SYNTHETIC APERTURE RADAR APPLICATIONS IN A DYNAMIC GLOBAL CONTEXT

Nick Austin
Nicole Herrmann
Noëlle Miliard

The Elliott School of International Affairs
International Science & Technology Policy Capstone

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INTRODUCTION

Today, space-based Synthetic Aperture Radar (SAR) systems play a vital role in Earth observation. From advanced mapping applications and disaster relief to measuring the thickness of ice sheets in the Arctic and tracking illicit drug cultivation and trafficking, potential uses for this high resolution, weather- and daylight- independent imagery is ever increasing. Yet rapid access to unclassified satellite imagery and the ability to share satellite imagery when needed is hampered by inconsistent national and international policies and regulations on remote sensing. The availability of commercial imagery, however, opens the doors to more easily accessible and shareable data.

The demand for commercial satellite imagery will continue to grow. Today, commercial SAR satellites are already producing massive archives of data that have yet to be fully exploited for mapping and monitoring applications. Access to archived data from various existing commercial satellite data providers presents incredible potential when it is combined with newly acquired imagery and value added products are developed.

The future development of commercial imagery sources looks promising. It is the authors' belief that a purely commercial SAR system, with an associated imagery analysis service would fill a deficiency in the current market for Earth observation capabilities, while also providing a simplified approach to data sharing. This paper proposes a three-satellite constellation, with associated ground segment and processing capability, as a potential solution. The proposed system would not only provide global situational awareness, but would also establish a commercial provider of SAR imagery for both the public and private sector.

In today's dynamic global context, SAR data and imagery have a crucial role to play in understanding the Earth and monitoring rapid changes whether they are naturally occurring

changes or due to natural disasters and crisis. Taking advantage of new data sources, such as the proposed ComSAR-X system, would open up the possibilities of what is achievable with SAR.

SYNTHETIC APERTURE RADAR SPECIFICATIONS & APPLICATIONS

Synthetic aperture radar (SAR) is an advanced form of radar utilized for observations, which provides more detail and information then simple optical observations would otherwise. SAR has been placed on a variety of platforms, including fixed ground stations and aircraft but, for the purposes of this paper, only applications as they pertain to space-based Earth observations by satellite mounted SAR systems will be examined, This type of SAR system works by illuminating a target with its own onboard microwave source, which then receives back a series of signals over the course of its flight path in view of the target area for observation. These return signals are dispersed by the characteristics of the target material. These dispersion characteristics can include shape, size, and the composition of the material itself. By making use of the Doppler shift of the signals and the known flight path and time of the spacecraft, those signals can then be brought into phase (combined) and converted into a usable image.[1]

As was stated previously, SAR is a radar system, and as such, it actively emits microwave energy to illuminate the observed area of interest. To do this, it typically utilizes wavelengths ranging from 1cm up to 1m, depending on the resolution required and the capabilities of the spacecraft and onboard equipment. These wavelengths typically fall into four bands (L-band, S-band, X-band, and T-band) which allow for different penetration depths, reflectivity, and resolution.[2]

So why is SAR synthetic? This is because unlike a normal radar system, which only has the width of the physical dish to act as the receiver, synthetic aperture radar systems are able to utilize a single dish to capture signals at different positions and times. This is important because

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[1] Sandia National Laborartories. *What is Synthetic Aperture Radar?* http://www.sandia.gov/radar/whatis.html (accessed January 19, 2011).
[2] Sandia National Laborartories. *What is Synthetic Aperture Radar?* http://www.sandia.gov/radar/whatis.html (accessed January 19, 2011).

just like with electro-optical systems, the bigger the receiving area the higher the resolution possible. However, because of the nature of microwave energy (i.e. it has a much lower energy density than visible light and a much longer wavelength) it requires a much larger antenna to have comparable resolution to optical systems.

SAR allows for multiple methods of image gathering. Two of the most common methods used are spot mode and strip mode. Spot mode typically allows for more detailed information and higher resolutions because of its persistence of view on a small target area, while strip mode gives the user a larger viewing angle but, as a consequence, it typically has a lower resolution.[3] Both methods are extremely useful and each provides unique data that makes both methods invaluable. SAR images will appear similar to black and white photos, but the visual representations of objects in them can be quite different due to the singular nature of microwave energy as compared to visible light. It typically takes a trained eye to understand exactly what is being viewed in any given image. Libraries of images of known targets exist as references for SAR observations to help users decipher imagery.

In addition to just imagery, other information can be gleaned from the returning microwaves, including polarimetry data, which allows the user to distinguish between different types of materials and even be able to see subterranean differences from one observation time to the next. Recent studies have even been done using SAR to map out mine fields with the use of polarimetry data. Another capability is interferometry, which is garnered from the phase data of the return waves. By using techniques like targeting the same region at two different times and imaging them from different incidence angles, the user can construct a three dimensional image. Terrain altitude and terrain motion can be detected which can be very useful for geological and

[3] Sandia National Laborartories. *What is Synthetic Aperture Radar?* http://www.sandia.gov/radar/whatis.html (accessed January 19, 2011).

geographical needs. Finally, Ultra Wideband (UWB) SAR can provide even better resolution and also provide more information about the reflective properties of targets in a given region.

So why choose SAR over optical space-based resources? SAR has many capabilities that optical resources are unable to provide. This includes the ability to function during the day and night since SAR is an active system that emits its own radiation that is then reflected back. SAR is also able to penetrate cloud cover, vegetation, and even soil when properly calibrated. Additionally, it can provide the polarimetry and interferometry data detailed in the previous paragraph. The only real drawbacks of SAR are that it requires a large amount of energy to operate because it is an active system and that a well trained eye is required to interpret and analyze SAR imagery properly.

With resolutions that can be on the order of meter and even sub-meter, SAR can be an extremely valuable data source for a wide variety of applications. For instance with climate change, measurements of ice sheet thickness and glacial movement can be extremely important and nearly impossible to do with optical observations. Furthermore, SAR has applications in tracking oil spills and slicks due to the way in which microwave energy is polarized differently by oil, as opposed to water. It can also be used to detect and track illicit drug farming and smuggling especially because of its 24/7/365 observation capabilities. This also applies to natural resource maintenance and monitoring farming practices. As was stated earlier, topographical information can also be gathered using methods like interferometry. Consequently, SAR is able to provide valuable information for relief efforts in the aftermath of natural disasters. Moreover, two other critical applications exist for SAR, pipeline construction and maintenance and maritime tracking. These applications provide potential business opportunities for any

future commercial SAR organization and will be examined in more detail further in this analysis because of their potential as business opportunities for any future commercial SAR organization.

A critical component to creating a successful business is anticipating what your costs will be; this is especially true for space-based industries, which contend with very high startup costs. Because of this, it is important to consider similar systems already in place that offer similar capabilities to what a commercial provider would be looking to offer. There are a wide variety of SAR systems currently on orbit, all of which are at least partially owned and/or operated by a national interest. While many SAR assets are classified, especially in the case of the United States, there are a number of non-classified (and even commercial) systems. These include COSMO-SkyMed, SAR-Lupe, and TerraSAR-X. These systems came into existence out of national priorities in their respective countries for a space-based SAR system. SAR-Lupe is the creation of the German government and OHB-System, a German contractor.[4] It was built as a reconnaissance system for German intelligence agencies but also has commercial applications. The system consists of five on orbit assets that cost a total of roughly 350 million Euros or 500 million dollars.[5] The system reduced costs by utilizing commercial off the shelf equipment and technologies. It also incorporates X-band radar, which is capable of sub-meter resolutions over a frame size of roughly 6 km x 6 km in spotlight mode and about 1 meter for a region 8 km by 60 km in strip map mode.[6] This system was launched over a two year period from 2006 to 2008 on Russian Cosmos-3M's. The next system currently in operation is COSMO-SkyMed, which

[4] Leuthold, Steffen. *OHB System AG: SAR-Lupe now officially transferred to Strategic Reconnaissance Comand.* December 4, 2008. http://www.a-zet.org/aerospace-industry-and-business-news/satellite/516-ohb-system-ag-sar-lupe-now-officially-transferred-to-strategic-reconnaissance-command.html (accessed February 15, 2011).
[5] Leuthold, Steffen. *OHB System AG: SAR-Lupe now officially transferred to Strategic Reconnaissance Comand.* December 4, 2008. http://www.a-zet.org/aerospace-industry-and-business-news/satellite/516-ohb-system-ag-sar-lupe-now-officially-transferred-to-strategic-reconnaissance-command.html (accessed February 15, 2011).
[6] Leuthold, Steffen. *OHB System AG: SAR-Lupe now officially transferred to Strategic Reconnaissance Comand.* December 4, 2008. http://www.a-zet.org/aerospace-industry-and-business-news/satellite/516-ohb-system-ag-sar-lupe-now-officially-transferred-to-strategic-reconnaissance-command.html (accessed February 15, 2011).

consists of four satellites put in orbit as a joint operation between the Italian Ministry of Defense and the Italian Ministry of Research.[7] It was created for both military and civilian (mainly scientific) applications. The system also provides global coverage with a repeat time of several times a day over any given region of the planet. At a cost of roughly 900 million Euros, the four satellites, launched between 2007 and 2010, cost substantially more than SAR-Lupe.[8] This is particularly interesting considering their operational lifespan is set at five years versus SAR-Lupe's projected ten year operational lifespan. Part of this additional cost may be attributed to the payloads being launched mainly on American vehicles through United Launch Alliance, typically a more expensive option but better suited for COSMO's sun synchronous orbits (SSO). TerraSAR-X is a one satellite system that was launched in 2007 as a public private partnership between the German Aerospace Center and Astrium, a wholly owned subsidiary of EADS N.V.[9] It was constructed and launched at a cost of 130 million Euros in 2007 and is expected to be operational for five years.[10] The system also uses X-band radar and has many of the same capabilities of the other systems previously mentioned here.

[7] Kramer, Herbert J. *COSMO-SkyMed.* http://www.eoportal.org/directory/pres_COSMOSkyMedConstellationof4SARSatellites.html (accessed March 15, 2011).
[8] Kramer, Herbert J. *COSMO-SkyMed.* http://www.eoportal.org/directory/pres_COSMOSkyMedConstellationof4SARSatellites.html (accessed March 15, 2011).
[9] DLR. *TerraSAR-X - Germany's radar eye in space.* July 8, 2009. http://www.dlr.de/eo/en/desktopdefault.aspx/tabid-5725/9296_read-15979/ (accessed April 12, 2011).
[10] DLR. *TerraSAR-X - Germany's radar eye in space.* July 8, 2009. http://www.dlr.de/eo/en/desktopdefault.aspx/tabid-5725/9296_read-15979/ (accessed April 12, 2011).

COMMERCIAL REMOTE SENSING POLICIES & REGULATIONS: A CRITIQUE

The first Earth observing satellites were launched in the 1960s during the "Space Race". The primary functions of these early remote sensing satellites were to collect weather data, to obtain intelligence information, and also to gain a better understanding of the lunar surface. The first civil Earth observing satellite, Landsat-1, was launched in 1972 and was specifically designed to obtain data of the Earth's surface for research purposes.[11] As a result of the deployment of remote sensing satellites, there was an emergence of international concerns over sovereignty. These anxieties grew out of the increasing awareness by the international community that their states were being observed without their consent.[12]

In 1984, the Land Remote Sensing Commercialization Act was passed as a result of requests from research programs for utilization of imagery and because of the potential for a commercial market to be established. The main component of this legislation was that it enabled the National Oceanic and Atmospheric Administration (NOAA), through the Department of Commerce, to solicit proposals from the private sector to manage the existing Landsat systems. Furthermore, the Act allowed NOAA to solicit bids from commercial providers for government subsidies to design and operate future remote sensing satellite systems.[13] Eight years later, the 1984 legislation failed because a commercial market for remote sensing imagery had not emerged. It was subsequently replaced by the Land Remote Sensing Policy of 1992.[14] This legislation allowed the government to retake control of the Landsat program, while still allowing NOAA to license and regulate the U.S. commercial remote sensing industry.

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[11] Lawrence W. Fritz. "High Resolution Commercial Remote Sensing Satellites and Spatial Information Systems." International Society for Photogrammetry and Remote Sensing (ISPRS).http://www.isprs.org/publications/highlights/highlights0402/fritz.html, 2.
[12] Ross M. Neil, "Space Technologies for Global Environmental Governance: Transitions in Thinking, Diffusions or Power." (paper presented at the International Studies Association Annual Convention, Honolulu, Hawaii, March 2005), 8.
[13] Fritz, 2.
[14] Ibid.

Internationally, in 1986, the United Nations annexed the "Principles Relating to Remote Sensing of the Earth from Outer Space," which included fifteen principles and primarily "recognized the importance of remote sensing to international governance, and formally established rules of the road to be followed by countries involved in remote sensing technology development."[15] The UN principles strongly encouraged international cooperation on all remote sensing activities, international data sharing, and advocated for providing opportunities for more states to participate in remote sensing activities.

The Clinton Administration saw the emergence of the commercial market for remote sensing imagery and issued the 1994 Presidential Decision Directive (PDD) 23, which ultimately was the remote sensing policy of the Clinton Administration. PDD 23 states that "the fundamental goal of our [Clinton Administration] policy is to support and to enhance U.S. industrial competitiveness in the field of remote sensing space capabilities while at the same time protecting U.S. national security and foreign policy interests."[16] The Clinton remote sensing policy, coupled with the Land Remote Sensing Policy of 1992, catalyzed the growth of the remote sensing industry by encouraging new commercial programs. Moreover, the policies sought to balance national security concerns with the goal of advancing the emerging remote sensing market for U.S. companies, which is something that had not been achieved through previous remote sensing legislation.

The current U.S. Commercial Remote Sensing Policy, released by the Bush Administration on April 25, 2003, was characterized by the Congressional Research Service (CRS) as attempting to strike a balance between "encouraging the development of commercial

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[15] Neil, 9.

[16] United States. The White House, Office of the Press Secretary. *Fact Sheet: Foreign Access to Remote Sensing Space Capabilities.* Presidential Decision Directive 23, 1994.

satellites that provide high quality data, while protecting national security."[17] The 2003 policy superseded all previous legislation and outlined five objectives including 1) The U.S. Government (USG) will rely on commercial remote sensing capabilities to the maximum extent for all government uses; 2) USG capabilities should be focused on meeting needs that the private sector cannot "effectively, affordably, and reliably" satisfy; 3) develop a sustainable relationship between the USG and the U.S. commercial remote sensing industry; 4) enable an efficient regulatory environment for licensing, operating, and exporting remote sensing space systems; and 5) enable the U.S. commercial remote sensing industry to successfully compete with foreign data providers, while also protecting national security and improving foreign policy.[18] This policy has received high praise for its efforts to "provide a strong government rationale for procuring high-resolution imagery from U.S. providers," establish a framework through which international customers can access data, while also encouraging "civil departments and agencies to integrate high-resolution data into daily operations, and more clearly delineating U.S. Government roles and responsibilities relating to the commercial industry."[19]

More significant, though, is the criticism that has fallen upon the United States' Commercial Remote Sensing Policy. A 2008 study prepared for the Department of Commerce, entitled *Leadership in the Remote Sensing Satellite Industry: U.S. Policy & Foreign Competition*, examined in part the U.S. Policy from the perspective of industry. One of the study's most significant findings was that "many key practices of the U.S. government run counter to the stated policy objective of the U.S. government, and are fostering the developments

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[17] Marcia S. Smith. "U.S. Space Programs: Civilian, Military, and Commercial." Congressional Research Service. September 28, 2004, 1.
[18] United States. The White House, Office of Science and Technology Policy. *Fact Sheet: U.S. Commercial Remote Sensing Policy*. April 25, 2003.
[19] Dennis Jones. "Commercial Remote Sensing and National Security." *Crosslink*, Summer 2004 (February 21, 2011), http://www.aero.org/publications/crosslink/summer2004/09.html, 3.

that policy is intended to minimize."[20] As a result, U.S. firms are at a significant disadvantage as compared with their foreign competitors because of the burdensome restrictions that are placed on the U.S. commercial remote sensing industry. According to the report, some of the main critiques from U.S. industry in regards to USG's desire to have "commercial leadership in all aspects of remote sensing" include,

- The USG is overprotective of capabilities and technologies, leading other foreign firms and governments to develop these capabilities independent of the U.S.
- Current U.S. policy "requires that a government-to-government agreement must first be negotiated for the export of a remote sensing satellite or certain key technologies before the U.S. firm(s) can be licensed to export the satellite or key system." This policy ultimately leaves the foreign investor with no guarantees, even though it has formally agreed to adhere to U.S. policies and regulations.
- The USG regulations associated with imagery dissemination conflict with the current practice of data distribution. U.S. policies appear to be more open than foreign firms based on image dissemination practices in other countries, but "U.S. imagery providers state that they confront a sense among clients that the U.S. is more likely to curtail access at some unforeseen point than are the governments of other imagery providers."[21]

The bottom line to U.S. firms is that the USG, while maintaining open and transparent policies, is not a strong or effective advocate of the U.S. commercial remote sensing industry. [22]

In examining the market for high-resolution images, the primary customers are foreign governments that seek to increase their national reconnaissance capabilities. A secondary

[20] J. Christian Kessler. "Leadership in the Remote Sensing Satellite Industry." (paper prepared for the U.S. Department of Commerce, NOAA Satellite & Information Service Commercial Remote Sensing Licensing Program, 2008), 2.
[21] Kessler, 2.
[22] Kessler, 3.

demand for high-resolution images also comes from foreign governments, but the images are sought for "other governmental purposes, such as disaster assessment and response, environmental monitoring, and land use management."[23] The collection and dissemination of high-resolution images in the U.S. is primarily executed through the National Geospatial-Intelligence Agency (NGA). The NGA procures the majority of remote sensing imagery from U.S. commercial providers while also acting as the contracting vehicle of the USG authorizing the collection and dissemination of data to foreign customers. In the Department of Commerce report, the NGA contracting approach was criticized as focusing "too much on the technical details of how imagery is to be collected – defining specific satellite architecture and operational modes – rather than defining what imagery it requires and permitting innovation by firms in designing the satellite systems."[24]

The USG also controls the distribution of high-resolution imagery and commercial remote sensing satellites by limiting the resolution at which images can be collected.[25] This collection and distribution policy utilized by the USG is known as a "two-tier" policy meaning, "For electro-optical imagery, the policy involved one resolution (currently 0.5 meter) for imagery that can be marketed generally and a second resolution (currently 0.25) for imagery that can only be disseminated with specific authorization and to recipients individually authorized by the USG."[26] The "tier two" data (.25 meter resolution) can also only be authorized for use by foreign governments. As discussed earlier, before a commercial firm is authorized to distribute high-resolution images, or "tier two" images, the State Department is required to secure

[23] Kessler, 7.
[24] Kessler, 6.
[25] Kessler, 8.
[26] Kessler, 8.

guarantees from the foreign government that they will adhere to the U.S. policies and not disseminate the images without USG consent.[27]

Conversely to the U.S. approach to imagery distribution and collection, other nations have "almost universally" adopted approaches that have varying forms of case-by-case reviews and/or have filters in place that determine if a case-by-case review is needed.[28] But, in observing international policies regarding commercial remote sensing and data dissemination, they all have fundamental components in common: "making data available for scientific, social, and economic benefit and restricting access to some data for national security reasons."[29] In another study commissioned by the Department of Commerce/NOAA, the National Center for Remote Sensing, Air, and Space Law conducted a global survey of land remote sensing laws and policies of more than thirty foreign governments. Besides the fundamental principles previously mentioned, it was found that there is relatively little formal legislation relating to remote sensing and imagery distribution. In countries that did have guidelines, it was mostly in the form of national policies. One reason cited for this is that "formal law and policy is difficult to find due to differences in legal systems, language barriers, and the perceived importance or lack thereof, of the subject matter."[30] For leading space actors such as the U.S., Germany, Canada, and France, among others, there are typically formal and transparent remote sensing policies and legislation. With regard to nations with more limited space capabilities, some have space laws and regulations that encompass remote sensing and data sharing without explicitly defining separate guidelines. While in others, policies are defined on a satellite-by-satellite basis because

[27] Kessler, 8.
[28] Kessler, 8.
[29] Joanne Irene Gabrynowicz. "The Land Remote Sensing Laws and Policies of National Governments: A Global Survey" (paper prepared for the U.S. Department of Commerce, NOAA Satellite & Information Service Commercial Remote Sensing Licensing Program, 2007), 3.
[30] Gabrynowicz, 3.

a national policy does not exist. In nations where the commercial remote sensing market is growing, but no national law exists, "private law and satellite operating licensing regulations of another country can govern a transaction."[31] The wide variety of policies, or lack thereof, can make international cooperation on data sharing difficult, but this study observed that there is a definite and visible trending towards increased legislation with remote sensing applications as a catalyst with the availability of affordable satellite technology and small satellite missions.

One aspect of international policy that could potentially inhibit cooperation is the lack of a consistent definition of "public", "private", and "commercial" in regards to a partnership or any other undertaking. These terms are defined differently in every nation; in Europe, for instance, "the term commercial means to generate revenue, and it applies to any entity that does so, regardless of by whom."[32] In the U.S., "commercial" means private sector with no government activity. Observing global trends, more countries are establishing public-private partnerships, or PPPs. Similarly, PPPs do not share a common definition among nations; nonetheless, it does imply risk sharing, making this option more appealing to the private industry because, in theory, the government will not go bankrupt if the enterprise fails.[33]

Another major theme found in global remote sensing policies is that, based on the UN Principles on Remote Sensing, access to data is the "norm," but there are always exceptions for national security, with these exceptions increasing. All civilian remote sensing data is readily open and available, especially in sensed states, but national security interests are being made a priority over general data access.[34] The UN Principles are most narrowly construed when a government enforces "shutter control" to limit data access. Shutter control can be defined as the

[31] Gabrynowicz, 8.
[32] Gabrynowicz, 15.
[33] Gabrynowicz, 16.
[34] Gabrynowicz, 13.

act of "forcing U.S. companies to discontinue obtaining or distributing imagery of certain parts of the world in times of crisis."[35] This kind of government intervention was exemplified when the U.S. initiated attacks in Afghanistan. During this time, the NGA bought exclusive rights to the imagery of the areas so that no one else could utilize the data without the NGA's approval. This type of restriction is colloquially known as "checkbook shutter control". In 2003, though, the U.S. did not limit access to commercial satellite imagery at the onset of the war in Iraq.[36]

These broader themes of international policies and practices provide a framework for which most commercial remote sensing image providers operate. Examining some of the nations that play a key role in the commercial remote sensing industry will provide a deeper understanding of how some of these companies do business and what regulations they impose on commercial image providers:

Canada currently has two SAR satellites, RadarSat-1, launched in 1999, and RadarSat-2, launched in 2007. These satellites were both built and are owned and operated by a Canadian commercial firm. This was a PPP in that the Canadian Space Agency (CSA) provided 80% of the funding for RadarSat-1, including its associated ground system.[37]

Canada maintains a close relationship with the USG and its associated remote sensing activities and to control data distribution of RadarSat imagery, Canada's authority is derived from a bilateral agreement with the U.S., "concluded in 2000, and on national legislation and regulations brought into force in 2007."[38] In distributing, "specified types of imagery products

[35] Smith, 5.
[36] Smith, 5.
[37] Kessler, 10.
[38] Kessler, 10.

are authorized for distribution to specified customers on the basis of governmentally approved agreements."[39]

China maintains an aggressive space program that includes a wide range of remote sensing satellites, but as a Communist government, has no privately owned commercial space industry. Though China has not entered the commercial remote sensing market, the Chinese government has sought out opportunities for cooperation with other governments such as Brazil, for civil and scientific remote sensing activities.[40]

France was initially the leader in the commercial remote sensing industry when they launched SPOT-1 in 1986. Today, the French Government closely monitors SPOT Image's data distribution (SPOT Image is the sole commercial distributor of imagery from the SPOT satellites). Individual transactions that are classified as sensitive may require a governmental review. According to the *Leadership in Remote Sensing* study, French export regulations are very similar to that of the USG's, noting that, "unlike many of its European Union partners, French export controls treat most components and technologies for satellites, including in particular high resolution remote sensing satellites, as munitions rather than dual-use items."[41]

In examining France's business practices, their remote sensing industry is trending "towards a more commercial, vice government sponsored, remote sensing industry." This can most notably be seen in Astrium's acquisition of an 81% share in SPOT Image, in which the French space agency, CNES, maintained a minority interest.[42]

Germany has rapidly established itself as a leader in the commercial remote sensing industry currently operating three remote sensing systems, including the constellation of SAR-

[39] Kessler, 10.
[40] Kessler, 10.
[41] Kessler, 11.
[42] Kessler, 11.

Lupe satellites, which are strictly utilized as a national reconnaissance and security system.[43] Within the German government, "all imagery [from the SAR-Lupe system] is treated as secret and distributed only among national intelligence agencies that are cooperating partners in the program."[44] In regards to the distribution of images collected from the TerraSAR-X system, Astrium has the exclusive rights to the commercial dissemination of the imagery. TerraSAR-X is "a joint enterprise among the German Ministry of Education and Science, the German space agency DLR, which together funded half the program, and the firm EADS Astrium, which funded the other half and built the satellite."[45] In controlling the distribution of imagery and the products associated with the imagery, the German Government maintains authority and regulates these activities. These regulations are based on "an evaluation of the sensitivity of a specific transaction considering the nature of the data to be provided, the location observed, and the recipient."[46] In cases deemed necessary for review, the German Foreign Office and German Defense Ministry has jurisdiction and these agencies maintain a cooperative relationship with the USG entities responsible for U.S. remote sensing policy.

India has a rapidly growing space program with strong remote sensing capabilities. Similar to China, India's space program is completely controlled by the government through the Indian Space Research Program (ISRO). India has a formal Remote Sensing Data Policy stating, "As a national commitment and as a 'public good', Government assures a continuous/improving observing/imaging capability from its own Indian Remote Sensing Satellites (IRS) programme."[47] According to the *Leadership in Remote Sensing* report, all commercial activities

[43] Kessler, 12.
[44] Kessler, 12.
[45] Kessler, 12.
[46] Kessler, 12.
[47] National Remote Sensing Centre. "Remote Sensing Data Policy (RSDP)." Indian Space Research Organization, Department of Space, Government of India. http://www.nrsc.gov.in/policy.html.

of ISRO are executed through the Antrix Corporation, ISRO's marketing subsidiary.[48] Antrix Corporation acts as a vehicle for all commercial remote sensing transactions including being the "sole agent for all foreign sales" of imagery collected by ISRO satellites as well as all foreign imagery products sold within India by foreign firms.

Russia's remote sensing programs are "directed, managed, and funded" by the Government of the Russian Federation.[49] They currently have one high-resolution satellite, which does provide imagery on a commercial basis. The imagery is distributed through a framework similar to that of India's via a commercial firm. In one exception to Russia's commercial remote sensing policy, Energia Space & Rocket Corporation produced a series of two EO and two SAR satellites, operated by Gazkom, for the sole purpose of monitoring Russia's oil and gas pipelines.[50]

These nations' remote sensing activities provide only a snapshot of the variety of policies and regulations each state imposes on its commercial space sector, while also providing an overview of the myriad ways in which a government can distribute high-resolution imagery.

[48] Kessler, 13.
[49] Kessler, 14.
[50] Kessler, 14.

SCENARIO 1: COMMERCIAL SAR & PIPELINE MONITORING

As has been made relatively clear by the number of examples listed above, there exists a variety of SAR systems that can meet a multitude of operational requirements. This led our group to carefully review and then decide on a general design for our own SAR capability in order to present a realistic model for any future commercial endeavor. This system, which we have dubbed ComSAR-X, would consist of a constellation of three SAR satellites in sun-synchronous orbit (SSO) providing complete global coverage and optimal solar energy gathering orbits. This constellation would allow for target area revisit times under one day while also providing some redundancy in case of issues with any one satellite. Additionally these satellites would be of a similar size and capability of the SAR-Lupe system because of their advanced features and low cost of construction and deployment. Each satellite would cost roughly 100 million dollars to build and launch, with the utilization of commercial off-the-shelf components and a Russian launch provider. The system itself would carry an X-band transmitter and receiver, allowing for sub-meter resolution, while also incorporating polarimetry and interferometry capabilities. Finally, this system would require downlink facilities, potentially three to four, each costing less than 10 million dollars to setup while also carrying operational costs. This roughly translates into a total system cost of 400 million dollars.

To better understand exactly how a system like ComSAR-X might be operated and marketed it is important to take a look at a couple of examples. The first example illustrates how ComSAR-X could help with the construction, and subsequent necessity for security, of an oil or natural gas pipeline. Oil and gas pipelines are some of the world's most critical infrastructures, while also being some of the least well monitored. It is estimated that world oil and gas

pipelines could total nearly six million miles[51], an astonishing total that is roughly 20 times the distance to the Moon. Currently, these pipelines are either monitored sporadically by air or visually on the ground... or not at all. This has led to substantial issues in regards to normal maintenance concerns and dealing with theft and sabotage. On the maintenance side of the equation, as these pipes age, corrosion and ground shift can lead to cracks and subsequent loss of product. This is in addition to the potential for loss of life and environmental damage. As the price of energy continues to increase and nations deal with both energy poverty and terrorism; increased instances of theft and destruction of oil and gas pipelines has become commonplace. Often native populations or factions not friendly to the government in power will view pipelines as a soft target to attack. This has, in turn, led to governments trying to monitor pipelines more closely through the use of security forces incorporating ground and air units. This issue would tie up substantial resources especially for developing nations who may not have the vehicles and man power at their disposal. While there are many regions of the world this would apply to, we decided to focus on South America in particular, which combines rugged terrain, substantial tree coverage of the targeted infrastructure and potential security concerns. SAR's unique capabilities are well suited to deal with these challenges.

Almost all of the countries in South America operate some length of oil or natural gas pipelines.[52] Peru has a number of existing and planned ones that would bring natural gas from the Amazon region of the country to both the coastal areas and to neighboring Chile. Previously built pipelines have had to deal with the mountainous terrain, famous for its Incan fortress of Machu Picchu, while also operating under the extensive tree and foliage cover present in the

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[51] Simmons, Matthew R. "The Rusty Global Oil and Gas Pipeline System." *oceanenergy.org.* March 18, 2008.
[52] The World Fact Book. *Crude Oil (petroleum) pipelines - Natural Gas pipelines - Products pipelines-South America.* May 6, 2008.
http://www.theodora.com/pipelines/argentina_bolivia_brazil_chile_ecuador_peru_uruguay_pipelines_map.html (accessed April 16, 2011)

Amazon. Additionally, the soft soil of the Amazon along with the hilly terrain and constant rainfall mean that ground shift can create real issues for a rigid pipe traversing hundreds of miles[53]. To pass into Chile, these pipelines must also travel through one of the world's most extreme deserts and the Andes mountain range. This is all in addition to dealing with native tribes hostile to a pipeline running through forests and regions they consider sacred.

A SAR constellation, such as the proposed ComSAR-X, would be able to provide daily imagery of the entire pipeline region with one meter resolution in StripMap mode. If areas of concern were spotted, and further detail was needed, high resolution spotlight imagery could be provided on a subsequent pass. This could be accomplished day or night with no interference from the extensive cloud cover that can be present in the region. The abilities of SAR for this circumstance go much farther than just imagery though. The value added polarimetry and interferometry data would allow a trained analyst the ability to determine a variety of characteristics in and around the target region. For instance, the analyst would be able to establish if there were vehicles or individuals around the pipeline, even if they were under dense tree cover. They could also determine if the ground or pipeline had shifted and if an oil leak was present. For the construction of a pipeline, SAR topography data could be used to determine the optimal path for construction to avoid potential hazards, like threats of landslides that may not be obvious from surface data. SAR can actually penetrate surface soil (to a certain extent) allowing a trained analyst a window into the density and even the composition of the soil. The system could then be used to monitor the construction and provide managers and planners operational awareness in a way never before possible.

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[53] Terra Erosion Control LTD. *CAMISEA PROJECT.* http://www.terraerosion.com/projects/consulting/1-camisea/camisea-project.htm (accessed April 10, 2011).

A common thread found throughout this example is the need for a well trained analyst or analysts who are capable of translating the complex SAR data and imagery. Because SAR operates utilizing microwave radiation instead of optical light, the "images" created often look very different when compared to an optical image of the same region. This coupled with that fact that interferometry and polarimetry data is extremely technical in nature means that a commercial SAR entity would need to offer more than just simple imagery to its customer. This would also mean a greater revenue stream for a commercial enterprise because it would be providing a service and not simply just a product to the customer. An a la carte approach to product and offerings would mean that customers could purchase a set of services that best suits their own needs and capabilities. These offerings could include operating a data center in the native country for storage and access of imagery and data if they had no such infrastructure already present. In the case of a Peru-Chile pipeline, dual centers could be established that would be interconnected to provide real time communications on potential issues that may arise on either side of the border. This would allow for a more cohesive response not fragmented by national boundaries. These centers would include the onsite analyst support already detailed, along with basic training programs for companies and nations to have a better understanding of the imagery and data themselves. A service offering like this would also provide a constant revenue stream to the commercial SAR provider because of the likely need for a long-term contracting vehicle. These contracts would not have to be based solely on number of images and raw data provided, but could instead be based on coverage area, revisit times, value added expert analysis and data management, and information sharing privileges. More creative revenue options could be made available as well by providing options for emergency prioritization and revisit of a target region in much the same way nationally operated systems have tiered levels of

organizations who have priority. While exact dollar figures for revenue from a contract dealing with pipeline imagery and analysis for countries like Peru and Chile is difficult to ascertain, it is widely known that current commercial SAR providers often sell their imagery in the thousands of dollars per image. With the value added that a purely commercial SAR capability could offer there is the potential for a vibrant and lucrative market.

SCENARIO 2: COMMERCIAL SAR & MARITIME DOMAIN AWARENESS

It happened again just a few weeks ago. In March 2011, in the Gulf of Aden off the east coast of Africa, pirates attacked an oil tanker with rocket-propelled grenades and guns and succeeded in hijacking it. The United Arab Emirates-flagged oil tanker, named Zirku, was traveling from Sudan to Singapore carrying a crew of twenty-nine and 150 million dollars worth of oil.[54] Despite reports that the Zirku had taken the necessary precautions to avoid being attacked, including registering with the Maritime Security Centre – Horn of Africa (MSCHOA) (a European Union agency that provides a manned monitoring service for vessels transiting through the Gulf of Aden), as well as regularly reporting to the UK Maritime Trade Operations (UKMTO) office in Dubai (the primary point of contact for merchant vessels transiting the area to liaise with military forces in the region), the ship was still overtaken. The Zirku was traveling just outside the Internationally Recommended Transit Corridor (IRTC) through the Gulf of Aden, but still well within the High Risk Area designated by the Best Management Practice (BMP) guidelines available to ships to deter piracy off Somalia.[55] As of the date of publication of this paper, there has been no resolution to the situation with the Zirku. The Pirates are demanding a $5 million ransom and the twenty-nine crew members are still held hostage.[56]

In recent months, the Gulf of Aden had been regarded as relatively safe due to the extensive coalition naval presence in the area. Nevertheless, there has been a marked increase in

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[54] "Pirates Hijack Oil Tanker off East Africa." MSNBC. Associated Press, 28 Mar. 2011. Web. 16 Apr. 2011. <http://www.msnbc.msn.com/id/42302609/ns/world_news-africa/>.

[55] "The Hijacking of the MV Zirku: A Case Study in Shipping Security – Analysis." Somalipirates. 20 April 2011. Web. 22 April 2011. < http://www.somalipirates.org/the-hijacking-of-the-mv-zirku-a-case-study-in-shipping-security-%e2%80%93-analysis>.

[56] Andrew Mwangura. "Pirates Want $5M Ransom For MV Zirku." SomaliaReport. 31 Mar. 2011. Web. 22 Apr. 2011.<http://www.somaliareport.com/index.php/post/423/Pirates_Want_5M_Ransom_For_MV_Zirku?PHPSESSID=768c1e49b6509045259f857b7b6569e1>.

attacks in the Indian Ocean, as pirates are forced further out to sea.[57] The complex maritime situation around the continent of Africa has an undeniable affect on global security, stability in the region, commercial shipping, commerce and the global economy. In a snapshot:

- 80% of Europe's cocaine supply passes through West Africa
- 60% of human trafficking occurs in Sub-Saharan Africa
- Losses for Sub-Saharan Africa due to illegal fishing total $1 billion per year
- 18% of U.S. crude oil imports come from West Africa
- Piracy at sea cost the global economy $16 billion per year, on average[58]

Subsequently, highly reliable and improved Maritime Domain Awareness (MDA), particularly in contentious areas of interest like the Gulf of Aden, is increasingly necessary.

Generically, maritime domain awareness is defined as "the effective understanding of anything associated with the maritime domain that could impact the [...] security, safety, economy, or environment [of a nation]."[59] From a U.S. Navy perspective, the purpose of MDA is "to facilitate timely, accurate decision making that enables actions to neutralize threats to [...] national security interests."[60] Successful MDA is an analysis of what is observable and known (also known as Situational Awareness) and what is anticipated or suspected (known as Threat Awareness). In other words, MDA is Global Maritime Situational Awareness (GMSA) plus Maritime Threat Awareness. Furthermore, MDA requires the understanding of the content, activity patterns, changes, and potential threats in the maritime environment. The following attributes provide a practical understanding of Navy's perspective toward MDA:[61]

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[57] "The Hijacking of the MV Zirku: A Case Study in Shipping Security – Analysis." Somalipirates. 20 April 2011. Web. 22 April 2011. < http://www.somalipirates.org/the-hijacking-of-the-mv-zirku-a-case-study-in-shipping-security-%e2%80%93-analysis>.

[58] Capt. J. D. Hood (USN). "Enhancing Maritime Safety and Security in Africa." PowerPoint presentation. November 2009.

[59] "National Plan to Achieve Maritime Domain Awareness." Department of Homeland Security. 26 Mar. 2008. Web. 01 Apr. 2011. <http://www.dhs.gov/files/programs/editorial_0753.shtm>.

[60] United States, Department of the Navy. Navy Maritime Domain Awareness Concept. Washington, 2007.

[61] United States, Department of the Navy. Navy Maritime Domain Awareness Concept. Washington, 2007.

What it is:	What it isn't:
Global	Just homeland security
Coalition & International	Only one nation
Joint & Interagency	Just defense
Security Partnerships	Just vessel tracking
Information Sharing	Just intelligence
All threats	Just terrorism
Origin to delivery	Just more sensors
A continual process	An end state

In today's environment, it is commonly accepted that MDA must be a combined effort. No single nation, and certainly no single agency, has the capability or capacity to achieve MDA on its own. MDA requires broad collaboration among many partners, each contributing to the effective understanding of the maritime domain. It also requires improving current collection, fusion, analysis, and dissemination of actionable information and intelligence (not just data) to all involved parties (e.g. operational commanders and decision makers).[62] Yet, all of this is undeniably costly, hence the increase in reliance on commercial space systems, including commercial satellite imagery, to drive down costs.

But what *technology* is required for comprehensive maritime domain awareness? A combination of advanced sensors is needed if one is to detect and monitor such things as pirated ships, drug smuggling, and human or weapons trafficking. Even standard Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) legacy systems can be reoriented and integrated with current and emerging sensor capabilities and applicable procedures. These capabilities must be fused in a common operating picture that is available to maritime operational commanders and accessible as appropriate throughout the U.S. government.[63] One such *emerging sensor capabilities* is Synthetic Aperture Radar (SAR). And

[62] "National Plan to Achieve Maritime Domain Awareness." Department of Homeland Security. 26 Mar. 2008. Web. 01 Apr. 2011. <http://www.dhs.gov/files/programs/editorial_0753.shtm>.
[63] "National Plan to Achieve Maritime Domain Awareness." Department of Homeland Security. 26 Mar. 2008. Web. 01 Apr. 2011. <http://www.dhs.gov/files/programs/editorial_0753.shtm>.

today, commercial SAR sensors are increasingly used to fulfill essential monitoring and security roles. A system such as the one proposed in the previous section, ComSAR-X, if paired with technologies such as airborne patrols, Automatic Identification System (AIS; an automated tracking system used on ships), and electro-optical satellite surveillance, would be an excellent option for the continuous monitoring of the African coastline.

Given SAR satellites' key characteristic of providing highly accurate geolocation in all weather conditions, day or night, it can perform a variety of tasks related to coastline monitoring, such as ship detection, classification and tracking. With some post image processing, the speed of ships can even be calculated. Presently, research is being conducted on vessel detection using SAR satellite data; the goal is to develop new processes for receiving and analyzing large maritime area data from multi-satellite and multi-frequency sensors, including SAR and EO sensors. Special algorithms are being developed to employ the data to detect vessels, including small ships, in harbors, littoral areas and the high seas. Algorithms are also being developed to integrate this vessel detection information with ground-based systems, such as AIS.[64] Current research using the TerraSAR-X SAR satellite system is demonstrating that it may be ideal for maritime domain awareness. In ScanSAR mode, TerraSAR-X can detect vessels as small as 10 meters and it is capable of detecting the metallic structures on fiberglass hulls.[65]

Still, current service capabilities do not fully meet the requirements of sustained MDA; although the performance of current, independent satellite systems is advanced and, when paired with other sensors and in-situ monitoring technologies (AIS, etc.) provides sufficient coverage, a constellation of commercial SAR satellites with an integrated commercial service would be

[64] J.K.E. Tunaley, "Radar Satellites and Maritime Domain Awareness." PowerPoint presentation, London Research and Development Corporation, Ontario, Canada.
[65] "MARISS GSE: European Maritime Security Services." PowerPoint presentation, GMES Service Element, European Space Agency. 06-08 March 2007.

highly beneficial to MDA. A constellation of three or more satellites, such as the proposed ComSAR-X system, and with a wide area swath capability of 350 km to 450 km, could do an excellent job of monitoring the east African coastline, particularly if paired with AIS information. An associated commercial service would provide advanced analysis of the SAR data taken in the particular area of interest. SAR imagery is far from being user friendly, hence a commercial service where the imagery is analyzed on a regular basis and then reported back to the client is essential.

With regard to combating piracy off the coast of Africa, SAR data and imagery could be used in a multitude of ways but ideally would be augmented by other sensors, such as electro-optical imagery or, in some cases, wide area AIS, in order to meet current requirements. The various cases of privacy have shown that, once a ship is taken over, the AIS system is routinely shut off so that the ships coordinates are less easily detected. This is where satellite imagery and data, especially SAR can play a role. A purely commercial SAR satellite, such as the proposed ComSAR-X system, could be used to detect the ship (all that would be necessary are approximate size and rough coordinates) then track its route and speed; nonetheless, this would require a certain level of analysis and expertise. As with the previous scenario, there is a distinct need for well trained analysts, capable of translating the complex SAR data and imagery and reporting back to the end user. A commercial service offering would help the customer define its requirements, set targets and interpret them. As discussed previously, SAR systems can collect images in a three specific mode (SpotLight, StripMap and ScanSAR); a commercial service would help the customer to select the ideal mode to satisfy the collection and detection constraints. Again, an a la carte approach could be taken to product and offerings, meaning that the end user could purchase a tailorable service to best suit his own requirements. Furthermore,

as a purely commercial service, this SAR data could be more easily shared among the concerned parties, such as coalition naval forces, international organizations such as the aforementioned MSCHOA or EU NAVFOR*, or commercial vessels and their captains. Nevertheless, it must be acknowledged that one radar satellite system alone cannot provide a satisfactory list of targets by itself. However, in concert with other sensors, it can make an extremely valuable contribution to MDA.[66] Data from a constellation like ComSAR-X, if used in collaboration with other sensor data, could provide near real time (NRT) surveillance in a cost effective manner. Over the next few years, more must be done to integrate satellite based surveillance techniques in order to achieve real maritime domain awareness but if this can be achieved, then there is the potential for a vibrant and lucrative market in SAR imagery monitoring services.

* EU NAVFOR acts in accordance with United Nations Security Councils resolutions. Its objectives are to protect vessels of the *World Food Programme*, humanitarian aid and African Union Mission in Somalia (AMISOM) shipping; help deter, prevent and repress acts of piracy and armed robbery; protect vulnerable shipping routes; and monitor fishing activities off the coast of Somalia.

[66] J.K.E. Tunaley, "Radar Satellites and Maritime Domain Awareness." PowerPoint presentation, London Research and Development Corporation, Ontario, Canada.

CONCLUSION

The proposed ComSAR-X system would undoubtedly fill a deficiency in the current market for Earth observation capabilities. SAR systems can provide more accurate and detailed data than current optical systems, while also maintaining the ability to provide high-resolution imagery day or night, regardless of atmospheric conditions, in addition to ground and foliage penetration. These unique capabilities would enable the ComSAR-X system to provide its customers with round-the-clock surveillance, whether the need is for pipeline monitoring, environmental research, humanitarian aid, maritime surveillance or countless other security and monitoring applications.

The commercial remote sensing industry currently operates in a framework that is unique to each nation. In establishing ComSAR-X as a high-resolution imagery provider, it may be necessary to comply with the national policies from where it chooses to operate in order to maintain the integrity of the enterprise. ComSAR-X could potentially run into obstacles as it deals with the various data collection and dissemination regulations of other nations and as such, it will be imperative for the ComSAR-X enterprise to gain an understanding of the broader themes of international policies and practices in which most commercial remote sensing image providers operate today.

As a purely commercial system, ComSAR-X may be able to navigate around some of the current policy constraints, which are not always routinely enforced. As demand increases and SAR imagery and services become more commonplace, these uneven remote sensing regulations and policies may soften, giving way to a more active market for satellite imagery. ComSAR-X's independent and commercial nature would provide a simplified approach to sharing vital high-resolution imagery and data, provided that it continues to be a responsible player in the space

sector. Providing this unique service, in a market where current SAR providers sell their imagery for thousands of dollars per image, in addition to the value added that an independent commercial SAR capability could offer opens the potential for a vibrant and lucrative market.

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