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Tsunami of Smallsat Mega-Constellations: C2 implications

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Abstract:

Command & Control (C2) is crucially dependent on the underlying communications infrastructure. This infrastructure may be wired and/or wireless, but until the opening of the space age it was exclusively terrestrial. Communication satellites in geostationary orbit revolutionised long-distance strategic communication, but have limited bandwidth, long latency times, and require bulky and expensive user terminals.

In the coming five to ten years, several commercial organisations will be launching mega-constellations consisting of hundreds or thousands of small satellites in low earth orbit. While some of these mega-constellations are aimed at earth observation, navigation and positioning, and meterology, the great majority will provide global broadband communications to low-cost user terminals and IoT devices. For example, OneWeb won FCC approval in June 2017 to operate 720 smallsats in K_u band, with an option to add another 1980 satellites. In a second FCC filing, they propose a 2560-satellite constellation using V-band. SpaceX is seeking authorisation to operate their Starlink constellation of 4425 broadband satellites using K_a and K_u bands. Other constellations are planned by ViaSat, Boeing, LeoSat, O3b Networks, and Theia Holdings. This concept paper considers the implications of this imminent "tsunami of smallsats" for C2 in military and emergency management operations.

1. Introduction

Command & Control (C2) is crucially dependent on the underlying communications infrastructure. This infrastructure may be wired and/or wireless, but if it is absent then C2 is severely restricted, if not impossible. This absence may have a natural cause, as when terrain, buildings, foliage, or adverse atmospheric conditions hinder line-of-sight communication links. The cause may be technical, as when sending or receiving equipment fails, or background radio noise or ionospheric conditions make long-distance links unusable. The cause may also be man-made, as when opposing forces destroy equipment or jam communication links.

The opening of the Space Age in 1957 made it possible to mitigate many of these threats. By placing a communications satellite (comsat) in orbit, intervening terrestrial obstacles can often be avoided. Atmospheric effects may be reduced, because the length of the link affected by rain, haze, or smoke is often shorter vertically than horizontally. However, the threats to ground-based and sea- and airborne terminals are unchanged. Although the satellite represents an additional source of risk, its remoteness should reduce the threat compared to similar communications facilities on or near the Earth's surface.

From the outset, the ideal location for using satellites to relay communications was regarded as being the Geostationary Earth Orbit (GEO), 35786 kilometres above the Earth's surface at the equator. While Arthur C. Clarke's (1945) *Wireless World* article contributed to the popularity of GEO, Hermann Oberth had already described the concept in 1923. Locating a satellite at GEO provides the widest area on the Earth's surface that can be reached by the downlink, with just three satellites needed for global coverage[1]. Moreover, because a GEO satellite "hovers" over the Earth's surface, ground-based antennae do not need to point so precisely at their target.

Comsats in GEO have revolutionized long-distance communications, although undersea cables have made a come-back for voice communications. Military use was strategic at first, but demand for tactical use of satellite communication has grown since the 1990-1 Gulf War. With the exception of a few technology demonstrators, military comsats are overwhelmingly large, complex satellites located at GEO. While the USA, Russia, China, and India have demonstrated the capability of shooting down satellites up to 865 kilometres above the Earth's surface, GEO satellites are as yet invulnerable to physical destruction. They may be jammed or hacked, and their optical sensors can be dazzled using lasers.

The disadvantages of GEO are that sending a signal requires more power, making the antenna larger and more expensive. The trip to GEO and back adds a half-second delay (a.k.a. latency) to the transmission time. While this does not matter for broadcasting (e.g. TV), it hinders voice communications. Many online services also work poorly over a connection with long latency times. In particular, this delay "is detrimental to the financial and gaming industries, as well as others where quick, delay-free actions are required" (MarketWatch, 2019). C2 fits the latter description.

[1] Ignoring the less-populated polar regions.

In the coming five to ten years, several commercial organisations plan to launch constellations consisting of hundreds or thousands of small satellites (smallsats) in low earth orbit (AWST, 2018c). Smallsats have a low launch mass, usually regarded as being below 500 kilograms. Miniaturizing satellites reduces cost, both in manufacturing them and for launching them. Multiple smallsats can be launched on the same rocket, reducing launch costs further. This in turn encourages designing smallsats to operate together in formation or as a constellation, a form familiar from the Global Positioning System (GPS; see Figure 1). A constellation consisting of hundreds or thousands of satellites is known as a mega-constellation.

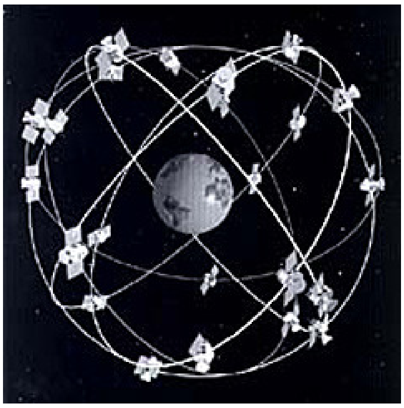

Figure 1. GPS constellation of 24 satellites distributed equally over six planes.

While some of the proposed mega-constellations are aimed at earth observation, navigation and positioning, and meteorology, the majority will provide global broadband communications to low-cost user terminals and IoT devices. For example, OneWeb won FCC approval in June 2017 to operate 720 smallsats (now reduced to 648) in K_u band, with an option to add another 1980 satellites. In a second FCC filing, they propose a 2560-satellite constellation using V-band. SpaceX is seeking authorisation to operate a constellation of 4425 broadband satellites using K_a and K_u bands. Other constellations are planned by ViaSat, Boeing, LeoSat, O3b Networks, and Theia Holdings, amongst others. Bryce Space & Technology[2] lists 32 communications constellations (13529 smallsats) and 34 Earth observation constellations (1407 smallsats) proposed for launch to Low Earth Orbit (LEO) in the coming ten years (AWST, 2019c). The total number of smallsats proposed is substantially more than all the satellites that have been launched since the start of the Space Age.

This concept paper contends that the forthcoming "tsunami of smallsats" (AWST, 2018a) will have dramatic implications for C2 in military and emergency management (EM) operations. The paper focuses on telecommunication smallsat constellations offering broadband Internet and Internet of Things (IoT) services from LEO. We will term these "comsat constellations". Broadband Internet access will become available worldwide in five to ten years to any member of the public (including C2 users themselves) with any Internet-capable device and a small (pizza-sized, US$200) user terminal. Latency will be decreased to 25 to 35 milli-seconds, and bandwidth will be increased to up to 10 gigabits per second, 10 times as fast as that of a fibre-optic Internet connection (MarketWatch, 2019). The large numbers of comsats in each constellation will offer resilience to kinetic attack and

[2] See https://brycetech.com/ (accessed 5 June 2019).

the diversity of constellations will provide some resistance to cyber attack. For users, Internet access will be available anywhere, anytime, even when terrestrial infrastructure has been destroyed.

The purpose of this paper is to predict the implications for C2. The paper is structured into five sections, plus references. After this introductory section, the second section outlines the known characteristics of the currently proposed LEO comsat constellations offering broadband Internet and IoT services. The third section segments the C2 "market", and analyzes each segment's need for information exchange and preferred communications media. The C2 implications are assessed in the fourth section, and conclusions are drawn in the fifth section.

2. LEO Comsat Constellations

2.1 Active satellites up to 2019

The United Nations Office for Outer Space Affairs (UNOOSA) maintains an Index of objects launched into outer space. According to UNOOSA, a total of 8378 objects had been launched since 1957, of which 4987 were still orbiting the Earth as at the start of 2019 (Pixalytics, 2019). In their most recent annual analysis of the UNOOSA index, the Union of Concerned Scientists (UCS) found that 1957 of these Earth-orbiting objects were still active on 30 November 2018 (UCS, 2019)[3]. Of these 1957 active satellites, the main purpose was communications for 777 (UCS, 2019). The military used 422 satellites, but this was outnumbered by 848 commercial satellites. There were 558 satellites at GEO, but this was dwarfed in number by 1232 LEO satellites.

The number of satellites is growing roughly exponentially. UCS (2019) has been maintaining its database for about 13 years. It took half of this time to grow from 800 to 1000 active satellites, but in the second 6½ years the total almost doubled. Much of the increase in number comes from the introduction of small satellites from 2013 onwards. There were 21 satellites on 1 January 2012 with a reported launch mass of 10 kilograms or less. By 30 November 2018, this number had grown to 470 satellites, representing roughly a quarter of all active satellites.

2.2 Comsat constellations proposed

In the late 1990s, three companies – Teledesic, Iridium, and Globalstar – invested heavily in Internet service from LEO. However, the technology of the time meant that service was very costly. In particular, special handsets were needed. Only Iridium survived, by redirecting its services to providing satellite telephony to aircraft, ships, and corporate employees in remote areas (e.g. exploring for oil).

Several advances in technology have since made it possible for companies to try providing Internet services from LEO again. The most important of these advances are as follows:

- *Miniaturization of satellites*. Smallsats can be made for a few hundred thousand dollars, instead of tens or hundreds of millions.

[3] A further 72 satellites were launched in December 2018.

- *Reduction in launch costs*. The advent of commercial space launch providers, such as SpaceX, have brought down the cost of launching a rocket to LEO by one or two orders of magnitude. Combined with satellite miniaturization, this enables 20 to 60 smallsats to be launched on one rocket.

- *Electronically-scanned phased-array antennae*. Fixed antennae can be used to send and receive signals from GEO satellites. However, LEO satellites move across the sky and may only be visible for ten minutes, before the antenna must be redirected to point at the next satellite. Moving the antenna mechanically leads to a heavy design, which is costly and will eventually wear out. Phased arrays enable the beam to scan across the sky electronically, without physical movement of the antenna. Not only can the beam be moved more quickly, there is no heavy mechanism to supply physical movement. This means that phased-array antennae can be made smaller, lighter, and more cheaply, both in the satellite and in the ground-based user terminals. In particular, businesses, homes, and vehicles can be fitted with their own user terminal.

- *IoT*. In the late 1990s, it was assumed that the users wishing to communicate were people. Since then, IoT devices have been introduced that also need to connect to the Internet to send and receive messages. The number of such devices now exceeds the number of Internet-connected people. This means that the market for comsat constellations is larger, bringing with it economies of scale.

Starting from the Bryce Space & Technology list published in Aviation Week & Space Technology on 2 May 2019 (AWST, 2019c), we gathered together key parameters for all constellations with 100 or more smallsats. Additional information was obtained from the NewSpace index of constellations[4], Wikipedia and manufacturer's webpages, AWST articles, and other publications. The key parameters include the name of the constellation, its nationality, the approved number of smallsats in the constellation (with possible future additions in brackets), the launch date and in brackets number of smallsats currently in orbit, the service provided (broadband Internet or IoT), whether its is funded, the frequency band used, the size of a smallsat (in kilograms), and whether or not the constellation will have inter-satellite links (ISL). However, much of this information is unavailable, as it is considered commercially sensitive. Where there are discrepancies between sources, it has not always been possible to identify which source is the more authoritative or recent. Some constellations withhold details for competitive reasons (e.g. Amazon's Project Kuiper (SpaceNews, 2019)). The results are shown in Table 1.

Table 1. LEO communication constellations of 100 or more smallsats.

Constellation name	Nation	Smallsats	Launch year	Services	Funded	Band	Size	ISL
SpaceX Starlink	US	4425 (7518)	2019 (60)	Internet	$1.6B	K_a, K_u & V	227 kg	Phase 2

[4] See https://www.newspace.im/ (accessed 30 May 2019).

Amazon (Project Kuiper)	US	3236			Yes			
Boeing	US	3016				K_a & V		
MCSat (Thales)	France	800 (4000)						
OneWeb	US	648 (2560)	2019 (6)	Internet	$1.7B	K_u	<150 kg	
Hongyan (CASC)	China	320	2018 (1)	Internet				
3ECOM-1	Lichtenstein	288						
Sky & Space Global	US?	200	2017 (3)	IoT	$11.5M	S		Yes
Swarm Technologies	US	157	2018 (7)	IoT				
Xingyun (CASIC)	China	156	2017 (2)	Internet & IoT				
Kepler	Canada	142	2018 (2)	IoT	$21M			
Telesat / LEO Vantage	Canada	117 (292)	2017 (2)	Internet				
Fleet	Australia	102	2018 (4)	IoT	$3.7M	L		Yes

2.2 Constellation architecture

The OneWeb, Starlink, and Telesat constellations are most widely documented in the press. Of the 22 AWST articles on LEO smallsat constellations since August 2016, there have been 14 articles on OneWeb, 12 on Starlink, and eight on Telesat. None of the other constellations appears in more than four articles, and six constellations are not documented at all. We use OneWeb and Starlink as examples of the architecture of a smallsat mega-constellation. Both constellations launched their first batch of operational smallsats earlier this year: OneWeb launched six on 27 February 2019 and Starlink launched 60 on 24 May 2019. Both constellations expect to start initial operations in 2020.

Straightforward descriptions of how LEO comsat constellations work can be found in SpaceNews (2018) and in the Economist (2018). This sub-section is adapted from the Economist's description, which is itself modelled on the OneWeb architecture.

Today's terrestrial mobile networks are formed by placing cell-phone towers at fixed locations on the ground, typically 15 kilometres apart. The signals broadcast from the towers forms cells serving mobile phones within each cell. By contrast, a comsat constellation can be viewed as an "upsidedown" mobile network, with the smallsats being functionally equivalent to the towers in a terrestrial network. Instead of being fixed, the smallsats and the 1 million square-kilometre cells that their signals form will move at 26000 kilometres per hour over the Earth's surface. Software hands over ground-based users between cells as they move into and out of range of the smallsats.

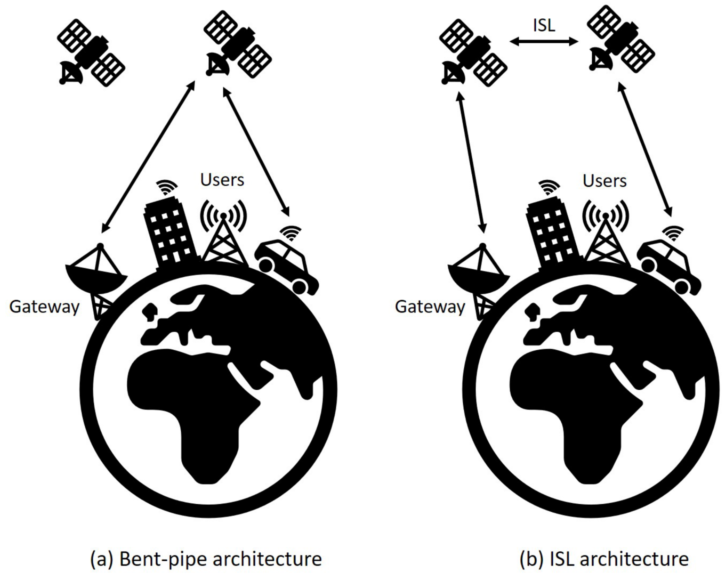

Figure 2. Constellation architectures.

In the earliest phase of most smallsat constellations, users will communicate with a smallsat, which will then relay the transmission to the Internet via a large, ground-based dish, called a gateway, as shown in Figure 2(a). This is known as a "bent-pipe" architecture, because the "pipe" connecting the user to the Internet is "bent" at the smallsat. Such an architecture limits how distant the user can be from the gateway. To mitigate this limitation, OneWeb plans to build 39 gateways around the world, with the first in Svalbard, a remote Norwegian island chain. In subsequent phases, improved smallsats will be able to communicate with one another by means of ISLs, as shown in Figure 2(b). ISLs are generally implemented using optical (laser) communications technology. When multiple hops over ISLs are possible, then users can be arbitrarily distant from the nearest gateway.

Figure 3. Prototype vehicle fitted with Kymeta's flat-panel satellite antenna (GeekWire, 2018).

Users have two ways to connect their phones, tablets, laptops, and other devices to the network. One way is to place an antenna on a terrestrial cell-phone tower, with the antenna communicating with passing smallsats. Users connect to the tower using conventional (e.g. 4G or 5G) mobile phone techniques. The other way is for the user to have an antenna (“user terminal”) fixed to his/her house, business, or vehicle; see Figure 3.

At least three companies are producing flat, electronically-steered antennae that can send and receive smallsat signals from LEO. Kymeta and Phasor will market their antennae to businesses, while Isotropic Systems have announced that they will produce antennae for consumers. OneWeb is aiming for a cost of no more than US$200 for a pizza-sized consumer user terminal.

2.3 Military use and threats

The potential use of commercial comsat constellations for military purposes has been discussed in AWST (2018b). However, as yet no comsat constellation appears to be planned specifically for military or EM use. Two military technology demonstrators are mentioned in the literature (AWST, 2019b): one for DARPA and the other for the (US) Air Force Research Laboratory. It seems that military and EM units will have to make dual use of commercial constellations for the next five to ten years at least.

As for terrestrial networks, any pre-existing towers with user terminals for connection to comsat constellations would be vulnerable to natural disasters or in a military operation to kinetic attack by opposing forces. A better scheme would be to provide all units and vehicles with user terminals, like that shown in Figure 3. In an EM operation, where there is no opposing force, it may be preferable to ship in and install replacement towers with user terminals in villages and towns. These towers would then serve communities of multiple citizens, as well as in-area NGOs. A substantial fraction of the general public may have their own user terminals in any case, because any citizen who can afford a US$200 smartphone could also afford a US$200 user terminal.

AWST (2019a) discusses the vulnerability of comsat constellations to kinetic and laser attack. While several nations have anti-satellite missiles that can reach LEO, the stock of missiles is likely to be less than the number of smallsats in a large constellation. While lasers might be particularly effective in destroying LEO smallsats quickly, they are restricted to attacking only those smallsats in view. Many laser installations widely distributed over the globe would be needed to take down a large constellation. Comsat constellations consisting of thousands of smallsats (e.g. SpaceX’s Starlink, Amazon’s Project Kuiper, and Boeing’s constellation) would need production lines to manufacture the number of smallsats needed. OneWeb’s factory produces two smallsats per day (AWST, 2019d). So a mitigating measure for kinetic or laser attack could be to carry a reserve stock of replacement smallsats and launch them on demand. Several military forces have been developing launch-on-demand capabilities over the past decade.

3. C2 User Segmentation Analysis

3.1 Segmentation model

The forthcoming comsat constellations are all commercial ventures and aimed at satisfying the telecommunication needs of the general public. In particular, they will offer broadband Internet and IoT services. At present, no plans are known to have been developed for constellations that address wider C2, military or EM needs. This implies that constellations will have differentiated effects on the communities involved in or affected by C2. Accordingly, we need to segment users into communities based on the information they wish to exchange and the media they prefer.

In the EM literature, researchers have developed a series of models for segmenting the users of communications media. Reuter, Marx, and Pipek (2011) proposed a two-segment model for the use of social media as infrastructure for crisis management. The two segments were (responding) Organizations and Citizens in the affected area. Their model is a two-by-two matrix of senders and recipients, with four types of information exchange.

Jongejan and Grant (2012) extended the Reuter et al (2011) model to three segments by decomposing Organizations into two parts based on control theory: a Controlling Process (CP) representing the commander and his/her command team, and a Process Under Control (PUC) representing the commander's assigned and attached forces in the field (or first responders in EM terminology). The resulting three-by-three matrix contains two empty cells because commanders and command teams rarely communicate directly with citizens. Instead, communications to and from citizens are routed through the forces in the field / first responders.

Independently, Manso and Manso (2012) proposed a four-segment model. Two of their segments correspond directly to Jongejan and Grant's (2012) CP – which Manso and Manso term Control Centres – and PUC – which Manso and Manso term First Responders. Their other two segments – Unaffected citizens and Victims – are a decomposition of Reuter et al's (2011) Citizens.

While promising, these segmentation models are limited in two ways. Firstly, they are drawn from the EM literature and thus lack a segment representing opposing forces. Secondly, they are limited to in-area participants. Constellations with ISLs will enable out-of-area participants to be involved. Two out-of-area communities are worth including in our model. First, family and friends have a strong need to contact unaffected citizens and victims to learn their location and status. Second, NGOs and volunteers wish to help citizens in the affected area. Volunteers may also assist the CP by extracting useful information from social media, e.g. crowdmapping reports from Twitter or Facebook. For simplicity, we regard all NGOs and volunteers as being out-of-area. In-area NGOs and volunteers can be regarded as unaffected citizens.

To sum up, the segments in our model are as follows:

- **In-area**: CP, PUC / first responders, Unaffected citizens, Victims, Opposing forces.
- **Out-of-area**: Family & friends, NGOs & volunteers.

3.2 Information sent by segment

The information exchange matrix between these segments has been constructed by considering each segment's goals. In this sub-section, the information sent and the intended recipients have been determined from these goals.

3.2.1 CP

The CP's primary goal is to achieve its mission by imposing its will on the opposing forces, while minimizing the number of victims created. It achieves the mission through action taken by its PUC.

The flow of information sent by the CP is shown in Figure 4. The primary intended recipients are the units within its PUC. The information sent can be requests for information from PUC units or (operation) orders issued to the PUC.

Since the CP is most likely embedded in a hierarchical (civil or military) organization, it will send (situation) reports (SITREPs) to the CP at the next higher level in the hierarchy. In a complex endeavour or network-centric operations, there will be other peer CPs. The CP sends requests (for information, for help, for resources) to selected peer CPs. In response to requests from its peers the CP may send them information. Help and resources are likely to be provided in a physical form, rather than as information.

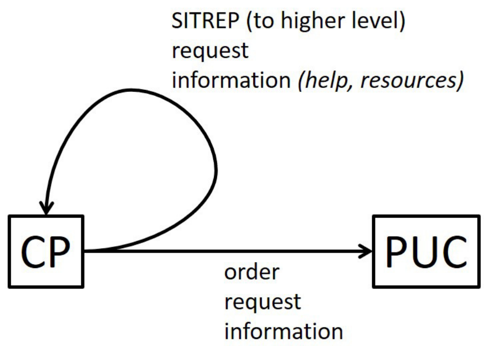

Figure 4. Information flow from CP.

The CP is likely to retain its preference for traditional communications media, such as the fixed-line public switched telephone network (PSTN), the cellular network for mobile telephony, and terrestrial and satellite radio. Voice calls, email, instant messaging (IM, a.k.a. chat), C2 application data, and file transfer will be the main forms in which information will pass over these media.

3.2.2 PUC

The PUC's primary goal are to impose the commander's will on the opposing forces, to minimize the number of victims and recover them for treatment, and to protect and evacuate unaffected citizens. To achieve its secondary, humanitarian goals, PUC units may also need to communicate with family & friends and with NGOs and volunteers.

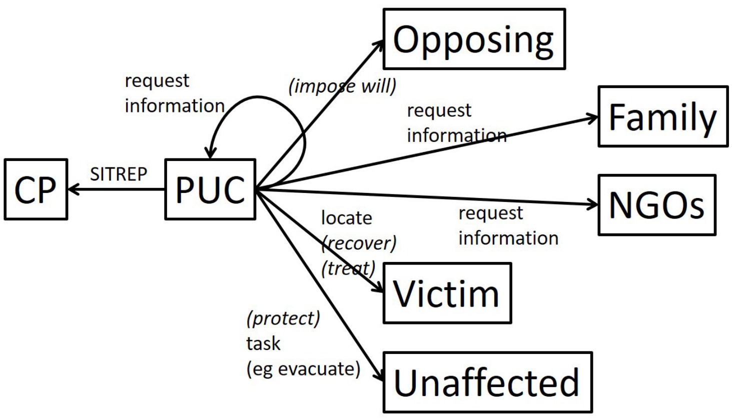

Figure 5. Information flow from PUC.

The flow of information sent by the PUC is shown in Figure 5. Their primary recipients are victims, unaffected citizens, family & friends, and NGOs & volunteers. Information sent to victims will be about their location, recovery, and treatment. Unaffected citizens will be sent information intended to protect them from action taken by the PUC or the opposing forces, such as instructions to evacuate dangerous areas. Information sent to family & friends will include the location and status of victims and unaffected citizens. NGOs & volunteers will be sent requests for information, help, or resources. Interaction with the opposing forces is likely to predominantly physical in nature, although some information may be exchanged (e.g. for psyops or stratcom purposes).

PUC units are likely to retain their preference for traditional communications media (viz. radio, cellular, and email), although this may be enriched with social media, IM, and C2 applications. There may be one or more units specifically tasked with public relations (PR) or civil-military coordination (CIMIC) a.k.a. civil-military interaction (CMI). If so, these units will also make use of webpages and TV and radio broadcasting. Specialised call centres for receiving 112 / 911 calls via the PSTN or cellular networks may also be regarded as part of the PUC.

3.2.3 Unaffected citizens

The primary goal of unaffected citizens is to avoid becoming victims. Their secondary goal is to help victims and other unaffected citizens. To maintain these goals, unaffected citizens may need to contact PUC units, opposing forces, family & friends of victims, and NGOs & volunteers.

The flow of information sent by unaffected citizens is shown in Figure 6. Their primary recipients are PUC units, family & friends of victims, NGOs & volunteers, and other unaffected citizens. The information sent to these recipients will be a request for information, e.g. about which areas to avoid and which areas are safe. Opposing forces are more likely to be observed, rather than sent information. Unaffected citizens may also help victims, but this takes a physical form rather than information transfer.

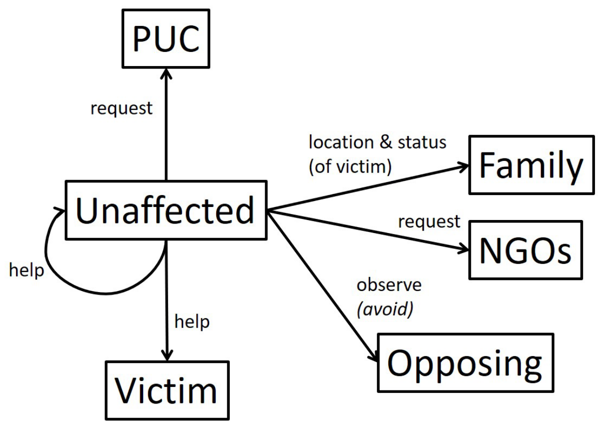

Figure 6. Information flow from unaffected citizens.

Unaffected citizens' preferred media will include traditional means, such as cellular calls, text messages, and email. In addition, they may add content to social networking services (SNS) and to webpages belonging to PUC units and to NGOs & volunteers.

3.2.4 Victims

The primary goal of victims is ensure that they are located, recovered, and treated. Secondary goals are to contact family & friends and to warn unaffected citizens of danger and areas to avoid. The flow of information sent by victims is shown in Figure 7. Their intended recipients are 112 / 911 call centres (i.e. regarded as a specialized PUC unit), unaffected citizens, and family & friends.

Victims' preferred media will include traditional means, such as cellular calls, text messages, and email. In addition, wearable media, such as activity trackers or health apps, may trigger 112 / 911 -like alerts and help in locating victims.

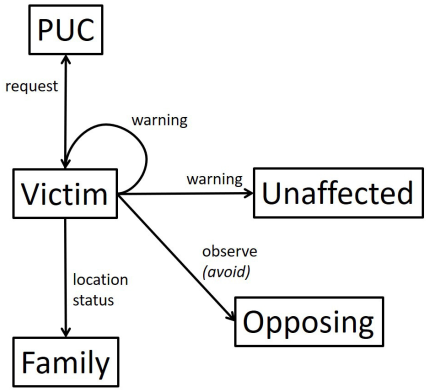

Figure 7. Information flow from victims.

3.2.5 Opposing forces

The primary goal of the opposing forces, if they are present in an operation, is to impose their will on the CP and PUC units. Secondary goals are to intimidate victims and unaffected citizens, to deter or terrorize family & friends, and to discourage NGOs & volunteers from working in the affected area. The flow of information sent by the opposing forces is shown in Figure 8. Their intended recipients are CP, PUC, victims, unaffected citizens, family & friends, and NGOs & volunteers.

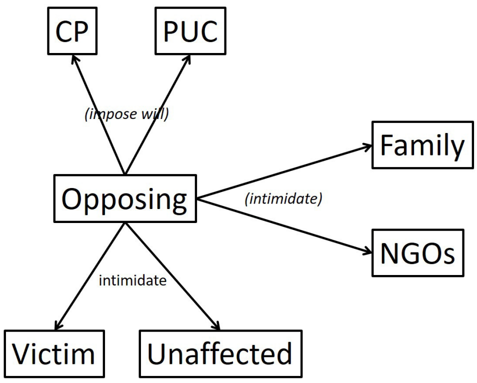

Figure 8. Information flow from opposing forces.

The opposing forces' preferred media include traditional media, such as fixed-line and cellular telephones, text messages, TV and radio broadcast, and posting propaganda, images, and video on SNS and their own webpages.

3.2.6 Family & friends

Family and friends are assumed to be outside the affected area (otherwise they would be classed under unaffected citizens). The primary goal of family & friends is to contact victims and unaffected citizens, to locate them, to learn about their status, and to help them if possible. To achieve this, they may also need to request assistance from PUC units, from NGOs and volunteers, and from opposing forces. The flow of information sent by family & friends is shown in Figure 9. Their primary recipients are victims and unaffected citizens, with PUC, NGOs & volunteers, and opposing forces as secondary.

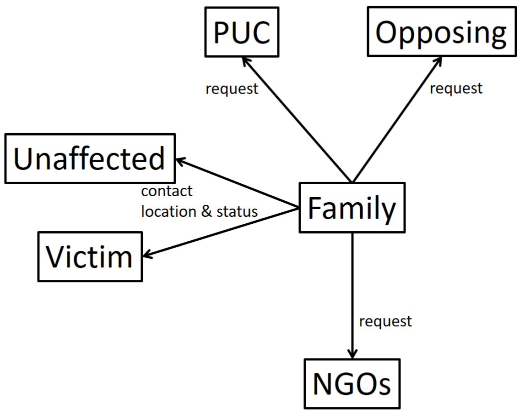

Figure 9. Information flow from family & friends.

Family & friends' preferred media include traditional media, such as cellular telephones, text messages, email, and posts to SNS webpages.

3.2.7 NGOs & volunteers

The primary goal of NGOs & volunteers is to help unaffected citizens and victims in the affected area. If in-area, a secondary goal might be to deconflict with the PUC units and with the opposing forces. Volunteers may also have a secondary goal of feeding crowdsourced information (e.g. crowdmaps with a plot of relevant tweets) to the PUC. The flow of information sent by NGOs and volunteers is shown in Figure 10.

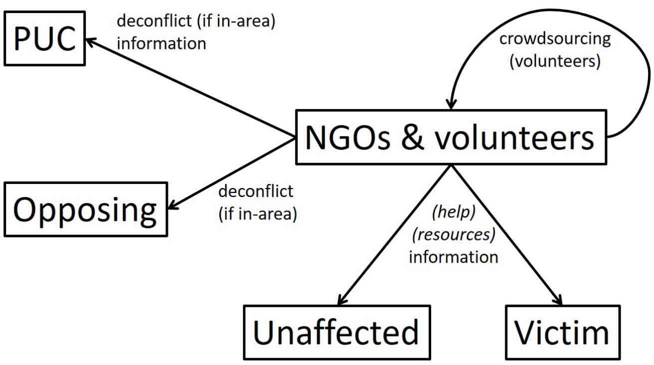

Figure 10. Information flow from NGOs & volunteers.

NGOs & volunteers' preferred media include traditional means such as cellular, text messages, and email. In addition, they may post to the organization's webpages, those of the opposing forces, or to their own webpages. Volunteers may use video teleconferencing tools (e.g. Skype and the like) and shared-working tools (e.g. Google Docs or the like) to work together with other volunteers. If they are working on crowdmaps they may also use freeware or shareware tools like Ushahidi[5], Sahana software[6], or mashups.

3.3 Information exchange matrix

The information flows from sender to receiver segments have been tabulated as an information exchange matrix at Table 2.

Table 2. Information exchange matrix from senders to receivers.

	Receiver								
Sender		**CP**	**PUC**	**Unaffected**	**Victims**	**Opposing**	**Family & friends**	**NGOs & volunteers**
	CP	report request info	order request info			*(impose will)*		
	PUC	report	request info	order	locate	*(impose will)*	request info	request info
	Unaffected		request	help	help	observe	location status	request
	Victims		request	warning	warning	observe	location status	
	Opposing	*(impose will)*	*(impose will)*	intimidate	intimidate		intimidate	intimidate
	Family & friends		request	contact location status	contact location status	request		request
	NGOs & volunteers		deconflict info	info	info	deconflict		crowdsource

3.4 Preferred media by segment

The preferred media have been tabulated by sender in Table 3. The types of media identified include:

- Public Switched Telephone Network (PSTN), a.k.a. fixed-line or land-line telephony.

[5] See https://en.wikipedia.org/wiki/Ushahidi (accessed 3 June 2019).

[6] See https://en.wikipedia.org/wiki/Sahana_Software_Foundation (accessed 3 June 2019).

- 112 / 911 is the public service for receiving emergency calls from fixed or mobile telephones.
- Radio include voice and data radio.
- Cellular a.k.a. mobile telephony.
- Electronic mail.
- Instant Messaging (IM) a.k.a. chat.
- C2-specific applications, including Blue Force Tracking.
- File transfer protocol (FTP).
- Text messaging a.k.a. SMS. This also includes similar Internet-based messaging services, such as Facebook's WhatsApp and Messenger, Apple's iMessage, and messaging apps such as Telegram and Signal.
- Social networking services (SNS), such as Facebook and LinkedIn.
- Organization or personal webpages.
- Wireless Emergency Alert (WEA) service to broadcast emergency text messages to all cellular / mobile telephones in a selected geographical area.
- TV and radio broadcasts.

Table 3. Preferred communications media by sender.

	CP	**PUC**	**Unaffected**	**Victims**	**Opposing**	**Family & friends**	**NGOs & volunteers**
PSTN	√				√		
112 / 911				√			
Radio	√	√					
Cellular	√	√	√	√	√	√	√
Email	√	√	(√)	(√)		√	√
IM	√	√					
C2 apps	√	√					
FTP	√						
Text / SMS		√	√	√	√	√	√
SNS			√		√	√	
Webpage		√	√		√		√

WEA (to cellular)		√ (EW)					
TV / radio broadcast		√ (EW & PR)			√ (PR)		

4. C2 Implications

The advent of smallsat constellations promises commercial broadband Internet and IoT services that will be always on and available anytime, anywhere. Being space-based, the constellations will be largely immune from destructive forces, natural or man-made, at ground level or in the atmosphere. The number of smallsats and their distribution over multiple orbits offer resilience to kinetic attack, even if this took the form of a nuclear magnetic pulse. Anti-satellite systems are unlikely to have a sufficient stock of missiles to destroy a constellation, although service may be degraded. Jamming and spoofing may affect particular geographical areas, but are most unlikely to be global in extent. If there are multiple constellations, there will be some resistance to cyber attack through diversity. A constellation may suffer attrition from laser attack, but the constellation's inherent capabilities for producing new smallsats (AWST, 2019d) and launching them on-demand in groups of 30 to 66 (AWST, 2019a) may well ensure their viability. An attacker would have to produce and deploy many laser systems widely across the globe and/or target the production and launch facilities to reduce the largest constellations to a non-operative status.

In military or EM operations, the existence of smallsat constellations will affect different C2 segments in varying ways, as the segmentation analysis has shown. We assume that professional military forces and EM responding organizations (i.e. the CP and PUC in the analysis) would continue to prefer using their traditional media, both for security and "train-as-you-fight" reasons. While CP and PUC could potentially benefit from the constellations' support for Internet-based media, such as IM / chat and FTP, this could only be for unclassified information. Hence, it is the other C2 segments – non-combatants and opposing forces – that stand to gain the most from smallsat constellations.

The smallsat constellations provide broadband Internet and IoT services. Accordingly, the media most aided by the presence of these constellations are the ones that are Internet-based, namely:

- *Electronic mail*. The segmentation analysis shows that this will benefit family & friends and NGOs & volunteers.
- *Internet-based text messaging*. We need to make a distinction between SMS text messaging using the cellular/mobile network from Internet-based text messaging applications, such as iMessage, WhatsApp, Telegram, Signal, Facebook Messenger, etc. Comsat constellations will support the latter. This will benefit unaffected citizens, victims, family & friends, and NGOs & volunteers. However, it will also benefit the opposing forces. The parts of the PUC that must exchange information specifically with citizens (e.g. for PR or CIMIC/CMI purposes) could also benefit.
- *Social networking*. This benefits unaffected citizens and family & friends, but also the opposing forces.

- *Organization or personal webpages*. This will benefit unaffected citizens and NGOs & volunteers, but also the opposing forces.

In major natural disasters and military operations, terrestrial networks, both fixed and cellular, are usually destroyed, heavily disrupted, or overwhelmed by demand. This happened, for example, during the 2010 Haiti earthquake[7] and the 2013 Haiyan (a.k.a. Yolanda) typhoon[8] in the Philippines. Towns may be cut off for days, local communities and NGOs in the affected area are unable to organize themselves, and victims fail to receive attention.

By contrast, the comsat constellations are highly likely to survive the natural and man-made forces that destroy or disrupt terrestrial networks (NBC, 2015). Towns will no longer be cut off. Local communities that have (or are given) user terminals will be able to organize their response more quickly via the constellations. Victims can be located and rescued, and NGOs can operate more normally.

This has implications for the professional military and EM responder organizations. Citizens, communities, and partner organizations will be better informed and empowered to self-organize. They are likely to be more assertive, placing more demands on the professionals. Military and EM responders will need to be prepared for such demands, organizing and resourcing themselves accordingly. At the same time, the opposing forces – where they are present – will also be enabled by the comsat constellations to influence citizens, communities, and other organizations in the affected area. So, in addition to increased demand for humanitarian action, the professional organizations will also face a pressing need to get their own narrative across. In sum, there will be an increasing emphasis on PR, CIMIC/CMI, and information operations (IO). If the C2 organization is not prepared to meet these demands, then its security mission will suffer.

One way of organizing C2 so as to meet these increasing CMI, CIMIC, and IO demands would be delegate them to out-of-area volunteers. The emergence of spontaneous volunteer groups is already a well established trend in emergency management. Using crowdsourcing techniques, such groups gather donations ("crowdfunding"), collate information from social media (e.g. victims' calls for help on Twitter) and plot it on maps ("crowdmapping"), develop web-based or smartphone applications on-the-fly (e.g. Ushahidi[9] and Sahana[10]), and find answers to questions from in-area citizens and organizations. For example, Haiti's road network was heavily damaged during the 2010 earthquake. Crowdmappers developed a map of the road network from satellite photographs showing where the road surface was broken up or the road was cut off by landslides.

Crowdsourced information has been shown to have higher resolution, to be more timely, and to be more accurate in many situations (Sutton, Palen & Shklovski, 2008). However, employing volunteers is not without problems for professional military and EM responder organizations (St. Denis, Hughes

[7] See https://en.wikipedia.org/wiki/2010_Haiti_earthquake#Damage_to_infrastructure (17 June 2019).

[8] See https://en.wikipedia.org/wiki/Typhoon_Haiyan (17 June 2019).

[9] See https://en.wikipedia.org/wiki/Ushahidi (17 June 2019).

[10] See https://en.wikipedia.org/wiki/Sahana_Software_Foundation (17 June 2019).

& Palen, 2012). A key issue is that of trust in volunteer groups. Another is whether the information they provide is of sufficient quality and in a compatible representation to incorporate into the organization's Common Operating Picture. A third is whether volunteer groups will accept being tasked by professional organizations, and a fourth is whether volunteer groups can be integrated into the professional organization's command structure. Nevertheless, professional organizations do use volunteers in the guise of reservists in other operational situations, e.g. in cyber operations. Perhaps the solution lies in training and exercising with selected volunteer groups, in the same way that selected NGOs are involved in CIMIC/CMI exercises. In any case, employing volunteer groups deserves concept development and experimentation.

5. Conclusions and Further Work

C2 is crucially dependent on the underlying communications infrastructure. In the coming five to ten years, several commercial organizations will be launching mega-constellations consisting of hundreds or thousands of small satellites (smallsats) in low Earth orbit. While some constellations are aimed at earth observation, navigation and positioning, and meteorology, the majority will provide global broadband Internet and IoT services. This paper considers the implications of this imminent "tsunami of smallsats" for C2 in military and emergency management operations.

The known characteristics of the currently proposed LEO comsat constellations are summarized. The biggest of these are SpaceX's Starlink project consisting of 4425 smallsats, Amazon's Project Kuiper with 3236 smallsats (SpaceNews, 2019), and Boeing's K_a- and V-band constellation of 3016 smallsats. The most information available in the public domain pertains to Starlink and OneWeb (648 smallsats), which have a similar architecture. Earlier this year both constellations launched their first batch of smallsats.

The analysis of the C2 implications was done by segmenting the C2 user "market". Each segment's primary goals formed the basis for determining the information flows that the segment would generate, yielding an information exchange matrix between senders and receivers. The preferred communications media used by each segment were identified, with the comsat constellations benefitting Internet-based media.

The professional military and EM responder organizations are assumed to prefer their traditional media for security and "train as you fight" reasons. This means that comsat constellations would most benefit citizens, NGOs and volunteers, and, with ISLs, out-of-area family and friends. Opposing forces, if present, would also benefit. The key implication for C2 systems is that they would have an increased humanitarian workload, emphasizing CMI, CIMIC, and information operations. Volunteer groups might have a role to play in meeting this increased demand, although EM experience shows that there are organizational issues that must be solved.

The main contribution of this paper is to forewarn professional military and EM responder organizations that they must be prepared and resourced to meet the increasing emphasis on CMI, CIMIC, and IO. The paper is unusual in the C2 literature in that it makes a prediction that can be tested empirically in a relatively short timescale, namely five to ten years' time.

There are several shortcomings of the methods used in this paper. The C2 user segmentation analysis is based on a plausible view on each segment's goals and information to be sent. This analysis could be improved by surveying the goals and information needs of each segment during exercises and live operations. The analysis could be made more rigorous by using a framework such as Herring's (2007) faceted classification scheme for computer-mediated communication.

As regards further work, a key direction would be to explore the measures to be taken and resources needed by concept development and experimentation.

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