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Commercial Satellite Imagery as an Evolving Open-Source Verification Technology:

Emerging Trends and Their Impact for Nuclear Nonproliferation Analysis

Frank Pabian

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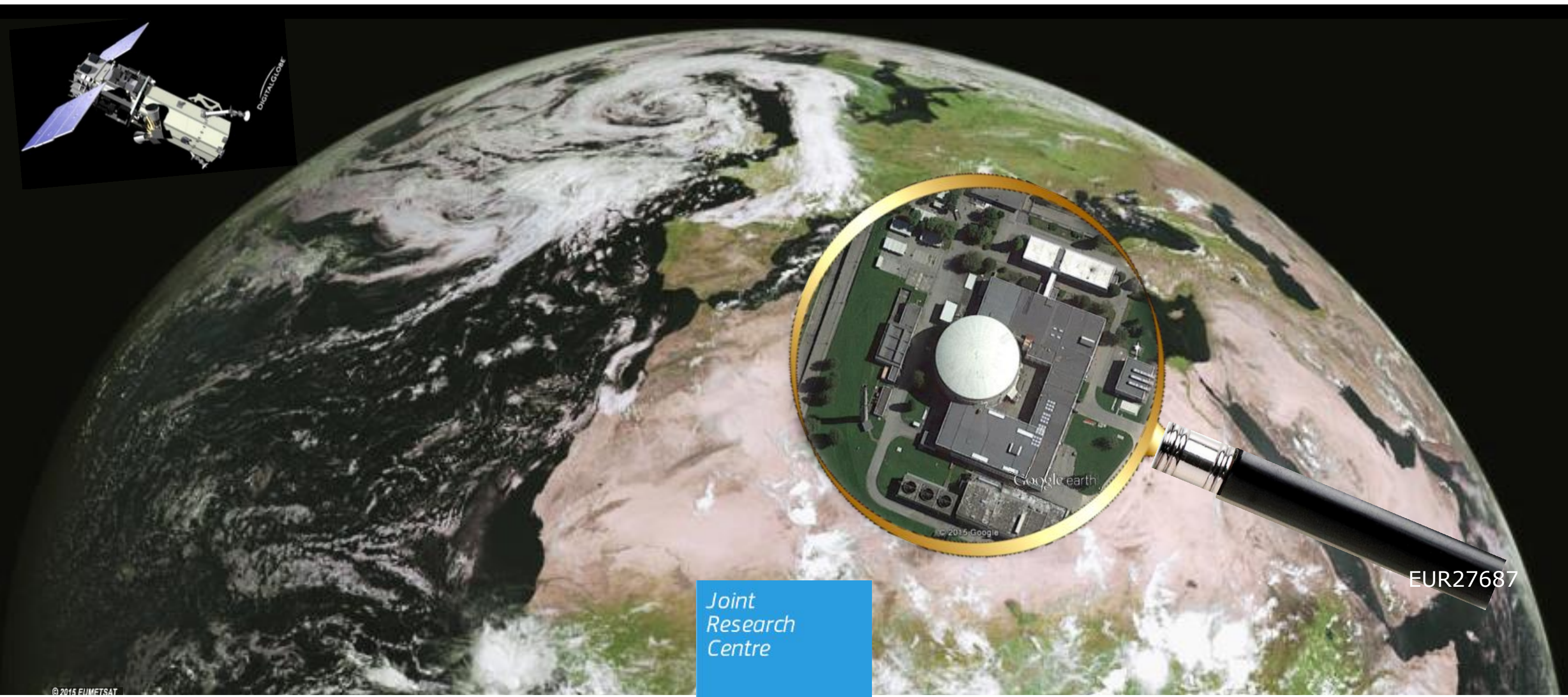

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Abstract

One evolving and increasingly important means of verification of a State's compliance with its international safeguards obligations involves the application of publicly available commercial satellite imagery. The International Atomic Energy Agency (IAEA) views commercial satellite imagery as "*a particularly valuable open source of information.*" In 2001, the IAEA established an in-house Satellite Imagery Analysis Unit (SIAU) to provide an independent capability for "*the exploitation of satellite imagery which involves imagery analysis, including correlation/fusion with other sources (open source, geospatial, and third party). Commercial satellite imagery not only supports onsite inspection planning and verification of declared activities*," but perhaps its most important role is that it also "*increases the possibility of detecting proscribed nuclear activities.*"

Analysis of imagery derived from low-earth-orbiting observation satellites has a long history dating to the early 1960s in the midst of the Cold War era. That experience provides a sound basis for effectively exploiting the flood of now publicly available commercial satellite imagery data that is now within reach of anyone with Internet access. This paper provides insights on the process of imagery analysis, together with the use of modern geospatial tools like Google Earth, and highlights a few of the potential pitfalls that can lead to erroneous analytical conclusions. A number of illustrative exemplar cases are reviewed to illustrate how academic researchers (including those within the European Union's Joint Research Centre) and others in Non-Governmental Organizations are now applying commercial satellite imagery in combination with other open source information in innovative and effective ways for various verification purposes.

The international constellation of civil imaging satellites is rapidly growing larger, thereby improving the *temporal* resolution (reducing the time between image acquisitions), but the satellites are also significantly improving in capabilities with regard to both *spatial* and *spectral* resolutions. The significant increase, in both the volume and type of raw imagery data that these satellites can provide, and the ease of access to it, will likely lead to a concomitant increase in new non-proliferation relevant knowledge as well. Many of these new developments were previously unanticipated, and they have already had profound effects beyond what anyone would have thought possible just a few years ago. Among those include multi-satellite, multi-sensor synergies deriving from the diversity of sensors and satellites now available, which are exemplified in a few case studies.

This report also updates earlier work on the subject by this author and explains how the many recent significant developments in the commercial satellite imaging domain will play an ever increasingly valuable role for open source nuclear nonproliferation monitoring and verification in the future.

1. Introduction

One steadily improving means of verification of a State's compliance with its obligations involves the application of publicly available commercial satellite imagery. The International Atomic Energy Agency (IAEA) views commercial satellite imagery as "*a particularly valuable open source of information*.[1] In 2001, the IAEA established an in-house Satellite Imagery Analysis Unit (SIAU) to provide an independent capability for "*The exploitation of satellite imagery which involves imagery analysis, including correlation/fusion with other sources (open source, geospatial, and third party)*.[2,3] Since then, commercial satellite imagery "*has become one of the most important information sources the IAEA's Department of Safeguards has for remotely monitoring nuclear sites and activities*." [4] It also "*increases the possibility of detecting proscribed nuclear activities*," while also providing an efficient means to support onsite inspection planning and verification of declared activities.[5]

Analysis of imagery derived from orbiting earth observation satellites has a long history dating to the early 1906s during the Cold War era, and provides a sound basis for effectively exploiting the flood of commercial satellite imagery data that now made available to anyone with Internet access. This paper provides insights on the process of imagery analysis, together with the use of modern geospatial tools, and highlights a few of the potential pitfalls that can lead to erroneous conclusions. A number of illustrative exemplar cases are reviewed to illustrate how academic researchers (including those within the European Union's Joint Research Centre) and others in Non-Governmental Organizations are now applying commercial satellite imagery in combination with other open source information in innovative and effective ways for various verification purposes.

Although commercial satellite imagery has already been proven to be an effective and accepted means for nuclear monitoring, verification, and mission planning for IAEA safeguards purposes[6], it is still a relatively new "open-source" technology for routine information collection and analysis for such purposes. Commercial satellite imagery (and its requisite processing and analysis) is continuing to evolve and advance as a result of radically new improvements in terms of spatial, spectral, and temporal resolutions from increasingly diverse and rapidly growing international satellite constellations. [7] Commercial satellite imagery, although not a stand-alone open-source panacea, remains a unique verification information source technology that provides an optimal non-intrusive capability to remotely "peer over the fence" to obtain unique information from otherwise inaccessible areas, anywhere on earth, on a consistently repetitive basis. Improved means of access to this multi-resolution imagery diversity (with rapid revisits for global surveillance in near-real time) will increasingly also provide a new basis for open-source information augmentation with previously unexpected synergistic effects.[8,9]

This report: 1) reviews some key elements of that technologically driven geospatial (r)evolution, 2) updates earlier work on the subject by this author,[10] and 3) explains how commercial satellite imagery will play an ever increasingly important role for nuclear nonproliferation monitoring and verification in the future.

2. A Short Retrospective: From CORONA to Commercial

Remote sensing from space-based orbital platforms for information collection had its beginnings with the dawn of the Space Age in the late 1950s/early 1960s, when it first became possible to place cameras in polar earth orbit to remotely photograph any point on the globe on a routine and predictable basis. Among the first applications for satellite-based imagery collection was for military intelligence information gathering or "reconnaissance" purposes. US Government reporting, now declassified (although formerly highly classified), provides a wealth of information on the utility and value (and limitations) that such a remote sensing capability could have, particularly with respect to verification and monitoring beginning with the US CORONA Program when "*Satellite imagery became the mainstay of the US arms-control verification process.*"[11] The classified cameras systems steadily and dramatically improved with time in terms of spatial resolution (the smallest adjacent ground features that can be distinguished as separate entities) from the initial **12** meters down to **1.5** meters for the CORONA systems when that program ended in 1972, to better than **61 centimeters** with the Keyhole (KH)-7 and -8 systems that were operated into the 1980s[12] (**see Figure 1**).

The CORONA program analytical reporting shows that, even with panchromatic imagery from non-digital/analog (photographic film-based) cameras, which provided resolutions (ground sample distance, or GSD) of **1.5** meters resolution or lesser quality[13], it was possible for "photo-interpreters" using micro-stereoscopes and light tables to discern and convey important treaty verification relevant information. The finished reporting often required significant use of artistic perspective drawings[14] or hand-built 3D models to assist policy makers to more effectively visualize the key aspects of those findings.[15](**See Figure 2**)

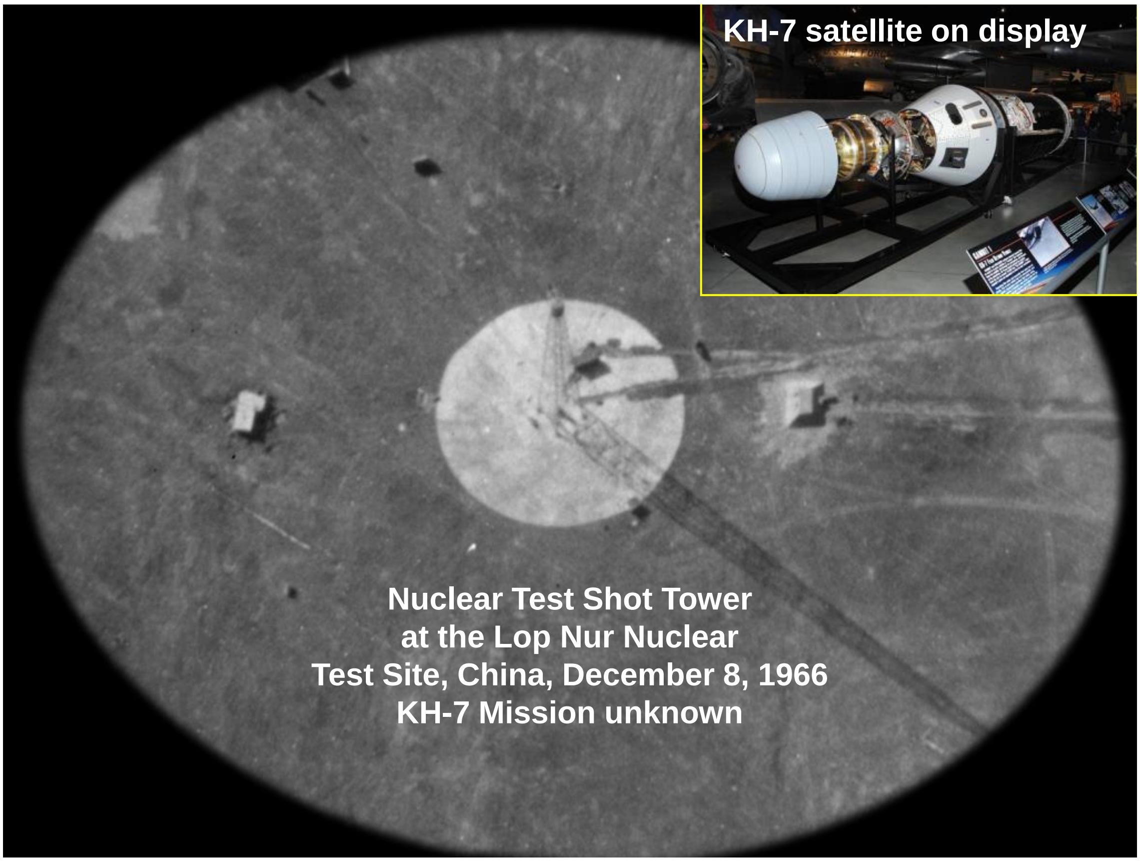

Figure 1: A declassified Keyhole exemplar satellite image of the Lop Nur nuclear test site in China acquired on December 8, 1966 by a KH-7 satellite as shown display in the inset. Sources: http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB186/index.htm *(inset: U.S.A.F. from* http://www.space.com/12997-photos-declassified-spy-satellite-pictures.html)

Among the declassified reporting were documents containing detailed descriptions of long-range ballistic missile deployments, nuclear weapons storage sites, uranium mines, nuclear test sites, and submarine bases.[16] With respect to the use of satellite imagery for nuclear facilities from a treaty monitoring and verification perspective, a CIA *Studies in Intelligence* article specified,

> *"Overhead imagery enabled the detection and analysis of critical elements of the Soviet nuclear infrastructure…Because of denial and deception counter-measures, however, the USSR's nuclear program was an exceptionally hard target. The lack of reliable on-the-ground intelligence made it difficult for the West to understand important developments inside the Soviet nuclear complex, which resulted in significant intelligence gaps."*[17]

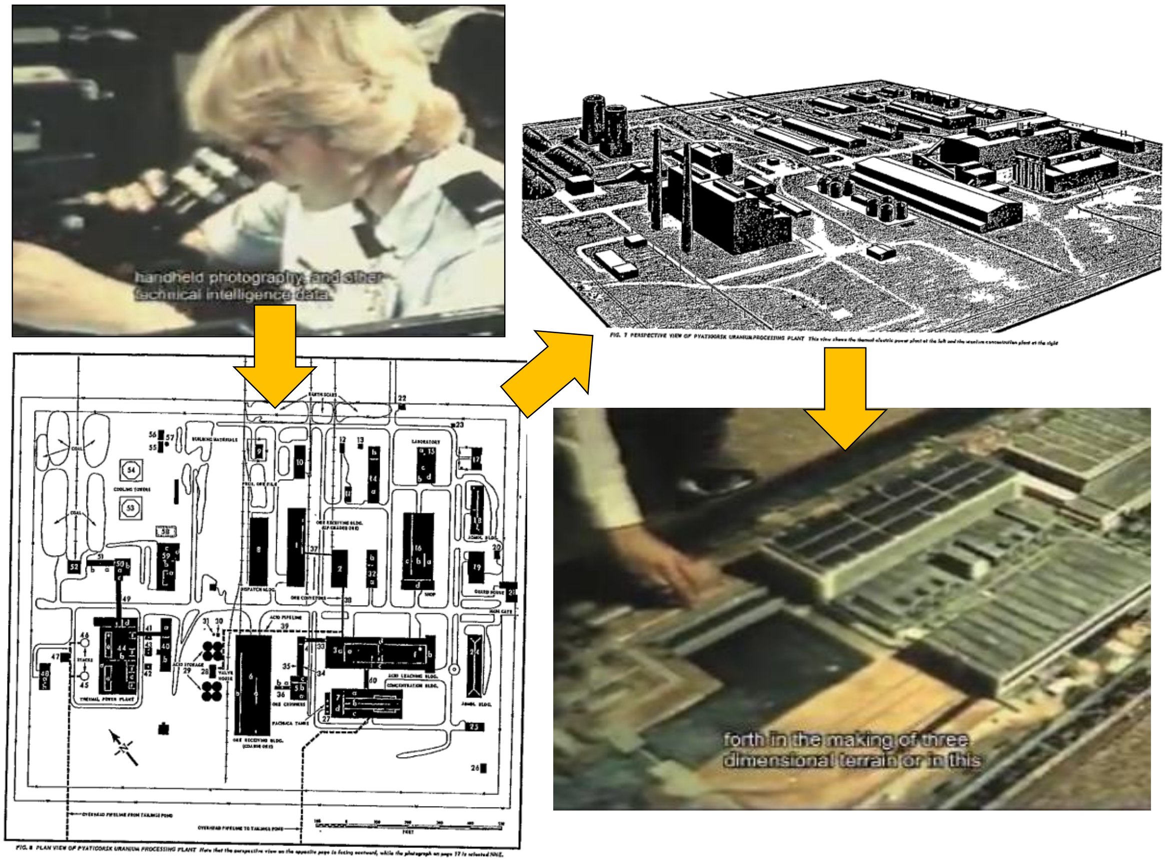

Figure 2: Cold war imagery analysis derived new satellite imagery-sourced information and then visualized the findings in maps, perspective drawings and hand-built 3D models of infrastructure. The upper left is a US "photo interpreter" (imagery analyst) using a stereomicroscope to view film positive imagery on a light table. The lower left image is a 1959 plot plan of the uranium ore concentration plant at Pyatigorsk in the former Soviet Union derived from US overhead imagery (in this case, U-2 aircraft imagery), and the upper right hand image is an artist's 3D perspective drawing of the same facility. The lower right hand image (video freeze-frame) shows a physical, hand built, 3D model of a submarine production facility in the former Soviet Union. The intent was to help policy and decision makers more readily visualize what the imagery analysts were observing and discerning. Sources:
http://www2.gwu.edu/~nsarchiv/NSAEBB/NSAEBB186/doc01.pdf and
http://www.nro.gov/foia/declass/GAMHEX/Videos/1.mov and
http://www.nro.gov/foia/declass/GAMHEX/GAMBIT/17.PDF

Princeton University researcher, Hui Zhang, compiled a number of declassified satellite images of nuclear materials production facilities at roughly **1.8** meters resolution in his historical review of the utility of that imagery for treaty verification. He showed how even at that resolution it was possible to identify major nuclear fuel cycle related facilities and monitor their operational status.[18] To sum up the significance of the role of satellite imagery for verification applications, David Sandalow (then Assistant Secretary for Oceans and International Environmental and Scientific Affairs with the U.S. Department of State) succinctly stated that,

> "*These remote-sensing capabilities provided an important element of stability to relations between the United States and the Soviet Union during the Cold War. Satellite information became, and remains today, an important tool for verification of arms control and non-proliferation treaties*."[19]

2.1 Landsat Heralded the New Era of Open-Source Satellite Imagery

In the unclassified "open source" realm, the US Government's civilian Landsat system (that began in 1972) provided the first publicly accessible imagery from space, and would also serve as segue for true commercial satellite imagery that was yet to come. The Landsat-1 satellite carried digital scanning sensors covering four multispectral bands that provided a spatial resolution of **80 meters** (the smallest object that could be discriminated from another would be roughly 80 meters square). Landsat-1 imagery provided beautiful synoptic color (multispectral) composite global coverage (in squares 185 by 185 kilometers, or 34,000 square kilometers per frame), but had very limited utility for verification and monitoring applications. Nonetheless, a declassified 1975 CIA report did speculate that foreign governments could still find that imagery useful to "*identify and target large cities, airports, port facilities, and transportation routes" and also "could be used to map and target even smaller features, such as larger Soviet SAM sites and soft ICBM sites,"*but not for *"targeting hard Soviet ICBM sites."*[20] The spatial resolution did not improve until 1984, when Landsat 5 was launched, which included the addition of the seven-spectral band scanner, **30 meter** resolution Thematic Mapper (TM) camera system.[21] Landsat 7, Launched in 1999, and Landsat 8, launched in early 2013, in addition to having eight-multispectral **30 meter** bands, and two thermal 100 meter infrared bands, also has a **15 meter** resolution panchromatic ("black and white") band used to "sharpen" the lower resolution multispectral band imagery.[22]

The first dramatic change occurred in early 1986, with the launch of the 20-meter multispectral and **10-meter** panchromatic ground resolution digital camera carrying French SPOT-1 (*Système Pour l'Observation de la Terre*) satellite. SPOT-1 was the first commercial imaging satellite with sufficient resolution to have the potential for verification applications (albeit still quite limited). The potential of remote sensing for open-source verification (and for foreign policy applications) was most clearly first demonstrated in the aftermath of the Chernobyl reactor disaster in Ukraine in April 1986.[23] Images from the SPOT-1 satellite were combined with those the improved Landsat-5 to provide the first example of open-source multi-satellite, multi-sensor, synergy for nuclear related verification applications.[24] Pioneer researchers soon began to envision how commercial satellite imagery could be applied to arms control and treaty verification to enhance international security.[25] Their findings have, for the most part, since been proven to be quite prescient.

2.2 Envisioning the Future in 1990

By early 1990, those researchers **correctly** expected that commercial satellite imagery would:

1) provide benefits to the international community by raising the salience of arms control issues to the public consciousness,
2) provide the necessary capability to support cross-border conflict monitoring, multi-lateral peacekeeping, crisis-decision making, and treaty verification and monitoring, and
3) facilitate competition for, and some loss of credibility of, official national intelligence reporting.
4) create new arguments about quality, cost , timeliness, censorship and shutter control.
5) lead to implementation of countermeasures in the form of camouflage concealment and deception by various nations and even corporate entities.
6) increase dramatically in availability with the number of satellites and the countries launching them, and that the ground resolution would improve.
7) cause mistakes to happen as the result of erroneous interpretations, particularly by inadequately trained imagery analysts or neophytes.

Among the expectations that were either **overestimated** or **underestimated** included that:

1) The researchers envisioned the creation of both an International Satellite Monitoring Agency (ISMA, to follow up on a French proposal in 1978[26]) and a MediaSat satellite exclusive for news media purposes[27], neither of which became reality (although the IAEA's Satellite Imagery Analysis Unit[28], the European Union Satellite Centre[29], and UNOSAT[30] could certainly be viewed as positive steps towards an ISMA)
2) The resolution of commercial satellite imagery would not become available below one meter resolution.
3) Imagery costs would be prohibitive for all but a select few (the researchers never imagined cost-free imagery to NGOs or the creation of digital virtual globes like *Google Earth*, etc., that have now been downloaded over 1.2 billion times.)
4) Commercial satellites would create cadres of competing imagery analysts vying for air time on television networks, and would be as common as TV weather forecasters. (clearly, this has not yet occurred)
5) The researchers never envisioned FTP data transfer rates, Wi-Fi, or the possibility of viewing high resolution imagery of practically any spot on earth with only a smart phone (which did not even exist at the time).

Among the researcher's **key conclusions on the future** of commercial satellite imagery:

1) Superpowers (or any other national government or agency) will no longer "control the narrative". Commercial satellite imagery would provide democratizing access to information otherwise previously unobtainable to the common man.
2) Commercial satellite imagery will be a double-edged sword. It will have both beneficial and malign applications, but on balance the potential for good would far outweigh the potential for evil.
3) Imagery does not come with labels. The researchers knew that it would require competent interpretation to have added value, and moreover, mistakes could and would be made, such that corroboration by other sources would always be a requirement.
4) Cost and timeliness would continue be a major concern.

Although the technology to provide commercial satellite imagery with a spatial resolution of **less than two meters** was deemed feasible, it was considered by most analysts at the time to be unlikely and would be unacceptable from both US government legal and policy perspectives.

The 1990s did see some steady improvements in resolution, beginning with the addition of the Indian Remote Sensing (IRS) satellites, which provided the first **sub-ten meter** commercial satellite imagery. In 1994, IRS-1C could acquire **5.8 meter** resolution panchromatic digital imagery. 1995 marked the advent of commercial synthetic aperture radar (SAR) imagery, with the Canadian RADARSAT providing resolution as fine as **ten meters**. In 1998, the Russians also began to market what they promoted as **2 meter** panchromatic imagery derived (scanned) from previously classified Russian satellite analog film based systems (although the quality seemed somewhat dubious).[31] Equipped with those capabilities, it had already become possible for researchers to correctly locate and characterize the reactor site in Algeria[32] and the nuclear test sites of both India and Pakistan when cued by other open-source information.[33]

3. Today's Reality: The Previously Unanticipated

In 1990, no one had correctly imagined what would be the full impact of constantly improving spatial, spectral, and temporal resolutions, and the timeliness of delivery due to improving information technologies, combined with the near ubiquity of commercial satellites imaging from low earth orbits. By the late 1990s, however, some researchers had begun to get a clearer vision of the resultant transparency and the impact on society that commercial satellite imagery was about to bring.

> *"The constant flow of imagery about to start up will be much more: a rich, textured portrait, endlessly evolving. With shared eyes we will watch the world carry its cargo of civilization—its roads, its fields, its cities, its landfills—through time and space. This portrait will be an image that can zoom in to the personal and pull out to the geopolitical, a new way to look at borders, a new way to look at news. It will be an illustration of everything: not, in the end, a view from nowhere, but a view from everywhere, for everyone."*[34]

> *"Public availability of timely high-resolution imagery represents a notable break with the past. We are moving from an era in which only a handful of governments had access to high-resolution imagery to one in which every government—and businesses, nongovernmental organizations, and terrorist and criminal groups—will have such access. Nonstate actors will be able to peer behind the walls of national sovereignty, accelerating a shift in power that is already under way."*[35]

3.1 The Number of Satellites and Their Capabilities Are Increasing

The number and variety of commercial imaging satellites that provide high resolution imagery sufficient for monitoring and verification applications continues to grow. In early 2000, there was only one commercial imaging satellite, Ikonos, capable of providing electro-optical imagery at a resolution of less than **two meters, see Figure 3**.[36]

As of this writing, there are currently nearly 30 earth orbiting commercial imaging satellites/systems with electro-optical spatial resolutions of **two meters** or better (**See Figure 4**), with the sharpest imagery currently available, via WorldView-3, at **~31 centimeters** (cm).

Although there has been a substantial consolidation of the US commercial satellite imagery industry in the US over the past few years (DigitalGlobe merged with GeoEye, which itself had earlier merged with Orbimage), there has also been a period of greater market segmentation with new imagery capabilities beginning to fill distinct market niches that may serendipitously potentially benefit open source nonproliferation analysts. New constellations of "refrigerator-sized" "small sats" and "shoebox-sized" "nano-sats" are now providing commercial satellite imagery with complimentary capabilities of those provided by the larger vendors such as DigitalGlobe and Airbus Industries.[37]

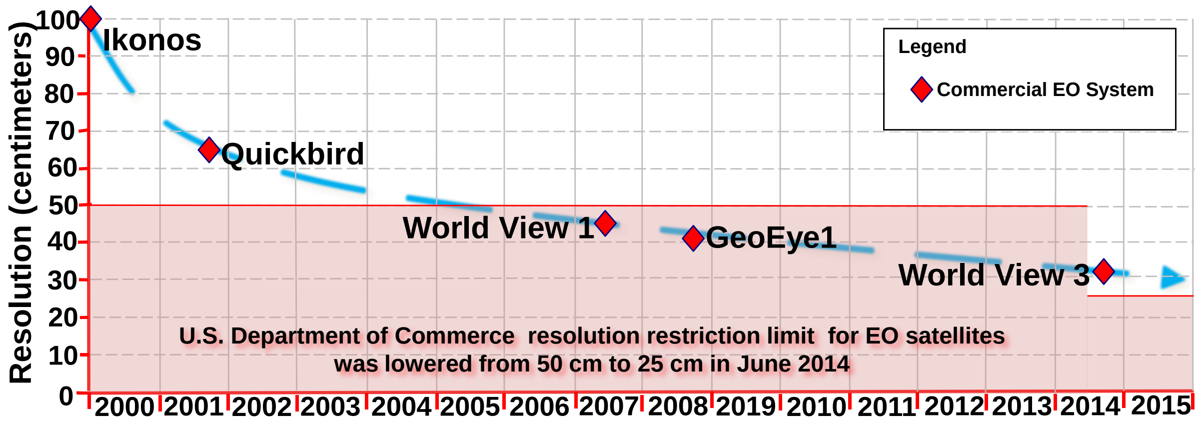

Figure 3: Benchmarks for increasingly fine resolution of commercial satellite imaging systems over time.

One US startup company, SkyBox (recently acquired by Google[38]) is operating two "small sats", known as SkySats 1 & 2,[39] by which it is acquiring **~90 cm** resolution panchromatic and multi-spectral imagery, providing new opportunities to augment data from existing higher (finer) resolution imaging constellations (**Figure 9** provides one exemplar).[40] SkyBox intends to offer multiple images by multiple satellites of any point on Earth at several different times per day (or night) when tasked, eventually having as many as 24 satellites in its constellation.[41] Previous acquisition time windows had generally been limited to around 10:30 to 11:30 a.m. local time (although DigitalGlobe's WorldView-3 acquires imagery at around 1:30 p.m. local time).[42]

The SkySat satellites can also acquire High Definition (HD) videos, utilizing sensors that can even collect imagery at night. Among the many unique attributes of the SkyBox imaging system is that it does not use line scanners, but sensors similar to those used on smart phone cameras that also allow for video stream capture.[43]

Urthecast, now based in Canada, which began by operating cameras on the International Space Station (ISS), is now in the process of creating its own free-flying satellite constellation of 16 satellites that is expected to provide frequent EO and EO video at **~50 cm**, with near coincident radar imagery.[44]

Planet Labs another recent startup company has already placed 101 "nano-sats" into orbit, which although limited to **three meters** resolution, will be able to image the entire planet in one day, every day.[45] The constellation will effectively provide, as the company claims, "*a line scanner for the planet*."[46] In 2015, Planet Labs acquired another satellite company, Blackbridge, which operates a five satellite constellation of **five meter** resolution EO "RapidEye" satellites formerly operated by the German firm RapidEye AG. Companies like the British Surrey Satellite Technology (SST) LTD, which built the RapidEye satellites, are now providing **one meter** resolution mini-satellite imaging capabilities for purchase on a turnkey basis. Three SST DMC-3 "mini-satellites" were successfully launched in 2015[47] and are currently being leased by the Beijing-based company, 21AT.

BlackSky Global, another US startup satellite imaging company, plans to deploy six **one meter** resolution imaging satellites in 2016 and have a full 60-satellite imaging constellation of by 2019, bringing "satellite imaging as a service."[48] The Canadian startup firm, NorStar Space Data Inc., intends to launch a constellation of 40 imaging satellites of as yet unspecified resolution to "enable predictive analytics to meet global challenges."[49] In 2013, the Argentinian firm, Satellogic, launched two nano-sats (CubeBugs 1 & 2) as prototypes of a future constellation intended "to image any spot on earth every few minutes," but specifics on resolution have yet been provided.[50]

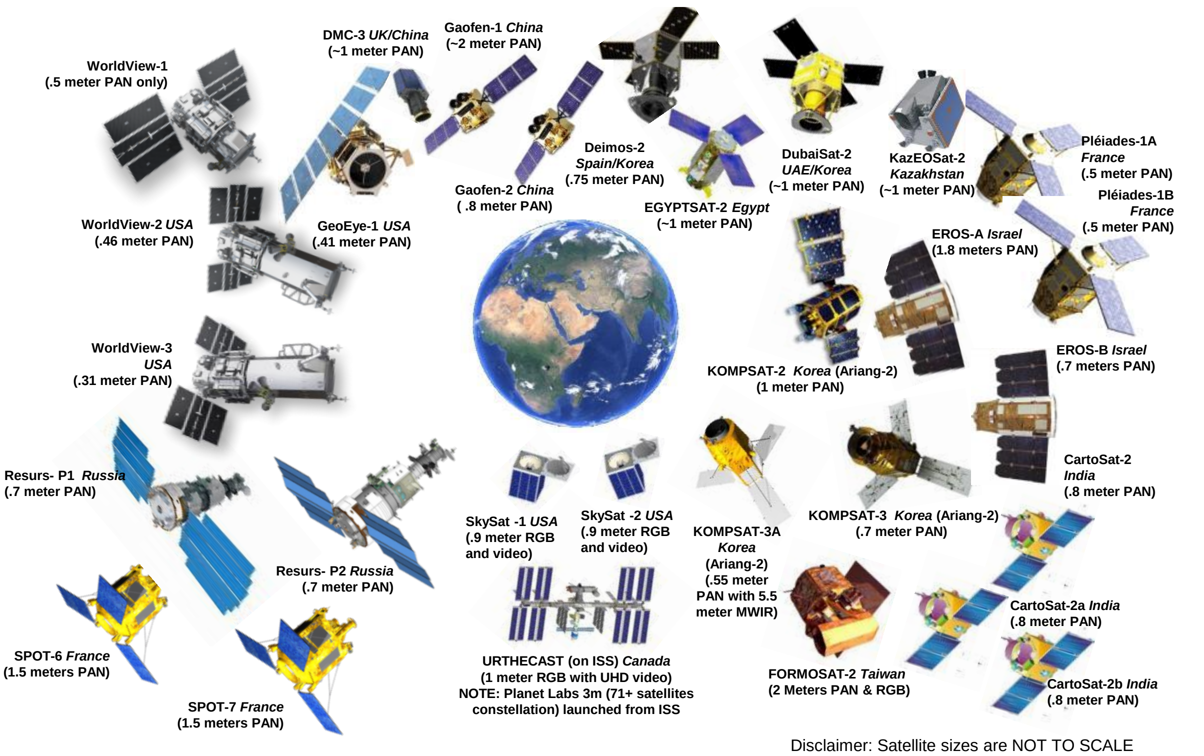

Figure 4: Commercial Satellites with Electro-Optical sensors having Ground Sample Distances (GSDs) of two meters or less in 2015. In early 2000, there was only one satellite with that capability. This is an original JRC graphic based on Internet-sourced images.

Such diversity will also provide greater access to what might otherwise be denied areas with some vendors, and also ensure the integrity and validity of the data obtained for the historical record.

Figure 5: Freeze-frame from Google/SkyBox night-time High Definition video over Las Vegas. In the original video, it is possible to see headlights of moving vehicles along the roads. Source: https://vimeo.com/112088357

3.2 Temporal Resolution and Revisit Time Improvements: Observing Activity

With such a large number of commercial imaging satellites and sensors orbiting the earth at one time, which one senior US Government official termed an "*explosion of small satellites*",[51] the previous concerns, regarding temporal resolution and timeliness of revisit, will no longer be an impediment with regard to verification applications. That rapid revisit capability provides what is in effect never before possible "persistent surveillance" on a global scale.

Commercial satellite coverage of the Chernobyl and Fukushima disasters shows how much has already changed in the past quarter century. For Chernobyl, commercial satellite images of **10 to 30 meters** resolution were taken days apart.[52] In monitoring Fukishima, DigitalGlobe not only acquired two **~50 cm** images of the Fukishima reactor site on the same day (March 14, 2011, using two different satellites in its constellation), but those images were acquired **one minute before**, and **only three minutes after**, the building housing Reactor Unit 3 exploded.[53]

Another exemplar showing the timeliness, responsiveness, and global coordination that is now possible from the commercial satellite imaging community involves the attempt to locate and rescue two lost hikers in the Andes Mountains. TomNod (Mongolian for "Big Eye"), sought and obtained commercial satellite imagery from DigitalGlobe, and within hours engaged nearly 800 globally-linked volunteers in the search. The imagery was not only made available within two days, but was of sufficient resolution (**~50 cm**) to see the lost and doomed hikers' footprint tracks in the snow.[54]

The introduction of video capabilities offers new advantages over still images in that it can allow more recognizable observation of plant operation signatures (rising cooling tower plumes) and other activity (vehicular and construction equipment movement) at sites of monitoring and verification interest. The SkySat satellites can also acquire High Definition (HD) videos[55], with durations of up to 90 seconds, utilizing **~1.1meters** resolution sensors capable of nighttime imagery (in one example, automobile headlights can be observed moving down the streets of Las Vegas, Nevada, **see Figure 5**[56]). Urthecast's **one meter** resolution imager located on the ISS can also acquire 60 second long Ultra-High Definition (UHD) videos, over any location that the space station orbits. This shortening time gap capability is bringing us ever closer to the asymptote of "persistent surveillance" on a global scale. Though varying in resolution from coarse to fine, "the types of spacecraft being developed by providers such as Sky-box, UrtheCast, and Planet Labs are intended to "darken"[57] the skies with sensors. Their advantage is the ability to revisit a target multiple times a day, offering more intelligence on the patterns of life and activities taking place there."[58] The more frequently any point on the globe is imaged (or videoed), the more difficult it becomes to conceal illicit operations. The resulting high repetitive revisit rate (from the sum of all the existing and planned EO systems) will also make it much easier to detect changes associated with the construction of larger features like roads and major buildings of potential relevance to monitoring and verification for nonproliferation applications. It is also becoming easier to detect such changes in an automated way using feature extraction tools (e.g., advanced machine learning algorithms) that are also currently under development.[59]

One other aspect of this new era of observation satellites that should not be overlooked is that they are increasingly agile, providing another way to reduce the time gap between two image captures. **Figure 6** shows how the same point was imaged three times on a single pass by the Airbus Industries' Pléiades 1B, ~50 cm resolution, commercial imaging satellite. While each image is still just a snapshot in time, the gaps between each snapshot can be reduced, potentially capturing on-the-ground activity not otherwise possible.

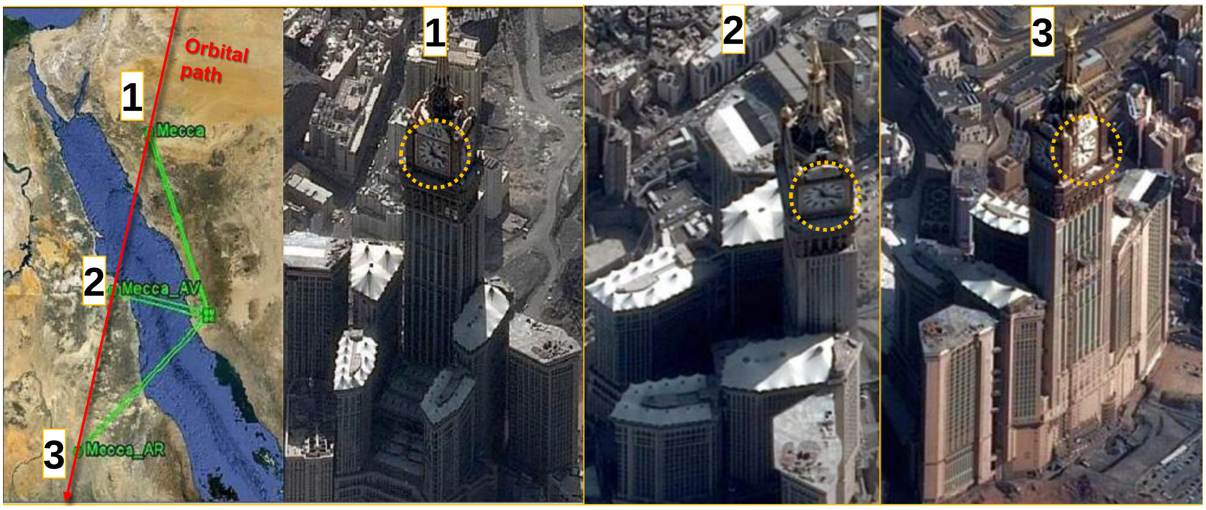

Figure 6: Three pictures on the Mecca "tower clock" acquired by Pléiades 1B every 90 seconds in a single pass to see the minutes needle moving! (Image credit: Airbus Industries). This graphic was first published in Reference 8.
https://directory.eoportal.org/web/eoportal/satellite-missions/p/pleiades#foot33%29
and http://seso.com/wp-content/uploads/2015/02/building.png

3.3 Spatial Resolution Improvements: Seeing Greater Detail

Among the most significant changes that have occurred since the beginning of the 21st Century was the public availability of one meter resolution commercial satellite imagery (the first one meter resolution images were provided by US commercial companies, allowed under a 1992 US federal law). Such high resolution marked the beginning of a new paradigm in global transparency and spawned two major publications surfaced at that time in recognition of that fact, one of which openly proclaimed in its title, "How Commercial Satellite Imagery Will Change the World." By 2008, 50 cm resolution imagery had become available via the GeoEye-1 satellite, and in 2014, 31 cm imagery first became available via the WorldView-3 satellite (a June 2014 change in US Federal law permitted US companies to sell satellite imagery with resolution as fine as 25 cm). Nine pixels at 30 cm is equivalent to the footprint of one pixel at 90 cm, which effectively represents a 900 percent improvement in image detail (resolution) from 15 years ago.

To more fully appreciate the significance of these improvements, it is worthwhile to view a few comparisons as shown in **Figure 7** (adapted from DigitalGlobe promotional media[60]). What is particularly noteworthy is that it is possible to "*identify automobiles as sedans or station wagons*", which was previously not possible with any other commercial satellite imagery. According to the Civil National Imagery Interpretability Rating Scale (NIIRS, a scale of zero through nine, with nine having the best interpretability[61]), such specific criteria qualifies the 30 centimeter resolution imagery posted by DigitalGlobe as being NIIRS 6.0. Interestingly enough, DigitalGlobe's own corporate literature only claims a lower NIIRS rating of 5.7.[62] And even at the lesser rating, DigitalGlobe advertises (via that same promotional media) that the 30 centimeter resolution imagery from its WorldView-3 satellite "*can resolve objects on the ground such as above-ground utility lines in a residential neighborhood, manhole covers, building vents, fire hydrants, and individual seams on locomotives*."[63] This capability will lead to improved monitoring and verification of nuclear facilities (e.g., potentially allowing differentiation of different types of UF_6 cylinders in open storage (see **Figure 7**), the identification of critical fuel cycle equipment either in transit or in open storage, or operational details associated with electrical power conditioning, and heating, ventilation, and cooling (HVAC) related equipment and infrastructure).

Figure 7: Interpretability comparison of high resolution commercial satellite imagery with differing resolutions below one meter. The top images are exclusively from commercial imaging satellites over Sao Paolo, Brazil; but each was acquired on a different day.[64] The bottom images are of UF_6 cylinders (lower right shows stiffening rings on large cylinders and eight small cylinders). This figure was first published in Reference 8.

3.4 Spectral Resolution Improvements: Seeing Beyond the Visible

To date, commercial satellite imagery being utilized for open-source nonproliferation and potential treaty verification applications has primarily involved electro-optical (EO) multi-spectral bands in the visible and near-infrared combined to create panchromatic sharpened naturally appearing color imagery. While not addressing all the implications of applying other commercial satellite-based sensor suites to promote additional synergies (that are not possible using only electro-optical (EO) visible spectrum imagery alone), it is important to at least be aware of their complementary strengths as each sensor adds a new perspective are also evolving with improving resolutions.

Synthetic aperture radar (SAR) imagery, with resolutions now available down to **~25 cm**,[65] is not only useful in all weather, for all hours, day or night, monitoring of activity, but it is particularly helpful in detecting security perimeters that might otherwise be obscured by vegetation. Hyperspectral imagery sensors (as are currently available on the US Hyperion satellite[66], the European Space Agency's (ESA) Proba-1 satellite[67], and soon to be on the German EnMap satellite[68]) is derived from data covering up to hundreds of bands (at resolutions of between 17 and 34 meters) and provides the capability to identify materials, e.g., uranium ore (vice copper or iron ore) at a suspect ore processing facility.[69] DigitalGlobe's newest WorldView-3 satellite, advertised as "super-spectral" with 29-bands (including panchromatic **0.31 meter** at Nadir and multispectral **1.24 meter** at Nadir), may provide similar unique insights. The additional new **3.7 meter** resolution shortwave infrared (SWIR) capability makes it possible to see through thick haze and smoke (see **Figure 8**).[70] Such a capability might be requisite for detecting some critical equipment movement of verification relevance not otherwise apparent by alternative remote-sensing means.[71] Thermal infrared satellite imagers, even with resolutions as coarse as 100 meters, can potentially provide unique operational information when combined with other geospatial information (see exemplar case in **Figure 11.**).

Perhaps the most important development However, one new development in the field of satellite-based thermal imaging is that Korean operated satellite, KOMPSAT-3A, was successfully launched in March 2015 and is now operational. The KOMPSAT-3A has a

5.5 meter resolution mid-wavelength infrared (MWIR) thermal imaging sensor, operating in the 3.3-5.2 micron range, with a coincident capacity for acquiring a **55 cm** EO imagery for cross-correlation.[72] Most significantly, KOMPSAT-3A now provides significantly finer resolution thermal imagery than both Landsat and ASTER, and that imagery can be also acquired at night. To what degree KARI's TIR imagery can be utilized for nonproliferation monitoring and verification has yet to be proven, but it is expected that it will provide the capability to readily detect warm water effluents and much more precisely locate "hotspots" (like the cooling unit example in **Figure 11**) arising from operations at a variety of nuclear-related facilities.[73]

Figure 8: Short Wave Infrared (SWIR) enables viewing through the dense smoke of an active fire to the ground beneath, as well as locating the flame front and hot spots in the fire. This is a WorldView-3 image of a forest fire burning at the Happy Camp complex in California's Klamath National Forest in August 2014. The upper image is what is only discernable in the visible part of the spectrum. The smoke completely obscures the ground. The lower image is of the exact same area as viewed with SWIR imagery: the smoke disappears, and the hot spots in the fire become clearly visible. The SWIR image is a "false color" composite made from three of the eight SWIR bands (bands 6, 3, and 1) that coincidentally give an orange color to the fires.

Source: http://www.digitalglobeblog.com/2014/09/03/revealing-the-hidden-world-with-shortwave-infrared-swir-imagery/

3.5 Improvements in Accessibility and Pricing

Another unexpected development was how even the most prescient researchers fell short of what is now commonplace with respect to how huge volumes of commercial satellite imagery are now accessible cost-free by anyone via the Internet. Virtual Globes (AKA Digital Earths), like *Google Earth*, *Here*, *Bing Maps*, *Esri ArcGIS*, etc., provide the capability to synoptically view multi-resolution, three-dimensional, virtual representations of the earth and created a new venue to "navigate through space and time" with high resolution imagery (including from commercial space-based satellite remote sensing systems).[74] In 2015, *Google Earth* Pro (previously priced at $399) became freely downloadable. It offers the additional key benefits (not previously available with the original free version) of allowing area measurements for facility size determinations; video movie-making of fly-throughs for pre-inspection familiarization, etc.; and the capability to create "view-sheds" to highlight all areas within a given line of sight to assess ground level masking, etc.[75]

Accessing supplemental imagery and purchasing it has also become easier. Searching the multitude of available imaging archives of the increasingly diverse vendor options would have been a daunting task if not for the creation of web-based applications such as Apollo Mapping's *Image Hunter*[76] or GeoCento's *Earth Images*[77], which provide quick agnostic access to multiple image archives of different vendors from different countries. However, as of this writing, there is still not a complete "one-stop-shop" for all vendors of commercial satellite imagery, but may emerge if present trends continue. (And even thumbnail versions of archived images can supply new useful information, as is exemplified in the upper right inset of **Figure 10**.)

The price of both acquisition and processing of imagery, which had been another major concern in the 1990s and early 2000s (in that individual frames of archived imagery originally cost about $3000-4000 a frame), has, in some but not all cases, dropped substantially such that archived imagery from DigitalGlobe (for example) can cost as little as $350 for a 25 square kilometer area, or around $500 for a similar area special order request. Competition between the United States, France, India, Russia, Canada, China, Israel, Japan, South Korea, etc., will likely continue to put downward pressure on prices, making commercial satellite imagery even more affordable from more diverse sources.[78] Perhaps, the most astounding development came with the development of an iPhone app that makes possible the purchase of a one kilometer square area of some archived commercial satellite imagery from a multi-corporate international satellite constellation of up to 26 satellites for as little as $10.[79] (see **Figure 10**) In April 2015, the ESA began providing SPOT and Pléiades data for free for research and application development through project proposals submitted via ESA's Earth Online Portal.[80]

Moreover, subsequent to a purchase, it is already possible to do on-the-spot analyses of such imagery using only that same smart phone, or as one recent blogger noted, "*Imagery analysis by iPhone. Neither Bud Wheelon nor Steve Jobs could have predicted this*."[81]

Neither did anyone expect to ever see commercial satellite imagery being provided at little or no direct cost as found on the various virtual globes like *Google Earth, Here, Bing Maps*, *Apple Maps*, and *ArcGIS My Map,* etc. (See Appendix A), which are also viewable on smart phones today (albeit without all the functionality available on a computer). Interestingly, when *Google Earth* first came on the scene in 2005, one common complaint was that the imagery was often too old and out of date (or more recently, that did not represent "a perfect planetary mirror"[82]), with the implication that separate imagery purchases would always be necessary for temporal currency. However, in some cases, particularly in those areas of high media interest, including nuclear facilities in Iran and North Korea, the imagery can be quite current. For example, at the North Korea's Punggye nuclear test site there are eight different archived high-resolution commercial satellite images acquired between the January 1, 2013 and February 12, 2013, the date of the third identified underground nuclear test. *Google Earth*'s historical layer view permits visual inspection of each of those images in that archive.

With respect to hardware and software expenses, those costs have also dropped dramatically, and the large file sizes associated with such imagery are also much easier to transfer, process, and store than ever before. Storage and processing in the cloud via open open-source frameworks like *Apache Hadoop*, which allows the storage and processing of big data in a distributed environment across clusters of computers using simple programming models, now empowers anyone, anywhere with unimagined, effectively cost-free computing power. *Hadoop* is designed to scale up from single servers to thousands of machines, each offering local computation and storage.[83] The mere fact that *Google Earth* and other commercial satellite and aerial imagery based maps are accessible via smart phones and other hand held devices (tablets), using either a cell-phone connection or WI-FI, shows how readily accessible commercial satellite imagery has become.

4. The Implications of Commercial Satellite Imagery for Creating Innovation in Verification Applications

The IAEA has already proven the utility of commercial satellite imagery to assist the IAEA in monitoring nuclear fuel cycle facilities and activities, but to also investigate possible undeclared activities.[84] The improved availability and access of commercial satellite imagery, together with the means to visualize it in a 3D geospatial context, has made possible a host of similar investigations by others, including NGOs, academics and hobbyists, that have resulted in somewhat surprising discoveries. Those discoveries were made in what would be otherwise "denied environments"; and which would have been impossible for anyone not previously having the resources of at least a super-power nation state.[85]

4.1 Exemplar Verification Successes with Commercial Satellite Imagery

Since the turn of the century and the advent of sub-one meter resolution commercial satellite imagery, there have been numerous examples of how such imagery can successfully be used to verify allegations concerning clandestine nuclear and missile related facilities and activities, and any significant changes associated with them. The identification and characterization of the Iranian underground uranium enrichment plant at Natanz in 2002, followed by similar investigative work by NGO analysts at the Institute for Science and International Security (ISIS), was trailblazing.[86] Since then, the frequency of such discoveries and their subsequent reporting has increased in keeping with the increased frequency of imagery coverage around the world, particularly those of high interest. The renovation and "refurbishment"[*] activity at the Iranian high explosives test facility at Parchin, allegedly part of an effort to cover-up previous nuclear weapons related activity was characterized and closely monitored by ISIS and others using multiple commercial satellite images over time.[87] Those reports were filed on both the ISIS website and Arms Control Wonk blog.

But not every open-source lead has had merit, as ISIS recently demonstrated in early 2013 when it also provided evidence that an alleged explosion at the Iranian underground uranium enrichment plant at Fordow (near Qom) could not be substantiated with imagery acquired the very day after the alleged event.[88] Other notable discoveries were made by Nick Hansen on behalf of IHS *Jane's Defense Weekly*, using commercial satellite imagery of the Iranian missile and space launch complex at Semnan, Iran. He was able to detect evidence of failed space launches of the Fajr satellite in May 2012, and again more dramatically in late September 2012 (a major explosion had occurred on the pad) that went entirely unreported by the Iranian Government, the Iranian media, and the international media.[89]

4.2 Multi-Satellite/Multi-Sensor Synergy

This section highlights the utility of combining information from multiple electro-optical satellites (e.g., each having different resolutions) or multiple satellites having different sensors suites (e.g., high resolution optical imagery with synthetic aperture radar imagery or thermal infrared imagery). With each combination, sometimes referred to as "multi-sensor data fusion,"[90] it is possible to derive a unique synergy, such that the whole of the information that can be gleaned from the combination is really greater than the simple sum of the information from the multiple images if each were to be analyzed in the absence of the others. However, for the purposes of this study, data fusion incorporates all sources of information not just sensor data. Four exemplars are below.

[*] IAEA Director General visited the site in late 2015 and noted the refurbishment from the inside.

1) The first example was derived when observing activity at the Punggye nuclear test site in North Korea. On May 1, 2014, two images were acquired of that test site such that the first image, a **50 centimeter** resolution electro-optical image acquired by DigitalGlobe was augmented by a **90 centimeter** resolution electro-optical image acquired by SkyBox of the test site that was acquired only 59 minutes later (See **Figure 9**).

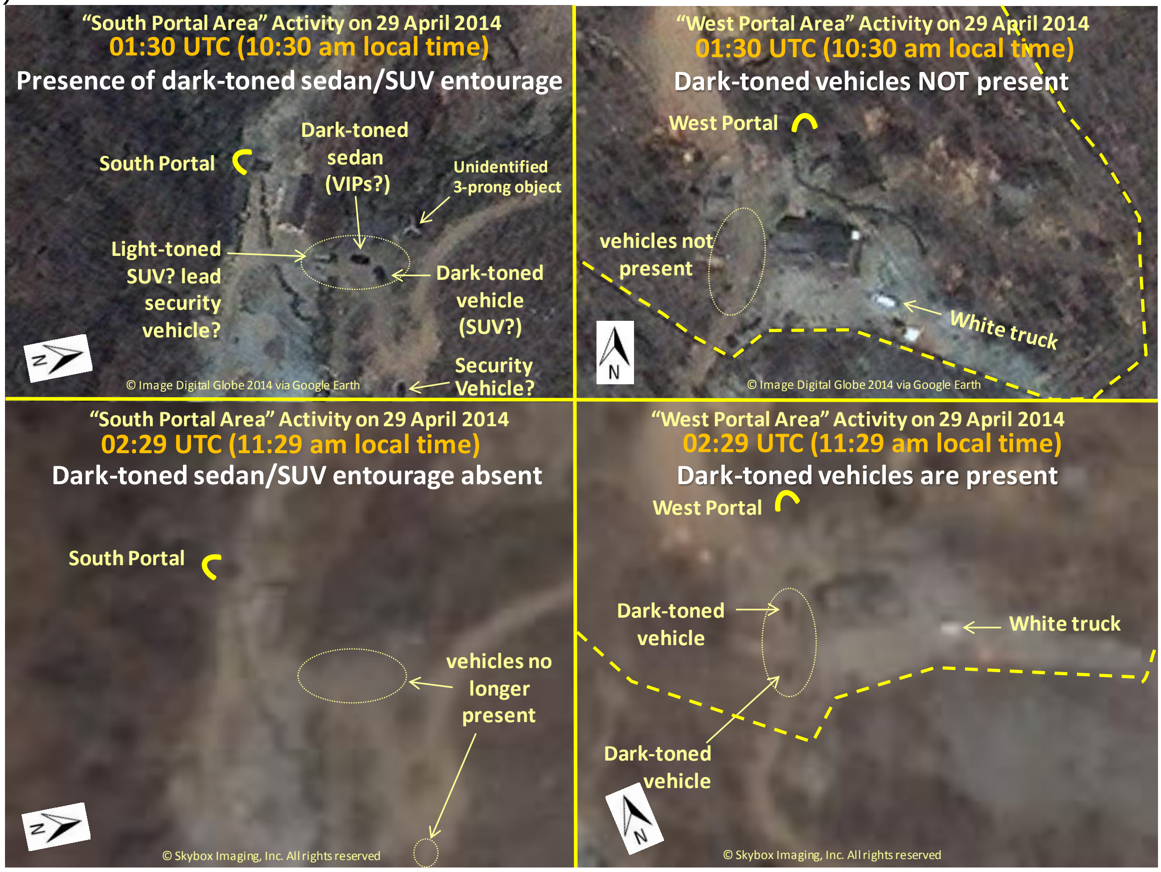

Figure 9: Multi-satellite coverage can provide synergy by allowing us to derive dark-toned vehicle movement between two nuclear test portal areas within one hour using different satellites from different vendors (left ~50 cm resolution image from DigitalGlobe, right 90 cm resolution from Skybox imaging) that is suggestive of an official visit/inspection to each of the two active test tunnels within an hour of each other.

The **~50 cm** image from DigitalGlobe (as found on *Google Earth*, **Figure 9**, **top left)** shows a multi-vehicle entourage involving two black sedans or SUVs (and two possible escort vehicles) near the South Portal, but not at the West Portal (**Figure 9, top right**), which is separated from the South Portal by about one kilometer. Although the subsequent **~90 cm** SkyBox imagery (**Figure 9, bottom left**) showed that the previous four vehicle entourage was no longer present at the South Portal (**Figure 9, bottom right**), that imagery did reveal that two dark-toned vehicles (albeit fuzzier due to the lower resolution) had arrived near the West Portal.)

2) The second exemplar (see **Figure 10**) shows how, through the use of multiple EO images from multiple commercial satellites provided free by Google Earth (along with a separately purchased image at low-cost) it was possible to newly locate, identify, and characterize a possible nuclear waste site by simply following-up on a single report from Iranian news.[91]

In late 2014, Iranian news reported that the, "*Chief of the Atomic Energy Organization of Iran (AEOI) Ali Akbar Salehi paid a visit to a long-term nuclear waste storage facility in the central province of Isfahan. Salehi visited the city of Anarak…to get* *update on the latest developments regarding the construction of the nuclear waste stabilization and storage facility*."[92] A rapid and relatively easy search of the area around the town of Anarak, Iran (using the most recent imagery available from Google Earth: July 16, 2013, **Figure 10, large bottom image**), made possible the location of a candidate site. A subsequent review of DigitalGlobe imagery archives (**Figure 10**, **top left**) revealed multiple acquisitions centered on that same site, indicating that this site first began attracting continuing interest by others (NFI) in early 2014 (although Google Earth shows that construction at the site was first underway by October 2011). The two most recent images (**Figure 10, top right**, from March 13, 2015 and May 17, 2015) are viewable for free directly from those archives (albeit at reduced resolution). Even at the reduced resolutions, they are sufficient to show continued construction and changes onsite, e.g., like the addition of a new blue roof to a small building in close proximity to the largest building onsite. The overall site, which is served by a newly paved access road and an outer entrance facility (**Figure 10, top right**), exhibits the requisite features for a secure storage vault-type radwaste structure situated in dry, stable, geology that is also not susceptible to flash flooding.

3) The third example illustrates how multi-sensor synergy can clearly have nonproliferation verification relevance. **Figure 11** is derived from a **90 centimeter** resolution Skybox electo-optical image of the North Korean Yongbyon gas centrifuge uranium enrichment facility, which was overlain (by Niko Milonopoulos[93]) with a much lower resolution (**100 meter resolution resampled to 30 meters**[94]) thermal infrared (TIR) image acquired by Landsat in September 2014.[95]

That co-registration indicated:

1) an apparent "hot spot" located at the northwest corner of the uranium enrichment facility;
2) in general, the entire centrifuge facility was generally warmer that the surrounding background.

Armed with that information, closer inspection of electro-optical imagery from different satellites having resolutions varying from 50 centimeters to one meter (as provided at no cost via *Google Earth* via its historical layer) revealed that there are: 1) two banks of three small cooling units located in that precise area of that "hot spot"; and 2) that there is one bank of three small cooling units associated with each of the twin cascade halls (each having ~2000 gas centrifuges[96]). Moreover, DigitalGlobe electro-optical imagery from mid-January 2014 (also available via *Google Earth*) revealed bright white deposits in close proximity to both banks of cooling towers, which, given the time of year and the presence of frozen water elsewhere on the image, suggests that flash frozen cooling water vapor was the source of those deposits. As a result, we have been provided a new signature for determining that both banks of cooling towers were operating as early as January 2014. Such information would not necessarily have been derived from any of these images they had been only viewed in isolation.

Particularly noteworthy is that Landsat imagery (including the thermal bands employed above) is continually being updated on a daily basis.[97] Moreover, all of the earlier acquired imagery, dating back to 1972 is available from archives that are readily accessible by anyone using the free online software application, "*Google Earth Engine*."[98] Until quite recently, the only publicly available TIR imagery was via Landsat[99] and ASTER.[100] Interestingly, the Multispectral Thermal Imager (MTI) satellite, which was specifically designed to develop and evaluate advanced space-based technology for nonproliferation treaty monitoring and other national security and civilian applications (including an unspecified resolution thermal imagery capability within a 15-band sensor array), is not providing data that is available to the public at this time.[101]

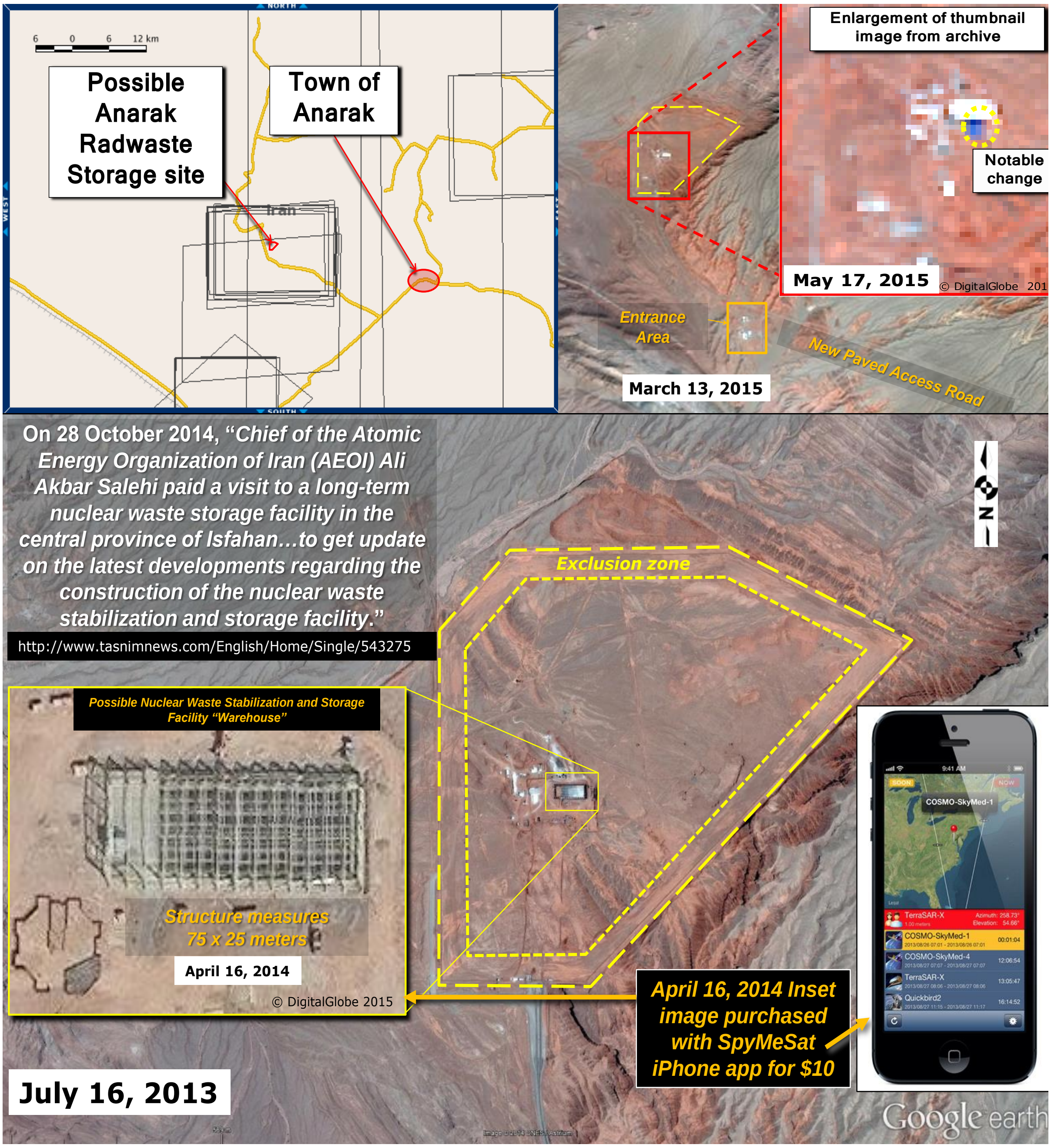

Figure 10: In following-up on one news report (see quote in inset), a possible "Nuclear Waste Stabilization and Storage Facility" nearing completion near Anarak, Iran could be identified. Having first located the candidate site on the most recent imagery available from *Google Earth* (July 16, 2013, large bottom image), a review of DigitalGlobe imagery archives (top left) revealed multiple acquisitions centered on that same site, indicating that this site first began attracting continuing interest by others in early 2014 (although *Google Earth* shows that construction at the site was first underway by October 2011). The most recent May 17, 2015 image (top right), which is viewable as a thumbnail for free directly from those archives (albeit at reduced resolution), is sufficient to see continued construction and changes from the last previous archived image from March 13, 2015. The site, which is also served by a newly paved access road and an outer entrance facility (top right), exhibits the requisite features for a secure storage vault-type radwaste structure situated in dry, stable, geology that is also not susceptible to flash flooding. Significantly, the April 16, 2014 inset photo (bottom left) was purchased via SpyMeSat for $10 and is more recent than that currently found on *Google Earth*. This figure was first published in Reference 8.

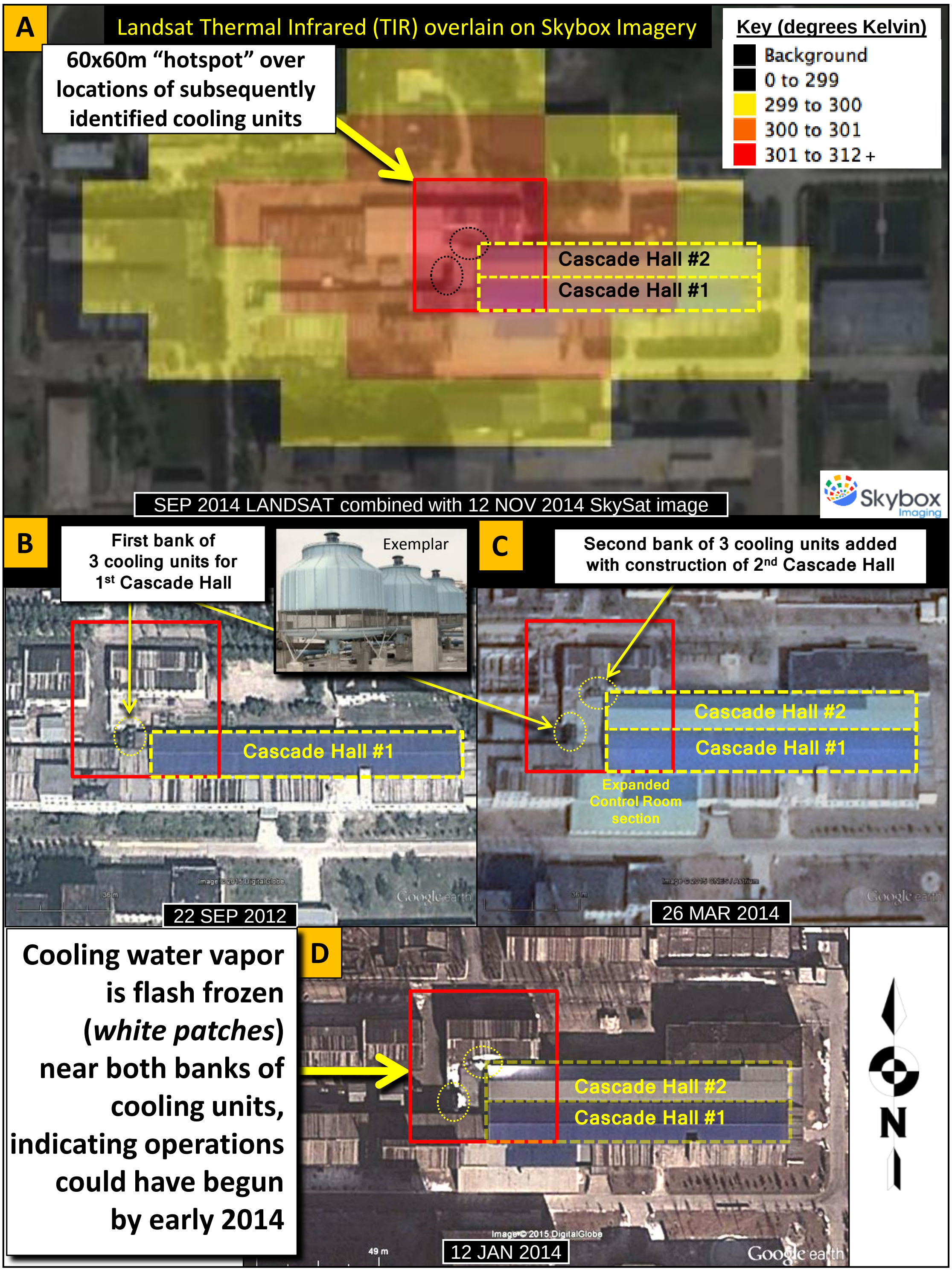

Figure 11: This figure provides an example of multi-satellite, multi-sensor, synergy, for verification applications. In this case, some operations at the North Korean gas centrifuge uranium enrichment plant at Yongbyon can be monitored remotely. The original cascade hall, consisting of ~2000 centrifuges, was visited by Dr. Siegfried Hecker in 2010. In 2013, what appeared to be a duplicate cascade hall and probable expanded control room were constructed. The low resolution LANDSAT thermal imagery directed our analytical focus to an area where cooling towers were identified with higher (finer) resolution optical imagery. While the lower (coarser) resolution thermal imagery could not distinguish whether one or both towers were operational in September 2014, the January 2014 DigitalGlobe finer resolution imagery (as is viewable with Google Earth) suggests that both were possibly operating as early as January 2014. This figure was first published in Reference 8.

4) The fourth and last example (**See Figure 12**) was published by the IAEA Satellite Imagery Analysis Unit (SIAU), and shows the utility of cross-correlation of electro-optical satellite imagery (in this case DigitalGlobe's WorldView-1 panchromatic imagery on top) with synthetic aperture radar (SAR) imagery from Airbus's TerraSAR-X satellite (via Infoterra) on the bottom. The key points to take away are that Radar imagery can provide cloud penetration for all weather and day or night observation and is highly sensitive to corner reflections of metallic anthropogenic objects such as vehicles and fence lines. Additional demonstrations of the utility of SAR imagery and its analysis specifically for electrical and power installations can be found at the *TerrSAR-X IMINT Manual* demo site available at http://tim.infoterra.de.

Figure 12: This figure provides an example how the comparison of electro-optical imagery (top) with radar imagery (bottom) can provide multi-sensor information synergy. Perimeter fence lines are more pronounced in the radar image. Also in the radar image, metal edges or railings on the tops of buildings create the bright reflections on the sides facing the incident radar beam (white arrow from right to left); while the opposite sides of the same structures are completely dark where the incident beam is blocked (creating discernable shadows, e.g., note the long linear shadow cast by the ventilation stack). Source: IAEA, see Reference 3.

5. The Role of Imagery Analysis

Imagery analysis is critical to any pertinent verification information extraction from commercial satellite imagery, but it is one of the least appreciated aspects, if for no other reason than there is the common assumption that "anyone can look at pictures." While that statement may be true, it is not true that anyone can be an imagery analyst who can derive new, value-added meaning from a satellite image. Imagery analysis requires studied interpretation of the raw unannotated imagery, and Albert Einstein fittingly observed that, *"information, however, is not knowledge. Raw data means nothing without interpretation*."[102]

Imagery analysis is the cornerstone upon which all the imagery data collection technologies and processing capabilities are built upon. For nuclear nonproliferation verification applications, commercial satellite imagery (and the associated geospatial tools with which to view and assess it, together with collateral information from other sources) **must** be competently interpreted by well-trained and experienced imagery analysts who are fully cognizant of the nuclear fuel cycle and its infrastructure, equipment, and operations. Those imagery analysts must also have a good command of other open-source information technologies and be able to draw upon them correctly under the rubric of what has been termed "Geospatial intelligence (GEOINT) tradecraft." Title 10 U.S. Code §467 establishes the definition of GEOINT as meaning, "*the exploitation and analysis of imagery and geospatial information to describe, assess, and visually depict physical features and geographically referenced activities on the Earth. GEOINT consists of imagery, imagery intelligence, and geospatial information.*" GEOINT tradecraft has been defined as "*unique and sometimes privileged organizational sources and methods for obtaining information of a place and making sense of the information to support the decision maker in understanding human activities and intentions. Methods comprise the technologic tools to organize geospatial data and the cognitive techniques used by the analyst to make sense of it when rendering judgments, insights, and forecasts*."[103]

5.1 Imagery Analysis Defined

Imagery analysis, as a subset of GEOINT, is the process by which to extract meaningful information from images, which, for this review, consist primarily of imagery obtained from low-earth-orbiting commercial imaging satellites. In a previous review, it was stated that commercial satellite imagery, as it is available for purchase today in its raw form, is nothing more than "*a pile of pixels*".[104] It is the job of the imagery analyst to derive meaning from those pixels. As one practitioner has pointed out, "*Pixels are becoming a commodity, and the real value is in extracting that data, making it understandable, and making it useful to customers*."[105] Imagery analysis is the means by which a body of pixels is holistically interpreted, and creatively combined, in light of other collateral open-source information (e.g., safeguards pertinent data) to synergistically derive new, "*value-added*," information from the raw un-annotated imagery. That information can then be added to the overall existing body of nonproliferation knowledge with respect to a particular facility, activity, or program. Imagery analysis is critical to nonproliferation verification and monitoring, particularly as it applies to identifying possible clandestine "undeclared facilities and activities". Commercial satellite imagery must be competently interpreted by well-trained and experienced imagery analysts who are fully cognizant of the nuclear fuel cycle and its infrastructure, equipment, and operations, and who are able to correctly distinguish those features from those that can be associated with other non-nuclear industrial processes.

5.2 Imagery Analysis is a Process

Imagery analysis is a process that begins with an initial examination of an image and its constituent features. Among the constituent features of any image that will aid in interpretation and which can lead to identifications:

- **Size:** is the aspect representing both the true physical size, and relative scale, of objects in the image. (which can be directly measurable with *mensuration* tools such as the "ruler" tool in *Google Earth*)
- **Shape:** is the physical appearance necessary for an object's recognition and help in identification. "Anthropogenic" features are most often geometric, while "natural" features are almost always amorphous.
- **Shadows:** are silhouettes that provide unique insights of shape that might otherwise not be apparent without them. ***(See an exemplar in Figure 13)***
- **Shade:** the brightness and contrast variations of one object compared to another.
- **Surroundings:** establish the physical setting and cultural context. What are the discernable associations that can be made with nearby objects in the broader view?
- **Signatures:** are natural or anthropogenic features that either alone or in aggregation are distinguishing characteristics that can lead to an identification of an object on an image. Anthropogenic signatures are those *generally* consistent associated features of a facility or activity used to discriminate and identify the type of facility based on unique required functional or operational characteristics. For example, a coal-fired power plant can be readily distinguished from a nuclear power plant. While both types of power plants will include generator halls, large cooling systems, electrical switchyards, and power lines; a coal fired power plant can be readily identified by the unique presence of expansive black coal piles adjacent to large conveyors for transporting coal the coal from the piles to the boiler (furnace). Moreover the coal fired power plants utilized smoke stacks vice ventilation stacks associated with nuclear power plants. Various parts of the nuclear fuel cycle have some generally consistent signatures; **(*see an exemplar in Figure 14*)**. Patterns, as another form of anthropogenic signatures, are distinctive, generally consistent and recurring spatial arrangement of features that are associated with certain groups of objects, e.g., linear arrayed fruit or nut trees in orchards, circular irrigated agricultural fields, cross-hatched street layouts in urban areas, or the "Star of David" layout of old Soviet-era SA-2 surface to air missile sites.[106] "Signature Keys" have been created to assist in imagery interpretation of various industrial processes (see for example the National Imagery and Mapping Agency's unclassified Photographic Interpretation Handbook published in 1996[107]).
- **Texture:** is the apparent roughness or smoothness of features in an image, e.g., water bodies appear much smoother than surrounding terrain.
- **Time:** is a factor manifested in temporal changes including construction history, activity levels, operations, etc.
- **Perspective:** Commercial satellite imagery is most often acquired with a view that is most nearly straight down from above. This is a view that is not normal for most human beings who are most familiar with horizontal terrestrial views. A cylindrical water tank or reactor dome, when viewed straight down, can appear as a circle/disk (the reactor dome on the cover is one example). So the imagery analyst must always realize that while any single image is only two dimensional, it must always be mentally processed in three dimensions**.**

Figure 13: "Shadows" are a critical element in the analysis of commercial satellite imagery. While the oblique view of the Washington Monument makes it relatively easy to identify without shadows, the near vertical view of the St. Louis Arch would be almost impossible to identify apart from its shadow. Adapted from (a no longer active link): https://www1.nga.mil/kids/geoint/imagery/Pages/Shadow.aspx

The next step in the imagery analysis process is to begin to make mental/internalized visual connections. This is done by both direct inspection and by inferences based on the previously mentioned constituent features of the image being analyzed. It also involves deductive reasoning such that the questions that are most commonly asked initially are 1) what? and 2) where? Then, with further review and comparison over time through the use of change detection, the question that can then be answered is 3) when? The final steps include seeking answers to 4) why?, 5) how?, and most importantly, 6) what is the significance?

There are a number of other steps involved in this process. The deductive (more precisely "abductive"[108]) reasoning or "sense making" of the extracted answers have to be viewed through a mental lens that can focus the disparate data elements into a cohesive narrative through "convergence of evidence" that leads to the "inference for the best explanation". The old saying, "if it looks like a duck, walks like a duck, and quacks like a duck…it is probably a duck," generally holds true in most imagery analysis situations. But the next step is not to be lulled into complacency with any conclusions so derived. Unlike pure scientific research, by which conclusions are empirically derived by objective data, imagery analysis of commercial satellite imagery for verification purposes can involve potentially manipulated data courtesy of a potentially deceptive adversary. Camouflage, concealment, and deception (including signature suppression) are constant threats to correct image analysis. Because the imagery analysis process is dealing with remotely collected information that is processed at some level through human interpretation and is therefore not necessarily empirically derived, imagery analysis is as much art as science in that the conclusions are only approximations of truth and only hypotheses that must be tested through remote critique. The hypotheses should be validated wherever possible with supporting collateral information, if any can be found. For verification and monitoring purposes, this is particularly difficult when evaluating clandestine "undeclared facilities and activities" and even more so when they are placed underground.

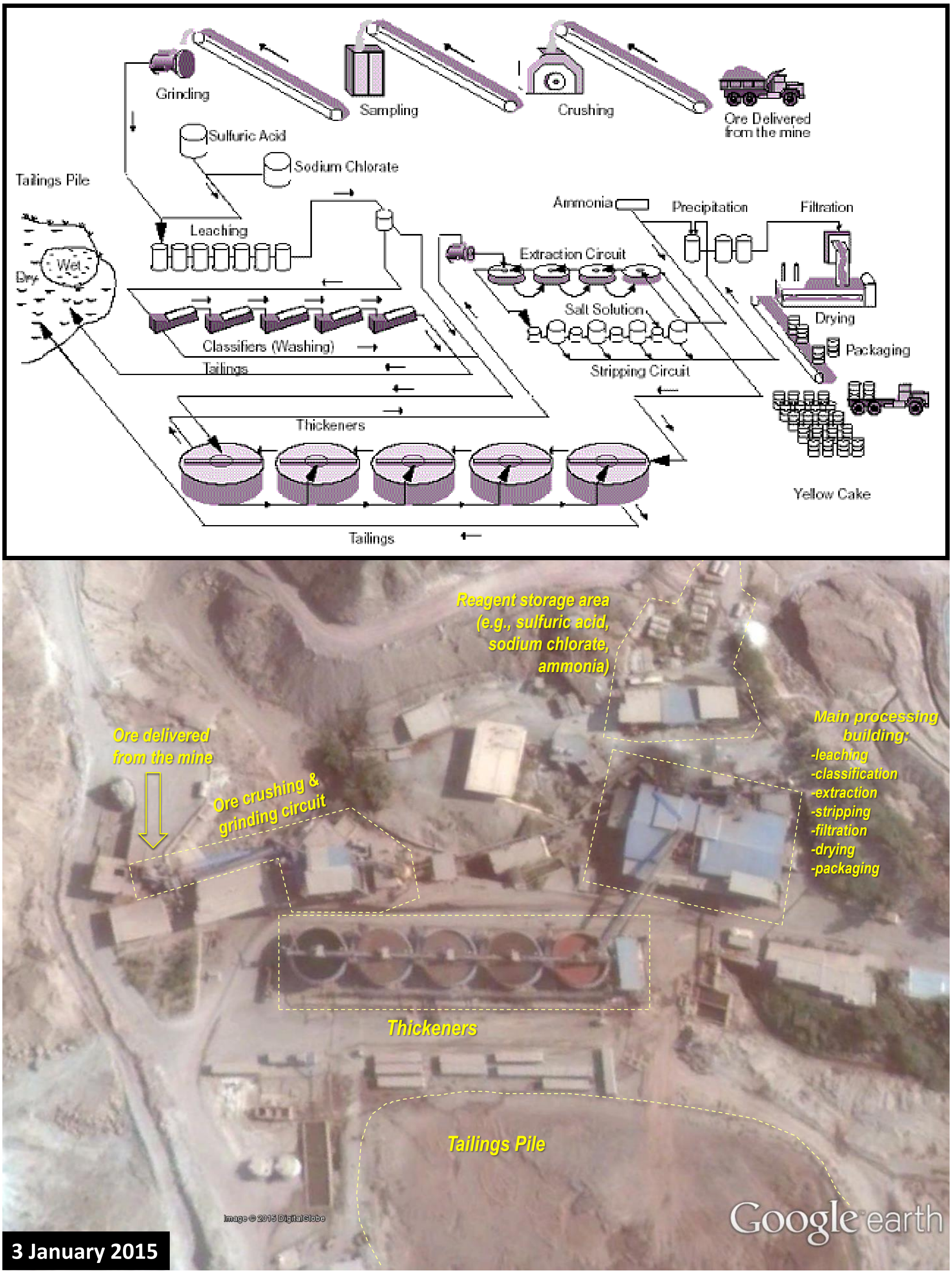

Figure 14: "Signatures" play a critical role in nuclear fuel cycle infrastructure analysis. The top view provides a flow diagram of the key components in the operation of a uranium ore concentration plant. The lower image is an operational uranium ore concentration plant, sometimes also referred to as a yellow cake production plant. Diagram source: http://www.nuclearweb.info/Uranium/Uranium_mill_news.html

Wherever possible, peer review should always be sought, but the imagery analyst should also always strive to be his or her own worst critic. The final conclusions should also be weighted in terms of confidence level by the addition of caveats; e.g., "suspect" (low confidence), "possible" (medium confidence), "probable" (higher confidence, or the conclusion is the best of all assessed possibilities). Without a caveat, any conclusion will be perceived by others to be no less than "certain". Imagery analysis, particularly when dealing with issues of verification should at least meet the same analytical rigor as that set forth in the US Intelligence Community Directive on Analytical Standards (no.203).[109]

Invariably one can find much in the open literature that emphasizes information technology (IT), geographic information systems (GIS), "geomatics", image processing, but almost nothing at all in relation to the human interpretation of imagery.[110] However, in addition to the more generic Manual of Photographic Interpretation published by the American Society for Photogrammetry and Remote Sensing in 2006,[111] there are a few insights from the military applications sector as aggregated and published by the Federation of American Scientists.[112]

Another point to consider with regard to imagery analysis involves the personal attributes of the analyst who is engaged in imagery analysis. John Jensen (2007) described factors that distinguish a superior image analyst. He said, *"It is a fact that some image analysts are superior to other image analysts because they: 1) understand the scientific principles better, 2) are more widely traveled and have seen many landscape objects and geographic areas, and/or 3) they can synthesize scientific principles and real-world knowledge to reach logical and correct conclusions."*[113] This author would also add that years of experience and familiarity with the subject area from "on the ground" as well as from above will make the critical difference.

Finally, in June 2000, David Sandalow provided this quote that is just as true today as it was at that time,

> *"We should explore ways to help improve interpretation of satellite imagery. Imagery interpretation can take considerable skill and training, and misinterpretation is not difficult. Without strong experience and training, it can be relatively easy to see proof of sinister intent in a benign image, or to miss details that would be conclusive to a knowledgeable photo interpreter. Again, the concern for policy makers is how that increased transparency could at times be a source of added instability…Satellite images have the potential, if interpreted incorrectly, to increase tensions among nations and create confusion during periods of crisis, rather than to promote stability. For example, widespread, incorrect interpretations could confound efforts of U.S. national security agencies to mediate or diffuse tensions along the India/Pakistan, Syria/Israel borders or along the Korean peninsula. This is not just a theoretical problem: in one incident, an image that a magazine claimed was the site of India's 1998 nuclear test turned out to be a livestock pen."*[114]

5.3 Imagery Analysis for Nonproliferation Verification: Exemplar Cases[115]

5.3.1. Test Positives:

Open source "New Media" content, together with commercial satellite imagery (and the means to better visualize it in a 3D geospatial context), has made possible a host of investigations resulting in somewhat surprising geo-spatial discoveries found in otherwise denied environments; and which would have been impossible for anyone not previously having the resources of at least a super-power nation state.[116] Two such examples are provided below. One recent such discovery, involving the work of a small team of subject matter experts and interested academics who were able to combine otherwise disparate pieces of an information puzzle (found exclusively through the use of open sources) into a cohesive and coherent narrative such that they were able to locate, identify, and characterize a potential ballistic missile transport vehicle checkout complex in DPRK. The second example is a case involving the location and identification of potential gas centrifuge manufacturing related facilities in the DPRK.

5.3.1.1 Exemplar: A Potential Ballistic Missile Transporter Checkout Complex in the DPRK

In an interesting case study account, Bryan Lee, Jeffrey Lewis, and Melissa Hanham, describe how they were able to identify and characterize two potential locations for ballistic missile transporter equipment checkout in North Korea by simply engaging the New Media.[117]

On April 15, 2012, the North Koreans paraded what appeared to be six road-mobile intercontinental (KN-08) ballistic missiles. Analysts working at the James Martin Center for Nonproliferation Studies together with collegial *Armscontrolwonk* bloggers in Washington, DC, and Vienna, Austria, were able to follow-up on blog posts by Chinese bloggers concerning what were identified as Chinese origin vehicles modified to make them suitable as mobile erector launchers for those missiles.[118] Using information published by Joshua Pollock, they were able to view a video from North Korea that depicted ballistic missiles on mobile transporters inside of buildings exhibiting unique elevated roof sections. By closely studying both the parade photos and the frame stills of the buildings from the video, together with dimensioned specifications as found on online brochures for the Chinese origin vehicles, those analysts were able to create digital 3D models of the transporters, missiles, and the buildings (using freely available modelling software downloaded from the web) to gain a sense of not only what the buildings would look like on the outside, but also the role of the unusual elevated roof sections, and how they would provide the means to operationally check-out the erector portion of a missile transporter while under roof cover.[119] Based on open defector reporting, they were able to locate two buildings on *Google Earth* that met those criteria.[120]

As the analysts reported in a more comprehensive report, all of the information that they used was derived from only open sources as found on the internet, but they were able to successively pick up additional pieces of the puzzle as they continued their investigation. That investigation involved, to one degree or another, all of what the authors defined as the five New Media functional venues: 1) content (e.g., Blogs), 2) social networking (for analysis and translations), 3) data mining (*Google Earth*'s layering), 4) problem solving (determining the search area with cluster of defense sites), and 5) gaming (simulation 3D modelling).[121]

In those authors' own case study review, they describe the steps necessary for such results and begin with project "Planning." However, project planning was actually a subsequent event, as it was only because of the original unforeseen event (involving the parade display of the purported KN-08 missile and its transporter) that initially triggered a domino effect and initiated the subsequent follow-up project planning.

For the record, at least some, if not all, of the six KN-08s on parade were judged by some observers to be merely mock-ups.[122] Moreover, even the best remote analysis cannot be proven as a true positive without additional source corroboration, ideally with onsite inspection, but such analyses can provide valuable starting points for any subsequent enquiries.

5.3.1.2 Exemplar: Potential Gas Centrifuge Workshops in the DPRK

In June 2013, R. Scott Kemp, did a guest post on the *Armscontrolwonk* where he noted the identification of a flow forming machines (suitable for making gas centrifuge rotors) at what was described as the Kanggye General Tractor Plant in a publicly released photo by North Korean media.[123] In September 2013, Jeffrey Lewis, in two additional posts on the *Armscontrolwonk* blog, described some additional investigative work that he had conducted together with Amber Lee on that facility and other reporting of additional computer controlled machine tool workshops in North Korea.[124,125] They compiled North Korean and South Korean press reporting of North Korean defector accounts, as previously culled and shared by researchers on other North Korea focused blogs. They then conducted their own research on *Google Earth* to correlate and locate various published ground images. They determined the physical location of a previously unknown potential site for gas centrifuge component manufacturing in the DPRK at the Huichon Ryonha General Machinery Plant. Based upon a number of interesting observations drawing from the derived information from the New Media, they appear to have made a plausible case.

5.4 False Positives: Mistaken Identities and a Means to Avoid Them

Just as the above cases illustrate some surprising positive results that can arise having significant nonproliferation monitoring and verification consequences, negative results can also arise that can nonetheless prove useful as well. Moreover history has shown that even large facilities can either be overlooked or misidentified.[126,127] However, before we begin this section, which also involves the detection and site characterization by remote means, it is worth taking a moment to reflect on this additional quote from David B. Sandalow:

"Imagery interpretation can take considerable skill and training, and misinterpretation is not difficult. Without strong experience and training, it can be relatively easy to see proof of sinister intent in a benign image, or to miss details that would be conclusive to a knowledgeable photo interpreter."[128]

5.4.1 Exemplar: "Mystery Complex" in China (in actuality a group of industrial facilities for commercial purposes)

In one mistaken identity incident, which occurred in early 2013, there was an over-reaction to a posting on a *Wired Magazine* Blog regarding some new construction in China that had been observed on *Google Earth*. A person who identified himself as "an ex-CIA analyst" had identified what he labeled a "Mystery Complex", which was suggestive that it had some kind of potentially sinister functionality. The media hype stopped abruptly when the noted geospatial blogger, Stefan Geens, was contacted by a reporter. Geens explained the realities: "*Yes, the reporter called me to talk, which is when I realized this non-story was going viral, so after we stopped chatting I wrote up something on my blog.*"[129] Geens then blogged that the "mystery complex" was nothing more than a benign new industrial park, drawing both from his skills as an experienced imagery analyst along with personal experience in the area and knowing the cultural context, and was thus able to speak with additional authority.

5.4.2 Exemplar: A suspect gas centrifuge facility in Syria (in actuality a cotton textile plant

One exemplar case of a false positive involved the identification and characterization of a cotton spinning plant in Hakasa, in northeast Syria, which had originally been alleged to have been under international scrutiny as a possible undeclared gas centrifuge enrichment facility.[130] With a bit of New Media sleuthing, involving a host of New Media sources, including social media photo sharing sites, and volunteered blogger/reader assistance (a German journalist, Paul-Anton Krüger, interviewed the chief engineer who constructed the Syrian cotton spinning plant) and some 3D modelling by Tamara Patton,[131] it was possible to make a compelling dispelling argument.[132] All of the available evidence pointed to the conclusion that the facility, while initially justified as being a focus of additional enquiry (based upon the implications of such an allegation), was nothing more than a cotton spinning plant. Moreover, in the event that an IAEA onsite inspection is ever conducted for transparency and verification purposes, such collected background information would prove to be quite useful.

5.4.3 Exemplar: A cylindrical concrete foundation suggestive of a reactor under construction in Iran (in actuality a large cylindrical hotel under construction)

As was shown in above case, innocuous facilities have the potential to be mistaken for undeclared facilities of potential interest for treaty monitoring and verification, particularly during early construction phases. One such example can be found where a large, deep and circular excavation had been observable in an area north of, and near, Shiraz. Shiraz is a city in southwest Iran that will be the location of a 10-MWth research reactor, according to declarations Iran has provided to the IAEA.[133] Using *Google Earth* historical archive imagery during the early construction phase of the site in question, the concrete foundation work exhibited some of the physical features that could have been suggestive of what had previously been observed during the early phase of construction of the IR-40 reactor at Arak, Iran. However, various social media user content, involving Panoramio posted ground photos and virtual globe labelling, along with associated links to appropriate descriptive construction websites, would have quickly dispelled any nuclear connection. The circular concrete foundation was identifiable as merely that for a 30-story cylindrically shaped hotel (now almost complete, and adjacent to what is now the largest shopping mall in the Middle East).[134] (See **Figures 15 and 16**) Moreover, the *Google Earth* historical imagery layer also reveals that the site was an amusement park in 2005.

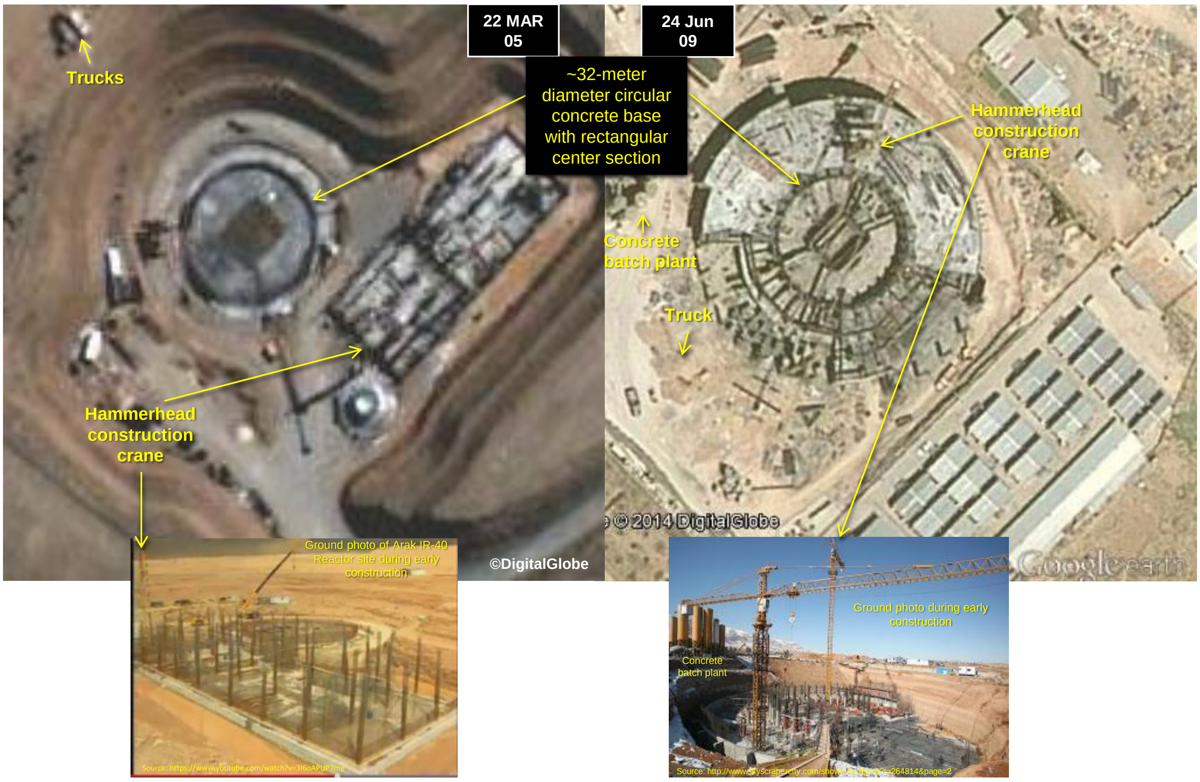

Figure 15: False Positive Exemplar, A. Left side shows the Arak, IR-40 (40 MWth), radioisotope production reactor under construction in 2005; the right side shows a large concrete structure under construction having somewhat similar attributes.

Figure 16: False Positive Exemplar, B. Left side shows the Arak, IR-40 (40MWth), radioisotope production reactor externally complete in 2014; the right side shows a 30-story cylindrical hotel nearly complete in 2014.

5.5 The Threats

"High-resolution satellite images could be used to support terrorism, espionage or military aggression, and thus must be a national security and foreign policy concern of the United States. We must continue to protect U.S. national security and foreign policy interests. On this, there can be no compromise."
- David B. Sandalow (June 2000)

While this was only mere speculation in 2000 (just as one meter was becoming available for use by the public at large), history has shown David Sandalow to have been correct. The availability of worldwide high resolution commercial satellite imagery can also be used by those seeking to do harm at various levels. Insurgent forces had reportedly used commercial satellite imagery available via *Google Earth* to plan attacks on US bases in southern Iraq,[135] and terrorists similarly reportedly planned attacks in the Mumbai bombings in 2008.[136] For more on this see:
http://www2.gwu.edu/~nsarchiv/NSAEBB/NSAEBB404/

This, sad to say, is the case for all such new technologies, e.g., while computers can be used by some people for humanitarian purposes, they can also be used by others to commit crimes against humanity.

5.6 Evasion and Countermeasures

Deliberate efforts to thwart the identification of clandestine nuclear installations began in the United States with the Manhattan Project during World War II, most notably by establishing nuclear materials production and processing facilities (e.g., Oak Ridge gaseous diffusion plant and the Hanford plutonium production complex) and the weaponization site (Los Alamos) in remote locations with limited access under cover names with only post office boxes instead of addresses. The Soviet Union followed suit with even more dramatic measures for its nuclear weapons program. One example was in Zheleznogorsk/Krasnoyarsk-26 where three plutonium production reactors and a reprocessing plant were built entirely underground inside a mountain along the Yenisei River.[137] Nonetheless, "*The Soviet Union also was unable to hide from overhead imagery systems its huge nuclear weapons production infrastructure. By 1965, the US intelligence program had correctly identified and characterized facilities with more obvious nuclear signatures, including all fissile material production centers, some uranium processing facilities, the Sarov warhead R&D center, the serial warhead assembly facilities in Lesnoy and Trekhgorny*."[138] China was similarly adept at hiding key nuclear infrastructures, as most of its second generation of nuclear weapons related facilities was placed in or around the Szechwan basin, which is usually obscured by low clouds. It had even begun (but never completed) construction of an underground plutonium production complex similar to the one in the Soviet Union, with evidence that another was also planned.[139,140]

Camouflage, concealment, and deception in association with nuclear program infrastructures have been applied by many other countries as well, For Example:

South Africa: The Circle nuclear weapons fabrication and assembly facility was built within the confines of a conventional military vehicle test track. A criticality test facility and initial nuclear explosive device assembly buildings were constructed in a visually obscured valley behind the Pelindaba nuclear research center.[141]

Iraq: Saddam Hussein's nuclear weapons effort placed his two electromagnetic Isotope Separation (EMIS) facilities along the Tigris River in an isolated valley (Ash Arkat) and in a huge date palm grove (Tarmiya) for ground level visual obscurity. High voltage electric power line connections were placed underground at Tarmiya for over about 1.5 kilometers to inhibit identification from overhead observation.[142]

Iran: The two known underground uranium enrichment plants in Iran at Natanz and Fordow were both originally covertly built underground in remote locations with cover stories. The one at Natanz was said to have had the cover story of being for anti-desertification, and the one at Fordow (near Qom) was built on a military reservation to suggest that it had only a conventional military related role.[143] Natanz also included signature suppression of electrical service with regard to buried utility connections and an enclosed electric substation that was constructed to look like an innocuous workshop. The only vehicle access to the underground area was concealed under a false façade constructed to look like a simple warehouse.[144]

Syria: Syria employed similar subterfuge with its allegedly North Korean assisted plutonium production reactor at Al Kibar (identified as Dair Alzhour by the IAEA[†]) by constructing it in a remote location, using terrain masking, and applying a variety of signature suppression techniques that included buried utilities and minimal observable onsite physical security. Most importantly, the reactor was built largely below grade with the reactor superstructure camouflaged under a false façade that was constructed to make the building appear simply as another one of several locale Byzantine fortresses situated along that stretch of the Euphrates River.[145]

Interestingly enough, the only publicly available means by which it was possible to determine the date of initial construction of the Al Kibar reactor (e.g., ~late July 2001) was via middle to very low resolution publicly available satellite imagery (varying from 80-250 meters) including that provided by ASTER and Landsat.[146] The commercial imagery archives of various vendors are currently accessible at no cost at similar low-resolution thumbnail versions and hence can be similarly also used for such "negation" dating. A negation date is the last date of imagery when a facility or activity was not extant, but which is known to be present afterward.

The exponential growth of commercial satellite imaging satellites has only increased the likelihood of the use of camouflage concealment and deception against overhead detection, identification, and assessment. In 2006, a Chinese Military journal contained an article that Google (Earth) "*has broken the monopoly position of traditional line-drawn maps and ushered in a new era of electronic maps [but] has also brought a certain amount of hidden security-related dangers that pose threats to every country and region*." The author recommended the adoption of "*various methods and measures and do all we can to get around the problems brought about by Google Earth and minimize the impact it has on national security*," and stressed "*the importance of anti-reconnaissance against satellites, properly camouflaging and protecting important secret facilities, and understanding a satellite's shooting intervals, which could be used for conducting major military activities*."[147] India and Norway have also both reportedly implemented such evasions and countermeasures by developing ways of "hiding defense installations from satellites, and would find other ways such as concealing buildings underground and in mountain installations."[148] Such efforts are not surprising, have been extensively employed since the dawn of aerial reconnaissance, and are rarely completely successful.[149]

[†] "*the Agency assesses that it is very likely that the building destroyed at the Dair Alzour site was a nuclear reactor which should have been declared to the Agency.*" Source: "Implementation of the NPT Safeguards Agreement in the Syrian Arab Republic," GOV/2011/30, Paragraph 33, May 24, 2011.

6. Commercial Satellite Imagery Is a Subset of the Larger Expanding "Open-Source" and "New Media" Information Data Stream

In late 2011, the US Assistant Secretary of State, Rose Gottemoeller, described the need to enhance and augment old verification methods, and to create new ones, and to integrate them as a system for more effective verification.[150] The rapidly expanding use of the Internet as a global social networking forum and the increasing number of venues available for collaborative information sharing (aka "crowdsourcing") of news, photos, and videos, together with geo-tagging and geo-positioning on commercial satellite imagery, has created new opportunities for data-mining of just such potential arms control relevance. The resulting geospatially-linked data can include information on nuclear fuel cycle infrastructure or strategic weapons systems sites, facilities, complexes, and associated materials, equipment, activities, and personnel. This data could provide a basis for new and important insights for treaty monitoring and verification.

This form of "societal verification" can be provided as posts to the blogs or simply as labels on information layers on the open available "virtual globes," in particular *Google Earth* and Google Maps, which host high resolution commercial satellite imagery that is viewable in a three-dimensional context. Several publicly available geospatially-linked ground imagery sharing venues (e.g., *Twitter*, *Flickr*, *Panoramio*, *Lookr, Wikimapia*[151]) can provide useful correlative information of potential relevance. Examples of existing commercial satellite imagery-based crowdsourcing platforms that could be applied to societal verification include (e.g., the *Ushahidi* Project, *Tomnod*, *Bellingcat*, or, in the case of human rights monitoring and analysis during the South Sudan independent transition, the *Satellite Sentinel Project*). One site, *Open Nuclear Iran*[152], has already been tailored toward nonproliferation-specific issues. Another particularly powerful geospatially-based social media search tool is *EchoSec*[153], which recently gained notoriety in obtaining geospatially-linked information from multiple social media venues like *Twitter*, *Facebook*, *Instagram, Foursquare,* and the Russian equivalent to Facebook known as *VK*.[154]

Several organizations and academic open-source analytical teams are currently leading the way in applying these multiple sources of crowdsourced and other geospatially relevant derived data with commercial satellite imagery to yield new multiple-source synergy relevant for nuclear nonproliferation applications (e.g., the James Martin Center for Nonproliferation Studies in Monterey and its Vienna Center for Disarmament and Non-Proliferation; the King's College London Alpha Project; the Institute for Science and International Security; the European Commission's Joint Research Centre, etc.).

Finally, just as this report was being compiled, commercial satellite imagery in combination with various new media tools now accessible via the internet continues to provide new and insightful value-added open source information for verification applications (particularly so when used creatively in the hands of experienced practitioners). The most recent case involves the open source follow-up of the Iranian dissident group (the National Council for the Resistance of Iran, NCRI) allegations of an underground gas centrifuge uranium enrichment plant in northeastern Tehran (identified as "Lavizan 3," thereby linking it to the NCRI's previously identified nuclear weapons program facility in the neighborhood known as Lavizan[155]). The documentation of that follow-up makes a very worthwhile read.[156] The alleged underground uranium enrichment plant was shown to be most likely a security identification badge processing center ("Matiran") based on the creative use by Jeffrey Lewis of "Open Street Map" (http://www.openstreetmap.org/) in which he found a Global Positioning System (GPS) track of a European technician who had visited the facility, and with whom Jeffrey was able to subsequently contact via email. As a result, Jeffrey was able to make a strong case for the facility having the security badge processing function.[157] Separately, another researcher, Phil Baxter, found other open-source evidence that undercut the validity of the allegations.[158] Most significantly, a blogger going by the name of "Florida Democrat" showed that the NCRI's published photographic evidence, purporting to have been taken inside the underground facility, was actually cropped from an above ground photograph published in an online corporate brochure.[159] Further doubt could be cast on the claim that the alleged enrichment plant was "Lavizan 3" by the simple fact that commercial satellite imagery showed that its construction had begun while the first Lavizan site was still in operation in March 2003, when that site was first publicly revealed by the NCRI. According to the NCRI, Lavizan 1 was subsequently moved to Lavizan 2 in 2003, and commercial satellite imagery showed that the site of Lavizan 1 was razed and replaced with a public park in 2004.[160]

It is perhaps also worth noting that Robert Cardillo, the Director of the US National Geospatial Intelligence Agency, addressed this new "open-source" paradigm shift (which he even identified as effectuating a "Seismic Shift"). "*The explosion of data and access outside of the government's control – Darkening Skies of small sats, global expansion of social media, and the Internet of Things....The smallsat constellation will continuously image thousands of facilities and activities across countries and continents—true global coverage…We must fully leverage nontraditional sources, especially open sources, and integrate them continuously in real-time with all of our other capabilities. We must do so throughout the day, all night, in all weather conditions, every day of the year, across the spectrum of sensors in the face of sophisticated denial and deception and both natural and man-made interference*."[161]

7. Conclusion

Commercial satellite imagery has already been proven to be a timely, accurate data source to support, supplement, and/or enhance nuclear related ongoing treaty monitoring and verification activities. Such imagery will also continue to be an enabler of independent action, in that it democratizes the availability and use of the medium by anyone in the world with digital information technology access (including smart phones), thereby limiting the control of what had been only a few central governments. It was recently noted that, "*data availability, data storage, and current transfer speeds put unprecedented compute power in the hands of the average person. Globally, people will be able to collectively wield the same power as a nation state in terms of information and intelligence creation.*"[162]

We have just entered a new era of new capabilities in earth observation that include large constellations of more agile and capable satellite having improved spatial, spectral, and temporal resolutions that even include high definition video. Those capabilities are synergistic in that the sum of derivable information is greater when the images are aggregated than the total of the information that they would otherwise provide when viewed in isolation. Commercial satellite imagery having global coverage is now also being made freely available via digital virtual globes. Moreover that imagery can be readily supplemented by focused additional imagery purchases from multiple platforms, with multiple sensors, from multiple companies, from multiple nations, and at least some can be purchased with only a smart phone for as little as ten US dollars. Despite the initial skepticism regarding quality, timeliness of acquisition and delivery, cost, and potential defeatablity; commercial satellite imagery has also more than proven its worth as a nonproliferation treaty monitoring and verification tool.

With respect to the impact of commercial satellite imagery for verification applications, Peter Zimmerman concluded in 1990 that, "*If civil remote–sensing systems ever achieve resolutions much better that one meter, many or the details of aircraft, missiles, and armored vehicles as well as of military installations would be visible to anyone with a modest bank balance and some curiosity. Were those high-quality pictures available on a timely basis, the consequences might be significant.*" The consequences have indeed already been proven to be significant. As the supporting reference material presented here shows, the work by various academic researchers, NGO researchers, and even hobbyists, creatively using commercial satellite imagery for verification applications has visually exposed numerous cases of heretofore clandestine facilities and illicit activities worldwide. As commercial satellite imagery capabilities and usage continue to evolve, those consequences for future verification efforts can only grow in significance.

Appendix A: What Do the Virtual Globes Bring to the Verification Toolkit?

Virtual globes (e.g., Google's *Google Earth*, including the "*Pro*" version which has advanced capabilities and recently became cost-free)[163], Nokia's *here*[164], Microsoft's *Bing Maps*[165], *Flash Earth*[166], *Apple's iOS 7 3D Maps*[167], *Skyline Globe*[168], *Géoportail*[169], and *Bhuvan*[170], *eAtlas*[171], etc.) are generally cost-free, but proprietary. They are generally versatile, readily accessible and user-friendly versions of what are known as **Geographic Information Systems** (**GIS**), which are designed to "capture, store, manipulate, analyze, manage and represent geographically referenced data."[172] In general, most GIS (ESRI's *ArcGIS Explorer*[173] is among the more widely known) are powerful applications that require professionally trained experts (and hence less intuitive than Virtual Globes) and which have capabilities that go beyond what is most often necessary for the imagery analysis and visualization purposes of greatest relevance to this report. Nonetheless, ESRI's ArcGIS website does offer some unique base map satellite imagery via *My Map*[174] that is both openly available and useful for the purposes of this study (see discussion below regarding the exemplar of Irbil, Iraq).[175]

Virtual globes are more than adequate for even a novice to virtually fly to any place on earth and gather information in a 3D geospatial context. They also provide a platform for additional information layers, which can include 3D structural models, additional separately purchased satellite images, and "crowdsourced" information such as labeling and ground images. While never sufficient as sole sources of such geospatial information, they have evolved to the point to where they can provide the necessary stepping stone upon which to embark for any subsequent commercial satellite imagery acquisition and analyses. Virtual globes have thus proven critical to providing the necessary locational and temporal awareness for nuclear infrastructure analysis, and can support any ongoing safeguards monitoring and verification applications in the open source realm, and because the satellite imagery is available on an essentially cost-free basis, also contributes to the overall financial resource efficiency of the Agency.

IAEA policy places certain limitations on the use of commercial satellite imagery and hence that which is provided as well on virtual globes. Imagery analysis is only to be used for the purposes of Safeguards verification. Moreover, while all State declared locations are subject to imaging, the IAEA is reportedly restricted from conducting any "*systematic, countrywide search for undeclared activities*." Nonetheless, commercial satellite imagery "*may be used in conjunction with complementary information that localizes a suspected activity.*" There are also requirements for imagery source diversification (multi-national) and for both security and confidentiality.[176] However, while the IAEA may not be specifically authorized to conduct broad area searches on its own, it would seem that it might at least leverage the use of openly available work published by others who have independently conducted broad area searches of entire countries on their own initiative. Some examples can be found in the Ogle Earth type blog postings[177] or in or in the *Google Earth* Community blog at least one blogger ("TheAmazingEye") went to the trouble of trying to label all the tunnels and underground sites in Iran and created a file that can be opened in *Google Earth*.[178]

A1. Not all Virtual Globes Were Created Equal

When thinking of virtual globes, one most often thinks exclusively of *Google Earth*[179]. Of all the virtual globes available, *Google Earth*[180] is by far most useful for a variety of reasons (that will be described below), however, one must be fully cognizant that *Google Earth* does not always offer imagery of the requisite resolution, either spatial or temporal, for all areas of the world to adequately conduct the overhead imagery reviews necessary to support all state evaluations. Just as one should not rely exclusively on only one open-source search engine (e.g., Google), one should not rely exclusively on a single virtual globe when searching for available online commercial satellite imagery. While *Google Earth* should almost always be viewed as the virtual globe of first resort, multiple virtual globes should always be accessed as part of any comprehensive analysis.

For example, **Figures 17 & 18** compare the latest high resolution imagery of Irbil, Iraq, as currently available on *Google Earth* with that which can be found on two popular alternative virtual globes. Somewhat surprisingly, *Google Earth*'s most recent high resolution imagery is over a decade old (from 2004), while those which are available on both "*Flash Earth*" (which includes imagery from several sources including "*ArcGIS*"), Microsoft's "*Bing Maps*", and "*Here*" (formerly *Nokia Maps 3D*) are from 2011, 2013, and 2014 respectively. One must also be cognizant of the fact that the satellite imagery available with these virtual globes is constantly being updated, and so what is true today for any given point on earth (e.g., Irbil, Iraq, as accessed for this study on March 24, 2015) may not necessarily be true tomorrow.

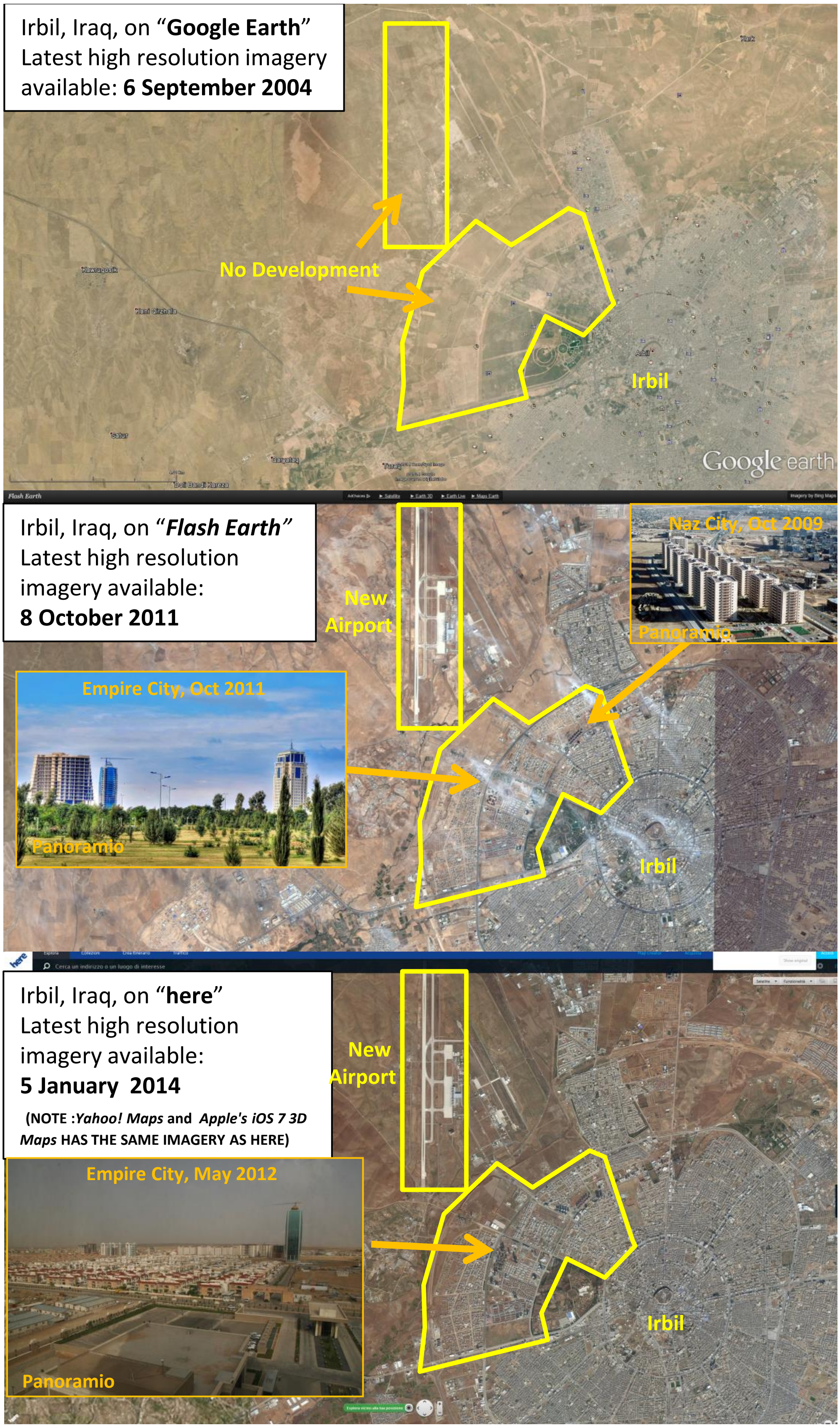

Figure 17: A comparison of commercial satellite imagery as is available on three different virtual globes: *Google Earth* (top), Flash Earth, and Here. The *Google Earth* image is over a decade old and does not show the substantial changes that include the addition of a new skyscraper city and international airport in the vicinity of Irbil, Iraq.

Figure 18: A comparison of commercial satellite imagery as is available on three different virtual globes, Close-up: *Google Earth* (top), Bing Maps (middle), and Here (bottom). The *Google Earth* image is over a decade old and does not show the substantial changes that include the addition of numerous multi-story buildings, roads, and traffic jams in the vicinity of Irbil, Iraq.

A2. Dates of Imagery Acquisition Are Critical for Any Analysis

The satellite imagery that is available on virtual globes will be of little use for nonproliferation purposes if it cannot be determined when such imagery was acquired. The only deficiency with both of the above mentioned alternative virtual globes is that neither directly provides the specific date of imagery acquisition as does *Google Earth*. Nonetheless, the exact dates can be still be indirectly derived. This is because each virtual globe does display their respective commercial satellite imagery source (e.g., the commercial satellite imagery vendors such as DigitalGlobe, Airbus [181], etc.). Such information is sufficient information to conduct an appropriate historical search of the named vendor's satellite imagery archive. Furthermore, the date range of that archival search can be significantly narrowed from the decade since the *Google Earth* image was acquired (reduced to only the last four years) by comparison of the substantial new building construction progress in the Irbil suburbs vis-à-vis that which is observable on commercial satellite imagery that is viewable on the openly accessible ESRI ArcGIS website. ArcGIS does provide the imagery dates of acquisition in the metadata associated with each "Imagery Basemap" image[182] (for the case of Irbil, the ArcGIS imagery is sourced to DigitalGlobe and was acquired on July 5, 2010). Bing Maps MetaData is also available (at least the month and year, not the exact date) by using this application: http://mvexel.dev.openstreetmap.org/bing/.

After having thus determined that both images were acquired post-July 2010 (e.g., both images show a completed tall hotel in the Empire City development that was only in the early stages of construction on the ArcGIS image), it is also possible to get an approximate date for each by comparing the construction status of new buildings with date-tagged ground imagery from the Panoramio layer on *Google Earth* (as is shown in the insets on Figure 1). Moreover, it was also possible to determine relative dates, in that the *Here* imagery was clearly the more recent of the two (e.g., more buildings had been newly constructed). Figure 2 provides a close-up of one area of the Irbil, Iraq, suburbs (known as Empire City), which has undergone the fastest and most substantial growth (along with dramatic increases in vehicle traffic as well).

However, to get the exact date of the two different satellite imagery acquisitions, the next step was to search the archives of the copyrighted source of the imagery. In this exemplar case, both are sourced to DigitalGlobe. To access the DigitalGlobe archives, one must go to this link:
https://browse.digitalglobe.com/imagefinder/main.jsp?

The next step is to zoom into the area of interest, in this case Irbil, Iraq. Then one should reduce the number of possible images to a minimum by adjusting the "search filter[183]" acquisition date range to post-July 2010, shown in Figure 3, middle left. Next, one must click on the "Search" button and, in this case, "13 images meet your filter criteria". By clicking on the catalogue tab, and clicking on "view list," the list of all nearly cloud free images appears (as is shown in the bottom of Figure 3). Then, by checking the various browse image boxes, the images can be viewed overlain on the accompanying search map. When an image appears that appears as though it might be a good candidate, the next step is to click on the browse image "view" link. Then, a new separate metadata box viewer opens, and a small browser image appears. An internally displayed "image resize" inset box also appears and usually displays "512 x 512" (e.g., small scale). However, by clicking on that tab arrow on the right of that little box, one option is "max available resolution," which will open the selected browser image at a high enough resolution (e.g., large scale) to make a valid comparison with the images visible in both *Flash Earth* and *Here* (see figure 3, lower right).

The actual process of determining the exact date of acquisition involves careful visual comparison of the features observable in the DigitalGlobe archive with those viewable in the *Flash Earth* and *Here*. Among the features useful for comparison include the angle and length of shadows cast by the tallest buildings, the presence of identical features (no more and no less) on the ground, where the features can either be anthropogenic (buildings, roads, parks, gardens) or natural (e.g., water levels in streams), or the presence or absence of clouds, smoke, or contrails, etc. For example, **Figure 19** shows that it is rather straightforward to determine that the *Flash Earth* Image was acquired on October 8, 2011, as the presence, orientation, and length of the short lived visible smoke plumes serve as an image identification fingerprint. The *Here* image was a bit more difficult, particularly given slight differences due to image color processing and ortho-rectification, but was similarly determined to have been acquired on January 5, 2014.

There are also two additional, and very important, side benefits of the above process involving the "max resolution available" browser imagery with the DigitalGlobe archive. By reviewing all of the available imagery of one's area of interest, it is possible to also determine 1) whether purchase of the full resolution version of the more current imagery is warranted, and 2) the browser images can be used as online low-resolution reference library for quickly answering questions regarding dates of construction for many larger infrastructure changes such as the excavation of a new uranium open pit mine, or the construction or razing of large fuel-cycle processing buildings, or the construction timelines of roads, rail lines, bridges, tunnels, and perhaps even utility lines/nodes, etc.

Another option to quickly peruse low-resolution versions of the majority of available high resolution imagery archives is to use a meta-search engine like Apollo Mapping's "*Image Hunter*" https://imagehunter.apollomapping.com/. That service is provided to expedite commercial satellite imagery sales through Apollo Mapping as a vendor, for which it is quite useful. However, it also makes it easy to locate high resolution imagery over any area of interest in such a way that you can use it as a cost-free means to determine the timing of significant changes like facility and road construction in previously undeveloped areas.

Finally, with regard to imagery archives, one must also be cognizant of the fact that some areas of interest can be deemed as "sensitive" by the US Government, and potentially subject US commercial satellite imagery vendors to US Government mandated distribution restrictions (thereby imposing "limited access," sometimes also known as "shutter control"), which could prevent some US-sourced satellite imagery from being available in any publicly accessible archive systems. As a result, one must always also review the archives of non-US commercial satellite imagery vendors when seeking to obtain the latest available high resolution imagery for any given requisite area of interest.

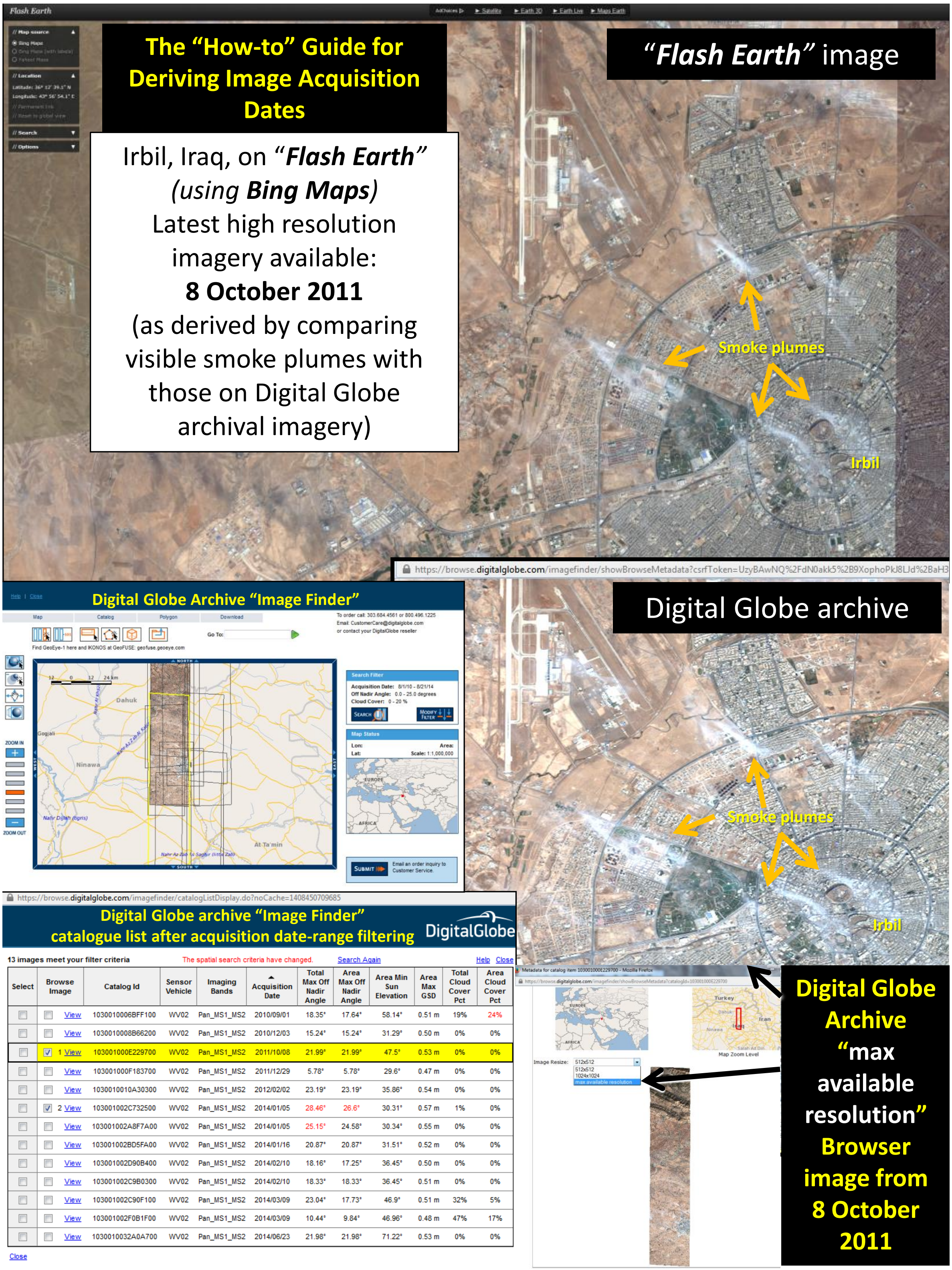

Figure 19: The acquisition dates of commercial satellite imagery that are not provided on some virtual globes can be deduced via a careful comparison search of imagery vendor archives. In this case the smoke plumes serve as a temporal "fingerprint".

A3. Advantages of Google Earth

Aside from the exemplar case of Iraq, as a virtual globe and layman's GIS, *Google Earth* does however offer some unique and important capabilities that should not be overlooked.

1) *Google Earth* is the only virtual globe to offer an historical commercial satellite imagery layer by which one can readily monitor changes and derive the necessary temporal context to support verification of facility related activities. One quirk of *Google Earth* is that the image viewed of an area when *Google Earth* is first opened is not necessarily the most currently available. In some cases (not all), only after one opens up the historical layer (one must click on the Clock icon) can the most recent acquisition be viewed, if a more recent one happens to be available.

2) *Google Earth* provides ground photo viewing layers from *Panoramio* and *Lookr*.

3) *Google Earth* also offers the unique capability to peruse "crowdsourced" labeling via the "*Google Earth* Community" layer (which is subordinate to the "Gallery" layer), and through separate user import of the *Wikimapia* Keyhole Markup Language (KML) layer[184]. Please note that similar but separate capabilities for ground photo viewing are also available on https://www.flickr.com/map, which includes a multi-resolution satellite imagery geo-location layer derived from "*Here*".

4) *Google Earth* offers the unique capability to review (in a browser format) archived imagery from DigitalGlobe (less than one meter over the period from 2002 to early 2010) and 2.5 meter SPOT imagery from AIRBUS industries over the period 2011-2012).

5) *Google Earth* provides the 3D terrain context in a user friendly fashion with several viewing options including "photorealistic atmospheric rendering (EXPERIMENTAL)."

6) *Google Earth* also provides a number of major cities in 3D construction (either via the old scheme using Trimble's *SketchUp*[185] modeling that was all created manually (the "legacy" option), or the new default version using models that have been automatically generated using laser radar). Most significantly, *Google Earth* allows one to viewing one's self generated 3D models created separately in *SketchUp* to be viewed in *Google Earth*'s virtual world 3D terrain context.

7) There is at least one case that this author is aware of where the *Google Earth* 3D building layer provides much more current imagery (2014 vice 2011), in higher resolution (due to it being from aircraft) than is presented with the 3D building layer turned off.

8) *Google Earth* provides the means to measure linear and path distances (*Here* does also), but in the *Google Earth* "Pro" version (which became entirely cost-free in 2015[186]), *Google Earth* allows one to also make measurements of area (e.g., floor space), create videos, and create and plot "view sheds" (e.g., line of sight maps from any location).

Note on *Here*: As of this writing, *Here* has established itself as a true "crowdsourcing" venue whereby anyone can add/change roads and add/change places directly onto the *Here* base map using the "Map Creator" function. Conceivably, this could eventually prove itself to be a useful means by which someone might volunteer and post new information of potential relevance to a Safeguards site investigation.

Note on *Bing Maps*: As of this writing, *Bing Maps* has brought back its excellent 3D building viewing capability for over one hundred major cities (that had been available earlier only in Microsoft's now defunct *VirtualEarth*) in addition to *Bird's Eye* viewing, but is only viewable via Microsoft's Windows 8.1. Microsoft's Bing Maps has also introduced "*Streetside*", which is similar to Google's "*Streetview*" (as available on both *Google Earth* and Google Maps), but *Streetside* presents ground imagery having its own unique views as acquired with different cameras, on different dates, in potentially different weather conditions. Microsoft's *Streetside* imagery is available in both Bing Maps and the Bing Maps Preview app (the latter being exclusively available on Windows 8.1[187]). With this latest release, *Streetside* has now surpassed 100 cities. While not necessarily relevant for many IAEA Safeguards relevant questions, arising from the geographic coverage limitations imposed on such drive-by or aircraft overflight viewing (e.g., large swaths of Asia, Africa, and the Middle East are not included as of this writing).[188] It is possible to access both *Google Maps Streetview* and Bing's *Bird's Eye* using "Dual Maps" available at http://www.mashedworld.com/dualmaps.aspx

A4. Automated 3D Modeling

Previously, the capability to create 3D models of nuclear relevant facilities, infrastructure and equipment for better assessments including walk-arounds or fly-arounds (e.g., for IAEA inspection planning, etc.) was then limited to only manual creation with digital modeling software. Such software included *SketchUp* (formerly owned by Google and now Trimble Navigation's (previously Google's), which is viewable in *Google Earth*; while Dassault Systemes' *3DVia* and *Geovia,* and Sampos' *3D Visioner*, are both viewable with Microsoft's Bing Maps. In the case of SketchUp, crowdsourcing volunteers had created 3D models that could be viewed as an additional layer of virtual globe content on *Google Earth* (see the "3D Buildings" layer). While such models are still available for viewing on *Google Earth* when viewed in legacy mode, *Google Earth*, in the updated *Google Earth* ver. 7, has enchanced the 3D Building layer to include 3D models that have been automatically created via digital stereophotogrammetry using high resolution aircraft imagery taken from four different views at a 45 degree angle off nadir. According to one recent report, "*Google is rolling out 3D at an extraordinary rate*."[189] Similar automated 3D modeling is also available on other virtual globes like *Here* and Microsoft's *Bing Maps* for Windows vers. 8.1[190] and the new "maps app for Windows 10" comes with new 3D cities of 190 locations[191]. Increasingly, the virtual globes like *Google Earth* and Google Maps have begun the quest to "*map the planet in 3D*" automatically creating "*3D cityscapes, complete with buildings, terrain and even landscaping, from 45-degree aerial imagery.*"[192]

Until 2015, such automated modeling coverage had been limited to those areas allowing such proprietary commercial overflights (Google uses its own aircraft[193]). However, given the increasing agility provided by the new commercial imaging satellites, which are now capable of acquiring the same 45-degree perspective imagery at nearly equivalent resolutions as aircraft, it was not unexpected that, at some point in the near future, the entire world, including denied areas, could be mapped and viewable in 3D on virtual globes like *Google Earth*. The 3D rendering shown in **Figure 20** was derived from multiple aircraft overflight images acquired on April 10, 2013. The 3D modelling (including buildings, trees, bushes, and even vehicles) was created entirely via an automated process run by Google. This could just as well have been any other nuclear facility of interest for monitoring and verification purposes. To date, however, such "cost-free" modeling remains limited only to areas accessible by aircraft. With the advent of highly agile, highly accurate, commercial satellite imaging satellites as are now available (e.g., DigitalGlobe's WorldView-3 **~30 cm** resolution and Airbus's Pléiades **50 cm** resolution), such automated 3D modelling is now also possible for any place on Earth with nearly the same fidelity. Notably, in May 2015, a new joint venture company was announced between DigitalGlobe and Saab, called Vricon, which has begun offering, on a "for-fee" basis, such automated 3D modeling, derived solely from commercial satellite imagery.[194] One initial exemplar, provided in a promotional video, shows an automated 3D model of the Natanz Uranium Enrichment Facility in Iran (**See Figure 21**). Similarly, Airbus Defence and Space has proven its ability to successfully and accurately produce a 3D model using thirteen Pléiades images, forming nine stereo pairs, combined to produce the 3D model, also viewable in a promotional video.[195] For the foreseeable future, however, manual 3D modeling will continue to be required for building interiors (see for example: "Approximate 3D Visualization of Yongbyon U-Enrichment Facility by Tamara Patton[196])

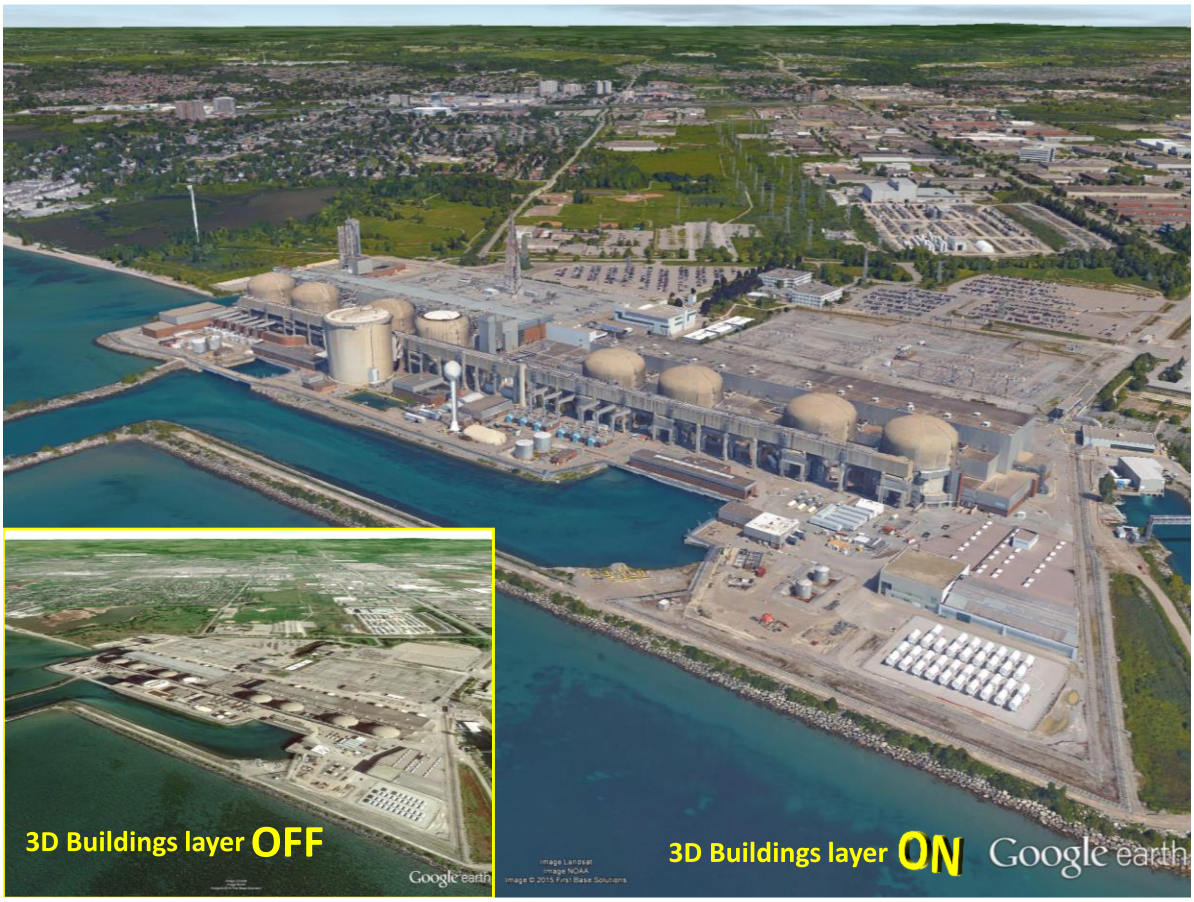

Figure 20: The Pickering Nuclear Power Station, Canada, as viewed on *Google Earth* with the 3D Building layer turned *ON* and *OFF* (inset). The 3D rendering was derived from multiple aircraft overflight images. The 3D modelling (including buildings, trees, bushes, and even vehicles) was created entirely via an automated photogrammetric process operated by Google.

Figure 21: Perhaps the very first automated 3D model of a nuclear-related facility using only commercial satellite imagery created via an entirely automated photogrammetric process (from DigitalGlobe) was displayed by Vricon in a promotional video. (See Ref 194)

Appendix B: Useful Resources

Entire blogs and magazines are now dedicated to the trends and developments in the rapidly evolving field of imagery analysis using commercial satellite imagery. Among the blogs of greatest import for verification applications include:

http://www.isis-online.org/;
http://armscontrolwonk.com/;
http://www.fas.org/blog/ssp/category/hans_kristensen;
http://geimint.blogspot.com/;
http://ogleearth.com/;
http://osimint.com/ ;
https://www.bellingcat.com/

Examples of blogs that are devoted to a single country (e.g., DPRK) that can provide additional imagery and contextual analysis include:

http://38north.org/
http://www.northkoreatech.org/
http://www.nkeconwatch.com/
http://freekorea.us/
http://nkleadershipwatch.wordpress.com
http://www.nknews.org/
http://kcnawatch.nknews.org/

Among the online magazines are:
Trajectory http://trajectorymagazine.com/;
Earth Imaging Journal http://eijournal.com/;
Apogeo http://apogeospatial.com/
(formerly *Imaging Notes* http://www.imagingnotes.com/)
Pathfinder https://www1.nga.mil/mediaroom/Publications/Pages/default.aspx
Geospatial Intelligence Forum
http://www.kmimediagroup.com/images/magazine-pdf/GIF_13-1_FINAL.pdf
Directions Magazine
http://www.directionsmag.com/
Earth Observation Portal Newsletter
https://eoportal.org/web/eoportal

Other Geospatial background resources can be found here:
https://www1.nga.mil/Pages/default.aspx
http://www.defence.gov.au/AGO/
http://www.satcen.europa.eu/
http://www.asc-csa.gc.ca/eng/satellites/default-eo.asp
http://www.unitar.org/unosat/
http://www.unoosa.org/
http://news.satimagingcorp.com/
http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-11-06467
http://defensetech.org/about-defense-tech/

Among the best all-around blogs for commercial satellite imagery development news is:
http://www.gearthblog.com/(because it is not just about *Google Earth*). There are numerous other related links to be found there as well e.g., http://www.gearthblog.com/reference

The US Government published a student handbook on photo interpretation that is useful for understanding various industrial process and observable features associated with them as well as a cursory look at the nuclear fuel cycle and related infrastructure. Please see:

http://sites.miis.edu/geospatialtools2013/files/2012/07/Photo-Interpretation-Student-Handbook.-Photo-Interpretation-Principles.pdf

Another unique source for insights on the art and science of imagery analysis can be found here: http://osimint.com/?s=I%26A+vol&submit.x=0&submit.y=0&submit=Go

This blog is entitled: Open Source IMINT http://osimint.com/ which also has a real time twitter feed. That website includes archived work by Sean O'Conner with excellent quizzes on the last page of each issue of IMINT & Analysis found here:
http://osimint.com/resources/imint-analysis/ia-volume-1/ and
http://osimint.com/resources/imint-analysis/ia-volume-2/m. One way to monitor is simply insert the search term "nuclear"
http://osimint.com/?s=nuclear&submit.x=0&submit.y=0

There is some additional supplementary material associated with this author's previous textbook chapter on commercial satellite imagery for safeguards applications. Please see:
http://booksite.elsevier.com/9780750686730/casestudies/Chapter%20Annexes.doc

Note: Although some of the links are no longer active, this page can still serve as a useful reference for anyone interested in geospatial tools for verification purposes. Most, if not all of the links may still also be accessible via the Internet Archive *WayBackMachine* at https://archive.org/web/web.php.

Appendix C: Summary of what's really NEW since 2008 (the year of the previous textbook chapter by this author on this subject)

We can conclude by saying that since the last review by this author on the subject of the use of commercial satellite imagery for nonproliferation applications, the significant increase in the number of satellites (including "small sats" and "nano satellites" and ISS basing) have created a new environment of "rapid revisits" almost to the point of "persistent surveillance" while also providing imagery that is much closer to "near real-time;" as well as:

a) Additional acquisition time windows are becoming available, e.g., it is no longer only late-morning (~10:30 to 11:00 am). Various vendors are in the implementation stage of providing imagery at all hours of the day or night. (See the example in **Figure 5**)
b) HD and UHD video from space is now available. Skybox and Urthecast are both new exemplar companies providing video. (See the nighttime video freeze-frame in **Figure 5**)
c) Improved agility and off-nadir viewing, including one-pass, multi-looks has now become routinely possible. (**See Figure 6**).
d) **25 cm** resolution imagery is now legally authorized in the United States (previously limited to **50 cms** for a decade). This is a 400% improvement allowance (four pixels at **25 cms** for every one previously at **50 cms**). (See **Figure 7**)
e) Short-Wavelength Infrared (SWIR) imagery at **3.7 meter** resolution is now available via WorldView-3 allowing significantly improved visibility through smoke and haze (**See Figure 8**).
f) More spectral bands are now available. Hyperspectral (~200 spectral bands) using satellites may not work for nonproliferation verification applications without improved resolution, but more selective bands ("Superspectral" or "hybrid hyperspectral" ~20-30 spectral bands) may be successful for identifying specific verification relevant materials and minerals like uranium and thorium.
g) Mid-Wavelength Infrared (MWIR) imagery at **5.5 meter** resolution is now available via KOMPSAT 3-A, which can be used to study emitted thermal radiation during observations during the night. This could have a profound impact
h) Smart Phone apps have been created to track commercial satellite imaging satellites and alert users to when imagery is available of their particular areas of interest and then to preview the imagery prior to possible purchase. Imagery of areas as small as one square kilometer can be purchased for as little as $10.00 and quickly downloaded to that same smart phone. (**See Figure 9**)
i) Thermal Infrared (TIR) imagery from Landsat can be overlain on higher resolution imagery for operational monitoring. (See the example in **Figure 10**)
j) Multi-resolution synergy from combining lower resolution with high resolution imagery now provides increased opportunities for new information extraction (**See Figure 11**).
k) High resolution imagery via the various virtual globes is now available for practically any point on earth (and in nearly all cases is also less than a year old).
l) Historical imagery layering became available on *Google Earth* in version 5.0 in 2009 (this is a critical resource for monitoring construction and other activities over time).
m) *Google Earth Engine* now provides the means for rapid review and access to all Landsat imagery and data (**including Thermal Infrared that is most significant for verification purposes**).
n) Commercial satellite imagery vendor historical imagery archive search capabilities provide an instant source of entire constellations' archives in useable form, albeit in

degraded low resolution, for rapid large-scale change detection purposes (e.g., detecting the presence of new roads, large excavations, and large new buildings).

o) *Google Earth* and *Google Maps* now include 3D modeling layers that have been auto-generated for areas imaged from aircraft (as opposed to the previously more limited number of individually created buildings created with *SketchUp*). (**See Figure 20**)
p) Given the availability of high resolution off-nadir imagery that is now provided by more agile satellite systems, 3D modeling of the entire terrestrial surface of the earth is now feasible. (**See Figure 21**)

Appendix D: A Note of Caution Concerning the Use of LANDSAT Thermal Infrared (TIR) Imagery

LANDSAT TIR imagery, because it is acquired only in daylight, is subject to generating false positives in areas of high solar thermal loading. Primary examples are sandy areas, such as beaches and sandbars in rivers. **Figure 22** illustrates how this can be a problem in some cases, and why, ideally, TIR imagery from future satellites should be acquired during nighttime hours.

The three images A, B, and C, respectively, show LANDSAT TIR imagery of the Yongbyon reprocessing building, the Yongbyon uranium enrichment plant, and a cordoned sandy triangular space (that was formerly used as a naval bombing target range) at the US Naval Base at Coronado near San Diego, California. While the first two images are more likely due to internal heating of the associated buildings, the third image displays similar features arising from thermal loading of a sandy triangular area. The variation in temperature values is due to interpolation of the TIR pixels and nearest neighbor comparisons that parallel the perimeter boundaries and show the highest relative temperature in the center of the triangle. The reality is more likely equal temperatures over most of the light toned sandy area which is enclosed by a triangular perimeter wall. Moreover, the TIR images have been re-sampled which can also cause additional false positive interpretations.

"Cubic convolution interpolation, or resampling, yields a rectified image that is generally smooth in appearance and is used if the final product is to be analyzed visually. However since it gives pixels on the display grid with brightnesses that are interpolated from the original data, it is not recommended if classification is to follow since the new brightness values may be slightly different from the actual radiance values measured by the sensors."[197]

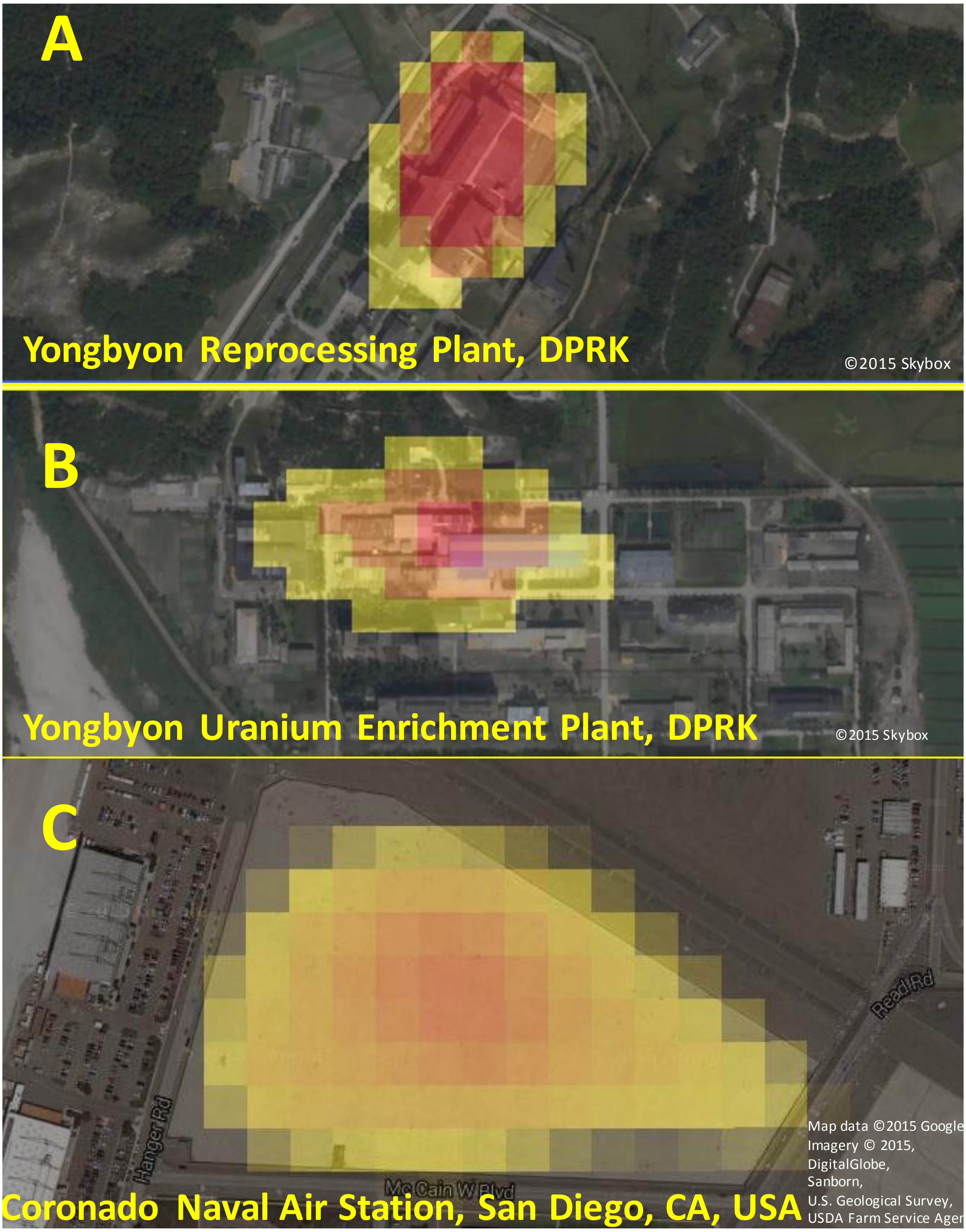

Figure 22: A Note of Caution when using LANDSAT Thermal Infrared Imagery. The three images A, B, and C, respectively, show LANSAT TIR imagery (overlain on SkySat EO imagery) of the Yongbyon reprocessing building, DPRK, the Yongbyon uranium enrichment plant, DPRK, and a cordoned sandy triangular space (that was formerly used as a naval bombing target range) at the US Naval Base at Coronado near San Diego, California. While the first two images are more likely due to internal heating of the associated buildings, the third image displays similar features artificially arising from thermal loading of a sandy triangular area. The variation in temperature values is due to interpolation of the TIR pixels and nearest neighbor comparisons that parallel the perimeter boundaries and show the highest relative temperature in the center of the triangle.

List of Abbreviations and Definitions

CIA: The US Central Intelligence Agency

EO: Electro-Optical imaging sensor systems (passive) that obtain imagery in the visible and near visible infra-red region of the electromagnetic spectrum

ESA: The European Space Agency

ESRI: Environmental Systems Research Institute) is a US based international supplier of Geographic Information System (GIS) software, web GIS and geodatabase management applications

GEOINT: Geospatial Intelligence

GIS: Geographic Information System, a system designed to capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data

GPS: Global Positioning System

GSD: Ground Sample Distance or the resolution/pixel determined by the distance covered on the ground between the center of each pixel in a satellite's sensor array

HD: High Definition quality, as is commonly applied to video imagery, nominally having a resolution of 720 or 1080 horizontal scan lines per sensor array

HVAC: Heating, Ventilation, and Air-Conditioning equipment and systems

IAEA: International Atomic Energy Agency

ICBM: Intercontinental Ballistic Missile

IRS: The Indian Remote Sensing satellite suite

ISMA: The proposed, but never instituted, International Satellite Monitoring Agency

ISS: The International Space Station

IT: Information Technology

ITU: The Institute for TransUranium elements, an institute located with the JRC

JRC: The Joint Research Centre of the European Commission

KH: "Keyhole" is the nominative term applied to US space based reconnaissance systems during the Cold War.

MWIR: Mid-Wave Infrared, the portion of the electromagnetic spectrum between 3 and 5 microns, most often used to study emitted thermal radiation in the dark of night.

NCRI: The National Council for the Resistance of Iran, and Iranian dissident group that provided significant tip-offs on clandestine nuclear facilities in Iran beginning in 2002

NGO: Non-Governmental Organization

NIIRS: The US National Imagery Interpretation Ratings Scale that is used as a basis to determine the quality of an image.

NIR: Near infrared, the portion of the electromagnetic spectrum between 0.7 and 1.1 microns

OSINS: Open Source Information and Analysis for Nuclear Security, a project funded by the European Commission to monitor nuclear related open source information and to perform technical analyses on selected nonproliferation issues for supporting European Union institutions.

PIXEL: Picture Element, the individual digital imaging sensor that makes up a two dimensional imaging array

SAM: A Surface to Air Missile

SAR: Synthetic Aperture Radar active imaging systems that can be used to create images of the earth's surface in all weather conditions, day or night.

SIAU: The Satellite Imagery Analysis Unit of the International Atomic Energy Agency

SPOT: Système Pour l'Observation de la Terre ("Satellite for observation of Earth"), the satellite system now operated by the French firm, Airbus Industries Defence and Space

SST: The UK firm, Surrey Satellite Technology, Ltd.

SWIR: Short Wave Infrared, the portion of the electromagnetic spectrum between 1.1 and 3 microns

TIR: Thermal Infrared imaging sensors (passive) that derive imagery from within the thermal infra-red regions of the electromagnetic spectrum, between 8 and 15 microns

TM: The Thematic Mapper, a multi-spectral imaging sensor on US LANDSATs 4 & 5 operated between 1982 and 2013 having a 30-meter resolution (and prior to February 25, 2010: a thermal Band 6=60 meters)

UF_6: Uranium Hexafluoride

UHD: Ultra High Definition quality, as is commonly applied to video imagery, nominally having a resolution of 2000 to 4000 horizontal scan lines per sensor array

UNOSAT: The United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme

Wi-Fi: a local area wireless computer networking technology

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[163] http://www.google.com/earth/

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[166] http://www.flashearth.com/

[167] https://www.apple.com/ios/maps/ See also, Daniel Eran Dilger, "Apple's iOS 7 3D Maps leave Google Earth, Nokia Maps 3D looking old fashioned," *Apple Insider*, July 30, 2013. http://appleinsider.com/articles/13/07/31/apples-ios-7-3d-maps-leave-google-earth-nokia-3d-maps-looking-old-fashioned

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[169] Primarily limited primarily to France and its territories, please see: http://en.wikipedia.org/wiki/G%C3%A9oportail

[170] Primarily focused on India, please see: http://en.wikipedia.org/wiki/Bhuvan

[171] http://maps.eatlas.org.au/

[172] http://it.wikipedia.org/wiki/Geographical_Information_System

[173] http://www.esri.com/software/arcgis/explorer
[174] http://www.arcgis.com/home/webmap/viewer.html
[175] http://www.arcgis.com/home/webmap/viewer.html?useExisting=1 The webpage of ESRI's ArcGIS (see "Gallery" tab) also provides its own, in some cases unique, satellite imagery base map, for which acquisition dates are also accessible via the "metadata".
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[179] For a useful introduction and overview of the basics of *Google Earth*, please see: http://serc.carleton.edu/sp/library/google_earth/index.html
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[182] http://www.arcgis.com/home/webmap/viewer.html?webmap=c03a526d94704bfb839445e80de95495
[183] The search Filter includes a number of options which require some practice to develop ways to best limit or expand searches. One example is that the filter default setting for the Maximum off nadir angle is set at 25 degrees. As a result, the May 25, 2013 image displayed on *Bing Maps* would not appear in any default searches because it was acquired at 27 degrees off nadir.
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