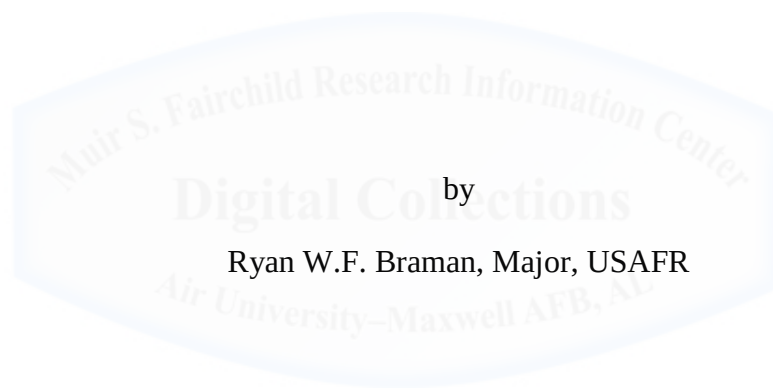


AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

**TECHNOLOGY PRIORITIZED FOR HA/DR:A SPACE BASED ISR
SOLUTION**



by

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A Research Report Submitted to the Faculty

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Abstract

The uncertainty of both the type of future conflict and the role of the US military in it creates challenges for ISR planners. The additional stress of humanitarian crises and natural disasters threaten regional stability and stretch US military commitments. However, by investing in technologies that advance ISR in support of HA/DR missions, the US can develop engagement opportunities with vulnerable states, improving interoperability and information sharing while simultaneously reducing instability and capitalizing on ISR's dual applicability to HA/DR and security. Specifically, the fields of neural networks and advanced computer processing lead to on-board processing of remotely sensed data. Processing data on satellites will become a necessity due to the increasing data size concurrent with increased spatial, temporal, and spectral resolutions. This will simultaneously reduce the influence of bandwidth constraints and mitigate limitations related to the number of man hours available to process and analyze data.

Humanitarian assistance (HA) and disaster relief (DR) operations provide a unique context through which the United States (US) can facilitate its national interests. US space-based intelligence, surveillance, and reconnaissance (ISR) capabilities supply at-risk states with valuable disaster mitigation and response tools and provide a point of ingress for US interaction with many states on the periphery of our normal engagement.¹ The chronic nature of natural disasters means that US HA/DR ISR assistance could be the catalyst for bilateral/multilateral engagement and additional memorandums of agreement with foreign states, increasing our influence with them and creating a status quo of ISR interoperability. Many of the ISR technologies that the US is developing for warfighting today have utility in a HA/DR context, which means that sensors developed for HA/DR can also be used for warfighting.² If ISR development were to be led by HA/DR priorities vice warfighting, the technologies we would see in 30 years would still have improved our security capabilities.³ Specifically, the areas of neural networks and processing lead to a future where most analysis can be done on-board the satellite, decreasing dissemination time and analyst hours.

Operation UNIFIED ASSISTANCE

On 26 December 2004, an earthquake off the coast of Indonesia triggered one of the deadliest natural disasters of the century. The resulting tsunami devastated Southeast Asia and Sri Lanka, causing deaths as far away as Somalia. Indonesia was particularly hard hit with an estimated 130,000 – 200,000 killed.⁴ US Pacific Command (USPACOM) responded by standing up a joint task force providing medical services, logistics and intelligence support, and delivering over 16 million pounds of supplies.⁵ Prior to 2005, US mil-to-mil engagement with Indonesia was limited due US policy directives in response to Indonesian military human rights abuses committed during the East Timor war of secession. While later Indonesian assurances sought to

re-energize the relationship, progress was slow. Following the tsunami and US relief efforts Indonesia redoubled their efforts to meet preconditions for engagement. In February 2005 the US Senate Committee on Foreign Relations conducted a hearing regarding the US tsunami response, with the future of the US/Indonesia's mil-to-mil relationship dominating much of the conversation.⁶ The hearings brought to light that "the experience with the tsunami has indicated areas in which having had more contact cooperation with the Indonesian military could have had some advantages."⁷ In June 2005 an Indonesia-US bilateral defense discussion was held in Honolulu, and in August 2005, an Indonesian-US Security Dialogue was held in Jakarta. The post-dialogue joint statement applauded the US military's efforts during the tsunami, and expressly stated Indonesia's commitment to human rights, a key precondition of increased US engagement.⁸ Additionally, this statement advocated greater exchanges on security issues, implicitly indicating that the contact between US/Indonesian military forces during the tsunami response highlighted the need for more cooperation, interoperability, and engagement events.⁹ It is clear that the US response to the Indonesian tsunami illustrated the security benefits that can be derived from a HA/DR effort to both Indonesian and US policymakers. These benefits apply to the entire spectrum of conflict; a useful characteristic given the uncertainty involved in conflict type and US involvement in the 'small war' type of conflict.

Uncertainty of large/small wars

Increasing complexity because of increasing globalization and technological changes creates an uncertain environment for crises.¹⁰ Predictions regarding the nature of future conflicts have a poor track record, with history demonstrating example after example where we picked wrong.¹¹ Both large and small wars provide a different scenario for ISR planners in that ISR utility varies along the spectrum of conflict as well as with sub-discipline within the ISR field. In

contrast to this uncertainty, natural disasters will continue at a regular rate, while climate related disasters such as floods and storms are arguably increasing.¹² If the US assumes a role in responding to these events, it ought to prioritize ISR development around them. This does not mean that ISR capabilities in support of security events need to decline. HA/DR and security concerns are linked, with growing awareness that the security impact of HA/DR crises extend beyond the immediate humanitarian and environmental concerns.¹³ ISR provides a platform that is relevant regardless of the type of crisis, and due to its 'strategic and multi-purpose nature,' is one of only a few technologies that can provide decision support for virtually every component of the National Security Strategy (NSS).¹⁴

HA/DR in the NSS, EU model

The 2010 NSS has 19 core themes supporting four broad interests in values, prosperity, security and international order.¹⁵ Of these, HA/DR capabilities directly influence 11 themes with an additional two indirectly supported.¹⁶ These themes indicate a growing recognition that disasters cause instability and instability fosters insecurity through opportunism on the part of aggressive states or through resource competition as a result of the disaster. While the US has yet to operationalize this through an articulated strategy, the European Union (EU) provides an example of what a HA/DR driven ISR policy may look like. As part of its post-cold war reassessment, the EU recognized the link between crises, instability and security and expanded their ISR scope to the full spectrum of conflict under the broad brush of international security.¹⁷ Their posture is well suited for HA/DR operations even though they lack experience in military operations, but have extensive experience in stability and security operations.¹⁸ In order to capitalize on this experience and support other security objectives, the EU recognized the absolute requirement of multilateral cooperation and strategic partnerships not only bilaterally

but as part of regional groups as well.¹⁹ Pre-emptive engagement, near real-time information flow to policy makers, and precisely focused information were all recognized as key components of a successful strategy to implement this plan.²⁰ The end result would be a military better postured for success in any region because of the engagement opportunities concurrent with an increased HA/DR role, the interoperability and information sharing mechanisms that derive from engagement, and a general improvement in regional stability.

Increased Engagement

One of the byproducts of US military involvement in HA/DR is increased engagement opportunities. Engagement is contact between US and foreign forces in a cooperative environment, designed to increase the capabilities of both independently and in concert. Besides the Indonesian example, there are dozens of other examples where HA/DR led to increased engagement with nations that have societal and security issues dovetailing our own.²¹ Military engagement (interaction/cooperation/joint exercises) is a lynchpin of our relationships with many nations. It is our ability to contribute to host nation and regional security by training forces to a higher level. It leverages our own security interests by building the relationships and interoperability necessary to take advantage of military relationships in a time of crisis. It serves as a forum through which our own values and culture can be communicated, in many cases, to the most influential segment of a nation's society. In a time of reduced defense funding and more complicated regional events, the ability to rely on security relationship with regional states is critical to protect and enhance US global interests. The recognition of this fact and its inclusion in the NSS is evidence of its importance.

The second order effects of engagement include interoperability and improved information sharing. Interoperability is the ability for forces to be able to communicate and

operate with each other in a combined environment and is the key enabler for multinational operations.²² Given the diversity of technology sources, interoperability is not a given, and HA/DR events provide the opportunities to develop interoperability in support of the joint functions of command / control and intelligence. Information sharing is facilitated by HA/DR events because the event is often the catalyst necessary to establish both a precedent of sharing as well as the development of good faith that necessary security protocols are in place to protect the information.²³ HA/DR events provide a relatively low-threat environment to test various sharing mechanisms, and once in place, provide critical circuits that can be used during a security crises.

Regional Stability

The final main benefit to developing a HA/DR based ISR architecture is that it allows the US to respond more quickly to HA/DR events, prevent more loss of life / resources, and in general contribute to regional stability. HA/DR events threaten not just individual states, but entire regions. Refugee flows between countries that share a contiguous border exacerbate tensions. Economic and political instability coincident with particularly severe events migrate with or without people, particularly when economies are closely linked through trade. Unregulated mass migration threatens “social cohesion, international solidarity, and peace.”²⁴ The additional stress of refugees placed on an already stressed society may degrade or destroy indigenous resources and exacerbate challenges. Predicting, mitigating and responding to HA/DR removes some of this stress by facilitating a more efficient use of resources or by limiting the amount of time that affected communities will be displaced through accurate damage assessment and reconstruction prioritization.

HA/DR and Security application overlap

Remote sensing is applicable to both security and HA/DR missions, as such there are common traits. Passive electro-optical (EO) sensors are generally the most useful for both scenarios due to their ability to resolve objects at a much finer scale. Additionally, damage assessment is a major task for sensors regardless if the damage was caused by munitions or disasters. Despite the commonality, there are also distinct differences in the characteristics of data that are most useful for each scenario. Spatial resolution tends to be valued the most in security disciplines. Decisions to send forces or target an object are made based on an image analyst's confidence in determining features within in image, largely facilitated by spatial resolution and explaining why it is so valuable. This is also useful for issues of strategic importance such as treaty verification and WMD monitoring. For HA/DR, spatial resolution is generally not as important because the HA/DR tasks simply do not require as much fidelity as security tasks. Instead, spatial coverage and temporal resolution are more important for HA/DR. This means getting imagery over a wide area as often as possible. The large scope of typical disasters means that large geographic areas are affected; given the inverse relationship between an image's spatial resolution and its coverage footprint, high-resolution imagery may not contain all the affected area in a single scene. Additionally, many disasters take form over time; fires rage for days to weeks, floods can last for weeks; even tsunamis with their reputation for suddenness can take hours to elapse. The ability to image events as they unfold is a critical element in HA/DR response.

Regardless of the different priorities, some of the supporting technologies remain consistent. One of the constraints for increasing spatial resolution is the data size of high resolution images. Doubling spatial resolution quadruples the amount of data inherent to an

image.²⁵ This increases the bandwidth burden and also the analyst's tasks to classify or otherwise interpret value from the image. Increased processing power is required in order to maintain constant throughput with the increased image size, as is some type of learning algorithm to facilitate the increase in data. For HA/DR tasks, increasing the temporal and spatial coverage requires more sensors in orbit. This requires improvements in reducing the size of optics, and the weight of materials in order to make launches more economical. Coordinating and optimizing the various orbits as well as fusing the various sensor data require adaptive, learning algorithms to respond in real-time.²⁶ These neural networks are also required to process the increased number of images. As with the requirement for increased spatial resolution, processing power must be increased in order to manage the increased throughput of additional images from the extra sensors. Of the list above, adaptive learning and processing power are common to both priorities of increased number of platforms and increased resolution, and therefore represent the most flexible investments.

Almost any sensor used for HA/DR has a security application. There are five sensor categories with which this relationship can be explored: RADAR, LiDAR, panchromatic / multispectral (MS), hyperspectral (HS), and thermal infrared (TIR). While the last three are passive sensors that present data in a form recognizable to even untrained observers, they have inherent limitations particularly relevant to disaster situations. Chiefly, since passive sensors depend on illumination from another source they have limited use when there is heavy cloud cover. In disaster situations involving areas with persistent cloud cover, disasters concurrent with cloud cover or volcanic ash in the atmosphere, this reduces their utility.²⁷ Panchromatic/MS and HS imagery have the added limitation of daytime use only.

SAR/InSAR

The primary advantage of RADAR is its ability to view areas at night. RADAR with specific frequencies can also penetrate atmospheric effects, imaging areas with chronic cloud cover. Other features of RADAR useful for HA/DR environments include the ability to image at shallow angles, determining surface properties (roughness, di-electric properties and moisture content), limited ability to penetrate solids (vegetation, soil, and snow), and synoptic views of large areas.²⁸ In HA/DR situations the day/night all-weather capability means that images can be taken without waiting for favorable environmental conditions. Soil moisture is useful in predictive analysis, for predicting drought conditions, fire and landslide risk. An EU assessment indicated that satellite based monitoring can reduce landslide costs in Europe up to 10% by 2020 simply through applying already existing sensors against known vulnerable areas.²⁹ In defense and security settings, RADAR is particularly well suited for change detection (CD). CD is the automated determination of differences between the same area at two different times. Figure 1 demonstrates how CD can identify buildings built or demolished as well as the presence of a ship and containers between two images.



Figure 1 - Radar change detection at a port; CD identifies new buildings (blue) and buildings torn down (red)³⁰

The all-weather, day/night capability of SAR allows full-time target confirmation, order of battle development, and any other mission that requires a determination of the presence or absence of something. InSAR has security applications not so much in its ability to determine velocity, but from the millimeter level of fidelity it can bring to current applications. The ability to identify disturbed earth from IEDs, equipment movement, or even subsidence due to tunneling are all areas where this capability can be used.

LiDAR

The HA/DR application of LiDAR has a tremendous upside but is also contingent on advances in data storage, bandwidth and processing. Urban visualization provides accurate pre-disaster cataloguing from which post-disaster assessments can be built. Infrastructure profiles permit rapid analysis of LOC integrity. Bare-earth terrain models can provide valuable inputs for hydrology related models (floods and tsunamis). Current LiDAR technology has a defense application in the fidelity of topographic/bathymetric information it provides. Submerged near-shore hazards can be identified for amphibious operations, and accurate digital elevation data facilitate overland route planning, targeting, and obstacle identification. LiDAR also provides incredible three-dimensional accuracy of objects, useful for targeting and BDA.

Visible spectrum (Panchromatic/MS)

Visible spectrum's utility lies in its ability to represent what a sensor sees as what human eyes would see. It presents information in a format that appears native to the analyst and can provide visual cues that allow them to make judgments concerning the effect of an event. While it is useful to 'see' an affected area, utilizing a computer's ability to sense variations undetectable to the naked eye, along with the computer's ability to quickly compare values with historical or probabilistic indexes can bring out the power of multispectral imagery. Computer assisted

analysis was used after the 2004 tsunami to determine the extent of wave inundation, well after the water had returned to normal levels.³¹ Visible spectrum imagery runs the gamut from low spatial resolution with wide scope or quick revisit time to high resolution with limited scope, but it all is important. Within the HA/DR context, image priorities may change. During and immediately after the event, an overview of the damage is more useful than an inventory of what it damaged, so high temporal resolution is valued.³² This allows observers to quickly assess damage and serves as a prompt by directing follow-on high resolution imagery.³³ During reconstruction, higher resolution imagery is important to identify affected areas and inventory damage.³⁴ Automated damage assessment can be accomplished through a change detection method that registers buildings in pre-event images by their roof shape and texture, and comparing those values at sub-pixel accuracy against the post-event image.³⁵ Tests of semi-automated algorithms using multi-sensor and multi-scale data over tsunami affected areas in Indonesia achieved almost 94% accuracy in evaluating the likelihood of flooding/non-flooded, presence or lack of debris, and structural integrity.³⁶ The high resolution available for visible spectrum sensors has made it a workhorse for military intelligence and planners. It has been used for everything from treaty monitoring to BDA and targeting, and continues to play an active role in security ISR because of its versatility and utility. The same algorithms and techniques that make it useful in HA/DR can be applied to identify BDA, while change detection has the potential to help analysts find changes in military force disposition.

Thermal IR

While TIR has been used for security applications for some time, it has taken the form of forward looking IR sensors on airborne platforms. The resolution limits of space based systems have prevented them from being used for operational security roles. The most well-known types

of space based TIR include the meteorological systems used for weather forecasts, and while it is easy to see their use for HA/DR situations, processing/algorithms are just recently reaching the point where they have security utility. Many meteorological satellites have geo-synchronous orbits, allowing them to maintain a constant view of the region of interest.³⁷ In a context where a HA/DR or security situation is unfolding in minutes or hours, this ability to have a sensor stay on target is invaluable. This comes at the cost of poor resolution, however, as these sensors are optimized for wide scope. Despite this limitation, image scientists have discovered ways to identify objects with a spatial signature much smaller than the sensor resolution.³⁸ In one example, the sensor demonstrated an ability to not only clearly identify a terrorist attack on an Iraq oil pipelines, but also provide 15 minute updates on changes to the fire and smoke signatures.³⁹ Various HA/DR applications for TIR include its ability to continually monitor thermal events such as fires and lava flows. Continual TIR data is also critical to correlate event propagation with other remote sensed data, such as vegetation health, in order to better predict the path of the event in the near-term and future event risk/spread. Security applications for current TIR data include the example cited above, as well as an ability to monitor particularly intense events such as the test or actual use of rocket boosters.

Hyperspectral⁴⁰

While panchromatic images can tell you the difference between wheat and cotton plants, multispectral can discriminate between healthy and unhealthy cotton, and hyperspectral differentiates species of cotton.⁴¹ HA/DR utility for hyperspectral includes any scenario which requires the separation of distinct signatures that may be obscured or similar to surrounding, less relevant signatures. Disturbed soil and saline deposits can be identified through hyperspectral, and allow analysts to determine the maximum extent of inundation in cases of storm surge,

tsunamis, other extreme wave events. This is true even when the wave might not have been large enough to cause visible destruction; if seawater touches a permeable surface, distinct markers (Br, Mg) will be left behind that a hyperspectral sensor can determine.⁴² The ability to distinguish disturbed earth also allows analysts to look at areas that are prone to various slides and determine if micro-land/mud/rockslides are imminent. In situations where disaster survivors may be mostly covered by debris or mud, hyperspectral may still be able to distinguish the survivor from the obscurant. The security role of hyperspectral is well known, given its proven ability to identify IED constituents, paint types, and disturbed soil that may indicate concealment efforts. Other applications include the ability to distinguish camouflage from forest cover, identify the presence of drug production effluents in streams, and distinguish illicit from legitimate crops. The only real limit to a hyperspectral sensor is the extent of the spectral library from which it can compare the signatures it sees.⁴³

Future Sensors

The integration of geocoded data into everyday life and ubiquity of multispectral images portend a larger movement in the commercial imagery industry, and through the interrelationship between the commercial and military sectors, will affect future availability of sensors for the DoD.⁴⁴ These two changes have already simplified and made less expensive some of the typical geoprocessing tasks involved in getting imagery to market. Imagery cost is being pushed down because of an increasing vendors and customer base. With lower image cost, new market segments are able to avail themselves to overhead data, with the second order that these segments provide incentives to commercial vendors to advance different types of sensors relevant to the new segment. In essence, government contracts will be less influential in determining future R&D than commercial demand. This reversal of the government-provider-

commercial customer relationship is due to the ‘synergistic’ relationship between demand, development and proliferation.⁴⁵ Already as early as 2006, business, not government, was seen as the primary consumer of commercial imagery.⁴⁶

With commercialization of data, further advances in the field of sensor development are expected. The obvious area to look for improvement is in spatial resolution. While the US government has restricted the release of sub-half meter panchromatic imagery, non-US commercial ventures will eventually achieve this, necessitating a change in US policy in order for US commercial interests to maintain a competitive advantage. Predicting something like future resolution is tricky when one considers the discontinuous technologies that enabled past improvements. If one considers data points starting in 1994, when the US first authorized the sale of commercial imagery, a general trend appears.

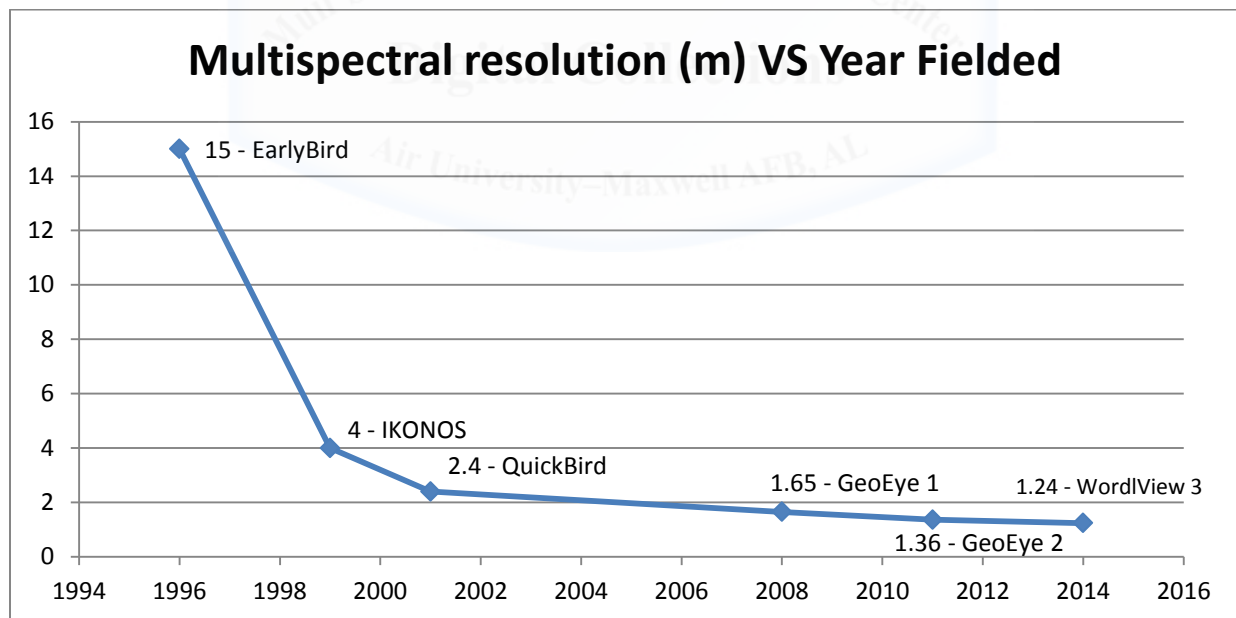


Figure 2 - MS resolution improvement since commercialization

From 1994 to 2001, there was an exponential growth in resolution concurrent with deregulation of the commercial market, while from 2001 onward the improvement shows linear characteristics.⁴⁷ Following a linear trendline from 2008 until 2014 shows an annual

improvement in resolution of close to 5%. If this trend continues we would expect to see multispectral imagery resolution of around 0.3 meters in 30 years. Panchromatic imagery has historically had resolution four times that of multispectral, which would indicate panchromatic imagery of 7 to 8 centimeters within 30 years.⁴⁸ This improvement would derive from evolutionary advances in materials (lighter), electronics / optics (smaller, programmable), and processing (faster); revolutionary changes in any of those fields could short-circuit the timeline and lead to greater resolutions.⁴⁹

In the field of LiDAR, space-based LiDAR will approximate the current airborne form within 30 years. Current space LiDAR operates as a laser altimeter, collecting data from a single beam along the platform's ground track. While wide area topographic mapping (similar to what was described in the LiDAR section above) has been demonstrated on lunar missions, it hasn't been operationalized for earth missions.⁵⁰ In the near-term, NASA is developing a sensor that will utilize 1,000 parallel beams to achieve 5m horizontal and sub-decimeter vertical resolution along a swath width greater than 5 km.⁵¹ This is comparable to the early (late-1990s) commercial airborne LiDAR platform, and provides a crude way to estimate where space-based LiDAR will be in 30 years. If the next generation of space-based LiDAR is where airborne LiDAR was 20 years ago, the 30-yr space-based LiDAR could be where current airborne LiDAR is at now. This would mean 1m horizontal and centimeter vertical resolutions, with the ability to achieve horizontal resolution better than 30 cm by oversampling.⁵²

In the realm of TIR, more developed techniques, such as the Robust Satellite Technique (RST), create a moving index of each pixel in an image that includes acceptable pixel variation.⁵³ When an anomalous event occurs, RST identifies its presence even when the naked eye can't determine any change in the pixel's brightness.⁵⁴ Future developments in this area

include the ability to discriminate smaller manmade or natural anomalous events, to the extent that small fires can be identified. This would indicate a resolution of approximately 1-3m.

Processing speeds

Processing speed requirements increase as spatial, spectral, and temporal resolution increase. This is particularly troublesome in that a doubling of spatial resolution quadruples the amount of data that needs to be processed. Based on the earlier rough forecast that spatial resolutions should be four times greater than what they are today, this would indicate a sixteen fold increase in data size.

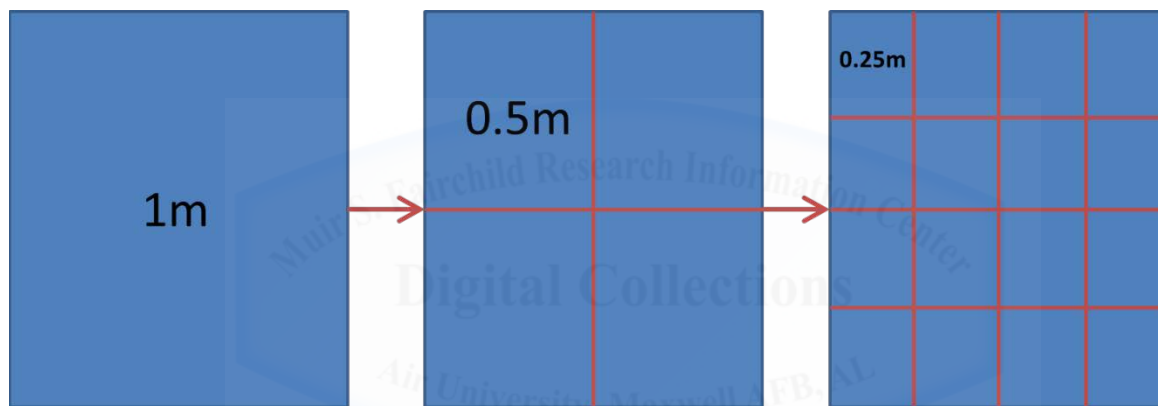


Figure 3 - sixteen-fold increase in data with quadrupling of spatial resolution⁵⁵

Recent advances in processor technology appears to make the continuation of Moore's Law theoretically possible, but constraints on power requirements, cooling, memory and software pose considerable hurdles.⁵⁶ Past breakthroughs have come from being able put more transistors in the same space, but have done little to reduce power or cooling requirements. Future processing advances will likely come from either carbon nanotubes or concepts that use optical impulses, such as IBM's work in silicon nanophotonics.⁵⁷ Carbon nanotubes are both higher speed and require less electricity than silicon, but have been plagued by problems growing the tubes and separating metallic from semi-conducting tubes.⁵⁸ Researchers have

recently been able to provide results overcoming those problems and produce a working, albeit limited processor.⁵⁹ Silicon nanophotonics on the other hand, have already been produced at industry-grade levels, with IBM achieving results of 25GB/sec on an otherwise standard chip.⁶⁰

This has been done by using silicon nanotubes as the system interconnects for chips.⁶¹

Regardless which technology advances, improvements in processing capability seem to project at a pace that exceeds estimated image resolution improvements. In fact, the ratio of processing speed to data size has only grown in recent years, providing even casual analysts the opportunity to process relatively large data sets on their home computers.⁶² This indicates that future advances in processing speed, while dependent on advances in one of the fields mentioned above, will not constrain image resolution.

Neural networks

The EU space program Copernicus has identified several development milestones to advance the program: increasing detection, forecast and warning capacity, developing risk models, better modeling uncertainty, and achieving near-real time observation and understanding of events.⁶³ The one constant in all of these milestones is that each task needs to process disparate data that may not follow typical stochastic models. Adaptive machine learning known as neural networking facilitates this. Neural networks are a type of artificial intelligence which breaks down the processing tasks into units responsible for a single task. Each unit receives an input from a different unit or external input, processes it according to some weighted condition, and forwards the output to another unit which will conduct its own process. The actual 'weight' used is subject to change based on its ability to help the entire network of units achieve either expected conditions or better organize/cluster the results.⁶⁴

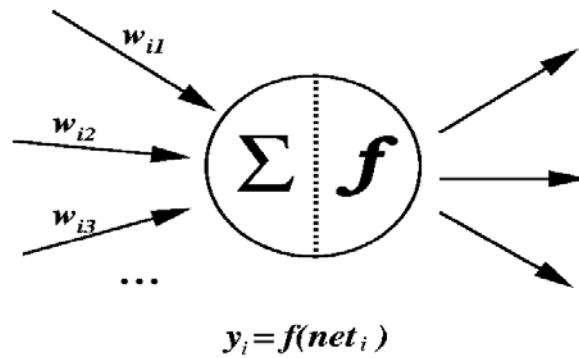


Figure 4 – Single neuron in a neural network; outputs scaled by input weights (w), as well as weight assigned in ‘neuron’⁶⁵

One of the areas that have greatly expanded the value of imagery is the ability to automate tasks necessary to interpret an image and display it in a different ways to provide utility for different audiences. One example is classifying various surfaces in the image (vegetation, metal, bare earth), conducting change detection, or otherwise interpreting variations in the image as something useful (number of tanks, planes, etc.). The typical workflow for this approach starts with the sensor transmitting the raw image to a ground station it is preprocessed. Preprocessing removes atmospheric effects, corrects sensor errors and performs necessary geometric corrections in order to attribute each pixel to a coordinate reference system. Further analysis is then done to derive utility from the image. This has typically been done by an analyst on a workstation with some type of image processing software. Recently there has been much research utilizing automated techniques to do all of these steps in various degrees. These tasks have been automated to the extent that most much of an image analysts job now is to assess what processing tasks need to occur on an image, and then just tell the software what those tasks are. The ability to fully automate this process has been limited in part because of the requirement of training data, which are specific pixels within an area of interest on the image for which ground truth is already known. Neural networks have demonstrated success in accomplishing image processing tasks without ground truth data.⁶⁶ This is significant because the ability to automate

most of the process would allow the image analysis to be done on the satellite itself, identifying images that are of little or no value. These images can be either archived in on-board storage or discarded. This is particularly important if advances in data transmission do not keep pace with the increasing resolution of data.

On-board processing

While it's realistic to assume continued growth (albeit at a lower rate) in onboard data storage and processing power, we remain constrained in our ability to train analysts to interpret sensor data. We can only capitalize on a future sensor system then, if this burden is reduced. In order to do this, sensors must maintain the ability to process data onboard, transmitting finished, or near-finished data to ground stations and archiving unused images either onboard or in another satellite whose sole purpose is to act as a data clearinghouse. Any effort to preprocess images onboard the satellite to reduce image size, lower workload for analysts, or avoid duplicity of effort also rests on future research in the field of neural networks. This processing must accomplish several steps common to all image requirements, yet stop short of the point where further processing could reduce the utility of an image or irreversibly modify the data. The first step is the radiometric correction, which removes any noise or other errors introduced into the image by the sensor or the atmosphere.⁶⁷ Following this, the image must be geometrically corrected to ensure each pixel in the image is in a 'proper planimetric position.'⁶⁸ The final steps include any appropriate image enhancements (sharpen, principal component analysis, contrast stretch, etc) to transform data into information more highly correlated to the ground situation, and classifying image pixels according to a predetermined technique.⁶⁹ By accomplishing this onboard, bandwidth is conserved by discriminating unusable imagery out and archiving

productive but irrelevant imagery to a separate platform to transmit when needed or when bandwidth is available. Analysts can then focus efforts on quality control.

Conclusion

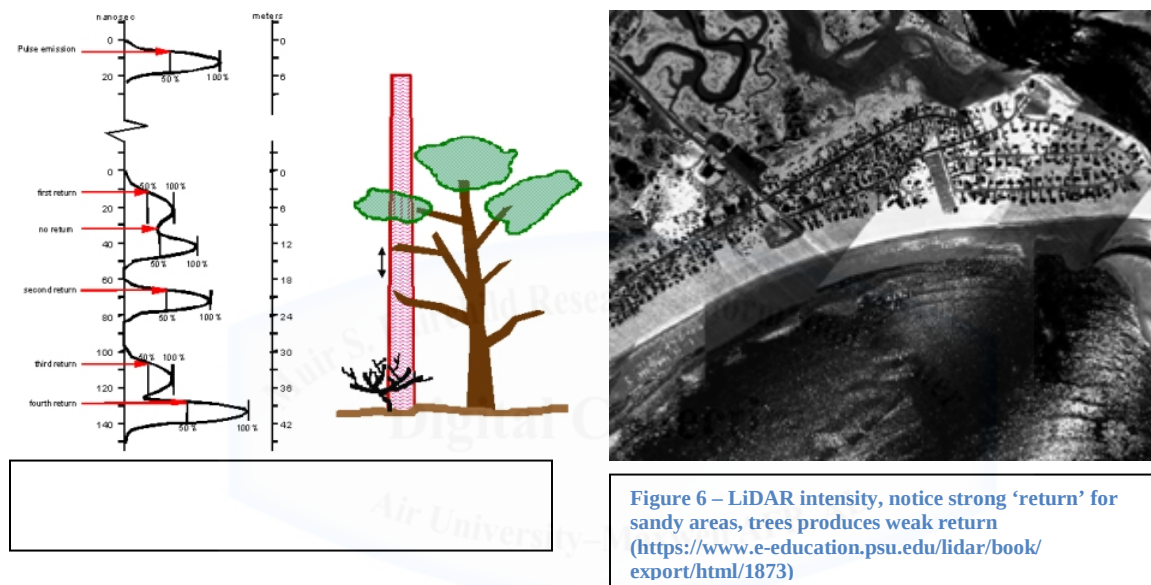
In a future global environment characterized by uncertainty, the best approach to prioritize development is to focus on technologies that can work in multiple environments. Neural networks and advanced processing technologies are two such areas which will advance future sensor capabilities and mitigate traditional constraints. Both areas are logical extensions of a HA/DR derived sensor prioritization methodology, but have equal use in the security applications. These technologies will not improve sensor capabilities by themselves, but in their role as enablers for on-board processing which removes bandwidth and analyst constraints. Improving the US's ability to use ISR to create better deterministic and probability based HA/DR forecasting models as well as accurately assess damage and vulnerabilities has second order effects in the security realm. The interoperability and information sharing that come from using US ISR in HA/DR events puts the US in a leadership role and builds influence and stability in peripheral regions.

Appendix 1 – remote sensing basics, overview of passive and active sensors

*SAR/InSAR*⁷⁰ – RADAR was used as early as the 1950s by the military.⁷¹ Modern space-based sensors are synthetic aperture RADAR (SAR), artificially forming an antenna much larger than the actual physical antenna and increasing the sensor's ability to resolve objects. When two RADAR sensors image a location from different angles or at different times, a highly accurate elevation model can be constructed with range resolution measured in millimeters. This technique is known as interferometric SAR (InSAR).⁷² SAR and InSAR are active microwave sensors. A pulse of EM radiation is sent out by the sensor at a wavelength that is significantly longer than that used by visible or infrared systems. Important characteristics of the pulse involve its direction and angles with respect to the sensor and the reflecting surface. The range direction is the direction of the illuminated area at a right angle to the direction of travel for the sensor itself. This parameter is significant in that it effects how objects on the surface appear; features that are indistinguishable in one range direction may become emphasized with a different look direction. The pulse is also polarized, that is it is filtered in a certain direction in order to help distinguish features in an image. RADAR resolution is determined by the length of the pulse as well as the antenna length itself. Range resolution increases with shorter pulses, a trend runs into practical limits once the pulse becomes so short (and therefore contains less energy) that the return is too weak to be of use. The azimuth resolution is determined by the antenna length, with shorter antennas permitting greater resolution. Since the amount of energy transmitted is known, the amount that returns in the form of backscatter can provide information about the reflecting surface. Less backscatter per unit area generally indicates a rougher surface, other environmental parameters held constant.

*LiDAR*⁷³ - Light Detection and Ranging (LiDAR) operates on similar principles as RADAR in that a pulse is transmitted and received by a sensor, with the time of return providing the distance between the sensor and the reflecting surface. The key difference is LiDAR transmits either an infrared or blue-green laser, with the former used for topographic mapping and the latter for bathymetry.⁷⁴ Because it transmits its own energy, LiDAR functions independent of ambient light levels, but since its signal consists of light, it cannot penetrate cloud cover like RADAR. The high pulse rate (can exceed 100,000 pulse/sec) combined with a relatively small pulse footprint creates incredibly dense point clouds from which detailed terrain data can be extracted. A pulse can also partially reflect off intermediary surfaces providing data about an object's vertical structure. For example, a pulse/return from a forested area may provide tree height, branch height, surface relief features such as shrubs or grass, and finally the bare earth return.⁷⁵ There is some diffusion of the light pulse through the atmosphere, proportional to the divergence of the laser and platform altitude, and inversely proportional to the instantaneous scan angle. The ultimate diffusion determines the laser footprint. Figure 5 below demonstrates how returns are sensed. The point spacing depends on the angular scanning speed, instantaneous scan angle, altitude and pulse repetition frequency (PRF) with multiple points per m² the norm for typical airborne missions. Besides the elevation information, intensity values are returned for each pulse. Significantly, this value represents the maximum of all returns related to a pulse, and can superficially appear as a panchromatic image (see figure 6 below). Intensity reflects the amount of backscatter returning to the sensor however, not just the native reflectance, so trees with deep foliage reduce the amount of energy backscattered toward the sensor and appear dark despite their typically strong return in near IR images. There are two general categories of LiDAR: topographic operating in the near-IR band and bathymetric operating in the blue-green band.

Unlike passive EO sensors (except for hyperspectral), LiDAR bands are relatively narrow. With topographic LiDAR PRF an order of magnitude higher than bathymetric LiDAR, it is not possible at this time to use one sensor to obtain the best results in both bathymetric and topographic settings. Although bathymetric LiDAR will provide ground returns, the lower PRF limits the high coverage rate that makes topographic LiDAR so useful. The return will indicate any horizontal surface that falls within that footprint up to a certain threshold.



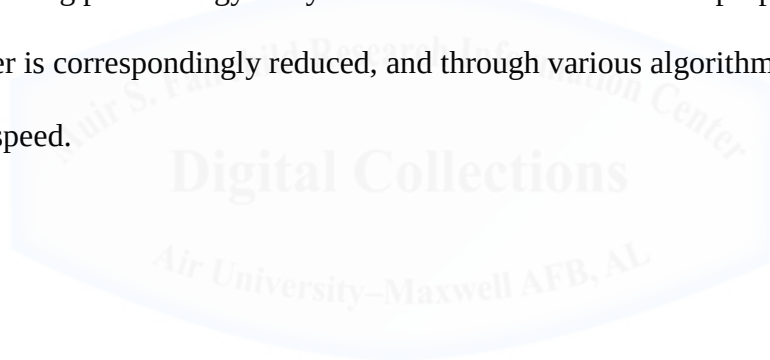
Visible Spectrum - Visible band EO is the most widely used remote sensing type used for HA/DR.⁷⁶ Visible EO utilizes the sun as its emitter, relying on the passage of solar energy through the atmosphere to a reflecting surface and back to the sensor itself. The most common type is a single band which simply presents the reflection along a scale of intensity set by the sensor capabilities, displayed as a two-tone image. This panchromatic image typically encompasses the entire visible light spectrum, from around 0.5 to 0.7 μ m. Multispectral is a second type which uses multiple spectrum bands instead of one, permitting more bandwidth specific information to be obtained from the reflecting surface. These multiple bands can be combined into various composites that approximate a true-color representation of the surface.⁷⁷

Thermal Infrared - Thermal infrared (TIR) operates on similar principles as visible spectrum imagery, the primary difference being that TIR detects a significantly longer wavelength than visible light (0.4-0.7 μm versus 3.0-14 μm).⁷⁸ Even though it is invisible to the naked eye this band identifies thermal characteristics of a surface relative to its surroundings. All objects with a temperature above absolute zero emit thermal energy in this spectrum, meaning that unlike visible EO, TIR can be used regardless of light conditions.

Hyperspectral - Hyperspectral (also known as imaging spectrometry) is identical to multispectral imaging in principle, but instead of utilizing a few spectral bands, acquires data in hundreds of relatively narrow bands. The value of hyperspectral lies in the fact that every material has a distinct 'spectral signature' in how it reflects or emits energy. By only looking at three relatively broad spectral channels, multispectral images can't resolve distinct differences. Hyperspectral sensors in contrast are able to identify characteristic features that may only be 20 to 40 nm wide.⁷⁹

*Altimetry*⁸⁰ – RADAR altimeters are active microwave sensors. They transmit a vertical pulse which is reflected from some surface (ocean or land) back to the altimeter. This pulse will illuminate a point on the surface and expand until the pulse's trailing edge reaches the surface. The pulse then continually illuminates an annular area with increasing radius and constant area. The primary usefulness of this return is the precise measurement of the time of return, which combined with a priori knowledge of the sensor location and microwave propagation characteristics, permits the cm scale resolution of surface elevation. Given the ability of altimeters to repeatedly image a given location, the various elements that determine that location's height can generally be derived from the measurement. For sea surface heights, this includes the wave field, currents and mesoscale eddies. For land surface heights, this includes

seismic disturbances, tectonic plate movements, and recently relevant, the mass balance of polar ice caps. As discussed in the paper, the altimeter return signal can be analyzed to determine not only wave fields characteristics, but also the local wind field characteristics. Significant wave height is derived from analyzing the slope of the linear rise in power of the pulse return, corresponding to the spread of the pulse over the reflecting surface. Rougher surfaces, such as that of a high sea state, cause the pulse to spread over a larger surface (the diagonal between wave crest and trough as opposed to a flat surface), and thus take a longer time to return to the altimeter. The pulse return slope is thus smaller and can be analyzed for statistical wave characteristics. Local winds increase sea surface roughness, creating more reflective wave surfaces and scattering pulse energy away from the sensor's direction of propagation. The mean backscatter power is correspondingly reduced, and through various algorithms, can be used to derive the wind speed.



Appendix 2 – Security Concerns

The National Security Presidential Directive (NSPD) – 3 signed in 1991 signaled a shift in US thinking about space based sensors in that it directed US agencies use commercial ‘products and services to the fullest extent feasible.’⁸¹ Later NSPD’s, Presidential Decision Directives (PDD), and NSTCs added to this to create a policy to incentivize commercial remote sensing industry in the US.⁸² One of the more recent directives, NSDP-27 seeks to balance the security concerns versus the many benefits of using commercial vendors for national security purposes by placing restrictions on the vendors ability to export technologies, components, and systems, and by prompting responsible USG agencies to focus sensor development only on those areas that cannot ‘effectively or affordably’ be provided by commercial vendors.⁸³ The key provision for providing for security is the use of ‘shutter control,’ which is the right for the DoS or DoD to limit or deny sale of imagery based on national security or other obligations.⁸⁴ This seems to be the right approach, as opposed to broad restrictions on the further improvement of sensor capabilities. As mentioned in the paper, government restrictions on commercial vendors will lose momentum as foreign commercial vendors approach US capabilities. The right question to ask regarding the integration of commercial remote sensing ventures into government work is not how to eliminate, but rather manage the risk. Civilian space capabilities are exponentially better than what they were even 20 years ago, with commercial space revenues exceeding USG expenditures on space as early as 1996.⁸⁵ With an annual growth rate of 20%, civilian space investment shows no sign of slowing down.⁸⁶

¹ For recent examples, see US interaction with Indonesia, the Philippines and Haiti

² Electro-optical sensors provide damage and vulnerability assessments, weather satellites for flight/operation planning provide valuable data inputs for forecasting models; multi/hyper-spectral satellites used for identify narcotics or IED constituents can determine crop health, damage by seawater inundation, etc.; thermal sensors used to identify insurgents can be used to find wounded survivors in debris fields.

³ This vulnerability is assumed because an HA/DR driven ISR platform would by nature have to create products that are releasable at the unclassified level to be a useful tool for foreign states.

⁴ Numbers vary based on Indonesian government figures. The Minister of Health's estimate was 130,000 while other government agencies stated it was higher.

⁵ Dorsett, 12.

⁶ CFR, 62-63.

⁷ CFR, 63.

⁸ Joint Statement, <http://www.embassyofindonesia.org/ina-usa/statement/jointstatementSDIII.htm>

⁹ Joint Statement.

¹⁰ Voigt, 34.

¹¹ ACSC, lecture notes

¹² See for example statistics provided by the UN Office for Disaster Risk reduction, <http://www.flickr.com/photos/isdr/7460711188/in/set-72157628015380393>

¹³ Voigt, 34

¹⁴ Voigt (35) makes a similar point about the utility of space platforms to support a EU framework underpinned by broad based security concerns.

¹⁵ NSS, 7.

¹⁶ The 11 themes are: 1) strengthen security and resiliency at home, 2) advance peace, security and opportunity in the middle east, 3) invest in the capacity of strong and capable partners, 4) enhance science, technology and innovation, 5) spend taxpayer's dollars wisely, 6) strengthen the power of our example, 7) promote dignity by meeting basic needs, 8) ensure strong alliances, 9) build cooperation with other 21st century centers of influence, 10) strengthen institutions and mechanisms for cooperation, and 11) sustain broad cooperation on key global challenges. The two indirect themes are: 1) use of force and 2) promote democracy and human rights abroad.

¹⁷ Cragg, 21.

¹⁸ Cragg, 22.

¹⁹ Cragg, 23.

²⁰ Cragg, 24.

²¹ For example widespread drought in North Africa leading to the breakdown of state governance and increase in radical Islam, annual flooding and typhoons in the Philippines and their strategic location with respect to mainland Asia.

²² See for example, JP 3-16 'Multinational Operations' and the abundance of references in said document to interoperability, to include the establishment of a Multinational Interoperability Council of nation's judged most likely to lead a coalition operation.

²³ Author's experience as USPACOM Security Engagement officer.

²⁴ Widgren, 749

²⁵ Bolstad, 45.

²⁶ For example, the Intensity-Hue-Saturation transform to combine radar with other data types (Harris, 1631).

²⁷ Beyer-Hall, 33.

²⁸ Jensen, 294.

²⁹ Copernicus 13, Landslide monitoring utilizes a hybrid of radar interferometry, high-res optical, seismic data from ground-based sensors, and GIS.

³⁰ <http://gs.mdacorporation.com/LandSurveillance/IntelProducts/ChangeDetection.aspx>

³¹ Van den Broek, 263.

³² Van den Broek, 261.

³³ Van Den Boek, 265.

³⁴ Van den Broek, 262.

³⁵ Van den Broek, 272.

³⁶ Van den Broek, 274.

³⁷ Jasani, 190.

³⁸ Jasani, 193.

³⁹ Jasani, 193.

⁴⁰ Jensen, J.R., Remote Sensing of the Environment: An Earth Resource Perspective 2 ed., Prentice Hall: NJ, 2006.

⁴¹ Jensen, 290.

⁴² Mero, 29.

⁴³ This is due to limitations in obtaining material samples from which spectral signatures can be derived. Much like using fingerprints to solve a crime, no amount of analysis can substitute for lack of the right signature within a spectral library.

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- ⁴⁴ Hanks, 61.
- ⁴⁵ Hanks, 62.
- ⁴⁶ A survey of terraserver.com found 30,000 customers served daily, with 50% of those customers coming from business, vice government. Macleod, 137
- ⁴⁷ Data taken from various tables of commercial satellite characteristics in Jensen (2006).
- ⁴⁸ For example, ratios of multispectral/panchromatic resolutions for Orbview, IKONOS, QuickBird and EarlyBird are all 4:1, Jensen 235-236.
- ⁴⁹ See for example Johathan Hartley's vision of 21st Century remote sensing which lists research areas in all of these. (Hartley, 1-3).
- ⁵⁰ Abshire.
- ⁵¹ Abshire
- ⁵² See NOAA's primer on LiDAR to get a sense of current capabilities with respect to temporal resolution and accuracy. LiDAR 101, NOAA CSC, November 2012.
- ⁵³ Jasani, 196.
- ⁵⁴ Another example of how this can be used for spatially 'small' events is the identification of the explosion at Hotel Hilton in Taba, Egypt (7Oct04). Despite the inability to perceive the explosion on a zoomed portion of the image, analysis of a brightness temperature vs. time and the change detection index vs. time charts clearly show the event. Jasani, 197-199.
- ⁵⁵ See also Bolstad, 45.
- ⁵⁶ See for example recent articles by Horst Simon, co-editor of the annual 'top 500' list that tracks supercomputer capabilities. <http://www.top500.org/blog/no-exascale-for-you-an-interview-with-berkeley-labs-horst-simon/>
- ⁵⁷ <http://www.sciencedaily.com/releases/2013/07/130703101349.htm>
- ⁵⁸ http://www.eetimes.com/document.asp?doc_id=1319660
- ⁵⁹ <http://spectrum.ieee.org/tech-talk/semiconductors/devices/first-computer-made-from-carbon-nanotubes-debuts>
- ⁶⁰ Assefa, 10.
- ⁶¹ Assefa, 10.
- ⁶² For example, the linux based QGIS and GRASS permit sophisticated image processing and GIS tasks to be performed on home computers.
- ⁶³ Copernicus 07
- ⁶⁴ Krose, 13-20. Krose's book is the best source I found for articulating the fundamentals of NN as well as providing working examples and applications for the major types of NN (Kohonen, principal component, recurrent, back-propagation).
- ⁶⁵ <http://www.willamette.edu/~gorr/classes/cs449/linear1.html>
- ⁶⁶ Chen, 112.
- ⁶⁷ Jensen, 26.
- ⁶⁸ Jensen, 26.
- ⁶⁹ Parametric, nonparametric and nonmetric extraction techniques are the ways and algorithms that analysts and scientists use to classify pixels in an image. Parametric techniques include maximum likelihood classifications, nonparametric includes ISODATA and Artificial Neural Networks, while nonmetric techniques utilize AI to learn heuristic rules about an image and incorporate those rules into future analysis. Jensen, 26-27
- ⁷⁰ All information regarding SAR and InSAR characteristics taken from Jensen, pp. 291- 334.
- ⁷¹ Jensen, 292.
- ⁷² Jensen, 291.
- ⁷³ All information regarding LiDAR characteristics taken from Jensen, pp. 335-353 and Guenther.
- ⁷⁴ Jensen, 336.
- ⁷⁵ Jensen, 339.
- ⁷⁶ Van den Broek, 261.
- ⁷⁷ For example, varying the order of the bands or which three bands make up the composite allows information such as vegetation health to clearly be seen.
- ⁷⁸ Jensen, 249
- ⁷⁹ Jensen, 237.
- ⁸⁰ All information on radar altimetry in this section is summarized from a comprehensive report on microwave radiometer characteristics from Katsaros and Liu.
- ⁸¹ Hays, 38
- ⁸² Hays, 39-40.

⁸³ Hays, 61

⁸⁴ Hays, 40.

⁸⁵ Dvorkin, 143.

⁸⁶ Dvorkin, 144.



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