent circuit representation for the microbolometer array is shown in Appendix C, Figure C-1, the details of which will now be discussed.

The left branch of the Wheatstone Bridge consists of two thermally invariant reference resistances ($\approx 100 \text{ k}\Omega$ each), whose precise value is known¹⁵ to a high degree of precision, and whose properties are such that these resistance values do not vary appreciably with temperature, over the thermal operating range of the microbolometer array.

The right branch of the bridge consists of the active MBO pixel element itself (which is sequentially switched in and out of the bridge circuit via the on-chip multiplexer), and the thermal compensation reference resistance (blind pixel) which allows for the implementation of some degree of signal compensation in the detected signal from the active pixel.

It is important to note at this point that, since the bolometer array is completely uncooled, it will be operating at close to the ambient spacecraft temperature. Under such conditions, most of the radiant energy falling on an active bolometer pixel element comes from the local environment around the detector, rather than from the scene being viewed through the optics of the sensor subsystem (Figure 3.6-1 [21]), and it is for this reason that the blind pixel element is employed.

Figure 3.6-1: Thermal Signal Conditions (Predicted) For The Uncooled Microbolometer [21]

¹⁵ These values are characterized on a batch-by-batch basis as the MBO arrays are fabricated by the manufacturer. Each MBO array is provided with its own operational specifications based on this characterization

The blind pixel¹⁶ is, as the name would suggest, a microbolometer pixel element whose physical characteristics are identical to those of the active pixels (upon which the infrared signal from the external source is incident), but is shrouded or encapsulated such that no external infrared light from the target source being view can impinge upon it.

Under these conditions, the blind pixel serves as an “on-chip thermometer” for the microbolometer array, allowing a compensating current to be generated which can be used to cancel out (subtract) the signal due to the array temperature from the detected signal of the active array pixels. Thus, should the array operating temperature drift, it is possible to compensate for this effect, and ensure that the output signal from the detector array reflects only those thermal changes in the microbolometer active pixels brought about by the emissions from the external infrared source.

It should however be noted that the blind pixel can not compensate for the loss of detector sensitivity with increasing temperature. As will be shown in later sections of this thesis, the performance / sensitivity of the microbolometer to incident infrared radiation is a function¹⁷ of the detector operating temperature. Thus while the signal resulting from the operating temperature of the detector can be measured and then compensated for by the blind pixel, the loss of detector sensitivity can not be corrected for without physically altering the temperature of the detector itself.

Having established that the pixels are arranged in a Wheatstone Bridge configuration, it can be noted from Appendix C, Figure C-1, that the selected COTS SAS detector array utilizes a buffered CTIA circuit¹⁸ to measure the potential difference across the bridge. This detected potential difference is then converted into a differential current and integrated in the CTIA as described in the previous section.

The integrated signal response is then stored in a sample and hold buffer until such time as the proper timing trigger pulse is received by the detector to release the signal

¹⁶ There may actually be several employed by the detector, depending on the number of pixels in the array and their arrangement both physically and electrically in the array

¹⁷ For devices such as those dealt with in this thesis, this relationship is an inverse, but proportional one. For transition-edge devices, there tends to be a direct relationship (due to the nature of the superconductive materials used)

¹⁸ To be totally accurate, the IMEC detector uses two of these circuits, one per multiplexer element in the detector package

through a dual operational amplifier circuit before reaching the detector array output terminal.

Another important operational feature to note in Appendix C, Figure C-1, is that a pulsed bias is applied to the detector array during operation. As noted in the previous section, this is done to reduce the substrate thermal sensitivity response, an effect more commonly referred to as “self-heating”.

Like any other electrical impedance circuit element, the microbolometer pixels and reference resistors are not 100% electrically efficient. Hence when the bias is applied and current flows through them, these circuit elements do consume a small amount of power, which is then dissipated as heat. If the detector array elements are biased for a long enough period, their temperature will naturally increase due to this heating effect alone, an increase that will then result in a change of MBO pixel resistance that is indistinguishable from that caused by external illumination of the pixels.

Owing to the high impedances and small physical dimensions of the circuit elements (which measure only a few microns in some cases) this self-heating effect can occur quite rapidly, thus the time duration of the bias pulse before this effect becomes significant is very short, often only 10 or 20 μsec .

It should be noted at this point that the duration of these bias pulses is more often referred to as the “integration time” of the detector, because this pulse duration represents the time period over which the differential current is integrated within the CTIA buffer capacitance. Likewise, the frequency of the clock source used to provide / trigger these pulses is referred to as the “integration frequency” of the microbolometer.

As it will be shown later in this thesis, during the discussion of the testing of the breadboard prototype electronics, the integration time of the detector does play a key role in detector performance, as it can be easily reasoned that the longer the integration time, the larger the resulting integrated differential signal response in the CTIA becomes, which basically equates to a stronger (higher amplitude) detector signal response to infrared light. This of course comes at the cost of increasing the possibility that self-heating will either degrade the MBO array response (sensitivity) properties, or, possibly artificially augment the detected external source temperature (signal). The inverse of this argument holds true for shorter integration times.

- Long integration time --> Strong MBO signal but induces self-heating
- Short integration time --> Smaller signal but reduces self-heating effects

It is therefore critical to determine the proper operational conditions for the detector when used in the COTS SAS system, so extensive testing, to be discussed in later sections of this thesis, was conducted in part, to determine precisely what these conditions should be.

3.7 The Advantages of Thermal Detector Arrays

The major advantage of the thermal detector array, over that of a QWIP, is the provision for room temperature operation and monolithic design of the complete sensor unit including multiplexer, which permits a low price per imaging system.

The typical performance requirement on detector arrays integrated with readout electronics, is a temperature resolution (NETD) $< 100\text{mK}$ [19]. Although this is nearly an order of magnitude “poorer” than that of a comparable QWIP system (NETD $< 30\text{mK}$), the ability of the thermal detector array to operate at much higher ambient temperatures, negating the need for active cooling methods, is seen as an acceptable compromise in many applications, including COTS SAS.

The major requirement for achieving high sensitivity in a thermal detector array is an efficient thermal insulation between the detector element and the substrate. The importance of this requirement can not be stressed enough, and it is helpful to remember the statement made earlier, that the thermal energy transfer between the thermometer and the heat sink is permitted via conduction alone. Thus all other forms of energy transfer, particularly convection, must be minimized or eliminated.

As a result, this thermal insulation requirement usually necessitates vacuum encapsulation of the detector, and it is the decay of this vacuum which often limits the performance and operational lifespan of these devices. However, in reference to the COTS SAS program, if this technology is utilized in a spacecraft / satellite application, the high-vacuum of space can theoretically be used to eliminate this design limitation.

The other key factor governing the sensitivity (utility) of thermal detectors is the nature of the thermometer materials used for temperature detection. Clearly, the ability of a

material to respond to even extremely low levels of IR energy will dominate the overall detector array design.

For this reason, any semiconductor-based material with a large thermal response coefficient, or the use of pyroelectric materials (such as Vanadium Oxide / Silicon Nitride (VO_2 / Si_3N_4)) are therefore logical choices in the construction of commercially available detectors of this type [18].

More recently, less “exotic” materials, such as poly-crystalline Silicon-Germanium (poly-SiGe) composites, have been pursued as a means of further reducing manufacturing costs for “room-temperature” operational detectors [25] which require only a passive means of thermal regulation while in normal operation.

With the further introduction of amorphous silicon composites to the microbolometer structure, NETD values as low as 30 mK have now been demonstrated under laboratory conditions [19], matching the performance of technologies such as QWIP-based detectors, while eliminating the need for cryogenic operating temperatures.

Thermal detector arrays are best characterized by their Temperature Coefficient of Resistance (TCR), a performance metric which will be examined in more detail at a later point in this thesis, but whose general definition can be summarized as the measure of the magnitude of the variation in resistance of the semiconductor material (microbolometer pixel element) in response to a unit change in the device temperature (signified by the intensity of the IR radiation incident upon the detector).

Principally due to the provision for “room-temperature” operation and the negation of the requirement for active cooling, the basic design for the COTS SAS system has been modeled around the use of a thermal detector array element system, specifically favoring the use of poly-SiGe technology if at all possible to keep the system costs to the end-user to an absolute minimum.

4.0 COTS SAS HARDWARE OVERVIEW

In this section, the basic hardware and design philosophy used during the initial stages of the COTS SAS development program will be discussed, in an effort to provide some background for later, more detailed, discussion of the test and characterization work, which is the focus of subsequent sections of this thesis. It is not the intention of this author to explore the design of the individual hardware components in great detail, and the reader is referred to the COTS SAS test and verification reports [10][14][15](of which this thesis makes reference) if such detail is desired.

4.1 The Conceptual Guidelines for Development [6]

The COTS SAS system is seen as an innovative approach to satellite Earth sensor technology, and was developed with the following guidelines in mind:

- Use a compact optical module
 - To be a feasible alternative for small satellite / microsatellite applications, the physical footprint of the actual SAS sensor module must be kept as small as possible.
- Limit current development to COTS parts as much as possible
 - In order to pass on the maximum savings to the end customer, the cost of research and development must be minimized from the outset of the program. Hence components must be found that either meet the COTS SAS requirements “straight out of the box”, or can be made to do so with only minimum modification (while not appreciably impacting the component performance).
- Use a commercially available poly-SiGe microbolometer array, located at the focal point of the optical module, as the core of the sensor system
 - To keep both system cost and complexity low, the microbolometer element must be an “uncooled” device, capable of room-temperature operation with no provision for temperature regulation or stabilization.
 - Locating the array at the focal plane of the optics module will further reduce the overall system cost and complexity by eliminating potentially problematic additional optical components that would be otherwise required for focusing of the module.

- Use a wide-band infrared range optical window, with a flat device response over wavelengths between $8\mu\text{m}$ and $12\mu\text{m}$.
 - Use of a detector and electronics infrastructure capable of viewing / processing a wide-bandwidth infrared signal will better improve optical sensitivity, and hence accuracy, of the system.
- Initial target market of LEO “small satellites” or microsatellites in nominal circular orbits
 - This is an initial conceptual model chosen to ensure that the hardware developed will maintain as small a form factor as possible.
 - These initial assumptions about the nature of the satellite and its orbit will be used for later simulation of the operational environment in which the developed hardware must meet all of the specified performance requirements for the COTS SAS program.
- Explore the economic savings associated with the use of COTS technology in satellite / space applications
 - The use of COTS parts is seen as an opportunity to dramatically lower development, production, and end-product costs. The ability to exploit this concept will be a driving factor throughout the COTS SAS program.

4.2 The Operational Assumptions Made:

Assuming a standard small satellite application employing a COTS SAS sensor package, the following properties are expected to be typically representative of the required sensor hardware installation:

- It is assumed that the optical modules will be located around the periphery of the satellite in either a clustered or distributed configuration, as dictated by the specific application requirements.
- Core signal processing and attitude determination electronics are to be housed within the satellite bus.
- A maximum of one meter (cumulative length) of interconnection cabling will be required to connect all optical modules to the central electronics package.

- Provision for up to a sixteen-bit digitization of the analog microbolometer array outputs will be required to ensure adequate system sensitivity and performance margins.

Basic power, EMI shielding, and grounding issues will have to be taken into account by the design, with provision for additional regulation or shielding to be provided if so required by the specific application operational environment.

4.3 Configuration

Although the underlying theoretical principles that govern the basic operation of the COTS SAS sensor remain essentially unchanged from those developed during the initial Spectral SAS program, the COTS SAS hardware configuration was treated as a “clean-sheet” design, driven by the selection of the individual COTS components as they were selected and evaluated [7].

For the initial breadboard prototype, which is the primary focus of this thesis, design constraints were deliberately kept to a minimum, ostensibly with the goal of first producing a sensor which met all the initial performance specifications, leaving factors such as physical size, weight, or power consumption to be dealt with in future design iterations. However, as will be discussed later in this thesis, as the COTS SAS program progressed, a series of technical setbacks led to a situation in which cost and time constraints became the principle factors which governed the overall hardware design.

Working with the original goal of producing an electrical and optical analog of the COTS SAS sensor which met the initially envisioned performance requirements established for the system, the design was quickly separated into two phases, electrical and optical, with the initial electronics design being conducted under contract from Spectral Applied Research (Spectral) by the Waves in Space Corporation (WIS)¹⁹.

As originally envisioned, once the prototype electronics had been fabricated and demonstrated to meet most of the key performance milestones, the working electronics model would be transferred to Spectral for development and integration of the optics assembly, after which point the electronics and optics would be further refined in parallel. As the program progressed, supply and technical difficulties limited the scope of the initial

¹⁹ 12 Vanessa Place, Cambridge, Ontario, Canada

design phase of the program to just the breadboard electronics, the design and testing of which became the focus of this thesis.

4.3.1 Simplifications Made to the Design

In keeping with the clean-sheet design philosophy, the initial electrical component layout was kept as open as possible to facilitate easy access to all the electronics, as it was expected that the system would be under constant refinement during its construction and early testing as candidate COTS subcomponents were evaluated.

Given all the potential issues that could be encountered when attempting the design of a product of this type, the project scope for the COTS SAS development was scaled back from the original Spectral SAS program.

The most significant change made was the decision to develop early iterations of COTS SAS using a single field of view optical aperture, as opposed to the multiple FOV / FOR system that was the hallmark of the original SAS sensor. This was done mainly to simplify the initial design, with the goal being to produce the lowest cost end-product possible, with which COTS SAS could establish a foothold in the small satellite market based on its economic advantages alone.

Another factor which contributed to the decision to restrict initial development plans to a single FOV was the argument that, later in the development program, results from planned simulations and testing would more accurately reflect the actual performance of the sensor, due to the elimination of additional sources of uncertainty that would have been introduced by the application of the Overlay Principle and the resulting issues with image discrimination that were mentioned earlier.

In addition to the single FOV limitation, it was decided to base the electronics design around an as yet untested microbolometer technology that offered a significant cost savings over all other similar products that currently exist on the market. It would later be found that this decision was of questionable wisdom, as supply and performance issues severely impeded project progress on several occasions.

Another key simplification made to facilitate shorter design and fabrication times during the early stages of the project, was the decision to, in the first breadboard model constructed, omit the ability to test the microbolometer in a vacuum with a proper IR filter window (a synthetic quartz aperture) or provide a means of actively regulating the thermal

environment surrounding the array to explore the properties of the system under different temperature extremes. These abilities were deferred until such time as an integrated microbolometer control board could be delivered from the manufacturer, with all of these features integrated into the board design.

From the standpoint of the electronics design, the decision was made to forego any specific efforts to provide isolation or shielding of the electronics from external sources of either electromagnetic interference or high energy radiation. Primarily a cost savings effort, this decision did have the benefit of greatly simplifying the electronics design and development process, and permitted a more accurate assessment of the performance characteristics of the electrical components when operated under such potentially disruptive conditions.

It was the hope of this author that several different electronics configurations could be evaluated, with the goal of selecting an overall hardware design that would best suit the goal of eventually marketing the COTS SAS system to the small / microsatellite industry. Unfortunately, as time did not permit such testing, the decision was made to base all of the development work on the first COTS SAS prototype around the original SAS design philosophy of utilizing a distributed electronics configuration, the merits of which will be discussed in the following section. For the sake of comparison, an envisioned "integrated electronics" approach will also be discussed.

4.3.2 Distributed Approach to the Electronics

At the time of writing, the COTS SAS hardware configuration employs a distributed, modular, approach wherein there exists a central electronics module, and multiple "remote" optical modules, the number of which would be dictated by the specific mission requirements.

The central module would ideally be housed well inside the satellite bus to provide the optimal thermal environment, as well as protection against detrimental effects resulting from debris impact and EMI / radiation. The module would be responsible for electrical distribution, control, and signal processing for the entire sensor array. It was envisioned that this central module will be capable of controlling and processing the input from up to six optical modules simultaneously, although as mentioned earlier, the SAS principle could function with as few as two modules.

The optical module(s), as the name suggests, would contain the microbolometer array and digital signal driver (amplifier), interfaced with the SAS optics. The optics themselves would be customized as necessary to provide the desired overall FOV or desired sensor resolution.

A given module would be mounted on the exterior of the satellite bus in a location deemed suitable by the satellite designer / manufacturer, such that the sensor is both properly oriented optically, as well as being compliant with the EMI, thermal, and radiation tolerance envelope of the sensor, and must also be positioned such that it causes no (or minimal) interference with other satellite functions or instrument requirements. The exact positioning and orientation of the module, while not in itself critical to the physical operation of the COTS SAS system, must be known to a high degree of precision, as the parameters which define the module orientation play a key role in the attitude determination algorithm employed, as mentioned earlier in the discussion of the SAS operational principles.

In the interests of minimizing weight and complexity, the current design requires that all external timing and control signals, as well as all necessary electrical bias lines, be provided externally from the central control module via a series of shielded power/data transmission lines.

Figure 4.3.2-1 below illustrates a schematic overview of the distributed electronics design philosophy, and the integration of the COTS SAS system with the rest of a prospective client satellite's systems.

Figure 4.3.2-1: COTS SAS System Integration with Client Satellite

4.3.3 The Self-Contained COTS SAS

Although time did not permit the testing of alternative hardware configurations for COTS SAS, it is thought that, in order to be fully competitive in the small-satellite / microsatellite marketplace, a more centralized approach to the sensor configuration is required. One such approach has been deemed by this author to be the self-contained or Integrated COTS SAS (iSAS).

As envisioned, the iSAS configuration would combine the electronics control module and a cluster of three optical modules into one unit. The electronics would be housed just inside of the satellite bus wall (if present), allowing the modules to protrude through the bus.

The merits of such a configuration change are:

- Consolidation of the differential driver and receiver electronics into one simplified, differential amplifier (since the transmission line between the control and optical modules would no longer be present)
- Elimination of the transmission lines between each optical module and the control module
- Reduced power requirements due to lower power losses (no transmission line losses, hence amplifier electronics need not be as powerful)
- Improved gain and signal quality
- Lower EMI susceptibility
- Lower weight and volume of the overall unit

In addition, for larger satellites where a six sensor cluster would be required to achieve the full net FOR required, it would be possible to cross-connect two iSAS modules together with a single, shielded, cross-link cable such that the attitude measurements from all of the sensors could be integrated to provide the overall satellite orientation. Further, since each iSAS module would be operating independently, the cross-link would provide a degree of redundancy, whereby one of the iSAS modules could be tasked to process inputs from all of the optical modules in the system, although at a lower sampling rate or resolution.

Addressing the issues of radiation tolerance and EMI shielding, in a small satellite, or microsatellite, the physical dimensions of a given satellite's bus are such that it is thought that the "additional shielding" gained from mounting the electronics towards the interior of the bus, as in the distributed approach, is most likely negligible.

This statement is made after giving some consideration to the close physical proximity of all components to one another in a small satellite bus, which suggests that any additional EMI shielding that the COTS SAS electronics may require in certain applications (for example, locating the COTS SAS electronics in proximity to a communications transceiver or power converter) would have to be provided regardless of where the electronics were situated in the bus structure.

In the area of radiation shielding, the radiation testing conducted on the COTS SAS electronics, to be discussed in more detail later in this thesis, has effectively demonstrated that most of a satellite's structure is essentially transparent to high energy radiation²⁰. This in turn suggests that the additional protection gained from mounting the electronics in the heart of the bus, while certainly non-zero, is of questionable value when weighed against the possible design savings mentioned earlier, combined with the projected operational lifetime for the sensor in a typical LEO satellite application.

4.4 Operational Parameters

Although the COTS SAS system is still in the early stages of its design evolution, the following preliminary performance criteria were outlined at the initiation of the program to be used as guidelines [1] during the selection and evaluation of potential COTS technologies of interest. These performance goals remain essentially unchanged, despite current design restrictions limiting its operation to a single FOV optical interface, and the elimination of the requirement to employ the Overlay Principle to enhance the sensor performance.

Table 4.4-1 details a comparison in performance metrics between the original SAS technology and that of the proposed COTS SAS sensor system. As can be seen, a decrease in the expected sensor resolution is expected, due to the elimination of the requirement for multiple FOV optics. Due to the goal of using only COTS parts in their original form

²⁰ Gamma particle energies or above is implied here. For the case of Beta particles, the presence of physically shielding is more relevant

factors where ever feasible, it may not be possible to fully optimize the mass or volume of the resulting COTS SAS system, hence these metrics remain true to the original SAS program specifications at this point in the COTS SAS development program. Metrics whose values have not been fully established, are indicated with a “(?)” notation after them.

	SAS [5]	COTS SAS [6]	
Mass	0.5 Kg	1 to 2 Kg	Includes 3 optical modules, cable harnesses, and central processing electronics
Power (Average)	2.0 Watts	2.0 Watts	Expected while operating at full system capability
Volume	1 L	1 L	Total volume occupied by all optical and electronics modules
Operational Lifetime	5 years	2 years	Based on a “typical” LEO orbiting small satellite application
Accuracy (Pitch and Roll)	Up to 0.05°	0.1° or better	Use of multiple optical modules assumed
LEO Operational Altitude Envelope	200 to 600 Km	200 to 600 Km	Circular orbits with inclinations of <60° assumed
Scan Update Rate ²¹	100 Hz 3 Hz	10 Hz (?) 3 Hz (?)	Attitude acquisition Attitude maintenance
Operational Temperature	-20°C to +60°C	5°C to 40°C Depending on detector selected	Assumes prolonged eclipse conditions and exposure to direct sunlight respectively
Power Converter	Integrated	Integrated	These features are included in the system design
Attitude Analysis / Control Electronics	Integrated	Integrated	
Self-Calibration	Integrated	Integrated	
Expansion	Up to six optical modules supported	Up to six optical modules supported (?)	Allows an additional three modules to be operated from the existing control electronics package

Table 4.4-1: COTS SAS Performance Criteria (c. 1998) [1] [8]

²¹ COTS SAS is envisioned to be capable of operating in two basic modes:

Full Precision – For use in high resolution ACS determination (>0.1° of arc)

Reduced Precision – Used for periodic attitude monitoring at a lower resolution (~0.5° of arc), and allows the system power consumption to be dramatically scaled back

4.5 Breadboard Component Synopsis

The original COTS SAS program plan called for two successive iterations of the breadboard electronics, to provide maximum design flexibility during the evaluation of prospective electrical components, before a temporary design freeze could be made to do similar development work on the companion optical assembly. The end result of these iterations was to have yielded the first engineering model of a fully functional COTS SAS sensor system.

The first breadboard system consisted of the individual electronics modules, each consisting of a COTS part whose performance was being evaluated. The modular design allowed for all the components to remain isolated for individual characterization, modification, or substitution, and were integrated together using a series of standardized connector interfaces, many of which would be eliminated as the design matured.

Part of this initial modular system included the fabrication of (what was intended to be) a temporary microbolometer electronics module, utilizing an engineering test sample microbolometer array delivered in a chip-on-carrier configuration from the manufacturer. This essentially involved the reverse engineering of the microbolometer itself, a time consuming, but educational exercise, as it highlighted some areas of the microbolometer operation which were not fully understood by the COTS SAS program team, or (as it was later discovered) the microbolometer manufacturer. This lack of understanding would later contribute to several problems during the test and evaluation of the breadboard system, which will be discussed in more detail in later sections of this thesis.

The second breadboard electronics model was intended to serve as a complete COTS SAS functional system, on to which the optics design and fabrication could be based. For this system, key electronics components from the first model would have been integrated semi-permanently with a prototype microbolometer sensor board provided by IMEC²². The integrated system would be engineered so as to conform as much as possible to the proposed COTS SAS mass and volume specifications, with some issues related to satisfying the required power and thermal specifications also being addressed at this time.

²² Formerly Xenics, and the primary contractor for the poly-SiGe microbolometer used in the COTS SAS system

The IMEC-supplied microbolometer detector array prototype board was to possess the capability of being operated as a stand-alone unit, providing all the necessary electrical requirements to operate the MBO array in an imaging capacity, and recover the captured image to an external computer. While it was not believed that the IMEC board, operating as a stand-alone unit, would have the performance necessary to fully comply with the COTS SAS requirements, it was intended to use the stand-alone results from the board to confirm the results obtained from the MBO array using the first COTS SAS breadboard system.

After some preliminary functional testing and characterization of the IMEC board, the additional components from the first COTS SAS electronics prototype (primarily the previously characterized ADC module) would be integrated into the system, bypassing the components on the IMEC board that performed similar functions, in an effort to enhance the performance of the resulting system so as to be fully compliant with the COTS SAS requirements.

Appendix A has a schematic diagrams of all electronic circuits tested during the SNR evaluation. Each of these configurations will now be described in the subsequent sections of this thesis, along with their functions and expected performance when evaluated at the quoted level of integration into the COTS SAS system.

4.6 Top Level System

The overall configuration of the COTS-SAS breadboard electronics is provided in Figure 4.6-1. Most of the characterization and testing for the electronics was performed at this level, with the microbolometer array in a “black-out” condition, where the array was completely enshrouded in an opaque enclosure. As mentioned earlier, standardized electrical interfaces were used whenever possible to simplify the design and reduce initial development costs, with all necessary power and signal sources being provided externally.

Some testing was to have utilized a modulated infrared (IR) light LED source to provide a means of optically stimulating the microbolometer array, in an effort to gauge the proper timing and control signals required to properly scan and process the microbolometer output signals. The IR LED modulation, while not equivalent to the signals produced by the array exposed to only long wave infrared, would provide a signal that could stimulate the remainder of the electronics in a manner that would make it

possible for further evaluation of certain system performance characteristics, such as the sensitivity of the analog to digital converter, and the dynamic range of the system.

Of the two engineering test samples obtained, the second²³ microbolometer was used for the actual system characterization and testing, as the first sample employed was effectively damaged during the initial fabrication and testing of the electronics system. Differences in the actual performance of the two samples required that some software modifications be made to the breadboard system before testing could actually begin. Most notable of the observed differences between the two samples, was a markedly different response to stray light, indicating that a slightly different digital timing sequence was necessary for what was thought²⁴ to be proper device operation.

Figure 4.6-1: COTS SAS Top-Level Schematic Overview

4.7 XenICs / IMEC Poly-SiGe Linear Microbolometer Array

In late May of 2003, XenICs (now IMEC) delivered, as the first of its contractual obligations, a pair of chip-on-carrier uncooled²⁵ poly-Silicon-Germanium (poly-SiGe) microbolometer (MBO) 200-pixel element linear array detector elements [28]. These devices were delivered directly to Waves in Space where they were then integrated²⁶ with the COTS SAS breadboard electronics components that were under development at this facility.

²³ The microbolometers were arbitrarily numbered for test purposes and treated as being identical, although small differences in their actual configuration were noted

²⁴ It remains unclear at this point as to whether the timing sequences were in fact correct for proper device operation. The device manufacturer was not able to render much assistance in this regard, due to the fact that the two devices were engineering test samples, and not fully characterized as a result

²⁵ "Uncooled" currently means "no active thermal regulation at all", i.e. no TEC present

²⁶ Under contract from Spectral

Consisting of thermally isolated microbridges²⁷, the poly-SiGe detector elements are surface micromachined directly into a CMOS circuit substrate, allowing the detector elements to operate in an essentially thermally invariant state, which allows the MBO array to function for extended periods of time with only passive thermal regulation. The linear MBO array selected for the COTS SAS system consists of a 200 pixel element detector with dual interleaved on-chip multiplexer²⁸ capacity, and is optimized for Long-Wave Infrared detection, with an optical wavelength of 8.0 μ m to 12.0 μ m. The average reference pixel resistance, and NETD values for this detector were quoted as 100 k Ω and 100 mK respectively.

These devices were not originally intended for use in a space environment, and an agreement was reached with IMEC such that early device samples would be available to the COTS SAS program, in return for the effective space-qualification testing that would be conducted through the course of the COTS SAS program.

Due to supply and manufacturing problems, IMEC was only able to supply the two engineering test samples in time to meet the COTS SAS test and verification schedule. As mentioned earlier, these devices were delivered mounted in a chip-on-carrier configuration, with little in the way of supporting documentation regarding proper device operating requirements or conditions. A basic MBO test module was constructed in an effort to integrate the detector into the electronic signal chain, to facilitate the development of a proper timing and sequencing procedure for efficient scanning of the array.

With regards to the evaluation conducted on the MBO as a discrete circuit element, the device was probed to assess bias voltages present on the constant current source pins, and the detector bias voltage required for adequate device sensitivity. This data was then used to tune the supporting electronics so as to obtain what was believed to be optimum device performance. All digital timing signals applied to the MBO were read using a digital oscilloscope to document variations in detector sensitivity and response to relative timing and signal levels applied to the device. The goal of this testing was to ascertain if the MBO and the analog to digital converter could be driven from the same master clock source when the electronics were integrated into a functional ACS sensor unit.

²⁷ Essentially a vacuum gap between the detector element and its supporting substrate

²⁸ 100 pixel elements per MUX

Please refer to Figure 4.7-1 for a photograph of the microbolometer detector array chip itself, and its subsequent integration into the customized detector electronics module. The dark cover seen in the second photo enshrouded the detector during testing, and protected the array from physical damage while the module lid was removed for modifications or direct probing. A more detailed schematic representation of the microbolometer electronics board can be seen in Appendix A, Figure A-1 at the end of this report.

Figure 4.7-1: Poly-SiGe Microbolometer (mounted on ceramic chip carrier) and MBO Electronics Module. A Canadian \$2 coin shown for scale in the photo on the left.

The key MBO performance requirements were defined as follows:

- On-chip gain and offset adjustment – Allows the MBO array elements to be periodically recalibrated on-orbit to compensate for the effects of aging, radiation damage, and prolonged shifts in the satellite thermal environment.
- Bad pixel compensation – In the event of pixel damage or failure, the MBO must be capable of dynamically bypassing bad pixels when performing an array scan.
- Temperature compensation – The MBO must behave in a predictable fashion when subjected to short-term temperature shifts, hence performance shifts, due to temperature, can be compensated for in the image processing subroutine.
- High radiation tolerance – MBO characteristics should not shift appreciably when subjected to a cumulative radiation exposure representative of the levels expected during the satellite operational lifetime. These radiation levels are a function of

satellite orbit / inclination, solar cycle, and the position of the sensor on the exterior of the satellite bus (relative amount of radiation shielding).

- Favorable manufacturing properties – In keeping with the COTS nature of the project, the MBO arrays must be of a design that facilitates a high manufacturing yield for a low-cost, low power consumption, device. This is by far the most difficult (and most subjective) device criteria, but none the less is essential for the overall success of the COTS SAS system.

4.8 Texas Instruments Analog to Digital Converter (TI ADC) Module

From the outset of the COTS SAS program, it was recognized that the performance of the COTS SAS system would be governed, to a large extent, by the performance characteristics of the Analog-to-Digital Converter (ADC) employed. For this reason, several potential ADC designs were evaluated, with the two most promising designs being selected for eventual integration into the COTS SAS system.

The primary ADC module selected for the first breadboard electronics model was a 16-bit Texas Instruments ADS 8344 ADC evaluation board. Accordingly, the breadboard electronics were customized to suite the operation of this evaluation board. In the event that this evaluation board either failed, or performed unsatisfactorily, extensive modifications to the breadboard electronics would have been needed in order to integrate the secondary / backup ADC board in its place. Despite the additional work that would have been required if such a replacement had been necessary, the performance of the ADC, and how it impacted the overall system performance, was of sufficiently high importance to demanded that a redundant component be maintained at this stage of the COTS SAS test program.

When suitably integrated with the rest of the breadboard electronics, the ADC module is required to provide a high resolution measurement of the microbolometer output at a high sampling frequency (which is currently hardware configurable).

In the COTS SAS breadboard electronics, the ADC is configured to accept the analog output signal from the microbolometer (via a dedicated transmission line, with appropriate signal amplification and filtering as required) and then digitizes this output to a 16-bit code word, which is then (currently) captured by a desktop computer digital acquisition interface (DAQ) for post-processing of the detected signal. In the final COTS

SAS configuration, the test computer would be replaced by a CPLD / FPGA unit, which would then perform the necessary signal processing and attitude determination calculations.

During the early stages of the assembly and testing of the breadboard electronics, the important ADC performance metrics were first characterized at the component level to provide a baseline for later evaluating the performance of the integrated system.

Performance parameters of particular interest / importance were the DC power consumption, input signal frequency range, and Signal-to-Noise Ratio (SNR) / Dynamic Range (DR), as these were the properties that were to be monitored during, and after, system integration. Measurement of these parameters was later repeated under adverse electromagnetic conditions during the EMI test phase of the program (to be discussed later) as the primary means of gauging possible system performance degradation under adverse operating conditions.

The signal noise floor was assessed using a DC input signal and a synchronous sine wave input. Further testing included all analog circuitry beyond the microbolometer to assess all noise floor effects on the overall system performance.

See Figure 4.8-1 for a photo of the TI ADC before being integrated into the COTS SAS test enclosure. As noted earlier, this was the only component which was integrated essentially as delivered from the manufacturer.

Figure 4.8-1: Texas Instruments ADS 8344 Analog to Digital Converter Board

4.9 Differential Analog Driver

Custom built, using a standardized IEEE IC amplifier template, the differential driver accepted a single-ended output signal from the microbolometer, representing the

thermal response of the MBO pixel elements to optical stimulus, and converted this signal into a relatively strong differential impulse for passage through a differential transmission line, of 1 meter design length, into a differential filter and receiver amplifier housed in the centralized COTS SAS electronics control module. See photo in Figure 4.9-1 and the schematic representation in Appendix A, Figure A-2, for views of the differential drive circuit constructed. Notice the addition of a microhenry inductor for signal filtration and impedance matching purposes.

The important characteristics of the driver are:

- Gain from input to either balance output line
- Output load sensitivity (to 500 ohm in parallel with 100 pf load)
- Signal to noise ratio
- Power consumption

Figure 4.9-1: Differential Driver Electronics

4.10 Differential Receiver

Similar in design and function to the differential driver discussed in the previous section, the differential receiver was also custom fabricated, using COTS IEEE IC components, to provide the necessary filtering and differential amplification of the signal received over the 1 m transmission line, converting the received signal to either a single-ended or differential form (as required by the specific ADC configuration), which is then suitable for driving the selected analog-to-digital converter.

Seen below in Figure 4.10-1 are photographs of the receiver module both before and after integration into the aluminum test enclosure. Notice the transmission line interface on the left side of the second photo, and the proximity of the receiver to the ADC board housed in the same enclosure. This enclosure represents the centralized electronics

control module that will be expanded in future COTS SAS iterations to include the control and signal processing electronics as well. In this future configuration, a CPLD / FPGA control board will replace the discrete electronics boards currently employed in this module. For reference, a schematic representation of the receiver circuit is provided in Appendix A, Figure A-3.

The important characteristics of this block are:

- Gain from either differential input to single-ended output
- Signal to noise ratio
- Power consumption

Figure 4.10-1 Differential Receiver Board and Integration into the Electronics Control Module.

5.0 OVERVIEW OF COTS SAS BREADBOARD ELECTRONICS PROTOTYPE TEST AND VERRIFICATON

5.1 Microbolometer Electronics System

The microbolometer electronics comprises the entire breadboard COTS-SAS electronics signal chain. This includes the microbolometer pixel array, on-chip multiplexers, analog driver / receiver modules, and the ADC. The key characteristics of this system are:

- **Functional Requirements:** The microbolometer electronics must be able to:
 - Be reset to a known starting state.
 - The multiplexer must respond to the designated control clock and be capable of clocking out successive pixel elements of the microbolometer array.
 - The ADC must be configured to respond to correct timing signals and produce the appropriate digitally sampled output.
 - The ADC must be integrated into the signal chain, such that it is capable of sampling the MBO signal at the end of the analog signal transmission chain.
- **Performance Requirements:** The microbolometer electronics must:
 - Respond to baseline timing values waveforms.
 - Achieve a signal-to-noise ratio (SNR) of a complete scan of microbolometer elements of greater than -56.2 dB. This is accomplished through the evaluation of an average of the root-mean-squared signal amplitude variation from at least 10 sequential scans of the microbolometer array in a dark pixel configuration (no incident light is allowed to impinge upon the microbolometer array).
 - The current consumption of each of the positive and negative rails supplied to the integrated MBO electronics must remain within +/- 5 % of the baseline current consumption (measured prior to radiation exposure).

5.2 Impressions of the Hardware:

Although commercially available components were used whenever possible, it was discovered that most of the electrical hardware for the COTS SAS prototype had to be

custom designed and fabricated, with the exception of the ADC module, which was used in its manufacturer provided configuration.

Without question, the hardest element to design and fabricate was the MBO electronics board, which had to be built from scratch to specifications that were defined while assembly was in progress. Essentially, the MBO was reverse engineered to determine its electrical requirements, which provided some excellent insight into the actual device properties and performance limitations. At several points it became clear that not even the manufacturer had a complete understanding of the functional requirements of the MBO array elements, and several discrepancies were found between the published device specifications, and the actual electrical requirements necessary for even minimal device operation.

It was at this point that the lack of a secondary (redundant) source of MBO detector technology became the most apparent. Clearly, future iterations of the COTS SAS system will have to be based on a much more mature MBO sensor technology in order to circumvent many of the difficulties encountered to this point in the COTS SAS development program.

Other aspects of the COTS SAS electrical development proved to be more promising, as it was confirmed that the ADC technology selected provided a level of performance that actually exceeded the needs of the COTS SAS in several respects.

Further, the performance of the custom fabricated amplification and signal processing components proved to be more than sufficient to meet the required COTS SAS preliminary specifications, indicating that commercial production of these designs could potentially be accomplished within the projected cost and time envelopes envisioned for the flight-certified hardware.

With the initial hardware selection accomplished, and the electronic components integrated into the COTS SAS breadboard design, testing began on the electronics in May of 2003. This testing will be the primary focus of the following section, although some comments on the initial testing and evaluation of the poly-SiGe microbolometers, carried out a year earlier, have been included for completeness.

5.3 The COTS SAS Electronics Test Apparatus

With the initial hardware selection accomplished, and the electronic components integrated into the COTS SAS breadboard design, testing began on the electronics in May of 2003. This testing will be the primary focus of the following sections, although some comments on the initial testing and evaluation of the poly-SiGe microbolometers, carried out a year earlier, have been included for completeness.

The details relating to the primary subcomponents of the electronics breadboard model have been discussed to some extent in previous sections. Now, with the hardware selected and integrated into a functional model of the COTS SAS system, the electronics radiation test apparatus can be treated as consisting of the following principle elements [15]:

- Microbolometer / analog differential driver board housing
- Analog receiver, analog-to-digital converter board, and housing
- Analog data interface cable
- IBM compatible personal computer running Microsoft Windows NT 4.0 or 2000, equipped with an NI DAQ PCI-DIO-32HS high speed digital I/O (DAQ) card
- National Instruments SCB-68 Interface box to facilitate interface between DAQ and COTS SAS electronics configuration
- National Instruments LabView™ Software (v.6.0 or later)
- Self-contained 3 rail (+/- 12 V, + 5 V) analog power supply
- Digital power supply (+5V)
- Power interface harnesses

For a qualitative check of the raw microbolometer output, basically an informal measure of the MBO health (uninfluenced by the rest of the system components), a test port was provided to allow monitoring of the MBO via an analog oscilloscope.

In the course of testing and refining the test configuration, some additional test equipment was occasionally employed to periodically monitor individual component characteristics, in order to ensure that the system remained within acceptable performance tolerances during the radiation test schedule.

Specifically, test equipment used included:

- 1 - HP 2222A analog 2 channel oscilloscope
- 1 - HP 3336B 20 MHz synthesized signal generator
- 1 - BK 3-rail variable DC power supply
- 1 - Lambda 2-rail fixed output (+/- 12 V) DC power supplies
- 1 - Analog Devices 950 single rail fixed output (+5 V) DC power supply
- A Windows compatible PC for off-line data analysis, differing from the test computer by being more powerful, and equipped with improved analysis software.

5.4 A Note on COTS SAS Signal Processing

As the primary focus of the early work on COTS SAS test program centered around the construction of an electrical model whose performance properties could be considered representative of the future flight-qualified hardware, the signal processing techniques developed and utilized during the early test program were of key importance. Thus, it is prudent to examine them in more detail.

Building on the theoretical foundations established for the original Spectral SAS program, the COTS SAS concept has been designed around the use of area arrays, where in a single line of microbolometer detector elements is treated as a “single pixel”. Accordingly, the signals from the individual array elements are added together to achieve the required pixel aspect ratio for optimum signal-to-noise ratio (SNR) performance [5].

By employing the microbolometer arrays in this fashion, the net pixel aspect ratio can take advantage of the essentially one dimensional nature of the horizon image imposed upon each optical subassembly. Further, defective pixel elements in each linear array can be bypassed without appreciably impacting the overall image resolution. This feature, when combined with the on-chip calibration capabilities of the microbolometer, allow the COTS SAS optical assembly to be re-calibrated periodically on-orbit to compensate for degraded performance due to aging or impact / radiation damage [5].

The signal processing scheme for COTS SAS, in its high accuracy attitude determination mode, is primarily based on the assumption that prior knowledge of the location and shape of the horizon arc will be available, and can then be used to enhance the SNR of the horizon-point determination.

In cases where more than one view of the horizon arc is available (up to six simultaneous views are envisioned), the redundant attitude information is used in a least-squares fit to determine the pitch and roll angles of the satellite.

Given the high imaging array scan rate, slow optics, and passive thermal control conditions, the expected SNR obtained from the microbolometer will be well below unity. Thus, it will be necessary to employ extensive averaging of the scanned array images in order to augment the effective SNR value to a useful level. Clearly, this averaging will impact the accuracy of the attitude determination capabilities of the sensor. However, as mentioned earlier, in the COTS SAS approach, multiple (linear) microbolometer elements are treated as a “single” pixel element, which in effect raises the effective SNR of each COTS SAS “pixel”.

This approach, when combined with temporal and spatial averaging of the individual pixel elements can be used to further increase the effective SNR of the detector array. It is expected that when the ambient system noise is uncorrelated (as is typically assumed), the SNR will increase in proportion to the square root of the number of elements averaged in the imaging process.

In the interests of reducing the COTS SAS power consumption, temporal averaging is implemented in hardware [5], leaving only the spatial and template matching of the horizon arc profile to be performed in software. Preliminary concepts for the temporal averaging hardware call for the use of a simple electronic adder circuit and a modest RAM buffer used in a feedback configuration to compare successive horizon arc images over a software-configurable averaging period, the duration of which will be determined from experiment with later versions of the COTS SAS prototype.

5.5 Evaluation of Signal-to-Noise Ratio (SNR) [9]

During the evaluation and testing of the COTS SAS system, there were many performance parameters of interest which were recorded, but only two of which were deemed necessary to demonstrate the feasibility of the COTS-SAS concept, these being the final signal-to-noise ratio response obtained from the microbolometer array, and the total DC power consumption of the integrated electronics.

The final power consumption measurements were never fully quantified, due to the delay in the construction of the second breadboard electronics prototype, caused by

manufacturing issues with the prototype microbolometer test board that was to be provided by IMEC. This left the SNR as the sole parameter by which to gauge the performance of the COTS SAS electronics prototype.

5.5.1 How is the SNR Requirement Derived? [9]

Based on work conducted for the original SAS program [21], the (optical) SNR performance requirement, allowing some margin for signal losses due to dead or degraded MBO pixel elements, was determined to be a signal ratio of at least 10:1 (20 dB) in order to ensure the proper detection of the Earth / space transition.

The microbolometer response can be calculated based on the predicted radiance of the Earth in the $8\mu\text{m}$ – $14\mu\text{m}$ LWIR band, which is the manufacturer-specified optical window for the MBO detector, combined with the focal number of the collecting optics, the exposed detector array area, and the appropriate values for the coefficient of resistance and thermal conductivity of the MBO pixel element poly-SiGe material. For a detailed example calculation, the reader is strongly urged to refer to reference [21].

Lacking the necessary MBO chemistry details, it was not possible to calculate the true response characteristics for the IMEC microbolometer array. Thus, at the suggestion of COTS SAS team members at Spectral Applied Research, reference was made to the work performed during the original SAS program on a more complex VO_2 / Si_3N_4 -based microbolometer design [21] in which it was determined that the calculated change in bolometer resistance due to the Earth's horizon is 0.2%. This value was further refined to a value of 0.1% in an attempt to ensure a sufficient margin of performance in the design of the COTS SAS system.

Based on this inferred MBO responsivity characteristic, and the stated (optical) SNR performance requirement of a 10:1 optical signal ratio, it was quickly determined that in order provide sufficient electronic gain and sensitivity to measure the transition of the horizon arc image across the detector array to this level of precision, the necessary SNR requirement for the electronics would have to be precise (repeatable) to within a 0.01% change in MBO pixel resistance.

5.5.2 Derivation of the Equivalent Signal-to-Noise Ratio Required to Detect a Thermal Transition with a Minimum 10:1 Optical Power SNR

As described earlier, the readout circuit employed by the microbolometer utilizes a Wheatstone bridge voltage divider configuration to determine variations in the active pixel resistance of the MBO.

The IMEC MBO utilized for COTS SAS utilizes a buffered CTIA amplifier configuration to provide a maximum analog output signal of 4.5V. This output value, combined with a manufacturer-specified pixel response correlation that indicates that a 0.01% change in microbolometer resistance will result in a 7mV change measured at the analog output of the detector array.

Thus, the required SNR requirement for the MBO readout electronics is:

$$\text{SNR (MBO output)} = 4.5/0.007 = 643 = 56.2\text{dB}$$

Thus, it was established that the integrated COTS SAS electronics signal chain must have a minimum SNR performance level of -56.2 dBfs at the input to the ADC board. Any improvement of the system SNR beyond this level will only serve to increase the overall measurement margin / sensitivity.

5.5.3 Calculation of Performance Margin or Deficit

Applying the conservative gain assumption given above, where a 10-fold increase in the microbolometer potential difference at the ADC input corresponds to approximately a 20 dB gain in power, then the available measurement margin for the detection of the Earth-space transition region during a single detector array scan can be defined as:

$$\text{Available margin} = \text{Existing signal chain SNR (dB)} - 56.2 \text{ (dB) of potential degradation}$$

Given the nature of the COTS components being used in the system, there exists the distinct possibility that, after the individual electronics components are first integrated together, the initial gain present in the signal chain between the MBO output and the ADC input, may not be acceptably close to the ideal value necessary to achieve optimal system

performance. In such an event, the relative detection threshold must be adjusted higher or lower in an effort to compensate.

Once again working with the performance values stated within the manufacturer-provided microbolometer specifications, the microbolometer output voltage under normal operational conditions, was expected to fall within the range of 0.5 - 4.5 VDC.

Since the COTS SAS differential amplifier electronics are to be custom-designed and built²⁹ there existed the opportunity to tailor the gain properties of these components during their fabrication. The ideal situation would be for the overall gain present in the signal chain between the MBO and ADC to be such that it would be possible to translate the potential difference at the MBO output into a measurable voltage response at the ADC input which corresponded to approximately 1/2 of the full scale ADC operational envelope.

The TI ADC selected at this point in the program, has a specified full scale range of 0 to 3.78 V (approximated as 4 V). For the stated microbolometer operating range above, it becomes evident that if the signal gain to the ADC input is 1/2 then no correction to the signal chain is required:

$$(\text{MBO output voltage}) \times (\text{Signal gain through signal chain}) = \text{Voltage at ADC input}$$

$$(4.5 - 0.5)\text{V} \times (1/2) = 2 \text{ V}$$

Thus a 4V potential difference at the MBO output becomes 2V at the ADC input.

Using this performance criteria, it was established that after the COTS components were first integrated, the initial signal gain between the MBO and the ADC would have to be measured. If this gain value is found to be higher than 1/2 (= -3dB), then the required SNR of the overall system should be dropped by the amount of the excess gain. The converse would be true for the case where the gain is too low (less than -3 dB), and the SNR requirements for the system would have to be increased in order to compensate for incorrect noise levels due to the deficiency in gain.

²⁹ Using only non-Class-S COTS electronic components

The underlying assumption present in the previous statement, is that the ADC noise floor is negligible, which was verified during the selection and characterization of the TI ADC, where independent measurements indicated that the noise floor is below - 80 dBfs at the sampling frequencies most likely to be used in the COTS SAS application.

5.5.4 SNR Performance of the Microbolometer Array

The SNR performance characteristics of the microbolometer array itself are best determined by measuring the end-to-end SNR response of the COTS SAS electronics. This measurement will include, by definition, all noise sources in the signal chain, from the microbolometer detector output, to the output of the ADC, and will include such factors as thermal noise, signal distortion, and ADC quantization noise.

If a synthetic signal source, of known characteristics, is then substituted for the microbolometer electronics module, the SNR response of the remaining electronics in the signal chain can be characterized as a unit. Simple math then dictates that this value, combined with the original end-to-end SNR response measurement, can be used to determine the SNR response of the microbolometer electronics module, which is as close to the response of the actual MBO array as it possible to measure with any acceptable confidence level in the results.

A measurement of this nature is depicted below in Figure 5.5.4-1 for the microbolometer array connected through all electronics, and clocked at a rate just below its maximum operational frequency of 50 kHz (39.0625 kHz). The array is illuminated with an IR LED light source to provide a quantifiable signal variation. The SNR response derived from this measurement was determined to be 58.4 dB, which provides a performance margin of 2.2 dB (58.4 dB – 56.2 dB).

When the synthetic reference source was substituted for the MBO electronics, the remaining electronics in the signal chain (from the differential amplifier to the ADC output) provided a 72 dB SNR response, indicating that, at the time of the previously performed integrated system SNR measurements, the microbolometer electronics contributed an additional 13.6 dB of noise, which obviously degrades the overall SNR performance of the system. This is certainly not unexpected, since the MBO has always been assumed to be the principle source of noise in the system, due to its extreme sensitivity to thermal variations.

Figure 5.5.4-1: COTS SAS Microbolometer Full System Averaged Signal Response

5.5.5 Evaluating the SNR Performance of the COTS SAS Breadboard Electronics

As discussed in the preceding sections, the final SNR value obtained from the microbolometer array, after removing contributions from dead or degraded pixel elements, and the inherent resistivity profile of the specific MBO array being used, must present a minimum signal ratio of 10:1 in order to meet the current specifications for required system performance. Consequentially, factors which can effect this final SNR value must be monitored if at all possible. For the purposes of the breadboard electronics test phase of the COTS SAS project, the following elements were deemed significant:

- Microbolometer detector array characteristics (including the thermal coefficient of resistivity for the 8 μm –14 μm infrared band)
- The signal chain elements comprising the transmission line
- The precision / repeatability of the analog to digital converter
- Any subsequent signal processing operations performed on the digitized output from the ADC, either in hardware or software, including the post-processing methodology used to analyze the test data captured from the system.

Since the COTS SAS configuration currently requires the use of sensor heads that are remote from the electronics, the possibility of electromagnetic interference on the

microbolometer intensity or other signals must be measured and accounted for. Similarly, effects due to the long-term (taken to mean 2 years here) radiation exposure must also be modeled to determine if any adverse effects on the COTS components can be observed.

As shown, the preliminary characterization and analysis of the test system as constructed, indicated that the SNR requirement for the system to meet a signal to noise ratio ($\text{SNR}_{\text{horizon}}$) of 10:1, with no margin, was 56.2 dB.

5.5.6 A Note on the Selected MBO Sampling Rate Requirements

The nominal timing for the IMEC microbolometer device in applications for which it was originally intended, is a pixel sampling frequency of 33 kHz.

Given that the current COTS SAS operational requirements call for an update rate of only 2 – 10 Hz (corresponding to the envisioned high and low sensitivity operating modes), the scan rate required for the full 200 pixel linear array scan is, nominally, 2 kHz at peak performance. Allowing for some additional factors, such as the possibility that the ADC will have to be shared between multiple MBO arrays to meet the system mass and power specifications, error correction, and thermal effects on the optics, it is prudent to provide some design margin in the final scan rate selected by increasing the required clock frequency to 4 – 10 kHz.

Estimates performed by experts at Waves In Space [9], indicate that if data averaging of the output frames is employed within the COTS SAS data processing algorithm, an increase of 15.9 to 22.9 dB in the signal to noise ratio (SNR) response is possible.

Taking this possibility into account, the expected, averaged, SNR achievable by the system is theoretically between 80 dB and 180 dB, depending on the selected MBO array update rate. However, the actual SNR increase realized by varying the update rate may be limited by spurious signal response and quantization noise (not random in nature). Thus, a more realistic expectation for the level of SNR improvement is a minimum of 10 dB improvement, which would boost the overall optical SNR performance level to approximately 30 dB or more (up from the specified 10:1 requirement = 20 dB).

5.6 EMI Testing of the COTS SAS Electronics Elements

In late May of 2003, with the preliminary breadboard hardware configuration established and characterized, Waves in Space (WIS) began the task of conducting some preliminary Electromagnetic Interference (EMI) testing on the signal processing electronics to assess the potential degradation in system performance due to a variety of potential RF interference sources that might be encountered by a COTS SAS system in a flight environment. Of particular concern was the possibility of noise or interference effects resulting from ground loop noise, inter-module signal leakage, and interference from the communications systems on board the satellite.

This testing was conducted primarily to evaluate the susceptibility of the individual electronic components to EMI – related disturbances, and highlight areas of concern in the current breadboard design that may adversely affect future system simulations. As such, the results obtained from the EMI tests were never intended to be indicative of the expected system level performance in later electrical or physical form factors that will be representative of a flight-qualified COTS SAS system.

For a complete, and much more detailed, synopsis of the EMI testing and hardware characterization, the reader is referred to the COTS SAS Electronics Evaluation Report [9].

5.6.1 Summary Of Tests Performed

The following sections provide a summary of the characterization and EMI testing performed to support COTS-SAS electronics evaluation.

All measurements were performed at WIS lab facilities at ambient environmental conditions (22.0°C – 24.0°C, 1 atmosphere). All reasonable efforts were made to maintain a standardized testing environment for all measurements collected, although it is acknowledged that some variation in performance is to be expected due to small changes made between the module-level, and integrated system tests. These changes were not viewed as being significant to the overall system performance characteristics.

5.6.2 Breadboard Characterization Testing

In preparation for the radiated EMI susceptibility testing, the entire test system had to be characterized in advance to establish a working baseline from which to ascertain the true level of performance degradation due to external radiated sources.

This testing was separated into two phases:

1. Module-level Tests

- The following measurements were made in a discrete configuration at the module level to assist in the data interpretation for higher level tests, and to form a baseline for future measurements to be performed
 - Digital timing signals to microbolometer
 - DC voltages at microbolometer bias lines (while operating)
 - Current consumption by rail for each module under test
 - Gain of the analog driver and receiver stages (at approximately 3 dB cutoff frequencies)
 - SNR response of the analog driver and receiver stages
 - ADC baseline sampling performance (DC input in addition to sine and square wave signals) at 2 clock rates.

Due to the fact that results from these measurements were, in effect, used to establish the baseline performance of the electronics system, no conclusions as such can be drawn from this data alone. It is the intention, at a time which post-dates the time of writing of this thesis, to re-characterize these components to gauge any measurable changes in performance that may have occurred due to radiation, component aging, and repetitive stresses incurred due to repetitive testing of the equipment in the integrated system configuration

2. Integrated System Tests [9]

- With the components now characterized individually, the modules were integrated together to form the prototype COTS SAS electronics model. The following tests were then performed on the system chain, which included the microbolometer array, differential drive electronics, a two meter balanced transmission line, differential receiver electronics, and finally the ADC module itself

- The microbolometer signal was sampled utilizing the ADC under varied illumination conditions:
 - Dark array
 - Nominal integration time (12 cycles) of a 1.25 MHz clock source, as well as at a reduced 4 cycle integration time
 - Illuminated and driven by an IR-LED modulator with a coherent frequency (LED sine wave modulated at 1.5625 kHz)
- The ADC was isolated and characterized with a full scale sine wave at the full MBO clock rate (39 kHz), and at half-rate (~20 kHz) as well, using a hardware clock divider circuit

Following these characterization tests, the EMI radiated susceptibility testing was conducted as follows:

- Dark array with radiated susceptibility (EMI) with all equipment in metal housings with no dedicated EMI shielding precautions taken
 - 450 MHz interfering signal at approximately 30 dBm Equivalent Isotropic Radiated Power (EIRP) at 1 m
 - 900 MHz interfering signal at approximately 25 dBm EIRP at 0.7 - 1 m
 - 2.4 GHz interfering signal at approximately 22 dBm EIRP at 1 m

See Figure 5.6.2-1 for a photo of the configuration of the COTS-SAS microbolometer and integrated electronics ready for EMI testing. Notice the additional foil shielding on the cabling and module housings, the necessity of which will be explained in the following section, indicating that these photos were obtained during the 450 MHz radiated susceptibility test phase.

Figure 5.6.2-1: Radiation Test Fixture During Assembly & EMI Testing
Hardware on the test bench (left) and 450 MHz EMI Radiation Source (right)

5.6.3 Performance Under Radiated Susceptibility Testing³⁰

As summarized above, the integrated COTS-SAS breadboard electronics model was subjected to limited radiated susceptibility (EMI) testing in its final configuration. The stated goal of these tests was to evaluate if the existing level of shielding inherent in the electronics modules was adequate in the expected EMI environment, or if additional shielding will have to be provided in future design iterations.

As stated earlier, three identified link frequencies from 450 MHz to 2.40 GHz were used to test the radiated susceptibility of the end-to-end signal chain, by illuminating the system, while in operation, with radio frequency signals of radiated intensity measuring approximately 30 dBm at standardized 1 meter separation to the equipment and interconnecting transmission line. Both horizontal and vertical linear signal polarizations were evaluated sequentially during these tests. At each of the respective frequencies, the radiated power level of the EMI sources was verified with an HP 437B power meter and HP 8481A power sensor before measurements were performed.

During exposure, the output sampled ADC signal was captured and analyzed to determine if acceptable SNR performance was achieved. Results from these tests demonstrated no susceptibility problems at either the 900 MHz or 2.4 GHz frequency bands, confirming earlier testing performed at the component level during the initial component selection and evaluation phase of the COTS SAS program. Testing at the 450

³⁰ The reader is again referred to reference [9] for full test details

MHz bandwidth did raise some performance issues, discussed in more detail in the following section of this thesis.

Figure 5.6.3-1 displays a baseline measurement of the system performance, as integrated, prior to any illumination by radiated sources, as well as a sample measurement taken during the 900 MHz susceptibility tests. As can be seen, no appreciable degradation in signal response can be observed and the SNR remains essentially fixed at 58 dBfs.

Commenting on this SNR value, it can be noted that the measured baseline SNR response was only 57.6 dB, a few dB lower than quoted from earlier full system characterization measurements.

This additional noise can be attributed to the increased noise coupling in the 9 m space radiation test power harness that was used during these tests. Not only was this cable not shielded, but the +5V analog and +5V digital supplies shared a common power supply at the source end of the cable, resulting in significant coupling of digital noise into analog signal lines.

Taking note of the degraded SNR response, it was decided to proceed with testing without further alterations to the hardware, as this test cable would represent a worst case in terms of power supply wiring. Testing in this configuration also provided some commonality with the high-energy space radiation testing conducted later in the program, using the hardware in the identical configuration to that discussed here.

Figure 5.6.3-1: COTS SAS Microbolometer (system) Response: Without EMI (left), and with exposure to a vertically polarized 900 MHz signal (right)

5.6.4 A Note on the 450 MHz Radiated Susceptibility Test Results

450 MHz susceptibility was not tested during the initial evaluation and selection of the COTS components for the program, and thus was performed during the EMI test phase for the first time. This was done on the hypothesis that COTS SAS could well find applications on small AMSAT relay satellites, or in other similar payloads of opportunity, where “low-end” HAM radio frequency bandwidths are either relayed, or perhaps used for Telemetry Tracking and Command (TTC – “T-Tac”) functions.

To measure susceptibility at this bandwidth, a 444.0 MHz (1W (30 dBm) radiated power) source was used to illuminate the electronics at a measured distance of 1 meter. This is the source shown earlier in Figure 5.3.2-1.

Initial measurements made with a vertical signal polarization, such as the one shown below in Figure 5.4.4-1, indicated that overall SNR performance was roughly identical to the baseline levels, at 57.5 dB. However, horizontal polarization of the signal yielded SNR performance which failed to meet the established specifications when first applied.

Using the same radiated power and distance between the hardware and the radiation source (1 meter), caused oscillation-like artifacts in the captured data, which can be observed in Figure 5.6.4-2 shown below.

Figure 5.6.4-1: COTS SAS Microbolometer Integrated System Response with EMI (450 MHz) Vertical Polarization. Acceptable Performance at SNR of 57.413 dBfs

Figure 5.6.4-2: COTS SAS Microbolometer Integrated System Response with EMI (450 MHz) Horizontal Polarization – Failure at SNR of 23.961 dBfs

After some investigation, it was determined that, in an attempt to rectify this problem, all power harnesses had to be wrapped (shielded) with Aluminum foil. This appeared to reduced susceptibility to some extent (no interference was observed to occur if a 1/10 radiated power level was used), but did not completely solve the problem.

It was noted that the primary culprit here was the 9 meter power cable mentioned earlier, which would not normally be present in the COTS SAS system. However, the test group at WIS was determined to satisfy the test specifications, and in so doing establish the level of EMI shielding required for a decidedly worst-case scenario configuration.

Further efforts to cure the susceptibility problem resulted in the disassembly of some equipment for testing separately to further isolate the principle victim of the interference. Exhaustive testing finally narrowed the problem down to the analog circuits in the ADC analog receiver box, with the likely cause of the problems being the high operational bandwidth (Response to several hundred MHz was noted) of both of the operational amplifiers used in the construction of the differential receiver circuit.

Test results indicated that, even with analog inputs disconnected, it was still possible for oscillations to be caused by the 450 MHz source. In response, a number of additional circuit modifications were made:

- A simple power line filter was added (3 shunt capacitors, 50 pF to ground on each of the three power rails). This filter did not seem to have a measurable effect, but was left in as it still serves to improve the overall circuit design.
- Ferrite beads were added to all power interfaces in the receiver module enclosure, and foil was wrapped around all of the unshielded ribbon cables which provided the ADC output signal to the NI interface box. This appeared to eliminate the susceptibility problem.

Unfortunately, when the analog input signal was then reconnected and the test repeated once more, the problem resurfaced. Ferrite beads were then added at the analog connector interface, and steps were taken to ensure that the analog signal connectors were well grounded, including at the microbolometer interface itself.

These final preventative measures improved the immunity of the system, but success was only possible when a foil shield was also placed around the new external shunt capacitor filter, and around the vicinity of the analog and digital connectors as well, as seen below in Figure 5.6.4-3.

Figure 5.6.4-3: COTS SAS EMI Shielded Breadboard Hardware

Top Row: Foil shielding of the shunt capacitor filter at the differential receiver input

Bottom Row: Receiver amplifier and ADC module with and without (metal lid on case removed to show module contents) additional foil shielding

The final horizontal performance results after resolving the susceptibility problem is depicted below in Figure 5.6.4-4. SNR response is now measured at 60.3 dB, higher than baseline, most likely due to the over all reduction in digital circuit power supply emissions and susceptibility offered by the shunt capacitor and ferrite bead filters.

Figure 5.6.4-4: COTS SAS Microbolometer Integrated System SNR Response With EMI (450 MHz) Horizontal Polarization – After Addition of RF (EMI) Shielding Elements

5.6.5 Conclusions on EMI Testing

When used with the appropriate shielding precautions, the IMEC microbolometer both on its own, and when integrated with the breadboard COTS-SAS hardware can be configured to exceed the COTS SAS SNR requirement of 56.2 dB under conditions which may include radiated susceptibility at 450 MHz, 900MHz, and 2.4 GHz without the requirement for dedicated signal averaging of microbolometer output signal. Which is to say that the “raw” or “real-time” SNR is sufficient in most cases to meet the COTS SAS performance requirements.

The analog circuits, as constructed and tested, contribute to negligible degradation in the overall signal, when compared to the effects noted from direct sampling of the ADC. However, due to the conducted susceptibility issues experienced during testing, the

receiver module must be redesigned in future hardware iterations to reduce bandwidth response to such interference.

The performance characteristics of the TI ADC was significantly poorer than predicted when tested at the desired clock rates intended for use with COTS SAS.

A recorded SNR response of 62 dB did not meet expected SNR of 80 dB when the component was tested in an isolated state from the other hardware. It is thought that the TI ADCs are not capable of operating at the manufacturer-specified 16-bit performance levels at high clock rates. Since the ADC was shown to provide substantially better performance at lower clock rates (5-10 ksamples/sec., compared to the 19 and 39 kHz frequencies employed during testing) the COT SAS system may benefit from the planned microbolometer sample rate of only 2 to 10 kHz when in on-orbit operation. If these lower clock frequencies are officially adopted in future hardware iterations, the SNR performance of the ADC should become less of an issue.

In general, the consensus was that the current breadboard configuration of the COTS SAS hardware was acceptable in terms of EMI performance, which was certainly encouraging given the level of compromises that went into the existing design and testing.

5.6.6 Recommendations Based on EMI Test Results

1. Differential receiver electronics design should be modified to lower the bandwidth sensitivity to external VHF/UHF signals (radiated susceptibility) at lower frequencies.
2. Effect of improved, shielded, power harnesses, and the use of independently regulated 5V digital and analog supplies must be investigated to determine impact on SNR performance. Cost savings made in this area were counter-productive, with the equivalent monetary value of the time and resources being expended on troubleshooting, more than equaling that which would have been involved in an initial capital outlay for shielded interface materials.
3. Results obtained thus far should be compared to IMEC 2-sided engineering PCB model microbolometer devices, when these become available.

5.7 Radiation Testing of the Microbolometer Pixel Elements [14]

Commencing in the summer of 2002, radiation testing of engineering samples of the proposed XenICs Microbolometer elements began at Spectral Applied Research to determine the feasibility of using these extremely low-cost long-wave IR MBO elements in a SAS application.

In addition to determining their radiation susceptibility, these samples were also used to characterize the temperature response of the MBO elements, with the goal of profiling the non-linear response characteristics that could be expected from the MBO elements when operated in an uncooled, essentially thermally unregulated, vacuum environment such as the exterior of a satellite or spacecraft.

XenICs was contracted to deliver six (6) TO-8 12-pin package test samples, each containing a microbolometer array in a pre-bonded configuration. Five out of the thirty existing pixel elements present in each microbolometer array were wire bonded to the pins of the carrier package for test purposes. These pixels were then characterized by XenICs, allowing their resistance values (in air) to be documented prior to shipment to Spectral.

After some initial evaluation and test work had been performed on each of the devices to confirm the XenICs test results, Spectral arranged for exposure of three of these samples to a 2378 Ci Co⁶⁰ gamma radiation source at the DRDC facility in Ottawa.

A cumulative dosage level of 20 kRads(Si)³¹ was experienced by the three samples, with basic characterization measurements on each device performed at 5 kRads(Si) dosage intervals. Each device was subsequently fully re-characterized once the full 20 kRads(Si) exposure had been accumulated.

To measure the possible effects of the radiation on the test samples, two MBO parameters were monitored:

- The pixel element resistance
- The Temperature Coefficient of Resistance (TCR)

³¹ This level is consistent with the exposure level the microbolometers would encounter over a typical two year operational period

TCR performance was determined by measuring the microbolometer pixel resistance as a function of temperature, under vacuum conditions. From this data, it was then possible to determine the activation energy for the pixels, which is related to the TCR.

A Note on the Probable Deformation in Thermal Barrier Coating of Some Test Samples:

During the course of the radiation testing of the microbolometer pixel samples, Spectral was informed by XenICs that some of the microbolometer test samples were not representative of fully qualified commercial devices. It became evident that XenICs had determined that the MBO pixel elements in two of the test samples had become deformed during the application of the thermal barrier coating layer. These deformations subsequently resulted in an order of magnitude increase in the thermal conductivity of the two affected samples. The remaining microbolometer samples, two of which were involved in the radiation testing at the time, were confirmed to be commercially representative devices. The results from the three radiation test sample devices later confirmed these findings from XenICs.

For full details on the test procedures and results obtained, the reader is referred to the reference document *Final Results of Radiation Testing on XenICs Poly-SiGe Microbolometers* [14].

5.7.1 Microbolometer Device Characteristics and Test Procedures

The three microbolometer test samples used for the radiation test program were selected from the six sample devices provided by XenICs, based on their initial characterization test results and their relative physical condition. The general characteristics of the three test samples selected are summarized below in Table 5.7-1. An arbitrary numbering system was employed for documentation purposes, and did not reflect the known performance properties of the devices up to the time when radiation testing commenced [14].

Microbolometer Sample #	Number of Active Pixels Tested	Comments
1	1	Non-representative device with improper thermal coating. Possessed elevated thermal conductivity as a result. Device served as the original calibration device during the development of test procedures and apparatus. Device performance may have been degraded by repetitive handling and testing during these operations.
2	2	Non-representative device with improper thermal coating. Possessed elevated thermal conductivity as a result. Both pixels were physically damaged shortly into the radiation test program.
4	3	Representative device – fully qualified. Pixels tested were distributed evenly throughout the microbolometer array.

Table 5.7-1: Microbolometer Radiation Test Sample Characteristics

5.7.2 Microbolometer Pixel Element Test Apparatus and Procedure

Characterization of the microbolometer samples was accomplished through the mounting of each of the three selected MBO test devices in a separate aluminum sample holder, to which it was possible to affix a small test enclosure. The enclosure was gasketed so as to maintain an airtight seal, and was then evacuated by means of a vacuum pump, with the vacuum level being monitored via a pressure tap and gauge on the vacuum line. As only one test enclosure was fabricated, it was required that the enclosure be removed and transferred between sample holders, with a new vacuum then being established, before testing each sample. The vacuum level was set at the maximum achievable by the mechanical pump (0.15 Torr) for all tests, unless otherwise noted.

The test chamber, cylindrical in design (which has an optical window on the top side), was inverted for all tests described in this report to prevent ambient illumination of the MBO test samples.

The test enclosure itself was then placed under a large opaque cover to prevent air currents from influencing temperature measurements made during each test session, which could last in excess of twenty minutes in duration, depending on the surrounding ambient test conditions.

The test process for measuring variations in microbolometer resistance with temperature was semi-automated via a simple test program created in National Instruments LabWindows CVI, which was used to command a temperature controller (LakeShore 331) via an GPIB (IEEE 488) interface.

The temperature controller regulated the thermal conditions in the microbolometer test enclosure by means of a simple resistive heating element connected to the outside of the enclosure. Temperature measurements were recorded through the controller using a calibrated thermistor element also affixed to the exterior of the test enclosure, but on the opposite side to that of the heating element.

Using this system, measurements of temperature and other device parameters were made at 5°C intervals up to a maximum of 50°C, starting from the ambient room temperature, which was nominally between 25°C and 28°C. The enclosure temperature, while under test, was regulated to an accuracy of 0.1°C at all times, with five sequential temperature measurements being made at each temperature increment. A tolerance limit³² of +/- 0.05°C or less of thermal variation between each of the sequential temperature measurements was applied, in an effort to ensure the thermal stability of the test enclosure before the MBO device parameters at a given temperature point were officially recorded.

Microbolometer resistance and bias voltage measurements, as well as control over the biasing conditions of the microbolometer, were made through a standard DAQ interface card and controller board, combined with a simple DC voltage amplifier circuit.

Microbolometer resistance was then determined by measuring the current through a calibrated load resistance placed in series with the microbolometer pixel element itself. One hundred sequential microbolometer current and bias voltage measurements were made at each temperature point (once thermal stability of the test enclosure had been established), and the corresponding microbolometer resistance values were then calculated. These resistance values were then averaged to provide the final microbolometer resistance value, which was then recorded by the test software.

A schematic diagram of the basic test setup is given below in Figure 5.7.2-1, and the test conditions can be found in Table 5.7.2-1 below, and a photo of the MBO device mounting plates is provided in Figure 5.7.2-2. Note the placement of the

³² Implemented via the GPIB-monitored temperature controller

Thermoluminescent Dosimeters (TLD) used for quantitative measurement of the cumulative radiation dosage during each radiation exposure session. TLDs were placed in close proximity to the MBO arrays to ensure accurate radiation measurements, with two TLDs per microbolometer to ensure even exposure to the Co^{60} source.

Figure 5.7.2-1: Microbolometer Pixel Element Radiation Test Apparatus

Figure 5.7.2-2: Microbolometer Pixel Sample Devices With TLD Monitors In Place

Parameter	Test Condition (or Range)	Uncertainty
Temperature	Ambient Room (~29°C) to +50°C in 5°C increments.	+/- 0.05°C
Bias Voltage	0.1 VDC	+/- 0.05 VDC
Vacuum Level	0.15 Torr	+/- 0.02 Torr

Table 5.7.2-1: Relative Microbolometer Pixel Element Test Conditions

5.7.3 Analysis of the Radiation Test Results

The microbolometers test devices were exposed to a total dosage of 20 kRads(Si), in 5 kRads(Si) increments, over a period of three weeks. After each dosage, the samples were allowed to “relax” for 48 hours before being tested for any change in their performance characteristics.

The results of these tests, characterized by the change in activation energy with progressive radiation exposure, are discussed below, with the two key measurement parameters, the microbolometer pixel resistance, and the TCR behavior of the pixel elements, examined in more detail.

5.7.4 Resistance vs. Dosage [14]

The microbolometers can be thought of as consisting of a series of simple resistive circuit elements, represented by each pixel in the microbolometer array, whose impedance is thermally regulated by the amount of IR radiation incident upon its surface. These resistive elements are arranged in a Wheatstone Bridge (voltage divider) configuration. By applying a known bias current through each pixel, and then measuring the relative voltage drop across the pixel element itself, the resistance of the pixel can be inferred.

The Wheatstone Bridge configuration utilized, consists of two fixed resistance elements (whose value is known to a high degree of precision, and whose resistance remains essentially constant over the entire thermal operating envelope of the sensor), a temperature-compensating reference resistance, and the pixel element itself, whose resistance is of course variable. In this case, the compensating reference resistance is the MBO dark pixel reference, which can be thought of as a pixel element which is always

shaded. This reference varies in resistance as the net MBO device temperature changes, but is not subject to incident IR radiation from external sources.

With the potential difference across the bridge measured, it is a simple matter to determine the corresponding change in pixel resistance using the general Wheatstone bridge equation. This is summarized in Figure 5.7.4-1. It should be noted that, since the MBO device uses a differential amplifier to measure the potential difference across the bridge, only the change in potential difference across the bridge is actually measured.

$$\Delta V = \frac{(R_1 + \Delta R_1)(R_3 + \Delta R_3) - (R_2 + \Delta R_2)(R_4 + \Delta R_4)}{(R_1 + \Delta R_1 + R_2 + \Delta R_2)(R_3 + \Delta R_3 + R_4 + \Delta R_4)} V_{bias} \quad \{1\}$$

$$R_1 = R_2 = \text{a constant (100k}\Omega\text{)}$$

$$\therefore \Delta R_1 = \Delta R_2 = 0$$

R_3 = Dark pixel resistance at a given reference temperature

$$R_3 + \Delta R_3 = R(T) = R_o \exp\left(\frac{E_a}{kT}\right)$$

E_a = Activation energy, k is the Boltzman constant

Values of E_a and R_o are experimentally determined or are manufacturer specified

$$R_4 = \text{MBO pixel resistance} = R(T)$$

ΔR_4 = Induced pixel resistance change due to incident external IR radiation

Making the necessary substitutions, it can be shown that {1} can be simplified to yield :

$$\Delta V \approx \frac{-\Delta R_4}{2[2R_1(R(T)) + \Delta R_4]} V_{bias}$$

As ΔR_4 decreases [becomes (-ve)] with increasing temperature,

$\Delta V \rightarrow V_{bias}$ as MBO temperature increases

Figure 5.7.4-1: Calculation Of Potential Difference Due To Incident IR Radiation

In the case of COTS SAS, the parameter of interest is not so much what the temperature of the imaged source is, but rather the perceived change in temperature (thermal gradient) resulting from the imaging of the limb (horizon arc) of the Earth, as illustrated in Figure 5.7.4-2.

Figure 5.7.4-1: Thermal Gradient Due Earth / Space Horizon Arc on the MBO Array
(Adapted from Thomas [21])

With a proper characterization curve being defined for the pixel elements, the MBO then becomes an IR detector, with the IR radiation intensity incident on its surface reflected in the proportional amount of pixel resistance change induced.

Thus, should exposure to high-energy radiation during operation in space produce a shift in the resistive properties of the poly-SiGe semiconductor, these changes must be evaluated and understood.

A plot of a statistical sample of MBO pixel elements, profiling the measured resistance of each pixel as the radiation dosage accumulated, is shown in Figure 5.7.4-3. Here the results for a temperature test point of 30°C is presented. Analysis of the results demonstrated that nearly identical plots can be obtained at other temperature points as well.

As is evident, the variation in pixel resistance was generally observed to be less than about 2 percent, with the exception of the first data points for microbolometer 1: pixel 10 and microbolometer 4: Pixel 20. These two anomalies are most likely attributable to spurious noise present in the system when the measurements were recorded, and could be eliminated in the future through the use of custom measurement electronics. However, the

conclusion reached from these results is that there was no significant degradation in the resistive properties of the MBO samples tested due to the radiation exposure.

Figure 5.7.4-3: Plot of Resistance vs. Dosage at 30°C for MBO Pixel Elements Tested

5.7.5 Temperature Coefficient of Resistance Determination

At the most basic device physics level, the poly-SiGe microbolometer is just another polycrystalline semiconductor material. As such, electrical conduction in a polycrystalline material of this nature is a thermally activated and driven process.

In general, the electrical resistance of such a material can be related to its operational temperature (expressed in degrees Kelvin (K)) using the following relation:

$$R(T) = R_0 \exp\left(\frac{E_a}{kT}\right)$$

where E_a is the activation energy (in Joules (J)), which represents the minimum energy needed to generate the flow of free charge carriers in the semiconductor, which depends on the doping concentration, grain size, and other compositional parameters of the particular semiconductor material.

The value of k is simply that of the Boltzmann constant ($1.3806624 \times 10^{-23}$ J/K, and R_0 is the resistance of the material (expressed in Ohms (Ω)) at a specified reference temperature, from which the relative temperature differential in the material is measured.

Thus the TCR, which profiles the rate of change of the material resistivity with temperature (in units of 1/K), is given by:

$$\text{TCR} = (1/R)(dR/dT)$$

Substituting in for dR/dT from the definition of $R(T)$ given earlier yields:

$$\text{TCR} = -E_a/kT^2$$

Utilizing the above equation for resistivity $R(T)$, it is possible to demonstrate that:

$$\log R(T) = (E_a/k)(1/T) + \log R_0$$

which states that the activation energy can be obtained from the slope of a plot of $\log R(T)$ vs. $(1/T)$. From E_a , the TCR at a particular temperature can then be calculated using the equation for TCR given above. It should be noted that as large a TCR value as possible is desired for the COTS SAS application, as it can be seen from the relations above that a large TCR equates to significant pixel resistance changes for only small changes in temperature of the source. This is to say that TCR is a direct reflection of the sensitivity of the MBO as an IR detector. Higher sensitivity (imaging resolution) allows for a more accurate determination of the precise location of the Earth horizon arc in the FOV of the sensor module, hence higher accuracy in the resulting determination of the current satellite attitude (and rates of change if applicable).

The determination of the activation energy for one of the sample microbolometers tested is presented below in Figure 5.7.5-1.

Figure 5.7.5-1: Determination of Activation Energy E_a/k

Complete radiation testing was performed on three devices as stated earlier. Post analysis of this test data focused around the task of determining the activation energy (in units of the Boltzmann constant) as a measure of the TCR for each of these samples. The activation energy, and the resultant TCR values, were recalculated for each active pixel on each of the test samples after each 5 kRads(Si) radiation dosage session. If large changes in the resulting TCR were discovered, this would be interpreted as indicating that the radiation exposure had resulted in degradation of the microbolometer samples, and would suggest that the MBO detector array would most likely experience non-trivial levels of performance degradation over a typical LEO satellite mission lifetime on-orbit.

The activation energy for microbolometer test sample 4 pixel 9, is shown below in Figure 5.7.5-2. As can be observed from this plot, the activation energy did not vary appreciably due to the radiation testing. The error bars in the plot delineate two standard deviations, derived from the curve fits, denoted by the linear trend lines also included in the plot.

Each of the pixel elements on each of the microbolometer test samples was analyzed in this fashion and demonstrated similar performance to that of sample 4, pixel 9, leading to the conclusion that, in general, the radiation exposure had no detrimental effects on the MBO samples tested.

There was one notable exception to this conclusion, resulting from one of the pixels sustaining physical damage during testing (the MBO pixels have no shielding or optical window to protect them, hence they are very easily damaged during handling or testing). Testing of this pixel was maintained to gauge the effects of such physical damage to a MBO array. Not unexpectedly, the results from these tests did not conform to the behavior of the remaining, undamaged, pixels. For this reason, the performance of the damaged device was not considered in the conclusions drawn from the radiation experiments.

Figure 5.7.5-2: Activation Energy vs. Radiation Dosage for MBO Sample 4 Pixel 9

5.7.6 Vacuum Testing Considerations

As mentioned earlier, the established test plan required that the microbolometer resistance measurements to be done under vacuum conditions. However, this deviates somewhat from standard practice in industry, where it is customary to make such measurements at atmospheric pressure for purposes of negating some of the factors which can degrade microbolometer performance. This made comparison of the COTS SAS test results with literature and publicly documented records of device performance more

difficult, but since the microbolometer itself was not yet³³ a commercial product, and hence not fully documented, these documentation issues were not considered to be prohibitive to the proposed test plan.

When operated normally under vacuum conditions, it is possible for the microbolometer temperature to differ from that of the test enclosure for two reasons:

1. It may view a scene of a different temperature, hence be exposed to elevated levels of incident IR radiation
2. It experiences self-heating due to the current generated in the semiconductor by the incident IR photons

With a basic understanding of microbolometer operational theory, it can be reasoned that testing under standard atmospheric conditions would minimize or eliminate both of these effects from TCR test results conducted under these conditions.

As indicated earlier in this thesis, it is now the general consensus of the majority of the COTS SAS project group (this author excluded) that the decision to test under vacuum conditions, given the test apparatus available, may have been incorrect.

The first concern raised by the use of vacuum conditions during TCR evaluation testing was that, depending on the bias potential (and as a result bias current) applied to a pixel during testing, there existed the potential for a pixel to experience self-heating effects that could skew the TCR response of the device. An argument was made to the effect that, if the pixels were tested under standard atmospheric conditions, thermal transport, via conduction and convection, would negate these self-heating effects and allow the device to remain in thermal equilibrium while the TCR evaluation is performed.

In the case of the TCR experiments discussed here, the applied bias voltage (0.9V) to the microbolometers was sufficiently low, so as to make the self-heating effects on the pixel element resistivity negligible (less than 2%). This reasoning is based on the fact that the manufacturer prescribed operational bias for the detector array is approximately 4.5V. Thus if the 0.9V bias did in fact generate significant self-heating effects, then the detector

³³ At the time of writing, it is still not a certified product, although it is listed as being commercially available by IMEC

array as a whole, when operated at the 4.5V bias level, should experience self-heating effects so severe, as to render the device completely non-functional.

At this point in this discussion, it is also convenient to address the possibility that the pixel test samples were exposed to an external IR radiation source.

As previously mentioned in section 5.7.2, the description of the test configuration, the test enclosure was placed face down on a table during testing, and then further enshrouded under an opaque shield. Thus, while the scene temperature was different from the housing temperature, it would have presented a constant temperature over the entire FOV of the array (to within a degree or less) throughout the tests, once again providing only negligible effects on the resistivity measurements.

The second concern that was later expressed by members of the COTS SAS project team about the use of vacuum conditions for the TCR evaluation pertained to the fact that, due to small fluctuations in the vacuum level in the test chamber that were occasionally observed during the data collection sequence, it was possible that the slow leakage of air into the test chamber may have been enough to stimulate uneven / irregular convective cooling of the pixel elements to an extent where the resulting TCR response of the microbolometer material may have been impacted.

As the individual responsible for conducting the majority of the TCR testing, this author can not help but note that it was an “unofficial” addendum to the test procedure that the vacuum level in the test chamber was to be “topped-off” occasionally, in between the capture of successive data points, in order to maintain as constant a vacuum level as possible. It should also be noted that if the vacuum level was observed / perceived to decay by more than ~ 0.05 Torr between three successive data points, the test run was aborted and the chamber vacuum seal on the test chamber was manually re-seated before another data collection sequence was initiated.

From a strictly theoretical point of view, the TCR response of a given pixel is an intrinsic property of the semiconductor material itself [27]. Thus, the TCR response should have been measurable, regardless of the presence of a vacuum in the test chamber. While a lack of sufficient vacuum purity would have rendered the pixel elements non-functional optically, and introduced a small amount of **uniform** convective cooling between the MBO

membrane and the detector substrate, the TCR response of the MBO material should not have been appreciably impacted.

However, with this said, some vacuum leakage was no doubt still present, and may have potentially influenced some of the higher temperature measurement data points in two possible ways.

First, depending on the severity of any leakage that was present, if the seal around the optical window was the source of this leakage, the resulting (low velocity) air stream could have impinged directly on the MBO array itself, resulting in some cooling of the pixel sample under test. Such an event, especially at the higher temperature test points, would probably produce very noticeable effects in the measured TCR performance, causing a significant deviation from the linear behavior that was in fact observed in the post-processed test results. Thus, this author has deemed it safe to conclude that no significant performance degradation due to this type of vacuum degradation was observed.

Second, it is possible that the effects of a very slow vacuum leak may have become relevant during test sequences where the temperature controller would occasionally take in excess of 5 minutes to sufficiently stabilize the temperature of the test chamber at a given test point.

These temperature stabilization anomalies were due to the comparatively large currents required to heat the load resistance on the chamber sufficiently to overcome conductive and convective losses to the surrounding atmosphere, and further raise the temperature of the chamber itself. At these higher current levels, the sensitivity of the current regulator in the temperature controller is automatically reduced, which in turn leads to “looping” (the temperature fluctuates between a local maxima and minima around the desired temperature test point) as the temperature controller attempts to stabilize the temperature of the chamber long enough to satisfy the measurement criteria embedded in the test software.

In these cases where unusually long measurement times were encountered, it is conceivable that the leakage of air into the test chamber may have altered the test conditions. However, any changes induced would have been introduced very slowly, over the period of the entire test sequence, and would have again resulted in a deviation from the linear TCR performance that was in fact observed for the test samples.

After consideration of the factors discussed above, it was the general opinion of the COTS SAS development team that future testing or evaluation of microbolometer arrays should be done under atmospheric conditions unless the integrity of the vacuum conditions during testing can either be more closely monitored or, better, be reliably maintained a constant level throughout an entire data collection sequence. This author supports this conclusion, but stands by the validity of the original TCR test results from a vacuum testing standpoint.

On the more general issue of whether or not the TCR properties of these kinds of microbolometers should be evaluated under vacuum conditions to begin with, it is certainly understandable, from the standpoint of the manufacturer, why it would be desirable for self-heating effects to be neglected, as the TCR performance of the device can be improved dramatically if the device is allowed to maintain thermal equilibrium with the surrounding atmosphere. Again, this self-heating effect is principally a direct function of the bias current through a given pixel element, and thus becomes correspondingly less significant at lower device bias levels.

Indeed, it is almost a certainty that the manufacture-provided specifications for the MBO devices tested during this phase of the COTS SAS program were obtained under such test conditions. However, since testing in this configuration renders the MBO array optically unresponsive, which is equivalent to inoperable, the decision to test under atmospheric conditions appears to be one driven by marketing considerations, rather than sound engineering practice.

Given that the MBO devices must, by definition, be operated under vacuum conditions in order to function properly (or even at all for that matter), it is unclear to this author as to why the effects of self-heating should be deliberately circumvented during the evaluation of the device performance. It seems only logical that the test conditions used in the evaluation of device performance should reflect, as closely as possible, the actual environment under which the device will be expected to operate, if representative device performance is to be properly evaluated.

While it is acknowledged that the XenICs MBO arrays were not originally intended for use in applications such as COT SAS, it is again the opinion of this author that all future device characterization testing be conducted under constant vacuum conditions, for

if the MBO device performance under vacuum conditions is appreciably degraded due to effects such as self-heating at bias levels reflective of the expected operating points for COTS SAS, then it would be hard to defend their long-term use in a space environment, where device performance reliability can not be compromised upon.

5.7.7 Author's Notes on Possible Concerns With the TCR Test Criteria:

It is this author's opinion that if any fault is to be found with the TCR test criteria or procedure, it should be the choice to conduct testing with no means of thermally controlling the test conditions such that they remained within the manufacturer specified thermal operating range (15°C to 30°C) for the microbolometer array. As noted at several points in previous sections, testing of the pixel samples often commenced at temperatures of 25°C or greater. Thus this author is left to wonder about the true representative nature of the test results obtained, when only $\approx 1/3$ of the thermal operating range of the microbolometer array was explored.

It is the recommendation of this author that all future testing of this type be conducted under conditions where FULL thermal control over the test samples can be exercised. If proper characterization of these devices is to be accomplished for an application such as COTS SAS, the test conditions MUST reflect the operational conditions the detector array will experience while operating in the environment of space.

This statement is perhaps even more relevant after taking into consideration the decision to forgo any thermal control over the MBO array itself in the final COTS SAS product, leaving the detector array open to the possibility of experiencing thermal operating conditions much more severe than even those proposed during the TCR test program thus far.

In view of the fact that COTS SAS is being marketed as a "user-friendly" and "unusually flexible" satellite attitude determination solution, it is really the end-user (client) that will determine how exactly COTS SAS will be integrated into their satellite, and as a result, will determine the thermal conditions the optical modules (MBO detector arrays) will experience. Prudence dictates that the test conditions must be an order of magnitude more severe than any the sensor can expect to experience in the hands of the customer. Thus far, this has not yet been accomplished, but this is not meant as a criticism of the COTS SAS program at this point, as this author fully acknowledges that the program

still has a great deal left to accomplish before a marketable product can be successfully introduced.

5.7.8 Conclusions on the MBO Pixel Element Radiation Tests:

Based on the test results obtained from the three MBO samples, it was determined that the device performance, in terms of the resistance and TCR response of the poly-SiGe microbolometer devices remains essentially unaffected by a cumulative radiation exposure of 20 kRads(Si). During the test program, there were two device failures of note, primarily caused by mechanical failures due to handling of the samples. There was also an anomalous result for sample 4, pixel 60 after the final radiation result that may be indicative of radiation damage, or possibly an electrostatic discharge-related event.

Based on the results obtained, the XenICs microbolometer arrays were certified for use in the further development of the COTS SAS system, resulting in linear arrays consisting of similar MBO pixel elements being incorporated into the breadboard electronics prototype hardware model. This model underwent a similar series of radiation tests while integrated as a function unit, and the results of these tests are the subject of the next section of this thesis.

5.8 COTS SAS Breadboard Electronics Radiation Testing [15]

With the unavailability of the IMEC PCB microbolometer board, and the resulting indefinite postponement of optical testing, the breadboard radiation testing on the assembled electronics represented the culmination of all the work done during the first phase of the development for the COTS SAS system.

Similar in both duration and procedure to the earlier radiation tests done on the microbolometer pixel element samples, the radiation testing of the breadboard electronics represented the first time a fully operational model of the COT SAS system would be subjected to some of the detrimental effects it would experience while in operation aboard a satellite.

Since nearly all of the COTS parts which comprised the electronics model had never been originally intended for use under conditions even remotely resembling those which the flight-qualified sensor hardware is likely to experience, the goal of these radiation tests was primarily to evaluate the effects of prolonged radiation exposure on the

electronic components comprising the sensor signal chain, as opposed to evaluating the MBO linear array itself.

Further, the reader is reminded that the MBO array used in the construction of the breadboard electronics model was an engineering test sample, whose performance characteristics, and perhaps even operating conditions, were not representative of those of a commercially qualified device. In fact, later in the program, the suspicions of this author were confirmed in that the MBO array must be tested under vacuum conditions, with a proper LW IR filtered optical window, and proactive thermal regulation, in order to achieve representative device performance from the detector.

With this said, the following subsections describe the preparations and work done during the electronics radiation test program. The same electronics configuration was maintained from that used for the EMI susceptibility testing discussed earlier, although some minor changes in the external supporting hardware were made to better facilitate the support of the test assembly during the actual exposure periods within the radiation test chamber.

5.8.1 Electronics Radiation Test Configuration

In May of 2003, XenICs (now IMEC) delivered, as the first of its contractual obligations, a pair of chip-on-carrier (CoC) microbolometer (MBO) sensors, each of which consisted of dual 100 channel multiplexers wire-bonded to 100 of the 200 available pixels of the MBO linear array. These devices were engineering prototypes / production rejects, whose specific device health and performance were not well characterized by the manufacturer. However, for the purposes of the breadboard stage of the COTS SAS project, their performance, based on manufacture provided documentation, was deemed sufficient for use in the preliminary work done on the sensor electronics components. Test specifications, as they pertained to the performance of the electronics, could technically have been met with as few as 10 functional MBO pixel elements, hence the MBO performance was not considered to be critical to the over all success of the test program.

Once obtained by Spectral, the MBO devices were then transferred to Waves in Space (WIS) where they were then integrated with the COTS SAS electronics components that were being developed at this facility.

The essential components of the COTS SAS electronics included the analog-to-digital converter (ADC), of which two versions (from Texas Instruments (TI) and Analog Devices (AD) respectively) were to be evaluated, an analog linear differential driver, analog differential receiver, and a potential candidate logic control device (Xilinx CoolRunner series CPLD/FPGA). All of the principle device elements were mounted on circuit boards or evaluation boards, some of which were then encased within custom-configured aluminum enclosures. All components were configured to permit the application of power (rudimentary DC bias voltages) during irradiation, and reduce the reconfiguration requirements necessary to facilitate pre and post-exposure performance evaluation of the devices.

In their radiation test configuration, the components were mounted in a stacked arrangement, such that all essential elements were fully exposed to the high-energy gamma emissions. Additionally, components not requiring direct radiation exposure were placed towards the outer edge of the radiated test area, and then shielded (if necessary) through the placement of lead bricks placed between the gamma source and the test fixture.

It should be noted that, in the currently chosen distributed electronics configuration used in the COTS SAS program, the radiation requirements for use on board a satellite would be significantly different between components mounted on the exterior of the satellite bus, and those mounted towards the interior of the bus, or behind instruments / satellite structures that are of considerable physical density. The radiation dosage quoted for a typical LEO satellite mission in the satellite interior is approximately 2 kRads(Si) whereas on the exterior it is nominally 20 kRads(Si).

It has been argued by this author that for many of the small satellite / microsatellite missions, which comprise the primary commercial market for COTS SAS, the satellites, instruments, or structures present will be such that, in a first order approximation, the radiation density will be essentially uniform at all points in or on the satellite structure.

At the radiation intensities used for test purposes in these experiments, it was estimated that ten centimeters of solid aluminum or some two-to-three centimeters of solid lead (based on the average "half-value thickness" dimensions for Pb and Al) would be needed to produce any sort of effective radiation shield for components in the test fixture. Since the only difference between the radiation test source and that of a natural cosmic

source is particle density, not energy, it is questionable as to whether the assumption of distinctly different radiation levels between the exterior and interior for such small satellite structures remains valid.

In a flight-qualified COTS SAS hardware configuration, involving multiple optical modules, due to the nature of the XenICs integrated microbolometer / multiplexer design, the multiplexers would currently be required to be located in the optical modules on the satellite exterior (although with some aluminum shielding provided by the SAS optical mounting). Many of the other principle electronics components, such as the ADC and the analog receivers, could be mounted in the interior of the satellite for additional radiation protection, with the notable exception being that of the analog line drivers, which must be co-located within close proximity of the optical modules. The CPLD could be in either location depending on its radiation tolerance and other architectural factors.

Preparation for the radiation testing essentially consisted of the following additional procedures, some of which involved verification of work already performed for the EMI test phase of the COT SAS program:

1. The various test components, modules, and boards were mounted on an aluminum back plate using standoff posts and steel screws, in order to properly situate them within a 6- inch diameter circular area to ensure proper radiation exposure. Once mounted in this configuration, all of the principle components could be transported and tested without disassembly or significant component reconfiguration.
2. For purposes of providing the necessary device DC bias voltages, power was provided via a 9-meter-long unshielded power harness, capable of servicing all the boards from a pair of fixed output DC power supply units located outside the radiation test chamber. All power interfaces were made with standardized DB-9 connectors to simplify the connections for test purposes. An abrasion-resistant sheath was placed around the power cable to prevent wear or degradation during frequent transport and reconfiguration of the test equipment.
3. To facilitate the performance testing on each component before and after each of the radiation dosage increments, test points, timing signals, and inter-module data communication, were provided via suitable analog and digital signal interfaces

between the electronics modules and the test computer. Standard DB-25 connectors were used to insure proper signal interfaces between the primary test elements.

4. Test software capable of end-to-end MBO electronics equipment testing was also developed, to quickly establish system health, as well as provide a measurement of the microbolometer and electronic equipment end-to-end signal to noise ratio.

5.8.2 Test Procedure

Test procedure consists of connecting all components as specified by WIS and executing the supplied LabView data capture software (also supplied by WIS) to record 625 sequential scans of the microbolometer array.

The raw data file captured by the LabView program is then post-processed using a custom-built MatLab data analysis algorithm, to extract the required performance metrics on the microbolometer, most important of which is the mean noise floor or SNR value over the 625 captured scans.

Figures 5.8.2-1 and 5.8.2-2 show the electronics radiation test configuration, and the positioning of the TLD measurement units for calibration of the average radiation dosage levels received by the various electronics modules. The physical module arrangement in the test assembly was dictated by the predicted beamwidth of the gamma radiation source. Key components (MBO, ADC, signal amplifiers) were placed so as to ensure maximum radiation exposure levels. It should be noted that the TLDs shown in Figure 5.8.2-2 were utilized only twice during the radiation test regime, at the 0 kRads(Si) and 20 kRads(Si) points to establish a baseline for the gamma source, and to ensure that dosage levels received by the electronics were what was being predicted / assumed by theory. The use of the TLDs was minimized in an attempt, to reduce the possibility of damage or alteration to the electronics and their performance characteristics.

Figure 5.8.2-1: Microbolometer Electronics Radiation Test Apparatus

Figure 5.8.2-2: Radiation Test Assembly Just Before Exposure

(Adhesive markings indicate placement of calcium fluoride thermoluminescent dosimeters)

5.8.3 ANALYSIS OF TEST RESULTS

Radiation testing of the COTS SAS electronics breadboard prototype proceeded smoothly between September 9th, and September 19, 2003, with exposure to the radiation source occurring at two day intervals on average.

Due to the decision to reposition the test fixture in the radiation beam to achieve a more uniform exposure level for all of the electronics components, it was necessary to lengthen the exposure times to approximately seven hours in order to achieve the desired 5 kRads(Si) cumulative dosage level. The post-exposure electronics performance testing then occurred approximately six hours after each exposure session ended.

Detailed in the following sections is a summary of the test results obtained over the entire 20 kRads(Si) cumulative exposure period.

5.8.4 Secondary Test Objectives: Analog Devices (AD) ADC & Xilinx CPLD / FPGA

These devices, mounted on far sides of the back plate of the radiation test fixture, received the lowest radiation exposure³⁴, due to the proximity of the MBO electronics components placed between them and the radiation source. This was deemed to be acceptable, since the AD ADC was intended to be a redundant alternative to the TI ADC, and since many models of the Xilinx FPGAs and CPLDs have been qualified for space applications before. As such, their actual performance was to be gauged on a qualitative basis only for future reference in the further development of the COTS SAS electronics design.

5.8.4.1 The Analog Devices Analog to Digital Conversion Board

It has been well established by this point that in COTS SAS system, the ADC employed must be capable of discerning the small changes in microbolometer pixel element resistance, characterized by a small AC ripple superimposed upon a large DC pedestal value, which together constitute the microbolometer output signal. Consequentially, the signal-to-noise ratio and/or the ADC linearity are critical to the overall performance of the COTS SAS system.

Given the critical role that ADC performance represents in the COTS SAS system, it was deemed prudent, given the design goals for the COTS SAS electronics subsystems, that two candidate ADCs should be evaluated during the test program in order to provide a degree of redundancy in the overall program timeline.

Based on its performance during the early design and characterization phases of the COTS SAS electronics design, the Texas Instruments ADC was selected to undergo extensive characterization during the radiation test phase of the program, and became one of the core modules around which the electronics design evolved.

³⁴ This shielding is believed to be of minimal impact to the test results, given the intensity of the gamma radiation used

The second device, from Analog Devices, was simply mounted on the radiation test fixture (Figure 5.8.4 – 1) so that any variation in its basic functionality due to exposure to elevated radiation levels could be monitored. To accomplish this, the ADC board was configured to operate using an internal clock, when power (and, optionally, an analog signal) was applied. The digitized output from the ADC was then evaluated using an oscilloscope.

Figure 5.8.4-1: ADC Radiation Test Apparatus

The secondary test criteria for the Analog Devices ADC required that the on-board clock source maintain a consistent and repeatable output at all levels of radiation exposure. The clock generator waveform was monitored from a pair of manufacturer-provided test points on the ADC circuit board, using an analog oscilloscope. At all levels of radiation exposure, no degradation was noted in the ADC performance.

5.8.4.2 The CPLD Prototype Board

In future iterations of the COTS SAS electronics suite, the essential digital control functions, as well as the necessary clocking signals for the individual microbolometer/multiplexers are to be provided by a CPLD/FPGA combination, replacing all the external test hardware that currently provides these functions in the electronics breadboard prototype. The particular device selected for evaluation in this role is the Xilinx “Cool-Runner” series of low power CPLD circuit board.

Owing to the fact that the COTS SAS electronics design was in a constant state of refinement during this early phase of the test program, it was not possible to integrate the CPLD with the rest of the electronics at this time. Never the less, the radiation tolerance of

the CPLD would be a crucial factor in the overall robustness of later COTS SAS designs and had to be evaluated as early as possible in the program.

Thus, for the purposes of the radiation testing, an integrated numerical counter, complete with 2-digit LED display, was utilized to gauge the continued health of the FPGA, with the test criteria requiring that the counter be able to maintain a smooth 100 second count rate. This counter is a manufacturer-provided feature of the proto board, for use as a simple diagnostic tool, and hence was ideally suited for the radiation test requirements.

Over the course of testing, no degradation to the CPLD/FPGA was observed.

Shown below in Figure 5.8.4-2 is a photo of the CPLD/FPGA board mounted on the radiation test frame. The slight distortion in the image of the board is caused by a layer of Kapton film was used as a safeguard against electrical shorting, as well as to protect the prototype layout area from damage during testing. It is in this area that future iterations of the COTS SAS electronics will be constructed. The sequenced LED counter can be seen functioning (inverted) to the upper left of the Kapton cover.

Figure 5.8.4-2: Xilinx CPLD/FPGA Radiation Test Apparatus

The results from the radiation testing of these secondary electronics components have been provided below in Table 5.8.4-1. As can be seen, there were no observable changes in the performance of either of the two components. These results confirmed the expected performance of these devices, and establish them as good candidates for use in the future development of the COTS SAS electronics system, although it should be noted again that if these devices are integrated into the primary system, much of the electrical characterization work previously discussed would have to be redone, or at least verified.

Analog Devices ADC & Xilinx CPLD/FPGA						
Device	Criteria Examined	Baseline	5 kRads (Si)	10 kRads (Si)	15 kRads (Si)	20 kRads (Si)
AD-ADC	Amplitude (mV)	320	320	320	320	320
	Frequency (kHz)	142.857	141.957	142.911	142.865	142.889
FPGA	Counter	Functional	Functional	Functional	Functional	Functional

Table 5.8.4-1: Qualitative Test Results for Analog Devices ADC & Xilinx CPLD/FPGA

5.8.5 Microbolometer Electronics

The performance of the IMEC microbolometer, digital driver, digital receiver, and the Texas Instruments ADC were tested and evaluated as an integrated unit, hence variations in the performance of any one of these components would be reflected in the overall performance of the electronics test article.

As mentioned previously, the microbolometer utilized in the electronics test article was non-representative in both performance and configuration to the MBO element called for in the COTS SAS specifications.

Consequently, the analog output of the MBO was separately monitored from a dedicated test port built into the test fixture for this purpose. This allowed a qualitative measurement of the MBO health at each of the sequential test points during the radiation testing, and allowed for the possibility of determining the impact any potential changes in MBO performance would have on the performance of the COTS SAS electronics as a whole.

5.8.5.1 A Note about the Microbolometer Array

Due to as yet unresolved issues with the functionality and performance of the microbolometer array, coupled with the fact that the array utilized in the radiation test fixture was not representative of a production-grade MBO device, several changes to the radiation test fixture were implemented. The most relevant of these changes was the decision to completely enshroud the MBO array and multiplexers to eliminate the possibility of external light contaminating the test results.

This had proven to be necessary during the developmental testing of the electronics, where it became apparent that the multiplexer elements were highly susceptible to external light contamination, leading to the saturation of the MBO analog

output signal to the digital drive circuit. Lacking the proper IR filter elements for the MBO array itself, it was thus necessary to fabricate a light-tight enclosure for the entire MBO device.

The enshrouding of the MBO array, precluded any ability to stimulate the integrated system with a simulated IR input. Consequentially, this elevated the prominence of the noise floor in the SNRfs determinations. This in turn proved to be detrimental to the ability of this experiment to accurately measure any small-scale performance changes in the integrated MBO electronics resulting from cumulative radiation effects.

Working from second hand information provided by IMEC, it is also believed that the MBO array needed to be thermally regulated (in this case, cooled) to ensure proper response characteristics.

5.8.6 Evaluation of Signal to Noise Ratio Performance

The key performance metric for the purpose of gauging the radiation tolerance of the COTS SAS electronics is the signal-to-noise ratio obtained from a complete scan of the microbolometer elements.

This full signal chain included the microbolometer encased in a metal housing, together with supporting power circuitry (3-terminal voltage regulators), and the analog differential drive circuit.

This was then connected via a 2-meter long shielded twisted pair cable to a second metal housing, containing the analog differential receive electronics which is co-located with the 16-bit TI ADC. Refer back to Figure 4.6-1 of this thesis for a diagram of this configuration.

This configuration was then tested using a National Instruments (NI) PCI-DIO-32HS high speed digital bi-directional I/O card, which provided both digital stimulus (control) signals to the microbolometer, and a means of capturing the serial digital samples from the ADC.

The most important characteristic of the MBO-electronics is the SNR obtained from a complete scan of the microbolometer elements. This was measured relative to the full-scale signal strength (SNR dBfs). These measurements were made at both the full MBO clock rate (40 kHz), as well as at a half-rate setting (20 kHz), which are derived from the same 1.25 MHz master clock source that provides the sampling rate for the TI ADC

module. The clock input to the MBO, and to the system in general, was manually selected prior to the capture of a performance data set. The COTS SAS specification calls for only the 20 kHz setting to be utilized, but both clock modes were tested to better evaluate the performance of the electronics.

For all of the measurements discussed here and in the sections that follow, the SNR is evaluated as the average standard deviation of time domain voltage samples at corresponding sample location (pixels) of the microbolometer. As an example, regardless of the mean value of the voltage registering on pixel 1 (e.g. 2 volts), if the standard deviation is 1 volt (rms), and the full scale voltage was 4 volts (max. rms sine wave is 1.41V), this would equate to an SNR of 3 dB.

In all cases, the raw test data was representative of a series of 625 sequential scans of the MBO array, over which the SNR for the system was determined. Shown below in Table 5.8-2 are the results from the measurement of the Signal-to-Noise Ratio relative to the full-scale signal strength (SNR dBfs).

It can be seen that, within the margins established for these tests, there was no appreciable change in the performance characteristics of the microbolometer electronics at either of the two MBO clock settings.

In all cases, the SNRfs performance of the system fully satisfied the performance specifications outlined for the COTS SAS system.

It should be noted that in some cases, more than three measurement data sets were captured in order to confirm the performance of the electronics. The results from these tests were in almost all cases identical to those observed in the first three tests shown in Table 5.8-2, and have been omitted for brevity.

IMEC Microbolometer Signal-to-Noise Ratio (SNR) in dBfs Timing signal set for Divide by Two			
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Trial	1	2	3
Baseline	-87.9	-90.19	
5kRads (Si)	-87.25	-87.73	
10kRads (Si)	-94.9	-94.43	-88.54
15kRads (Si)	-89.05	-93.15	-87.41
20kRads (Si)	-87.18	-87.19	-87.85

IMEC Microbolometer Signal-to-Noise Ratio (SNR) in dBfs Timing signal set for Divide by One			
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Trial	1	2	3
Baseline	-87.3	-87.73	
5kRad (Si)	-87.87	-91.25	
10kRads (Si)	-87.23	-88.16	-94.76
15kRads (Si)	-87.28	-94	-91.76
20kRads (Si)	-90.88	-87.6	-87.28

Table 5.8-2: SNR Test Results for Microbolometer Electronics

COTS SAS specifications call for SNR performance of ~56.2 dB or better in all cases, and the unofficial test criteria was a degradation margin of no more than 3 dB over the course of 20 kRads(Si) of radiation exposure.

With the MBO pixel elements in a darkened configuration, these criteria were met or exceeded in nearly all cases, with only one example of a detrimental variation in performance of more than 3 dB. When testing in this configuration, the performance level of the system during a given test is, to some degree, a function of fluctuations in the noise floor of the system, as well as small variations in the DC bias conditions in the principle components.

Shown below in Figure 5.8.6-1 are two representative frequency response plots generated during radiation testing. Both represent a FFT averaged response over the 625 scan period, and demonstrate that the noise floor of the MBO remained unchanged by the radiation exposure. Noise spikes can be seen in both plots, which are the result of small experimental variations in test conditions, as well as the small inter-scan reset pulse which occurred at the start of each new scan sequence.

Figure 5.8.6-1: COTS SAS Baseline System Response & 20 kRads(Si) Response

5.8.7 Post-processing of the Test Results

As testing progressed, it became apparent that the SNRfs of the MBO electronics appeared to vary by approximately ± 10 dBfs between sequential measurements made at either of the two MBO clock rate settings.

Further analysis of the raw performance data indicated that the use of an accelerated ADC data in/out timing waveform had the effect of generating sporadic bit errors in the captured data. This timing method chosen based on the belief that the use of the accelerated waveform would increase the noise floor slightly, yielding an overall improvement in system performance.

However, since the TI ADC board is a successive approximation (SAR) ADC, when a new sampling cycle was started, it sometimes had the effect of upsetting the bit(s) that were "in play" at the time. These upset bits, when they occurred, had the effect of generating a transient during the critical sampling interval(s) for a given data capture. The default ADC timing diagram, which incorporates the accelerated timing sequence, is presented in Appendix B.

It should be noted that this point that the use of this timing sequence for data capture did not impact the characteristic response of the system in any way, since the ADC can be validly clocked in this way. However, when used in this mode of operation, the system performance is definitely not up to expectations.

The solution to this issue was to remove the erroneous bit errors during the post processing of the data. It should be reiterated that not all of the data captures displayed the

disruption due to the bit errors, and the corrections were made in an effort to achieve consistency between sequential data captures at a given clock frequency.

In order to maintain the basic integrity of the raw test data, the filter for the erroneous bits was quite rudimentary in nature, and hence, occasionally, could not fully remove the distortion to the SNRfs performance of the system. This results in a residual variation in the system performance between sequential data captures. This variation is evident to some degree in the results presented in Table 5.8-2 of the previous page, where an occasional shift of -3 dBfs between sequential measurements can be observed. When the residual bit errors are taken into account, the run-to-run SNRfs variation is observed to be within 1 sigma of the baseline value, and not statistically very significant to the overall system performance.

5.8.8 An Inter-pixel Glitch in the Analog Microbolometer Output

As mentioned previously, a test port was utilized to allow for the qualitative monitoring of the analog MBO output signal before it entered into the input of the digital drive circuit, making it possible to gauge the performance of the MBO array separately from the rest of the electronics.

During the majority of the radiation test program, monitoring of the MBO analog output had shown little or no deviation in the performance of the device. However, after the final radiation exposure sequence, bringing the cumulative exposure level up to approximately 20 kRads(Si), a distinct change in the output waveform was observed.

From all the evidence that is currently available, it appears that the electrical properties of the MBO array experienced a (permanent) partial shift in its inter-pixel response to background noise and thermal conditions. The shift appears as an inversion of the MBO output waveform, around the mid-point of the 100-pixel array.

Repetitive testing over the course of several days after the last radiation exposure, confirmed that the change in performance was both real and not the result of a transient response due to the temporary accumulation of excess charge carriers in the semiconductor material of the MBO. Given the nature of the change, it is likely that the new analog performance characteristic is a result of radiation damage to the on-chip multiplexer, or an indication of a direct impact of a high energy photon on an array pixel element, resulting in permanent damage to the pixel substrate. Such damage could degrade, but not disable, the

performance of one or more pixels in this area of the array. Referring back to the original SAS operational theory, it can be noted that the plans to treat subgroups of successive pixel elements on the array as comprising a “single pixel” were made to compensate for precisely this type of array degradation.

5.8.9 Conclusions And Recommendations Based On Radiation Test Results

The results of the radiation testing of the COTS SAS integrated electronics test element to a cumulative radiation dosage level of 20 kRads(Si) indicates that there is no appreciable change in system performance due to detrimental radiation effects. In fact, the measured noise floor exceeds the COTS SAS requirement by at least 30 dB. This suggests that there is no reason to perform any additional analog testing pertaining to performance shifts due to radiation effects, and that the use of a 16-bit ADC more than meets the performance requirements for the system.

The COTS SAS electronics hardware continues to function well within specified performance metrics, and confirms the selection of the signal processing electronics elements for further use in the development of the COTS SAS system.

6.0 EVALUATION OF THE COTS SAS PROJECT:

In terms of satisfying the COTS SAS project objectives stated at the beginning of this thesis, the following observations can be made:

- Use a compact optical module
 - Given the current MBO and electronics footprints, it is thought that with some refinement, and a higher quality MBO detector array, the originally envisioned optical module configuration can be adhered to.
- Limit current development to COTS parts as much as possible
 - At several points throughout the project, commercially available hardware proved itself to be up to the task of satisfying the design requirements.
 - A higher degree of device customization proved to be required than was first envisioned. Fortunately, most of this work utilized commercially available sub-components whose performance proved to be adequate to meet the project needs.
 - Both EMI and radiation testing verified that even with non-class-S components, the design lifetime for COTS SAS could be met. With the addition of future vacuum, thermal, and optical environment testing, it is believed that the design assumptions made, with regard to the use of commercial grade parts, are valid.
- Use a commercially available uncooled Poly-SiGe microbolometer array, located at focal point of the optical module, as the heart of the system
 - The decision to negate any ability for thermal regulation of the MBO array may prove to be problematic for device performance. Optical characterization of the MBO will determine if this design choice needs to be revisited.
 - There remains a great deal of uncertainty as to the suitability of the IMEC microbolometer for use in a COTS SAS application. Perhaps as the product matures it will prove to be worthy of additional consideration.
 - For the moment, it can not be stated strongly enough that an ALTERNATE source for microbolometer detector technology must be established to ensure the health of the COTS SAS program.

- Use a wide band infrared range
 - Due to the afore mentioned problems with the MBO detector elements, the optical characteristics of the COTS SAS system were not able to be evaluated to the extent that would allow for meaningful conclusions to be drawn.
- Initially limit target market to LEO microsatellites in nominal circular orbits
 - Given the performance levels of the breadboard prototype electronics model, it is clear that COTS SAS operations should be limited to LEO operational design requirements until such time as the remaining optical and electrical sensitivity issues can be satisfactorily resolved.
 - Further maturation of the COTS SAS design will have to occur before a flight-representative hardware model can be constructed.
- Explore the economic savings associated with the use of COTS technology in satellite / space applications
 - Based on the experimental results obtained thus far in the program, the cost savings realized through the use of COTS components is hard to quantify.
 - COTS electronic components, such as the ADC and differential amplifiers, appear to be viable options for future use in space-related applications. Further testing to verify this preliminary finding is still recommended.
 - In the case of the MBO detector array, problems with product availability, and performance, currently make it premature to pass judgment on the viability of the COTS approach in this area.
 - Should MBO technology, such as that selected for the COTS SAS program, be brought to full maturity, the potential for cost savings is certainly present. However, the additional time and research effort involved in making this possible, may, in the end, negate the true value of the COTS approach.

7.0 CONCLUSIONS AND RECOMMENDATIONS:

At this point in the COTS SAS development program, few definitive conclusions can really be drawn about the system as a whole, as all aspects of the system are still in the formative stages. As outlined in the previous section, many of the original design goals for the system remain to be met, but progress is slowly being made as the necessary resources become available for further hardware evaluation.

The COTS SAS prototype work remains significantly behind schedule, with the critical task of evaluation of the optical performance still to be conducted. However, the preliminary testing and evaluation of the electrical performance of the prototype hardware has produced favorable results which appear to verify the basic feasibility of the COTS SAS concept as a whole.

Electrically, the existing COTS SAS design has proven to be remarkably robust, given the constant state of revision the design currently exists in, as well as the “abuse”, both physical and electrical, the system has been subjected to over the course of the test program thus far. This is certainly promising, as it serves as an indication that positive performance results may well be achieved when future design iterations are subjected to more extensive thermal and vibrational testing.

It is the opinion of this author that if the COTS SAS program had to be evaluated as a whole at this point in the program, the conclusions that would be reached would best be summarized by paraphrasing some of the conclusions from the recently released report of the United States Defense Science Board / Air Force Scientific Advisory Board Joint Task Force on the Acquisition of National Security Space Programs [12]:

Cost has replaced mission success as the primary driver in managing acquisition processes regarding space-related programs, resulting in excessive technical and schedule risk. This trend must be reversed in order to re-establish mission success as the overarching principle for program acquisition. It is difficult to overemphasize the positive impact key members involved in the project planning and acquisition process can achieve by adopting mission success as a core value.

Space-related programs have become strongly biased to produce unrealistically low cost estimates throughout the design and development processes. These estimates lead to unrealistic budgets, unacceptably high component performance expectations, and unexecutable programs. It is advisable that, among other things, that budget allocated for space-related development programs be adjusted to reflect a more realistic cost model based on the requirements necessary to achieve a higher probability of program success, thereby better ensuring a positive return from the initial expenditure.

These last observations are made as general recommendations for future work on the COTS SAS satellite attitude sensor system, and are not meant to be a specific criticism of the management of, or individuals involved with, the COTS SAS program, whose professionalism and the caliber of work is above reproach.

This author suggests that the present failure to satisfy many of the original COTS SAS project objectives is a symptom of current industry trends related to the development of new space hardware, where once again attempts to limit the costs and risks associated with the development and implementation of new space technology has resulted in a proportionally limited degree of program success.

While the space industrial base is adequate to support current programs, long-term concerns still exist. A continuous flow of new programs—cautiously selected—is required to maintain a robust space industry. Without such a flow, critical shortcomings in capability in the payload and sensor areas are an all but certain result. As commercial and industrial space applications continue to evolve, new technologies (such as COTS SAS) must already be in place to allow continued growth in satellite capabilities.

GLOSSARY OF ACRONYMS AND TERMINOLOGY:

For the sake of clarity and consistency, the following terminology will be employed throughout this article, unless noted otherwise:

Attitude: The orientation and dynamic state of a satellite defined with respect to a prescribed coordinate frame of reference.

Attitude Control System (ACS): Dedicated instrumentation required to regulate the orientation of a satellite.

Attitude Determination and Control (ADCS): The determination and regulation of the orientation of the satellite in relationship to the Earth and the Sun.

Commercial-Off-the-Shelf (COTS): Components, or technology in general, which is available for commercial sale or distribution. It is implied that these components constitute stand-alone products and are not extensively customized for specific applications prior to delivery from the manufacturer.

Field of Regard (FOR): The apex angle of the effective viewing cone obtained through the superposition of multiple, independent, fields of view. If the individual fields of view are designed to overlap with adjacent fields around them, the field of regard is said to be “continuous”. Otherwise, the field of regard is thought of as “effective” or “virtual”.

Field of View (FOV): Area a given imaging sensor can observe from a fixed orientation / location on a satellite. Defined by the apex angle of the unobstructed viewing cone of an optical aperture or instrument.

Geosynchronous Earth Orbit (GEO): An equatorial orbit in which the orbital period of a satellite may be reasonably approximated to 24 standard hours, thus giving the illusion that the satellite can essentially “hover” over a fixed point on the surface of the Earth. This

definition may also be extended to Geostationary orbits, which imply a 0° orbital inclination. Average orbital altitude is usually taken to be 42,868 km.

Inclination: The angle between the orbital plane of a satellite and the equatorial plane of the Earth.

Infrared (IR) (light or image): The low-frequency / long-wavelength end of the electromagnetic spectrum, sometimes referred to as “heat waves”. Infrared is defined as emissions between ($1\ \mu\text{m}$ to $1000\ \mu\text{m}$). For most imaging applications, this is then further classified into Medium Wavelength Infrared (MWIR) of $3\ \mu\text{m}$ to $5\ \mu\text{m}$, and Long Wavelength Infrared (LWIR) of $8\ \mu\text{m}$ to $12\ \mu\text{m}$. In these windows, the ratio of atmospheric transmission to absorption of IR energy is maximized, yielding the cleanest signals.

Low Earth Orbit (LEO): A stable orbit between 200 km and 1000 km. Orbital period is always less than the rotational period of the Earth.

Satellite: Defined, for the purposes of this thesis, as an artificial body in orbit about the Earth. This definition will be applied somewhat loosely in order to include manned space vehicles (technically “spacecraft”) in orbit about the Earth

Spacecraft: Any semi-autonomous vehicle primarily designed for operation at altitudes of 100 Km or more above the surface of the Earth. Usually includes all man-rated orbital bodies, or autonomous vehicles operating at inter-planetary distances

REFERENCES AND MATERIALS USED

- [1] Berman, R., Hersom, C., Hornsey, R., Shah, J., *Digital Sun Sensor Using Multiple Pinholes*, CASI ASTRO 2002.
- [2] Chetty, P.R.K. *Satellite Technology and its Applications*. Blue Ridge Summit: Tab Books, 1988.
- [3] *Commentary: Waiting for the Revolution*, SpaceNews August 11, 2003, pg.13-14
- [4] Harris R., *Multiple Field-of-View Attitude Determination Sensor Technology: A Question of Adaptability vs. Accuracy*, Carleton University, 2002
- [5] Hersom, C., Thomas, P., Pitre, G., Mullins, M., Hollinger, A., Staley, D., Afik, Z., Stoev, N., Demmer, D., *Satellite Attitude Sensor With Microbolometer Detector Arrays*, CASI ASTRO 1996.
- [6] Hersom, C.; *Commercial Off-the-shelf Satellite Attitude Sensor*; COTS SAS Kick-Off Meeting Minutes; July 19, 2002.
- [7] Hersom, C., Personal Communication. 2001-2003.
- [8] Hersom, C., *Spectral's Satellite Attitude Sensor*, Electronic Brochure, Spectral Applied Research. 2001.
- [9] Macikunas, M., *COTS-SAS Microbolometer SNR Evaluation Report*, WIS-SAR-COTS-SAS-MS-001, Rev. 2, June 10, 2003
- [10] Macikunas, M., *COTS – SAS Electronics Evaluation Report*, WIS-SAR-COTS-SASER001Rev. 2, Waves in Space, 2003
- [11] Martin, M., Klupar, P., Kilberg, S., Winter, J., *Techsat 21 And Revolutionizing Space Missions Using Microsatellites*, Air Force Research Laboratory (AFRL), 2001.
- [12] *Report of the Defense Science Board / Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs*, Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, Washington, D.C. 20301-3140, May 2003
- [13] Pitre, G., *Spinning Mode Algorithms for the Satellite Attitude Sensor*, M.Sc. Thesis, Carleton University, 1999.
- [14] Sinclair, P., Harris, R., Erhardt, L., Final Results of Radiation Testing on XenICs Poly-SiGe Microbolometers, Report # ST-222423-02 Rev A, Spectral Applied Research, 2002

- [15] Sinclair, P., Macikunas, M., Harris, R., Erhardt, L., Estan, D., *Final Results of Radiation Testing on Commercial Parts for COTS SAS*, Report # ST-222423-03 Rev A, Spectral Applied Research, 2003
- [16] Samaan, M., Mortari, D., Pollock, T., Junkins, J., " *Predictive Centroiding for Single and Multiple FOVs Star Trackers* ", AAS/AIAA Space Flight Mechanics Meeting, San Antonio, TX, 27-31 January, 2002.
- [17] Staley, D., *Orbital Mechanics and Spacecraft Control*, Course notes for Engineering 88.515, Carleton University, 2003.
- [18] Stemme, G., Eriksson, P., Anderson, J. Y., *Theoretical and Experimental Investigation Of Interferometric Absorbers For Thermal Infrared Detectors*, Sensors and Materials, Vol. 9 (1997) pp. 117-130.
- [19] Swales Aerospace, *Final Report: Nanosat Dispenser Ship Performance Feasibility*, SAI-RPT-284, 1999
- [20] Tissot, J.L., Mottin, E., Bain, A., Martin, J.L., Ouvrier-Buffet, J.L., Bisotto, S., Yon, J.J., *Uncooled Amorphous Silicon Technology Enhancement for 25 μ m Pixel Pitch Achievement*, Infrared Technology and Applications XXVIII, SPIE Vol. 4820, 2002
- [21] Thomas, J., Hornsey, R., Sinclair, P., *Offset and Gain Compensation in an Integrated Microbolometer Array*, IEEE Aerospace Conference, Aspen Colorado, 1999.
- [22] Wertz, J.R., and Larson, W.J. *Space Mission Analysis and Design*, 3rd ed. El Segundo: Microcosm Press, 1999, Pg.368-375.

Internet Literature:

- [23] NASA/TP-3560, *A Conceptual Design for the Attitude Control and Determination System for the Magnetosphere Imager Spacecraft*, Polites, M.E. and Carrington, C.K. , Structures and Dynamics Laboratory, Science and Engineering Directorate and the Preliminary Design Office, Program Development. NASA Marshall Space Flight Center, AL 35812, May,1995, pp. 29, viewed online (June 2003) at:
<http://trs.nis.nasa.gov/archive/00000274/01/tp3560.pdf>
- [24] STD 15, STD 16 *Infrared Scanning Earth Sensors*, viewed online (March 2003) at
<http://www.esa.int/est/prod/prod0564.htm>
- [25] TechOnLine: *Silicon and Chocolate: IMEC's Investment in Tomorrow's Technologies*, Jim Lipman, TechOnLine Content Director, last viewed online (September 2003) at:
http://www.techonline.com/community/tech_topic/csoc/20822

[26] *Infrared Detector Arrays for Thermal Imaging: A Tutorial*, ACREO Semiconductor Institute (Under Publications > Tutorials) last viewed online (February 2004) at:
<http://www.acreo.se/acreo-rd/smpage.fwx?page=242>

[27] *XenICs: Characterization of the Mechanical Properties of Polycrystalline Silicon Germanium (poly SiGe) Surface-Micromachined Structures*, last viewed online (October 2003) at:
<http://www.imec.be/wwwinter/student/en/thesis/2002/topicP5.shtml>

[28] *XenICs: SiGe Microbolometer Basics*, last viewed online (October 2003) at:
<http://www.xenics.com/Products/Sige.php>

APPENDIX A

Schematic Diagrams of COTS SAS Electronics Equipment Under Test [9]

Figures A-1 through A-4 provide schematic diagrams of the microbolometer, differential drive circuit, differential receiver, and ADC and sampling and sampling electronics blocks that were tested.

Microbolometer Board

Figure A-1: COTS SAS Microbolometer Electronics Board

COTS-SAS TI ADC Evaluation Set-up

Figure A-2: COTS SAS ADC Module and Clock Interface

Figure A-3: COTS SAS Differential Driver Module

Figure A-4: COTS SAS Differential Receiver Module

Figure A-5: Schematic Overview of COTS SAS Radiation Test Assembly

ADC Digital Interface

Figure A-6: Schematic Overview of ADC to PCI Card Interface

APPENDIX B

COTS SAS Microbolometer Timing Diagram

Figures B-1 and B-2 provide a pictorial representation of the basic COTS SAS microbolometer and electronics timing diagrams used throughout the entire EMI and radiation testing programs.

Figure B-1: Basic Microbolometer Electronics Timing Diagram for EMI & Radiation Testing [9]

Figure B-2: Basic COTS SAS Electronics Timing Diagram for EMI & Radiation Testing

Please reference Table B-1 for definitions of signal inputs

Parameter	Definition or Explanation
Clock	Microbolometer clock signal 33 kHz nominal. Used for scanning of the MBO array
OSCanc	On-chip Amplifier off-set cancellation, 1 μ sec nominal
Reset	Capacitive TransImpedance Amplifier (CTIA) reset pulse. The CTIA consists of a dual op-amp circuit, which serves a detector buffer stage. The CTIA ensures the linearity of the detector current to output voltage conversion
Sample	Sample & Hold closed switch potential Toggles the S&H on the CTIA
Start R/L	Bolometers switched to CTIA, start data read and output sequence
ADC Serial In	Initializes ADC to receive data from MBO scan
Enable	Switches on the Bias amplifier (Active Low)
In R/L	Array scan start pulse. Initiates scan of 100-pixel array (referred to as left or right based on chip pin number wirebonding)
Out	Typical analog data output waveform from one half (100 pixels) of the MBO array multiplexer

Table B-1: Basic Definitions For Signal Inputs To COTS SAS Electronics

APPENDIX C

COTS SAS Microbolometer Equivalent Circuit Diagram

Shown in Figure C-1 on the following page, is the representative electrical circuit for the IMEC poly-SiGe microbolometer array selected for the COTS SAS program. It should be noted that this is meant to illustrate the operational principles of the microbolometer, and not the physical configuration of the actual detector array.

The reader is reminded of the following items:

- Long integration time --> Strong MBO signal but induces self-heating
- Short integration time --> Smaller signal but reduces self-heating effect
- About 3/4 of signal on the active pixel, comes from internal thermal emissions
- The blind pixel compensates for MBO array temperature
- The blind pixel does not compensate for sensitivity loss with increasing MBO array temperature

Figure C-1: Representative Circuit Arrangement For The COTS SAS Microbolometer Detector Array

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