Airborne infrared persistent imaging requirements

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ABSTRACT

The task of detecting, identifying, and engaging asymmetric threats operating amongst civilian populations is a significant challenge for modern armies. Enemy activities in urban areas can be very difficult to detect and monitor using traditional intelligence, surveillance, and reconnaissance (ISR) assets. The concept of Persistent Surveillance provides a new methodology for detecting and identifying hostile forces operating amongst civilians in urban battlefields. The sensors, platforms, and data architectures which compose a persistent surveillance system must be chosen to maximize coverage and minimize obscuration while providing timely and relevant data to friendly forces on the ground. An illustrative example considering the specific operational concepts and resulting system choices for optimizing an airborne infrared persistent imaging system will be discussed.

Keyword list: persistent surveillance, wide area motion imagery, ISR

1. Persistent Surveillance: Background and Motivation

Recent conflicts and peace keeping activities have magnified the need for improved warfighting approaches to address asymmetric warfare in urban environments. Today's threat is one that is often times difficult to distinguish from the indigenous civilian population. The enemy will not wear distinctive uniforms, drive military-style vehicles or rely solely on traditional military weaponry. Instead they will operate in civilian population centers, and seek to blend into and fight from amongst the non-combatant population [1]. The enemy will be able to choose the time and location of engagements with opposing forces. They will have access to a myriad of improvised explosive devices, with ever evolving employment and detonation techniques, and use these concealed weapons to disrupt force movement and inflict both physical and psychological damage. Recent experience has shown that in complex urban environments, many traditional methods to identify and address an active asymmetric threat are ineffective [2]. New methodologies and systems are therefore necessary to robustly identify and combat enemy forces conducting asymmetric warfare in urban environments.

The concept of persistent surveillance offers a new framework for detecting and identifying enemy activities amongst civilians in urban battlefields.

1.1. Episodic vs. Synoptic Surveillance

A persistent surveillance approach seeks to use any and all available sensors to capture a complete record of all activities that have occurred and are occurring within a potential battlefield. If successful, persistent surveillance data will capture a record of all civilian and enemy actions over an extended period of time. This data can then be exploited in a variety of ways; real-time distribution to engaged units in the city can provide useful situational awareness of current and potential threats, while forensic analysis of recorded

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data can be used to work backwards from an enemy attack to find the geographic origins of the enemy activity and to understand and root out established enemy networks. While capturing a truly complete and persistent picture of all activities occurring in a densely populated urban environment is not practical (or arguably possible), it is useful to examine the differences between this persistent surveillance approach to understanding enemy activity and the surveillance approaches employed by traditional battlefield intelligence-gathering assets. Successful persistent surveillance seeks to provide synoptic coverage of all events occurring in a given area over a given time. Enemy threats in this area are not identified by their uniforms or their vehicles or their appearance, but rather by their behavior; the historical and current differences between how enemy forces behave and how the surrounding civilian population behaves. Surveillance sensors in the past have sought to identify enemy activity episodically, by providing short periods of high-resolution coverage of potential targets. Episodic identification in this manner is much more difficult in asymmetric urban environments where enemy forces remain well-concealed amongst dense civilian populations until moments before an attack. In the past, episodic surveillance sensors have concentrated on providing the fidelity necessary to uniquely identify enemy forces by their distinguishing physical features. This has led to complex and expensive systems providing high resolution data from the standoff ranges necessary for the observing sensor to remain covert. By contrast, the synoptic coverage required for persistent surveillance can often be achieved with simpler sensors providing lower instantaneous resolution, since enemy forces will be identified by their recorded behavior in both time and space, not solely by their unique physical features at a particular point in time. Accepting that persistent surveillance sensors will thus meet a different set of requirements from those of other surveillance sensors, it is worth considering the strengths and weaknesses of the available modalities and locations that such sensors might utilize.

2. Comparison of Modalities/Systems

Ground-based persistent sensors can provide very high fidelity coverage, due to the relatively short ranges between the sensors and their intended targets. However ground-based sensors will have difficulty covering large areas, as they will be limited in range by line of sight obstructions, especially in urban environments. Limited area coverage per sensor will require more sensors to cover a given space. Challenges with sensor emplacement, power, communications and survivability will grow exponentially as the density of sensors increases, especially if they must operate in un-pacified urban environments.

Air-based persistent sensing approaches can provide much larger area coverage per sensor compared to ground-based approaches, as their operating geometries are much less hampered by urban line of sight obscurations. Numerous manned and unmanned platform options exist. One challenge involves the potential atmospheric obscurations between the sensor and the ground; optical imaging approaches cannot penetrate most clouds. Visible imaging approaches are further limited to day-only operations. Infrared imaging systems can provide true 24 hour coverage, but generally at a higher size, weight, and cost per pixel than visible systems. Radar approaches, while less sensitive to weather, will have other challenges when operating above complex urban environments [3]. Distinguishing true target signals from passive clutter can be very difficult, and high-resolution synthetic aperture imaging approaches work best at relatively low slant angles between the sensor and the ground, which leads to limited coverage due to geometric shadowing from buildings in an urban scene.

Each system and emplacement option has associated strengths and weaknesses. Currently, air-based imaging system concepts appear to offer the most advantages from an area coverage and logistics standpoint, and more operational flexibility than ground-based or airborne radar-based approaches in urban terrain. The remainder of this paper will focus on air-based persistent imaging approaches for military applications.

3. Operational Considerations

Air-based persistent imaging systems have unique challenges and limitations that need to be considered during the system design and subsequent deployment and operation phases. Arguably, the top two challenges involve obscurations due to collection geometries and intervening cloud layers.

Geometries of urban environments will dictate feasible airborne collection geometries and associated ground coverage. The relationship between building height, road width and airborne platform location is depicted in Figure 1. For the case of persistent vehicle or personnel tracking it is important to image as much of the road and adjacent sidewalks as possible; buildings will tend to mask all or part of a road for certain collection geometries.

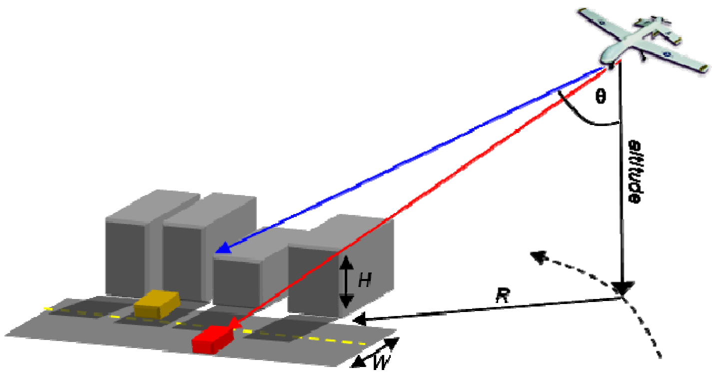

Figure 1 - Geometric relationships of building height, road width and aircraft location

Road obscuration will occur in the presence of buildings for any appreciable diameter of persistent coverage. The graph in Figure 2 plots the geometric relationship between road obscuration and persistent coverage diameter at three different altitudes. Each plot assumes an aircraft flying a circular orbit around a fixed center point, and a typical 13 meter road width and a 2-story building height. It can be seen that operation at higher altitudes will decrease the amount of road obscuration for a given coverage diameter, or will increase the available area coverage for a fixed acceptable level of road obscuration.

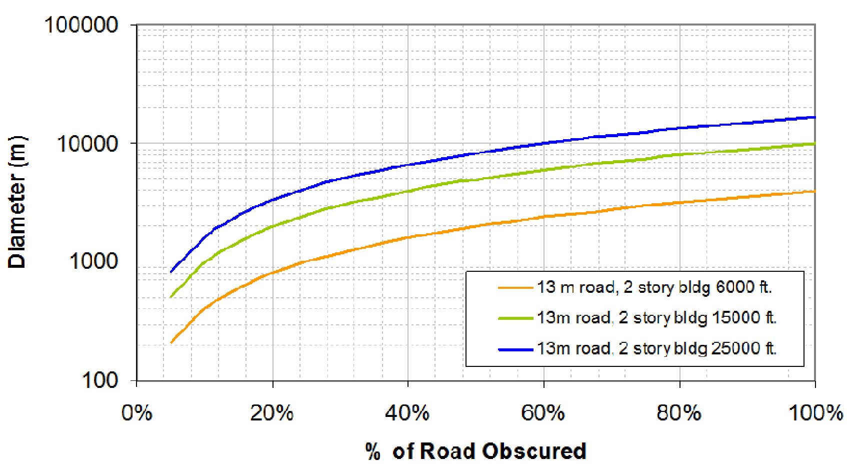

Figure 2 – Area coverage versus road obscuration for altitudes of 6000, 15000 and 25000 feet.

This simple relationship between urban obscuration and operating altitude has important consequences for persistent sensor evolution. As technology improves and sensors become available with increasing fidelity (e.g. as the available pixels in a single digital visible sensor increases from dozens of megapixels to hundreds), it will not be possible to arbitrarily increase coverage area from a given airborne platform.

Geometry will put a hard limit on useful urban coverage unless the platform aircraft can rise in altitude to accommodate the larger sensor fidelity. If the aircraft cannot rise to higher operational altitudes, improvements in sensor pixel density should therefore be utilized to provide increased resolution in a fixed area, and not more coverage area at a fixed resolution.

As mentioned earlier, careful consideration must also be paid to the anticipated meteorological conditions for the area of operations, specifically cloud ceiling height and likelihood of occurrence. Persistent imaging sensors cannot choose the best days to fly – by definition, persistent coverage requires continuous operation over extended periods of time, irrespective of changing weather patterns. Figure 3 shows cloud ceiling statistical data for the climatologic wettest and driest months for example cities in three different regions of the world. As can be seen, imaging sensor operations at altitudes above 10,000 ft. will be significantly impacted by cloud obscuration in certain seasons and parts of the world. Even operation at low altitudes in certain areas does not guarantee the ability to see the ground all months of the year.

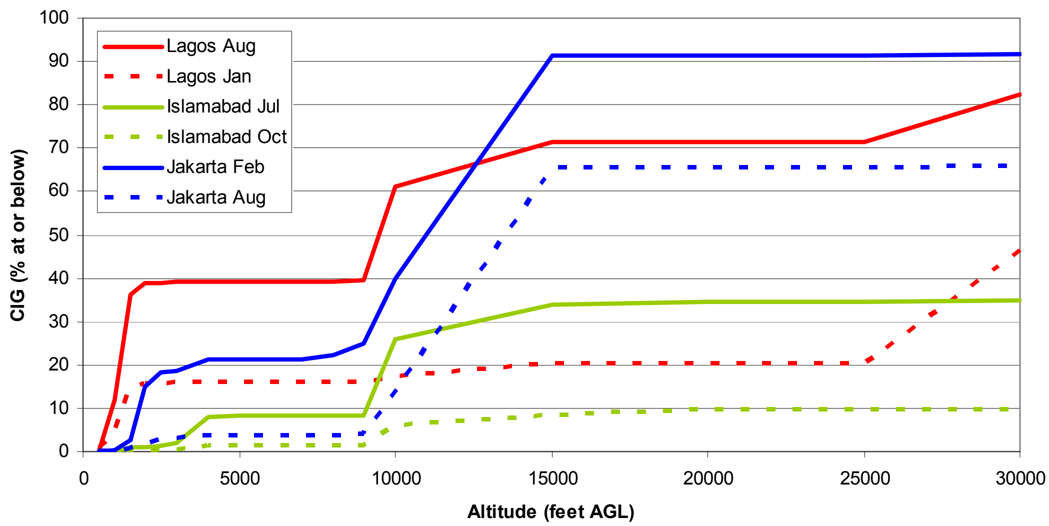

Figure 3 - Likelihood of cloud layer at or below a particular altitude for various geographic locations. Data provided by 14th Weather Squadron, Air Force Combat Climatology Center

The factors of geometric and meteorological obscuration can work together to limit the available options for operationally useful airborne persistent imaging approaches. Higher system altitudes will reduce geometric obscuration in urban terrain but also raise the likelihood of obscured vision due to cloud cover. Lower altitudes will reduce the un-obscured coverage area visible from any single platform, but enable imaging sensors to fly beneath the clouds. One potential solution to these counter-acting factors could be to construct a network of relatively small airborne imaging sensor platforms operating together over the region of interest. Such a network could provide synchronous coverage of a large urban area from favorable imaging geometries while remaining below the typical cloud ceilings for the region.

4. System Concepts and Requirements

Air-based persistent imaging systems must include several key components and sub-systems. These include the host platform, the imaging sensor assembly, an image data processor, and the data storage system, or an image data link to a ground-based storage and analysis site. Careful consideration and analysis must be made with respect to mission requirements, logistics, technology and budget when selecting the combination of these components to assemble into a viable persistent surveillance system concept.

4.1. Platforms

Identification of the candidate air platform (or platforms) is arguably the most important initial selection to be made. This decision will define limits for many important parameters to include operating altitudes, endurance, payload size/weight/power and communications/storage requirements. Platform type (e.g. manned or unmanned) will also heavily influence persistent imaging system design. Manned platforms generally offer more size, weight and power than unmanned offerings. Availability of onboard operators can simplify system design and expand robustness. However, manned platforms can place pilots and operators in harms way, and will limit the maximum duration of any single surveillance mission. Unmanned platforms appear well suited for many aspects of persistent imaging missions. In addition to removing soldiers from harm's way they offer long endurance, and can relieve personnel workloads since it is conceivable for one operator to control multiple platforms (e.g. program orbit and periodically check status). Unmanned aerostats are another viable option for certain applications. These can be either powered or tethered and are able to loiter at a particular spot in space instead of flying an orbital pattern over the region of interest. Each of the loitering approaches (stationary vs. orbital) has its advantages and disadvantages. Example coverage patterns for each approach are shown in Figure 4. Staying at a single location over the region of interest with a fixed viewing geometry will increase the area of persistent coverage as compared to orbiting collection patterns. It will also ease processing with respect to image ortho- and geo-rectification, maintain a constant ground sampled distance (GSD) for each area in the scene and eliminate perceived motion of stationary objects due to parallax. Disadvantages of the fixed point loiter include the fact that any areas occluded by buildings or similar will remain occluded. In contrast, orbiting the region of interest will allow all but the most occluded areas to be imaged at least periodically. Orbiting, however, introduces GSD variations, angular distortion, parallax and other undesirable features into the collected persistent imagery.

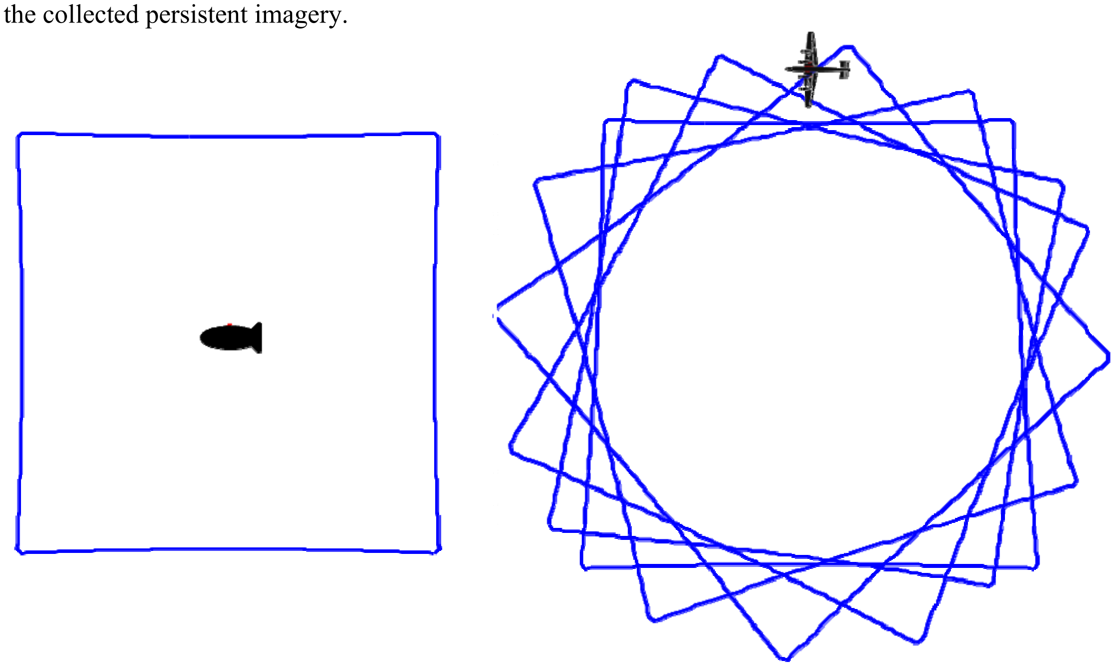

Figure 4: Graphical comparison of a stationary coverage pattern (left) and a sample orbital coverage pattern (right). The pixel count and focal length are the same for both examples. The orbital pattern shown covers about 20% less persistent area, and has a maximum look angle (off nadir) twice that of the stationary sensor

4.2. Onboard hardware

The imaging sensor system installed on the chosen surveillance platform will include the imaging cameras, the image processing electronics, a storage and or datalink system, and the associated pointing, stabilization and scanning hardware. The camera assemblies are typically mounted on a multi-axis gimbaled platform to facilitate independent pointing and stabilization of the sensor irrespective of aircraft motion. Image scanning is typically accomplished through the use of a motorized fast steering mirror (FSM). FSMs can also be used to accomplish image stabilization. The approach chosen for image pointing and stabilization is in large part driven by desired GSD and selection of platform and orbit. The type of required scanning (if any) will be dictated by sensor selection/availability and desired ground coverage/update rate.

By definition, persistent imaging seeks to deliver uninterrupted 24–hour operation. Providing this capability with an optical camera system requires either operation in the thermally emissive infrared (e.g. longwave or midwave) or the use of a reflective band sensor utilizing active or passive illumination. Unlike the visible portion of the spectrum, there are few 'large' pixel format device options in the infrared and those that are available are relatively expensive. Generally speaking, camera cost and size increase with operating wavelength. The following will compare available nighttime sensors and their associated scanning options.

Near infrared (NIR) and shortwave infrared (SWIR) devices are sensitive to energy present in the spectral regions from 0.7-1.0 microns (um) and 1.0-2.5 um, respectively. Energy at these wavelengths is reflective in nature with illumination sources including the sun, moon, stars, cultural lighting and active sources such as lasers. Image quality in terms of signal to noise ratios (SNRs) and dynamic range are dependent on the intensity and distribution of scene illumination. Figure 5 shows some typical limitations in SWIR imagery associated with very bright and dark nighttime illumination conditions in urban terrain. Commercially available SWIR focal plane arrays are available at pixel dimensions up to 1280 x 1024.

Midwave infrared (MWIR) and longwave infrared (LWIR) are thermally emissive bands and consist of wavelength regions from 3-5 um and 8-12 um, respectively. Example MWIR imagery taken at the same time as the SWIR imagery in Figure 5 is shown in Figure 6. Operation in these bands does not require an external illumination source, as objects at typical ground temperatures emit adequate amounts of radiation to create imagery. Thermal variation within a natural infrared scene is also not as dramatic as in NIR or SWIR imagery, leading to much less intra-scene dynamic range to be accommodated in nighttime thermal imagery. Optical diffraction limits favor sensors operating in the MWIR band; optics optimized for a particular resolution will always be smaller in the MWIR versus LWIR [4]. A example of this MWIR diffraction advantage is plotted in Figure 7. However photon availability favors operation in the LWIR band; the lower photon energies associated with longer wavelengths will result in more photons being emitted per second per unit energy in this band [5]. The higher photon flux in LWIR scenes allows for shorter integration times, and thus enables faster scan rates in the LWIR versus MWIR at a given signal to noise ratio.

Figure 5. – Limitations of nighttime SWIR imagery in high and low illumination conditions: Local-area processing has been applied to the regions highlighted in the insets. It can be seen that bright objects in the image saturate, while very dim areas are overpowered by background sensor noise. Intra-scene dynamic range is a significant challenge for nighttime SWIR (and VNIR) imagery in urban environments.

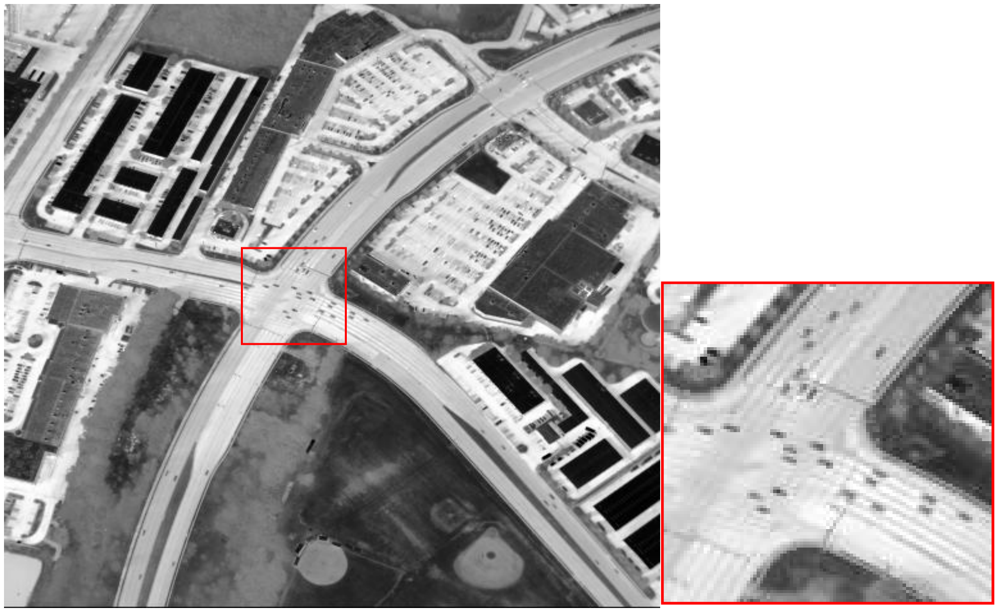

Figure 6 –MWIR image taken of the same scene in Figure 4, above. Passive radiation from the scene enables adequate SNR across the image, and image quality is not limited by dynamic range issues

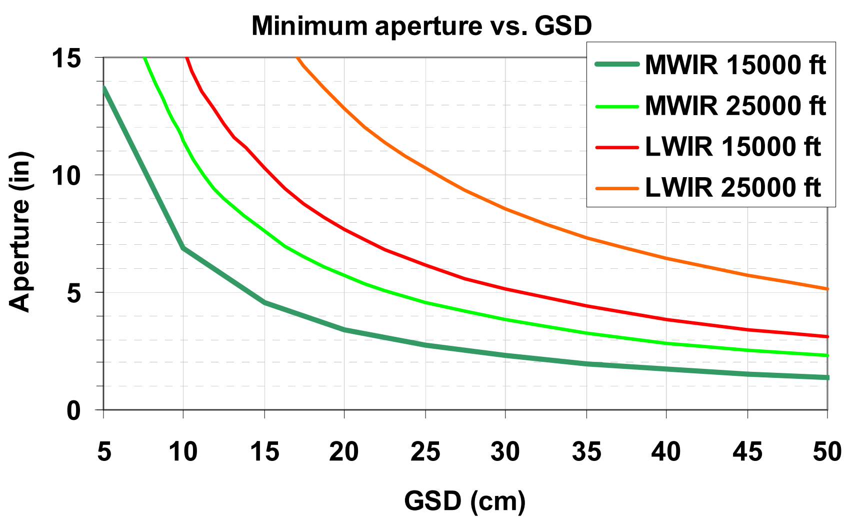

Figure 7 - Comparison of minimum aperture diameters at a variety of desired optics resolutions (measured by ground sampled distance, GSD) for LWIR and MWIR operation. It can be seen that higher resolutions can be achieved for smaller optics apertures using MWIR detectors, holding all other parameters equal.

The relatively small pixel counts of currently available MWIR or LWIR focal plane arrays combined with the size, weight and cost of each infrared FPA and camera assembly makes ganging of multiple cameras to cover large areas impractical for cooled thermal infrared sensors. Currently, staring MWIR infrared arrays can be obtained at pixel counts up to 4096 x 4096. LWIR arrays have been fabricated with 1280 x 1024 pixel elements. Linear infrared arrays are available with pixel counts up to 6144, with time delay and integration (TDI) capabilities providing increased sensitivity along the scanned direction. Due to the slow and risk-intensive process of developing very large format infrared FPAs (>16 megapixels) , practical, near-term infrared persistent imaging systems will use proven FPA technologies combined with either step stare or TDI scanning techniques to maximize area coverage at a reasonable scene update rate. Step stare approaches literally step a sensor across a scene by mechanically moving the field of view. Integration time, angular step size, mechanical pointing limitations, degree of image overlap and desired revisit rate will dictate viable scan patterns and rates. This approach is quite flexible and allows for real time modification of the scan pattern and coverage area. TDI scanning is used with specialized linear infrared arrays that consist of a few rows (4-16) of pixels that are hundreds to thousands pixels across. The devices have the ability to transfer charge down each column while scanning, which allows multiple pixels to view the same portion of a scene and contribute to the collected signal. This capability also results in 100% effective pixel operability as bad pixels can be ignored since other pixels in the column will sample the same area. Both TDI and step-stare approaches have been demonstrated in first generation airborne infrared persistent surveillance imaging systems.

4.3. Onboard processing and storage

Platform selection and mission will strongly influence the onboard processing and storage requirements for a persistent surveillance imaging system. Although early persistent surveillance sensors have chosen the architecturally simplest approach of storing all raw image data onboard the aircraft for subsequent post-mission processing, this approach will scale poorly for long-duration missions, and can lead to significant latencies in producing useful surveillance information to users after mission completion. Ideally, one would like to conduct image processing on board immediately after capture, and only save or send resulting information products (e.g. vehicle and personnel track files) to the user. The fact that most of any single image captured by a persistent surveillance sensor has not changed from the previous frame taken moments before suggests that processing techniques which detect and save (or transmit) data on image-to-image changes within the scene could yield dramatic amounts of reduction in data from the sensor. Such change-based processing will require fast and efficient processing hardware and robust algorithms to rapidly ortho- and geo-rectify large image files before they are compared to previous frames for changes. Future generations of airborne persistent imaging sensors will likely use a variation of this change-based processing approach to handle the large quantities of imagery captured per mission. Any selected processing and storage techniques must also include the ability to associate accurate time and location metadata with the saved or transmitted image information.

5. Conclusions

Airborne persistent imaging systems show great promise to aid the warfighter in combating asymmetric threats in complex urban terrain. Properly optimized airborne imaging systems can enable a full range of real-time overwatch capabilities and simultaneous forensic coverage to permit the determination of enemy trends and tactics through longer duration monitoring of networks and activities. A first-generation of airborne persistent surveillance imaging sensors has been operationally demonstrated, and future systems are being actively developed by a number of laboratories [6]. Passive infrared persistent imaging systems provide particular value by enabling continuous overwatch and activity monitoring both day and night. Operationally, careful consideration must be made to collection geometries and meteorology. Component technologies are currently available to support multiple viable infrared persistent imaging system approaches. Platform selection and availability will help define limits for many important parameters and ultimately make the system development trade space more manageable. Development of robust and efficient image processing techniques that can be implemented on the aircraft alongside the sensor system will assist in the areas of data storage, data transmission and/or post processing.

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