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Affordable SAR Constellations to Support Homeland Security

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ABSTRACT

This paper describes the applications, benefits and customers for synthetic aperture radar (SAR) payloads carried on small low cost space missions. Although numerous current and soon-to-launch carry SAR, affordability of such missions to serve particular types of customers is poor. This is in part due to the high cost of SAR payloads, and specific needs such as high power drain and support for large, heavy antennae which have mandated large, costly satellites. The paper explores the trade-space between application, customer and performance to show how there is a market for a Disaster Monitoring Constellation class SAR, or DMC-SAR which can support a number of unmet needs in the Earth observation sector. A DMC-SAR mission is shown to be feasible, with various options for sourcing and mating the critical SAR instrument to a small low cost SSTL bus. A price of $50M for such a mission is justified from a bottom up system engineering perspective and a top-down business case driven approach. The value proposition offered by a constellation of DMC-SAR spacecraft is global imagery with a daily revisit, unaffected by weather , day / night operation, with a system robustness far in excess of a single large satellite, and at a price point that allows potential data sales revenue to more than offset the price of the system.

1. INTRODUCTION

This paper will describe the applications, benefits and customers for synthetic aperture radar (SAR) payloads carried on small low cost space missions, as well as exploring the trade-space for an affordable small satellite SAR mission, DMC-SAR. Although numerous current and soon-to-launch carry SAR instrumentation, affordability of such missions and availability of data to many customers is poor. This is in part due to the high cost of SAR payloads, and specific needs such as high power drain and support for large, heavy antennae which have mandated large, costly satellites. The authors argue that an affordable SAR mission, priced at $50M including launch, is feasible with the current state of small satellite bus and SAR technology. A wide potential customer base exists which makes it possible to close a business model based on sale of SAR data, as has been the case for small satellites carrying optical payloads. The trade space explored in this paper covers applications, customers and performance, and shows that for a particular set of each of these parameters, a 'sweet spot' exists for a highly affordable mission with a unique value proposition for homeland security and other civil applications, the DMC-SAR.

The benefits of using active microwave instrumentation, in particular the imaging synthetic aperture radar or SAR to complement optical sensors are well known. The image below, taken by an optical camera on SSTL's Disaster Wide Monitoring Constellation of DMC satellite illustrates how the utility of an optical image from orbit can easily be reduced by clouds or aerosols, in this case smoke in the lower left of the image from large area forest fires in the San Bernardino area of California.

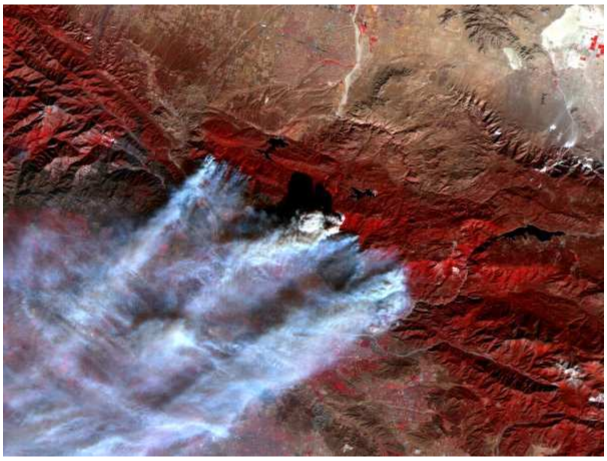

Figure 1: Optical DMC image showing effect of smoke from fires obscuring ground features

Large areas of the world, particularly tropical zones lie under near permanent cloud. SAR has no difficulty penetrating cloud cover, and is an invaluable tool for synoptic mapping, and providing imagery for acute needs such as disaster response. A large portion of optical images from any given satellite must be discarded due to cloud obscuration. Other areas of the world, such as the polar regions suffer from low light levels for much of the year, SAR mitigates this problem.

The ability of SAR instruments to provide day and night coverage is especially useful where time is of the essence, for example in disaster response, or for military applications. SAR images are also free of sun angle constraints which vary seasonally and make comparison of images difficult; this reduction in the need for tight control of the Local Time of Ascending Node (LTAN) also reduces the orbit precision and propulsion demands for the host satellite.

SAR spacecraft and data products serve a range of markets, from military, to civil governments, and a growing range of commercial users. Numerous systems and data products exist: this paper focuses on value which a small satellite based SAR can offer to a range of users whose needs are not well served by current capability. Table 1 summarises some of the SAR missions currently flying and planned for launch, emphasizing the high resolution performance.

Table 1 illustrates the very high cost of most SAR carrying missions, which can be compared with the price of small satellites constellations built to image in the optical wavebands. For example, the first 5 DMC spacecraft were built launched and commissioned for $50M; and the 5 RapidEye spacecraft buses and a ground station which deliver daily images at ~6.5m GSD of the Earth were built for $40M.

Mission	**Origin**	**Launch**	**GSD (m)**	**Image area (km)**	**Mission cost $**
ERS-2	ESA	1995	30	100 × 100	650M (1995)
Radar-SAT-1	Canada	1995	25×28 (std.) 10×9 (fine)	100km (std.) 45km (fine)	650M excl launch
ALOS (PalSar)	Japan	2006	10	70 × 70	
Terra-SAR-X	Germany	2007	1 16	10 × 5 100 × 100	120M excl launch
SAR-LUPE	Germany	2006-2008	<1	5.5 × 5.5	420M inc launch
TEC-SAR	Israel	2008	1-8	Up to 100km	~200M excl launch

Note: GSD = Ground Sampling Distance (m)

Image area examples: not all data products shown.

Table 1: Space based SAR missions

Small Earth observation satellites are currently serving a number of markets, for example Landsat Earth resources (thematic mapping such as land cover particularly forestry), disaster monitoring, agricultural insurance loss adjustment, and national / regional security. However spacecraft carrying SAR sensors are only poorly serving a number of markets which would benefit from radar images to complement optical data. These include disaster monitoring, both in developed and developing countries, monitoring of traffic across the entire arctic region, and homeland security, in areas such as coastal border protection.

DMC-SAR mission is targeted at unmet needs in the Earth observation community at an affordable price. A price target of $50M has been set, for a mission capable of delivering medium resolution imagery over wide areas (noting that DMC offers – 20-30m GSD 3-band optical images over a 600km swath). A SAR constellation able to offer an attractive revisit time and area coverage rate at this relatively modest resolution has great value, but will be challenging to deliver since few buses and no known SAR payloads are suitable for small satellite missions which are constrained in volume, power and attitude control.

2. CUSTOMERS FOR SAR DATA FROM SPACE

Customers with an interest in SAR data and a budget for a mission or missions have tended to fixate on the system resolution, with a target of 1m GSD being clearly attractive where security and surveillance is the primary requirement. Some SAR carrying spacecraft offer medium or coarse resolution modes, able to cover wide areas, as shown in the table below:

Satellite	**Band / pol.**	**Image area (km) / GSD (m)**	**Price (£/km^2)**
Radarsat-1	C HH	300 × 300 / 50 100 × 100 / 25	0.03 0.25
ENVISAT	C VV, HH	100 × 100 / 30	0.06
ALOS	L	70 × 70 / 10 *or* 20	0.09
TerraSAR-X	X VV, HH, dual	100 × 100 / 16	0.17

Table 2: Medium resolution SAR data

Table 2 also shows processed SAR imagery costs as little as 5c / km^2 at the coarsest resolution of interest, to as much as 40c / km^2 at a resolution of 25m. TerraSAR-X imagery is competitively priced compared with Radarsar-1, at only 25c for one km^2 of imagery at a resolution of 16m.

The majority of medium resolution SAR data is earmarked for specific national needs, e.g. the Canadian Ice service for RadarSat; or for scientific purposes for ENVISAT, or is simply insufficient or cannot be delivered in a timely enough fashion for the wide range of markets which require it. Application specific radar data and SAR instruments tailored to those applications are also lacking despite strong civil user community need. This contrasts with optical remote sensing data where multiple providers compete in the market and many different (small) bus and instrument solutions exist.

Table 2 therefore provides insight into the performance and cost which a DMC-SAR mission will need to target. This can be further explored by an analysis of the specific customers who might be interested in a DMC-SAR spacecraft (constellation) and / or the data it could generate.

3. UNMET NEEDS – THE DMC-SAR COMMUNITY

A target system price of $50M, almost an order of magnitude below the costs of current space based SAR systems is deemed sufficient to meet the information requirements for existing users of current 20-30m optical data (the DMC community) and potential new users.

Core applications for a DMC-SAR are likely to be:

1. Ship and ship wake detection, in support of coastal security. A particular benefit of a DMC-SAR would be to scan large areas and cue higher resolution sensors to targets of interest.
2. Oil spill monitoring
3. Rice and other crop monitoring
4. Flood management in particular coordination of emergency response.
5. Disaster response in particular use of SAR interferometry to monitor Earthquake impact and potential volcanic activity.
6. Geological mapping

Key potential customers are therefore:

1. Homeland security and disaster response agencies, who have a remit to respond to hazards and natural disasters, and to provide security information e.g. for coastlines.
2. Commercial entities seeking information on remote and / or hazardous areas of the Earth for operations, for example oil and gas companies prospecting in the polar regions.
3. The current DMC community, including Algeria, Turkey, Nigeria, China and Spain.
4. Future DMC customers, who also have a need for all-weather remote sensing, and for application specific radar data such as flood monitoring and rice crop monitoring. These include nations such as Vietnam, Colombia, Malaysia and Peru.

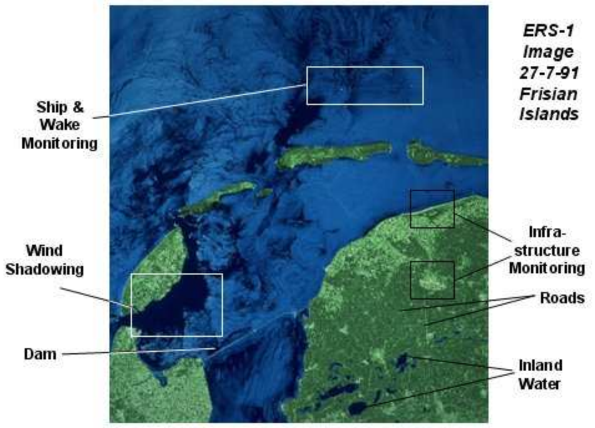

Figure 2: ERS-1 SAR image (30m GSD) showing targets of interest *(courtesy ESA)*

Figure 2 shows that a relatively modest resolution (30m GSD) image can allow identification of various features germane to the applications listed above, including critical infrastructure, ships and their wakes, and inland water or flood boundaries.

4. INSTRUMENT PARAMETERS

Radar, in particular the chirp pulsed scanned beam form used in space based synthetic aperture remote sensing, typically demands high pulsed power levels, large antennae and accurate spacecraft pointing or electronic beam steering. Generating SAR imagery from a small satellite, or a constellation of small satellites is difficult, or results in limited performance. What is meant by performance? The following parameters are most often specified:

Spatial Resolution,

Separated into along track (azimuth), which is driven by antenna size (length) and pulse frequency, and across track (range), which is driven by the bandwidth of the radar pulse, itself impacting radar electronics complexity and cost.

Orbit altitude, and hence range to the target does not actually drive spatial resolution but will drive the transmit power required to achieve a return pulse which is discernable from noise.

Radiometric resolution,

Effectively image quality (contrast), which is determined by receiver design and antenna size.

Swath / image size

Swath or the image across track dimension is driven by antenna size in the across track direction, and the radar pulse frequency. The length of the image, or its along track dimension is primarily limited by the duty cycle the radar instrument can operate for (essentially a spacecraft power limitation), and the ability to either store the generated data on-board or transmit it directly to the ground in real-time.

Particularly in the security application domain, spatial resolution tends to be overspecified, driving up the complexity and cost of the radar instrument. The applications for DMC-SAR will actually benefit most from an ability to cover wide areas, and achieve a frequent revisit over targets or regions of interest. A relatively modest resolution as explained earlier should be attractive the target market.

Thus, the principal mission performance parameters in order of importance are

1. Swath – ideally comparable to DMC (300-600km), 100km would be acceptable.

2. Spatial resolution, ideally 20-30m in azimuth and range, 50m would be acceptable.

3. Radiometric resolution -19 to -20dB. This will enable the imagery to calibrated to accepted commercial standards to enable commercial data sales when not needed for disaster response.

4. Antenna pointing: either electronic beam steering using a phased array (costly), or an ability to roll the spacecraft to widen the field of regard either side of track. This will both improve the revisit time, and ensure a sufficient incidence angle to minimize ambiguities in the returned signal (max. angle in the range 45° or more). Avoiding electronic or antenna steering will keep the SAR simple and low mass.

Image modes

A detailed discussion of possible image modes is outside the scope of this paper. At minimum, a stripmapping mode with the swath width limited by the elevation ambiguities will be needed. The ability to look Left and Right of track using a slow spacecraft roll to fixed station will improve the revisit time but constrains the spacecraft to having a symmetric design.

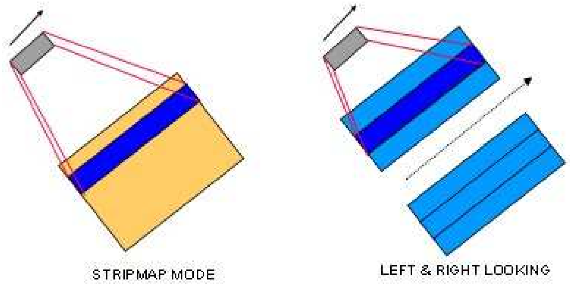

Figure 3: Critical operational mode for DMC-SAR

Other operational modes such as ScanSAR for wide swath, spotlight for high resolution, moving target indicator and interferometry modes are likely to be cost drivers and thus are not critical for DMC-SAR.

Similarly, although a multipolar antenna incorporating RF switching at the front end could offer alternative and alternating polarisations such as HH, VV, HV or VH, this is again likely to be a cost driver and is considered unnecessary.

5. CRITICAL TRADE-OFFS:

The trade space explored in this paper covers applications, customers and mission performance. For a particular set of parameters in each area, a 'sweet spot' exists for a highly affordable, customer focused mission, the DMC-SAR.

The schematic below attempts to illustrate how steering the trade-space away from a (resolution) performance focused, surveillance application and typically military customer focused requirements leads to a set of parameters appropriate for the proposed DMC-SAR:

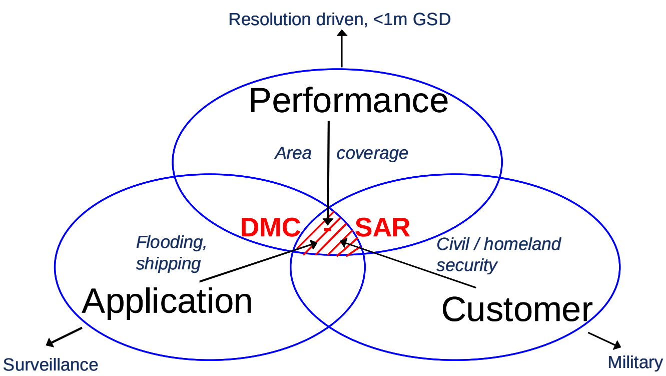

Figure 4: DMC-SAR trade-space

DMC-SAR is a mission driven by a need for wide area coverage (or frequent repeat period), delivering imagery suitable for flood monitoring, ship tracking and disaster response applications, and targeted at customers such as civil agencies dealing with, for example, homeland security and disaster management.

The Table below sets out the baseline and ideal performance characteristics for DMC-SAR

	Frequency	**Polarisation**	**Performance.**
Base-line	X or C band	Single HH	Single mode GSD 20m, swath 100km, max incidence angle >45°
Ideal	C band	Dual HH / HV	*2 modes:* 10-15m GSD, 100km swath, max inc. >45° *and* 30-50m GSD, >150km swath, >45°

Table 3: DMC-SAR performance specification

C-band is preferred as it is the most widely used space based radar frequency to date, and it is a compromise between X- and L-band in terms of complexity of RF electronics and size of antenna. Lower frequencies while providing access to a range of desirable land cover and forestry applications are deemed prohibitive for DMC-SAR, at least until affordable large lightweight deployable structures become available so support the required antenna sizes.

HH polarization is also preferred, since the customers targeted are likely to prioritise ship detection over oil slick detection.

Bus requirements

Meeting the requirements with a suitable SAR instrument will have a number of impacts on the supporting spacecraft bus design. Key concerns for a small satellite are

1. Power / duty cycle (peak v. average power)
2. Antenna size, deployment and pointing
3. Downlink data rate required

Instrument constraints

Selection or development of a SAR instrument which does not make unreason able demands on the small satellite subsystems highlighted above requires consideration of a number of issues. These include:

- Instrument bandwidth – dependant on type of electronics and impacting achievable range resolution.
- Pulsed / chirped mode v. continuous wave operation, impacting availability of inexpensive, off-the-shelf avionics such as power amplifiers, and transmit /repeat or T/R modules. and in contrast requiring consideration of whether a bistatic system would be practical compared to a monostatic radar.
- Antenna size and deployment: Supporting the and accurately pointing the antenna has historically driven the size, mass and cost of the entire spacecraft. For example in Radarsat-1, the antenna mass was 800kg, resulting in an eventual spacecraft mass of 3000kg.
- The antenna type and complexity: Options include a flat phased array, a parabolic reflector, and the compromise of a reflectarray. Although a flat phased array is the most versatile, it is also the most complex and costly, in terms of deployment, shape maintenance and the cost of the number of T/R modules. Conversely, a simple inexpensive parabolic antenna, employed most effectively on the SAR-LUPE constellation spacecraft requires the spacecraft to point the antenna, making advanced modes such as ScanSAR less attractive, and may be less suited to the objective of launching a number of DMC-SAR spacecraft together inside the fairing of a small low cost launcher such as Dnepr.

Activity is ongoing to find payload options which address the above issues, and are suitable for mating to a small satellite bus such as the SSTL-300.

6. PROGRAMME (TECHNOLOGY STATUS)

SSTL has held discussions with a number of potential payload providers, giving consideration to various missions which might be required by different customers. A High performance option (a) might be based on the TerraSAR-X SAR instrument. This instrument is capable of delivering extremely high resolutions and operating in various modes. However the degree of integration between the payload and the bus, shown in the Figure below, suggests that only limited aspects of the SSTL low cost approach and heritage hardware would be possible with this instrument. Hence a cost not much less than the repeat build cost of TerraSAR-X, publicized for TanDEM-X as ~$115M can be expected:

Figure 5: TerraSAR-X and TanDEM-X spacecraft

Option (b) has been explored in considerable detail between SSTL and EADS Astrium UK, and is called AstroSAR-LITE. This spacecraft would employ a novel structural configuration called Snapdragon, which allows a phased array antenna and solar panels to be incorporated within a compact launch configuration, as shown below. A complete suite of SSTL's low cost avionics, together with an Astrium designed structure and a radar payload sourced from Astrium is the basis of AstroSAR-LITE (and its UK customer focused variant AstroSAR-UK). The performance of this mission is again targeted at the military customer, with the radar operating in X-band and delivering a resolution of between 3 and 5m, with the capability to provide different polarizations. AstroSAR-LITE can be built and delivered within 30 months of signing a contract for ~$100M.

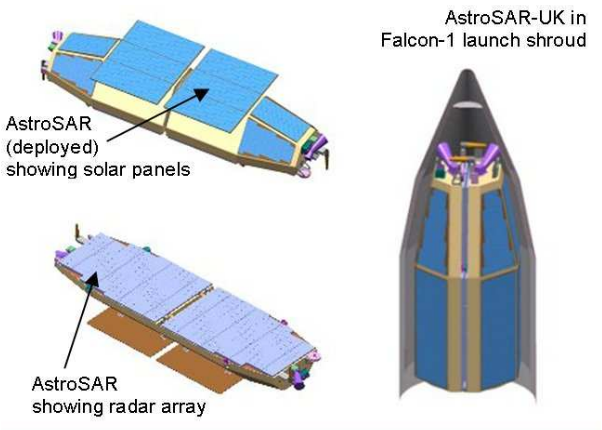

Figure 6: AstroSAR concept

SSTL has also been pursuing and entirely in-house concept design. At present, this has reached the stage of specifying the performance of the payload and establishing a development plan, and exploring different bus configurations. The objective of the present activity is define the concept in sufficient detail to confirm the target price and instrument performance with a high level of confidence. 2 possible configurations are shown below, using either SSTL's larger bus configuration, the SSTL-600, and first flown on the GIOVE-A mission for ESA; and a reduced performance demonstrator instrument hosted on the SSTL-150 bus as used for the RapidEye mission. The '-600' and '-150' numbers refer to the approximate wet mass of the spacecraft in kilograms.

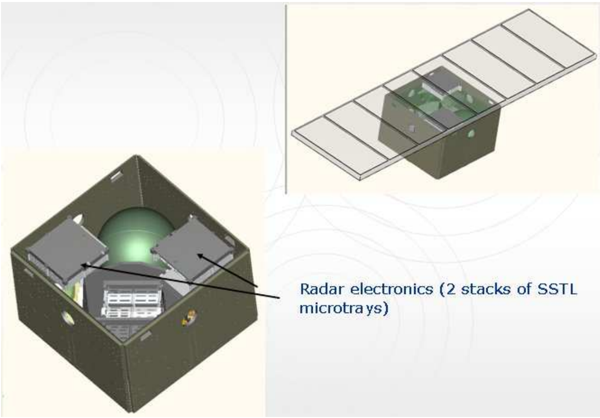

Figure 7: DMC-SAR concept using SSTL-600 bus

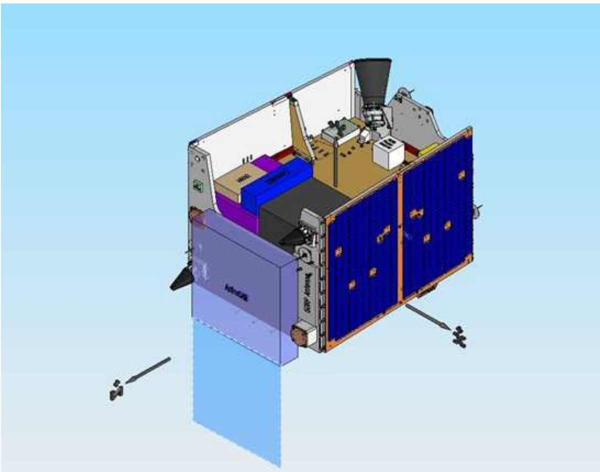

Figure 8: DMC-SAR concept using SSTL-150 bus

Preliminary analysis has suggested that the baseline DMC-SAR performance specification given in Table 3 could be met by the first concept. The phased array antenna size is ~1 × 4m with a mass of under 200kg in this case. A demonstration showing the ability of SAR instrument to image and deliver data, at a coarser resolution of 50-100m could be achieved using a more modest antenna ~0.5m on a side, with a mass of <50kg which is within the capability of the smaller bus.

7. PRICING

Can the price of $50M for a complete DMC-SAR system be met, assuming the combination of a number of costed elements, and making no assumptions about the non-recurring engineering development required to deliver an appropriate level of system performance and reliability? A preliminary price breakdown is given below:

Element	Details	Price $M
Satellite bus	SSTL-300 or 600	15
Radar instrument	Various suppliers	20
Launch	Falcon-1e*	11
Ground station including SAR data processor	SSTL and 3rd party elements	2.5
Operations (5 years)	SSTL	1.5

** Shroud envelope Cylinder 1.35m ∅ × 1.2m L + cone. Launch mass to 500km SSO is ~600kg using 2 burn injection.*

Table 4: Price of DMC-SAR mission elements

Clearly the target of $50M is attainable with a reasonable level of confidence, making some basic assumptions about the bus to be used, an appropriate launcher (launch costs could also be shared between multiple spacecraft to reduce prices) and the likely instrument vendor.

Considering the value of the system from the alternative perspective of data sales revenue is also useful. This will allow the target price of $50M to be assessed for its validity in a business case.

Assuming that the satellite operates in a 100min SSO, 14 orbits / day, with 2% duty cycle, 2 options have been explored:

1. The first option assumes a DMC-SAR able to deliver data products with a coarse resolution of 30-50m GSD over a swath of 100km. This allows an area covered per day of 1.14Mkm^2. Assuming a 5 year mission life, gives a total imaged area in excess of 2×10^9km^2. If all the imagery generated can be sold at a price of $0.05 / km^2 (based on the figures given in Table 2), the total potential revenue exceeds the mission price of $50M by more than 50%.

2. A second option assumes a system operating at the best possible resolution for DMC-SAR, delivering data products with a resolution of between 10 and 30m GSD over a swath of ~30km. Assuming again a 5 year mission life, the total imaged area is $\sim 0.5 \times 10^9 km^2$. If all If all the imagery generated can be sold at a price of \$0.40 / km^2 (based on the figures given in Table 2), the total potential revenue exceeds is more than double the DMC-SAR target mission price.

The simplistic calculations above make some gross assumptions about the utility of the imagery, the spacecraft instrument availability and the actual market for the data; but serve to illustrate that the revenue earning capacity of DMC-SAR is roughly comparable to the likely price which the system would be sold at. Under the right market conditions, data sales could more than offset the price of a system. A higher fidelity business model which explores in particular the price for different data products and specific target customers is under development.

8. SMALLSAT SAR CONSTELLATIONS

The value proposition represented by DMC-SAR becomes most apparent if deployed in a constellation. Currently the (optical) Disaster Monitoring Constellation is able to offer a revisit time of approximately a day, at 32m resolution. The 2nd DMC constellation will commence launching in July 2009 and will improve the resolution to 22m with no degradation of revisit time. A constellation of 4 or 5 SAR carrying DMC spacecraft could be built launched and operated for a price not exceeding \$200M, which is competitive with a single large SAR carrying satellite such as RadarSat or TerraSAR.

The constellation approach offers a number of unique advantages, in particular:

- Global access
- Daily Revisit
- Robustness to failure of any one element of the system such as a single spacecraft
- Capacity uptake (data sales revenue) can be closely matched to cost of system deployment, because of the low cost of entry starting at \$50M for a single spacecraft.

Figure 9: DMC-SAR constellation offering global coverage and daily revisit

The value proposition of a constellation of DMC-SAR spacecraft is therefore: global imagery with a daily revisit, unaffected by weather, day / night operation, complementing existing DMC optical images, and a system robustness far in excess of a single large satellite (effectively guaranteeing data availability), and at a price point that allows potential data sales revenue to more than offset the price of the system, coupled with a low cost-of-entry.

9. CONCLUSIONS

The applications, benefits and customers for SAR payloads carried on small low cost space missions. Have been described Although numerous current and soon-to-launch missions carry imaging radar instruments, affordability of such missions to serve particular types of customers is poor. This is in part due to the complexity and high cost of the SAR instrument, and specific needs such as high power drain and support for large, heavy antennae which have mandated large, costly satellites.

The paper explored the trade-space between application, customer and performance and discussed the market for a Disaster Monitoring Constellation class SAR, or DMC-SAR targeting unmet needs in the Earth observation sector. A DMC-SAR mission is feasible, with various options for sourcing and mating the critical SAR instrument to a low cost SSTL bus. A target price of \$50M for such a mission is reasonable from a bottom up system engineering perspective and a top-down business case driven approach. The value proposition offered by a constellation of DMC-SAR spacecraft is global imagery with a daily revisit, unaffected by weather , day / night operation, with a system robustness far in excess of a single large satellite, and at a price point that allows potential data sales revenue to more than offset the price of the system.