Optical Engineering 44(5), 056401 (May 2005)

Imagery improvements in staring infrared imagers by employing subpixel microscan

John M. Wiltse, MEMBER SPIE
John L. Miller, MEMBER SPIE
FLIR Systems Inc.
16505 SW 72nd Avenue
Portland, Oregon 97224

Abstract. Imagers based on focal plane arrays (FPAs) risk introducing in-band and out-of-band spurious responses, or aliasing, due to undersampling. IR systems can use microscan (or dither) to reduce aliasing. We describe a generic microscan technique and the benefits of microscanning, including an analysis of and experiments on four-point microscan employed in IR imagers, in which the image is mechanically shifted by 1/2 pixel between fields, in each dimension. Our purpose is to describe the benefits of microscanning for IR systems employing sensitive detectors. Through analysis and experiments on production systems, we show that microscanning is an effective way to improve the resolution of imaging systems. In addition, we present experimental data that shows that this increased resolution results in lower minimum resolvable temperatures (MRTs) than an equivalent nonmicroscanned system; and that this improvement in MRT is accompanied by an increase in detection, recognition, and identification (DRI) range performance in a real-world system. The microscan hardware can also be used to null out residual gimbal jitter in a stabilized imaging system, resulting in a jitter reduction of 35 to 50%. We show that this technique, known as microscan stabilization (MSS), is complementary to microscan, and further increases the imaging system performance. [DOI: 10.1117/1.1917312]

Subject terms: microscan; dither; sampling; aliasing; resolution; stabilization.

Paper 040469R received Jul. 20, 2004; revised manuscript received Nov. 15, 2004; accepted for publication Nov. 24, 2004; published online May 25, 2005.

1 Introduction

1.1 *Background*

Microscanning is defined as moving the image by a fraction of a pixel across a focal plane array (FPA) faster than the frame rate, and then reconstructing an image in real time (within the frame time) to exploit the increased information content. Microscanning enables staring FPA systems to recapture some of the excellent point and edge detection capabilities of high-end scanning systems. Microscanning also works well with the human eye-brain architecture to improve user performance and reduce fatigue.

Microscanning to improve resolution represents a major step forward in cost-effective high-resolution imaging. It enables modern high-sensitivity focal planes to use their natural unexposed time (or dead time) within a video frame to improve resolution and stability. Unlike brute-force methods of increasing payload weight and FPA pixel count to increase stability and resolution, microscanning provides an innovative, cost-effective technique that can be implemented in a small package with minimal power and cost impacts for a gimbaled electro-optical system.

Microscan provides four major benefits to users of imaging systems:

1. resolution enhancement
2. elimination of direct staring array sampling artifacts and deficiencies
3. improved stability
4. reduced operator fatigue

1.2 *Prior Art*

Previous researchers (listed in the following) have documented the advantages to microscanning: increased resolution and sensitivity equal to or greater than equivalent non-

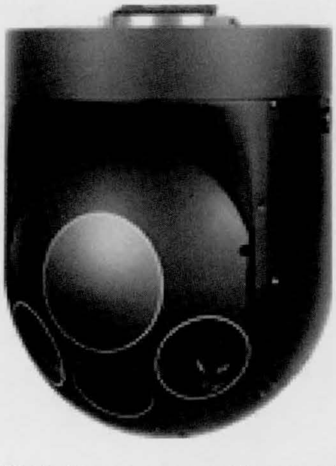
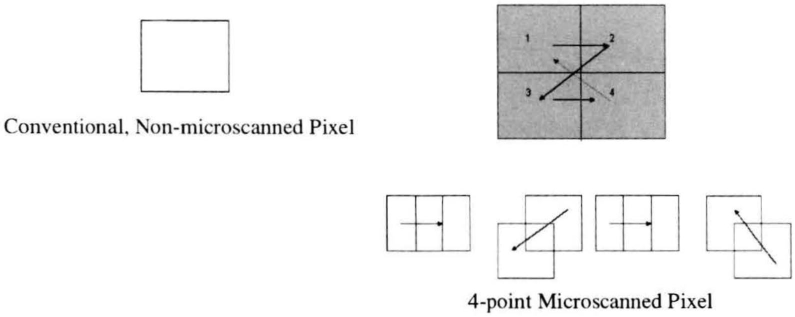


Fig. 1 COTS AN/AAQ-22 system uses microscanning for resolution enhancement and improved stabilization.



Conventional, Non-microscanned Pixel

4-point Microscanned Pixel

Fig. 2 Optimal four-point microscan pattern.

microscanned systems. This resolution improvement was modeled initially as improvement of the sample-scene phase modulation transfer function (MTF), but current modeling describes it as reduction of aliasing (or spurious response).

FPA detectors (especially those with less than 100% fill factor) inherently undersample the image. This means that they do not reproduce image details to the detector's resolution limit. Microscanning overcomes this problem and increases the total number of pixels in much the same manner that scanning systems produce a complete image from a small number of detector elements. Watson et al.[1] demonstrated the use of microscanning to reduce aliasing and spurious response. They found that the amount of aliasing that is tolerable depends on system parameters, particularly the fill factor of the array. A two-point microscan was found to significantly reduce aliasing, and a four-point microscan reduces it even further. Higher level microscans provide diminishing returns. In their simulations, they showed that microscanning is able to reduce the moiré pattern created by undersampling a spoke pattern (or star pattern). Gillette et al.[2] extended the analysis to uncontrolled microscanning as well. In uncontrolled microscanning, the image shifts are not induced, but instead are the result of uncontrolled random motion. In controlled microscanning, on the other hand, the subpixel shifts between image fields are controlled, and therefore are known *a priori*. In the latter case, minimal processing is required and the technique can be more readily implemented in real time. Blommel et al.[3] showed the effects of microscanning on sample scene phasing artifacts. That is, by shifting the scene slightly with respect to the sampling lattice, vastly different images were obtained. Even at the best phasing, however, the images still had artifacts. With the worst phasing, the artifacts were significantly worse. But 3×3 microscanning eliminated all the phasing artifacts.

Hock[4] modeled the effects of oversampling in pixel arrays using statistical means. He showed that the pixel MTF does not adequately describe sampled systems because it does not account for phasing effects. He introduced a pixel transfer function (PTF) to incorporate the sampling lattice and thus provide a more accurate representation of FPAs. After sampling, the expected value of the new amplitude $E(A_2)$ is given by the expression

$$\frac{E(A_2)}{A_1}=\operatorname{sinc}\left(\frac{\pi f_0}{f_p}\right)*\operatorname{sinc}\left(\frac{\pi f_0}{f_d}\right),$$

where $f_p = 1/(\text{pixel pitch})$, $f_d = 1/(\text{pixel size})$, A_1 is the input modulation amplitude, A_2 is the output amplitude, and f_0 is the spatial frequency. Note that there are no restrictions on f_p and f_d: the pixel pitch can be less than the pixel size (as in the case of microscanning). The first term of this expression can be expressed[5] as the familiar sample-scene phase MTF:

$$\mathrm{MTF}_{\text{phase}}=\operatorname{sinc}\left(\frac{\pi f_0}{f_p}\right),$$

where f_p is the spatial sampling rate. An advantage of four-point microscanning is that it doubles f_p and hence improves the MTF.

More recently, however, Vollmerhausen and Driggers[6] as well as Krapels et al.[7] found that a sample-phase MTF did not do an adequate job of predicting performance of sampled image systems. Aliased content can act either destructively or constructively, depending on phase. An average sampling MTF, which models these effects by an average degradation, does not adequately model what occurs in nature. Instead, they have shown that tracking the system response and the spurious (aliased) response separately, and

Fig. 3 Microscan hardware.

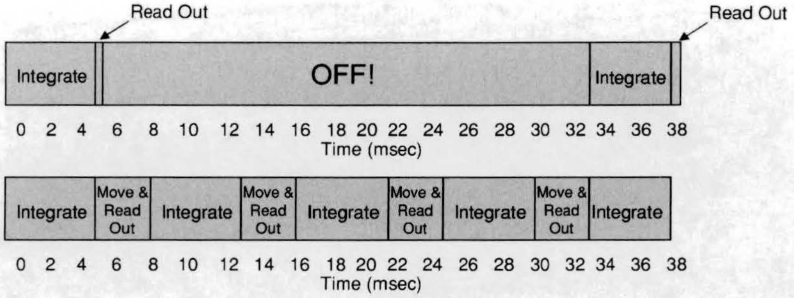


Fig. 4 Microscanning makes use of the natural dead time of highly sensitive focal planes such as InSb [for short-wavelength IR (SWIR) and mid-wavelength IR (MWIR)], InGaAs (for SWIR), silicon [for the visible and near IR (NIR)], and HgCdTe [for SWIR through long-wavelength IR (LWIR)], as illustrated in this notional depiction.

then using the amount of spurious response to predict the reduction in recognition and identification ranges, predicts measured performance more accurately. This methodology is now used[8] in the IR performance modeling software NVTherm.

Reduction in aliasing (at the time modeled as an improvement in sample-scene phase MTF) has also been shown to lead to an increase in resolution. Luengo Hendriks and van Vliet[9] showed that uncontrolled microscanning (or superresolution) can increase the resolution of an undersampled imaging system. In Sec. 3 we show that controlled microscanning has the same effect.

For insensitive detectors, microscanning can provide a trade-off between resolution and sensitivity. However, Vollmerhausen and Driggers[6] show that for highly sensitive focal plane arrays (InSb or HgCdTe), microscanning can be accomplished with no loss of sensitivity, since the detector would not be integrating for the whole time anyway. This is in contrast to a lower sensitivity detector array (such as Pt:Si or an uncooled microbolometer), which would suffer from a loss of sensitivity if microscanned.

2 Hardware

Microscanning has been employed using fast-steering mirrors, natural random jitter, piezoelectric actuator (PZT) movement of refractive elements, and electro-optical modulators. PZT-actuated microscanning is employed in numerous fielded gimbal systems similar to the one shown in Fig. 1. PZT-actuated microscanning is practical to implement and field in real-world applications. Microscanned systems have been installed in aircraft, ship, and ground installations and are used in battlefield environments, and the failure rate of the microscan hardware is extremely low. Consider that, at the time of writing, the authors have knowledge that over 800 systems incorporating microscanning for resolution enhancement, and over 500 systems incorporating microscanning for both resolution enhancement and improved stability, have been fielded.

A four-point microscan pattern, as illustrated in Fig. 2, moves the image both vertically and horizontally to increase resolution and thereby provide increased target detection, recognition, and identification ranges. Generally, little additional benefit is gained from 8- or 12-point microscanning and integration time is limited by such architectures. Initially a portion of the scene is aligned to the center of the detector element indicated by the number 1 and the detector signal is measured. Next the image is sequentially shifted so that the portion of the image is centered on the locations indicated by the numbers 2, 3, and 4, where measurements are also made. The four sequential images are interlaced in the video buffer in real time and a composite image is formed.

Figure 3 shows a piezoelectric nanopositioner used to shift the image by 1/2 detector pitch horizontally and vertically in the pattern shown in Fig. 2. These devices have demonstrated a high degree of performance and reliability because of the fast response and solid-state nature of piezoelectric elements. The movement is under closed-loop control to eliminate the effects of hysteresis in the piezoelectric material.

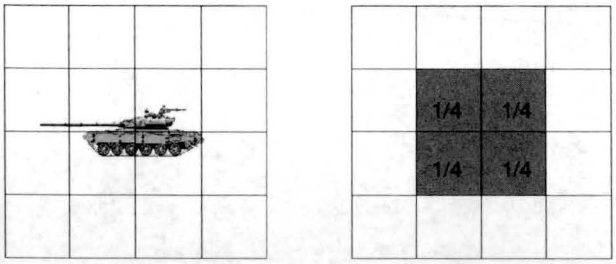
It is important for the hardware to move the image rapidly and settle quickly. Generally, with piezoelements and fast-steering mirrors this requires a few milliseconds, which can be easily accommodated within the video frame time of a sensitive focal plane, as illustrated in Fig. 4. Electro-optical modulators and other solid state beam-steering technologies offer the potential to reduce this time by orders of magnitude, enabling future growth potential for less-sensitive detector materials.

Friedenberg[10] derived an MTF for continuous-scan microscan systems (in which the detector is integrating while the image is being shifted) as is frequently done with scanning systems. This continuous-microscan system is different from the discrete-microscan (or step-stare microscan) system used by the authors, for which there is no MTF loss. The data presented here are from systems that do not integrate while moving, but physically stop before integrating (as illustrated in Fig. 4). This eliminates the MTF loss and


FLIR's microscanning oversamples image, preventing lost targes (16 pixels with no dead space)

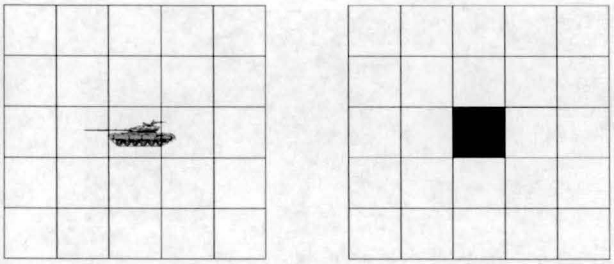
Competitor's reticulated array allows target to be lost between pixels (4 pixels with dead space)

Fig. 5 Microscanning prevents high-resolution targets from getting lost in the middle of an FPA dead zone.



Object can fall between pixels.

Displayed image has signal spread among multiple pixels.



The microscanned image minimizes the split pixel effect for brighter small objects.

Fig. 6 Microscanning can increase the contrast and brightness of small targets.

other potential artifacts from an integrate-while-microscan architecture.

3 Image Improvement Using Microscan

3.1 *Elimination of Deleterious Artifacts from Staring Arrays*

Nonmicroscanned, direct-view staring systems directly map an FPA pixel to a display pixel. These systems can exhibit several deleterious artifacts, which can reduce mission performance and cause user fatigue. One artifact of focal planes with less than 100% fill factor is illustrated in Fig. 5. It is possible that small targets can fall within the dead zone of a focal plane and thus not be detected. Since microscanning oversamples the image, this effect is eliminated.

Figure 6 shows the analogous artifact for a 100% fill factor focal plane. In this case, a target falling in the middle of four pixels has the energy divided among four pixels, and might not achieve a sufficient SNR to provide confident detection. The same is true for high-frequency target details, resulting in shorter recognition and identification ranges, or even in misidentification of targets. Microscanning mitigates these problems by providing a better SNR and improved resolution.

Another artifact from direct-view staring arrays can arise from the long integration times to achieve sufficient sensitivity, which results in blurred images. A microscanned array employs shorter integration times and multiple images, and then electronically reconstructs the signals to produce a higher resolution, unblurred image with almost the same sensitivity as yielded with a longer, but blurred, integration. If microscanning is combined with microscan stabilization (as described in the following), the sensitivity of longer integration times is maintained, but without the performance-degrading blurring artifacts that result from direct-view's long integration times.

3.2 *Elimination of Aliasing and Spurious Response*

Nonmicroscanned FPAs are typically undersampled, leading to aliasing (or spurious response). Figure 7 (left) shows MTFs of a simple MWIR system with a fill factor of 100%. The MTF curves show that the system MTF has dropped to a value of about 0.3 at the Nyquist frequency. By definition, the first-order replica has the same value at the Nyquist frequency as the baseband. The shaded region represents spurious content, or aliasing. Note that both the baseband signal and the first-order replica are filtered by the post-sample filters (not shown), including the monitor and eye. Figure 7 (right) shows the same system with microscan added. Because the Nyquist frequency has been increased by a factor of 2, there is no longer any spurious response.

3.3 *Quantitative Resolution Improvement*

Vollmerhausen and Driggers^6 state that microscanning "reduces sensor sampling intervals without increasing detector count." Microscaning improves resolution by significantly reducing aliasing in the image so a staring FPA can resolve images to the resolution limits of the optics and detectors (beyond Nyquist). Additionally, when coupled with E-zoom, the deleterious effect of pixelization and limited display resolution can be effectively eliminated. This provides the ability to detect targets at increased standoff ranges, for increased effectiveness and survivability as well as improved identification of friend or foe.

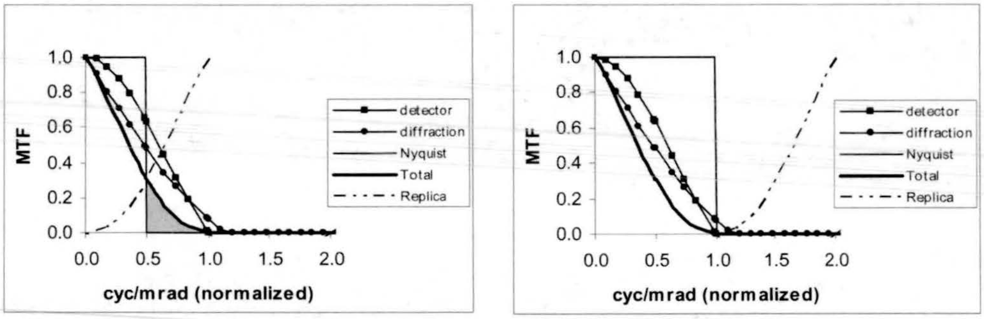


Fig. 7 MTFs of a theoretical system without (left) and with (right) microscanning. Note the large amount of spurious response (gray-shaded region) in the system without microscan.

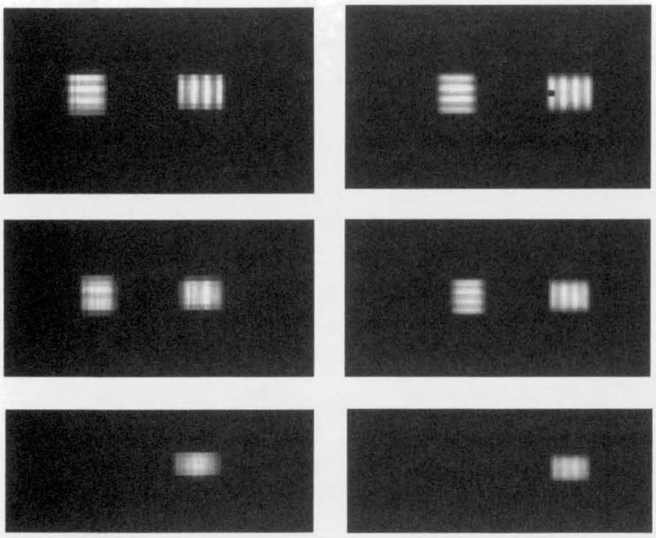


Fig. 8 Images without (left) and with (right) microscanning. Without microscanning the near-Nyquist images of a four-bar pattern can barely be discerned (top); with microscanning, the images slightly beyond (center) and well beyond (bottom) Nyquist can clearly be discerned, even with losses due to the software and printing losses associated with the electronic or printed version of this paper that you are viewing.

Results of this process are illustrated in the images of Figs. 8 and 9. The images in Figs. 8 and 9 are actual IR images in "direct-view" mode (left) and microscanned mode (right). Please note that all the images that you will view on any version of this paper were generated by frame grabbing and copying into computer applications, formatting and editing, printing, and possibly being reproduced by copying machines. In every step, there is an MTF loss, so be aware that the original digital images from the IR sensor had far greater resolution than represented here and thus the differences were far greater than in the printed pages you are now reading. In Fig. 8, the spatial frequencies of the bar patterns are 0.93× Nyquist (top), 1.12× Nyquist (center), and 1.33× Nyquist (bottom). Without microscanning, only the lowest resolution target is (barely) resolvable. With microscanning, even the highest resolution target (at 1.33× Nyquist) can be easily resolved.

The in-band spurious response of the direct-view system leads to image artifacts such as moiré patterns. Figure 9 shows the moiré pattern that occurs in a spoke target. These are actual IR images acquired with and without microscanning. Four-point microscanning eliminates aliasing, eliminates the moiré pattern, and thus increases resolution.

3.4 *Qualitative Image Resolution Improvement*

An important resolution enhancement feature of microscanning is the elimination of the annoying "saw tooth" effect of an edge that is diagonal to the sampling FPA. Figures 10 and 11 show IR images of diagonal and curved surfaces acquired with a direct-view sensor (left) and with a microscanned sensor (right). The figures show the qualitative improvement that microscan provides.

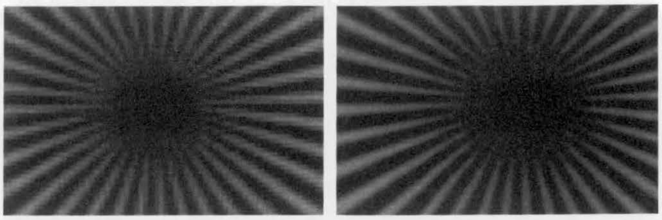


Fig. 9 Image of a spoke pattern without (left) and with (right) microscanning. Microscanning eliminates aliasing, eliminates the moiré pattern, and thus increases resolution.

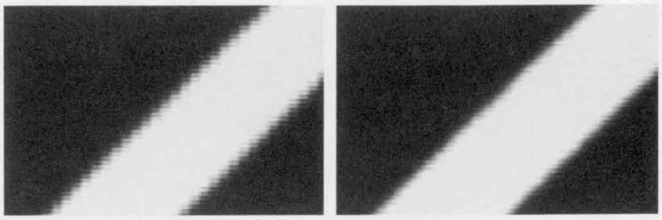


Fig. 10 Diagonal (relative to the detector) line as viewed by a nonmicroscanned sensor (left) and a microscanned sensor (right). Microscanning reduces the jagged edges that would otherwise be present.

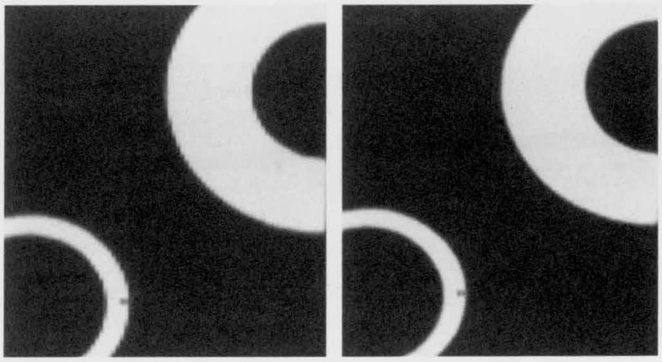


Fig. 11 Further demonstration of edge smoothing capability of a four-point microscan. The edges of the image taken with the microscanned system (right) do not have the stair-stepping artifacts seen in the nonmicroscanned image (left).

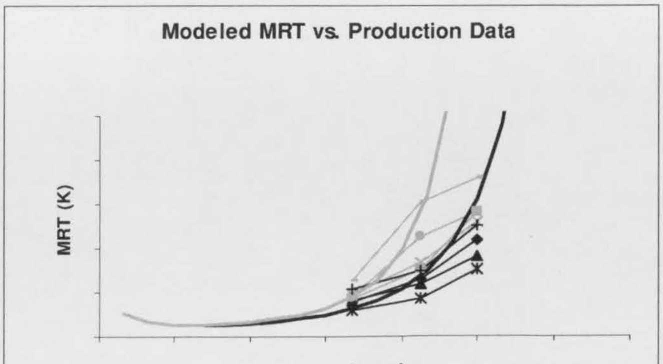


Fig. 12 Production MRT data showing the improvement due to microscan. Solid lines are MRT modeled in NVTherm, and symbols are from four different production systems. MRT with microscan (black) is better (i.e., lower) than without (light gray).

Table 1 Range improvement due to microscanning.

Observation Task	Range improvement Realized by Four-Point Microscan (%)	Standard Deviation of Range Data When Microscan was "On" in Percentage of Range	Standard Deviation of Range Data When Microscan was "Off" in Percentage of Range
Detect aircraft in high background, cluttered environment	18.0	4.8	5.0
Recognize that the aircraft has its landing gear deployed	17.7	5.0	11.4
Identify details of the aircraft's landing gear	17.6	8.9	6.9

3.5 *Minimum Resolvable Temperature Difference (MRT) Improvement*

Microscan provides substantial MRT improvement at all critical spatial frequencies, as shown in Fig. 12. The data from Fig. 12 is from four production systems with and without microscanning employed. MRT is substantially improved using microscan, yielding improved ranges. The NVTherm modeling tool, developed by the U.S. Army, can accurately predict the improvement in MRT due to microscanning, as shown by the modeled curves in the figure.

3.6 *Range Improvement in Field Tests*

To compliment the previous laboratory tests, a series of field tests were conducted to measure the range improvements due to four-point microscanning. The tests consisted of three resolution-limited observation tasks conducted in a stressful environment. The observers were airport officials who were all experienced observers of approaching aircraft. The observers' tasks were to detect and locate an airplane in a clouded and cluttered night sky, recognize that the landing gear was down, and then identify details of the landing gear. A series of 22 landings of aircraft of this type was observed with microscan on and off. The observer was not informed whether the microscan was on or off, but several observers correctly indicated that they could tell the state by the image quality. Range was determined by radar and displayed with 30-m precision. Meteorological conditions did not noticeably change during the test, and although there were several aircraft, they were all of the same type. The sensor had a 12-deg field of view and a 320×240 InSb FPA. Microscan stabilization was not employed on this sensor as it was in a low-vibration installation. Thus the data represents the effects of increased resolution only. Table 1 details the improvement in range due to microscanning. As shown in the table, the range improvement was approximately 18% for all observation tasks.

Although the performance model "NVTherm" underpredicted the range by approximately 23%, the model did quite well in predicting the range improvement due to four-point microscanning. The model predicted ranges for these scenarios would increase by about 18.6% with microscanning enabled. To yield this result, NVTherm was configured for four-point microscan by setting "Horizontal Dither" to "Yes", "Vertical Mechanical Interlace" to "2", "Electronic Interlace" to "No", and "Frame Rate" to 30 frames/s.

Users of microscanned systems during long missions consistently report less fatigue as a benefit of microscanning. In a stressful environment viewing resolution-limited images, it appears that there is less fatigue when microscanning is employed to increase resolution. The authors' conjecture is that this may be due to an improved k in the psychometric function (especially when trying to detect targets in clutter) and reduced image blurring. Also, microscanning can eliminate moiré patterns caused by a cyclical undersample of a periodic scene, which result in poor imagery, cause operator fatigue, and reduce the P_d/P_{FA} ratio.

3.7 *Potential Artifacts Caused by Microscan*

Theoretically, a microscanned image can create undesirable artifacts. However, with almost 800 systems fielded by the authors' company (at time of writing), only one complaint has been reported, and this user had extremely high angular rates. Although users have the ability to turn microscanning off, we are aware of no users who do so, other than a few in the arctic who sometimes turn it off to improve sensitivity for targets and backgrounds of less than approximately 240 K.

One unfounded argument against microscanning is the risk of doubling part of a moving target if it is moving in the direction of the microscan, as illustrated in Fig. 13. This is unlikely to happen with the four-point bow-tie microscanning described in Sec. 2, although blurring is possible at extremely high angular rates, as experienced by only one user. For this doubling or any blurring effect to occur, the target must be moving at angular rates generally exceeding

Fig. 13 Rarely seen microscanning artifact produced by observing target moving at extremely high angular rates.

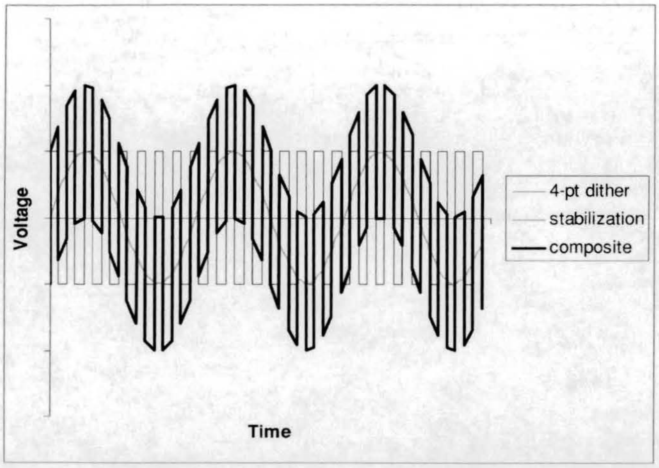


Fig. 14 Concept of the MSS drive waveform. The stabilization drive signal is added to the four-point microscan drive signal. The composite drive waveform is then used to drive the microscan element, providing four-point microscan and MSS at the same time, with the same hardware.

1/2 of the total sensor field of view per second (e.g., 15 deg/s for a 30-deg field of view). Although such high angular rates can occur for some situations (e.g., air-to-air engagements), such rates are problematic for both direct-view and microscanned sensors. Targets moving through the field of view at such rates are difficult to track, result in substantial display streaking, direct-view blurring, and may disappear in a direct-view system due to their energy being dissipated over multiple pixels. Vollmerhausen and Driggers[6] indicate that having a delay time between subimages of 8 ms or less is adequate for most military purposes. Any longer (16 or 33 ms) and the delay artifacts may reduce operator effectiveness, and hence limit the use of microscanning for low-sensitivity detectors such as microbolometers.

4 Microscan Stabilization

A key benefit of systems with microscanning is that the mechanically microscanned optic can also be used as an additional superfine gimbal axis to refine the image stabilization beyond the capabilities of the conventionally stabilized gimbal itself. Thus, microscanning can be used to improve stability by providing an extra two axes of stabilization. The gimbal gyroscope measures a rate error, which is then integrated numerically to a position error. The position error is then scaled by the microscan magnification (micrometer per microradian) and added to the microscan drive waveform. This is shown conceptually in Fig. 14. Four-point microscanning and microscan stabilization (MSS) occur at the same time, using the same hardware. Thus, the image is not shifted exactly 1/2 pixel, but by some other amount (determined in real time) to counteract the jitter. This was quantified by a series of tests on several production systems. Stabilization was measured on several production systems with MSS off and on, as tabulated in Table 2. Systems showed an improvement in stability from 20 to 59% when MSS was used. With MSS enabled, FLIR Systems has measured stability of better than 2 μ-rad on a system subjected to a large disturbance input. Future electronic and mechanical improvements are identified to reduce this to well under a microradian.

Table 2 MSS of several systems.

	Average Percentage Improvement in Stability	Standard Deviation (%)
Azimuth	31	4
Elevation	48	8
Combined	39	6

In modern IR and electro-optic (EO) imaging systems deployed on tactical platforms, stabilization is often the limiting MTF. Figure 15 (left) shows a system without MSS and Fig. 15 (right) shows the same system with MSS. These modern systems employ relatively large apertures to increase the diffraction blur MTF. At the same time, small instantaneous fields of view (IFOVs; defined as the FPA pixel pitch divided by the focal length) can increase the detector MTF. The result is a system that exhibits high resolution in a static, or laboratory, environment. When this system is installed on a dynamic platform (aircraft, ship, ground vehicle, or vibrating space vehicle), jitter often causes it to perform significantly worse than expected [Fig. 15 (left)]. MSS can be used to increase stabilization MTF (the limiting MTF of the system in this case) and thus significantly increase the performance of the system in real-world applications [Fig. 15 (right)].

This reduction in jitter results in MTF improvement, lower MRT, and less operator fatigue in a busy environ-

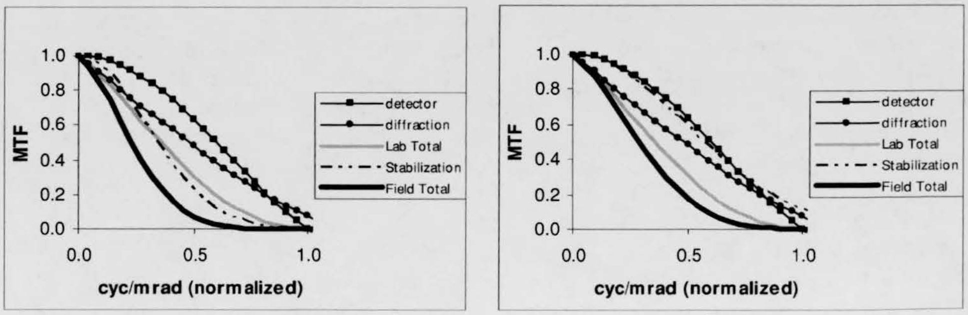


Fig. 15 MTFs of a theoretical system (left) without MSS and (right) with MSS. Both systems use four-point dither for microscanning. Without MSS, stabilization is the limiting MTF, resulting in significantly worse resolution in the field than in the laboratory.

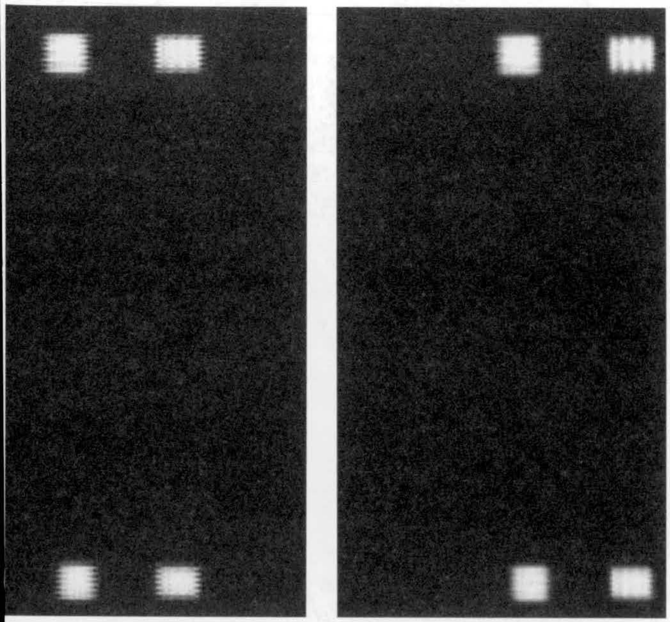


Fig. 16 Images of a bar target with the gimbaled system subjected to an angular disturbance. MSS is off in the image on the left, and on in the image on the right. The spatial frequency of the top bar pattern is 0.93× Nyquist and the spatial frequency of the bottom bar pattern is 1.12× Nyquist.

ment. Unlike electronic stabilization techniques, MSS reduces both frame-to-frame and within-frame image jitter. To demonstrate the effects of MSS, we placed a gimbaled IR system on a rotational rate table and observed a bar chart with MSS on and off. The results are presented in Fig. 16. With MSS activated, the target at 1.12 times Nyquist could be resolved. However, with MSS disabled, neither the target at 1.12 times nor at 0.93 times Nyquist could be resolved, due to the MTF loss from the vibration.

Note three key features of this technique:

1. MSS works well for highly dynamic scenes where the target is moving and especially when the platform is jittering.
2. MSS improves the stability within an integration time, which is the most critical for target detection, recognition, and identification.
3. MSS does not reduce the FOV by discarding edge pixels as do most electronic stabilization algorithms.

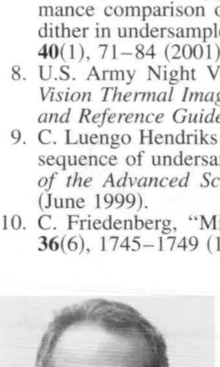
5 Conclusions

Microscanning is a cost-effective technology to improve performance of large-gimbal systems, where the volume and cost justify it. For minimal increase in size, weight, power, and cost, it provides substantial improvements in performance.

1. The hardware required is easily implemented in tactical gimbals and pods 33 cm or larger in diameter.
2. Microscanned images from a given FPA are always better than direct-view images from the same FPA.
3. Microscanning provides reduction or elimination of numerous deleterious "direct-stare" artifacts due to undersampling.
4. Microscanning does not limit sensitivity for InSb-based systems with target temperatures above approximately 260 K.
5. Rapid (faster than video rate) microscanning generally negates any potential artifacts, and there is no loss of sensitivity for highly sensitive focal planes (InSb, HgCdTe, InGaAs, silicon CCD or CMOS) as these detectors fill up their wells with short integration times relative to video frame times.
6. Microscanning provides substantial improvement in minimum resolvable temperature/minimum resolvable contrast (MRT/MRC) curves, enabling resolution beyond the sensor's native (nonmicroscanned) Nyquist frequency.
7. Target range discrimination increases of approximately 18% are attributed to four-point microscanning.
8. Microscanning has the greatest benefits on moving and vibrating platforms as it can be also used for additional stabilization.
9. Improvements in stability of approximately 40% are attributed to MSS without the added mass of a larger, bulky gimbal.
10. Users report less fatigue when the image is microscanned.

References

1. E. Watson, R. Muse, and F. Blommel, "Aliasing and blurring in microscanned imagery," in *Infrared Imaging Systems*, *Proc. SPIE* **1689**, 242–250 (1992).
2. C. Gillette, T. Stadtmiller, and R. Hardie, "Aliasing reduction in staring infrared imagers utilizing subpixel techniques," *Opt. Eng.* **34**, 3130–3137 (1995).
3. F. Blommel, P. Dennis, and D. Bradley, "The effects of microscan operation on staring infrared sensor imagery," in *Infrared Technology XVII*, *Proc. SPIE* **1540**, 653–664 (1991).
4. K. Hock, "Effect of oversampling in pixel arrays," *Opt. Eng.* **34**(5), 1281–1288 (1995).
5. G. Holst, *Electro-Optical Imaging System Performance*, pp. 185–190, 212–217, JCD Publishing, Winter Park, FL (1995).
6. R. Vollmerhausen and R. Driggers, *Analysis of Sampled Imaging Systems*, pp. 111–138, SPIE Press, Bellingham, WA (2000).
7. K. Krapels, R. Driggers, R. Vollmerhausen, and C. Halford, "Performance comparison of rectangular four-point and diagonal two-point dither in undersampled infrared focal plane array imagers," *Appl. Opt.* **40**(1), 71–84 (2001).
8. U.S. Army Night Vision and Electronic Sensors Directorate, *Night Vision Thermal Imaging Systems Performance Model User's Manual and Reference Guide*, distributed by Ontar, Inc. (Dec. 2002).
9. C. Luengo Hendriks and L. van Vliet, "Resolution enhancement of a sequence of undersampled shifted images," in *Proc. 5th Annu. Conf. of the Advanced School for Computing and Imaging*, pp. 95–102 (June 1999).
10. C. Friedenberg, "Microscan in infrared staring systems," *Opt. Eng.* **36**(6), 1745–1749 (1997).



John M. Wiltse received his BS degree in engineering and applied science from the California Institute of Technology in 1988 and his MS degree in aerospace engineering in 1989 and his PhD degree in mechanical engineering in 1993, both from the University of Arizona. He has written papers on active flow control, alphanumeric recognition, and microscanning. He developed inkjet printers for 3 years at Tektronix, and in 1999 took a position with FLIR Systems, where he is currently a senior systems engineer. His work involves precision stabilization of gimbaled imaging systems, optomechanical analysis and design, and system-level IR and electro-optical design, analysis, and testing.

John L. Miller received his BSc degree in physics from the University of Southern California and his MBA from Regis University and has completed graduate courses at the University of Hawaii and Cal State Long Beach. In the past 25 years, he has held positions as research and development director, chief scientist, program manager, functional manager, lead engineer, and electro-optical engineer on IR sensors, multispectral sensors, space surveillance sensors, missile defense sensors, IR astronomical instruments, missile warning systems, helmet-mounted cameras, IR lasers, image prcessing algorithms, lidar imagers, and active television systems. He has written more than 30 papers and four books (*Principles of Infrared Technology* and the series of three *Photonics Rules of Thumb* books) on electro-optical technology. He is the vice president of Advanced Development for FLIR Systems, overseeing several imaging development programs.