The Diffusion of Constellations of Small SAR Satellites: A Complex Systems Approach

Ludmila Deute Ribeiro

deute.ludmila@gmail.com

UnB Gama Faculty of Engineering, University of Brasilia, Brazil

Manuel Nascimento Dias Barcelos Júnior

manuelbarcelos@gmail.com

UnB Gama Faculty of Engineering, University of Brasilia, Brazil

Abstract:

Marine oil spills may cause major environmental damage. SAR (Synthetic Aperture Radar) sensors seem to be one of the most effective instruments for oil spills monitoring. SAR imagery, provided by large satellites carrying SAR instruments, has been successfully employed in this task. But the fabrication and deployment issues associated with placing a large SAR satellite into orbit are not compatible with the growing demand for spaceborne SAR imagery. Any failures in these satellites can cause irreparable damage to the user community, because its replacement into orbit is expensive and time consuming. These constraints might open a "market window" for a new technology which has recently been developed: the constellations of small SAR satellites. The present paper proposes an analytical tool for exploring the diffusion of this innovation in the global market of marine oil spills SAR monitoring: a hybrid model based on Bass Model and Social Network Analysis.

Keywords: Radar, Synthetic Aperture Radar - SAR, oil spill, diffusion of innovations, Bass Model, Social Network Analysis - SNA.

1. Introduction

Marine oil spills may cause major environmental damage, especially in coastal waters. Oil spillages occur frequently in the Gulf of Mexico, due to geological causes. However, the major sources remain the deliberate discharge of oils by ships carrying it as cargo, and the accidental oil released in activities associated with the exploration of seabed. About 75% of oil reserves discovered in Brazil are located in deep water (between 400 meters and 1,000 meters) and ultra-deep water (above 1,000 meters), and the drilling and transportation of oil favor the occurrence of accidental spillages.

The most effective instruments for monitoring of marine oil spills seem to be Synthetic Aperture Radar - SAR sensors carried by airborne or spaceborne observational platforms. The spaceborne SAR radar sends radio wavelengths to Earth's surface and the antenna on the satellite collects the wavelengths hat are reflected back. These wavelengths are also called "backscatter". SAR imagery produces a grey-scale image which represents the radar backscatter from water at the sea surface. The radar backscatter from the sea surface is reduced in areas where oil is present. The result is that oil slicks turn out as dark areas on a brighter background of normal sea water (Souza, 2006).

For marine oil spills monitoring, high-to-coarse spatial resolution SAR images can be used, but the area of the Earth's surface imaged by the satellite must be most suitable as it offers better swath area, so that large areas of water can be better detected for oil spills. This imagery have been mostly provided by high-performance large SAR satellites often placed in a Sun-Synchronous Orbit - SSO, generally Medium Earth Orbit - MEO or Low Earth Orbit - LEO. However, considering the life-cycle costs, development, and deployment issues related to these traditional satellite systems, we can conclude that they cannot supply the growing demand for marine oil spills monitoring by spaceborne SAR sensors.

The main requirements of any satellite missions for monitoring marine oil spills can be summarized as follows: (a) provide imagery captured over the same spot (on the Earth's surface) with high revisit frequency; (b) provide imagery day and night, and in unfavorable weather conditions (clouds, haze, rain and fog); (c) provide imagery with large swath areas; (d) provide high-to-coarse resolution imagery; and (e) provide lower costs of satellite manufacture and launch and minimum deployment time in case of failure.

The requirement (b) can be attended by any SAR satellite missions. Compliance with requirements (c) and (d) depends on the image acquisition modes of the satellites.

However, single, large SAR satellites are not compatible with requirements (a) and (e). First, the detection of contingencies is possible only if a sufficient number of spaceborne sensors is available, then the constellations appears the only solution in order to limit the temporal gaps of acquisition caused by utilization of a single spacecraft. Second, the replacement of these traditional satellites into orbit is expensive and time consuming, and might be affected by budget constraints of the space agencies responsible for its development, launch, and operation. Any failures in these satellites can cause irreparable damage to the user community of images and products.

These constraints might open a "market window" for a new technology which has recently been developed: the constellation of small SAR satellites.

The present paper proposes an analytical tool to explain the diffusion of this technology innovation in the global market of marine oil spills monitoring by spaceborne SAR sensors: a hybrid model based on The Bass Model and Social Network Analysis -SNA.

The structure of the paper is as follows. In Section 2, we analyze the constellations of small SAR satellites for oil spills monitoring, advantages and disadvantages of this innovation when compared to the traditional technologies. In Section 3, we briefly review the main models for innovation diffusion. In Section 4, we present the hybrid model and, finally, in Section 5, there is a roadmap for its future implementation.

2. Marine Oil Spills Monitoring by Spaceborne SAR Sensors

Remote sensing is the group of techniques that allow us to acquire information of objects or phenomena, without the necessity of being in contact with them. Nowadays, when we talk about remote sensing, it generally means the use of imaging sensor technologies including the use of aircraft and spacecraft boarded instruments (Mondéjar, 2009).

There are two classes of remote sensing systems. Passive sensors detect natural radiation that is emitted or reflected by the object or the area being observed. Reflected sunlight is the most common source of radiation measured by passive sensors. On the other hand, active sensors emit energy with the intention to scan objects and areas. Imaging RADAR (RAdio Detection And Ranging) is an example of active remote sensing and has become an alternative technique for Earth observation, due to several advantages provided by spaceborne RADAR, the most important of which is the ability to achieve global coverage (Mondéjar, 2009).

A SAR is a coherent radar system that can generate high- resolution images. Since SAR is an active sensor, which provides its own source of illumination, it can therefore operate day and night; able to illuminate with variable look angle and can select wide area coverage. The use of SAR for remote sensing is particularly suited for tropical countries, because the microwave sign can penetrate clouds, haze, rain and fog and precipitation with very little attenuation, thus allowing operation in unfavorable weather conditions. The potential of SAR in a diverse range of application led to the development of a number of airborne and spaceborne SAR systems (Chan and Koo, 2008).

Spaceborne SAR imagery has provided a strong contribution in a large number of disasters such as the explosion of the Deepwater Horizon oil platform on April 20, 2010, off the southeast coast of Louisiana, United States. Shortly after the explosion, oil began leaking from the broken wellhead nearly one mile beneath the surface of the Gulf of Mexico. During the disaster, the detection and mapping of oil slicks included space-based SAR imagery such as RADARSAT (Canadian), Cosmo SkyMed (Italian) and TerraSAR-X (German), the major Earth Observation programs that are operationally in orbit and which are based on state-of-art SAR instruments.

RADARSAT is a large satellite placed in a low SSO, 798 kilometers above the Earth. So far, the RADARSAT program succeeded in launching two satellites RADARSAT-1 and RADARSAT-2, of which only the second is still operational.

Launched in November 1995, and equipped with a SAR instrument operating in C-band, RADARSAT-1 was a Canadian-led project involving the Canadian federal government, the Canadian provinces, the United States and the private sector. It provided useful information to both commercial and scientific users in such fields as disaster management, interferometry, agriculture, cartography, hydrology, forestry, oceanography, ice studies, and coastal monitoring. In May 2013, the first Canadian Earth Observation Satellite has been officially declared non-operational after a final anomaly consigned the satellite to what will be a very slow de-orbit to a final burn-up in Earth's atmosphere. Launched in December 2007, RADARSAT-2 offers technical advancements that enhance many environmental SAR applications. RADARSAT-2 imagery has been successfully used in marine oil spills monitoring.

The evolution of this program is the RADARSAT Constellation. A constellation is composed of two or more spacecraft in similar orbits with no active control by either to maintain a relative position (Sandau, 2010).

The mission development has begun in 2005, with satellite launches planned for 2018. The baseline mission includes three medium-size satellites, but the constellation is designed to be scalable to six satellites. The RADARSAT Constellation is being designed for three main uses: (i) maritime surveillance; (ii) disaster management; and (iii) ecosystem monitoring (CSA, 2014).

COSMO SkyMed (COnstellation of small Satellites for Mediterranean basin Observation) is a dual-use Earth Observation mission, commissioned and funded by Italian Space Agency - ASI and Italian Ministry of Defense - MoD. Since the beginning of 2011, the system is fully operational. It consists of four medium-size satellites, each one with total mass at launch of 1,700 kg, and equipped with a multi-mode high resolution SAR instrument operating in X-band (9.6 GHz), providing COSMO SkyMed adequately supports user needs such as world-wide coverage and high revisit frequency in the order of few hours. Due to the need of many combinations between swath width and spatial resolution, the COSMO-SkyMed SAR was chosen as a multimode sensor operating in: (i) a SpotLight mode, for metric resolutions over small images; (ii) two StripMap modes, for metric resolutions over tenth of km images; and (iii) two ScanSAR modes for medium to coarse (100 m) resolution over large swath ~200 km in Huge Region Mode (Angelucci and Giampaolo, 2012).

The synergic use of X and L band is also possible by cooperation between the Italian Space Agency (Agenzia Spaziale Italiana -ASI) and the Argentine National Commission on Space Activities (Comisión Nacional de Actividades Espaciales - CONAE) relevant to the Italian-Argentine System of Satellites for Emergency Management - SIASGE, integrated by the four X-band COSMO-SkyMed satellites and the two L-band SAOCOM satellites.

The German SAR system TerraSAR-X/Tandem-X development is based on a public-private-partnership agreement - PPP between the German Aerospace Center DLR and EADS Astrium GmbH. The medium-size satellite TerraSAR-X (total mass at launch = 1,230 kg) also combines the ability to acquire high resolution images for detailed analysis as well as wide swath images for overview applications.

TerraSAR-X imagery can be acquired in one of these main acquisition modes: (i) *staring SpotLight mode*: down to 0.25m resolution, 4 km (swath width); (ii) *high resolution SpotLight mode*: up to 1m resolution, 5 to 10km swath width; (iii) *SpotLight mode:* up to 2m resolution, 10km swath width; (iv) *StripMap mode:* up to 3m resolution, 30 km of swath width; (v) *ScanSAR mode*: up to 18.5m resolution, 100km swath width; and (vi) *wide Scan SAR mode*: up to 40 m resolution, 270 km swath width.

In 2010 TerraSAR-X was joined by his "twin" TanDEM-X. The two satellites now fly in a unique satellite constellation at a distance of 200 meters. The TerraSAR-X and TanDEM-X main mission objective is to generate High Resolution 3D SAR imagery via interferometry.

To better understand the characteristics of the three major SAR satellite systems for oil spills monitoring see Table 1.

A new concept of spaceborne synthetic aperture radar implementation has recently been proposed - the constellation of small spaceborne SAR systems. In this implementation, several flight-formations of small satellites cooperate to perform multiple space missions (Li, Bao, Wang, and Liao, 2006).

Constellations of small SAR satellites have many advantages over conventional SAR satellite systems. The coherent combination of several SAR images obtained from different observing angles can improve the image resolution and provide accurate geometric information. Furthermore, combining a broad illumination source with multiple small receiving antennas placed on separate formation-flying small satellites, we can obtain high-resolution SAR images of wide areas. The implementation of satellite constellations to increase the time resolution and ground coverage is a unique feature of small satellites. Another reason for using the constellation of small SAR satellites is to mitigate the cost, fabrication, and deployment issues associated with placing a large SAR satellite into orbit. Furthermore, the likelihood of system failure can be reduced since failure generally occurs only to individual small satellites, instead of a large satellite carrying an entire system (Li, Bao, Wang, and Liao, 2006).

In short, instead of launching a single, large-to-medium, high-performance satellite, the capabilities of the system are distributed across several satellites, increasing revisit frequency, and introducing a more robust (resistant to random failures), flexible system that can be maintained at lower cost and launched into orbit using smaller, less expensive launch vehicles. This brings the responsiveness that is needed for emergencies and for disaster support.

Table 1. Three major SAR satellite systems that are operationally in orbit

ITEMS	Cosmo SkyMed	RADARSAT-2	TerraSAR/Tandem-X
Satellites/Payload Band	4 satellites/X-Band	1 Satellite/C-Band	2 Satellites in close formation/X- Band
Mass at Launch	1,700 kg	2,200 kg	1,230 kg
Orbit Altitude	620 km SSO	798 km SSO	500 km SSO
Funding and Operation	Italian Space Agency (ASI)	Canadian Space Agency (CSA)	PPP between German Aerospace Centre (DLR) and EADS Astrium
Prime Contractor	Thales Alenia Space Italy	MacDonald Dettwiler Associates (MDA)	EADS Astrium
Satellite Imagery Distributor	e-GEOS	MDA Geospatial Service	Astrium Services
Launch Vehicle	Boeing Delta II	Soyuz II	Dnepr-1
Resolution (Ground Sample Distance - GSD)	1 meter	up to 3 meters	down to 0.25 meters
Swath Width	~ 200 km, ScanSAR mode	500 km, ScanSAR wide mode	up to 270 Km, Wide ScanSAR mode
Revisit Time	140 minutes	24 days, depending on acquisition mode.	11 days in average; northern Europe has a revisit time of typically 3–4 days.
Innovations	Generation of High Resolution 3D SAR imagery via interferometry.	Higher Spatial Resolution, Higher Revisity Frequency, data can be accessed more quickly.	Generation of High Resolution 3D SAR imagery via interferometry.
Interoperation with other systems	SAOCOM L-Band	Next RADARSAT Generation	Upcoming constellation with Spanish satellite PAZ to be launched in 2014.
Suitable features for marine oil spills monitoring	High Spatial Resolution High Revisity Frequency, Interoperation with other systems.	Satellite imagery can be combined with other imagery and data to improve Revisity Frequency	High Spatial Resolution, High Geometric and Radiometric Accuracy

Source: Elaborated by the authors from Euroconsult (2012), Angelucci and Giampaolo (2012), and sites of CSA and Astrium Services.

Exploring these advantages, a new generation of low-cost spaceborne SAR mission is under planning. Among these the Nova-SAR-S, developed by Surrey Satellite Technology - SSTL Ltd, spin-out from University of Surrey in 1985, now owned by European Aeronautic Defence and Space Company - EADS. SSTL Ltd has successfully developed the Disaster Monitoring Constellation - DMC, a constellation of optical remote sensing small satellites operated for the Algerian, Nigerian, Turkish, British and Chinese governments by DMC International Imaging (Baker, Davies, and Boland, 2010; Sweeting, 2012).

NovaSAR-S mission, with up to 3 small satellites (total mass at launch = 400 kg) to be launched in the upcoming years, is a combination of Commercial Off-The-Shelf - COTS technologies, SSTL's tested SSTL-300 avionics, and a S-band solid state power amplifier technology developed by EADS Astrium. NovaSAR-S satellites will have a flexible range of image acquisition modes: (i) *ScanSAR mode*: spatial resolution up to 20 meters, and swath width of 100 km; (ii) *Maritime surveillance mode*: spatial resolution up to 30 meters, and swath width of 750 km; (iii) *Stripmap mode*: spatial resolution up to 6 meters, and swath width of 15-20 km; and (iv) *ScanSAR wide mode*: spatial resolution up to 150 meters, swath width of 30 km. ScanSAR modes will detect oil spills in coastal areas and in open ocean (SSTL, 2013).

The mission is designed for several polar and equatorial orbits depending on the target area of interest. A single satellite using the fine resolution stripmap mode can return to the same place anywhere on the globe twice a week. A constellation of three satellites can provide oil spills monitoring with up to one and a half days revisit time in ScanSAR mode.

Existing systems have been deployed into high inclination orbits - optimized for northern hemisphere coverage but with very poor service to the equatorial and tropical regions. Whilst this does provide global access the revisit rates at the equator are typically less than one per day. Injection into low inclination orbits is of paramount importance in providing maximum access and revisits to the equatorial and tropical regions. The AstroSAR-Lite satellite provides a spaceborne SAR system focused to provide high revisit frequency (up to 15 times a day) and coverage with high resolution for the regional user in the tropics and sub-tropics (Honstvet, Encke, Hall, and Munro, 2007).

AstroSAR-Lite is optimized to maritime, environmental, security and disaster monitoring applications. The baseline satellite operates in various modes to obtain images ranging from 10 km x 1,000 km at 3 meters resolution, up to 100 km x 1,000 km at 20–30 meters resolutions over the 'footprints' of each of several regional users.

The needs for SAR have also been increasing in Asia. Advanced Satellite with New system Architecture for Observation - ASNARO is a research and development project for internationally competitive advanced small satellite system. It has been executed by NEC Corporation and Japan Space Systems under the contract of Ministry of Economy, Trade and Industry - METI.

ASNARO satellite bus employs the small standard satellite bus (300 kg) NEXTAR, developed by NEC Corporation, and a small spaceborne SAR designed to achieve high resolution (less than 0.5 m GSD), by utilizing the X-band radio waves of the 9 GHz band. ASNARO will operate in three image acquisition modes: (i) Stripmap mode, a conventional mode, 10 km swath width; (ii) Sliding Spotlight mode, for less than 1 m resolution, 10 km swath width; and (iii) ScanSAR mode, 30 km swath width, suitable for oil spills monitoring (Kimura, Fujimura, and Ono, 2011).

The traditional users of spaceborne SAR imagery are space and environmental agencies, but today there is a growing interest in oil spills spaceborne SAR monitoring: the potential new users are oil companies and emerging countries. Miranda et al (2004), Rodrigues (2011), and Lima (2011) showed that RADARSAT images have been successfully used by oil companies for oil spills monitoring. So we assume that some oil companies would be interested in constellations of small SAR satellites provided to meet their specific needs.

Since the advent of modern technologies, such as microelectronics, small satellites have also been perceived to offer an opportunity for countries with a modest research budget and little or no experience in space technology, to achieve Earth Observation and defense capability, without relying on inputs from the major space-faring nations. (Sandau and Briess, 2008 ; Sandau, 2010).

Constellations of Small SAR Satellites can be developed and maintained at lower cost - small SAR satellites can be built using COTS technologies - and launched into orbit using smaller, less expensive launch vehicles. Considering all the aspects, its technical performance is almost equivalent to the performance of traditional, large, high-reliability SAR satellites. So we assume that developing countries would be also interested in constellations of small SAR satellites provided to meet their specific needs. In fact, a new generation of low-cost small spaceborne SAR missions is under planning and some of them (e.g., ASTROSAR-Lite) are designed to meet the needs of regional users in the tropics and sub-tropics.

There is, however, a crucial difference between these two technologies: Constellations of Small SAR Satellites (A_1) has not been tested to date, all constellations of small SAR satellites are in development or deployment phases. In contrast, Large SAR Satellites (A_2) have been tested in orbit for years. This fact reduces A_1 attractiveness, given that potential users may have questions about its performance. But these questions will be overcome after the beginning of the commercial operating phase, planned for the next two years. Assuming that they have similar cost/ performance, A_1 can substitute A_2 for some applications, and even become dominant in the global market. Table 2 provides analysis of technical and economic factors that can influence the growth and diffusion of A_1 in the market dominated by A_2.

Any decision about adopting or not space technologies involves considerable risks, not counting the transition costs from one technology to another and possible interoperability problems. Thus, the understanding of the space technologies adoption process can provide some useful insights for government agencies, universities, and companies.

Table 2 - Factors that can influence the growth and diffusion of A_1 in the market dominated by A_2.

FACTORS	Constellations of Small SAR satellites (A1)	Large SAR satellites (A2)
TECHNICAL		
Platforms Reliability	Medium Reliability	High Reliability
Spatial Resolution	Medium to High Spatial Resolution Higher Resolution : less than 0.5 m GSD(ASNARO)	High Spatial Resolution Higher Resolution: down to 0.25 m GSD (TerraSAR)
Revisit Frequency	High (<1 day for all constellations)	Medium (< 1 day only for COSMO SkyMed)
Swath Width	100/150 Km in ScanSAR mode	~ up to 100 km (TerraSAR/ Tandem ScanSAR mode); 500 Km (RADARSAT-2)
Launch Vehicle Reliability	Medium Reliability (Dnper, Cosmos, Minotaur, PSLV, Epsilon)	High Reliability (Soyuz II, Boeing Delta II, and Dnper-1)
ECONOMIC		
Launch Prices	Low cost per launch for groups of satellites and for piggyback launch (US$ 9,5 million/500 kg satellite)	High cost per launch: Falcon-9: US$ 61.2 M; Falcon Heavy: US$ 85 M for up to 6,400 kg GTO
Potential Interest by government agencies of developed countries	Growing interest in the constellation development (United Kingdom and Japanese companies and research centers)	Interest in constellation development (Italy, Canada, and Germany space agencies)
Potential Interest by government agencies of developing countries	Growing interest in the constellation development (e.g, DMC constellation)	Growing interest in imagery acquisition
Potential interest by oil companies	Growing interest in imagery acquisition	Growing interest in imagery acquisition
Potential Use of COTS	High Potential	Low/Moderate Potential
Satellite development cost	Relatively Low Costs (~20% of large satellites development costs)	Higher Costs
Number of Prime Contractors	Small Number of innovative companies (ex: SSTL Ltd)	Large Number of Traditional Prime Contractors

Source: Elaborated by the authors

3. Models for Innovation Diffusion

This section reviews and presents some models and modeling approaches for innovation diffusion. This review intends to be introductory. Our goal is to develop a model for exploring the diffusion of innovations on the market of oil spills monitored by spaceborne SAR sensors. This market can be classified as a Complex Adaptive System - CAS: a kind of system that involves many components that adapt or learn as they interact, and it is at the heart of important contemporary problems (Page and Miller, 2007; Holland, 2006; Rogers, Medina, Rivera, and Wiley, 2005).

In complex systems modeling, one can follow different paths. Cybernetics, general systems theory, catastrophe theory, and chaos theory all address deterministic dynamical systems. These systems are represented by a set of equations that models their dynamical behavior and determine how the systems are modified on their state space from time t to time t + 1. Another way of modeling complex behavior, it is based on examining regularity that emerges from interaction of individuals connected together in CAS (Anderson, 1999).

The analysis of a Bass Model System Dynamic - SD is a typical example of the deterministic modeling. In contrast, CAS models represent a genuinely new way of simplifying the complex, by encoding natural systems into formal systems. CAS models typically show how complex outcomes flow from simple schemes and depend on the way in which agents are interconnected. Social Network Analysis - SNA and Agent-Based Modeling - ABM can be applied to generate CAS models for Innovation Diffusion.

Starting with the Bass Model, also known as Mixed-Influence Diffusion Model, the diffusion rate dA/dt can be represented as (Vishwanath and Barnett, 2011):

$$\frac{dA}{dt} = (a + KA_t)(N - A_t) \qquad (1)$$

where:

a is the external influence coefficient;

N is the population;

K is the constant rate of change or coefficient of diffusion;

$\mathbf{A_t}$ are the (prior) adopters; and

$\mathbf{(N - A_t)}$ are the potential adopters.

Integration of the Mixed-Influence Model yields the following cumulative adopter distribution:

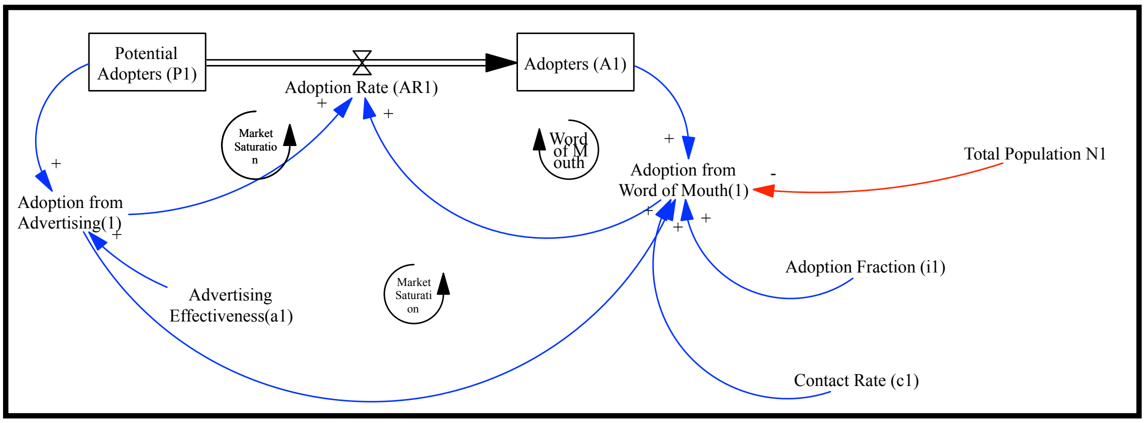
$$A_t = \frac{N-[a(N-A_0)/(a+KA_0)\exp[-(a+KA_t)(t-t_0)]}{1+[k(N-A_0)/(a+KA_0)\exp[-(a+KA_t)(t-t_0)]} \qquad (2)$$

The plot of the cumulative adopter distribution (Equation 2) results in a generalized logistic curve (sigmoid function), the shape of which is determined by both **a** and **b.**

For the analysis of the Bass Model SD, the adoption of innovations can be viewed as epidemics spreading by positive feedback as those which have adopted the innovation (prior adopters) "infected" those who have not (potential adopters). Once the population of potential adopters has been depleted, the adoption rate falls to zero. The Bass Model includes also an external source of adoption, usually interpreted as the effect of advertising and other external influences. These two sources of adoption are assumed to be independent. Thus, the total adoption rate is the sum of adoptions resulting from advertisement and any other external influence (Sterman, 2000).

The original model, developed by Sterman(2000), has 2(two) state variables: Potential Adopters and Adopters. However, because P = A + N, only one of these stocks are independent, and the model is actually first order (Figure 1).

Figure 1 - Analysis of Bass Model SD



Source : Sterman, 2000.

The arrangement of terms resulting from the analysis of the Bass Model SD (Figure 1), such as described by Sterman (2000), can be expressed more compactly as:

$$AR = aP + ciPA/N \tag{3}$$

where:

i is the adoption fraction and correspond to the proportion of contacts that are sufficiently persuasive to induce the potential adopter to adopt the innovation;

a is the advertising effectiveness that is a fraction of the adoption rate due to advertising (l/time period) and corresponds to the influence external coefficient in Equation (1);

c is the contact rate between (prior) adopters (A) and potential adopters (P);

ci corresponds to the coefficient of diffusion K in equation (1);

P are the potential adopters; and

A are the (prior) adopters.

Assuming N is a constant, then:

$$N = P + A \tag{4}$$

Even though the reinforcing feedback loop "Word of Mouth" dominates after an early growth phase, the first adopters are induced through advertisement. The "conversion" from potential adopter into adopter is generated through the number of contacts between adopters and potential adopters and the probability that a contact is successful in attracting a new adopter. The number of adopters compared to the Total Population, where the innovation takes place, dilutes this effect. As the number of adopter increases, the number of potential adopter decreases and the balancing feedback loop "Market Saturation" takes control. "Market Saturation" feedback loop reduces gradually the growth rate until there are no more potential adopters (Kunc, 2011).

Social Network Analysis - SNA is a technique used to understand the pattern of interpersonal communication in a social system by determining who talks to whom.

Classical diffusion of innovation models such as Bass Model and SNA has complemented each approach for over 50 years. Diffusion of innovation research has been greatly enhanced by SNA because it allows for a more precise specification of who influences whom during the diffusion process. SNA has benefited from diffusion research by providing a real-world application to compare and clarify network models.

In the adoption of innovations, decisions often entail some risk, or decision making under uncertainty. The presence of risk and uncertainty during the diffusion of an innovation means that individuals are more likely to rely on the behavior of immediate others (peers) rather than on some perception as to what the social norm is. That is, risk and uncertainty force individuals to turn to their peers to gain more information and reassurance about decisions of potential adoption (Valente, 1999).

This assumption seems to us perfectly adapted to our social system. In fact, in the market of marine oil spills monitoring by spaceborne SAR sensors, it seems reasonable to assume that the decisions of companies and government agencies are taken based on observed behavior and the information provided by their peers. Thus, it is likely that networks play a larger role in the diffusion on innovations in this specific market.

4. The Hybrid Model

The Hybrid Model is an analytical tool focus on explaining the diffusion of innovation A_1 in the global market of marine oil spills SAR monitoring: Bass Model extensions and Network Diffusion Model.

A previous step to modeling is innovation classification. Innovations are neither introduced into a vacuum nor do they exist in isolation. Other innovations exist in the social system and may have an influence, positive or negative, on the diffusion of an innovation.

Mahajan and Peterson (1985) have identified four categories of innovation interrelationships that can affect the adoption rate. Innovations may be: (a) *independent* - innovations are independent of each other in a functional sense, but adoption of one may enhance adoption of others (e.g., microelectronics and small satellites); (b) *complementary* - increased adoptions of one innovation result in increased adoption of other innovation (e.g. small satellites and constellations of small satellites); (c) *contingent* - adoption of one innovation (e.g. remote sensing small satellites) is conditional on adoption of other innovations (e.g. high resolution remote sensing small instruments that can be deployed on small satellite platforms); and (d) *substitutes* - increased adoption of one innovation result in decreased adoption of other innovations (e.g. constellations of small SAR satellites *versus* large SAR satellites).

Using data on Table 2, it's possible to say that the constellations of small SAR satellites should be classified as a substitute innovation of large SAR satellites. Relative advantages, as global coverage and high revisit rates of target areas, associated with reduced costs of development and launch, make this a very attractive option in terms of cost/ performance. However, we must do some caveats as follows.

Hybrid satellite constellations using multiple layers of LEO small and large satellites can be designed to meet the emerging remote sensing market. In this case, A_1 and A_2 should be better classified as independent innovations. Another possible scenario is that large SAR satellites will continue to be developed to meet the high expectations of government agencies of space-faring nations, in parallel with the development of constellations of small SAR satellites, by space agencies of developing countries, as a way to get autonomous access to space and develop its own remote sensing capacity. Some oil companies may also be interested in constellations of small SAR satellites provided to meet their specific needs. In this scenario, there would be no substitution, but temporal coexistence of two technological innovations, each one in its specific market.

4.1 Extending the Bass Model

Mathematical models do not support heterogeneous populations such as government agencies and oil companies. Additionally, the parameters **a** and **K** may not be calculated from historical data or time series, leaving us the subjective evaluation of external and internal factors that may influence the diffusion of innovation A_1, which in turn, inevitably leads to a line of "soft modeling", in which models do not work as a representation of the real world, but rather as a way to generate debates and views on the real world. Thus, the SD modeling approach seems to be the best choice for exploring the dynamical behavior of this social system.

Before applying SD modeling tools, let’s try to extend the Bass Model to explain the diffusion of emerging technology A_1 (Constellations of Small SAR satellites) in the global market of marine oil spills monitoring by spaceborne SAR sensors. The proposed extensions are described below.

4.1.1. Extending the Bass Model to express the substitution relationship between A_1 and A_2.

For the purpose of this paper, let’s suppose there is a substitution relationship between A_1 and A_2, vying to become market leader, in a market with size **N,** where **N** is a constant. Thus, the first Bass Model extension is designed to represent the first category of innovation interrelationship - the substitution relationship between emerging technology A_1 (Constellations of Small SAR Satellites) and mature technology A_2 (Large SAR Satellites) - by the following diffusion rate equations: (Mahajan and Peterson, 1985).

$$\frac{dA_1(t)}{dt} = (a_1 + K_1 A_1(t) - c_1 A_2(t)) - [N_1 - A_1(t)] \qquad (5)$$

$$\frac{dA_2(t)}{dt} = (a_2 + K_2 A_2(t) - c_2 A_1(t)) - [N_2 - A_2(t)] \qquad (6)$$

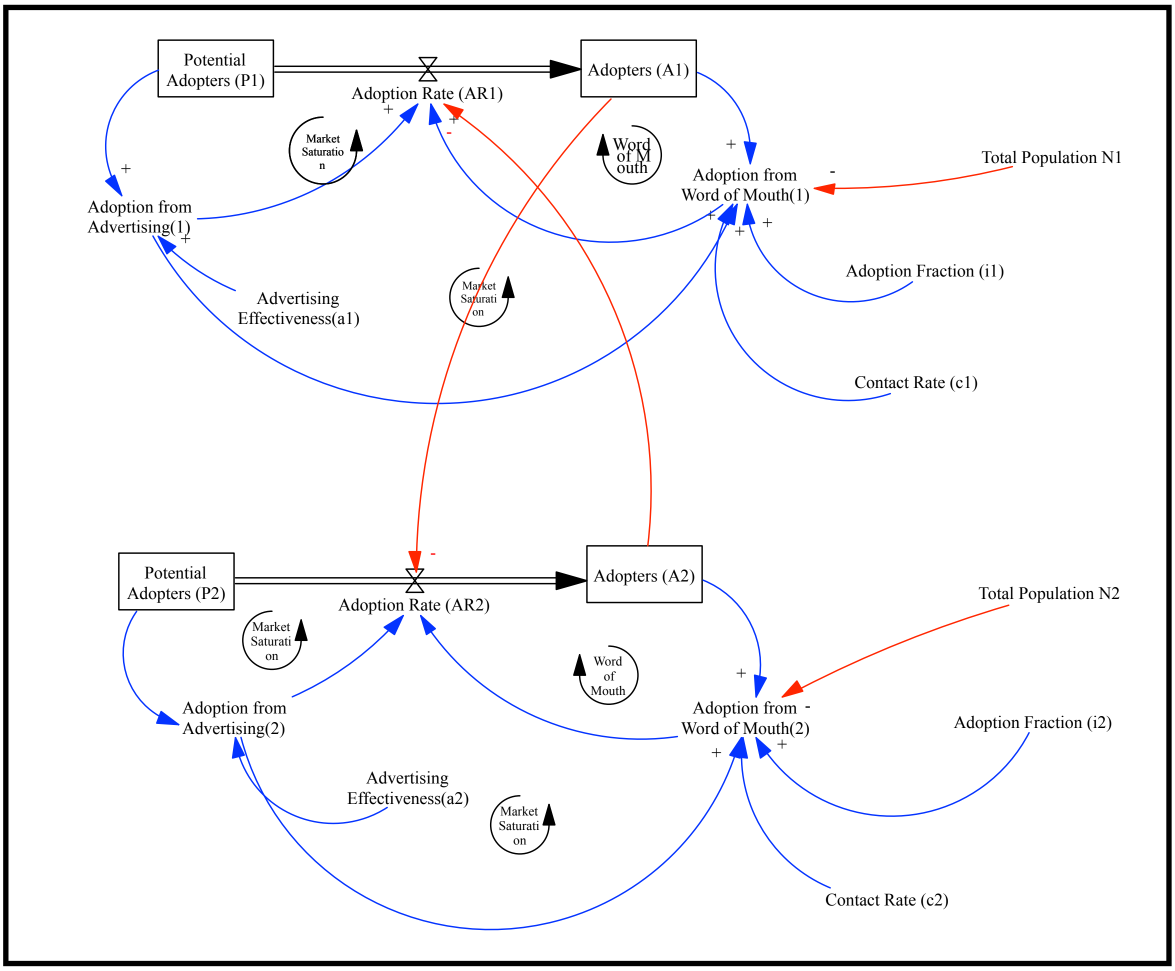
In Equations (5) and (6), $\mathbf{c_1}$ and $\mathbf{c_2}$ represented the hypothesized substitution effect of the technologies on each other (MAHAJAN and PETERSON, 1985). Equation (5) can be rewritten as:

$$\frac{dA_1(t)}{dt} = a_1[N_1 - A_1(t)] + k_1A_1(t)[N_1 - A_1(t)] - c_1A_2(t)[N_1 - A_1(t)] \tag{7}$$

The term in equation (7) that contains the constant $\mathbf{c_1}$ represents an interaction between the adopters of A_2 and non- adopters of A_1 which results in a decrease in the rate of diffusion for emerging technology A_1. Equation (6) can be also rewritten as:

$$\frac{dA_2(t)}{dt} = a_2[N_2 - A_2(t)] + k_2A_2(t)[N_2 - A_2(t)] - c_2A_1(t)[N_2 - A_2(t)] \tag{8}$$

Figure 2 - The Bass Model SD expressing the substitution between A1 and A2.



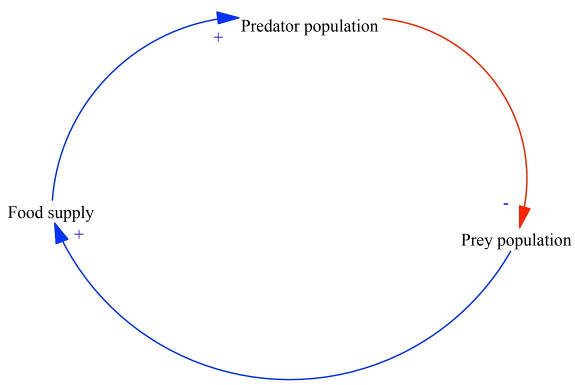
Source: Adapted from Sterman, 2000.

In Equations (7) and (8), $\mathbf{c}_1$ and $\mathbf{c}_2$ represented the hypothesized substitution effect of the technologies on each other. Similarly, these differential equations can be viewed as an extended SD Bass Model (Figure 2) with 2 populations and 4 state variables. Because P1 = A1 + N1, and P2 = A2 + N2, only two of these stocks are independent.

If the signs of c_1 and c_2 are negative, both technologies have negative impact on one another, and due to the large market level of mature technology, the emerging technology never gets the chance to diffuse in the market.

However, if the sign of c_1 is positive and the sign of c_2 is negative, the emerging technology (A_1) will benefit from the existence of mature technology (A_2). Under these circumstances, one can state that there's a predator-prey relation among these technologies and that the model will reach an equilibrium condition in which both technologies coexist in the same market. The dynamics of predator and prey populations have an oscillatory behavior due to the presence of strong counteracting feedback loop that forces the system to oscillate around a set of conditions. This feedback mechanism is illustrated in Figure 3 (Ahmadian, 2008).

Figure 3. Counteracting Feedback loop in the Predator-Prey System



Source: Ahmadian(2008)

According to Ahmadian (2008) technical artifacts and infrastructures are factors which affect the market potential of a technology. For example if there is a common artifact used in production of both mature technologies and emerging technology, emerging technology can benefit from the presence of those artifacts. In this case, the mature technology has a positive effect on the emerging technology which makes the interaction predator-prey interaction.

To study the real dynamics between the two technologies A1 and A2, it will be necessary to pin point what factors can influence the growth and diffusion of an emerging technology in our specific market. Table 2 shows a first evaluation of these factors.

4.1.2. Extending the Bass Model to express that a potential adopter population continuously in flux is to be expected for a single technology (A_1)

As mentioned before, the Bass model assumes that the ceiling on the number of potential adopters in a social system, (N-A_t), is fixed at the time an technology innovation is introduced and remains constant over the diffusion process. Obviously such an assumption is not tenable with regard theory or practice. From a theoretical perspective, there is no rationale for a static potential adopter population. In practice, we found that the market size for oil spills monitoring is increasing. New potential adopters, such as government agencies of developing countries and oil companies, are becoming more interested in oil spills monitoring by spaceborne SAR sensors.

In response to this kind of situation, Mahajan and Peterson (1985) proposed extending the Bass Model to express that a potential adopter population continuously in flux is to be expected. In this extended model, N is permitted to vary over time:

$$N(t) = f(S(t)) \tag{9}$$

Thus, if f(S(t)) is substituted for **N** in equation (1), a dynamic Bass Model results:

$$\frac{dA(t)}{dt} = (a + KA_t)[f(S(t)) - A_t) \tag{10}$$

The solution of equation (11) is:

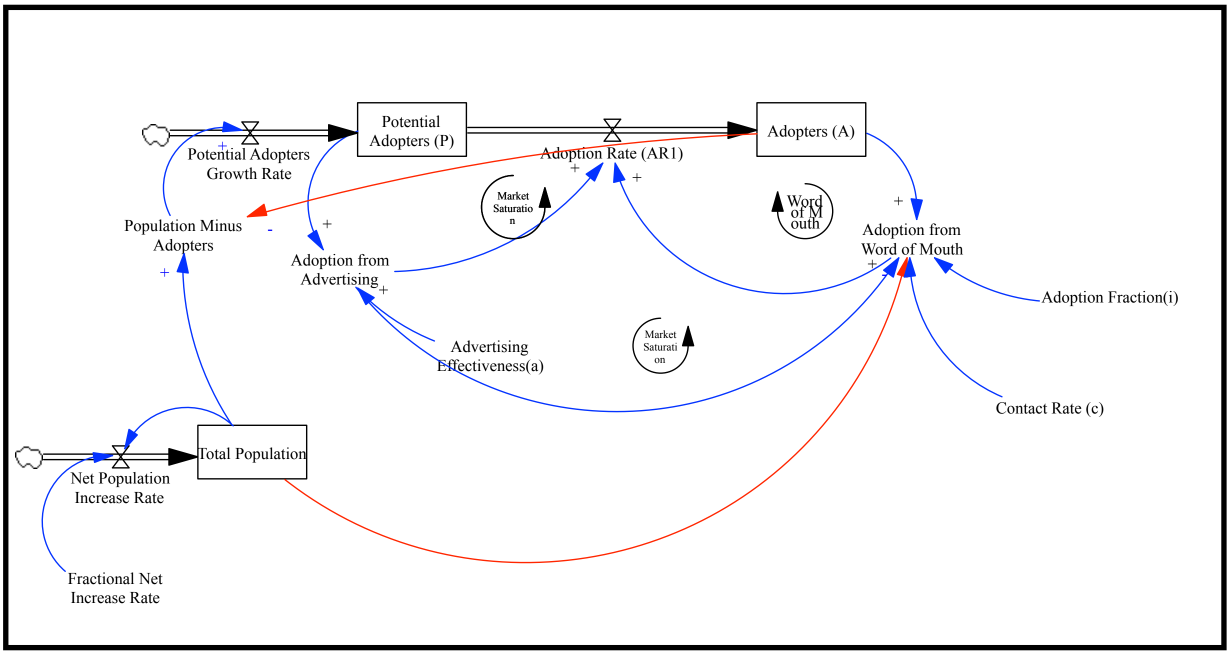
$$A_t = -\frac{a}{k} + \frac{\exp\{a(t-t_0) + K\phi(t)\}}{(\dfrac{k}{a+KA_0}) + k\displaystyle\int_{t_0}^{t} \exp\{a(x-t_0) + K\phi(x)\}\,dx} \tag{11}$$

where $A(t{=}t_0){=}\ A_0$ and

$$\phi(t) = \int_{t_0}^{t} f(S(x))\,dx \tag{12}$$

An equivalent SD model, also proposed by Sterman (2000), assumes that the total population size is a stock increased by a Net Population Increase Rate that aggregates births, deaths, and net migration. The Net Population Increase Rate is given by the total population and the Fractional Net Increase Rate, which can be assumed constant (Figure 4).

Figure 4 - The Bass Model SD incorporating growth in the size of total market



Source: Adapted from Sterman, 2000

Assuming that all increases in population size add to the pool of potential adopters, the potential adopter population can be written as P = N - A. Even though the potential adopter population is a stock, it is fully determined by the total population and adopter population.

4.1.3. Estimation of the parameters, a, K, and N, for a single technology (A_1)

Starting from the equations (7) and (8) for A_1 and A_2, let's estimate its parameters. Because the Bass Model is essentially a 3-parameter model (a, K, and N), parameter estimation requires time-series data on the number of adoptions in a minimum of three time periods. Parameters can be also estimated by means of certain innovation-specific analogues. According to Mahajan and Peterson (1985), estimation begins by rewriting the Bass Model in terms of its discrete analogue:

$$A(t+1) - A(t) = aN + (KN - a)A(t) - bA^2(t)$$

$$= A_1 + A_2 A(t) + A_3 A^2(t) + e(t) \tag{13}$$

The "A terms" can then be evaluated numerically by means of ordinary least squares regression analysis and **a**, **K**, and **N**:

$$A_1 = aN \tag{14}$$

$$A_3 = -b \tag{15}$$

$$N = \frac{-A_2}{2A_3} \pm \sqrt{A_2^2 - 4A_1A_3} \tag{16}$$

In the absence of historical or time-series data, parameters can be estimated by means of certain innovation-specific analogues or expert judgments. Using estimated values it's possible to simulate the dynamical behavior of our specific market.

4.2. Network Models of the Diffusion of Innovations

Studies on the diffusion of innovations on networks usually start from the questionnaires, through which respondents must provide details of their interaction with others. Using these data, it is possible to reconstruct the network in which vertices represent individuals and links represent interactions. Usually, questionnaires address issues of centrality (which individuals are more connected to others and which have most influence) and connectivity (whether and how individuals are connected to others through the network).

Network centrality is the degree that the links in a graph are concentrated in one or a group of individuals. A centralized network contains a few members who are the locus of contacts, whereas a decentralized network has the connections spread among many members in the network. Centralized networks have faster diffusion because once the innovations are adopted by a central member of members, it is more rapidly spread to the rest of the system. In a decentralized network, it takes longer for the innovation to reach everyone in the network. However, in situations of greater risk/uncertainty, with slower diffusion, when the perceived advantageousness of the innovation is in question, centrality impedes diffusion (Valente, 1995).

Centrality refers to an individual vertex and is defined by the *in-degree* of a vertex divided by (N-1). *In-degree* measures how many edges are incident on a vertex. *Centralization* characterizes the entire networks and captures the inequality on the distribution of centrality (Valente, 1995).To calculate the *centralization*, we can use the Freeman's general formula:

$$C_D = \frac{\sum_{i=1}^{g} [C_D(n^*) - C_D(i)]}{[(N-1)(N-2)]} \tag{17}$$

where:

$C_D(n*)$ = maximum value of centralization in the network;

$C_D(i)$ = centrality of a particular node, and

N = number of vertices or nodes.

Betweenness Centrality measures the degree an individual lies between other individuals on their paths to one another. A high *Betweenness Centrality* indicates that individuals acts an intermediary between many others in the network. To calculate the *Betweenness Centrality* we use:

$$C_B(i) = \sum_{j<k} g_{jk}(i) / g_{jk} \tag{18}$$

where:

g_{jk} = the number of the shortest paths connecting **j** and **k**;

g_{jk} (i) = the number that actor *i* is on.

Usually normalized by:

$$C_B(i) = C_B(i) / [(n-1)(n-2)/2] \tag{19}$$

Finally, *Closeness Centrality* is the extent an individual is near other individuals in the network. Thus, closeness centrality individuals act as rapid conduits for an innovation because they are able to rapidly spread information and influence concerning the innovation to numerous others. (Valente, 1995).

Closeness Centrality is based on the length of the average shortest path between a vertex (or node) and all vertices in the graph:

$$C_c(i) = [\sum_{j=1}^{N} d(i,j)]^{-1} \tag{20}$$

where:

d(i,j) = is the number of ties in the geodesic between i and j. Usually normalized by:

$$C_c(i) = (C_c(i)) / (N-1) \tag{21}$$

There are countless software tools for SNA. GEPHI platform allows visualization and basic network metrics calculation. NETLOGO may be useful in understanding the basic properties of dynamic processes on networks, including diffusion. iGraph is for programming. There is a SNA package for “R”, a statistical programming language. PAJEK is a free software that allows network analysis and visualization. There are many other platforms not mentioned here.

5. Conclusions

The previous Section presented an hybrid model - a combination of Bass Model extensions and SNA Model – for exploring the diffusion of the constellations of small SAR satellites, in the specific market of marine oil spills monitoring by spaceborne SAR. In order to meet this goal, we have selected, in Section 4, three Bass Model extensions and some essential network metrics. The hybrid model has not been implemented yet, because parameters calculation depends on field research. The future hybrid model implementation should follow these steps:

(a) Bass Model Implementation:

- 4.1.1 and 4.1.2 Bass Model extensions;
- Parameters (a, K, and N) estimation in 4.1.2. using time-series data on the number of the adoptions in a minimum of three times periods as described in 4.1.3. In the absence of time-series data, parameters can be estimated by means of certain innovation-specific analogues or expert judgments. (This is a more realistic option, given that the emergent technology A_1 is being developed); and
- Use of computational tools to simulate different scenarios on innovation diffusion.

(b) Network Diffusion Model Implementation:

- Application of questionnaires, through which respondents must provide some details of their interaction with others, in order to calculate network metrics;
- Visualization of the network and network metrics calculation using software tools (e.g. GEPHI); and
- Inferences about the diffusion process on network, using software models(e.g. NETLOGO models).

Acknowledgements:

We would like to thank Professors Ricardo Matos Chaim and Rita de Cássia Silva for their comments and suggestions, and the other members of UnB Gama Faculty of Engineering for the support and friendship provided throughout this work.

References

Ahmadian A. 2008. System dynamics and technological innovation system: Models of multi-technology substitution processes. Master of Science Thesis. ESA Report nº 2008: 15, Chalmers University of Technology. Göteborg, Sweden Retrieved July 20, 2014, from http://publications.lib.chalmers.se/records/fulltext/74728.pdf/

Astrium Services. 2014. TerraSAR-X Radar Satellite Imagery. Retrieved July 20, 2014, from http://www.astrium-geo.com/terrasar-x/

Anderson P. 1999. Complexity Theory and Organization Science. *Organization Science* **10**(3): 216-232 Special Issue: Application of Complexity Theory to Organization Science. Retrieved July 20, 2014, from http://www.jstor.org/stable/2640328/

Angelucci M. and Giampaolo D. 2012. COSMO SKYMed e-GEOS Supports Development of Innovative Services. *13th IICWG (International Ice. Charting Working Group), Tromsø, Norway, October 15-19, 2012*. Retrieved July 20, 2014 from https://nsidc.org/noaa/iicwg/presentations/IICWG-2012/Angelucci_COSMO_SkyMed_e-GEOS.pdf/

Baker AM, Davies P, and Boland L. 2010. Moving Towards Commercial Earth Observations Services with Small Satellite Constellations. In Sandau, R; Roeser, HP; Valenzuela, Arnoldo (Eds). *Small Satellites for Earth Observation: Selected Contributions.* XXII, 406 p, Springer.

Canadian Space Agency (CSA). 2014. The RADARSAT Constellation. Retrieved July 20, 2014, from http://www.asc-csa.gc.ca/eng/satellites/radarsat/

Chan YK, and Koo VC. 2008. An Introduction to Synthetic Aperture RADAR (SAR). *Progress In Electromagnetics Research B* **2**: 27–60. Retrieved July 20, 2014, from http://www.jpier.org/PIERB/pierb02/03.07110101.pdf/

Euroconsult. 2012. Opportunities in Earth Observation Satellite Services: Lessons of the Past for the Future. *Industry Symposium. 49th Scientific&Technical Subcommittee*

COPUOS. OSSA, Vienna, February 13. Retrieved July 20, 2014, from http://www.oosa.unvienna.org/pdf/pres/stsc2012/2012ind-02E.pdf/

Holland JH. 2006. Studying Complex Adaptive Systems. *Jrl Syst Sci & Complexity* **19**: 1–8. Retrieved July 20, 2014, from http://deepblue.lib.umich.edu/bitstream/handle/2027.42/41486/11424_2006_article_1.pdf?sequence=1

Honstvet I, Encke I, Hall D, and Munro Y. 2007. ASTROSAR-Lite. *Anais XIII Simpósio Brasileiro de Sensoriamento Remoto, Florianópolis, Brasil (21-26 abril),* INPE, p. 4907-4913. Retrieved July 20, 2014, from http://www.jpier.org/PIERB/pierb02/03.07110101.pdf/

Kimura T, Fujimura T, and Ono K. 2011. Small SAR Satellite Technology Promotes Dissemination of a Comprehensive Space Utilization System. *NEC Technical Journal,* **6**(1). Retrieved July 20, 2014, from http://www.nec.com/en/global/techrep/journal/g11/n01/pdf/110115.pdf/

Kunc M. 2011. Systems Dynamics and Innovation: A complex problem with multiple levels of analysis. Warwick Business School. Coventry, UK. Retrieved July 20, 2014, from https://www.theorsociety.com/Media/Documents/Users/CaraQuinton01011978/OriginalDocument/13_09_2011-09_57_13.pdf/

Li Z, Bao Z, Wang H, and Liao G. 2006. Performance Improvement for Constellation SAR using Signal Processing Techniques. *IEEE Transactions on Aerospace and Electronic Systems* **42**(2). Retrieved July 20, 2014, from http://www.geo.uzh.ch/microsite/rsl-documents/research/SARlab/GMTILiterature/PDF/LBWL06.pdf/

Lima SC, Landau L, and Miranda FP. 2011. Utilização de imagens SAR orbitais para a detecção de exsudações de óleo na porção offshore da Bacia de Camamu- Almada. *Anais XV Simpósio Brasileiro de Sensoriamento Remoto-SBSR, Curitiba, PR, Brasil,* (30 de abril a 05 de maio), INPE, p. 3618. Retrieved July 20, 2014, from http://www.dsr.inpe.br/sbsr2011/files/p0579.pdf/

Miranda FP, Marmol AMQ, Pedroso EC, Beisl CH, Welgan P, e Morales, LM. 2004. Analysis of RADARSAT-1 data for offshore monitoring activities in the Cantarell Complex, Gulf of Mexico, using the unsupervised semivariogram textural classifier (USTC). *Canadian Journal of Remote Sensing,* **30**(3): 424-436. Retrieved July 20, 2014, from http://pubs.casi.ca/doi/abs/10.5589/m04-019/

Mahajan V, and Peterson RA. 1995. Models for Innovation Diffusion. *Series: Quantitative Applications in the Social Sciences*. Sage Publications.

Mondéjar AG. 2009. Feasibility Study on SAR Systems on Small Satellites, Barcelona, (January). Retrieved July 20, 2014, from https://upcommons.upc.edu/pfc/bitstream/2099.1/6631/1/Final.pdf/

Page SE, and Miller JH. 2007. Complex Adaptive Systems: an Introduction to Computacional Models of Social Life. Princeton University Press.

Rodrigues DF. 2011. Obtenção de Campos de Vento na Superfície do Mar no Golfo do México a partir de imagens de Radar de Abertura Sintética (SAR). Dissertação de Mestrado apresentada à COPPE, Universidade Federal do Rio de Janeiro.

Rogers EM, Medina UE, Rivera MA, Wiley CJ. 2005. Complex Adaptive Systems and The Diffusion of Innovations. *The Innovation Journal: The Public Sector Innovation Journal*, **10**(3).

Surrey Satellite Tecnology - SSTL Ltd. 2013. NovaSAR-S Brochure: The Small Satellite Approach to Synthetic Aperture Radar. Retrieved July 20, 2014, from http://www.sstl.co.uk/Downloads/SSTL-Brochure-pdfs/SSTL-NovaSAR-Brochure-2013/

Sandau R. 2010. Status and trends of small satellite missions for Earth Observation. Acta Astronautica **66:** 1-12.

Sandau R. and Briess K. 2008. Potential for Advancements in Remote Sensing Using Small Satellites. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol XXXVII, Part B1, Beijing.

Souza DL. 2006. Sistema Inteligente para Detecção de Manchas de Óleo na Superfície Marinha através de Imagens SAR. Dissertação de Mestrado. Programa de Pós-Graduação em Engenharia Elétrica, Centro de Tecnologia, Universidade Federal do Rio Grande do Norte.

Sterman JD. 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill, Boston.

Sweeting M. 2012. Small Satellites quo vadis? AIAA Space 2012, Pasadena, California. Retrieved July 20, 2014, from https://www.aiaa.org/uploadedFiles/About-AIAA/Press-Room/Key_Speeches-Reports-and-Presentations/2012/Sweeting_Thurs%20_PM.pdf/

Valente TW. 1999. Network Models of the Diffusion of Innovations. The Hampton Press Communication Series.

Vishwanath, A, and Barnett GA. 2011. The Diffusion of Innovations: A Communication Science Perspective. Peter Lang Publishing Inc, New York.