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Microsatellite Constellation for Disaster Monitoring

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Abstract. Every year natural and manmade disasters cause devastation around the World through loss of life, widespread human suffering, and huge economic losses. Remote sensing satellites can contribute to mitigation of this devastation through early warning, event monitoring, and after-the-event studies. Unfortunately, present satellite remote sensing systems do not provide the high temporal resolution required for this activity. Additionally, the images they provide come at high cost per scene.

The Surrey Space Centre at the University of Surrey has designed a constellation of remote sensing microsatellites that delivers 35 m ground resolution over a 600 km width scene in up to four spectral bands. Cost-benefit tradeoffs show that such images can fulfil many needs with the disaster monitoring community.

However, spatial and spectral resolution are not the primary requirements for disaster monitoring; Disaster monitoring users demand high *temporal resolution*. Emerging manmade or natural disasters must be monitored on a daily basis if mitigation efforts are to be effective. Low-cost microsatellites applied in large constellations provide the only cost-effective solution to this design driver.

This paper reports the details of Surrey's Disaster Monitoring Constellation, describing the key subsystem technologies which deliver the desired price/performance ratio, and the overall system design which exploits the low unit cost of microsatellites to deliver a large constellation in affordable and useful increments.

Introduction

The need for a system that can provide dedicated disaster monitoring World-wide is clear. Every year lives are lost, and huge economic losses incurred, due to natural and manmade disasters [1, 2].

Only space-based systems can practicably offer global coverage. Additionally, the monitoring of disaster 'hot spots' and general surveillance requires a certain frequency of observation. Current Earth observation satellites are sometimes used for monitoring disasters if this does not impact the nominal mission significantly. In the best instance, they offer revisit times in excess of a week and coverage of the disaster is not guaranteed and cannot be relied on.

Historically, data from these satellites has come at high cost, often as much as $2000 - $4500 per scene. Even new systems promising significant cost reductions are still estimated at around $600 - $1000 per scene, making use of this data (if available) on a daily, global basis prohibitive [3].

A constellation of these high performance satellites could be designed to provide daily coverage of the globe. Taking the average cost of one of these satellites as $100M - a 5 to 7 spacecraft network would cost between $500M - $700M. These high costs have prevented the implementation of a network of satellites dedicated to disaster monitoring.

The Surrey Space Centre at the University of Surrey has designed a constellation of remote sensing microsatellites that may be dedicated to disaster monitoring. The Surrey Disaster Monitoring Network will deliver multispectral 35 m ground resolution over a 600 km width scene on a daily basis. The entire network cost is less than $50M.

Since 1981, Surrey have placed thirteen 50 kg microsatellites and a 350 kg minisatellite into low Earth orbits. A further two microsatellites and a 5 kg nanosatellite will be launched at the end of this year. These satellites have carried a variety of remote sensing, space science, communications and technology demonstration payloads [4].

The Thai-Putt spacecraft, launched in 1998, demonstrated for the first time high-quality multispectral remote sensing from an inexpensive microsatellite [5]. The commercial off-the-shelf remote sensing technology validated on Thai-Putt provides the key to development of affordable microsatellites delivering useful remote sensing products.

The Disaster Monitoring Constellation will, where appropriate, reuse components and subsystems from previous missions. Throughout the programme the ‘Smaller, Faster, Cheaper’ techniques, pioneered at the Surrey Space Centre, will be applied enabling Surrey microsatellites to deliver a large constellation in affordable and useful increments.

Mission Requirements

The two key mission drivers were daily revisit world wide and low cost per satellite. These drivers constrain the mission as is seen in **Figure 1**, leading to use of constellations of small satellites.

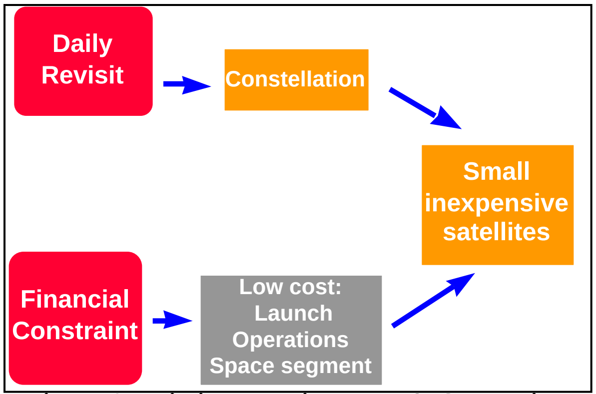

Figure 1. Mission Requirements & Constraints

Each satellite can deliver 35 m ground resolution over a 600 km width scene in up to four spectral bands. The network assumes one spacecraft and one groundstation per partner

Secondary requirements are to maximise the number of scenes delivered and to include a disaster warning broadcast system.

System Design

As guaranteeing daily revisit from the constellation is a primary mission driver, a propulsion system is required to perform station acquisition and station maintenance manouevers.

The low cost constraint not only leads to the requirement for a low cost launch but also reduced space segment and operations costs. As with previous Surrey missions Commercial Off-The-Shelf (COTS) technology will be used where possible and a high level of autonomy in spacecraft operations implemented.

Space Segment

Orbit Selection

Selection of an appropriate orbit involved trade-offs between platform power; Earth coverage and payload sizing; orbital decay and constellation maintenance.

Reduced altitudes lower the required downlink power transmission and antenna size. Higher altitudes reduce the atmospheric drag component - reducing the fuel requirement for stationkeeping.

A 772 km circular Sun-synchronous orbit inclined at 98° gives an exactly repeating ground track and global coverage with the seven satellites. The orbit is good for platform power generation, is thermally benign, and is at an altitude low enough for high resolution imaging, yet high enough not to be severely affected by atmospheric drag. Nine Surrey satellites have been placed into Sun-synchronous orbits and the behaviour of satellites in this environment is well understood.

Constellation Design

In designing the constellation the main considerations were the number of satellites, single satellite swath width, orbital height and acceptable geometric distortion.

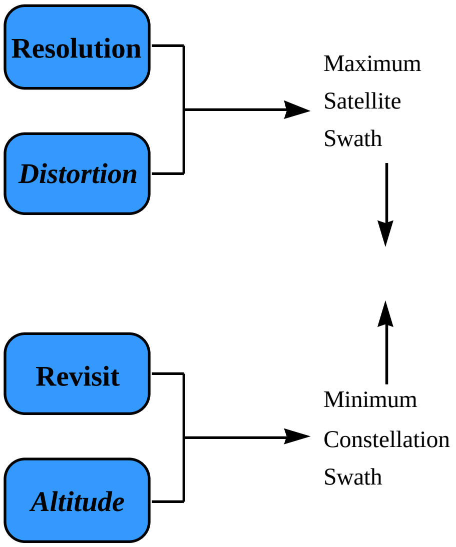

Figure 2 Constellation Design Drivers

As seen in Figure 2 the minimum swath to provide global daily revisit is derived from the simple relationship between spacecraft altitude and Earth rotation beneath each spacecraft. The maximum swath depends on the acceptable degree of geometric image distortion for a given ground resolution element.

A swath around 600 km, or a ≤ 22° offpoint limit, is achievable, if up to 15 % distortion is taken as the worst acceptable case for a 35 m ground element. Assuming that the payload can be designed to provide this swath width, yields a requirement for a minimum number of five spacecraft for global daily revisit to be achieved. It may reasonably be assumed that the maximum number of spacecraft in the network is limited by practical issues such as cost, timescales, and the likely number of partners.

The optimum number of satellites for a particular constellation may differ from the minimum requirement through dependence on the cost per partner, total network downlink time, and redundancy in the event of a satellite failure. Table 1 considers these factors and looks at the network downlink time for a case study constellation.

The seven groundstation sites were chosen to reflect likely partners for the network. The geographic spread of the sites is reasonable and the analysis therefore represents an 'average' case. Groundstations were removed (in order to analyse downlink time variations) so as to maximise the geographic spread.

Table 1 Optimal number of satellites in network

No of S/c[1]	Swath km	Daily revisit	Downlink/day (hrs)	Redundancy
4	600	No	-	-
5[4]	600	Yes	14.36	None
6[3]	600	Yes	24.32	1 s/c
7[2]	600	Yes	35	2 s/c

1. Assumes 1 groundstation per spacecraft
2. Groundstations: Chile; Guildford; Latvia; Mexico; Mongolia; Uzbekistan; New Zealand
3. Groundstations: C; G; Mex; Mon; Uz; NZ
4. Groundstations: C; G; Mex; Uz; NZ
5.

A constellation of six or seven satellites would meet the mission performance requirements. Trading between the cost per user, redundancy, and image quality has led to **a seven satellite network baseline**. The increased coverage overlap with this system means that it is not imperative to utilise the full available swath width, and geometric image distortion may be reduced to less than 10% should this be required. The main driver is, however, the increased downlink time. As one groundstation and one satellite is assumed per user this is the best solution in terms of total downlink time. (An approximate value of 35 hours is used for the 7 satellite, 7 station network. The calculated 43.41 hours downlink time does not take into account the overlap between Guildford and Latvian groundstations. In order to give a fair representation in the trade-off the 'worst estimated case' was considered.) Total network cost does not increase linearly with additional spacecraft so the seven satellite constellation is more cost effective than the six satellite case when the cost per image is considered.

Removing the 1:1 satellite to groundstation ratio provides additional options - a six spacecraft constellation would be more attractive with, say, seven or more ground stations.

A five satellite constellation gives a significantly reduced access time, although the main concern is the lack of redundancy. Loss of a single satellite would result in the entire constellation not meeting the desired performance plateau.

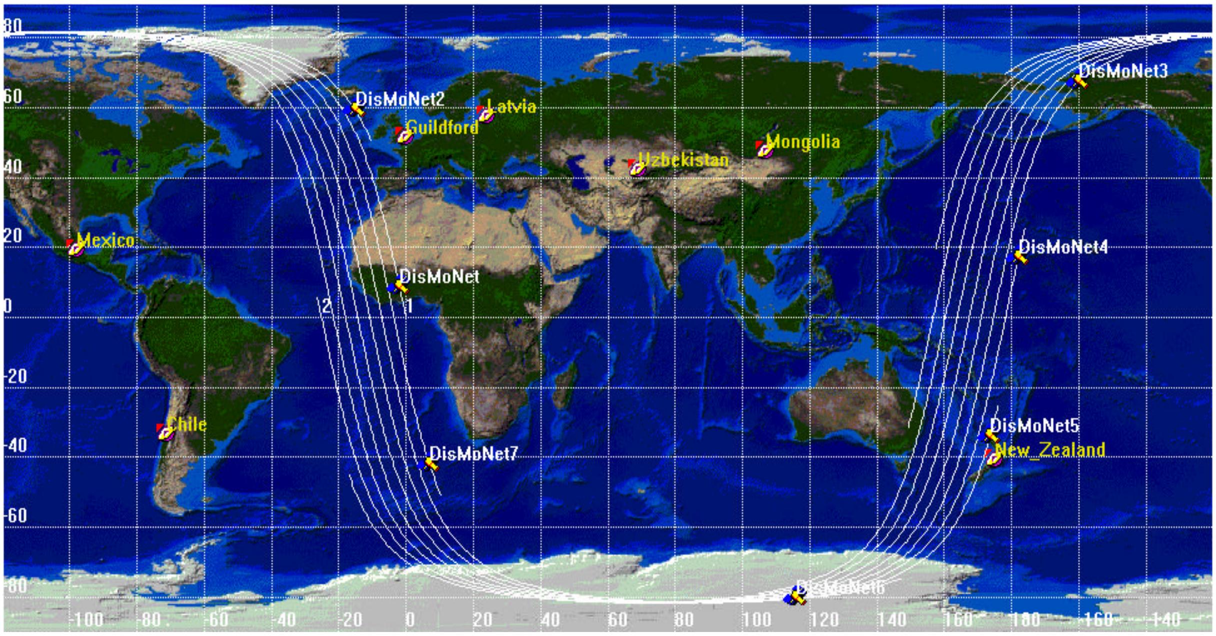

Figure 3 Disaster Monitoring Constellation

Payload Definition

The imaging requirements are for a 600 km swath per satellite, with a 30-40 m ground sample distance and up to four spectral bands.

To meet the challenge of achieving a wide swath and high resolution imaging the following trade spaces were explored:

- area or linear CCD array
- staring versus steered
  - steering options:
    - mirror
    - platform
- single or multiple imagers
- refractive versus reflective optics
- commercial or custom made aperture
- fixed or selectable filters

Sensor Choice

All Surrey imaging satellites to date have employed staring area array CCD sensors. The main advantage being guaranteed geometry under all circumstances due to the fixed pixel structure of the CCD. The snapshot camera is also immune to any residual drifts in attitude stability, which has relaxed ADCS requirements on Surrey satellites, allowing reduced system cost, size, and complexity [6]. High quality commercially available area arrays are available with up to 4096 pixels. Such large arrays are rare and are consequently higher in cost. As the number of pixels increase, pixel to pixel variations become problematic, while the requirements for mechanical shuttering and

A 4096 area array yields a 120 -160 km swath at the required 30 - 40 m resolution - significantly less than the minimum requirement. Potential solutions may be to mount 4 or 5 such sensors side by side, steering a mirror to fold a wide swath onto the array, and slewing the spacecraft. Multispectral imaging could be achieved either by use of a mechanical filter wheel or additional cameras with fixed filters.

The mass and volume requirements associated with these options are likely to drive the platform choice to minisatellite. Surrey's UoSAT-12 minisatellite platform is currently carrying imagers mounted side by side to increase swath width.

Slewing the entire spacecraft by approximately ±22° would provide a 600 km swath. Such a solution is currently being implemented on the Surrey and Tsinghua University microsatellite, Tsinghua-1.

Linear arrays require good platform pointing control and a high degree of platform stability to ensure that successive scan-lines remain close to parallel. Surrey ADCS developments for the UoSAT-12 minisatellite [7] and Tsinghua-1 microsatellite [8] have made pushbroom imaging from low cost small satellites viable. It is possible for a low cost microsatellite operated in momentum bias control mode to offer pointing accuracy better than 0.5° and platform stability in excess of 0.01°/s.

For the Disaster Monitoring the detector must have between 15,000 and 20,000 pixels to satisfy the requirement for 30 - 40 m per pixel over a 600 km swath. High quality, linear arrays up to 12,000 pixels long are commercially available from a variety of manufacturers. Two arrays of suitable length may be mounted side by side, at fixed offset, to provide the 600 km swath.

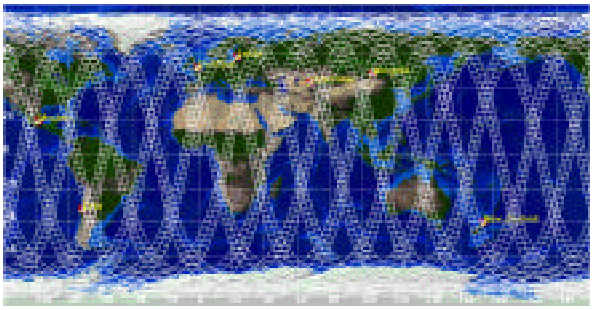

Figure 4 Single Satellite Coverage - 600 km Swath

For multispectral imaging three bands are readily available integrated onto the sensor, a fourth band may be included at additional cost. Each band is one pixel wide and spans the entire length of the detector.

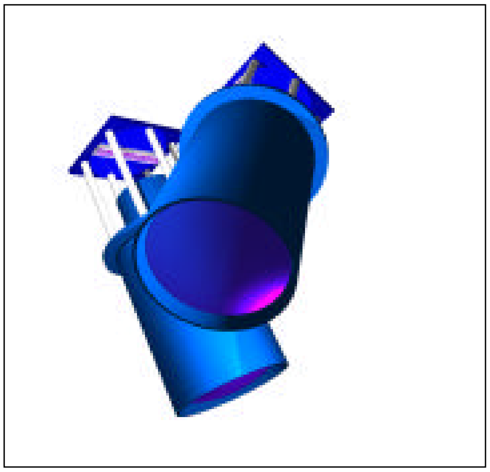

Figure 5 Camera Concept

Two 10,000 pixel sensors mounted side-by-side provide the desired swath and full redundancy. Global daily revisit could still be offered with this system even if one imager was lost on several of the spacecraft. No moving mirrors or spacecraft slewing is required, making this inherently simpler and more robust solution more attractive.

Choice of Optics

When choosing the optics the first decision must be between refractive or reflective elements.

Custom-made mirrors are used for high resolution imaging in most traditional remote sensing spacecraft. Mirrors perform well for small field angles and do not suffer from chromatic aberrations, making them ideal for multi-and hyper-spectral systems. Mirror surfaces must be well figured to very high accuracies, generally making them a costly option. The main considerations in the space environment are their sensitivity to temperature change and deterioration of surface coatings with age.

Lenses perform well for low resolution and wide field angle applications, that involve only a few spectral bands. Chromatic aberrations are severe for wide spectral coverage. Image quality is determined by the use of optically homogeneous glass. Large optically homogeneous disks are difficult to manufacture and as the lens thickness increases with diameter, and so too does the amount of absorption. So, large lenses will give a poorer transmission than an equivalent mirror system. For small to medium apertures the transmission efficiencies of refractors and reflectors are comparable [9].

The main consideration in the space environment is darkening of the lens due to solar and cosmic radiation. Unlike mirrors, lenses are relatively insensitive to temperature changes. Low cost, radiation tolerant COTS lenses have been successfully employed in all Surrey cameras to date.

For the disaster monitoring network a wide swath width at relatively high resolution is required, with a maximum of four spectral bands. A commercially available f/4, 150 mm focal length lens can provide 36 m resolution over a 600 km swath from the 772 km orbit. This low cost, lightweight option can meet the desired performance required and has been baselined. A reflective system would be better suited to a sub-10m imaging system and a narrow field angle.

Attitude Control Options

The options discussed for the Surrey microsatellite enable both wide swath and high resolution to be achieved. Final selection between offpointing the spacecraft and a linear array operated in pushbroom mode was heavily influenced by Surrey's recent advances in attitude control achievable at low cost.

The control options and the basic parameters considered are outlined in Table 2.

Table 2 Attitude Control Options

Control	Gravity gradient & magnetic	Momentum biased	3-axis reaction wheel
Sensors	sun & magnetic	sun & magnetic	sun, star & magnetic
Cost	low	medium	high
Complexity	low	medium	high
Lifetime	high	medium	low
Mass	low	medium	high
Volume	low	medium	high
Accuracy	pitch, roll 1°, yaw 5°	pitch, roll, yaw ≤ 0.5°	pitch, roll, yaw 0.1°
Drift rates	0.05°/s	0.005°/s	0.001°/s
Comments	accuracy fundamentally limited	redundant wheel improves lifetime; accuracy improves with sensors	accuracy improves with sensors

The inherent simplicity of gravity gradient and magnetic spacecraft control leads to a low cost, low mass, reliable mode of stabilisation with long lifetimes. Unfortunately, platform stability from gravity gradient and magnetic control is not sufficient to support linear array pushbroom imaging. Offpointing could be achieved by mounting cameras at a fixed offset and slewing around the Z-axis with a yaw wheel. However, for <50 m imaging the control accuracy becomes problematic. Also, the changing yaw angle means that successive scenes cannot simply be patched together. Complex processing would be required before any contingous coverage could be provided. For these reasons this mode of stabilisation was rejected

In momentum bias mode, a momentum wheel with its spin axis mounted along the pitch (Y) axis is run at nearly constant high speed. This provides gyroscopic stiffness in the roll and yaw axes making this form of stabilisation unsuitable for any offpointing manoeuvers. Surrey's UoSAT-12 platform demonstrates good control and stability when operated in momentum bias mode, confirming suitability of this control mode to linear pushbroom imaging [7]. This ADCS solution meets the performance requirements of the preferred imaging option at modest cost, mass, and lifetime expectation.

Zero momentum mode requires three reaction wheels - one along each axis. This solution can support both the pushbroom and slewing options. It is the most flexible and most accurate control mode. It is also however the most costly, complex and the lifetime is limited.

Imaging Payload Description

The baseline selected for the Disaster Monitoring Network, is a linear array operated in pushbroom mode, on a platform stabilised in all three-axes and controlled about the pitch axis using a momentum wheel. This solution meets the imaging requirements, within the mission constraints. Table 3 provides a summary of the imager characteristics.

Table 3 Imager Characteristics

Sensor:	COTS
Detector	Linear array CCD
Pixel size	7 μm
No of pixels	10,000 x 3
Spectral bands	G, R, NIR
Optics:	COTS
Aperture diameter	100 mm
Focal length	150 mm
GSD	36 m
Swath	600 km (120 km overlap)
Electronics:	Surrey build
A/DC	1 per band
Readout rate	2 MHz per band
Electronics mass	2 kg
Imager:	
Dimensions	100(d)x200(l) mm
Mass	1.5 kg
Peak power	10 W
Max offpoint angle	±22 °

Image System Architecture

Each line (band) on the CCD is digitised to 8 bits using an analogue to digital converter. The digitised data is then read out by a serial register into two 256 Mbyte solid state data recorders. Housing two 512 Mbyte SSDRs on the Surrey microsatellite platform may also be possible. Until this is confirmed the smaller data storage capability is assumed.

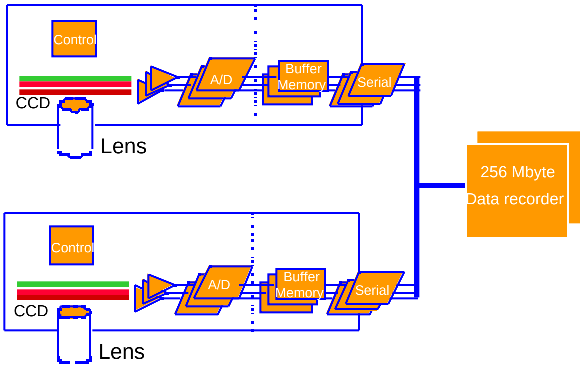

Figure 6 Image System Architecture

Imager System Capacity

A 100 km square "scene" is defined, for convenience, to allow some analysis of system capacity. Each scene occupies 23 Mbytes of memory, allowing a maximum of 22 scenes (total of 2200 square km) to be stored on-board at any one time. These scenes may be patched together in a variety of architectures.

A Surrey wide angle camera is also included, giving 2 km per pixel from the 772 km orbit. The camera is fitted with an optical filter giving near-IR sensitivity, providing strong contrast between land, sea and cloud. The camera may be used for meteorological imaging, but will likely act as a 'spotter' camera to assist in locating the scenery from the high resolution cameras.

Platform Description

The platform options are the Surrey 50-70 kg standard microsatellite, 70-150kg enhanced microsatellite or the 250-400 kg minisatellite. In view of the very low cost constraint the minisatellite was not considered in this case. Furthermore, this platform is far in excess of the accommodation requirements for the selected optical payload. The minisatellite may however prove to be an ideal low cost option for disaster monitoring networks carrying radar and thermal imaging payloads [4].

With the Surrey microsatellite and enhanced microsatellite options, the design goal was to determine which of the two could meet the mission requirements.

The total mission cost, launch cost, and launcher availability drives the decision towards the microsatellite option. However, platform performance - propulsion, ADCS,

requirements - push towards a larger, more costly platform. Surrey microsatellites and the UoSAT-12 minisatellite demonstrate increasingly capable ADCS performance. The development of a propulsion system for the microsatellite is already underway. Given these factors, and the fact that the spacecraft carries only one dedicated (optical) payload, the study shows that the standard Surrey microsatellite can meet the mission requirements. The remainder of this paper looks at the microsatellite subsystems required to provide 35 m gsd imaging in 4 bands over a 600 km swath, with a daily revisit, at low cost.

Baseline Microsatellite

The spacecraft design employs the standard Surrey modular microsatellite stack. Electronics modules are stacked on top of one another to form a structure onto which the solar panels and instruments are mounted. The organisation of the various microsatellite subsystems, housed in the module boxes, is shown in Figure 7

Mounted on to the Earth facing facet of the spacecraft are the Earth imaging cameras, a high gain communications antenna and a sensor suite for attitude determination. The payload electronics and attitude control actuators are housed in the payload bay. The entire propulsion system is housed in a 350 x 350 x 100 mm module box, located at the spacecraft centre of mass. Fixed on to the space facing facet is an omnidirectional S-band antenna, GPS antenna, and the launcher separation interface, which may be tailored as required for the appropriate launch vehicle.

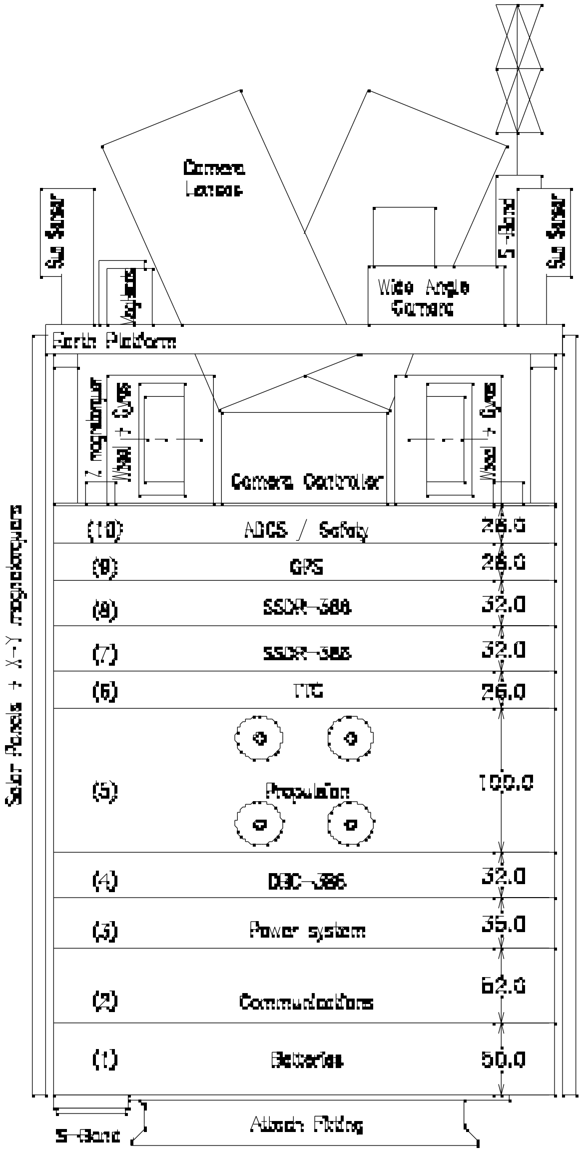

Figure 7 Baseline Microsatellite

Mass Budget

The preliminary mass budget for the Disaster Monitoring Network is presented below.

Table 4 Disaster Monitoring Network Mass Budget

Subsystem	Mass (kg)
GPS Module	2
S-Band Transceiver Module	4
On-Board Computer-386	1.5
Telemetry & Command	1.5
ADCS	7.4
Power & Harness	3.3
Battery	6.3
Cold Gas Propulsion System + fuel	15
Solar Panels + Magnetometers	10
Structure	4.5
Platform Total	**55.5**
Payload & Payload Electronics	7
SSDR-386	1.5
SSDR-386	1.5
Satellite Total	**65.5**

This is comfortably within the maximum mass limit of 70 kg for the standard Surrey microsatellite platform.

ADCS

The study of attitude control options outlined in the 'Payload Description' section resulted in a momentum bias control baseline. This control mode meets the payload requirements and allows both high resolution imaging and coverage over a wide swath, at modest cost, mass, and risk.

The ADCS system will provide nadir pointing with ≤ 0.5° control accuracy in all axes and platform stability ≤ 0.01°/s to support the linear array in pushbroom mode.

ADCS Subsystem baseline

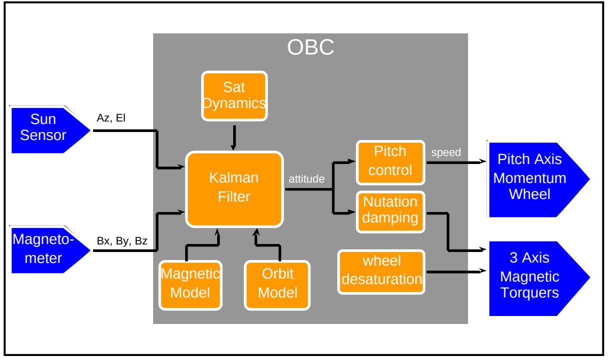

Figure 8 ADCS Subsystem

The attitude is determined with Surrey sun sensors and magnetometers. Four two-axis sun sensors will provide attitude knowledge up to 0.2°. Dual redundant three-axis magnetometers are used to measure the Earth's magnetic field with an accuracy within 1°. During thrusting, for station acquisition and station keeping manoeuvers, magnetometers and a solid state gyroscope are used to maintain the yaw angle to within 10° of the velocity vector.

Sensor data is fed into a Kalman filter, which estimates the attitude by comparing the predicted measurements with those obtained by the sensors. When the estimated attitude differs from the target attitude, the appropriate actuator command is generated. The Surrey magnetorquers and momentum wheel are activated under software control to create the desired torque around the satellite axes.

A momentum wheel with its spin axis mounted along the pitch axis enables attitude control around the pitch axis by torquing the wheel. Desaturation of the pitch wheel will be achieved using the magnetorquers.

The use of fixed body-mounted solar panels enables the platform to generate sufficient power to allow communications and recovery in all attitude conditions. Therefore no mission specific attitude safe modes are required.

The most significant difference between the Disaster Monitoring Network satellites and previous Surrey spacecraft is the absence of the gravity gradient boom for extended mission lifetime or backup. Therefore, spacecraft lifetime is limited by the on-board consumables and the lifetime of the momentum wheel bearings. A redundant momentum wheel is carried to cover the event of failure. A five year nominal lifetime is comfortably covered by the fuel margin and redundant wheel.

Standard ADCS software can be reused, except during orbit phasing. Software to determine and control the attitude during propulsive manoeuvers is being developed at Surrey and much may be applied to this mission. Cold gas propulsion system control software is currently exercised on-board UoSAT-12 and this may also be adapted to the Disaster Monitoring Network Constellation.

ODC

The orbit will be determined using a GPS receiver. Control will be achieved using the propulsion system. The self contained propulsion module is mounted within the stack and may be commanded by the on-board computer via the CAN serial bus in the same way as the other modules.

Orbit Determination Options

Table 5 Orbit Determination Options

	RADAR (NORAD)	Ranging	GPS
Cost	none	high	medium
Complexity	none	medium	medium
Accuracy	1 km error	< 100 m error	< 100 m error
Availability	depends on NASA /USAF	independent	depends on GPS system
Suitability	ground station tracking	orbit det. before & after phasing	autonomous orbit det. & control
Comments	Keplerian elements available over internet	Phase-locked up & down- link plus extra groundstation equipment	Surrey SGAR on-board receiver

The Surrey space GPS receiver has been developed in collaboration with ESA using state of the art, radiation tolerant, commercial components. This will allow precise autonomous orbit determination and control to within 100 m.

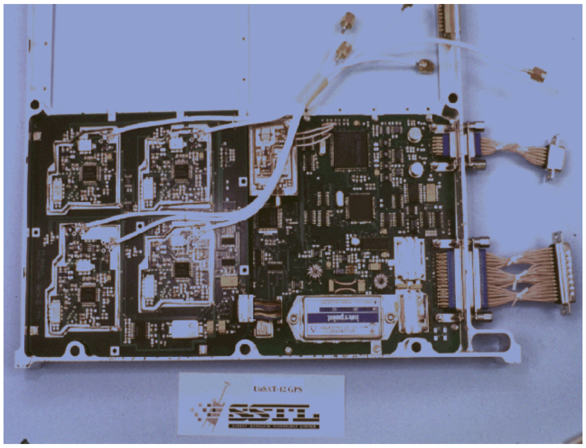

Figure 9 Surrey Space GPS Receiver

Propulsion Requirements

The delta-V budget was calculated for the period 2001 - 2006 and takes into account high solar activity. Station acquisition over a 30 day period. requires a maximum of 5 m/s (only two of the satellites in the constellation will need to travel this maximum distance around the orbit). The maximum requirement for station keeping to counteract the effects of drag and maintain altitude is 6 m/s, although 2m/s is more likely. Giving a maximum delta-V requirement of 11 m/s and a likely requirement of 7 m/s.

Propulsion Options

The propulsion system is required to deliver 7-11 m/s total delta-V. Thrust levels must be kept low to ensure that the satellite remains stable during thrusting.

In order to select an appropriate system for the microsatellite the following constraints were considered:

- mass and volume
- power required
- system price
- technical risk
- safety cost (personal risk)
- integration cost
- logistics cost
- previous experience

Table 6 Microsatellite Orbit Control Options

	Hydrazine Monoprop	Electrical (resistojet)	Differential Drag	Cold Gas
Cost	high	medium	low	medium
Power	< 1W	500 W	none	< 0.5 W
Safety	hazardous	safe	safe	safe
ISP (s)	225	185	N/A	65
Density ISP	226.8	185.0	n/a	14.95
Other	hazardous fuel increases costs	possible thermal difficulties	variable ballistic ratio exploits structure	400 bar storage raises density ISP

The cold gas system has been selected, despite its low density ISP, as it is a safe, low power solution, in an area of Surrey experience.

For orbit control four 0.1 N thrusters, delivering a specific impulse of 65 seconds, will be mounted as close to the satellite centre of gravity as possible in order to minimise the offset and ensure spacecraft stability. The solid state gyroscope will monitor the spacecraft attitude during thrusts to ensure that the thrust vector is as closely aligned with the velocity vector as possible. During thrusts offsets may be corrected by phasing the use of the thrusters.

Microsatellite Propulsion System

The propulsion system must be housed in a 100 mm high self-contained module box, in order for it to be accommodated in the module stack and so, compliant with the microsatellite bus.

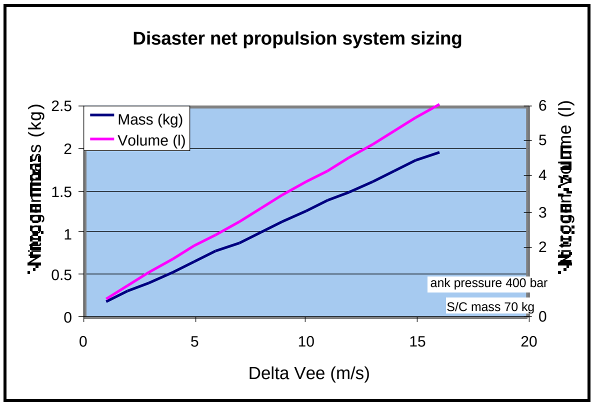

Figure 10 Variation in Storage Volume with Delta-V for a 400 bar Nitrogen Propulsion System

The module box volume is fixed at seven litres, the total tank volume is fixed at 3 litres, so carrying 11 m/s fuel results in a storage pressure of 600 bar. At 600 bar Nitrogen gas exhibits non-ideal behaviour - small temperature increases produce large pressure increases. No suitable prequalified tanks were found that could withstand the maximum expected operating temperature. Suppliers to undertake this development have been identified, but costs and timescales are a significant issue. Export clearance could also be costly, or problematic, for such high pressure systems.

The propulsion system will be sized around the more likely fuel requirement of 7 m/s. As seen in Figure 10, 8 m/s or 1.1 kg Nitrogen can be stored in a 3 litre volume at 400 bar. Nitrogen gas behaviour is almost linear at this pressure - pressure changes with temperature, although significant, are less extreme.

Although operating at this reduced pressure will ease development costs, timescales and export clearance issues - 400 bar still represents a highly pressurised system. In order to reduce system pressure further the following should be addressed in more detail in the next study phase:

- delta-V reduction
    - for station acquisition
    - no stationkeeping
- passive drag control
- liquefied gas propulsion system

Delta-v reduction

Total delta-V may be reduced further by increasing the time taken for station acquisition. Increasing phasing time from 30 days to 41 days gives a 1 m/s delta-v reduction for a 180 degree drift, or 60 days reduces the requirement by 2 m/s.

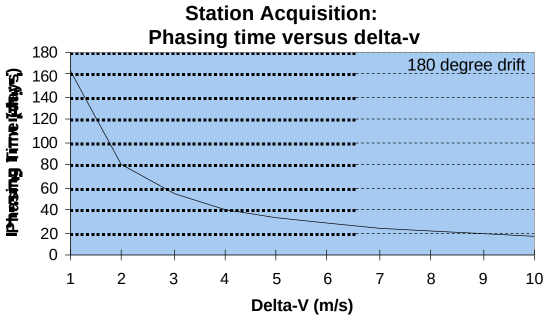

Figure 11 Variation in Delta-V with Phasing Time

After station acquisition is achieved the constellation may be allowed to decay as a unit. This would reduce the delta-V by a minimum of 2 m/s in the likely case, or 6 m/s in the worst instance. For a spacecraft at an altitude of 772 km, the mean orbit decay rate is roughly between 0.1 and 0.2 km a year - or less than 1 km over the five year nominal lifetime [12]. In the worst case a decay in altitude between 8 and 14 km could be expected over the mission lifetime. Further analysis would be required to ascertain more accurate values and to assess the affect on the imaging system performance in terms of ground track knowledge and daily revisit.

Passive Drag Control

The would exploit differential drag between two spacecraft as a means for controlling their relative positions. This is one of the solutions being analysed for use on a constellation of radar altimeters for sea-state monitoring, currently being developed by Surrey and Satellite Observing Systems Ltd (SOS), UK [13]. This solution may be suitable for the Disaster Monitoring Network. Potentially the Dnepr Launch Vehicle could ‘drop’ each satellite off at its desired station within the orbit plane. This, combined with the differential drag solution for relative station maintenance, would eliminate the requirement for a propulsion system. This significantly simplifies the microsatellite design and offers substantial reductions in cost. Again, further analysis would be required to assess how much we will need to trade on requirements to achieve this lower design cost.

Liquefied Gas Propulsion System

Surrey are currently investigating a liquefied gas propulsion system that can be accommodated on a standard microsatellite platform. The system is essentially the same as that proposed for the cold gas system - the main difference being the use of either Nitrous oxide or Carbon dioxide gas as the fuel. CO_2, for example becomes liquefied at 48 bar at room temperature. The specific impulse of these fuels is reduced (around 60s) when compared to Nitrogen (70 s). However, as the density ISPs are higher, the same fuel mass of $C0_2$ and N_20 will occupy a slightly smaller volume than the nitrogen - so additional fuel may be carried in the fixed volume tanks.

At these pressures, safety of handling and export are no longer issues, and commercially available tanks may be used - reducing development costs and timescales.

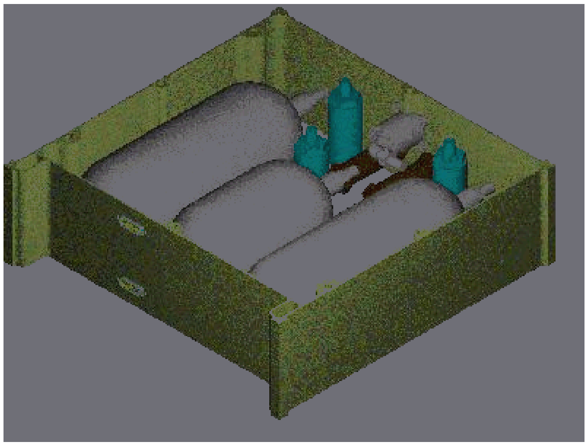

Figure 12 Microsatellite Propulsion Module

Propulsion System Baseline

In short, 1.1 kg of Nitrogen gas can be stored in two 1.5 litre tanks at 400 bar, giving 8 m/s dV. This meets the likely 7m/s fuel requirement for station acquisition and subsequent station keeping over the nominal five year lifetime. The whole system can be housed in a self contained 350 x 350 x 100 mm module box as illustrated in Figure 12. Nitrogen cold gas propulsion has been successfully demonstrated on UoSAT-12 minisatellite. Should the 400 bar system be problematic, then a 50 bar nitrous oxide, or carbon dioxide liquefied gas propulsion system could meet the system requirements with reduced cost and complexity, although further development would be necessary.

Power Subsystem

Platform power is generated by four GaAS solar panels, fixed to the microsatellite body. These provide 50W peak power, an average of 23 W per orbit. Electrical power is stored in a ten cell, rechargeable, 6 Ah NiCd battery pack for use when the spacecraft is in eclipse, or during periods where consumption exceeds platform peak power.

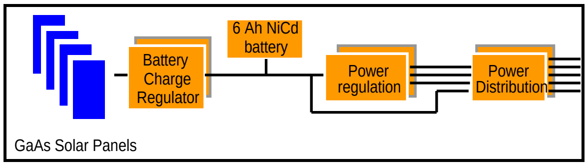

Figure 13 Power Subsystem Architecture

The power subsystem conditions and regulates the electrical energy generated by the solar panels. It provides all other systems with regulated voltage supplies at +5 v and ± 12V, as well as providing an unregulated supply direct from the battery which fluctuates between 12 and 14 V.

Preliminary Power Budget

Table 7 shows the worst case power budget for the platform and payloads.

Table 7 Disaster Monitoring Network Power Budget

Subsystem	Power W	Duty Cycle %	Average W
S-band Rx module	1.0	100	1.0
S-band Tx module	16.0	50	8.0
Power	0.5	100	0.5
Cold gas propulsion	5.0	2	0.1
Housekeeping computer	2.0	100	2.0
GPS module	5.0	2	0.1
ADCS	0.6	100	0.6
Platform Total			**12.3**
Data recorder	2.0	75	1.5
Data recorder	2.0	75	1.5
Imager	10.0	75	7.5
Satellite Total			**22.8**

The duty cycle for the communications downlink is an overestimate as 50% downlink is not possible with a seven station network. Likewise, for the payload, imaging will be constrained by the on-board data storage capacity and is unlikely to approach 75% of the orbit period. All the same, in terms of the power budget near-continuous imaging is achievable.

Telemetry & Command

As with previous Surrey microsatellites, the telecommand system can communicate directly with the groundstation or through the OBC. The OBCs provide timed telecommand events around the orbit, through a 'diary' formulated at the groundstation and uploaded during passes.

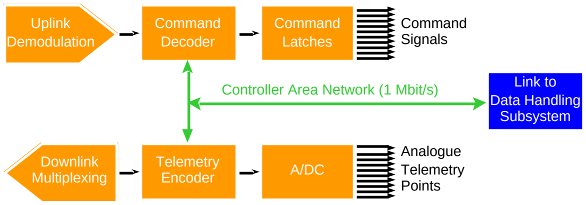

Figure 14 Telemetry and Command Subsystem

Telemetry from the on-board systems and payloads is similarly gathered by the OBC-386, stored in the RAMDISK, and transmitted when the satellite is in range of the control station. When no OBCs are available the central telemetry system can gather, format and downlink telemetry frames to the groundstation.

Data Handling Subsystem

The on-board data handling (OBDH) subsystem comprises three Surrey 80386-based computers each with 256 Mbytes of Ram. These handle satellite control and housekeeping functions; capture, process and format payload data; and manage the communications link. Point to point links allow 10 Mbit/sec data capture whilst a 10 Mbit/sec shared Ethernet link provides Local Area Networking. A Controller Area Network (CAN) provides 1 Mbit/sec links for command and telemetry.

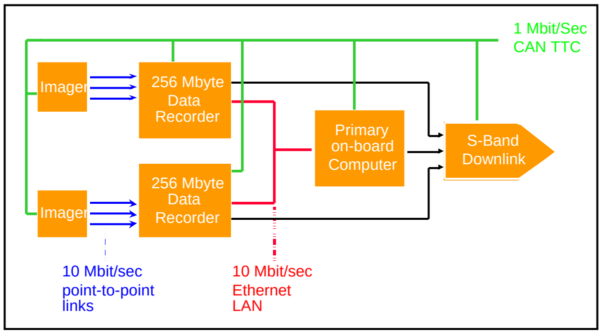

Figure 15 On-Board Data Handling Subsystem

One OBC80386 will be dedicated to housekeeping functions, while the other two will be used to store payload data. Each computer will be able to perform all functions providing full redundancy in the event of a failure.

Data Handling Rates

The 8Mbit/sec S-band downlink is the main data bottleneck. On-board data rates associated with imager buffers & data recorders also impose limits as seen in Figure 17.

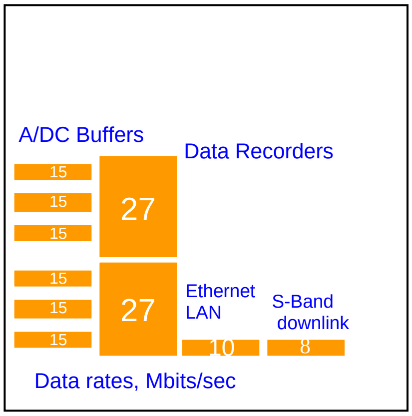

Figure 16 On-board Data Handling Rates

Solutions to reduce on-board data rates are to compress stored data and to select one of the two available user selectable options. Operating the imager in high resolution mode would require throughput of only desired pixels by specifying spatial, spectral and temporal targets. Lower resolution imaging could be achieved through use of subsampling or pixel binning techniques, significantly easing the rates and amount of storage required. Above 100 m GSD continuos imaging is possible.

Communications Subsystem

On-board the spacecraft, a S-band transceiver module will allow transmission of housekeeping and payload data, and will receive commands from Earth. A diplexor is therefore required to isolate transmitted and received signals as illustrated in Figure 17

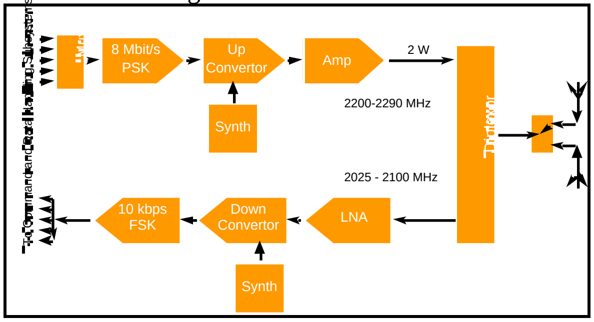

Figure 17 Communication Subsystem Architecture

Groundstation commands will be transmitted via the uplink operating in the 2025-2100 Mhz Earth-to-Space, spacecraft operations band.

Both telemetry and payload data will be will transmitted on a 2200-2500 Mhz Space-to-Earth, spacecraft operations band downlink. A high-gain quadrifiler helix antenna is mounted on the Nadir (+Z) facet for groundstation communications. An omni-directional patch antenna is mounted on the space facet (-Z) to ensure communications if attitude is uncontrolled.

Communications Link Margin

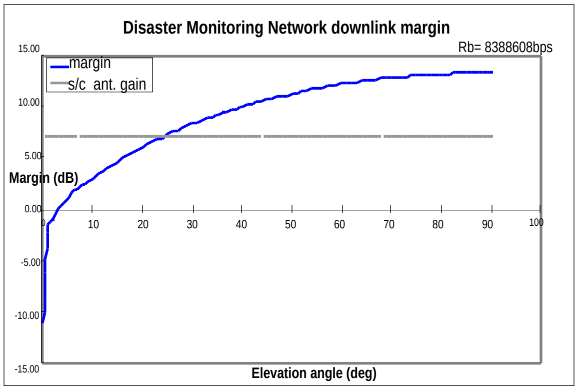

Figure 18 Communications Link Margin

A data rate of 8 Mbps is achieved using a high-gain quadrifiler helix antenna transmitting at 2W RF power to a 3.5 m ground station dish.

Data budgets

Using the 100 km square, 25 Mbyte, 3 colour ‘scene’, for convenience, the image throughput of the system can be quantified.

Consider one satellite with a 8Mbit/sec S-band downlink in view of one ground station. The Surrey ground station would see the satellites for an average of 61 minutes per day enabling 150 scenes per day to be downloaded. Obviously the downlink time varies with groundstation latitude - with sites at higher latitudes giving more frequent satellite accesses, and less access time at near equatorial sites. In our study, the limiting case is Mexico, with an average of 37 minutes downlink time, or 90 scenes, a day. In the best case, the groundstation at Latvia is in contact with a single spacecraft for an average of 75 minutes per day, enabling up to 184 scenes to be received per day. On average of 130 scenes are available per day from one spacecraft to one groundstation.

Now consider, the 7 station 7 Satellite Disaster Monitoring Network. The total network downlink time is over 2605 minutes, or over 43 hours, per day enabling transmission of over 6300 scenes to Earth every day.

These calculations assume contact with the spacecraft between 5° and 85° elevation angles between some of the groundstations. In this case study, there is an overlap between the Guildford and Latvian groundstations, resulting in a loss of downlink time over one of these sites. Further analysis is required to establish exactly how much downlink time will be lost.

Disaster Monitoring Network Space Segment Summary

A network of 70 kg microsatellites will be phased, in a single plane, around a 772 km Sun Synchronous Orbit using a cold gas propulsion system. Orbit determination during phasing will be achieved using the Surrey-ESA GPS receiver. The spacecraft will operate in momentum biased 3-axis stabilised mode to support 35 mm resolution linear pushbroom imaging over a 600 km swath. Payload data will be stored in two dedicated 256 Mbyte Surrey 80386 data recorders. An additional OBC 80386 will be used to perform housekeeping functions. Data will be transmitted to the ground via a 2W 8Mbit/s S-band downlink.

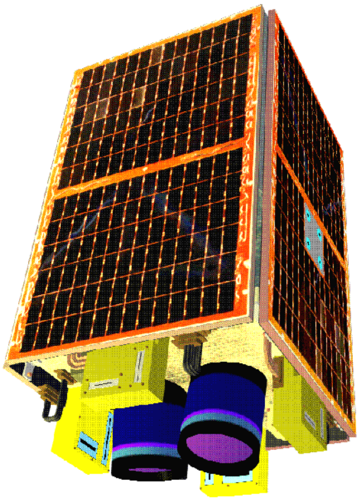

Figure 19 Disaster Monitoring Network Spacecraft

Ground Segment

As seen from the link budget, the 8Mbit/sec S-band payload data downlink and the limited on-board power for transmission mean that a 3.5 m dish is required at each groundstation. With this size dish a radome would be required for shielding against high winds.

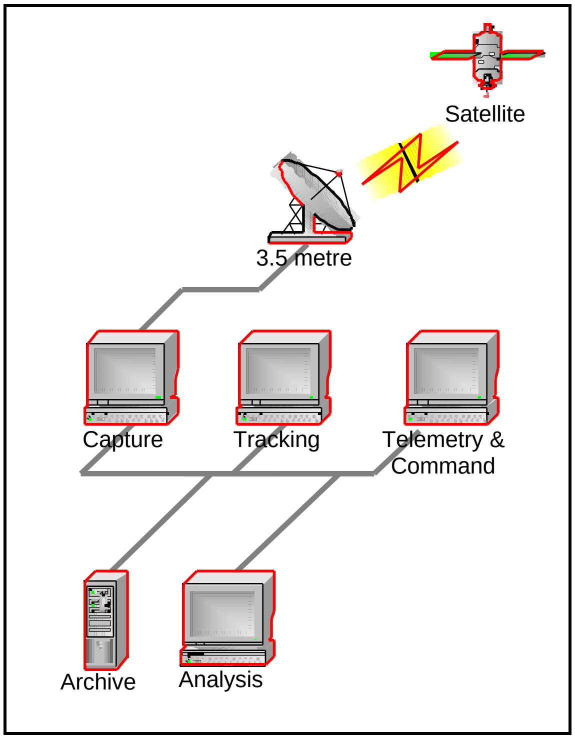

Figure 20 Disaster Monitoring Network Ground Segment

Station Network

The stations could be connected via the internet, leased line, or satellite links. Data can currently be transferred over the internet at a rate up to 1Mbit/sec and this should improve significantly when the information superhighway is fully operational. At present the internet offers the simplest, lowest cost solution and its use will be assumed for all nominal station networking tasks.

Sharing protocols for the network must be agreed by all parties. In the case of disasters and satellite emergencies, sharing must be agreed by all parties. All other data and operations sharing must be agreed bilaterally. A shared data archive can be implemented using the internet.

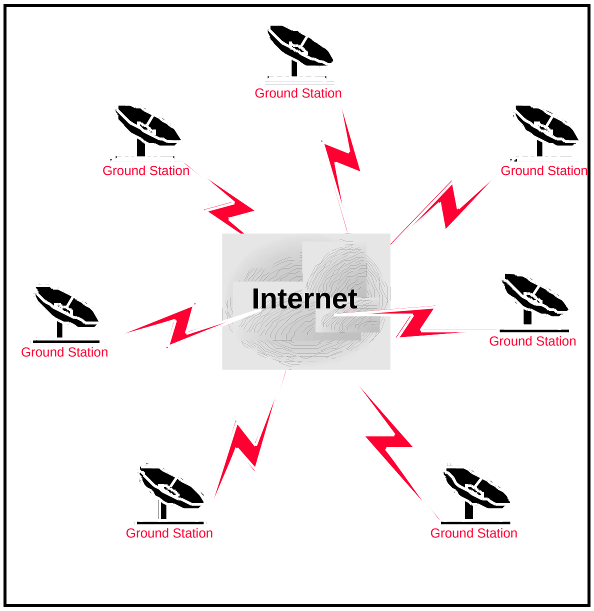

Figure 21 Ground Station Network

Asset sharing levels could take on the following form:

- Disaster monitoring operations
  - All space and ground resources shared
- Spacecraft emergency operations
  - All ground resources shared
- Spacecraft normal operations
  - Sharing by bilateral agreement
- Normal imaging operations
  - Sharing by bilateral agreement

This system offers the all the benefits of a shared network, yet it ensures that partners keep independent ownership of their satellite.

Operational Scenario

A typical procedure for a bilaterally agreed imaging operation is illustrated in Figure 22. A user at ground station (G1) wants an image of a specified target.

- Using only agreed shared assets, the data handling computer at G1 calculates
  - the next viable satellite (S) and the time (T2) for the imaging opportunity
  - the time (T1) and the groundstation (G2) to program operation
  - Time (T3) and the groundstation (G3) to download image
- G1 transmits the requests via the internet to G2 and G3
- G2 and G3 data handling computers calculate availability and priority based on agreed assets
- At T1, G2 programs operation on S
- At T2, S takes the image
- At T3, G3 downloads image and sends to G1 on internet.

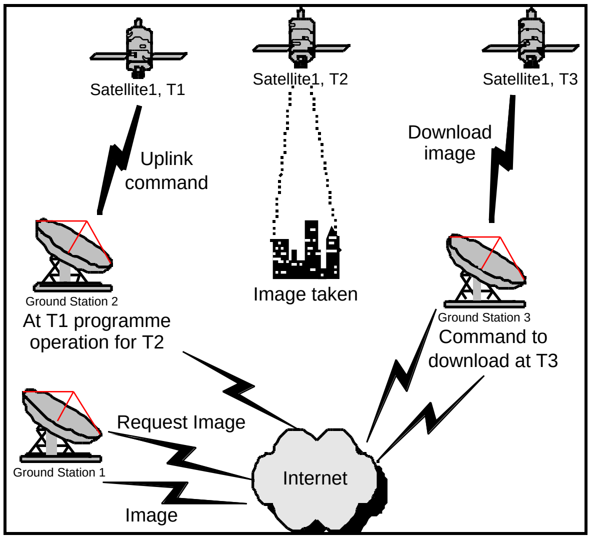

Figure 22 Bilaterally Agreed Imaging Example

Such a distributed, optimised scheduling task is readily implemented using artificial intelligence techniques.

Disaster Warning Paging System

A secondary mission requirement was to include a paging system for disaster warning. This system should be capable of broadcasting a simple warning message to users in remote regions or any other users in 'action' away from the usual modes of communications.

The link budget for the S-band system on-board the Disaster Monitoring Network Satellites, shows that the secondary requirement can be met. The quadrifiler helix antenna system, transmitting at 2W RF power on board the spacecraft, can deliver up to 1.2 kbits/sec to an omnidirectional antenna. This can be packaged into a robust, compact, hand held terminal, providing a lightweight, low-cost option.

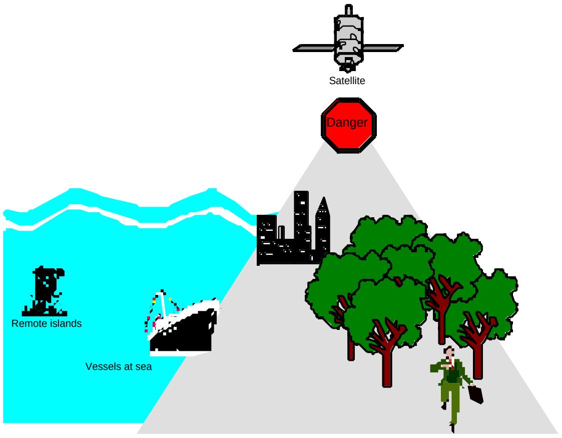

Figure 23 Satellite Broadcast to Hand Held Pagers

The 2170-2200 MHz Space-to-Earth mobile communications channel could be used for the broadcasts. Should there be any licensing difficulties with this channel then the 2483.5 - 2500 MHz Space-to-Earth channel could be used, although operation at these frequencies would impact the diplexor design.

Launch Segment

The Surrey microsatellite bus is designed to be compatible with several launch systems. As well as increasing launch vehicle options, this can offer leverage in negotiating launch cost.

Table 8 Launch Vehicle Options

Launch Vehicle	Company	Performance to SSO, 700 km, 98° (kg)	Cost Est. ($M)
Dnepr[1]	Kosmotras	600 2500 (C5M)	8.5 11
Rockot[2]	Eurockot	800 (Breeze)	12*
PSLV	ISRO	1300	15*
Strela[3]	NPO Mash	950	10*
K1[3]	Kistler	1700	17*

1 Successfully launched Surrey's UoSAT-12, April 22nd 1999
2 Surrey & DBSI constellation launch scheduled for Dec. 2000
3 Under development, 1st flights scheduled 2000
Published in the "International Space Industry Report", July 6, 1998

Table 8 shows the launch vehicle options considered for the disaster monitoring network. The launch vehicle choices were constrained by the following :

- low cost
- constellation launch capability
- availability
- reliability
- compatibility
- performance margins

The Dnepr is selected as the mission baseline, with Rockot as backup, should Dnepr availability be an issue.

Figure 24 Launch Vehicle Integration

Finance

A Rough Order of Magnitude (ROM) cost for the constellation defined in this technical feasibility study is given in Table 9. This estimate has assumed that all seven, identical, spacecraft are built together, and launched together on a single launch vehicle. It has also been assumed that in-orbit commissioning of the constellation will be carried out from the Surrey Space Centre Mission Control Ground Station in Guildford.

Table 9 Total Network Cost (ROM) (USD, 1999)

Constellation	Cost (USD)	Cost/Satellite (USD)
7 spacecraft & payloads 7 ground stations Launch campaign & EGSE	24,300,000 3,735,000 965,000	
Launch	8,500,000	
Insurance	4,500,000	
Total	**42,000,000**	**6,000,000**

Baseline Mission Summary

Parameter	Value	Remarks
Network	7 spacecraft, 7 groundstations	
Platform dimensions	350X350X700 mm	High packing density for constellation launch
Satellite launch mass	70 kg	High packing density for constellation launch
Payload dimensions	100mm aperture, 200mm length each hi-res camera WAC	Hi-res cameras mounted at fixed offset
Payload mass	2 x 1.5 kg High resolution cameras 1 kg Wide angle camera 2.2 kg Payload Electronics	New imager architecture for Hi-res WAC flown on previous Surrey missions
Solid state data recorders	2 x 256 Mbyte OBC80386	2 x 512 Mbyte under feasibility study
Constellation Orbit	772 km, 98°, circular, Sun synchronous, single plane	Repeating ground track
Power	4 GaAS fixed, body mounted panels 23 W orbit average, 50 W peak	Standard arrays flown on previous Surrey missions
Battery	10 NiCd cells, 6Ah capacity	Standard cells flown on previous Surrey missions
Orbit determination	GPS receiver	Surrey SGAR
Orbit control	Pressurised cold gas delta-V: 7 m/s Nitrogen at 400 bar 4 x 0.1 N thrusters	Liquefied gas system under consideration, CO2 or N20at 50 bar. Propulsion systems & thrusters mounted at s/c COG
Attitude determination	Three-axis magnetometer 4 two-axis Sun sensors Solid state gyro	
Attitude control	Three-axis magnetorquers Momentum wheel (pitch axis) dual redundant	
Communications	**Spacecraft** S-band transceiver, diplexor, Quadrifiler helix antenna, 2W RF 8 Mbps payload data downlink, 2200-2290 Mhz Space-to-Earth *1.2kbps broadcast paging system* *2170-2220 Mhz mobile comms band* **S-band Groundstations** 3.5 m dish, radome 2025-2120 Mhz Earth-to-Space, TTC	Omni-directional patch antenna on s/c space facet for comms even in uncontrolled attitude modes Paging to small, hand-held terminals
Operations & asset sharing	Agreed protocols for disaster monitoring , spacecraft emergencies and non-disaster scenarios	Groundstations networked via internet. Shared data archive.
On-board computer	OBC80386	SSDRs can perform the same functions giving full redundancy
Programmatics: Total network cost Expected launch date	<$50M 2002	1999 figure for constellation Constellation launch

Expected performance

Figure 25 Expected Performance from Disaster Monitoring Network Microsatellites

Costs per Scene

Using the ROM $42 Million cost generated for the network, the price per 100 km square ‘scene’ can be estimated.

The study has shown that a single spacecraft, can transmit an average of 130 scenes per day to a single ground station. This gives roughly 250, 000 scenes over the five year nominal mission lifetime. Considering this worst case - with images transmitted from one spacecraft to only one groundstation, the cost per ‘scene’ is roughly $25.

In the best case, with the 7 station 7 Satellite network sharing all resources, a total of over 6300 scenes may be transmitted to Earth every day. Over the five year mission lifetime the Disaster Monitoring Network can download over 12 million, 100 km square images, resulting in a cost per scene of less than $5.

Acknowledgements

Throughout the study many ideas have, and a lot of hard work has, been contributed from all the teams within the Surrey Space Centre. The authors would like to recognise this support and say - thank you.

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