Lockheed Martin's 640 x 480 MWIR Imaging Systems

March 1998

Davis Lange
Lockheed Martin Fairchild Systems
Syosset New York

Mark Goodnough and Robert Jones
Lockheed Martin Santa Barbara Focalplane
Santa Barbara California

Abstract

Lockheed Martin is presently manufacturing imaging systems having greater than 640 x 480 resolution utilizing the MWIR technologies Platinum Silicide and Indium Antimonide. This paper identifies key operational characteristics of these focal plane array technologies including readout rate, readout architecture, and performance parameters such as quantum efficiency, nonuniformity, and MTF. System performance measurements on camera systems based on these two infrared technologies is presented including nonuniformity correction and stability, noise equivalent temperature and MTF.

1.0 Introduction

Lockheed Martin (LM) developed under IR&D large area MWIR FPA's with greater than 640 x 480 resolution in two IR detector technologies, Platinum Silicide (PtSi) and Indium Antimonide (InSb). The 656 x 492 PtSi InfraRed Focal Plane Array (IRFPA) utilizes a monolithic architecture with a cryogenic 4 phase Charge Coupled Device (CCD) readout. LM's PtSi process utilizes greater than 95% of the processing steps of a visible CCD providing a basis for the high yield and producibility of these devices exceeding 99.99% operability.

In contrast to PtSi, Lockheed Martin's 640 x 512 InSb technology utilizes a Hybrid architecture with a custom silicon based cryogenic CMOS readout bump-bonded to the detector fanout. The InSb technology utilizes improved indium bump-bonding processes with an advanced CMOS multiplexor design as well as a controlled InSb diode process to reliably produce these large area devices exceeding greater than 99.5% operability.

This paper begins with a short introduction discussing the fundamental differences between the physics of photodetection in PtSi and InSb detectors. We discuss key design issues of the large area PtSi and InSb Focal Plane Arrays and present data from our IRFPA's supporting LM's capability to produce highly uniform, high performance PtSi and InSb detectors. Results from system modeling and measured data on sensors built around

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)
01-03-1998

2. REPORT TYPE
Conference Proceedings

3. DATES COVERED (FROM - TO)
xx-xx-1998 to xx-xx-1998

4. TITLE AND SUBTITLE
Lockheed Martin?s 640 x 480 MWIR Imaging Systems
Unclassified

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lange, Davis ;
Goodnough, Mark ;
Jones, Robert ;

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME AND ADDRESS
Lockheed Martin Fairchild Systems
Syosset, NYxxxxx

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS
Director, CECOM RDEC
Night Vision and Electronic Sensors Directorate, Security Team
10221 Burbeck Road
Ft. Belvoir, VA22060-5806

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APUBLIC RELEASE
,

13. SUPPLEMENTARY NOTES
See Also ADM201041, 1998 IRIS Proceedings on CD-ROM.

14. ABSTRACT
Lockheed Martin is presently manufacturing imaging systems having greater than 640 x 480 resolution utilizing the MWIR technologies Platinum Silicide and Indium Antimonide. This paper identifies key operational characteristics of these focal plane array technologies including readout rate, readout architecture, and performance parameters such as quantum efficiency, nonuniformity, and MTF. System performance measurements on camera systems based on these two infrared technologies is presented including nonuniformity correction and stability, noise equivalent temperature and MTF.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT
Unclassified

b. ABSTRACT
Unclassified

c. THIS PAGE
Unclassified

17. LIMITATION OF ABSTRACT
Public Release

18. NUMBER OF PAGES
11

19. NAME OF RESPONSIBLE PERSON
Fenster, Lynn
lfenster@dtic.mil

19b. TELEPHONE NUMBER
International Area Code
Area Code Telephone Number
703767-9007
DSN
427-9007

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39.18

these devices provide insight to their utilization for missile sensor systems, FLIR's, manufacturing process monitors, surveillance and security systems. Additionally, data gathered over the last year on LM's IR&D Platinum Silicide sensor show that correction stability for greater than one year can be obtained using this technology.

2.0 LM IRFPA Detector Fundamentals

PtSi and InSb IRFPA's have little similarity in their physical structure or process of photodetection other than they both operate primarily in the MWIR spectral band. In the following paragraphs, we discuss the basic structure of the IRFPA technologies and highlight some of the IRFPA characteristics and attributes.

2.1 Platinum Silicide (PtSi)

PtSi detectors are formed by the reaction of Pt on silicon, where annealing of the resultant structure forms PtSi. The PtSi layer over the silicon substrate forms a Schottky barrier having a characteristic barrier height. The barrier height determines the effective cutoff wavelength of the PtSi detector. Additionally, the barrier height is directly correlated to the amount of dark current generated by the device as a function of temperature. PtSi photodetectors sense radiation through a process of internal photoemission, where the photon is absorbed in the PtSi creating an electron-hole pair (very short lifetime) and the resulting "hot-hole" can therefore ballistically travel over the "barrier" of the interface and be collected in the silicon or be reflected and athermalized in the PtSi. The ability for the "hot hole" to emit over the barrier is directly related to the structure of the PtSi and the quality of the PtSi/Si interface.

Quantum efficiency in PtSi detectors is described in a simplistic form by the modified Fowler Equation, where the original equation described photoemission from a metal surface into a vacuum and the modified Fowler equation relates photoemission into a semiconductor instead of a vacuum as given by Equation (1), where Y is the yield in electrons.

$$\sqrt{Yh\upsilon} = \sqrt{C_f}\left(h\upsilon - \Psi_{opt}\right) \qquad (1)$$

The detector's fundamental optical parameters are given by the C_f (emission coefficient) and the optical barrier height (Ψ_{opt}). Correspondingly, the dark current for a PtSi detector is basically described by the Schottky diode equation in the reverse biased condition. The effective electrical barrier height (Ψ_{dark}) related to dark current generation is slightly lower (5-10 meV) than the optical barrier height of equation (1) and is a function of bias voltage as is the optical barrier height.

$$I = 32AT^2 e^{-\left(\frac{\Psi dark}{kT}\right)} e^{\left(\frac{qV}{nkT}\right)} \qquad (2)$$

PtSi detectors generally use a backside illuminated geometry where the silicon substrate forms a natural cold filter to visible energy. The photoresponse of LM's PtSi detectors is augmented by the use of a tuned optical cavity on the detectors to enhance quantum efficiency and the application of an antireflection coating to maximize absorption.

Readout of the PtSi detectors is achieved by an interline transfer CCD readout architecture with a single output amplifier achieving greater than 70 dB dynamic range. The single output amplifier design prevents nonuniformity issues that may result from amplifier drift using multiple output designs. The Charge Transfer Efficiency of this CCD architecture typically exceeds 0.99995 per transfer providing nearly theoretical MTF from the arrays. The low readout noise and high charge saturation capacity (typically in excess of 10^6 electrons) of the interline transfer CCD architecture allows LM's PtSi systems to achieve dynamic range beyond 60 Celsius with NEΔT's of better than 100 millikelvin for tactical backgrounds operating at 30 hz framerates. The low readout noise and highly uniform photoresponse of LM's PtSi technology lead to high quality imagery from this technology. Furthermore, the silicon based processing of PtSi technology leads to nearly nonexistent defect counts in 656 x 492 arrays and extremely stable nonuniformity correction over long periods of time.

2.2 Indium Antimonide (InSb)

InSb detectors form by P++ doping of N-type InSb substrates creating P-N junction diodes. The diodes are formed by either a planar process where the detectors are in the same plane as the substrate, or by generating mesa structures where the diodes are delineated as active areas through etching onto the InSb substrate. InSb detectors in FPA's operate in a photovoltaic mode and utilize absorption in the depletion region of the P-N junction to detect incident photon energy. The doping densities, junction properties, and bandgap of InSb determine the fundamental optical and electrical characteristics of these devices. However, the quality of the InSb process determines the ultimate capability of the detectors to operate in FPA's.

The principle of photodetection in InSb is analogous to general photodiode theory found in almost any physics text. An incident photon with energy greater than the bandgap of InSb can generate an electron-hole pair resulting in photocurrent that is sensed by the readout circuitry. The photocurrent accompanies an intrinsic reverse bias diode current and typically an additional leakage current dependent upon the InSb architecture and InSb processing, especially the passivation of the InSb surface. Equation 3 defines the current voltage relationship for a photovoltaic detector and is given by the following:

$$I = I_{sat}\left[e^{\left(\frac{qV}{nkT}\right)} - 1\right] - I_{photo} + I_{leakage} \qquad (3)$$

The photocurrent (I_{photo}) is given by equation 4 where the quantum efficiency, η, and the incident photon flux, E, are dependent on wavelength.

$$I_{photo} = qA\eta(\lambda)E(\lambda) \qquad (4)$$

The fundamental detector parameters for InSb photodiodes are the effective quantum efficiency $\eta(\lambda)$ of the device, the bandgap (smaller with increasing temperature) that determines the effective cutoff wavelength, and the total dark current including saturation and leakage current in the device for the chosen operating point.

LM has developed a well-controlled InSb fabrication process over the years that led to the successful production of the 640 x 512 InSb IRFPA. Our detectors feature an extremely well matched antireflection coating that achieves quantum efficiencies in excess of 90% at peak wavelengths. LM optimized its process so that the detectors can be exposed to visible and UV light without any degradation in detector performance. The InSb devices can be processed for use in the ultraviolet, visible and IR or can be optimized for use in the MWIR only.

To fully utilize the high quantum efficiency of the InSb detectors requires a readout architecture with a high saturation charge capacity. LM developed a cryogenic CMOS readout that is hybridized through bump-bonding to the InSb detector fanout. LM's multiplexor features greater than 90 dB dynamic range with its 17 million electron full well capacity. The multiplexor features 4 outputs to accommodate fast frame rates up to 120 Hz. Additionally, the IRFPA can achieve 30 Hz framerates utilizing only a single output port. The multiplexor is programmable to allow extremely high rates for small subwindows of the IRFPA suitable for high frame rate tracking systems. LM's systems utilizing InSb FPA technology achieve NEΔT's of less than 30 millikelvin for tactical backgrounds and a dynamic range that is programmable via the variable integration time feature of the multiplexor readout.

3.0 Lockheed Martin MWIR Imaging Sensors

Due to the dynamic range and low noise of the PtSi and InSb IRFPA architectures, LM has developed complimentary analog and digital electronic designs to process the image data from these devices. The PtSi architecture requires the high speed capability of todays 12 bit analog to digital converters, where the pixel rate is 12.5 Mhz at the readout. Depending on the application, InSb based designs incorporate either 12 bit or 14 bit analog to digital converters to process the data where the maximum output rates are around 10 Mhz. The raw digital data then passes into a digital signal processing board to correct for pixel to pixel variations in responsivity and remapped via automatic gain control or histogram processing for output to a suitable viewing port (eg computer monitor or real-time compatible display).

The significant factors affecting the performance of an MWIR imaging sensor are the detector sensitivity, pixel to pixel nonuniformity, and the Modulation Transfer Function (MTF) of the total system. In the case of PtSi and InSb imaging sensors, the fundamental system architecture is nearly identical in terms of lens requirements, electronic processing, and cooler needs. To achieve identical temperature sensitivity to PtSi sensors, systems based on InSb can utilize slightly higher operation temperatures and slower optical systems where system constraints mandate such tradeoffs. However, missile systems generally use nitrogen based cryostats where FLIR and surveillance systems utilize helium closed-cycle coolers that work equally well with either PtSi and InSb IRFPA's. Additionally, slower optical systems degrade the resolution performance of both IRFPA technologies and therefore is not generally a good tradeoff to make unless absolutely necessary for the application.

4.0 Performance Modeling of PtSi and InSb Imaging Sensors

High Performance PtSi and InSb IRFPA's along with low-noise electronic designs are the basis for LM's high resolution MWIR imaging systems achieving outstanding image quality and sensitivity. As a basis for comparison, we chose to model the sensor systems at a conservative operation temperature of 79 Kelvin (consistent with N2 cryostat operation) with an f/2.5 optical system (ideally diffraction limited) having a total overall transmission of 75% (easily achievable in conventional lens designs). The band of operation was chosen as 3.4 to 4.9 μm, consistent with the best atmospheric transmission. The integration time for the InSb and PtSi was chosen to allow a 70 Celsius saturation temperature for both systems to emulate use in a tactical background situation.

The modeling predicts temporal noise NEΔT's as low as 15 and 80 millikelvin at 25 Celsius Scene Temperatures for the InSb and PtSi based systems, respectively, as shown in Figure (1). For imaging systems requiring spatial recognition such as correlation trackers or "man-in-the-loop"target acquisition, inclusion of nonuniformity noise (Figure 2) results in a spatial NEΔT of ~30 millikelvin for the InSb imaging sensor and ~85 millikelvin at 25 Celsius for the PtSi imaging sensor as shown in Figure 3. The spatial noise for the modeling was set at a constant relative corrected nonuniformity level appropriate for each technology. However, as seen by the measured data on the InSb and PtSi imaging systems in the next section, a standard two point correction allows significantly better nonuniformity performance near the points of correction.

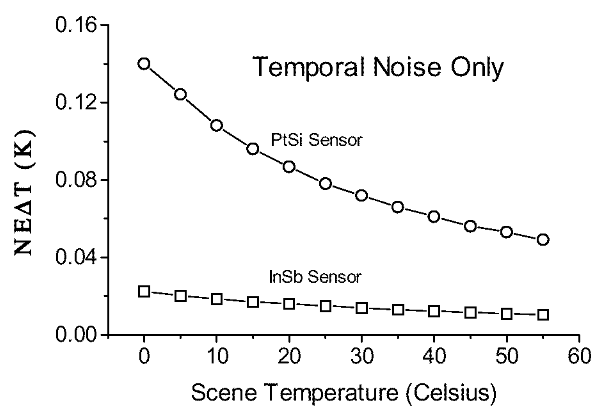

Figure 1. PtSi and InSb modeled system performance for temporal NEΔT

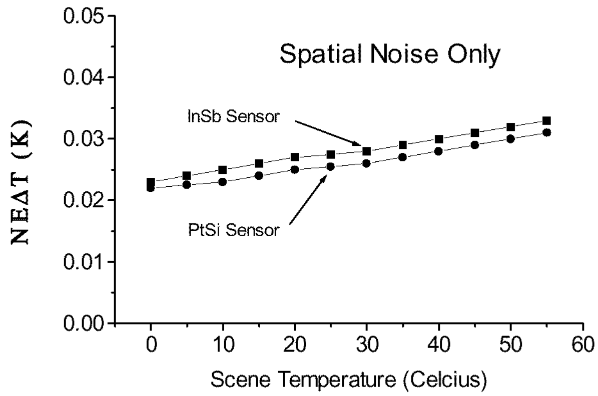

Figure 2. PtSi and InSb modeled system performance for spatial NEΔT

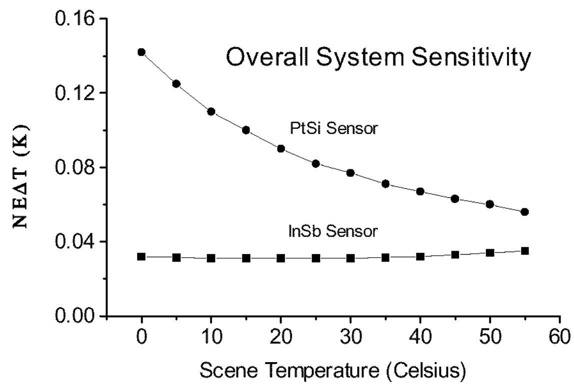

Figure 3. PtSi and InSb modeled system performance for overall imaging NEΔT

5.0 Measured Performance of PtSi and InSb Imaging Sensors

Performance measurements on LM's PtSi and InSb imaging sensors support the conclusions of the system modeling presented above. Data presented for the PtSi image sensor originated from an IR&D sensor built in 1996 that has flown test flights and now resides in the laboratory as an analysis tool.[1] The system contains an f/1.94 lens and combination warm/cold cold shielding design with an overall transmission of ~ 75%. The data shown for the InSb sensor originates from a 256 x 320 image sensor utilizing the same multiplexor structure/technology and InSb process/diode configuration. Due to a test set limitation allowing only 8 frames of data to be taken for the 640 x 512 InSb sensor, the temporal NEΔT and Spatial NEΔT data is perturbed from its ideal values. Therefore, data from the 640 x 512 image sensor will be given in the text to accompany the 256 x 320 data with the understanding that the 640 x 512 performance is expected to follow the performance of the 256 x 320 sensor in all areas.

Figure 4 shows the measured temporal NEΔT for a 256 x 320 InSb sensor taken against a scene temperature of 20 Celsius. This data was taken on an f3.6 system with an integration time of 6.4 milliseconds. The mean NEΔT for the array is 17 millikelvin, where the measured data includes the effects of $\cos^4(\theta)$ shading. The relatively tight distribution in the NEΔT data indicates a well-controlled InSb fabrication process for these systems. Data from the 640 x 512 image sensor provided an NEΔT of ~ 25 millikelvin at 22 C. Our model used in the previous section predicts an NEΔT of 15 millikelvin for the conditions of this test on the 320 x 256 device.

Figure 5 shows the averaged NEΔT as a function of scene temperature for the central 128 x 128 pixels of the IR&D PtSi system. The data shows a temporal NEΔT of 73 Kelvin for a scene temperature of 27 Celsius. Our model used in the previous section predicts an NEΔT of 65 millikelvin for the system under consideration using the best known values of the systems parameters. Note that a PtSi sensor is fundamentally temporal noise limited for all tactical environments as shown by the resultant spatial NEΔT data presented below.

Figure 6 shows the spatial NEΔT for the InSb and PtSi imaging sensor systems. The data for the InSb sensor includes all 320 x 256 pixels and is based around a standard two point correction at 20 C and 40 C. The data for the PtSi sensor was taken for the central 256 x 256 pixels of the FPA. This was done due to the known vignetting effects of the IR&D sensor lens assembly which would introduce slowly varying differences across the array and lead to a faulty conclusion about the relative performance. The results on the InSb sensor show the system performed better than expected by modeling of the previous section and is an indication of the quality of the InSb systems available from LM. The PtSi data shows that the central 256 x 256 area of the sensor maintained nonuniformity consistent with the model using a two point correction at 10 C and 50 C.

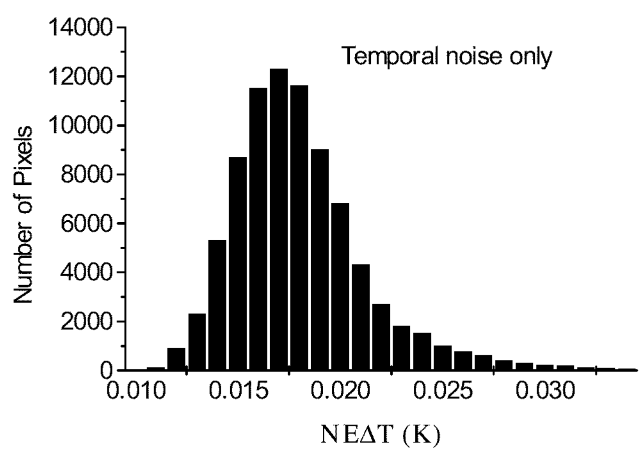

Figure 4. Measured temporal NEΔT for InSb sensor at 20 Celsius

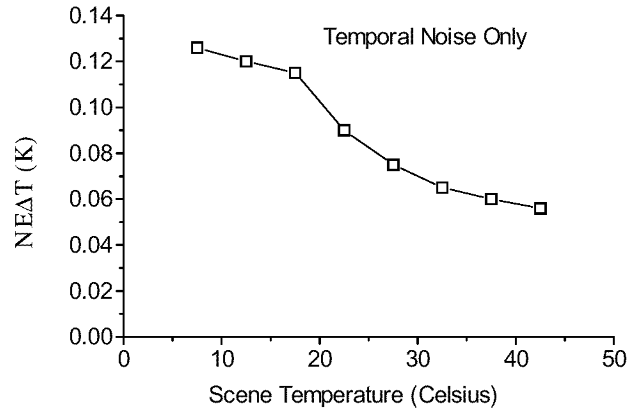

Figure 5. Meaured temporal NEΔT for PtSi sensor as a function of scene temperature

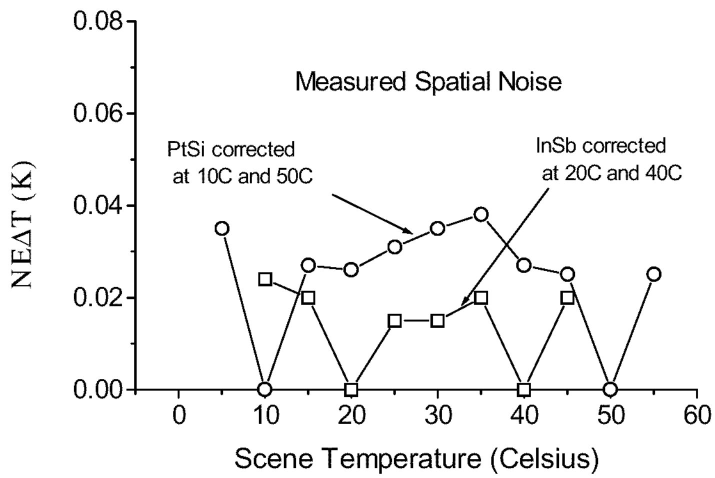

Figure 6. Measured spatial NEΔT for PtSi and InSb Sensors

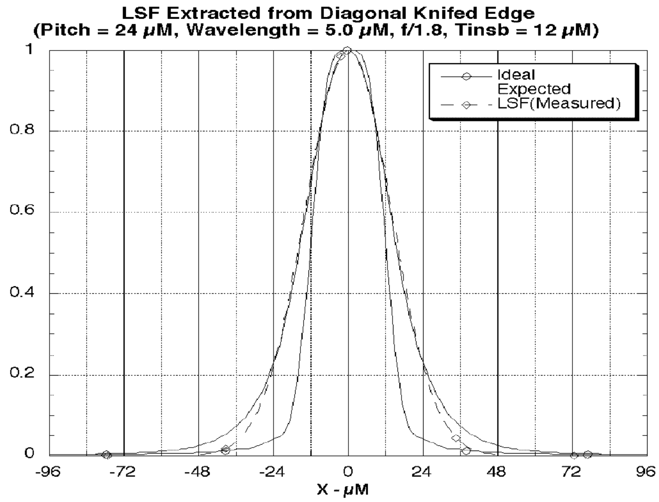

Figure 7. Measured and modeled line spread function for InSb photodiodes using "slanted edge" technique

PtSi detectors fundamentally have ideal MTF. PtSi detectors exhibit almost no measurable crosstalk under normal illumination conditions. Since LM's 4 phase CCD is designed for better than 0.99995 CTE, less than 5% degradation is expected at the center of the array (median number of transfers to output) from the ideal MTF. InSb detectors, however, when not properly designed can exhibit extremely poor MTF near array Nyquist due to crosstalk between adjacent pixels. We measured the line spread function for the 640 x 512 IRFPA using a "slanted edge" technique, where a sharply defined straight edge focused by the optical system is at a slight tilt to the orientation of the IRFPA pixels. The resultant accumulated image down a column (or row) of the IRFPA then approximates the edge response of the pixel. Figure 7 shows the result of such a test which indicates that LM's InSb systems provide results consistent with a model by D.T. Cheung for HgCdTe using InSb material parameters within the accuracy of the measurement.[2] [3] For an ideal f/1.8 lens, an expected MTF of approximately 30% is expected from our InSb imaging systems.

6.0 Long Term Stability of LM's PtSi Imaging Sensor

PtSi imaging sensor systems are known for their ability to maintain correction for long periods of time during operation. Long term stability of sensor systems is a key requirement for "wooden round" missiles and systems that do not permit occasional correction for gain and offset variations during use. LM designed high stability electronics for operation of PtSi sensors to meet the requirements of these "wooden round" systems.

Figure 8 shows the stability achieved by our IR&D PtSi sensor system over greater than a one year period. The central 100 x 100 pixels of the IRFPA were corrected using gain and offset coefficients generated by data taken in February, 1998. The gain and offset coefficients were applied to data frames taken in January and August of 1997. The data taken in January of 1997 consisted of only 32 frame averages, whereas the data taken in August, 1997 and February 1998 consisted of 64 frame averages. Hence, when gain and offset coefficients are generated with the January data, some residual nonuniformity propagates into the coefficients resulting in slightly higher residual values when applied to the August 1997 and January 1998 data. The data was taken under laboratory conditions, so variation of operating environment temperatures still needs to be addressed in terms of stability. Additionally, the system has only experienced minimal aging at this point in time. However, the data clearly indicates favorably at this point in time that this PtSi sensor system is truly a "wooden round."

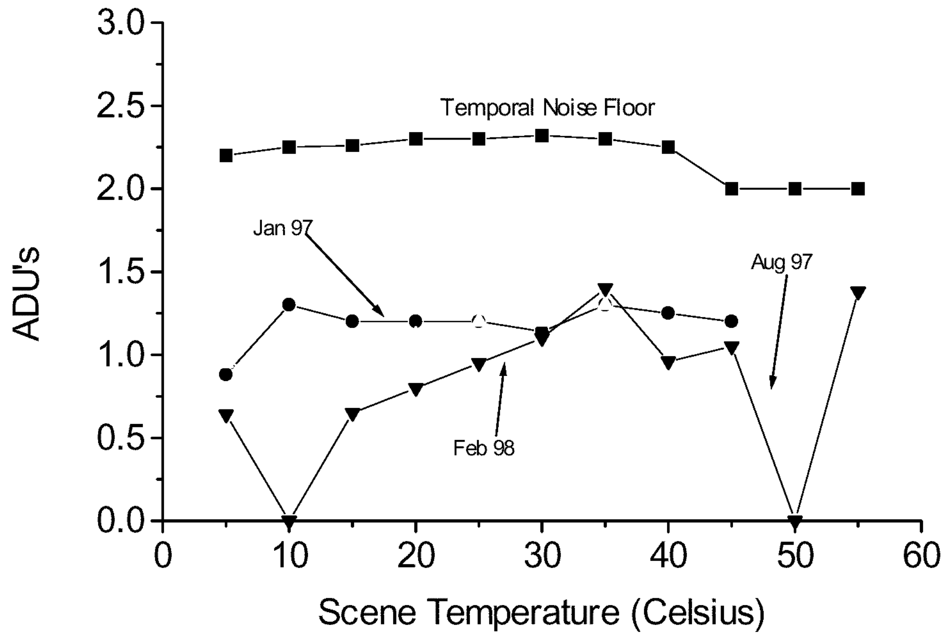

Figure 8 Spatial noise derived from data of central 100 x 100 pixels of PtSi imaging sensor from January 1997 to February 1998

7.0 Conclusion

Lockheed Martin has developed large area MWIR imaging systems utilizing InSb and PtSi detector technologies. Measurement data from our PtSi and InSb systems show NEΔT performance of 30 and 85 millikelvin, respectively, for 300 Kelvin backgrounds. Spatial nonuniformity for both InSb and PtSi systems is shown to be well controlled over greater than 40 C variation in background temperatures. Additionally, measurements on our InSb sensor systems show the MTF near array Nyquist is very good, with values close to 30% with fast optical systems. Finally, our PtSi sensor systems have preliminary demonstrated the ability to maintain gain and offset corrections for periods of greater than one year. Our PtSi and InSb sensor systems are readily packaged using either a cryostat or cryocooler dewar/FPA and single or multiple field of view optical systems to meet the needs of missiles, affordable airborne navigation FLIRs and surveillance and security systems.

[1] D. A. Lange, IRIS IR Passive Sensors, 1997.
[2] D.T. Cheung, Infrared Physics, Vol 21, p. 301 1991.
[3] M.A. Goodnough et al., SPIE, 1997.