The Open Skies Treaty: Qualitative Utility Evaluations of Aircraft Reconnaissance and Commercial Satellite Imagery

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Abstract

The International Open Skies Treaty provides for the independent collection of aircraft imagery, in addition to commercially available satellite data, over selected arms and weapons facilities. This paper compares the joint and relative utility of commercially available satellite data and aircraft imagery in an analysis of information content for Open Skies Treaty monitoring requirements. Thematic Mapper Simulator (TMS), Thermal Infrared Multispectral Scanner (TIMS), and APD-10 radar data were used to simulate a range of spatial resolutions and to determine the utility of each data set. A qualitative analysis of the simulated aircraft imagery, at progressively improved resolutions, revealed an exponential increase in Treaty-specific information content starting with 10-m resolution.

Introduction

The Open Skies Treaty was signed on 24 March 1992 by the United States, Canada, other NATO members, and former Warsaw Pact states, including Russia, Ukraine, and Belarus. Designed as a confidence-building measure, the agreement allows member party states to overfly the territory of other member states using aircraft fitted with a variety of treaty-specified sensors. Though the specific sensors and aircraft continue to be negotiated by the Parties, certain sensor categories have been determined (Banner *et al.*, 1990). The "allowed" sensor types include optical framing and panoramic and video cameras, infra-red line scanning devices, and side looking synthetic aperture radar (SLAR). The agreement has provisions for the future addition of sensors. Possible future additions might include such systems as electro-optical cameras, air sampling devices, and multispectral sensors; however, additions must be approved by mutual agreement among all Treaty participants. Currently, the minimum allowed ground resolution for optical sensors is 30 cm, 50 cm for infra-red line scanners, and 3 m for the SLAR capabilities, and these far exceed both SPOT and Landsat capabilities. Data from Open Skies sensors will be available not only to the observed and observing parties but also to any Treaty party submitting a request.

This report provides a preliminary (Phase I) assessment of the potential utility of simulated Open Skies Treaty imagery as well as additional, simulated complimentary commercially available imagery.

Background

For the first year after entry-into-force (EIF) of the Treaty, the United States is obligated to accept up to 31 overflights. Unless otherwise agreed, this number will rise to 42 per year for the life of the Treaty, which has unlimited duration.

Each overflight may vary in actual flight path and timing. Flight paths may be unique for every overflight following any path from straight line to serpentine. The observing party is, however, restricted from loitering over one point, except on take-off and landing, and from crossing its own flight path more than once. The time the observing party allocates to execute the flight plan is largely at their discretion. They have a total of 96 hours from the time they arrive at the Point of Entry (POE) to complete their observation overflight. Designated POEs, for example, are Dulles Airport, Washington, D.C., and Travis Air Force Base, Fairfield, California. Included in this 96-hour period are allowances for formal greeting procedures, travel to an Open Skies Airfield (if different from the POE), inspection of the aircraft to ensure sensor operation within Treaty allowances, and discussion of the proposed flight plan. At any point during their overflight, the observing party may also stop at agreed airfields for rest or refueling (any airfield is eligible to be designated as a weather alternate or emergency divert). Thus, the actual time spent collecting data during an Open Skies observation overflight will vary with each occurrence.

Table 1 indicates the maximum number of overflights each additional member country must accept and the number of flights each is currently scheduled to host and conduct. With regard to equipment, as indicated previously, the basic decisions that have been agreed upon are

- imaging sensor resolutions
  - minimum of 30 cm for panoramic cameras
  - minimum of 30 cm for video cameras
  - minimum of 50 cm for thermal infrared sensors
  - minimum of 3 m for side looking radar sensors
- aircraft requirements
  - flight plans must be submitted in advance
  - selection of host aircraft or own for overflights
  - mandated use of specific sensors on aircraft overflights
  - host country observer will accompany each flight
  - all imaging products must be shared with host country
  - collected imagery may be sold to other interested countries
- number of flights
  - maximum of five flights a year per country
  - maximum of 40 flights per year over any one country
  - collections must occur within a 96-hour planning window

Although generic electromagnetic "windows" through which the reconnaissance could be acquired were chosen,

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TABLE 1. OVERFLIGHTS SLATED UNDER THE OPEN SKIES TREATY

Country	Passive Quota*	Flights Received in First Year**	Flights Conducted in First Year**
Germany	12	5	4
America	42	4	8.5
Russia/Belarus	42	28	26
Benelux	6	2	2
Bulgaria	4	3	3
Canada	12	2	4.5
Denmark	6	2	2
Spain	4	0	1
France	12	3	4
UK/Ireland	12	3	4
Greece	4	3	2
Hungary	4	3	2
Iceland	4	0	0
Italy	12	3	3.5
Norway	7	2	3
Poland	6	5	3
Portugal	2	0	0
Romania	6	4	4
Czech & Slovak	4	3	2
Turkey	12	5	4.5
Ukraine	12	9	6

*Passive quota indicates the number of flights a country is committed to accept, if requested by other treaty parties. Depending upon overflight requests, the passive quota may or may not be filled. For the first three years after entry into force, countries are required to accept only 75 percent of their passive quota.

**The first year distribution of active quotas will be valid from the date of entry into force of the treaty until 31 December of the following year.

specific sensors continue to be considered. As an example, a window was chosen that would accommodate an electro-optical imaging sensor, but whether that sensor would acquire panchromatic, color, or multispectral products was not identified. The stippled areas in Figure 1 depict where these windows fall in relationship to the electromagnetic spectrum. Note especially that both the infrared and radar windows can accommodate a wide variety of sensors.

Because the significant above detail has yet to be resolved, it was the study goal to review a variety of simulated data, to be made commercially available to global customers, from both commercial satellite and reconnaissance aircraft sensors. This analysis, then, was conducted to determine what types of information could be acquired through Open Skies reconnaissance activities.

Imagery and Reconnaissance

Technical and political battles have been waged since the early 1950s on the utility of satellite imaging sensors versus aircraft imagery reconnaissance. Many of the technical decisions used at that time helped to justify the U2 aircraft and other National Technical Means which remain pertinent today, although how such systems and sensors would be used has changed significantly.

To determine the spatial resolutions necessary for specific types of analyses, it is appropriate to examine the sizes, densities, and contrasts of features that will eventually be under investigation (Welch, 1982). Indeed, as previous studies have suggested (NASA, 1983; Botkin *et al.*, 1984), the level of detail for an investigation is primarily a function of spatial resolution. Multispectral and multisensor resolutions are also important; however, these parameters are not as critical as spatial resolution (Jensen, 1986). Thus, the determination of the needed spatial resolutions for Open Skies interpretations is a function of the analytical requirements for the monitoring activities.

For Open Skies, there will be a variety of interpretation requirements ranging from site generalization to item-specific identification. These ranges and the required spatial resolutions closely parallel documented requirements (Anderson *et al.*, 1976; Welch, 1982; Jensen *et al.*, 1983) for traditional land-cover and land-use investigations. Accordingly, virtually all obtainable data ranging from the 7- by 7-km NOAA GOES to the proposed high resolution aircraft imagery have the potential to contribute information to Open Skies databases.

Using current commercial satellite capabilities and those of commercially available aircraft, Table 2 provides a general review of the advantages and disadvantages of both collection capabilities. Most pertinent to this study are the unpredictability of aircraft flights, the high spatial resolutions of their sensors, and the vast global reservoir of experienced photographic interpreters; and the non-intrusiveness of satellite coverage, poorer spatial resolutions of their sensors, the capability of covering enormous surface areas, and the added sophistications necessary to exploit most of their products.

This imagery assessment makes several working assumptions concerning Treaty modalities and future behavior. Generally, the Treaty allows for the following:

- There will be between four and 31 overflights of United States territories during the first year after the Treaty enters into force. The United States is currently obligated to accept up to 31 overflights in the first year after IEF. Other state parties have targeted the United States for only four overflights

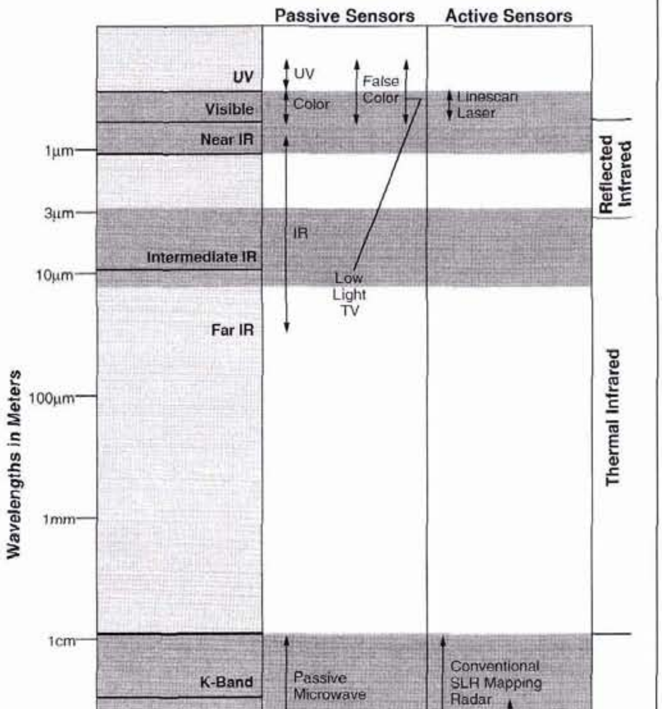

Figure 1. Relationship of unconventional imaging sensors to the electromagnetic spectrum.

TABLE 2. ADVANTAGES/DISADVANTAGES OF COLLECTION SYSTEMS

Advantages and Disadvantages of Satellite Imagery Collection	
Advantages	Disadvantages
Non Intrusiveness	Poor Spatial Resolutions
Stable Platform	Poor Response to Equipment Failure
Wide Area Global Coverage	Additional Training Needed
Periodicity of Coverage	Poor Response Times
Cost of Coverage Per Square Mile	Priorities Controlled by a Few Nations
Long Life Cycle	
Advantages and Disadvantages of Aircraft Imagery Collection	
Advantages	Disadvantages
Rapid Response Times	Political Visibility
High Spatial Resolutions	Vulnerable to Intercept
Unpredictable Collection Times	Vulnerable to Weather
Large Reservoir of Available Trained Analysts	Terrain and Obstruction Masking
Some Control by Host Country	Amenable to Industrial Spying
Low Altitude Oblique Viewing	

during this time; however, state parties may still request more overflights. As additional state parties sign the Treaty, they may also request overflights.

- The U.S. will be obligated to accept up to 42 overflights per year for the life of the Treaty.
- Electro-optical, air sampling, and multispectral sensors may eventually be added to the current, agreed upon sensor suite. The Treaty provides for additions to the allowed sensor suite, although the above sensor types were deleted from the suite late in negotiations.
- Sensor data will be obtained and used by all Treaty party states. The Open Skies Treaty provides for distribution of overflight data to all member states upon request.
- Secondary data distribution may occur. Because of the large number of Treaty parties and the nature of the data collected, the possibility of overflight data distribution to nations outside the Treaty framework can not be discounted.
- All Conference on Security and Cooperation in Europe (CSCE) member states will join and ratify the Treaty.
- Treaty modalities will vary with the world political climate. Although the United States is initially scheduled for a small number of overflights in the first year of the Treaty, the situation could quickly change according to the political or military motivations of member states.
- Facilities will have short-notice of impending Open Skies overflights. Overflown facilities will have less than 24 hours notice of an impending overflight.

During the past years, the technical capabilities of spaceborne imaging sensors have been slowly evolving and are reaching a point where the advantages of high spatial resolution may no longer reside strictly in the aircraft domain. As an example, Russia is currently selling 2-m spatial resolution panchromatic, 5-m multispectral products, and 15-m Synthetic Aperture Radar (SAR) imagery to global customers. Further, the success of the Landsat and SPOT satellites has spawned a plethora of other proposed commercial multispectral sensors.

To advanced space-based commercial systems, improved aircraft platforms pose additional threats beyond those of spatial resolution. As a comparative example, imagery acquired from orbital altitudes provides near planimetric area scenes; in fact, with the exception of the French SPOT sensor, this is the intent. Aircraft coverage, acquired at low altitudes using similar sensors, has the capability of acquiring oblique information about facilities beyond what can be acquired by satellites. Practical illustrations of this would include the capability to identify power transformers, and lead-ins adjacent or attached to walls or under roof overhangs. Looking into large facility bays through open aircraft hanger doors or under "environmental" covers over open storage will make conventional concealment efforts less effective, security guidelines more complicated, and general security procedures to protect proprietary rights more expensive. Conversely, however, the additional masking of objects by the terrain and other obstructions could occur due to the low altitudes being flown.

The high spatial resolutions from the aircraft sensors may provide a significant potential for industrial spying and for the reverse engineering of sensitive industrial processes. Means must be devised to bound the vulnerabilities of major facilities to industrial spying and establish protective measures without adversely affecting Open Skies policies.

Details frequently overlooked when comparing imagery products are how much the additional spectral data acquired from multispectral sensors compensate for their poorer spatial resolution, and whether the merging of multiple sensor products synergistically adds to intelligence derived from individual sensor products. Generally, the more sophisticated the equipment and analysts are in exploiting multiple products, the greater will be their advantage over others using conventional techniques to exploit individually the same sensor products. Such data must be placed in the equation when considering the extent of the information that can be acquired from products made available to all participants.

Methods

To bound the extent and usefulness of data to be acquired from scheduled aircraft overflights of sensitive installations as well as data available from current and pending commercial satellite sensors, baseline tests were devised to estimate imagery utility.

Specifically, Thematic Mapper Simulator (TMS), Thermal Infrared Multispectral Scanner (TIMS), and APD-10 radar data were evaluated to determine obtainable information content levels relative to variant spatial resolutions of the imagery. For each data set, the imagery was degraded to predetermined spatial resolutions, and, starting with the largest resolution and proceeding to the smallest resolution, interpreters rated the utilities of each data set for satisfying Open Skies identification requirements.

The TMS imagery set was acquired by the NASA Lear jet aircraft over Barksdale Air Force Base, Louisiana. (During the collection, B-52, KC-10, and A-10 aircraft were resident at Barksdale.) To compliment these data, a Zeiss RMK 15/23 aerial mapping camera was also used during the collection. The TMS data of Barksdale were collected on 28 April 1986 from 17:03:38 to 17:04:48 (local time) at a nominal altitude of 1006 m (or 3,300 ft); from this height, the TMS provided imagery with a 2.5-m spatial resolution. In comparison, the coincident Zeiss RMK 15/28 imagery (Kodak 2443 color infrared (CIR) film) had a photographic scale of 1:16,600, yielding a spatial resolution of better than 0.3 m. Spectral resolutions of the TMS are provided in Table 3.

To degrade the spatial resolution of the TMS imagery, a

TABLE 3. SPECTRAL RESOLUTION OF TMS BANDS

Bands	Spectral Range (micrometres)
1	0.46-0.52
2	0.53-0.60
3	0.63-0.69
4	0.77-0.90
5	1.53-1.73
6	2.06-2.33
7	10.30-12.30

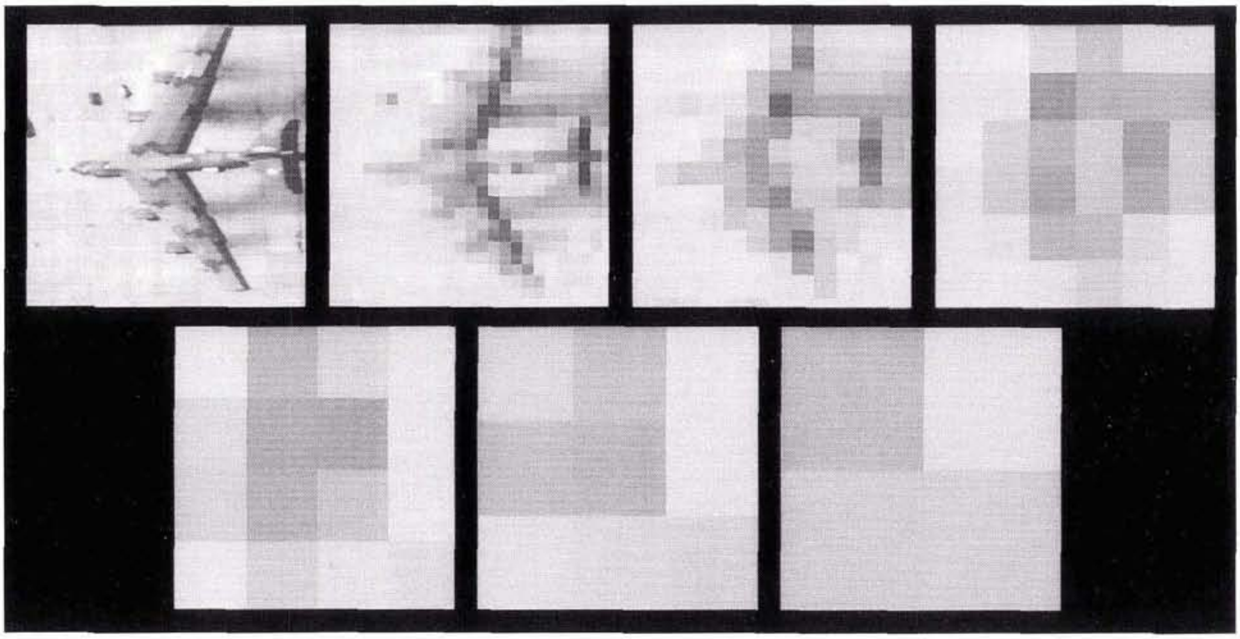

Figure 2. Panchromatic example of imagery degradations. Shown, starting at the upper-left, is a B-52 at 0.3-, 2.5-, 5-, 10-, 15-, 20-, and 30-m spatial resolution.

pixel averaging technique was employed which consolidated the original 2.5-m spatial content. Using the process, a given output pixel (BVout) was comprised of the original brightness values divided by a scaling factor. By doing this, BVout became an averaged pixel based on all associated original radiometric values from the appropriate 2.5-m pixels. Figure 2 depicts an example of this spatial degradation with reference to a B-52.

The first TMS imagery evaluation set consisted of a Band-3 (panchromatic) collection. This one-band collection was created to simulate the type of information obtainable from space-borne and aircraft panchromatic systems. The specific degradation levels are provided in Table 4.

The next set of TMS images comprised a reflective color infrared composite (Bands 4, 3, and 2). These were similar to data obtainable from space-borne and aircraft multispectral systems. The degradation levels were the same as the panchromatic examples (Table 4).

The TIMS data were also collected by NASA over Barksdale on 28 April 1986. The collection time window, however, changed and was from 19:34:20 to 19:35:12 (local time) and the altitude was increased to 1371 m (or 4,500 ft). The resultant spatial resolution was 3.0 m. Spectral resolutions of the TIMS are provided in Table 5.

Using the degradation technique discussed previously, the thermal data were degraded accordingly and prepared for evaluation. Although a multispectral thermal data set, the evaluation images were retained as panchromatic images using Band 1. (Band 1 provided the best contrast and also had the least detector error/noise.) The specific degradation levels are provided in Table 6.

Lastly, the APD-10 radar data were collected in 1965 over the Cherry Point Marine Corps Air Station, North Carolina. The APD-10 was an X-band radar system, and the original resolution of the data was approximately 5 m. As with the other data sets, the radar imagery was degraded to specific levels and prepared for evaluation (Table 7).

Understanding the intent and goal of the Open Skies program, experienced image evaluators were asked to review the respective data sets. Again, for each type of data, the evaluation started with the largest spatial resolution and progressed to the smallest. The goal was to have the evaluators qualify the relative Open Skies contributions and utilities of the respective data sets and resolutions.

The responses from the imagery evaluators were then qualitatively analyzed. The goal of these inductive processes was to derive a linear analytic generalization (Yin, 1989) and summarize the descriptive inputs. This included a pattern-matching logic (Cook and Campbell, 1979) whereby the empirical response patterns were matched with a predicted pattern of increased utility being a function of increased spatial resolution. To study these patterns, the evaluators' inputs were placed into information arrays; categorical, checklist, and dynamics matrices (Miles and Huberman, 1984); and

TABLE 4. DEGRADATION LEVELS FOR TMS PANCHROMATIC AND REFLECTED COLOR INFRARED IMAGE EXAMPLES

Resolution (metres)
30
20
15
10
5
2.5
< 0.3*

*Digitized photography.

TABLE 5. SPECTRAL RESOLUTIONS OF THE TIMS BANDS

Bands	Spectral Resolution (micrometres)
1	8.2-8.5
2	8.6-8.9
3	9.0-9.3
4	9.6-10.2
5	10.3-11.1
6	11.3-11.6

Table 6. Degradation Levels for TIMS Panchromatic Image Examples

Resolution (metres)
120
30
20
10
3

Table 7. Degradation Levels for APD-10 Radar Image Examples

Resolution (metres)
25
15
5

critical incident charts (Glaser and Strauss, 1967; Stiegelbauer *et al.*, 1982).

Results

For site-specific interpretation applications, there were exponential advantages associated with improved levels of spatial resolution (Figure 3). This was particularly the case for the panchromatic and color infrared TMS data. The initial increase occurred at approximately 10 m and progressed rapidly to the 0.3-m level. In comparison, the TIMS imagery was not rated as highly as the TMS collection; however, the highest spatial resolution (3.0 m) was substantially less than the 0.3-m TMS imagery. Nevertheless, the same increase of information content was noticed as resolution increased. Finally, for the radar examples, the increase pattern was observable but not to the degree of the TIMS or TMS increases.

From these results, it is suggested that the poorest acceptable resolution for obtaining data utility for item-specific Open Skies applications is in the 10-m range. Furthermore, as spatial resolution improves from this 10-m point, the relative and absolute utilities of the data increase dramatically.

Typical replies from viewing imagery at or near the spatial resolutions selected by the Open Skies forum include

- Visible electro-optical imagery at 0.3 m spatial resolution provides very high intelligence value such as
  - identification and classification of aircraft types;
  - detection of people conducting activities;
  - analysis of paint schemes, minor structural detail of objects, buildings under construction, etc.; and
  - vehicle and facility equipment identification.
- Thermal infrared 3-m spatial resolution imagery provides moderate intelligence value (although Open Skies can provide thermal imagery at 50 cm, no examples could be found in the time allocated). Its most obvious capability is to record data at night when electro-optical sensors cannot operate, thereby adding flexibility to overflight scheduling. At 3 m spatial resolution, intelligence can be acquired as follows:
  - operating vs. non-operating vehicles or equipment;
  - fuel status of aircraft, storage tanks, etc.;
  - identification of aircraft by type; and
  - relative thermal differences in effluents and cooling ponds.
- Radar 5-m spatial resolution imagery provides low intelligence value (although Open Skies can provide radar imagery at 3 m, no examples could be found in the short time allocated; however, the APD-10 radar imagery used in this test was purported to be 3 m but was likely slightly larger). Foremost in its collection capabilities are those of acquiring imagery regardless of time of day or weather conditions. The following are the kinds of intelligence that can be acquired by a 5-m radar system:
  - identification of airfields,
  - detection of presence or absence of small aircraft,
  - detection of aircraft sizes (small, medium, large), and
  - detection of small ships and ship wakes.

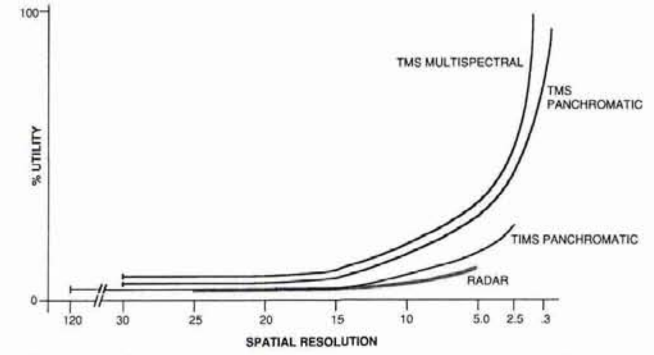

Figure 3. Results from the TIMS, TMS, and radar utility comparison.

Summary and Conclusions

Based upon this baseline resolution analysis, generalized conclusions can be made. First, aircraft imagery collections conducted under the current Open Skies agreements will provide a significant amount of intelligence data beyond that which can be acquired by current and pending commercial satellite sensors, although satellite systems, in particular, the 10-m SPOT system, will play an important role in Open Skies activities.

Second, the highest quality commercial orbital thermal capability resides in the Landsat Thematic Mapper which produces its product at 120-m spatial resolution and allows little potential for detecting individual objects other than very large facilities, cooling ponds, and thermal pollution of natural water bodies. Comparatively, aircraft thermal sensor products providing 50-cm spatial resolution will understandably offer much greater utility.

Third, current commercial satellite imaging radar systems provide no better than 15 m spatial resolution, thereby limiting their utility for the detection of changes in activity levels at facilities, regardless of weather or time of day. At this resolution, major changes of activity levels at airfields or industrial facilities, aircraft on field, and presence or absence of large ships at docks can be detected. Radar imagery less than 5m spatial resolution can, however, provide a wealth of intelligence regardless of the time of day or weather conditions.

Conclusions beyond those based strictly on the imagery evaluation suggest multiple image exploitation and database management will provide additional intelligence beyond that which can be produced from a single sensor. An example would be the registration and superpositioning of products from optical and thermal sensors of differing spatial resolutions to identify precise information. Also, multiple spectral bands, regardless of sensor type, can be registered and exploited through conventional and evolving multispectral analyses to produce additional spectral information about a targeted facility.

Finally, with regard to data collections, the capability of aircraft to fly "under the weather" and at any given time within a 96-hour window provides much greater scheduling flexibility than can be provided by commercial satellites. More importantly, the use of panoramic imagery collected by low flying aircraft provides an ability to acquire intelligence data that is usually masked from observation by orbiting satellite systems.

Certainly, with these Open Skies data being available to the global community, the Open Skies mission—being to